AUTOMATED SEARCHES FOR EXTRAGALACTIC NOVAE

Matthew J. Darnley
Astrophysics Research Institute

A thesis submitted in partial fulfilment of the requirements of
Liverpool John Moores University
for the degree of
Doctor of Philosophy.
June 2005
Abstract

Classical novae (CNe) are interacting binary systems in which the white dwarf undergoes unpredictable explosive outbursts. The energy of a nova outburst is only surpassed by that of gamma-ray bursts, supernovae and a small number of luminous blue variables. However, the outbursts of CNe are far more common than any of these other stars. Due to their brightness and occurrence in both Population I and Population II systems, novae are potentially important as extragalactic distance indicators and tools in the exploration of binary star evolution in galaxies.

The POINT-AGAPE survey is an optical search for gravitational micro-lensing events towards the Andromeda galaxy (M31). As well as micro-lensing, the survey is sensitive to many different classes of variable stars and transients, including CNe. In this work we describe the automated detection and selection pipeline used to identify M31 CNe and we present the resulting catalogue of 20 strong CN candidates observed over three seasons.

The CNe we discover are observed both in the M31 bulge region as well as over a wide area of the M31 disc. Nine of the CNe are caught during the final rise phase (which is often missed in Galactic novae) and all are well sampled in at least two colours. The excellent light-curve coverage has allowed us to detect and classify CNe over a wide range of speed classes, from very fast to very slow. Among the light curves is, for example, a moderately fast CN exhibiting entry into a deep transition minimum, followed by its final decline. We have also observed in detail a very slow CN which faded by only 0.01 mag day$^{-1}$ over a 150 day period. The
CN catalogue constitutes a uniquely well-sampled and objectively-selected data set with which to study the statistical properties of CNe in M31. As a by-product, we have detected other interesting variable objects, including one of the longest period and most luminous Mira variables.

An analysis of the MMRD relationship in M31 was performed using the resulting POINT-AGAPE CN catalogue. Within the limits of the uncertainties of extinction internal to M31, good fits were produced to the MMRD in two filters. The MMRD calibration was the first to be performed for Sloan $r'$ and $i'$ filters. However, we were unable to validate the existence of a $t_{15}$ (or similar) relationship for either filter.

The subsequent analysis of the automated pipeline has provided us with the most thorough knowledge of the completeness of a CN survey to-date. Using this analysis we were able to probe the CN distribution of M31 and evaluate the global nova rate. Using models of the galactic surface brightness of M31, we were able to show that the observed CN distribution consisted of a separate bulge and disk population. We were also able show that the M31 bulge CN eruption rate per unit $r'$ flux was up to an order of magnitude greater than that of the disk. This adds weight to the findings of some other authors with respect to nova rate versus stellar population type in extragalactic systems.

Through a combination of the completeness, M31 surface brightness model and our M31 CN eruption model, we were able to deduce a global M31 CN rate of $59 \pm 13$ year$^{-1}$, a value much higher than found by previous surveys. Given our understanding of the completeness and an analysis of other sources of error, we are confidently able to conclude that the true global nova rate of M31 is at least 50% higher than was previously thought.

Finally, we go on to introduce an extension of our survey to the extragalactic systems M81 and NGC 2403. This involved a pilot project, using the Isaac Newton and Jacobus Kapteyn telescopes on La Palma, which is now being executed as an approved programme on the 2m Liverpool Telescope (LT). Preliminary results of
the LT programme are presented and this, and other future work is discussed.
Acknowledgements

I would like to thank all of the members of the Astrophysics Research Institute who have helped me through my time here, especially those that have felt the brunt of my “over enthusiastic” shots during football every Friday.

Of course I would also like to especially thank my three supervisors, Mike Bode, Eamonn Kerins and Andy Newsam for all their time and effort in helping me complete this work.

Additionally I would like to thank Gavin Dalton, Nick Jelley and Neil Johnson who all helped me greatly as an undergraduate and who helped convince me to continue my studies.

I would also like to thank PPARC and Liverpool John Moores University, who gave me the opportunity to embark on my PhD studies. Thanks also go to the members of the POINT-AGAPE collaboration, who provided me with the dataset on which this work is based and who were always willing to offer help and advice.

Last, but certainly not least, I would like to thank Laura for all her help, love and support throughout the last seven years (and of course for proof reading this thesis countless times).
Contents

Abstract ii

Acknowledgments v

Contents vi

List of tables xiv

List of figures xvi

Declaration xxii

Publications xxiii

1 Classical Novae 1

1.1 Introduction 1

1.2 Why study novae? 2

1.3 Photometric evolution 4

1.3.1 Typical CN evolution 8

1.3.2 Nova speed class 10

1.3.3 Bolometric luminosity 11
1.3.4 Maximum magnitude, rate of decline relationship . . . . . . 13
1.3.5 Absolute magnitude 15 days after peak . . . . . . . . . . . 16
1.3.6 Colour two days after maximum light . . . . . . . . . . . . 17
1.4 Hα emission . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 19
1.5 General spectroscopic evolution . . . . . . . . . . . . . . . . . . 19
1.6 Nova remnants . . . . . . . . . . . . . . . . . . . . . . . . . . . 20
1.7 CN central systems and models of the outburst . . . . . . . . . . 20
1.7.1 Novae as cataclysmic variables . . . . . . . . . . . . . . . . . . 21
1.7.2 Bolometric maximum . . . . . . . . . . . . . . . . . . . . . . . 21
1.7.3 Visible maximum . . . . . . . . . . . . . . . . . . . . . . . . 22
1.7.4 Constant bolometric luminosity . . . . . . . . . . . . . . . . 23
1.8 Extragalactic distance indicators . . . . . . . . . . . . . . . . . 24
1.9 Automated CN detection . . . . . . . . . . . . . . . . . . . . . . . 25
1.10 This work . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 25

2 Extragalactic Surveys for CNe and the POINT-AGAPE Project 27
2.1 Introduction . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 27
2.2 Galactic novae . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 27
2.3 Extragalactic novae . . . . . . . . . . . . . . . . . . . . . . . . . . . 28
2.4 The Andromeda Galaxy – M31 . . . . . . . . . . . . . . . . . . . 29
2.5 Surveys for CNe in other galaxies . . . . . . . . . . . . . . . . . 31
2.5.1 M33 . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 31
2.5.2 M49 . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 31
3 Data Reduction and CN Detection Pipeline

3.1 Introduction .................................................. 44

3.2 Image pre-processing ......................................... 45

3.3 Data reduction ................................................ 46
  3.3.1 Image alignment and trimming ....................... 46
  3.3.2 PSF-matching .......................................... 47
  3.3.3 Background estimation and bad pixel masking .... 48

3.4 Aperture photometry detection pipeline ................. 50
  3.4.1 Standard star selection ................................ 52
  3.4.2 Object definition ...................................... 53
3.4.3 Preliminary nova selection .................................. 54
3.5 PSF-fitted photometry pipeline ............................... 56
  3.5.1 Relative PSF-fitted photometry .......................... 57
  3.5.2 Photometric calibration and colour selections ........... 59
  3.5.3 Astrometry ............................................. 62
3.6 Summary .................................................... 62

4 The M31 Nova Catalogue ......................................... 64
  4.1 Introduction ............................................... 64
  4.2 The catalogue .............................................. 64
  4.3 Very fast novae ............................................ 65
  4.4 Fast novae ................................................. 68
    4.4.1 PACN-00-06 ........................................ 68
    4.4.2 PACN-01-02 ........................................ 68
  4.5 Moderately fast novae ..................................... 73
    4.5.1 PACN-99-06 ........................................ 73
    4.5.2 PACN-00-04 ........................................ 73
    4.5.3 PACN-00-05 ........................................ 74
    4.5.4 PACN-01-04 ........................................ 74
    4.5.5 PACN-01-06 ........................................ 74
    4.5.6 PACN-00-07 ........................................ 74
  4.6 Slow novae ................................................. 75
    4.6.1 PACN-99-04 ........................................ 87
4.6.2 PACN-01-03 ............................................. 87
4.7 Very slow novae ............................................ 87
  4.7.1 PACN-00-02 ............................................. 87
  4.7.2 PACN-01-01 ............................................. 91
4.8 Distribution of CNes ....................................... 94
4.9 Pipeline detection efficiency ............................... 94
4.10 Borderline and other light-curves .......................... 96
  4.10.1 A very long period Mira ............................... 96
  4.10.2 Micro-lensing event PA-99-N2 ......................... 97
4.11 Summary .................................................. 97

5 Analysis of the MMRD and $t_{15}$ Relationships 101

  5.1 Introduction ............................................. 101
  5.2 Extinction ............................................... 101
    5.2.1 Foreground galactic extinction ...................... 102
    5.2.2 Extinction within M31 ............................... 102
  5.3 Maximum magnitude, rate of decline ...................... 103
    5.3.1 Maximum light uncertainties ....................... 110
    5.3.2 Extinction corrections .............................. 115
    5.3.3 Comparison with previous results ................... 116
  5.4 The $t_{15}$ relationship ................................ 119
    5.4.1 Maximum magnitude and extinction uncertainties ... 120
    5.4.2 Comparison with previous results ................... 123
5.5 Summary and discussion ........................................... 124
  5.5.1 The MMRD relationship ...................................... 124
  5.5.2 The $t_{15}$ relationship ...................................... 127

6 Parent Stellar Population and the Overall Nova Rate 129
  6.1 Introduction .................................................. 129
  6.2 Seeding the data ............................................ 129
    6.2.1 Creating test light-curves .............................. 130
    6.2.2 Seeding the raw POINT-AGAPE data ................. 130
    6.2.3 Re-running the nova detection pipeline ............ 131
  6.3 Completeness distribution ................................. 133
  6.4 Probability distribution ................................... 136
    6.4.1 Testing the probability distribution – Wilcoxon-Mann-Whitney Test ........................................ 138
    6.4.2 Testing the probability distribution – Kolmogorov-Smirnov Test ........................................ 142
    6.4.3 The $\alpha$ probability model .......................... 143
  6.5 Modelling M31’s galactic light ............................. 146
  6.6 Testing the bulge or disk-only distributions ............ 153
  6.7 The two population model .................................. 156
  6.8 Maximum likelihood testing ................................. 160
  6.9 Fast and slow populations .................................. 165
    6.9.1 Fast novae ............................................. 165
6.9.2 Slow novae .................................................. 170
6.10 The M31 nova rate .......................................... 174
6.11 Summary and discussion ................................... 179
  6.11.1 Completeness ............................................. 179
  6.11.2 CN population of M31 ................................... 181
  6.11.3 M31 nova rate ............................................. 182

7 Classical Novae in Other Galaxies 185
  7.1 Introduction .................................................. 185
  7.2 The Liverpool Telescope ..................................... 186
  7.3 LT extragalactic CN survey target galaxies .............. 187
    7.3.1 M81 ....................................................... 188
    7.3.2 NGC 2403 ............................................... 189
    7.3.3 M64 ....................................................... 189
  7.4 The initial pilot - The Excitement of Science project ... 190
  7.5 Progress to date with LT CN programme ................. 192

8 Summary and Further Work 196
  8.1 Summary of results to-date .................................. 196
    8.1.1 CN detection pipeline ................................... 196
    8.1.2 POINT-AGAPE CN catalogue ............................ 196
    8.1.3 Novae as distance indicators ............................ 197
    8.1.4 M31’s CNe population .................................... 198
8.1.5 The M31 nova rate ........................................... 200
8.1.6 Surveys for CN in other galaxies .......................... 200

8.2 Further work ..................................................... 201
  8.2.1 The POINT-AGAPE dataset ............................... 201
  8.2.2 The Liverpool Telescope CN survey ....................... 201
  8.2.3 The Angstrom project ................................. 202

Bibliography .................................................................. 203

  A Colour System Transformation .................................. 213
  B The Wilcoxon-Mann-Whitney Rank Test ....................... 216
  C LT extragalactic CN Programme Observing Schedule To-date 218
  D Journal Papers ...................................................... 228
## List of Tables

1.1 CN speed classes ................................................. 11
1.2 Nova $M_{15}$ values for various pass-bands ................... 18

2.1 Principal M31 CN surveys ....................................... 30
2.2 The distribution of each of the three seasons of POINT-AGAPE observations by field and filter band. ......................... 40

3.1 Data lost during the trimming and masking process ............. 50
3.2 The number of non-varying standards identified in each of the CCDs using the aperture photometry pipeline. ....................... 53
3.3 The number of non-varying standards identified in each of the CCDs for all bands using the PSF-fitting photometry pipeline. ... 59
3.4 The effect of each stage of our selection pipeline upon the classical nova candidate catalogue. .......................... 60

4.1 The POINT-AGAPE classical nova catalogue – Part I. .......... 66
4.2 The POINT-AGAPE classical nova catalogue – Part II. ........ 67
4.3 M31 classical novae speed class distribution. ................... 67
4.4 The distribution within each CCD of candidates selected by our CN detection pipeline. ............................. 91
### Contents

5.1  $r'$ and $i'$ maximum observed magnitudes and corresponding $t_2$ times for each CN detected in the POINT-AGAPE data.  

5.2  Maximum magnitudes and corresponding maximum magnitude error and average extinction correction for the POINT-AGAPE novae.

6.1  The effect of each stage of our selection pipeline upon the synthetic CN catalogue.

6.2  M31 model predictions for the overall nova rate.

6.3  M31 model predictions for the global nova rate.

7.1  Break down of LT CN observations by filter.

A.1  Best-fit $\Gamma$ and $\beta$ coefficients for colour equations (A.1–A.4).

C.1  M81 LT observation schedule to date.

C.2  NGC 2403 LT observation schedule to date.
List of Figures

1.1 Image sequence showing the photometric evolution of a CN. . . . 3
1.2 McLaughlin’s ideal CN light-curve. ................................. 5
1.3 Nova V1500 Cyg. .................................................. 6
1.4 Nova V705 Cas. .................................................... 6
1.5 Nova HR Del. ....................................................... 7
1.6 Nova V603 Aql. .................................................... 7
1.7 Schematic multi-frequency development of a CN outburst .... 12
1.8 MMRD relationship for CNe in M31 and the LMC. ............. 15

2.1 Frequency distribution of maximum magnitudes of M31 CNe . 36
2.2 The positions of the North and South POINT-AGAPE fields. . 38
2.3 Response curves for the WFC $g'$, $r'$ and $i'$ filters. ............ 39
2.4 The cumulative temporal coverage of the POINT-AGAPE survey. 41
2.5 False-colour image of M31, created from the POINT-AGAPE data. 42

3.1 A histogram of POINT-AGAPE observation FWHMs. .......... 49
3.2 Schematic diagram summarising the classical novae detection process. ............................................. 51
3.3 Standard star light curve .................................................. 58
3.4 A colour–magnitude diagram showing the 52 CNe candidates remain- ing prior to colour selection. ............................................. 63

4.1 PACN-99-07 – Classified as a very fast CN ............................... 69
4.2 (a) PACN-99-05 – A fast CN .............................................. 70
4.2 (b) PACN-00-06 – A fast CN .............................................. 71
4.2 (c) PACN-01-02 – A Fast CN .............................................. 72
4.3 (a) PACN-99-01 – A moderately fast CN. ............................... 76
4.3 (b) PACN-99-03 – A moderately fast CN. ............................... 77
4.3 (c) PACN-99-09 – A moderately fast CN. ............................... 78
4.3 (d) PACN-00-01 – A moderately fast CN. ............................... 79
4.3 (e) PACN-00-03 – A moderately fast CN. ............................... 80
4.3 (f) PACN-00-04 – A moderately fast CN. ............................... 81
4.3 (g) PACN-00-05 – A moderately fast CN. ............................... 82
4.3 (h) PACN-00-07 – A moderately fast CN. ............................... 83
4.3 (i) PACN-01-04 – A moderately fast CN. ............................... 84
4.3 (j) PACN-01-05 – A moderately fast CN. ............................... 85
4.3 (k) PACN-01-06 – A moderately fast CN. ............................... 86
4.4 (a) PACN-99-02 – A slow CN. ............................................ 88
4.4 (b) PACN-99-04 – A slow CN. ............................................ 89
4.4 (c) PACN-01-03 – A slow CN. ............................................ 90
4.5 (a) PACN-00-02 – A very slow CN. ...................................... 92
4.5 (b) PACN-01-01 – A very slow CN. ........................................ 93
4.6 The positions of the 20 detected CNe within M31. ............... 95
4.7 V14148 D31C – POINT-AGAPE data. .............................. 98
4.8 V14148 D31C – POINT-AGAPE and DIRECT data. ............ 98
4.9 Micro-lensing event PA-99-N2. ........................................... 99

5.1 Plot showing the distribution of the estimated average $r'$ extinction
between the Earth and the far side of M31. .......................... 104
5.2 Initial POINT-AGAPE CNe $r'$ MMRD plot. ....................... 108
5.3 Initial POINT-AGAPE CNe $i'$ MMRD plot. ....................... 109
5.4 POINT-AGAPE CNe $r'$ MMRD plot including maximum magni-
tude errors. ................................................................. 113
5.5 POINT-AGAPE CNe $i'$ MMRD plot including maximum magni-
tude errors. ................................................................. 114
5.6 $r'$ POINT-AGAPE CNe MMRD plot. ................................. 117
5.7 $i'$ POINT-AGAPE CNe MMRD plot. ................................. 118
5.8 Superposition of $r'$ light-curves – photometric errors .......... 121
5.9 Superposition of $i'$ light-curves – photometric errors .......... 122
5.10 Plot of the distribution of $r'$ magnitude scatter (green line) and the
$i'$ magnitude scatter (red line) between observed nova magnitudes
for a range of times following maximum light. ...................... 125

6.1 The POINT-AGAPE CN detection pipeline completeness distri-
bution. ................................................................. 135
6.2 The M31 CN detection probability distribution map. ............ 137
6.3 Plots showing the CN eruption probability model for a range of values of $\alpha$. .................................................. 139

6.4 Plot showing the distribution of $\alpha$ against the z-ratios of the normal distribution for the Mann-Whitney Test. ......................... 141

6.5 Plots showing the projected disk semi-major axis position against cumulative number of the 20 POINT-AGAPE CNe and the CNe seeded for the K-S testing. ........................................... 144

6.6 Plot showing the distribution of $\alpha$ against the confidence probabilities of the K-S Test. .................................................. 145

6.7 A plot of M31 flux against disk-semi-major axis. ......................... 148

6.8 A plot of the difference between the M31 surface brightness and the computed M31 disk model against the bulge-semi-major axis. 150

6.9 The modelled CN eruption probability distribution of M31. ....... 151

6.10 The modelled CN eruption probability distribution of M31 overplotted with the computed probability data. .............................. 152

6.11 Comparison of the distribution of POINT-AGAPE novae with the bulge detection probability model ..................................... 154

6.12 Comparison of the distribution of POINT-AGAPE novae with the disk detection probability model ........................................ 155

6.13 Comparison of the distribution of POINT-AGAPE novae with the galactic light probability model ........................................ 157

6.14 Plots showing the CN eruption probability model for a range of values of $\theta$. ................................................................. 159

6.15 A plot showing the distribution of $\theta$ against the z-ratios of the normal distribution for the Mann-Whitney Test. .......................... 161
6.16 Plots showing the projected disk semi-major axis position distribution of the 20 POINT-AGAPE CNe and the CNe seeded for the K-S testing. ................................. 162

6.17 Plot showing the distribution of $\theta$ against the confidence probabilities of the K-S Test. ................................................................. 163

6.18 Plot showing the distribution of normalised likelihood probabilities against bulge fraction ................................................................. 166

6.19 Completeness and detection probability maps for the fast CNe. . 168

6.20 Plots showing the distribution of $\alpha$ for fast CNe ................. 169

6.21 Plots showing the distribution of $\theta$ for fast CNe ................. 171

6.22 Completeness and detection probability maps for the slow CNe. . 172

6.23 Plots showing the distribution of $\alpha$ for slow CNe ................. 173

6.24 Plots showing the distribution of $\theta$ for slow CNe ................. 175

7.1 The light-curves of four novae in M81 ................................. 191

7.2 False-colour image of M81, created from the INT Excitement of Science data. ................................................................. 193
Declaration

The work presented in this thesis was carried out in the Astrophysics Research Institute, Faculty of Science, Liverpool John Moores University. Unless otherwise stated, it is the original work of the author.

While registered as a candidate for the degree of Doctor of Philosophy, for which submission is now made, the author has not been registered as a candidate for any other award. This thesis has not been submitted in whole, or in part, for any other degree.

Matthew J. Darnley,
Astrophysics Research Institute,
Liverpool John Moores University,
Twelve Quays House,
Egerton Wharf,
Birkenhead
CH41 1LD,
UK

June 2005
Publications

Most of the original work contained in this thesis appears in the following papers, which are included in Appendix D:


In preparation:


Chapter 1

Classical Novae

1.1 Introduction

The Oxford English Dictionary defines the term *nova* as:

*nova* *n.* (*pl. novae*) a star showing a sudden large increase of brightness and then subsiding. [Latin, fem. of *novus* ’new’, because originally thought to be a new star]

Classical novae (CNe or novae) have been observed by humans since they first began to gaze at the skies. Ancient Chinese celestial records dating back to 1500 BC first recorded the phenomena we now recognise as novae. For example, the Korean Chronicle Sejong Sillok reports that in AD 1437 “a guest star began to appear between the second and third stars of *Wei*, nearer to the third star and about half a *chih* away; it lasted for 14 days”. Stephenson (private communication), concluded that this event was most likely to be a CN rather than a supernova (SN). However a search for its progenitor proved inconclusive (Shara et al., 1990).

CNe were initially thought to be the birth of new stars, the term *nova* derives from the Latin *nova stella* meaning “new star”. These early observers were far from realising the truth however, in fact they were observing events that occur
towards the end of a star’s life.

The oldest securely identified CN is Nova WY Sagittae (1783) which was discovered by French astronomer D’Agelet with its remnant identified by Weaver (1951). However, for some time it was believed that Nova CK Vulpeculae (1670) was the first recorded nova to be observed in Europe. CK Vul was discovered by Pere Dom Anthelme, a Carthusian monk in Dijon, France and is listed in Flamsteed’s catalogue as 11 Vulpeculae (Flamsteed, 1725). Subsequently, Evans et al. (2002) have cast doubt on CK Vul’s validity as a CN.

Later, Nova Ophuichi 1848 was observed by Hind (1848a) as a “new star” in Ophiuchus, then as a “changing star” (Hind, 1848b,c). Hind’s observations indicated the presence of a “planetary disk” around the nova however, later observations with larger telescopes confirmed that this nova had “nothing planetary in its appearance”.

Each year only two or three new CNe are discovered within our own Galaxy, many of these still by amateur astronomers. To-date a total of about 250 Galactic novae are known. In the early 20th century the first CN was discovered in a galaxy other than our own, Ritchey (1917b,a) and Shapley (1917) independently discovered a nova within the “Andromeda Nebula”. Recently Neill et al. (2005) have reported the discovery of the first intra-cluster novae, i.e. in intergalactic space. They discovered six strong nova candidates in the Formax Cluster. A typical CN eruption is shown in the sequence of four images in Figure 1.1.

1.2 Why study novae?

CNe undergo unpredictable outbursts with a total energy that is surpassed only by gamma-ray bursts, SNe and some luminous blue variables. However, CNe are far more commonplace than these other phenomena (Warner, 1989). Given that relationships exist between certain properties of the outburst and the nova’s luminosity (see Sections 1.3.4 and 1.3.5 which show the calibration of novae as dis-
1.2. Why study novae?

Figure 1.1: A sequence of $r'$-band images of PACN-99-05 from CCD1 of the northern field of the POINT-AGAPE INT WFC Survey Data. These images show the photometric evolution of a Fast CN over the period of about a week either side of maximum light.
1.3 Photometric evolution

Most CNe undergo a fairly similar photometric evolution, from the initial outburst, through maximum-light and into the decline. A reproduction of the “ideal” CN light-curve (McLaughlin, 1939, 1960) is shown in Figure 1.2. Most CNe follow the general trend of the ideal light-curve, however the maximum magnitude and decline rate of different novae may vary greatly. Figures 1.3, 1.4, 1.5 and 1.6 show examples of four typical - although markedly differing - CN light-curves. A CN light-curve is generally divided into five stages: the pre-nova; the initial rise; pre-maximum halt; final rise and maximum-light; initial decline and transition; and final decline and post-nova.
Figure 1.2: A reproduction of the "ideal CN" light-curve with three possible transition behaviors (McLaughlin, 1939, 1960).
1.3. Photometric evolution

Figure 1.3: The visual light-curve of the “fast” nova V1500 Cyg. The data were obtained from the American Association of Variable Star Observers (see http://www.aavso.org).

Figure 1.4: The visual light-curve of the nova V705 Cas, which shows a prominent “DQ Her” type transition minimum. The data were obtained from the American Association of Variable Star Observers (see http://www.aavso.org).
1.3. Photometric evolution

Figure 1.5: The visual light-curve of the “slow” nova HR Del. The data were obtained from the American Association of Variable Star Observers (see http://www.aavso.org).

Figure 1.6: The visual light-curve of the “very fast” nova V603 Aql, which shows large-scale transition region oscillations. The data were obtained from the American Association of Variable Star Observers (see http://www.aavso.org).
1.3.1 Typical CN evolution

Pre-nova stage

To-date no previously targeted star has undergone a CN outburst. As such, the only available data regarding the pre-nova stage of a CN has been obtained serendipitously from general sky surveys. Pre-nova light-curves have been constructed for the following novae: V533 Her, LV Vul CP Lac, BT Mon and GK Per, with some of the most recent being V1500 Cyg (Wolf, 1977) and Nova Cas 1993 (Munari et al., 1994). These were all fast novae and they showed a significant rise in their luminosity for $\sim 1 - 5$ years before outburst (Robinson, 1975).

Initial rise

Following the pre-nova stage (or the brightened state of fast novae mentioned above) the nova increases in brightness to a level around two magnitudes below maximum. Although very few novae have been observed during the initial rise phase, the small amount of data available points to a time-scale for the initial rise of $2 - 3$ days for even the slowest novae (McLaughlin, 1960). Examples of CNe for which some data for the initial rise stage exist are V1500 Cyg and Nova LMC 1991 (della Valle, 1991). The V1500 Cyg data, which cover most of the initial rise phase, show that it took less than a day (Liller et al., 1975).

Pre-maximum halt, final rise and maximum-light

In a number of novae there is a short pause in the light-curve, ranging from a few hours for the fastest novae up to a few days for the slowest, which usually occurs around two magnitudes below the peak brightness. For some of the slowest novae (e.g. HR Del, V1548 Aql, V723 Cas and DO Aql) the duration of the pre-maximum halt may be up to several months. However, observations of Nova Sct 2000, a fast nova, indicated a pre-maximum halt of at least 24 days (Kato et al.,...
Following the pre-maximum halt the nova will continue to brighten to its visual maximum taking a further one or two days for fast novae and up to a few weeks for the slowest. The nova will remain at or around maximum-light for only a few hours for fast novae and a few days for slow novae.

**Early decline and transition**

Novae often decline from their maximum-light quite smoothly. However, some of the slow novae exhibit irregular light-curves with variations on timescales of $1 - 20$ days with amplitudes of up to two magnitudes.

Beginning around $3 - 4$ magnitudes below maximum-light, CN light-curves enter a region in which they show the greatest diversity in their behaviour. This part of the light-curve is known as the “transition region”. There are three general forms that the light-curve can take within this region:

- Some CN light-curves exhibit a deep minimum sometimes $7 - 10$ magnitudes deep which can last for up to a few months. Following the minimum these novae will again brighten before continuing into their final decline stage. The light-curves of both DQ Her and T Aur exhibit deep transition minima. The deep transition minima are associated with dust formation within the ejecta and is often referred to as a “DQ Her minimum” (Evans & Rawlings, 2005) (see Figure 1.4).

- Another group of CN light-curves show large-scale oscillations within the transition region. V603 Aql (see Figure 1.6) exhibited oscillations with period $\sim 12$ days with amplitude $\sim 1$ magnitude and GK Per a period of $\sim 5$ days and amplitude $\sim 1.5$ magnitudes (Hack et al., 1993). More recently, observations of Nova Oph 2002 (Kato et al., 2002b) show oscillations with amplitude $\sim 1$ magnitude with a period of $\sim 10$ days.
1.3. Photometric evolution

- The final group of CN light-curves passes through the transition period showing little or no deviation from the trend of the early and late decline stages. CP Pup and V1500 Cyg (see Figure 1.3) are good examples of novae whose light-curves were undeviated through the transition phase.

Final decline and post-nova

Following the transition phase, most CNe show a steady decline in brightness which generally only shows small fluctuations. As the brightness approaches that of the post-nova stage the photometric and spectroscopic properties of the post-nova slowly emerge.

Robinson (1975) noted that (with the possible exception of BT Mon\(^1\)) all 18 of the novae for which post-nova and pre-nova magnitudes were known at the time, their post- and pre-nova magnitudes were equivalent. Known exceptions, however, now include, CP Pup (1942) and V1500 Cyg (1975).

1.3.2 Nova speed class

A commonly used method of describing the overall timescale of an eruption and classifying CNe, is the concept of the nova “speed class”, developed by McLaughlin (1939) and Bertaud (1948). Their definition of the various nova classes depends on the time taken for a nova to diminish by three magnitudes from maximum-light, \((t_3)\). Throughout this thesis we will use the speed-class definition, modified by Payne-Gaposchkin (1957), for \(t_2\) times, given by Warner (1989) and reproduced in Table 1.1. Historically it was difficult to follow a nova to three magnitudes below the peak so the \(t_2\) measurement was generally adopted. Now, with the availability of larger telescopes and much more sensitive detectors, it is usually possible to follow a CN through three magnitudes below peak and beyond for most Galactic and many extragalactic novae.

\(^1\)The post-nova magnitude of BT Mon was later found to be equivalent to its pre-nova value (Schaefer & Patterson, 1983).
1.3. Photometric evolution

\begin{center}
\begin{tabular}{lcc}
\hline
Speed class & \( t_2 \) (days) & \( dV/dt \) (mag day\(^{-1}\)) \\
\hline
Very fast & \( \leq 10 \) & \( \geq 0.20 \) \\
Fast & 11–25 & 0.18–0.08 \\
Moderately Fast & 26–80 & 0.07–0.025 \\
Slow & 81–150 & 0.024–0.013 \\
Very slow & 151–250 & 0.013–0.008 \\
\hline
\end{tabular}
\end{center}

Table 1.1: The classification of CN light-curves into various speed classes according to the time taken to decrease in brightness by two magnitudes (\( t_2 \)) and their V-band rate of decline (\( dV/dt \)) from maximum light (Warner, 1989).

1.3.3 Bolometric luminosity

A seemingly obvious assumption to make would be that the brightest, fastest novae are more energetic than their fainter, slower counterparts. However, the integrated optical luminosities of the fast novae are actually smaller than those of the slow novae (Payne-Gaposchkin, 1957). These findings indicate the unreliability of using the optical CN light-curve as a measure of the bolometric variation of an eruption.

Once a CN has risen to bolometric maximum its bolometric luminosity may decrease slightly until it enters a phase which exhibits an almost constant bolometric luminosity. This phase was first identified by Gallagher & Code (1974) for Nova FH Serpentis 1970. With the OAO-A2 satellite they were able to study the UV portion of FH Ser’s eruption, a region that had previously been inaccessible. Using their UV data in conjunction with that of others in the radio, IR and optical, they were able to construct the first true bolometric light-curve of a nova and determine that the optical light-curve was a poor indicator of the overall luminosity evolution of a CN. Figure 1.7 shows a schematic multi-frequency CN light-curve. It was found that FH Ser had a constant bolometric phase lasting 60 days.

A more detailed discussion of the CN eruption theory including the bolometric maximum and constant bolometric phases is given in Section 1.7.
Figure 1.7: Schematic multi-frequency development of a CN outburst with times at which a remnant with $v_{\text{exp}} = 1000 \text{ km s}^{-1}$, $d = 1 \text{ kpc}$ becomes spatially resolved in the radio (MERLIN), plus optically from space (HST) and on a conventional ground-based telescope (WHT). Reproduced from Bode (2002).
1.3.4 Maximum magnitude, rate of decline relationship

From his years of observations of CNe in M31, Hubble (1929) noted that the brighter a nova appeared at maximum the more rapidly its visible light diminished. Given that all M31 novae can be considered to lie at equal distances from the observer, Hubble’s observations clearly implied a relationship between the nova speed class and its maximum magnitude. Hubble’s observations for extragalactic novae were later confirmed for Galactic novae by McLaughlin (1945) who used a combination of expansion parallax, interstellar line strengths and Galactic rotation methods to measure the distances of the nearby novae.

Over time the empirically determined “maximum magnitude, rate of decline” (MMRD) relationship for CNe has become accepted and refined (Pfau, 1976; de Vaucouleurs, 1978; Cohen, 1985; Downes & Duerbeck, 2000). The general form of the relationship is given below in Equation 1.1,

\[ M = a_n + b_n \log t_n \]  

where \( t_n \) is the time taken for the nova to decline by \( n \) magnitudes from maximum light, \( M \) is the absolute magnitude at maximum light and typically \( n = 2 \) or 3.

A recent calibration of the MMRD relationship was made by Downes & Duerbeck (2000) using new distances, derived from expansion parallaxes, for a sample of 28 Galactic novae, and is shown in Equations 1.2 and 1.3 below.

\[ M_V = (-11.32 \pm 0.44) + (2.55 \pm 0.32) \log t_2 \]  
\[ M_V = (-11.99 \pm 0.56) + (2.54 \pm 0.35) \log t_3 \]

Downes & Duerbeck (2000) concluded that a linear relationship is sufficient to model the Galactic MMRD. They also derived a typical scatter of \( \sim 0.6 \) magnitudes for CNe about their linear fits. Much of this scatter is thought to be due to
difficulties in measuring accurate distances to the novae (Gill & O’Brien, 2000; Warner, 2005; Shafter, 2005) and from an intrinsic scatter of the properties of a nova’s optical decline.

However, it is also known that the linear-MMRD relationship is not valid for the fastest and slowest novae (Arp, 1956; Schmidt, 1957). Novae from M31 and the Large Magellanic Cloud (LMC) are better described in terms of a “stretched” S-shaped curve. The form is somewhat supported by theoretical modelling of the nova eruption (Livio, 1992). The “flattening” of the MMRD for brighter novae is thought to be caused as the mass of the white dwarf in the central system (see Section 1.7) approaches the Chandrasekhar limit (Livio, 1992). The flattening of the MMRD for the fainter novae is thought to be an observational selection effect (Warner, 1995). Capaccioli et al. (1989) were drawn to the conclusion that the same MMRD relationship is valid in all galaxies of all Hubble types. This idea could then be exploited to combine data from many different galaxies. The S-shaped MMRD curved has been most recently calibrated by della Valle & Livio (1995) using CNe from both M31 and the LMC. Their calibration is shown in Equation 1.4 and Figure 1.8 shows the M31 and LMC CNe data and their computed MMRD.

\[ M_V = -7.92 - 0.81 \arctan \left( \frac{1.32 - \log t_2}{0.23} \right) \] (1.4)

The MMRD relationship can be used as a fundamental distance indicator and it is also an important nova model constraint (Shara, 1981a). However the use of the MMRD relationship as a viable distance indicator is dependent upon being able to accurately measure the maximum brightness of a particular nova and its speed class, requiring good sampling of both the maximum light and the decline.

Using the steady state, constant luminosity, continuous ejection model for CNe (Bath & Shaviv, 1976) and the assumption that novae “shut–off” because of envelope exhaustion (Prialnik et al., 1978, 1979), Shara (1981a) attempted to put the MMRD relationship on a more physical basis and derived the theoretical
Figure 1.8: MMRD relationship for CNe in M31 (filled circles) and the LMC (filled triangles). The “best fit” MMRD shown in Equation 1.4 is represented by the solid line, the upper and lower curves are located at ±3σ above and below Equation 1.4. $v_d$ is the rate of decline of the CN. Reproduced from della Valle & Livio (1995).
1.3. Photometric evolution

MMRD relationship, for $B$–band magnitudes ($M_B$), shown in Equation 1.5.

$$M_B = -10.1 + 1.57 \log t_3 \text{ mag} \quad (1.5)$$

It has been suggested that a better physical explanation of the form of the MMRD relation would be reached if all novae were placed into two distinct groups based upon the form of the nova’s light-curve and the mechanics of the outburst (Duerbeck, 1981). This idea is discussed in more detail in Section 2.6.

Della Valle (1991) made the observation that there is evidence for a small number of super-bright CNe. These novae lie outside of the $\sim 0.5$ magnitude spread of the MMRD and account for less than 10% of all novae.

### 1.3.5 Absolute magnitude 15 days after peak

If the maximum light of a nova eruption is missed, or the decline is not well sampled, large errors can be introduced into the distance modulus deduced from the MMRD relationship (Equations 1.1, 1.2, 1.3 and 1.4). This is especially true for the brightest, fastest, novae. However, Buscombe & de Vaucouleurs (1955) observed that all CNe appeared to reach approximately the same absolute magnitude 15 days after their maximum light ($M_{15}$). The apparent constancy and value of $M_{15}$ is yet to be fully explained, despite attempts to place it on a more physical footing. Sometimes referred to as the $t_{15}$ relationship or the “Buscombe-de Vaucouleurs relationship”, its general form is given by;

$$M_{15} = K \text{ (constant)} \quad (1.6)$$

The most recent calibration of the $t_{15}$ relationship was carried out by Ferrarese et al. (2003) using nine newly discovered novae from Hubble Space Telescope (HST) observations of M49. Their calibration is shown in Equation 1.7.
Using his theoretical MMRD relation (Equation 1.5), Shara (1981b) had some success in deriving a theoretical $t_{15}$ relationship that even predicted the weak dependence of $M_{15}$ on $t_3$ as is noted from observational data. This relationship, for $B$-band data, is shown in Equation 1.8.

\[ M_{15,B} = -10.1 + 1.57 \log t_3 + \frac{45}{t_3} \text{mag} \] (1.8)

Shara was also able to show that the B-band magnitude of novae ($M_B$) is predicted to have a minimum spread at $\simeq 18$ days after maximum-light, in broad agreement with the 15 days derived from observational methods.

Shown in Table 1.2 are a collection of observational values for $M_{15}$ for various different filters. As can be seen from the $M_{15}$ values for the V-band data, there is a great inconsistency in the calculated values. More recent results have called into question the reliability of using the $t_{15}$ relationship for distance derivations and the validity of the relationship itself (Jacoby et al., 1992; Ferrarese et al., 2003).

### 1.3.6 Colour two days after maximum light

van den Bergh & Younger (1987) made the observation that novae two magnitudes below their maximum-light have an intrinsic colour $< B-V >_0 = -0.02 \pm 0.04$ magnitudes, with a dispersion of $\sigma_{B-V} < 0.12$ magnitudes. This relationship may be used as a measure of line-of-sight interstellar extinction to a particular nova, which would prove invaluable for extragalactic novae, especially those within galactic disks. In this thesis we will refer to this relationship as the “van den Bergh - Younger” relationship.
1.3. Photometric evolution

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Filter</th>
<th>$M_{15}$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buscombe &amp; de Vaucouleurs</td>
<td>V</td>
<td>$-5.2 \pm 0.1$</td>
<td>1</td>
</tr>
<tr>
<td>Schmidt</td>
<td>pg</td>
<td>$-5.86$</td>
<td>2</td>
</tr>
<tr>
<td>Pfau</td>
<td>B</td>
<td>$-5.74 \pm 0.60$</td>
<td>3</td>
</tr>
<tr>
<td>de Vaucouleurs</td>
<td>pg</td>
<td>$-5.5 \pm 0.18$</td>
<td>4</td>
</tr>
<tr>
<td>Cohen</td>
<td>V</td>
<td>$-5.60 \pm 0.43$</td>
<td>5</td>
</tr>
<tr>
<td>van den Bergh &amp; Younger</td>
<td>V</td>
<td>$-5.23 \pm 0.16$</td>
<td>6</td>
</tr>
<tr>
<td>van den Bergh</td>
<td>V</td>
<td>$-5.38$</td>
<td>7</td>
</tr>
<tr>
<td>Capaccioli et al.</td>
<td>V</td>
<td>$-5.69 \pm 0.14$</td>
<td>8</td>
</tr>
<tr>
<td>Downes &amp; Duerbeck</td>
<td>V</td>
<td>$-6.05 \pm 0.44$</td>
<td>9</td>
</tr>
<tr>
<td>Ferrarese et al.</td>
<td>V</td>
<td>$-6.36 \pm 0.19$</td>
<td>10</td>
</tr>
</tbody>
</table>

References: (1) Buscombe & de Vaucouleurs (1955); (2) Schmidt (1957); (3) Pfau (1976); (4) de Vaucouleurs (1978); (5) Cohen (1985); (6) van den Bergh & Younger (1987); (7) van den Bergh (1988); (8) Capaccioli et al. (1989); (9) Downes & Duerbeck (2000); (10) Ferrarese et al. (2003);

Table 1.2: $M_{15}$ values for various pass-bands (Warner, 1995).
1.4 Hα emission

Following shortly after maximum-light, CNe develop strong Balmer emission lines. After only a few days the Hα emission strength surpasses that of the local continuum, as the continuum emission declines further the Hα emission remains. From observations of Galactic novae, a difference of up to five magnitudes between the Hα emission and fainter continuum is not uncommon at times following maximum-light (Popper, 1940; Meinel, 1963). The Hα emission of novae can be used to detect eruptions weeks or even months after the event. The Hα line was first used to detect extragalactic novae by Ciardullo et al. (1983) who detected four CNe in M31, with the first dedicated CN Hα survey soon following (Ciardullo et al., 1987). Strong Hα emission from other variable stellar objects is rare, hence transient Hα sources can almost exclusively be classified as CNe.

The Hα emissions of CNe have now become an almost indispensable tool for their detection. A deep Hα image can potentially provide a much longer “snapshot” of time in a galaxy’s CN eruption history. With many modern surveys consisting of only a handful of observations, spread over a relatively long time, Hα detection is ideal for maximising the number of recovered CNe from a survey.

1.5 General spectroscopic evolution

The first spectral classification of CNe was carried out by McLaughlin (1943) with this work added to by Payne-Gaposchkin (1957) and McLaughlin (1960). This scheme consists of six stages: pre-maximum, principal, diffuse-enhanced, Orion, nebular and finally the post-nova spectrum. Each stage is characterised mainly by the presence, or lack, of particular absorption or emission lines, or sometimes by changes in line widths. However, these classifications are not based upon the physical characteristics of the nova system.

More recently, however, the work of Williams et al. (1991), Williams (1992) and
Williams et al. (1994) has led to a new classification system, sometimes referred to as the “Tololo Classification System”. This system is based upon the relative intensities of the dominant lines at different stages of the nova remnant evolution, which relate to parameters that dictate the physical conditions.

1.6 Nova remnants

The imaging and spectroscopy of optically resolved CN remnants may allow the use of the expansion parallax method to determine the distance to the remnant more accurately than by any other method. The modelling of nova remnants can also provide further information about the underlying central system and the thermonuclear runaway (see Section 1.7) that led to the outburst (Bode, 2002). For a galactic nova with a typical expansion velocity ($\sim 1000 \text{ km s}^{-1}$) at a typical distance ($\sim 1 \text{ kpc}$), one would expect the remnant to become resolvable only a few months after eruption for space-based observations, or around 2 years for ground-based observations.

1.7 CN central systems and models of the outburst

The first connection between CNe and binary star systems was made by Walker (1954) who discovered that DQ Her was an eclipsing binary. However it was a further ten years until Kraft (1964) was able to show that all novae almost certainly arise from binary systems with a short orbital period. The orbital periods of CN systems are generally less than 24 hours, with the majority of the known periods being less than 10 hours (Warner, 2002, 2005).

\footnote{The Tololo system was developed using spectral data collected at the Cerro Tololo Inter-American Observatory, La Serena, Chile.}
1.7.1 Novae as cataclysmic variables

CN variables (CVs) have subsequently been identified as a sub-class of cataclysmic variables (CVs). The canonical model for CVs (Crawford & Kraft, 1956) is that they are close binary systems, generally of short period, containing a low-mass G or K type near-main-sequence (the “secondary”) that fills its Roche (or “critical”) lobe and a more massive carbon-oxygen or oxygen-magnesium-neon white dwarf companion (the “primary”) (Duerbeck, 1996). The white dwarf mass can have a wide range, up to the Chandrasekhar mass limit, but it is usually found to be greater than $0.5 M_\odot$. As the secondary fills its Roche lobe, any tendency for it to increase in size through evolutionary processes causes a flow of material through the inner Lagrangian point into the primary’s lobe. The high angular momentum of the transferred material causes it to form a thin disc around the white dwarf. Viscous forces\(^3\) within this accretion disc act to transfer material inwards, so that a small amount of the accreted hydrogen-rich material falls on to the primary’s surface (King, 1989). In CN systems the mass accretion rate is lower than $10^{-9} M_\odot$ year\(^{-1}\) (Cassisi et al., 1998). Some mixing can occur between the outer layers of the white dwarf and the accreted hydrogen-rich envelope, allowing both carbon and oxygen nuclei to be present in this layer. As the accreted layer grows, the temperature and pressure of the material in the base of the accreted envelope increases.

1.7.2 Bolometric maximum

When a critical temperature and pressure are attained, hydrogen burning is initiated in the degenerate hydrogen-rich envelope. Initially this occurs mainly via proton-proton chains. In stellar cores the hydrogen burning rate is moderated by the equation of state of the material, essentially that of an ideal gas. Consequently, if the burning rate increases, the temperature increases which causes an

\(^3\)Classical “molecular” viscosity alone is not sufficient to remove the required energy from the accreted matter whilst transporting the angular momentum. One favoured mechanism is “turbulent eddy” viscosity.
increase in the pressure of the material, hence the material expands, reducing the burning rate. However, in degenerate material the temperature and the pressure are decoupled, so the hydrogen burning rate can increase unchecked. Given the correct conditions, the onset of nuclear reactions within the accreted envelope can eventually lead to a thermonuclear runaway (TNR), which will lead to the ejection of some or all of the accreted envelope. Typically a mass in the range $10^{-5} - 10^{-4} M_\odot$ will be ejected from the system (Grotrian, 1937; Bath & Harkness, 1989).

Whilst the proton-proton chain is dominant, the shell temperature will increase relatively slowly (due to the $\sim T^4$ dependence of the proton-proton burning rate). Proton-proton chain hydrogen burning will be ongoing within the accreted enveloped for the majority of the quiescent period of the nova system’s lifetime. However, once a certain temperature threshold is surpassed the CNO hydrogen burning pathway starts to become dominant.

The CNO cycle has a much higher temperature dependence ($\sim T^{18}$), so once initiated the temperature of the envelope begins to increase rapidly. Once a temperature of $\sim 2 \times 10^7$K is surpassed, a convective region begins to form within the envelope just above the nuclear burning shell. As the temperature continues to increase, the convective layer grows until it reaches the surface of the envelope, finally allowing the surface luminosity to increase towards its bolometric maximum. CNe at bolometric maximum are expected to be very luminous extreme-UV or X-ray sources.

1.7.3 Visible maximum

Once a CN has reached its peak energy production and nuclear burning shell temperature, the accreted envelope will begin to expand\textsuperscript{4}. The peak visible luminosity will occur when the expanding pseudo-photosphere reaches its maximum effective

\textsuperscript{4}It is thought that the surface luminosity of the fastest novae will exceed the Eddington luminosity which will act to transform the envelope from a state of hydrostatic equilibrium to one of hydrodynamic expansion much more quickly.
1.7. CN central systems and models of the outburst

radius, defined by the recombination temperature of hydrogen ($\sim 8 \times 10^3$K). As
the mass-loss rate from the white dwarf decreases the pseudo-photosphere will
contract back in towards the white dwarf.

1.7.4 Constant bolometric luminosity

It can be shown from models that, at most, only 50% of the accreted envelope is
ejected in the initial outburst. The remaining material expands at a large veloc-
ity behind the ejected shell. This material then slows and returns to a state of
hydrostatic equilibrium with stable shell Hydrogen burning. The remnant enve-
lope then shrinks over a period of a few days and as its temperature increases the
envelope becomes entirely convective. The envelope’s structure becomes analo-
gous to that of an asymptotic giant branch star. Once the remnant has returned
to hydrostatic equilibrium it will be radiating energy at close to the Eddington
limit. As the mass-loss rate from the white dwarf decreases, the photosphere con-
tracts back towards the white dwarf. As the energy input into the photosphere
remains constant, the reducing effective radiating radius causes an increase in the
effective black-body temperature of the pseudo-photosphere. The increase in the
effective photosphere temperature shifts the peak of its spectrum blue-wards. So
as the photosphere contracts, the nova emission in the visible bands decreases,
producing the “classical” nova light-curve shown in Figure 1.2. The decline seen
in the visible magnitude can be explained by a shifting of the peak energy of the
remnant envelope’s spectrum towards the blue, into the UV then the extreme-
UV as the photosphere contracts (see Figure 1.7). See Starrfield & Sparks (1987);
Starrfield (1989); King (1989); Starrfield et al. (1998); Starrfield (1999); Starrfield
et al. (2000); Starrfield & Iliadis (2005) for reviews.
1.8 Extragalactic distance indicators

The definition of a primary extragalactic distance indicator includes classes of objects that can be readily observed and measured in nearby galaxies, exhibiting a small cosmic dispersal about a stable mean, which can also be calibrated within our Galaxy by fundamental geometric methods (de Vaucouleurs, 1978).

There are a number of primary extragalactic distance indicators; including, CNe, Cepheid variables, RR Lyrae variables, type B and A super-giants and eclipsing binaries. Novae may be calibrated by expansion parallax and interstellar line intensities; Cepheids by a variety of methods using period-luminosity relationships; RR Lyrae variables from parallaxes and zero-age main-sequence fits of globular clusters; super-giants using the Barbier-Chalonge-Divan method and eclipsing binaries by the Gaposchkin method.

CNe exhibit outburst amplitudes of $\sim 10 - 20$ magnitudes and, at maximum light, display an average absolute blue magnitude of $M_B = -8$ with a limit of around $M_B = -9.5$ for the fastest (Shara, 1981b; Warner, 1989). As was discussed in Section 1.3.4, they are potentially useful as standard candles for extragalactic distance indication as they exhibit a correlation between their luminosity at maximum light and the rate of their decline (Hubble, 1929; McLaughlin, 1945; Arp, 1956).

As well as being intrinsically bright CNe are also relatively easy to discover. Novae are far more suitable tools for the determination of distances to galaxies than Cepheids (van den Bergh & Pritchet, 1986). CNe at maximum light are more luminous than all but the longest period Cepheids and unlike Cepheids, which only occur in Population I systems, CNe occur in both Population I and Population II environments. Consequently, CNe can be used to measure the distances to galaxies of all Hubble types. Cepheids are commonly concentrated in the spiral arms of galaxies, hence the distance determinations are often complicated by extinction uncertainties, whereas CNe within galactic bulges or elliptical galaxies only suffer minimally from extinction.
Unfortunately, poor light-curve coverage, small sample sizes (especially of Galactic novae) and a current lack of understanding of how the properties of CNe vary between different stellar populations have limited their usefulness in this context.

### 1.9 Automated CN detection

In order for robust statistical statements to be made about CN populations in extragalactic systems it is important to take account of the bias induced by the unresolved galactic surface brightness component, which in the inner regions of galaxies may mask much of the CNe light-curve evolution, making both identification and classification more difficult. One approach to remedy this is to make the selection procedure for CN candidates completely automated (Darnley et al., 2002), so that the detection efficiency for the various CN light-curve morphologies may be assessed as a function of position objectively through Monte Carlo simulation. This is a far from trivial task because the light-curve structure of CNe varies considerably with nova speed class. Automation of the pipeline also requires that, in the absence of Hα observations, the light-curves are well sampled.

### 1.10 This work

The aim of this study is to produce the first fully automated search for CNe which can be used to assess the statistical properties of the CN population in M31 in an objective manner. The work described here has produced some of the finest examples of extragalactic nova light-curves observed to date. We have also studied the spatial distribution and rate of novae in M31 and assessed the potential of our nova candidates as distance indicators by calibrating the MMRD and other proposed relationships (Buscombe & de Vaucouleurs, 1955).

The outline of this thesis is as follows. In Chapter 2 we discuss previous extra-
galactic nova surveys, especially those in M31, we outline some of the recent work on nova populations and summarise the POINT-AGAPE project, its results and their data. In Chapter 3 we detail the initial data reduction stages and describe the main nova detection pipeline used to define our CN catalogue. The POINT-AGAPE CN catalogue itself is presented in Chapter 4. Here, the light-curve of each nova is shown and discussed and a number of other objects found within M31 are also included. In Chapter 5 we asses the validity of the MMRD and $t_{15}$ relationships with respect to the POINT-AGAPE catalogue. We discuss our statistical analysis of the pipeline and its results in Chapter 6, using a completeness map in conjunction with galactic models to investigate the distribution of detected novae in M31 and to compute expected nova rates. Chapter 7 discusses the early work on the extension of our CN survey to a number of other galaxies; M81, NGC 2403 and M64, and presents some preliminary results. Finally, Chapter 8 contains both a summary of our results and presents a number of avenues for further study.
Chapter 2

Extragalactic Surveys for Classical Novae and the POINT-AGAPE Project

2.1 Introduction

In this chapter we will discuss some of the advantages and disadvantages of the use of both Galactic and extragalactic novae as tools for understanding the properties of CNe and their populations. We also summarise some of the past results of CN surveys of M31 and briefly cover some CN surveys in other galaxies.

A brief description of the POINT-AGAPE collaboration is also given, including a summary of their results to-date. The POINT-AGAPE dataset, the main resource upon which the work in this thesis is based, is also described in detail.

2.2 Galactic novae

Despite the high luminosities of CNe, our position within the Galaxy prevents us from directly observing more than a small fraction of Galactic CNe that erupt
2.3. Extragalactic novae

CNe can be readily identified in other galaxies. The earliest observations of extragalactic CNe were reported by Ritchey (1917b,a) and Shapley (1917), who both observed novae within the Andromeda Galaxy. However, the importance of the study of novae in other galaxies was not universally recognised until the time of Hubble (1929), with his extensive survey of M31.

However, there are great difficulties in obtaining the frequency and duration of observations with large enough telescopes to determine the peak magnitude and speed class for a meaningful sample of objects (della Valle, 2002; Shafter, 2002). In addition, prior to, and following, an outburst, extragalactic novae are not able to be resolved from the parent galactic background. It is quite likely that a nova is only resolvable during the brightest parts of its outburst. As such, it is not surprising that, to-date, no extragalactic nova has been caught during the “initial rise” stage, i.e. before the pre-maximum halt; in fact only a handful have been observed at all before maximum.
2.4 The Andromeda Galaxy – M31

The Andromeda Galaxy is our closest large neighbour galaxy. It makes up the Local Group, along with our own Galaxy the Milky Way, M33 and others. The Andromeda Galaxy is a spiral galaxy of Hubble Type Sb and is at a distance of 0.9 Mpc.

Surveys of CNe in M31 have been carried out by Hubble (1929), Arp (1956), Rosino (1964, 1973), Ciardullo et al. (1987), Capaccioli et al. (1989), Sharov & Alksnis (1991), Tomaney & Shafter (1992), Rector et al. (1999) and Shafter & Irby (2001) amongst others. These surveys have resulted in the discovery of around 450 novae and have indicated the global nova rate in M31 to be $\sim 30 - 40$ yr$^{-1}$ (Shafter & Irby, 2001). Table 2.1 summarises the findings of many of these past surveys, with most of the data reproduced from Shafter & Irby. The relatively high nova rate in M31 and its close proximity to our own Galaxy are major advantages of targeting M31 for nova surveys. However, since M31 is nearer edge-on than face-on, with an inclination angle of $\sim 77^\circ$ (de Vaucouleurs, 1958), the task of unambiguously distinguishing between novae erupting within the disk or within the bulge is rather difficult (Hatano et al., 1997). Consequently there remains debate surrounding the distribution and rate of novae within M31. The large inclination angle also introduces additional extinction complications.

The early M31 CN surveys of Arp (1956) and Rosino (1964) found that the nova distribution decreased significantly towards the centre of the bulge, with Rosino (1973) reporting the centre of the bulge to be “devoid of novae”; all of this was despite their attempts to detect novae within the central bulge regions. However, the first M31 Hα survey (Ciardullo et al., 1987) found that the nova distribution follows the galactic light all the way into the centre of the bulge. A combination of the Arp (1956) novae with the Ciardullo et al. (1987) catalogue yielded the result that the bulge nova rate per unit $B$ light was an order of magnitude greater than that of the disk, implying that the vast majority of the M31 novae arise from the bulge population. This result was later confirmed by Capaccioli et al. (1989)
## Table 2.1: Principal M31 CN surveys

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Epoch</th>
<th>Filter(s)</th>
<th>Detector</th>
<th>Novae</th>
<th>Annual rate</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hubble</td>
<td>1909–1927</td>
<td>B Plates</td>
<td>85</td>
<td>~30</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Arp</td>
<td>1953–1954</td>
<td>B Plates</td>
<td>30</td>
<td>24±4</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Rosino et al.</td>
<td>1955–1986</td>
<td>B Plates</td>
<td>142</td>
<td>-</td>
<td></td>
<td>3, 4, 5</td>
</tr>
<tr>
<td>Ciardullo et al.</td>
<td>1982–1986</td>
<td>B, Hα CCD</td>
<td>40</td>
<td>-</td>
<td></td>
<td>6, 7</td>
</tr>
<tr>
<td>Tomaney &amp; Shafter</td>
<td>1987–1989</td>
<td>Hα CCD</td>
<td>9</td>
<td>-</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>Shafter &amp; Irby</td>
<td>1990–1997</td>
<td>Hα CCD</td>
<td>72</td>
<td>37+12</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Rector et al.</td>
<td>1995–1999</td>
<td>Hα CCD</td>
<td>44</td>
<td>-</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>Darnley et al.</td>
<td>1999–2002</td>
<td>r′, i′, g′</td>
<td>CCD</td>
<td>20</td>
<td>*</td>
<td>12</td>
</tr>
</tbody>
</table>

References: (1) Hubble (1929); (2) Arp (1956); (3) Rosino (1964); (4) Rosino (1973); (5) Rosino et al. (1989); (6) Ciardullo et al. (1987); (7) Ciardullo et al. (1990a); (8) Sharov & Alksnis (1991); (9) Tomaney & Shafter (1992); (10) Shafter & Irby (2001); (11) Rector et al. (1999); (12) Darnley et al. (2004).

* See Sections 6.10 and 6.11.3.
after undertaking a comprehensive analysis of all M31 CN data. However, there were potentially biases caused by extinction, especially within the disk, as the Hα surveys had focused primarily on the bulge, using much earlier $B$ band surveys to “fill in” the disk data. In an attempt to tackle the lingering extinction issues Shafter & Irby extended the Hα observations into the M31 disk. Using M31’s planetary nebula distribution for comparison, they arrived at the conclusion that the M31 CN distribution is consistent with an association with the bulge.

### 2.5 Surveys for CNe in other galaxies

A relatively small number of other extragalactic nova surveys have been carried out to-date. These include the following.

#### 2.5.1 M33

The “Triangulum Galaxy”\(^1\) or M33 is a prominent member of the Local Group and is located at a distance of just under 1 Mpc away. M33 is a spiral galaxy of Hubble type Sc. A recent Hα survey conducted by Williams & Shafter (2002) discovered four CNe, the authors computed a global nova rate of $4 \pm 2 \text{ year}^{-1}$.

#### 2.5.2 M49

The “first ranked” member of the Virgo Cluster, M49 is optically the brightest galaxy in the local super-cluster. M49 is a giant elliptical galaxy of Hubble type E4 and lies at a distance of around 18-19 Mpc. There have been two CN surveys of M49 to date; Pritchet & van den Bergh (1987) discovered eight CNe with Ferrarese et al. (2003) discovering a further nine novae.

\(^1\)M33 is also referred to as the “Pinwheel Galaxy” a name it shares with M101
2.5.3 M51

The “Whirlpool Galaxy”, M51 is a spiral galaxy of Hubble Type Sc. It is the dominant member of the M51 group which is at a distance of about 11 Mpc. Shafter et al. (2000) discovered a total of nine CNe in M51 and calculated the global nova rate to be \(18 \pm 7\) year\(^{-1}\).

2.5.4 M60

M60 is a giant elliptical galaxy, Hubble type E2, located in the Virgo cluster at a distance of 18-19 Mpc. Pritchet & van den Bergh (1987) observed M60 for 15 nights but failed to detect any CNe.

2.5.5 M81

“Bode’s Galaxy” or M81, is a spiral galaxy of Hubble type Sb. It is the brightest and dominant galaxy of the nearby M81 group at a distance of around 3.7 Mpc. Moses & Shafter (1993) discovered a total of 15 CNe and computed a global nova rate of \(24 \pm 8\) year\(^{-1}\). Data obtained from the 1950-1955 Palomar campaign, re-compiled by Shara et al. (1999), revealed 23 CNe. Recently Neill & Shara (2004) have reported the discovery of a further 12 CNe in M81 and have computed an elevated nova rate of \(33^{+13}_{-8}\) year\(^{-1}\).

M81 is also one of the principal targets of the Liverpool Telescope’s Extragalactic CN survey, which we discuss further in Chapter 7.

2.5.6 M87

M87, or “Virgo A”, is the dominant galaxy in the Virgo cluster. Like M49, it is a giant elliptical galaxy, but of Hubble type E1. M87 lies at a distance of around 18-19 Mpc. There have been a number of CN surveys of M87, Pritchet & van
2.5. Surveys for CNe in other galaxies

Den Bergh (1985) first observed two CNe in M87. Shafter et al. (2000) discovered a further nine novae and calculated a global nova rate of $91 \pm 34 \text{ year}^{-1}$. More recently, Shara (2002) and Shara & Zurek (2002) have reported the discovery of 400 nova candidates and estimated a nova rate of $\gtrsim 300 \text{ year}^{-1}$.

2.5.7 M101

M101 lies at a distance of around 8 Mpc and is a spiral galaxy of Hubble Type Sc. It is commonly referred to as the “Pinwheel Galaxy”. Twelve CNe were discovered in M101 by Shafter et al. (2000), who also calculated a global nova rate of $12 \pm 4 \text{ year}^{-1}$.

2.5.8 NGC 4365

Located in the constellation of Pegasus, NGC 4365 is an elliptical galaxy of Hubble Type E3 at a distance of about 17 Mpc. Pritchet & van den Bergh (1987) observed NGC 4365 for 15 nights as part of their Virgo Cluster CNe survey that also took in M49 and M60. They discovered a single nova in NGC 4365.

2.5.9 NGC 5128

The Seyfert 2 galaxy NGC 5128, more commonly known as the radio source Centaurus A, is well known to be one of the most peculiar galaxies in the sky. Part of the M83 group of galaxies, NGC 5128 is at a distance of about 4.6 Mpc and is our closest radio galaxy. Ciardullo et al. (1990b) conducted a five year Hα survey of NGC 5128 discovering 16 CNe. They found a global nova rate of $28 \pm 7 \text{ year}^{-1}$ for NGC 5128.
2.5.10 LMC

The Large Magellanic Cloud (LMC), a satellite galaxy of the Milky Way, is an irregular galaxy, found at a distance of only 55 kpc, it is the second closest galaxy to our own. The first LMC nova was discovered by Buscombe & de Vaucouleurs (1955) and to-date around 30 CNe have been discovered in the LMC (Subramaniam & Anupama, 2002), although there have been no extensive surveys carried out. The computed nova rate for the LMC is $2.5 \pm 0.5$ year$^{-1}$.

2.6 Nova populations

The idea that CNe may arise from two distinct populations was first postulated by Duerbeck (1990). This was further explored by della Valle et al. (1992) who presented evidence that fast novae were concentrated closer to the Galactic plane than slower novae. Additional spectroscopic data have revealed that there may exist two spectroscopic classes of CNe, the Fe$\text{II}$ and He/N novae (Williams, 1992). It has been shown the the He/N novae tend to cluster close to the Galactic plane and that they tend to be brighter and faster than the Fe$\text{II}$ type (della Valle & Livio, 1998).

Theoretical studies of CN outbursts (e.g. Shara et al., 1980; Shara, 1981a; Prialnik et al., 1982; Livio, 1992; Prialnik & Kovetz, 1995) have shown that the form of the outburst depends upon properties such as the white dwarf’s mass, accretion rate and luminosity. These white dwarf properties may vary with the underlying stellar population. These findings lend support to the idea that CNe in differing stellar populations may have distinctly different outburst properties.

The surface gravity of a white dwarf increases with increasing white dwarf mass. This leads to a higher pressure at the base of the accreted envelope when the TNR begins (see Section 1.7), resulting in a more powerful outburst. It also follows that, as the pressure at the envelope base is greater for more massive white dwarfs, a lower mass of accreted material is required for the envelope to
achieve the temperature and density required for a TNR to be initiated. Thus, the more massive white dwarfs are expected to have shorter recurrence times and to exhibit faster light-curve evolution.

It was suggested by della Valle et al. (1994) that there may be systematic differences between the nova rate per unit K luminosity within galaxies of different Hubble types. They found that late-type (almost bulge-less) galaxies are around three times more prolific CN producers than early-type (bulge dominated) ones.

From his survey of M31, Arp (1956) was able to show that the distribution of nova speed classes exhibited a bimodal distribution (see Figure 2.1); perhaps implying the existence of two populations of novae. However, later studies seem to disprove his findings (Rosino, 1973; Sharov, 1993; Shafter, 2002). More recently the evidence has indicated the existence of two distinct populations (Shafter, 2005).

### 2.7 The POINT-AGAPE project

POINT-AGAPE (Pixel-lensing Observations with the Isaac Newton Telescope - Andromeda Galaxy Amplified Pixels Experiment) is searching for gravitational micro-lensing events against the mostly unresolved stars in M31 (Paulin-Henriksson et al., 2003). It uses the wide-field camera (WFC) on the 2.5m Isaac Newton Telescope (INT) located on La Palma, the Canary Islands, Spain, to survey a 0.6 deg$^2$ region of M31 in at least two broadband filters. The survey has very good temporal sampling over the M31 observing season (August – January) for three complete seasons$^2$ and is therefore potentially an excellent database within which to look for novae.

The high inclination of M31 (see Section 2.4) causes an asymmetry in the observed rate of micro-lensing events within the halo (Crotts, 1992). The POINT-AGAPE

---

$^2$A fourth season of data has recently been made available but has not been included within this work.
survey was designed to map the global distribution of micro-lensing events in M31 and to attempt to quantify any large scale gradient in this distribution (Aurière et al., 2001). As any micro-lensing events within M31 are expected to become resolved only for substantial magnifications, the collaboration makes use of the “Pixel-Lensing” technique (Tomaney & Crotts, 1996) to detect candidates. To-date the POINT-AGAPE collaboration has reported the discovery of 3 very strong micro-lensing candidates and a further 3 strong candidates (Belokurov et al., 2005). The collaboration has also published the a catalogue of 35,414 variable stars in the field of M31 detected as a by-product of their micro-lensing survey (An et al., 2004).

Whilst Hα observations have been shown to be a particularly helpful diagnostic for CN identification (Payne-Gaposchkin, 1957; Ciardullo et al., 1983), the excellent sampling of the POINT-AGAPE survey more than makes up for an absence
of Hα data as it allows us to classify the light-curve profiles of different novae.

2.8 The POINT-AGAPE dataset

Between the end of August 1999 and the end of January 2002, the WFC on the INT in La Palma was used to regularly monitor two fields positioned north and south of the M31 centre and covering 0.6 deg². The north field is located at \( \alpha = 0^h44^m00^s.0, \delta = +41^\circ34'00''0 \) and the south field at \( \alpha = 0^h43^m23^s.0, \delta = +40^\circ58'15''0 \) (J2000), with respect to the centre of CCD4 of the WFC. The WFC consists of a mosaic of four 2048 × 4100 pixel CCDs, and the field locations are indicated in Figure 2.2. The field placements were primarily chosen to be sensitive to compact dark matter candidates, or Machos, which are predicted to be most evident towards the far side of the M31 disk (Kerins et al., 2001).

The observations were conducted over three seasons in at least two broad-band Sloan-like pass-bands\(^3\). The three filters used by POINT-AGAPE were \( g' \), \( r' \) and \( i' \), corresponding to effective wavelengths of 486, 622, 767 nm respectively. The efficiency curves of the three filters are shown in Figure 2.3. There were \( r' \)-band images taken throughout the three years which were combined with a mixture of \( i' \) or \( g' \)-band images during the first season, but the \( g' \) observations ceased at the end of the first season. Throughout the second and third seasons \( r' \) and \( i' \)-band images were always taken together. Pairs of exposures were taken in each band to avoid saturation and to aid the identification and elimination of cosmic rays. The exposure time for each observation was around 320 seconds, chosen to maximise the signal to noise ratio whilst remaining within the nightly allocation of 3,600 seconds.

The monitoring of M31 was only possible for periods when the WFC was mounted on the INT. This, combined with bouts of bad weather, led to a series of relatively

---

\(^3\)The combination of the throughput of the filters and the response curve of the thinned EEV CCDs of the WFC produce pass-bands similar to the original Sloan Digital Sky Survey band.
2.8. The POINT-AGAPE dataset

Figure 2.2: The positions of the North and South POINT-AGAPE fields. Each rectangle represents one of the four WFC CCDs and are numbered accordingly. The origin is the centre of M31 at (J2000) \( \alpha = 0^h42^m34^s324, \delta = +41^\circ16'08"53 \) (Crane et al., 1992). Also indicated are ten representative M31 “isophotes” from the surface photometry of de Vaucouleurs (1958), along with representations of the positions and sizes of M32 (within the southern field) and NGC205 (in the North West quadrant).
2.8. The POINT-AGAPE dataset

Figure 2.3: Response curves for the WFC $g'$, $r'$ and $i'$ filters. The blue curve represents the $g'$ filter, the green is $r'$ and the red $r'$. The dashed line shows the wavelength of the $H\alpha$ line, 656 nm.
2.9. Summary

Table 2.2: The distribution of each of the three seasons of POINT-AGAPE observations by field and filter band.

<table>
<thead>
<tr>
<th>Season</th>
<th>$r'$-band observations</th>
<th>$i'$-band observations</th>
<th>$g'$-band observations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>North/South</td>
<td>North/South</td>
<td>North/South</td>
</tr>
<tr>
<td>1</td>
<td>105/98</td>
<td>44/36</td>
<td>72/75</td>
</tr>
<tr>
<td>2</td>
<td>154/150</td>
<td>144/134</td>
<td>0/0</td>
</tr>
<tr>
<td>3</td>
<td>74/70</td>
<td>78/73</td>
<td>0/0</td>
</tr>
</tbody>
</table>

During the first few nights of the POINT-AGAPE season, data were taken in all three Sloan bands. These data were used to generate a false-colour image, shown in Figure 2.5.

2.9 Summary

In this chapter, we briefly presented some of the results of previous CN surveys in our own Galaxy and a number of others. We discussed in detail past surveys of M31, which is by far the most extensively studied galaxy for CN, more so even than our own Galaxy. To-date, almost 500 novae have been discovered in M31 since 1917 and their spatial distribution has been studied extensively. Despite this, there is still great debate about the underlying nature of the M31 CN population. We also briefly introduced the notion of the two populations of CNe, based upon the two spectroscopic classes, the Fe II and He/N novae.

We outlined the aims and results of the POINT-AGAPE project, on whose
Figure 2.4: The cumulative temporal coverage of the POINT-AGAPE survey in the $r'$, $i'$ and $g'$ bands for the northern field. The southern field data-set has a similar distribution.
Figure 2.5: False-colour image of M31, created from the POINT-AGAPE data.
dataset this thesis is based. The POINT-AGAPE project is a search for gravitational micro-lensing events within M31, the survey’s good temporal sampling made it an excellent resource in which to search for CNe.

In the next chapter, we describe in detail the pipeline, developed for this work, used to detect and analyse CNe within the POINT-AGAPE dataset. In this discussion, we include the rationale behind the choice of selection criteria used to classify a CN light-curve.
Chapter 3

Data Reduction and Classical Nova Detection Pipeline

3.1 Introduction

This chapter presents in detail the CN detection pipeline specifically developed for the detection and analysis of CNe within the POINT-AGAPE dataset. The data reduction process, object detection, photometry and light-curve production methods are described. We also detail the criteria used to classify nova light-curves and discuss the rationale for selecting each criterion.

For robust statistical statements to be made about CN populations in external galaxies, it is highly desirable that a completely automated detection procedure should be used (Darnley et al., 2002). Due to the highly variable, often unresolved, galactic background and the variability of CN light-curves, this task is far from trivial. This chapter introduces the main concepts and stages involved.

Initially an attempt was made to implement the pipeline using currently available standard packages, such as the NOAO IRAF system and Starlink packages.

---

1 The data reduction techniques and the CN detection pipeline described within this chapter have been published in Darnley et al. (2004).

2 IRAF is distributed by the National Optical Astronomy Observatories, which are operated...
3.2. Image pre-processing

However, it quickly became apparent that most of the packages provided were unsuitable for the task at hand. For example, the IRAF standard objects detection packages, such as `daofind` or `starfind`, are not designed to deal properly with strongly varying backgrounds, such as those present within galactic images or surveys.

The pipeline we have developed was itself split into three major parts:

1. Data reduction – this was carried out using custom scripts to run a number of IRAF packages to carry out initial tasks such as image alignment, trimming, background subtraction and point-spread function (PSF) matching.

2. Aperture photometry pipeline – this was carried out using custom software developed specifically to detect CN-like objects within multi-epoch, single colour, data.

3. PSF-fitting photometry pipeline – this last part of the pipeline consisted of a mixture of custom-written software and IRAF scripts to perform optimal photometry on CN candidates to produce the final catalogue.

A detailed description of each of the components of the process follows below.

### 3.2 Image pre-processing

The POINT-AGAPE data that we received had already been preprocessed by the POINT-AGAPE collaboration using the WFC reduction package `WFCRED`\(^3\), the processing stages of which include:

1. Linearity correction – early on in its lifetime the INT WFC was discovered to be non-linear to some level in each of the four CCDs - this non-linearity

\(^3\)The `WFCRED` package is designed to use standard IRAF commands to pre-process INT WFC data.
3.3 Data reduction

can also be time variable.

2. CCD processing – this refers to the standard practise of de-biasing and flat fielding. The de-biasing was conducted by subtracting the constant bias value from the CCD’s overscan strip or by subtracting a mean bias frame. The flat fielding was carried out using a previously defined flat field.

3. De-fringing – for $i'$ images it was necessary to subtract a scaled mean “fringe frame” to correct for fringing effects.

4. “Squishing” – this refers to a “lossy” compression that was applied to the data, whereby non-useful data values ($<-1,000$ and $>80,000$) are clipped at these limits.

5. World Coordinate System (WCS) definition – this provides a rough estimate of the WCS, calculated using the values in the image’s header and the known geometry of the camera.

The de-fringing portion of the WFCRED pipeline was not sufficient to fully remove the fringing effects from the $i'$ images. As such, the $i'$ images were de-fringed by the POINT-AGAPE collaboration using a process that they developed (An et al., 2004).

3.3 Data reduction

Following the pre-processing stage, the data reduction steps below were carried out using custom automated scripts from within the NOAO IRAF environment.

3.3.1 Image alignment and trimming

The first step involved geometrically aligning the image stack. The images were aligned at this stage to aid the detection of objects within the data. Using IRAF
commands to align the image stack removed the need for the custom aperture photometry pipeline to compute the transformations between images needed to match objects between epochs. Before the alignment was carried out, the same three reference stars were identified in each frame. These reference stars were used by the alignment software to calculate the initial, “first guess”, transformation. The alignment was carried out using three packages: \texttt{xyxymatch} to produce lists of matched reference coordinates; \texttt{geomap} to calculate second-order geometric transformations between images; and \texttt{geotran} to apply the geometric transforms to the images.

The aligned images were then trimmed to produce a common overlap region. The data loss due to the trimming process is summarised in Table 3.1. Overall the trimming accounted for a loss of 4.5% of the initial data. Any region of M31 that did not lie within the overlap region was not analysed further by the pipeline process.

### 3.3.2 PSF-matching

The next stage in the reduction process was to match the PSFs of the $r'$ images. We chose to PSF-match the data stack to simplify the aperture photometry pipeline, as when using the PSF-matched data any dependence of the photometry on the aperture parameters will be the same for every epoch and can effectively be ignored for relative photometric purposes. The data reduction and candidate selection was performed initially in $r'$ as this dataset had the greatest temporal coverage. The \texttt{psfmeasure} package was applied to a list of secondary standards (Magnier et al., 1992; Haiman et al., 1994, hereafter Magnier catalogues) in order to compute their Gaussian full-width half-maximum (FWHM) on the INT frames. We then selected a reference image for each of the CCDs with an average FWHM closest to, but less than, 1.67 arcsec (5 WFC pixels). The distribution of the best-fit FHWMs is shown in Figure 3.1. Any images that exhibited a poorer seeing than 5 pixels were discarded at this stage (accounting for $\sim 10$ images per
3.3. Data reduction

Images that showed high ellipticity in their PSFs, further effects of bad atmospheric conditions or instrumental/software deficiency\(^4\) were also removed from the process. Around 10 – 20 images per CCD were removed for these reasons. The aligned images then had their PSFs matched to that of the reference image using a PSF kernel size that contained 90% of the flux of objects in the reference image. The matching was carried out by applying `psfmatch` to a list of stars selected from the Magnier catalogues which had good PSFs and were resolved in all the images.

3.3.3 Background estimation and bad pixel masking

An estimate of the background (including mainly the unresolved M31 light) was produced for each PSF-matched image to enable background subtraction. The background image was constructed by passing a $49 \times 49$ pixel sliding filter, using IRAF’s `median` function. The value of 49 pixels was chosen as this corresponded to the size of the PSF kernel used for the PSF-matching process. The filter size was also large enough to remove the majority of light from resolved objects but not so large as to wash-out the majority of features – such as the dust lanes – contained within the unresolved light from M31.

Within the data there were a significant number of pixels that contained counts arising from the extended diffraction structure of saturated sources within, or close to, the observed fields. Image masks were therefore constructed to identify these regions to the detection pipeline so that they could be treated correctly. The mask was created for each CCD by creating and analysing two co-added images generated using the background estimation data from all epochs and the PSF-matched data from all epochs. The summation was carried out using the IRAF routine `imsum`. A 24 pixel border around each CCD was also excluded in the pixel mask as the `median` package did not function reliably near the edges of images. When regions of the median filter were outside the boundaries of the data,

\(^4\)A number of images exhibited object trails that were caused by a failure in the INT’s tracking.
Figure 3.1: A histogram showing the distribution of the best-fit Gaussian FWHM for each $r'$ POINT-AGAPE epoch. The dashed line represents the 1.67 arcsec cut-off.
Table 3.1: The extent of the data lost due to the trimming of the aligned images and the masking of regions of bad data.

<table>
<thead>
<tr>
<th>CCD</th>
<th>% lost by trimming</th>
<th>% lost by masking</th>
<th>Total % lost</th>
</tr>
</thead>
<tbody>
<tr>
<td>North 1</td>
<td>4.57%</td>
<td>4.23%</td>
<td>8.80%</td>
</tr>
<tr>
<td>North 2</td>
<td>4.80%</td>
<td>3.89%</td>
<td>8.69%</td>
</tr>
<tr>
<td>North 3</td>
<td>4.25%</td>
<td>4.27%</td>
<td>8.52%</td>
</tr>
<tr>
<td>North 4</td>
<td>3.89%</td>
<td>4.96%</td>
<td>8.85%</td>
</tr>
<tr>
<td>South 1</td>
<td>3.37%</td>
<td>3.68%</td>
<td>7.05%</td>
</tr>
<tr>
<td>South 2</td>
<td>4.96%</td>
<td>7.18%</td>
<td>12.14%</td>
</tr>
<tr>
<td>South 3</td>
<td>5.01%</td>
<td>4.65%</td>
<td>9.66%</td>
</tr>
<tr>
<td>South 4</td>
<td>5.51%</td>
<td>5.58%</td>
<td>11.09%</td>
</tr>
</tbody>
</table>

The median package attempted to estimate the data values within these regions; while this may have been acceptable on smooth, “well-behaved” backgrounds, this approach was not suitable for the strongly varying background of M31. The pixel masks accounted for a further loss of 4.5% of the data. Table 3.1 summarises the amount of data lost in both the trimming and masking processes.

### 3.4 Aperture photometry detection pipeline

Following the alignment, trimming and PSF-matching, of the $r'$ images, they were “fed” into the aperture photometry section of our CN detection pipeline. This portion of the pipeline was written in C and C++ using standard Unix/Linux libraries and the CFITSIO\(^5\) and CCfits\(^6\) libraries. A flowchart of the pipeline, including the major steps and selection criteria, as discussed in this section, is shown in Figure 3.2.

\(^5\)CFITSIO is a library of C and Fortran subroutines for reading and writing data files in FITS data format.
\(^6\)CCfits is an object-oriented interface to the CFITSIO library.
3.4. Aperture photometry detection pipeline

Perform aperture photometry on every potential object (~64,000,000 pixels, ~300 epochs)

Create a list of 10 sigma objects (267,368 objects)

Eliminate any objects that are not resolved in 5 or more consecutive images (1st pass = 142,691 objects removed, 2nd pass = 61 objects removed)

Remove objects with no primary peaks (1st pass = 114,842 removed, 2nd pass = 290 removed)

Eliminate objects if the first peak is not at least two magnitudes brighter than all of the other peaks (1st pass = 1,964 objects removed, 2nd pass = 97 objects removed)

Search for secondary peaks, those with 5 of more consecutive points, all at least 15 sigma above the baseline after increasing the flux of all points by 2 magnitudes)

Eliminate objects with secondaries peaks that are not at least 2 magnitudes fainter than the 1st primary peak (1st pass = 4,297 objects removed, 2nd pass = 95 objects removed)

Remove objects with 90% of points contained within primary peaks (78 objects removed)

Remove candidates whose light-curves do not contain at least 5 good g’ or i’ points (5 objects removed)

Calibration of the g’, r’ and i’ magnitude scales

Remove any candidates that do not show significant colour evolution (44 objects removed)

Remove any candidates with a $dr'/dt<0.004$ (19 objects removed)

Remove any candidates that are outside the colour-magnitude crteria (34 objects removed)

20 classical novae

Figure 3.2: A schematic diagram summarising our classical novae detection process. The number of objects removed or surviving at each stage of the process is also indicated.
3.4.1 Standard star selection

In order to detect objects which vary in flux, the first step in our pipeline was to prepare a list of resolved standard stars known not to vary in luminosity throughout the observations. We later calibrated the light-curves of our CN candidates relative to these stars to eliminate any seeing effects in the data. This selection was carried out using the secondary standard stars from the Magnier catalogues of M31, which contain BVRI magnitudes of 485,425 objects of many different types. As the catalogues make use of a different filter system from that used by our survey, we later used data provided by the Cambridge Astronomical Survey Unit (CASU) INT Wide Field Survey (WFS) to accurately calibrate our magnitude scales. However, for the purpose of relative calibration of the candidate light-curves, we initially used a fiducial zero point of $r' = 25$ to provide a rough estimate of the magnitude scale of our data.

Candidates for non-varying stars were selected from the Magnier et al. catalogues by virtue of their type (i.e. stars), reliability (more than one observation) and apparent magnitude (within the magnitude range of the point-like resolved sources in the POINT-AGAPE data). Light-curves for each of the selected non-varying star candidates were then produced using aperture photometry. Standard stars that contained any points in their light-curves which corresponded to saturated pixels in any observation epoch were immediately eliminated. To define a sample of standards that did not vary over the survey lifetime, we firstly made the assumption that any variation in flux was due entirely to extraneous factors such as seeing variations. Then, for each epoch, we calculated the mean flux correction such that the stars had statistically the same flux as measured in the reference image. We then tested the initial assumption that all the selected stars did not vary by fitting each standard star with a constant flux light-curve. If any of the standard stars had fits with a reduced-$\chi^2 > 3$, then the star exhibiting the poorest fit was assumed to have varied in flux. This process was iterated, i.e. removing the star with the poorest fit, re-computing the statistical correction and refitting the light-curves until all of the remaining stars had a reduced-$\chi^2 \leq 3$. 
3.4. Aperture photometry detection pipeline

### Table 3.2

<table>
<thead>
<tr>
<th>Field</th>
<th>CCD1</th>
<th>CCD 2</th>
<th>CCD3</th>
<th>CCD4</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>12</td>
<td>9</td>
<td>5</td>
<td>16</td>
</tr>
<tr>
<td>South</td>
<td>24</td>
<td>4</td>
<td>3</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 3.2: The number of non-varying standards identified in each of the CCDs using the aperture photometry pipeline.

The number of $r'$ standards identified by the aperture photometry pipeline for each CCD is shown in Table 3.2.

#### 3.4.2 Object definition

To produce an initial list of CN candidates, we first created a list of “objects” for each observation epoch. We defined an object to be a resolved structure in a PSF-matched image with a flux at least $10\sigma$ above the corresponding local median background flux. The flux difference was designated to be the object flux. Our object detection routine, based upon the IRAF `daofind` package, allowed us to deal with the strongly varying background and used median-filtered images to estimate the local background.

We eliminated any objects from the candidate list if they did not have $10\sigma$ detections for at least five consecutive observations. This allowed us to eliminate from our candidate list any rapidly variable objects (which are unlikely to be novae), cosmic rays, contamination from bad pixels and many of the remaining effects of the extended structure of unmasked saturated objects. When comparing objects between different images, some leeway was needed in the position of the objects to allow for alignment and centring errors. We allowed $\pm 1$ pixel for the maximum error in our custom centring algorithm and $\pm 0.5$ pixels for the maximum error in the image alignment. In fact the majority of the images were aligned to within $\pm 0.1$ pixels across the CCD. Thus we treated objects on different frames which were positioned to within $\pm 2$ pixels as the same object. Giving this amount of leeway resulted in a small number of multiple detections arising from nearby contaminating variable sources, particularly when the contaminants were bright.
However these duplications were easily identified and removed at a later stage.

### 3.4.3 Preliminary nova selection

It was our aim to define a set of selection criteria that were general in the sense of not making unnecessary assumptions about CN light-curve morphology, since we wanted to minimise the risk of biasing against the detection of certain CN speed classes in favour of others. Our starting points were the catalogues of Galactic nova light-curves compiled by Duerbeck (1981) and van den Bergh & Younger (1987) and the “ideal light-curve” (see Figure 1.2) (McLaughlin, 1960). Our aim was to derive a set of criteria that allowed us to select “CN-like” light-curves from our object list. This was a difficult task since, for example, moderate speed class novae, such as T Aurigae 1891 (McLaughlin, 1941) and DQ Herculis 1934 (Adams & Joy, 1936), exhibit minima $7 – 10$ magnitudes deep during the transition stage (see Figure 1.4). There was also a clear correlation between the morphology of CN light-curves and their rate of decline. These difficulties were compounded for extragalactic nova detection since it was possible that the transition stage of a moderate speed class nova may have been obscured by the host galaxy’s own surface brightness. As a result, these novae may have appeared to have multiple peaks.

Given the different behaviour of CN light-curves and the extended range of light-curves due to potential contaminating objects, it was not possible, a priori, to define objective selection criteria that were truly effective. Thus, the development of the algorithm used to isolate a sample of CN light-curves involved an iterative process in which the results of visual inspection of a subset of light-curves surviving each stage in the selection-pipeline were used to refine the selection criteria. To ensure that the objective nature of the selection criteria was preserved, no more than 10% of the candidates surviving at each stage in the selection-pipeline were inspected visually. It was also the case that the feedback from the visual inspection to the refinement of the selection criteria was concerned primarily with
reducing the contamination of the CN candidate sample by various classes of variable star. Only at the final stages, where colour cuts were adopted, was it necessary to inspect all the candidates; although by this stage the “obvious” CN candidates were reasonably clearly delineated in magnitude and colour from the other light-curves.

Our first task in the selection was to produce calibrated light-curves for each of the remaining objects in our candidate list. At this preliminary stage the light-curves were produced using aperture photometry and calibrated using the previously located standard stars. For each light-curve we calculated a baseline flux by taking the minimum value obtained from a sliding seven-epoch mean. We also required that the seven consecutive points which defined the baseline each lay within \(3\sigma\) of the baseline value. Windows of seven points containing saturated data, or points lying outside the \(3\sigma\) limit, were discarded. If any candidate’s light-curve contained no valid windows (i.e. it wasn’t possible to calculate a baseline flux) then that candidate was also discarded.

To characterise CN light-curves, we introduced the notion of primary and secondary peaks. CNe can have complex light-curve structures but are generically characterised by an initial, large peak (the primary peak) which, in some cases, may be followed by one or more lesser peaks (secondary peaks). Secondary peaks tend to be at least two magnitudes fainter than the primary. The peaks themselves can exhibit some sub-structure and therefore care was required in defining what constitutes a peak.

We defined a primary peak as being bounded by points at least \(15\sigma\) above the baseline flux. The other points within the primary peak had to either lie at least \(15\sigma\) above the baseline or within \(3\sigma\) of the previous \(15\sigma\) point (in which case they were regarded as “substructure” points). A primary peak could contain any number of substructure points so long as there were never more than three consecutive substructure points. Finally, a primary peak had to contain at least five points overall. At this stage we were able to discard the majority of candidates as they did not contain any primary peaks. We initially kept any candidates which
contained one or more primary peaks.

For the surviving light-curves, we calculated the characteristic width of each primary peak. We defined the end of each primary peak as the first point following the peak maximum at which the flux of the object dropped below $3\sigma$ above the baseline, or the final observation if this occurred first. Using a similar definition for the start of each primary peak, we were able to specify the size of each peak. Overlapping primary peaks were then re-assigned as a single primary peak. At this stage, for light-curves with more than one primary peak, we required that the time between the maximum flux of the first and last primary peak was less than half the total baseline time of the survey. This criterion was introduced in order to eliminate “contained” periodic variables.

From our studies of a large proportion of all past Galactic nova light-curves, we noted that maxima occurring after the transition phase of the nova were always at least two magnitudes fainter than its maximum light. This presented a simple way to eliminate the majority of the multiple primary peak candidates: we required that all primary peaks after the initial one were at least two magnitudes below the first peak.

From the remaining light-curves we searched for secondary peaks. We defined a secondary peak as being five or more consecutive points lying at least $15\sigma$ above the baseline after increasing the flux of each data point by two magnitudes. Points already associated with primary peaks were excluded from the search. We then eliminated candidates unless their secondary peaks were at least two magnitudes fainter than the first primary peak.

### 3.5 PSF-fitted photometry pipeline

The aperture photometry portion of the pipeline produced a preliminary catalogue of CNe, with a monochromatic light-curve for each of these candidates. The next stage of the process was to produce higher accuracy – “optimal” – multi-
3.5. PSF-fitted photometry pipeline

colour photometry that was correctly calibrated to known standards. The CN selection portions of the aperture photometry stage were then re-used to further select good candidates. Five new criteria, based upon the colour behaviour of the CN candidate light-curves, were then introduced to further select good CN candidates.

3.5.1 Relative PSF-fitted photometry

The result of the CN detection pipeline at this stage was a preliminary catalogue of 741 candidates, compared to the 9,835 strongly variable objects (i.e. objects with at least one primary peak) originally identified from 267,368 $10\sigma$ objects detected within the two fields. The contaminants within this preliminary catalogue were expected to be mainly long-period variables such as Miras. Elimination of further objects required accurate, multi-colour photometry. This was performed for each surviving candidate in all three colours ($g'$, $r'$ and $i'$) for all three seasons.

Accurate photometric measurements were obtained by PSF-fitting rather than relying on the aperture photometry used previously. The PSF-fitting handled the strongly variable background more robustly than the simple aperture photometry technique. This was carried out for each of the selected standards from the Magnier catalogues, as well as for the CN candidates.

A PSF template was created for every epoch; this was carried out using the IRAF psf command on a list of carefully selected stars from the Magnier catalogues. We required that these PSF stars existed within all epochs of the data and that they must have exhibited a “good” PSF profile with minimum contamination from other nearby objects.

Instrumental magnitudes were then extracted using the peak routines within IRAF’s daophot package. After this more accurate calibration, the flux stability of the standards was re-checked using the procedure outlined in Section 3.4.1. In total, 758 standards with stable $r'$ light-curves were identified, the number
3.5. PSF-fitted photometry pipeline

Figure 3.3: A plot showing the light-curve of one of the 230 standards identified in CCD1 of the north-field. The black points represent the uncorrected instrumental magnitudes. The red points show the correct instrumental magnitudes and the red dashed line indicates the assumed instrumental magnitude of the standard.

of standards per CCD ranged from nine (south-field CCD2) to 342 (north-field CCD1). The large range of identified standards was due partly to the stellar density across the fields and the coverage of the Magnier catalogues. The number of standards identified within each CCD can be seen in Table 3.3.

The criteria previously used in Section 3.4.3 were now re-applied to eliminate further candidates, by taking advantage of the more accurate photometry. This re-processing proved very important in order to remove spurious candidates that had been allowed by the aperture photometry method. At this stage, a further 543 candidates were eliminated – more than 70% of the surviving sample. A breakdown of the candidates eliminated at each stage in the pipeline is given in Table 3.4. The higher photometric reliability also allowed us to introduce further selection criteria. We required that the light-curves did not contain more
Table 3.3: The number of non-varying standards identified in each of the CCDs for all bands using the PSF-fitting photometry pipeline.

<table>
<thead>
<tr>
<th>CCD</th>
<th>Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r'</td>
</tr>
<tr>
<td>North 1</td>
<td>230</td>
</tr>
<tr>
<td>North 2</td>
<td>110</td>
</tr>
<tr>
<td>North 3</td>
<td>41</td>
</tr>
<tr>
<td>North 4</td>
<td>98</td>
</tr>
<tr>
<td>South 1</td>
<td>22</td>
</tr>
<tr>
<td>South 2</td>
<td>6</td>
</tr>
<tr>
<td>South 3</td>
<td>196</td>
</tr>
<tr>
<td>South 4</td>
<td>55</td>
</tr>
</tbody>
</table>

than 90% of their points within primary peaks. This was essentially a second “containment” criterion which allowed us to eliminate long period variables. To investigate colour evolution we further required that the candidates comprised at least five points in either $g'$ or $i'$.

### 3.5.2 Photometric calibration and colour selections

To calibrate our instrumental $g'$, $r'$ and $i'$ magnitudes we used the calibrated zero points for the INT WFC as calculated by the CASU WFS team (Hodgkin, private communication). Their zero points, calculated for many of the nights on which POINT-AGAPE observations were taken, allowed us to test our relative photometry.

Since the colour of CNe is known to vary strongly throughout the eruption (especially just after maximum light), we demanded that the $r' - i'$ and $g' - r'$ colours of our candidates showed significant colour evolution. Accordingly we computed the reduced-$\chi^2$ for a constant colour fit and rejected those light-curves where the reduced-$\chi^2 < 3$. This criterion essentially rejected light-curves unless they exhibited colour evolution at a high level of significance.

To eliminate candidates from the catalogue which decayed too slowly to be CN, we introduced a rate-of-decline criterion. Using the speed class definitions in
### Table 3.4: The effect of each stage of our selection pipeline upon the classical nova candidate catalogue.

<table>
<thead>
<tr>
<th>Pipeline stage</th>
<th>North-field</th>
<th>South-Field</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixels</td>
<td>$8 \times 10^6$</td>
<td>$8 \times 10^6$</td>
<td>$8 \times 10^6$</td>
</tr>
<tr>
<td>$10\sigma$ objects</td>
<td>29,423</td>
<td>29,931</td>
<td>39,921</td>
</tr>
<tr>
<td>5 consecutive detections</td>
<td>17,976</td>
<td>15,901</td>
<td>19,292</td>
</tr>
<tr>
<td>$\geq 1$ primary peak</td>
<td>1,366</td>
<td>898</td>
<td>1,073</td>
</tr>
<tr>
<td>Periodicity test</td>
<td>1,036</td>
<td>686</td>
<td>731</td>
</tr>
<tr>
<td>Primary peak height</td>
<td>794</td>
<td>539</td>
<td>464</td>
</tr>
<tr>
<td>Secondary peak height</td>
<td>145</td>
<td>77</td>
<td>62</td>
</tr>
<tr>
<td>5 consecutive detections</td>
<td>135</td>
<td>66</td>
<td>59</td>
</tr>
<tr>
<td>$\geq 1$ primary peak</td>
<td>66</td>
<td>43</td>
<td>38</td>
</tr>
<tr>
<td>Periodicity test</td>
<td>66</td>
<td>43</td>
<td>38</td>
</tr>
<tr>
<td>Primary peak height</td>
<td>59</td>
<td>33</td>
<td>26</td>
</tr>
<tr>
<td>Secondary peak height</td>
<td>35</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>$&lt; 90%$ of points in peaks</td>
<td>22</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>$5 , g'$ or $i'$ points</td>
<td>22</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Colour evolution</td>
<td>12</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Rate of decline</td>
<td>9</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Colour–magnitude criteria</td>
<td>4</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

Pipeline 1st pass – aperture photometry

Pipeline 2nd pass – PSF-fitting photometry

Further candidate elimination stages

Final candidates 4 4 1 3 0 0 6 2 20
Table 1.1 as a guide, and applying them to the \( r' \) band, we removed light-curves where \( dr'/dt < 0.004 \) mag day\(^{-1} \) (equivalent to \( t_2 > 500 \) days). At this stage we were left with the 52 candidate light-curves. These are plotted on the colour-magnitude diagram in Figure 3.4, which shows \( r' \) at peak versus \( r' - i' \) near peak. Specifically, \( r' - i' \) in Figure 3.4 represents the mean colour of the object in the magnitude range \( r'_{\text{max}} < r' < r'_{\text{max}} + 3 \). The mean was used in order to average over colour variations near maximum light. In some cases, where the peak flux occurred during poor observing conditions, the mean \( r' - i' \) was better determined than \( r' \) at peak. The candidates were for the most part segregated into two clumps, one at \( r' \sim 20, r' - i' \sim 1.5 \) and the other at \( r' \sim 18, r' - i' \sim 0 \). If the remaining candidates lay within M31, we expected them to suffer to varying degrees from extinction within that galaxy (the foreground extinction was assumed to be constant across the M31 field). However, as the \( r' \) and \( i' \) filters were relatively closely spaced in wavelength, we expected that the change in \( r' - i' \) due to extinction was small, compared to the decrease in both \( r' \) and \( i' \), and much smaller than the change in \( g' - r' \). Therefore, the use of colour-magnitude criteria to eliminate further CN candidates was practical. In order to eliminate “bogus” candidates from the list, we introduced two further criteria:

\[
r' - i' < 0.5 \quad (3.1)
\]

\[
r' - i' < 8 - 0.4r' \quad (3.2)
\]

The rationale behind Equation (3.1) was that we expected novae to have approximately equal brightness in all bands at around maximum, after which they become bluer as the eruption develops. These selection criteria effectively eliminated the clump at \( r' \sim 20, r' - i' \sim 1.5 \), which appeared to be mostly comprised of Mira variables. The second colour criterion (Equation 3.2) was almost orthogonal to the line joining the two clumps and also to the expected direction of the reddening vector indicated in Figure 3.4. This ensured that, whilst we might
potentially have missed CNe due to reddening, extinction should not have caused Miras or similar objects to have been mistaken for CNe. This second criteria also dealt with novae whose maximum light may have been missed; we would have expected these novae to appear fainter and bluer. A summary of all of the selection criteria, and their impact for the number of surviving candidates at each stage for each CCD is given in Table 3.4.

3.5.3 Astrometry

To calculate the astrometric positions of each CN, we first computed the pixel positions of each nova whilst at, or near, maximum light using the apphot center function. The pixel coordinates of the selected standard stars were determined in the reference frames using the wcsctran package. Image position solutions for each CCD were obtained using matched celestial and pixel coordinate lists for the novae within the ccmap package to calculate second-order geometric transformations. Finally, the celestial coordinates for each CN were calculated using the computed solutions with the cctran package.

3.6 Summary

In this chapter we described in detail the nova detection pipeline that we developed for analysis of the data provided by the POINT-AGAPE collaboration. The pipeline uses a number of specially designed analysis techniques and selection criteria in order to detect and analyse CNe and their light-curves. In the next chapter, we present the CN catalogue generated by the pipeline along with the multi-colour light-curves of each nova.
3.6. Summary

Figure 3.4: A colour–magnitude diagram showing the 52 candidates remaining prior to colour selection. The 20 objects located within the region defined by Equations (3.1) and (3.2) are the classical novae discovered by this survey. The group of objects centred at $r' \sim 20$, $r' - i' \sim 1.5$ appear to be mainly Mira variables. A notable non-nova candidate is indicated, this is discussed in more detail in Section 4.10. The arrow indicates the direction of the reddening vector. The apparent discrepancy in the relative sizes of the $r'$ and $r' - i'$ errors seen on some of the points (e.g. V14148 D31C), can be understood by considering that the $r'$ error is drawn solely from the brightest observation (which may have been on a night where no $i'$ data were taken or when the object was not visible in $i'$) where as the $r' - i'$ points, and hence their errors, are drawn from the average colour following maximum light.
Chapter 4

The M31 Nova Catalogue\textsuperscript{1}

4.1 Introduction

This chapter presents the POINT-AGAPE CN catalogue, including the position and speed class of each nova. The full $r'$ light-curves and colour light-curves of each nova are also provided. We also discuss a small sample of other non-nova light-curves that were rejected at various stages of the CN pipeline but are interesting objects in their own right.

4.2 The catalogue

Following the implementation of our nova detection pipeline and candidate selection criteria, we identified 20 CN candidates. The positions of each of the CNe and further information is tabulated in Tables 4.1 and 4.2. The $dr'/dt$ parameter was estimated from the general slope of the $r'$-band light-curve between the brightest observation and the observation closest to 2 magnitudes fainter than the maximum. The speed class of each CN was then estimated using the definition given in Table 1.1. However, note that the various speed classes in Table 1.1 were

\textsuperscript{1}The POINT-AGAPE CN Catalogue has been published in Darnley et al. (2004)
4.3. Very fast novae

Very fast novae are defined for $V$-band light-curves, whilst we are applying them to $r'$-band data. Since novae become bluer as they decline, we expected a slight over-estimation of the speeds of the CN relative to the $V$-band definitions. Table 4.3 shows the distribution of our sample of CNe with speed class.

Figures 4.1 to 4.5 provide the $r'$-band light-curves for each of the 20 CNe discovered and identified in Tables 4.1 and 4.2. Also shown are the $g' - r'$ and $r' - i'$ colours, where available. The span of our three observing seasons, and the approximate $r'$-band magnitude limit of the PSF-fitting are indicated by the horizontal lines in the $r'$-band panels. This magnitude limit was determined in the immediate region of each candidate by adding successively brighter artificial PSFs to the data until they were recognised by the PSF-fitting routine. This was performed only on our reference CCD frames (those with a seeing scale closest to five pixels), and so represent only an approximate limit for data at other epochs.

Where points in the $r' - i'$ light-curves are apparently “missing” this was usually due to the object being particularly blue. This, coupled with the higher ($\sim 1$ magnitude) zero-point of the INT CCDs in $i'$, meant that very blue objects, such as novae, were often unresolved in $i'$-band observations.

The following subsections describe in some detail features of the light-curves of selected CNe from each speed class.

### 4.3 Very fast novae

A lone “very fast” nova was identified by the pipeline, PACN-99-07, which is plotted in Figure 4.1. This CN exhibits a $\frac{dr'}{dt} = 0.2$ equivalent to a $t_2 \sim 20$ days. However, this nova shows a very unusual light-curve which may have affected the estimation of the speed class. PACN-99-07 reached a maximum magnitude of $r' = 18.1 \pm 0.1$. This was much lower than would be expected for a very fast nova at, or near, peak brightness at the distance of M31 (assuming no significant extinction). As such, its classification as a very fast nova is rather
<table>
<thead>
<tr>
<th>Nova</th>
<th>(t_0(r')) (JD-2451000)</th>
<th>(r'(t_0))</th>
<th>(i'(t_0))</th>
<th>(g'(t_0))</th>
<th>(dr'/dt) (mag day(^{-1}))</th>
<th>(t_2(r')) (days)</th>
<th>Speed class</th>
</tr>
</thead>
<tbody>
<tr>
<td>PACN-99-01</td>
<td>392.63</td>
<td>16.53 ± 0.03</td>
<td>16.39 ± 0.03</td>
<td>17.40 ± 0.01</td>
<td>0.06</td>
<td>30.50</td>
<td>Moderately Fast</td>
</tr>
<tr>
<td>PACN-99-02</td>
<td>394.65</td>
<td>18.91 ± 0.03</td>
<td>19.19 ± 0.04</td>
<td>20.22 ± 0.02</td>
<td>0.02</td>
<td>99.48</td>
<td>Slow</td>
</tr>
<tr>
<td>PACN-99-03</td>
<td>395.71</td>
<td>17.79 ± 0.02</td>
<td>17.60 ± 0.04</td>
<td>-</td>
<td>0.03</td>
<td>59.62</td>
<td>Moderately Fast</td>
</tr>
<tr>
<td>PACN-99-04</td>
<td>400.61*</td>
<td>18.41 ± 0.02</td>
<td>18.34 ± 0.07</td>
<td>18.83 ± 0.02</td>
<td>0.02</td>
<td>164.39</td>
<td>Slow</td>
</tr>
<tr>
<td>PACN-99-05</td>
<td>427.69</td>
<td>17.70 ± 0.04</td>
<td>-</td>
<td>18.47 ± 0.02</td>
<td>0.02</td>
<td>25.82</td>
<td>Fast</td>
</tr>
<tr>
<td>PACN-99-06</td>
<td>432.69*</td>
<td>16.17 ± 0.01</td>
<td>-</td>
<td>16.91 ± 0.01</td>
<td>0.06</td>
<td>20.00</td>
<td>Moderately Fast</td>
</tr>
<tr>
<td>PACN-99-07</td>
<td>484.50</td>
<td>18.1 ± 0.1</td>
<td>18.02 ± 0.04</td>
<td>18.5 ± 0.1</td>
<td>0.2</td>
<td>9.80</td>
<td>Very Fast</td>
</tr>
<tr>
<td>PACN-00-01</td>
<td>760.52</td>
<td>17.73 ± 0.04</td>
<td>17.58 ± 0.8</td>
<td>-</td>
<td>0.05</td>
<td>38.65</td>
<td>Moderately Fast</td>
</tr>
<tr>
<td>PACN-00-02</td>
<td>761.63</td>
<td>18.15 ± 0.03</td>
<td>18.86 ± 0.05</td>
<td>-</td>
<td>0.01</td>
<td>198.55</td>
<td>Very Slow</td>
</tr>
<tr>
<td>PACN-00-03</td>
<td>766.64</td>
<td>18.54 ± 0.03</td>
<td>18.19 ± 0.04</td>
<td>-</td>
<td>0.06</td>
<td>33.02</td>
<td>Moderately Fast</td>
</tr>
<tr>
<td>PACN-00-04</td>
<td>766.65*</td>
<td>17.61 ± 0.03</td>
<td>17.33 ± 0.04</td>
<td>-</td>
<td>0.07</td>
<td>30.65</td>
<td>Moderately Fast</td>
</tr>
<tr>
<td>PACN-00-05</td>
<td>786.54</td>
<td>17.30 ± 0.01</td>
<td>17.11 ± 0.01</td>
<td>-</td>
<td>0.03</td>
<td>59.21</td>
<td>Moderately Fast</td>
</tr>
<tr>
<td>PACN-00-06</td>
<td>838.52*</td>
<td>17.09 ± 0.01</td>
<td>16.64 ± 0.01</td>
<td>-</td>
<td>0.1</td>
<td>13.85</td>
<td>Fast</td>
</tr>
<tr>
<td>PACN-00-07</td>
<td>854.46*</td>
<td>19.53 ± 0.04</td>
<td>19.48 ± 0.05</td>
<td>-</td>
<td>0.03</td>
<td>55.21</td>
<td>Moderately Fast</td>
</tr>
<tr>
<td>PACN-01-01</td>
<td>1135.64</td>
<td>18.45 ± 0.02</td>
<td>18.16 ± 0.04</td>
<td>-</td>
<td>0.01</td>
<td>213.12</td>
<td>Very Slow</td>
</tr>
<tr>
<td>PACN-01-02</td>
<td>1142.71*</td>
<td>17.14 ± 0.03</td>
<td>16.71 ± 0.04</td>
<td>-</td>
<td>0.09</td>
<td>22.06</td>
<td>Fast</td>
</tr>
<tr>
<td>PACN-01-03</td>
<td>1148.67*</td>
<td>17.30 ± 0.04</td>
<td>16.88 ± 0.06</td>
<td>-</td>
<td>0.01</td>
<td>143.71</td>
<td>Slow</td>
</tr>
<tr>
<td>PACN-01-04</td>
<td>1148.69*</td>
<td>17.90 ± 0.03</td>
<td>17.38 ± 0.04</td>
<td>-</td>
<td>0.05</td>
<td>47.29</td>
<td>Moderately Fast</td>
</tr>
<tr>
<td>PACN-01-05</td>
<td>1191.48</td>
<td>15.90 ± 0.01</td>
<td>15.61 ± 0.01</td>
<td>-</td>
<td>0.07</td>
<td>28.15</td>
<td>Moderately Fast</td>
</tr>
<tr>
<td>PACN-01-06</td>
<td>1194.62*</td>
<td>17.38 ± 0.01</td>
<td>16.88 ± 0.03</td>
<td>-</td>
<td>0.04</td>
<td>52.13</td>
<td>Moderately Fast</td>
</tr>
</tbody>
</table>

\(a\) D31J04439.3+414433.1 (Bonanos et al., 2003). \(b\) CN NMS-1 (Joshi et al., 2004). \(c\) CN NMS-2 (Joshi et al., 2004). \(d\) \(t_2(r')\) values taken from Table 5.1 for comparison. * these novae have been observed before maximum-light, in their final rise phase.

Table 4.1: The POINT-AGAPE classical nova catalogue. The epoch \(t_0(r')\) is the time of the brightest \(r'\)-band observation. The maximum magnitudes \(r'(t_0)\), \(i'(t_0)\) and \(g'(t_0)\) are the brightest observed magnitude in each band. \(dr'/dt\) is an estimate of the rate of decline. The speed class is estimated by assuming the \(V\)-band definition in Table 1.1 also applies to our \(r'\)-band data.
### Table 4.2: The POINT-AGAPE classical nova catalogue.

$x$ and $y$ are the positions from the M31 centre measured in arc-minutes along the M31 major and minor axis, respectively.

<table>
<thead>
<tr>
<th>Nova</th>
<th>R.A. (J2000)</th>
<th>Decl. (J2000)</th>
<th>$x$ (arc-min)</th>
<th>$y$ (arc-min)</th>
<th>CCD1</th>
</tr>
</thead>
<tbody>
<tr>
<td>PACN-99-01</td>
<td>$0^h43^m27^s.2$</td>
<td>$+41^\circ24'11''1$</td>
<td>-8.0</td>
<td>8.0</td>
<td>N1</td>
</tr>
<tr>
<td>PACN-99-02</td>
<td>$0^h44^m39^s.2$</td>
<td>$+41^\circ44'32''4$</td>
<td>-21.4</td>
<td>28.4</td>
<td>N3</td>
</tr>
<tr>
<td>PACN-99-03</td>
<td>$0^h42^m34^s.9$</td>
<td>$+41^\circ08'24''5$</td>
<td>1.8</td>
<td>-7.7</td>
<td>S3</td>
</tr>
<tr>
<td>PACN-99-04</td>
<td>$0^h42^m46^s.1$</td>
<td>$+40^\circ53'35''3$</td>
<td>-0.3</td>
<td>-22.6</td>
<td>S4</td>
</tr>
<tr>
<td>PACN-99-05</td>
<td>$0^h42^m41^s.1$</td>
<td>$+41^\circ19'12''2$</td>
<td>0.6</td>
<td>3.1</td>
<td>N2</td>
</tr>
<tr>
<td>PACN-99-06</td>
<td>$0^h43^m15^s.9$</td>
<td>$+41^\circ23'05''4$</td>
<td>-5.9</td>
<td>6.9</td>
<td>N1</td>
</tr>
<tr>
<td>PACN-99-07</td>
<td>$0^h43^m06^s.7$</td>
<td>$+41^\circ30'14''2$</td>
<td>-4.2</td>
<td>14.1</td>
<td>N4</td>
</tr>
<tr>
<td>PACN-00-01</td>
<td>$0^h42^m44^s.0$</td>
<td>$+41^\circ17'56''5$</td>
<td>0.1</td>
<td>1.8</td>
<td>N2</td>
</tr>
<tr>
<td>PACN-00-02</td>
<td>$0^h43^m06^s.0$</td>
<td>$+41^\circ30'48''3$</td>
<td>-4.1</td>
<td>14.7</td>
<td>N4</td>
</tr>
<tr>
<td>PACN-00-03</td>
<td>$0^h42^m44^s.6$</td>
<td>$+41^\circ20'42''1$</td>
<td>-0.1</td>
<td>4.6</td>
<td>N2</td>
</tr>
<tr>
<td>PACN-00-04</td>
<td>$0^h42^m37^s.6$</td>
<td>$+41^\circ17'38''6$</td>
<td>1.3</td>
<td>1.5</td>
<td>N2</td>
</tr>
<tr>
<td>PACN-00-05</td>
<td>$0^h43^m08^s.9$</td>
<td>$+41^\circ29'16''6$</td>
<td>-4.6</td>
<td>13.1</td>
<td>N4</td>
</tr>
<tr>
<td>PACN-00-06</td>
<td>$0^h42^m57^s.1$</td>
<td>$+41^\circ07'16''3$</td>
<td>-2.4</td>
<td>-8.9</td>
<td>S3</td>
</tr>
<tr>
<td>PACN-00-07</td>
<td>$0^h43^m53^s.8$</td>
<td>$+40^\circ55'43''5$</td>
<td>-13.1</td>
<td>-20.4</td>
<td>S4</td>
</tr>
<tr>
<td>PACN-01-01</td>
<td>$0^h42^m30^s.6$</td>
<td>$+41^\circ14'36''8$</td>
<td>2.6</td>
<td>-1.5</td>
<td>S3</td>
</tr>
<tr>
<td>PACN-01-02</td>
<td>$0^h42^m18^s.4$</td>
<td>$+41^\circ12'40''3$</td>
<td>4.9</td>
<td>-3.5</td>
<td>S3</td>
</tr>
<tr>
<td>PACN-01-03</td>
<td>$0^h43^m10^s.6$</td>
<td>$+41^\circ17'57''6$</td>
<td>-4.9</td>
<td>1.8</td>
<td>N1</td>
</tr>
<tr>
<td>PACN-01-04</td>
<td>$0^h42^m40^s.6$</td>
<td>$+41^\circ07'59''9$</td>
<td>0.7</td>
<td>-8.1</td>
<td>S3</td>
</tr>
<tr>
<td>PACN-01-05</td>
<td>$0^h44^m32^s.5$</td>
<td>$+41^\circ25'21''9$</td>
<td>-20.3</td>
<td>9.2</td>
<td>N1</td>
</tr>
<tr>
<td>PACN-01-06</td>
<td>$0^h43^m03^s.2$</td>
<td>$+41^\circ12'10''5$</td>
<td>-3.5</td>
<td>-4.0</td>
<td>S3</td>
</tr>
</tbody>
</table>

$^a$ D31J04439.3+414433.1 (Bonanos et al., 2003). $^b$ CN NMS-1 (Joshi et al., 2004). $^c$ CN NMS-2 (Joshi et al., 2004).

### Table 4.3: M31 classical novae speed class distribution. See Table 1.1 for the speed class definitions.

<table>
<thead>
<tr>
<th>Speed class</th>
<th>Number of CN</th>
<th>CN observed before maximum-light</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Fast</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Fast</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Moderately Fast</td>
<td>11</td>
<td>5</td>
</tr>
<tr>
<td>Slow</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Very Slow</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>
4.4 Fast novae

As shown in Table 4.3 and Figure 4.2, three of the CNe discovered were fast novae, taking between 11 – 25 days to decrease in brightness by two magnitudes from maximum light. Two of these fast CNe (PACN-00-06 and PACN-01-02) have been caught in their final rise phase before maximum-light. PACN-99-05 appears to have been first observed at or around its maximum light.

4.4.1 PACN-00-06

PACN-00-06 was observed four times during its final rise phase. It was first observed at on 19th October 2000 with \( r' = 18.08 \pm 0.01 \), before rising to \( r' = 17.09 \pm 0.01 \) on 21st October. The nova was again observed two weeks later about 1.5 magnitudes fainter. PACN-00-06 was followed for about four magnitudes. This nova was also observed by the Naini Tal M31 micro-lensing survey group (Joshi et al., 2004), and was designated by them CN NMS-1.

4.4.2 PACN-01-02

PACN-01-02 was observed several times before maximum light, first on 15th August 2001. It increased in brightness by 1.3 magnitudes until it reached a maximum-light of \( r' = 17.14 \pm 0.03 \) on 21st August. The light-curve was well sampled through maximum-light and into the initial decline phase and was followed for around three magnitudes below peak.
Figure 4.1: PACN-99-07 – Classified as a very fast CN
Figure 4.2: (a) PACN-99-05 – A fast CN
Figure 4.2: (b) PACN-00-06 – A fast CN
Figure 4.2: (c) PACN-01-02 – A Fast CN
4.5 Moderately fast novae

We discovered eleven moderately-fast novae, those with a $dr'/dt$ in the range $0.025 - 0.07$ mag day$^{-1}$. Their light-curves are shown in Figure 4.3.

Five of these novae (PACN-99-06, PACN-00-04, PACN-00-07, PACN-01-04 and PACN-01-06) were first seen during their final rise phase, with the remaining novae all appearing to be first observed around or just after maximum-light. Two of the moderately-fast novae (PACN-00-04 and PACN-00-05) exhibit strong oscillations in their light-curves around maximum light, as is expected for some moderately fast novae. PACN-00-05 also shows evidence of a large transition phase minimum between its early and late decline stages. This is typically associated with the rapid formation of an optically thick dust shell in the ejecta (Evans & Rawlings, 2005).

4.5.1 PACN-99-06

The light-curve of PACN-99-06, contains four points in both $r'$ and $g'$ during the final rise phase before reaching a maximum of $r' = 16.17 \pm 0.01$ and $g' = 16.91 \pm 0.01$. This CN was first observed on 7th September 1999 with $r' = 17.36 \pm 0.03$. When observed again, just over 24 hours later, it had increased in brightness by 0.9 magnitudes. Two days later is was observed at its maximum-light (11th September); in the 78 hours prior to maximum-light this CN had increased in brightness by 1.2 magnitudes. PACN-99-06 was followed for about five magnitudes below peak.

4.5.2 PACN-00-04

The nova PACN-00-04 was observed six times before maximum light, first on 8th August 2000 with $r' = 19.34 \pm 0.06$, before rising to $r' = 17.61 \pm 0.03$ just over two days later. A secondary maximum was observed at $r' = 18.07 \pm 0.03$ on 1st
4.5. Moderately fast novae

September 2000. This nova was only followed for about 2.5 magnitudes below peak.

4.5.3 PACN-00-05

PACN-00-05 was first observed on 4th August 2000, during the second season. Its maximum observed brightness was $r' = 17.58 \pm 0.03$. A secondary maximum of $r' = 19.59 \pm 0.03$ occurred about 500 days after maximum light following a transition phase. Unfortunately the transition phase occurred between the end of the second season and the start of the third, so no information is available for this nova during this phase. The nova was followed through two magnitudes of decline before the end of the second season.

4.5.4 PACN-01-04

The light-curve of PACN-01-04 contains six points before the observed maximum of $r' = 17.90 \pm 0.03$ at 4:25 on 27th August 2001. It was first observed at on 24th August at 1.9 magnitudes below peak and was followed for about two magnitudes after its maximum light.

4.5.5 PACN-01-06

The CN PACN-01-06 was also discovered by the Naini Tal micro-lensing group (Joshi et al., 2004), and was designated CN NMS-2 by them.

4.5.6 PACN-00-07

The classification of PACN-00-07 as a CN is more uncertain. At first glance its light-curve looks very much like that of a CN and the rate of decline would indicate that it is a moderately fast nova. However, with a maximum magnitude
of $r' = 19.53 \pm 0.04$ it is much fainter than the other ten moderately fast CNe which all have maximum light in the range $r' = 15.9$ to 17.9. Interestingly, PACN-00-07’s colour evolution appears to be more like that of a Mira than of a CN (see Figure 4.7 for comparison), but its position on the colour-magnitude diagram (Figure 3.4) is much nearer to the CN group than that of the other objects. Perhaps tellingly, it is the object which lies closest to the dividing line between the groups. This position is suggestive of a significant extinction effect ($\sim 1 - 2$ magnitudes in $r'$). Accordingly it is possible that PACN-00-07 is either a highly extinguished nova, or that it is a CN whose maximum light occurred during the gap between the first and second season and in this case, we are just observing a local maximum in the light-curve. Additionally, it is also possible that this object does not belong to the main population of CNe, or that the object has been misidentified as a CN. A search of the NED$^2$ and Simbad$^3$ astronomical databases revealed no known objects in or near the position of PACN-00-07.

4.6 Slow novae

Three slow novae were discovered, with a $dr'/dt$ of $0.013 - 0.024$ mag day$^{-1}$. These are displayed in Figure 4.4. Two of these slow CNe, PACN-99-04 and PACN-01-03, were first observed during their final rise phase. However, as slow novae are generally fainter than fast novae at maximum light, it was not possible to follow either PACN-99-02 or PACN-99-04 into their transition stage. Although somewhat brighter, PACN-01-03 occurred at the end of the third season.

$^2$The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

$^3$The SIMBAD database, operated at CDS, Strasbourg, France.
Figure 4.3: (a) PACN-99-01 – A moderately fast CN.
4.6. Slow novae

Figure 4.3: (b) PACN-99-03 – A moderately fast CN.
Figure 4.3: (c) PACN-99-09 – A moderately fast CN.
Figure 4.3: (d) PACN-00-01 – A moderately fast CN.
Figure 4.3: (e) PACN-00-03 – A moderately fast CN.
4.6. Slow novae

Figure 4.3: (f) PACN-00-04 – A moderately fast CN.
4.6. Slow novae

Figure 4.3: (g) PACN-00-05 – A moderately fast CN.
Figure 4.3: (h) PACN-00-07 – A moderately fast CN.
4.6. Slow novae

Figure 4.3: (i) PACN-01-04 – A moderately fast CN.
Figure 4.3: (j) PACN-01-05 – A moderately fast CN.
Figure 4.3: (k) PACN-01-06 – A moderately fast CN.
4.6.1 PACN-99-04

PACN-99-04 was first observed on 4\textsuperscript{th} August 1999 (the first epoch of the first season) with \( r' = 18.84 \pm 0.04 \). The maximum light was observed on 9\textsuperscript{th} August with \( r' = 18.41 \pm 0.03 \). The nova was followed for about two magnitudes below peak.

4.6.2 PACN-01-03

The CN PACN-01-03 was observed seventeen times throughout its final rise phase. It was first observed with \( r' = 19.27 \pm 0.08 \) and rose steadily for eight days to its observed maximum of \( r' = 17.30 \pm 0.04 \) on 27\textsuperscript{th} August 2001. This nova was only followed during its initial decline phase for around two magnitudes before the end of the third season.

4.7 Very slow novae

As shown in Figure 4.5, we discovered two very slow CNe; PACN-00-02 and PACN-01-01. Very slow CNe take 151 – 250 days to decrease by two magnitudes from maximum light.

4.7.1 PACN-00-02

The maximum in the \( r' \)-band light-curve of PACN-00-02 was observed at the beginning of the second season on 4\textsuperscript{th} August 2000 and the nova was still clearly visible by the end of the second season on 3\textsuperscript{rd} January 2001. However, it had become unresolved by the beginning of the third. This CN reached an observed maximum light of \( r' = 18.15 \pm 0.03 \) and had diminished by only 1.8 magnitudes by the end of the second season, 150 days later, with an estimated \( dr'/dt \simeq 0.01 \) mag day\(^{-1} \). PACN-00-02 has a relatively smooth light-curve, except for a feature
4.7. Very slow novae

Figure 4.4: (a) PACN-99-02 – A slow CN.
4.7. Very slow novae

Figure 4.4: (b) PACN-99-04 – A slow CN.
Figure 4.4: (c) PACN-01-03 – A slow CN.
4.8. Distribution of CNe

<table>
<thead>
<tr>
<th>CCD</th>
<th>Candidates</th>
<th>Percentage of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>North 1</td>
<td>4</td>
<td>20.0%</td>
</tr>
<tr>
<td>North 2</td>
<td>4</td>
<td>20.0%</td>
</tr>
<tr>
<td>North 3</td>
<td>1</td>
<td>5.0%</td>
</tr>
<tr>
<td>North 4</td>
<td>3</td>
<td>15.0%</td>
</tr>
<tr>
<td>South 1</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>South 2</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>South 3</td>
<td>6</td>
<td>30.0%</td>
</tr>
<tr>
<td>South 4</td>
<td>2</td>
<td>10.0%</td>
</tr>
</tbody>
</table>

Table 4.4: The distribution within each CCD of candidates selected by our CN detection pipeline.

about 100 days after maximum light in which the nova brightened by about a third of a magnitude, before continuing to decline again.

4.7.2 PACN-01-01

PACN-01-01 is an interesting object, although there are some reasons to doubt its classification as a nova. It was not possible to sample enough of PACN-01-01’s light-curve to make a reliable measurement of $dr'/dt$, as this nova remained around maximum-light for the majority of the time that it was observed. If it is a CN, its speed class is therefore uncertain. However, it is worth noting that it passed all of our selection criteria. The third season data are similar in some respects to the structure around the maximum light of the light-curves of some of the moderately fast (DQ Her-like) novae in this catalogue, e.g. PACN-00-04 and PACN-00-05. However, there may be a more marked similarity to the light-curve around maximum of the very slow nova HR Del 1967 (Drechsel et al., 1977). It is also worth noting that PACN-01-01 is only three arcmin from the centre of M31 and hence suffers significantly from a highly variable background.
Figure 4.5: (a) PACN-00-02 – A very slow CN.
Figure 4.5: (b) PACN-01-01 – A very slow CN.
4.8 Distribution of CNe

The distribution of candidates with CCD can be seen in Table 4.4. Figure 4.6 gives a graphical representation of each candidate’s position within our fields. The distribution shows some evidence of spatial concentration around the bulge; however, the significance of this cannot be properly estimated before we make Monte-Carlo completeness tests of our selection criteria (this is carried out in Chapter 6). One nova (PACN-00-07) lies well outside the main disk light on the far-disk side of M31. If this nova is associated with the M31 disk then it must lie at a de-projected distance of around 25 kpc from the centre of M31, or around four disk scale lengths.

As can be seen from Figure 4.6, one of our CNe may be located within the dwarf spheroidal galaxy M32. This nova, PACN-99-04, is located 22.6 arcmin from the centre of M31, but is only 1.8 arcmin from the centre of M32.

4.9 Pipeline detection efficiency

Chapter 6 details a careful assessment of the efficiency with which CNe have been detected by our pipeline. However, a useful comparison can be made with the CNe which have been announced on IAU Circulars during the lifetime of the POINT-AGAPE survey. An et al. (2004) found that 12 of the 14 CNe which were announced in IAU Circulars during our survey are present in the POINT-AGAPE dataset. All of these CNe are located within a few arcminutes of the centre of M31 and are of fast or moderately fast speed classes. Our automated pipeline has identified 7 of the 12 CNe listed in Table 4 of An et al. (2004). Of the remaining five, two (26285/26121 and 79136, using the An et al. identifiers) occur too late in the survey to be properly sampled (and therefore failed the selection criteria). One CN (78668) was lost due to the image trimming process of the pipeline as it occurs close to the northern edge of CCD3 in the southern field. Another (83479) was lost due to the masking of a diffraction spike of a very bright
Figure 4.6: The positions of the 20 detected CNe within M31. The lines and contours are as for Figure 2.2. The different symbols indicate a very fast nova (solid triangle), fast novae (closed circles), moderately fast novae (open circles), slow novae (closed boxes), and very slow novae (open boxes).
star. The final missed CN (26277/25695) failed the initial $15\sigma$ selection criteria. Therefore, at this stage we can conclude that our pipeline successfully recognised CNe within the boundaries of our defined selection criteria. In Chapter 6 we describe the procedure used to produce a pipeline completeness map of M31, which is carefully formulated to take account of the selection effects mentioned above.

4.10 Borderline and other light-curves

An inspection of the CNe in our catalogue allows us to be confident that at least 18 of the candidates are true CNe. However, as previously indicated, we are less certain about the classification of two CNe; namely PACN-00-07 and PACN-01-01. Furthermore two other interesting objects were contained within the catalogue at a preliminary stage, were later discarded by the pipeline and are discussed below.

4.10.1 A very long period Mira

As shown in Table 3.4, thirty-two CN candidates were eliminated only by applying the two colour-magnitude criteria. As can be seen in Figure 3.4, these candidates appear to be located in a "clump", indicating that they may be similar types of object. From inspection, the majority of these candidates appear to be Miras or Mira-like variables, with a few exceptions. Figure 4.7 shows the light-curve of the brightest Mira discovered. Its position in the colour-magnitude diagram is indicated in Figure 3.4. This object exhibits a very smooth light-curve and its position ($\alpha = 0^h44^m23^s7, \delta = +41^\circ28'4"1$) is coincident with an object exhibiting a remarkably similar light-curve from the DIRECT survey (Stanek et al., 1999), V14148 D31C, observed between September and October 1996. Figure 4.8 shows both the DIRECT $I$-band data and POINT-AGAPE data that has been transformed into $I$-band data, as well as the span of the 1st and 2nd POINT-AGAPE
observing seasons. The transformation of the POINT-AGAPE data to the $I$ band is obtained by deriving a best-fit linear transformation from $i'$ and $r'$ to $I$ using standard stars identified from the Magnier catalogues (see Appendix A). From a simple analysis of the DIRECT and POINT-AGAPE data and, given that the Mira was unresolved throughout the first and third POINT-AGAPE seasons, we arrive at two possible periods for this Mira, either $\sim 700$ days or $\sim 1400$ days. This makes it one of the longest period Miras observed to-date. At the distance of M31, it is also one of the most luminous.

### 4.10.2 Micro-lensing event PA-99-N2

The high signal-to-noise ratio micro-lensing event PA-99-N2 (Paulin-Henriksson et al., 2003) was also identified and was eliminated from the catalogue via the colour evolution selection criterion; as expected for a strong micro-lensing event as the micro-lensing magnification is the same at all wavelengths. The light-curve of the event produced using the CN detection pipeline is shown in Figure 4.9. A recent detailed analysis of this event using “super-pixel” photometry indicates anomalies near the peak of the light-curve which are well explained as being due to a binary lens system (An et al., 2004). The PSF-fitting photometry independently undertaken for this study confirms the anomalous “kink” on an otherwise smooth and achromatic light-curve, occurring on the rising side near peak.

### 4.11 Summary

In this chapter we have presented the entire POINT-AGAPE CN catalogue, including the multi-colour light-curves, position and initial speed class estimate of each nova. The catalogue included examples of novae covering the full range of speed classes, from very slow to very fast, although there is some uncertainty about the speed class assignment of the very fast nova. A brief, visual, analysis of the distribution of our detected CN suggest some spatial concentration around
4.11. Summary

Figure 4.7: Mira variable V14148 D31C as observed by our survey.

Figure 4.8: Mira variable V14148 D31C. Earlier data from the DIRECT survey (Stanek et al., 1999), later data from this survey. The horizontal lines indicate the length of the 1st and 2nd POINT-AGAPE observing seasons.
Figure 4.9: The PSF-fitted light-curve of the micro-lensing event PA-99-N2 discovered previously by Paulin-Henriksson et al. (2003) using “super-pixel” photometry. The event is investigated in detail by An et al. (2004).
4.11. Summary

the bulge, however there are also a number of strong candidates for disk novae. From a simple evaluation of our completeness, using mainly IAU Circulars, we are confident that our pipeline successfully identifies CNe within our defined limits.

We also presented the light-curves of two interesting non-nova objects detected (and discarded) at various stages of the pipeline. The high signal-to-noise microlensing event PA-99-N2 and, what is potentially the brightest and longest period Mira variable found to-date. The Mira has a period of either $\sim 700$ or $\sim 1400$ days, with a maximum absolute luminosity of $M_I \sim -7.0$.

In the next two chapters, we present a full statistical analysis of the POINT-AGAPE CN catalogue. This analysis includes the calibration of both MMRD and $t_{15}$ relationships for the dataset and an investigation of the distribution, underlying population and global nova rate of M31.
Chapter 5

Analysis of the MMRD and $t_{15}$ Relationships

5.1 Introduction

In Chapter 5 we discuss the line of sight extinction towards and within M31. We then reassess the speed class assignment of each of the detected novae and assess both the MMRD and $t_{15}$ relationships with respect to the POINT-AGAPE CN catalogue. Finally, we compare our results with previous analyses including fits to these relationships for Galactic novae.

5.2 Extinction

The interstellar extinction is a complicating factor in deriving relationships involving absolute magnitudes. Trumpler (1930) first realised that the dust in interstellar space both diminishes and reddens the light from distant stars. The interstellar dust accomplishes this by the scattering and absorption of incident photons. These processes are collectively known as extinction. The amount of extinction and reddening suffered is dependent upon the size, shape and compo-
sition of the dust particles. Dust grains efficiently absorb and scatter photons whose wavelength is comparable to or smaller than themselves. With a typical size of \( \sim 100 \text{nm} \) interstellar dust grains extinguish UV light most efficiently. The extinction is defined as the difference between the observed magnitude and the magnitude that would have been observed in the absence of any interstellar dust. The reddening, often denoted via the colour excess, \( E(B-V) \), is then defined as the difference between the observed B-V colour and the intrinsic (no dust) \( B-V \) colour of the star.

### 5.2.1 Foreground galactic extinction

In order to calculate the line of sight Galactic extinction in the direction of M31 we used the maps of dust IR emission of Schlegel et al. (1998). However, M31 (along with other large nearby galaxies such as the LMC and SMC) can not be removed from their maps as its temperature structure is not sufficiently resolved. As such, we used their estimate of the reddening, based upon the median dust emission in annuli surrounding the galaxy. For M31 they found, \( E(B-V) = 0.062 \text{ mag} \), which equates to an extinction in the three POINT-AGAPE filters of: \( g' = 0.24 \), \( r' = 0.17 \) and \( i' = 0.13 \) magnitudes respectively.

### 5.2.2 Extinction within M31

In M31, as with most disk and spiral galaxies, the vast majority of the dust lies close to the disk plane. As such, we expected that novae that appeared to be located within the M31 disk would suffer a varying range of extinction. Also, unless these novae were actually in the far-disk (and we were observing them through the entire bulge) we expected bulge novae to all have approximately the same extinction as each other.

The POINT-AGAPE collaboration has produced extinction estimates derived from calibrated M31 colour maps and synthetic stellar models (Girardi & Salaris,


5.3 Maximum magnitude, rate of decline

2001; Salaris, private communication). The synthetic stellar models were used to generate a synthetic colour map \( \langle r' - i' \rangle \) of M31 which was then compared to the true colour map of M31. By using the two colour maps, in conjunction with the standard reddening law, they were able to deduce the reddening within M31. The computed extinction estimates are however a factor \( \sim 2.5 \) larger than expected for Sb type galaxies (Holwerda et al., 2004) such as M31; the estimates also assume that the internal extinction of M31 is uniform along the line of sight through the disk. This over-estimate is thought to have resulted from uncertainties in the synthetic stellar models and the parameters used by these models which are optimised to reproduce the stellar population of our own Galaxy.

In order to correct the over-estimation of the POINT-AGAPE extinction estimates, we made the assumption that the typical \( I \)-band opacity for Sb galaxies (Holwerda et al., 2004, see their Figure 11) should be comparable to the opacity of M31. Using the data of Holwerda et al., we estimated the mean \( I \)-band extinction of a Sb galaxy to be \( A(I) = 0.8 \) magnitudes. Using reddening data from Schlegel et al., we were able to equate this to a reddening of \( r' = 1.2 \) and \( i' = 0.9 \) magnitudes respectively. Taking the mean extinction within the POINT-AGAPE fields, as computed by the POINT-AGAPE collaboration, to be indicative of the true mean extinction within M31, we were able to correct the initial extinction estimates by scaling both the \( r' \) and \( i' \) estimates by a factor 0.4. Figure 5.1 shows a map of the estimated \( r' \) extinction in M31.

5.3 Maximum magnitude, rate of decline

The essence of the empirically determined MMRD relationship for CNe is that the brighter a nova appears at its maximum for a given distance, the faster its visible light-curve will diminish (Hubble, 1929). The MMRD relationship is discussed in more detail in Section 1.3.4. As noted earlier, this relationship is important as it can potentially be used as a tool to derive the distance to a population of CNe (such as within a galaxy) by comparison to the MMRD in our own Galaxy.
5.3. Maximum magnitude, rate of decline

Figure 5.1: Plot showing the distribution of the estimated average $r'$ extinction between the Earth and the far side of M31.
5.3. Maximum magnitude, rate of decline

This is possible by assuming that the MMRD is valid for all CNe in all stellar populations (Capaccioli et al., 1989).

The decline rates shown for the detected novae in Table 4.1 were estimates based upon the assumption that the general trend of the light-curve between the maximum observed point and the point closest to two magnitudes below the maximum was linear in nature. However, in order to assess the MMRD relationship for our catalogue of CNe a much more robust measurement of the decline rate \( t_2 \) in this case is required. To calculate the value of \( t_2 \) for each CN, we evaluated the light-curve between the points bracketing two magnitudes below the observed peak. By assuming that the light-curve behaves linearly between these observations, we were able to deduce \( t_2 \) values of the 20 POINT-AGAPE CNe. This was carried out for both the \( r' \) and \( i' \) observations. The \( g' \) observations were omitted as they were only available for seven of the detected novae. The measured maximum light and \( t_2 \) values for each CN candidate are shown in Table 5.1. The novae PACN-99-01, PACN-00-01 and PACN-01-01 were excluded because they were likely already to have been in decline at first observation; hence it was not possible to accurately determine the uncertainty in their maximum light or decline rate. In addition, only a small portion of the light-curve of PACN-99-07 is sampled; as such, due to its erratic behaviour, we are doubtful whether the classification as a very fast nova is a true representation of this nova’s speed class. Also, there was no \( i' \) data available around maximum light for PACN-99-05 and PACN-99-06 so it was not possible to determine a \( t_2 \) value for these novae. Therefore, only 16 novae were used for the \( r' \) MMRD analysis and 14 novae for the \( i' \) analysis.

The distribution of maximum observed magnitudes and nova decay rates\(^1\) is shown for the \( r' \) data in Figure 5.2 and for the \( i' \) data in Figure 5.3. An evaluation of these distributions, weighting each point solely by their observational error and using the expected MMRD relationship, shown in Equation 1.1, was expected to produce a poor fit given that the scatter of both distributions is

\(^1\)The nova decay rate, defined as \( \log[200d/t_2] \), is used for historical reasons. Its use also allows visual comparison between previous MMRD plots.
5.3. Maximum magnitude, rate of decline

\[ r'(t'_0) \quad t_2(r') \quad i'(t'_0) \quad t_2(i') \]

<table>
<thead>
<tr>
<th>Nova</th>
<th>( r'(t'_0) )</th>
<th>( t_2(r') ) (days)</th>
<th>( i'(t'_0) )</th>
<th>( t_2(i') ) (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PACN-99-01</td>
<td>16.53 ( \pm ) 0.03(^a)</td>
<td>30.50</td>
<td>16.39 ( \pm ) 0.03(^a)</td>
<td>37.53</td>
</tr>
<tr>
<td>PACN-99-02</td>
<td>18.91 ( \pm ) 0.03</td>
<td>99.48</td>
<td>19.19 ( \pm ) 0.04</td>
<td>58.09(^b)</td>
</tr>
<tr>
<td>PACN-99-03</td>
<td>17.79 ( \pm ) 0.02</td>
<td>59.62</td>
<td>17.60 ( \pm ) 0.04</td>
<td>34.16</td>
</tr>
<tr>
<td>PACN-99-04</td>
<td>18.41 ( \pm ) 0.04</td>
<td>164.39(^b)</td>
<td>18.34 ( \pm ) 0.07</td>
<td>87.25(^b)</td>
</tr>
<tr>
<td>PACN-99-05</td>
<td>17.70 ( \pm ) 0.04</td>
<td>25.82</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PACN-99-06</td>
<td>16.17 ( \pm ) 0.01</td>
<td>20.30</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PACN-99-07</td>
<td>18.1 ( \pm ) 0.1</td>
<td>9.80</td>
<td>18.02 ( \pm ) 0.04</td>
<td>2.28</td>
</tr>
<tr>
<td>PACN-00-01</td>
<td>17.73 ( \pm ) 0.04(^a)</td>
<td>38.65</td>
<td>17.58 ( \pm ) 0.08(^a)</td>
<td>11.88(^b)</td>
</tr>
<tr>
<td>PACN-00-02</td>
<td>18.15 ( \pm ) 0.03</td>
<td>198.55</td>
<td>18.85 ( \pm ) 0.05</td>
<td>817.19(^b)</td>
</tr>
<tr>
<td>PACN-00-03</td>
<td>18.54 ( \pm ) 0.03</td>
<td>33.02</td>
<td>18.19 ( \pm ) 0.04</td>
<td>22.44(^b)</td>
</tr>
<tr>
<td>PACN-00-04</td>
<td>17.61 ( \pm ) 0.03</td>
<td>30.65</td>
<td>17.33 ( \pm ) 0.04</td>
<td>36.44(^b)</td>
</tr>
<tr>
<td>PACN-00-05</td>
<td>17.30 ( \pm ) 0.01</td>
<td>59.21</td>
<td>17.11 ( \pm ) 0.01</td>
<td>198.32</td>
</tr>
<tr>
<td>PACN-00-06</td>
<td>17.09 ( \pm ) 0.01</td>
<td>13.85</td>
<td>16.64 ( \pm ) 0.01</td>
<td>13.44</td>
</tr>
<tr>
<td>PACN-00-07</td>
<td>19.53 ( \pm ) 0.04</td>
<td>55.21</td>
<td>19.48 ( \pm ) 0.05</td>
<td>100.27(^b)</td>
</tr>
<tr>
<td>PACN-01-01</td>
<td>18.45 ( \pm ) 0.02(^a)</td>
<td>213.12(^b)</td>
<td>18.16 ( \pm ) 0.04(^a)</td>
<td>330.86(^b)</td>
</tr>
<tr>
<td>PACN-01-02</td>
<td>17.14 ( \pm ) 0.03</td>
<td>22.06</td>
<td>16.71 ( \pm ) 0.04</td>
<td>17.08</td>
</tr>
<tr>
<td>PACN-01-03</td>
<td>17.30 ( \pm ) 0.04</td>
<td>143.71</td>
<td>16.88 ( \pm ) 0.06</td>
<td>66.21(^b)</td>
</tr>
<tr>
<td>PACN-01-04</td>
<td>17.90 ( \pm ) 0.03</td>
<td>47.29</td>
<td>17.38 ( \pm ) 0.04</td>
<td>37.24</td>
</tr>
<tr>
<td>PACN-01-05</td>
<td>15.90 ( \pm ) 0.01</td>
<td>28.15</td>
<td>15.61 ( \pm ) 0.01</td>
<td>15.83</td>
</tr>
<tr>
<td>PACN-01-06</td>
<td>17.38 ( \pm ) 0.01</td>
<td>52.13</td>
<td>16.88 ( \pm ) 0.03</td>
<td>38.24(^b)</td>
</tr>
</tbody>
</table>

\(^a\) the light-curve was visible at, or shortly after, maximum-light in the first observational epoch of the season, hence it was only possible to place a lower limit on its maximum-light.

\(^b\) it was not possible to follow these light-curves through two magnitudes below their observed maximum light; hence, the value of \( t_2 \) has been estimated from the general trend of these light-curves.

Table 5.1: \( r' \) and \( i' \) maximum observed magnitudes and corresponding \( t_2 \) times for each CN detected in the POINT-AGAPE data.
clearly much greater than that implied solely by the photometric uncertainties. This prediction was confirmed through analysis of the data.

Given the general trend that photometric errors depend greatly upon the brightness of the object, it would be more informative to produce un-weighted MMRD fits. Consequently, the following MMRD fits were produced by using an un-weighted least-squares method:

\[
m_{r'} = (15.5 \pm 1.3) + (1.3 \pm 0.8) \log t_2 \tag{5.1}
\]

\[
m_{i'} = (15.4 \pm 1.0) + (1.3 \pm 0.6) \log t_2 \tag{5.2}
\]

These un-weighted results are shown by the red lines in Figures 5.2 and 5.3. The average scatter about the fit in these MMRD plots is \( \sim 0.6 \) and \( \sim 0.7 \) magnitudes for the \( r' \) and \( i' \) distributions respectively. This is broadly consistent with the typical linear MMRD uncertainty of \( \sim 0.5 \) magnitudes found by Downes & Duerbeck (2000).

As the MMRD relationship is thought to be more of a “S-shape” rather than linear (see Section 1.3.4), we repeated the MMRD fitting over the linear region of the \( V \)-band MMRD, i.e. \( 10 \lesssim t_2 \lesssim 50 \) (Capaccioli et al., 1989). The \( r' \) and \( i' \) fits are shown below and they are represented by the blue lines in Figures 5.2 and 5.3.

\[
m_{r'} = (14.0 \pm 2.2) + (2.3 \pm 1.4) \log t_2 \tag{5.3}
\]

\[
m_{i'} = (12.5 \pm 2.4) + (3.4 \pm 1.6) \log t_2 \tag{5.4}
\]

The average scatter for these fits are \( \sim 0.6 \) for both the \( r' \) and \( i' \) distributions. We extended the linear fitting region slightly to \( 0.5 \leq \log[200d/t_2] \leq 1.5 \) to allow
Figure 5.2: Plot showing the relationship between the $r'$ brightness at maximum light and the decay rate ($v_2(r') = \log[200d/t_2(r')]$) of the 16 POINT-AGAPE CNe with well defined maximum lights and decay rates. The range of the error bars represents the photometric errors in the maximum observed magnitude. The red line represents an un-weighted fit performed on all the data (Equation 5.1) while the blue line shows an un-weighted fit on the data in the range $0.5 \leq \log[200d/t_2(r')] \leq 1.5$ (Equation 5.3). The vertical dashed line represents the “slow” boundary of the linear region of the MMRD ($\log[200d/t_2(r')] = 0.5$).
Figure 5.3: As Figure 5.2, but for the $i'$ data.
for any uncertainties between the $r'$ and $i'$ MMRD relationships and the more commonly used $B$ and $V$ MMRDs\(^2\). As was expected, a slightly better fit was achieved by limiting the data used to the linear region of the MMRD.

### 5.3.1 Maximum light uncertainties

In an attempt to further refine our MMRD relationship, and either reduce or help to explain the large scatter, we then considered that the brightest observation of each nova is only a lower limit of that nova’s true maximum light. In the majority of cases each maximum observation was straddled by observations from the following and preceding nights, leading to a small error in the assignment of the true maximum light. We then estimated the maximum potential error on our measurement of the maximum light. Taking a good estimation of the general slope of each light-curve to be that of $2/t_2$ magnitudes/day we calculated the amount that each light-curve could have possibly increased in brightness between the two points straddling the brightest observation. The maximum potential error induced by missing the maximum light for each CN is shown in column three of Table 5.2. The large maximum light errors derived for PACN-99-07 and PACN-01-05 were due to a combination of a fast decline rate and poor sampling around maximum light. In particular, the speed class assignment of PACN-99-07 was known to be suspect, with a much slower decline time seeming more fitting. As previously mentioned, this CN was excluded from this analysis due to the uncertainty of its decline rate.

The estimated maximum range of each nova’s maximum light, combined with the observational uncertainties, are represented by the displacement of two error bars in Figures 5.4 and 5.5 for the $r'$ and $i'$ distributions respectively. The two error sources are combined by simple addition as the maximum light error is a systematic rather than a random error. As the actual maximum light is equally

\(^2\)These uncertainties would include any differing form of nova light-curves as seen through different broadband filters and the expected faster decline of light-curves observed through redder filters.
<table>
<thead>
<tr>
<th>Nova</th>
<th>$r'(t'_{0}^{e})$</th>
<th>Estimated max error on $r'$ maximum light</th>
<th>Estimated average $r'$ extinction</th>
<th>$i'(t'_{0}^{e})$</th>
<th>Estimated max error on $i'$ maximum light</th>
<th>Estimated average $i'$ extinction</th>
</tr>
</thead>
<tbody>
<tr>
<td>PACN-99-01</td>
<td>16.53 ± 0.03</td>
<td>-</td>
<td>-0.67</td>
<td>16.39 ± 0.03</td>
<td>-</td>
<td>-0.51</td>
</tr>
<tr>
<td>PACN-99-02</td>
<td>18.91 ± 0.03</td>
<td>-0.03</td>
<td>-0.57</td>
<td>19.19 ± 0.04</td>
<td>-0.04</td>
<td>-0.43</td>
</tr>
<tr>
<td>PACN-99-03</td>
<td>17.79 ± 0.02</td>
<td>-0.02</td>
<td>-0.60</td>
<td>17.60 ± 0.04</td>
<td>-0.06</td>
<td>-0.46</td>
</tr>
<tr>
<td>PACN-99-04</td>
<td>18.41 ± 0.04</td>
<td>-0.02</td>
<td>-0.52</td>
<td>18.34 ± 0.07</td>
<td>-0.02</td>
<td>-0.39</td>
</tr>
<tr>
<td>PACN-99-05</td>
<td>17.70 ± 0.04</td>
<td>-0.04</td>
<td>-0.66</td>
<td>-</td>
<td>-</td>
<td>-0.50</td>
</tr>
<tr>
<td>PACN-99-06</td>
<td>16.17 ± 0.01</td>
<td>-0.13</td>
<td>-0.67</td>
<td>-</td>
<td>-</td>
<td>-0.51</td>
</tr>
<tr>
<td>PACN-99-07</td>
<td>18.1 ± 0.1</td>
<td>-4.2</td>
<td>-0.65</td>
<td>18.02 ± 0.04</td>
<td>-0.88</td>
<td>-0.49</td>
</tr>
<tr>
<td>PACN-00-01</td>
<td>17.73 ± 0.04</td>
<td>-</td>
<td>-0.58</td>
<td>17.58 ± 0.08</td>
<td>-</td>
<td>-0.44</td>
</tr>
<tr>
<td>PACN-00-02</td>
<td>18.15 ± 0.03</td>
<td>-0.01</td>
<td>-0.65</td>
<td>18.85 ± 0.05</td>
<td>-0.00a</td>
<td>-0.49</td>
</tr>
<tr>
<td>PACN-00-03</td>
<td>18.54 ± 0.03</td>
<td>-0.06</td>
<td>-0.67</td>
<td>18.19 ± 0.04</td>
<td>-0.09</td>
<td>-0.51</td>
</tr>
<tr>
<td>PACN-00-04</td>
<td>17.61 ± 0.03</td>
<td>-0.07</td>
<td>-0.66</td>
<td>17.33 ± 0.04</td>
<td>-0.06</td>
<td>-0.50</td>
</tr>
<tr>
<td>PACN-00-05</td>
<td>17.30 ± 0.01</td>
<td>-0.18</td>
<td>-0.65</td>
<td>17.11 ± 0.01</td>
<td>-0.06</td>
<td>-0.49</td>
</tr>
<tr>
<td>PACN-00-06</td>
<td>17.09 ± 0.01</td>
<td>-0.09</td>
<td>-0.65</td>
<td>16.64 ± 0.01</td>
<td>-0.14</td>
<td>-0.49</td>
</tr>
<tr>
<td>PACN-00-07</td>
<td>19.53 ± 0.04</td>
<td>-0.03</td>
<td>-0.48</td>
<td>19.48 ± 0.05</td>
<td>-0.02</td>
<td>-0.37</td>
</tr>
<tr>
<td>PACN-01-01</td>
<td>18.45 ± 0.02</td>
<td>-</td>
<td>-0.61</td>
<td>18.16 ± 0.04</td>
<td>-</td>
<td>-0.47</td>
</tr>
<tr>
<td>PACN-01-02</td>
<td>17.14 ± 0.03</td>
<td>-0.10</td>
<td>-0.64</td>
<td>16.71 ± 0.04</td>
<td>-0.12</td>
<td>-0.48</td>
</tr>
<tr>
<td>PACN-01-03</td>
<td>17.30 ± 0.04</td>
<td>-0.02</td>
<td>-0.62</td>
<td>16.88 ± 0.06</td>
<td>-0.03</td>
<td>-0.47</td>
</tr>
<tr>
<td>PACN-01-04</td>
<td>17.90 ± 0.03</td>
<td>-0.05</td>
<td>-0.65</td>
<td>17.38 ± 0.04</td>
<td>-0.06</td>
<td>-0.49</td>
</tr>
<tr>
<td>PACN-01-05</td>
<td>15.90 ± 0.01</td>
<td>-0.93</td>
<td>-0.57</td>
<td>15.61 ± 0.01</td>
<td>-1.68</td>
<td>-0.43</td>
</tr>
<tr>
<td>PACN-01-06</td>
<td>17.38 ± 0.01</td>
<td>-0.12</td>
<td>-0.63</td>
<td>16.88 ± 0.03</td>
<td>-0.10</td>
<td>-0.48</td>
</tr>
</tbody>
</table>

Table 5.2: Maximum magnitudes and corresponding maximum magnitude error and average extinction correction for the POINT-AGAPE novae.
likely to lie at any point between the observed value and the computed potential
maximum value, we “re-sampled” the “observation” of the maximum light to be
the mid-point of the computed range for each CN for the purpose of fitting of the
MMRD relationship. The re-evaluated M31 MMRD relationship is given below:

\[
m_{r'} = (15.2 \pm 1.3) + (1.4 \pm 0.8) \log t_2 \quad (5.5)
\]

\[
m_{i'} = (15.0 \pm 1.0) + (1.5 \pm 0.6) \log t_2 \quad (5.6)
\]

Rather than using the least-squares method to fit that data, as had been employed
earlier, we now used a minimum absolute deviation method as our errors are no
longer in the form of a Gaussian distribution and are dominated by systematic
uncertainties. The scatter on these MMRD fits remains at \( \sim 0.6 \) magnitudes and
\( \sim 0.7 \) magnitudes for the \( r' \) and \( i' \) data respectively. This implies that the scatter
in the MMRD relationships is not significantly affected by missing the maxi-
mum by a day or two, as is the typical interval expected in the POINT-AGAPE
data. The similarity between these fits and the previous two (Equations 5.1 and
5.2) is also indicative of the apparent minimal effect induced by considering the
possibility of missing the maximum light by a small amount of time.

The MMRD fitting was again repeated for the linear regime of the “S-shaped”
MMRD relationship \( (0.5 \leq \log[200d/t_2] \leq 1.5) \), using the minimum absolute
deviation method, yielding the following results:

\[
m_{r'} = (13.8 \pm 2.2) + (2.4 \pm 1.5) \log t_2 \quad (5.7)
\]

\[
m_{i'} = (11.5.0 \pm 2.4) + (3.9 \pm 1.6) \log t_2 \quad (5.8)
\]

Again, these results are similar to those found previously (Equations 5.3 and 5.4)
Figure 5.4: Plot showing the relationship between the $r'$ brightness at maximum light and the decay rate ($v_2(r') = \log[200d/t_2(r')]$) of the 16 POINT-AGAPE CNe with well defined maximum lights and decay rates. The range of the error bars represents the maximum estimated range of the maximum light of each nova combined with the observational uncertainty. The red line indicates an un-weighted fit performed on all the data (Equation 5.5) while the blue line shows an un-weighted fit performed on the data in the range $0.5 \leq \log[200d/t_2(r')] \leq 1.5$ (see Equation 5.7). The vertical dashed line represents the “slow” boundary of the linear region of the MMRD ($\log[200d/t_2(r')] = 0.5$).
5.3. Maximum magnitude, rate of decline

Figure 5.5: As Figure 5.4, but for the $i'$ data.
5.3. Maximum magnitude, rate of decline

with a similar scatter of the data about the fit, again indicating the minimal effect of missing the maximum light of a nova by a day or two.

5.3.2 Extinction corrections

Each CN’s light-curve may still be affected by extinction within M31 and our own Galaxy. As discussed in Section 5.2, the Galactic extinction in the direction of M31 is well defined and relatively small compared to the maximum potential extinction experienced within M31. The extinction experienced by each nova’s light will depend upon the column density between the nova and the observer, with the maximum potential extinction dependent upon the CN’s position (see Figure 5.1 which shows the average\(^3\) extinction map of M31).

Ideally we would use two independent methods to estimate the extinction experienced within M31. The first uses the computed extinction map (see Figure 5.1) to provide an estimate of the maximum potential extinction experienced by each nova. The second uses the van den Bergh - Younger relationship (see Section 1.3.6) to produce an estimate of the relative reddening experienced by the light from each nova. Unfortunately it was not possible to use the “van den Bergh - Younger” relationship to evaluate the reddening experienced by each nova. The relationship was defined to describe the \(V\) and \(B\)-band behaviour of a nova’s light-curve. As the POINT-AGAPE survey was carried out predominately in \(r'\) and \(i'\) we can not be certain whether such a relationship exists for these bands, of the magnitude of any relationship, nor of any differing time scale after maximum light. It is also not possible to reliably transform from the POINT-AGAPE filters to both \(V\) and \(B\) (see Appendix A) to take advantage of this relationship. So we are only able to use the first method in this case.

The first method may be applied to the 16 CNe for which valid \(r'\) decline rates could be computed and the 14 novae with valid \(i'\) decline rates. The computed

\(^3\)The maximum potential extinction is simply defined as double the average extinction (see Section 5.2.2) as the extinction model used computes the average extinction to the mid-point of the line of sight through M31.
average extinctions are shown in Column 4 of Table 5.2. Figures 5.6 and 5.7 show the distribution of extinction corrected and maximum magnitude error corrected \( r' \) and \( i' \) data respectively. The base of the error bars represents the actual maximum observed light, with the length of the bars representing the absolute range of the actual maximum light. As with the maximum magnitude errors we have assumed that the extinction is equally likely to lie at any value between zero and the maximum estimate. Again, for this analysis the three error sources have been combined by simple addition. As the maximum light error and the extinction error are both independent absolute maximum errors, the maximum error that can be experienced due to both of these sources is simply the sum of the two – in the direction of increasing luminosity. We again “re-sampled” the maximum light data point to lie equally distant between the observation and the extreme maximum error for the purpose of the MMRD fitting. The fits are shown and discussed in the next section (see Equations 5.9 and 5.10).

### 5.3.3 Comparison with previous results

The computed MMRD plots, including photometric, maximum magnitude and extinction uncertainties are shown in Figures 5.6 and 5.7 for the \( r' \) and \( i' \) datasets respectively. The resulting fits, including the above uncertainties are:

\[
m_{r'} = (14.5 \pm 1.3) + (1.5 \pm 0.8) \log t_2 \tag{5.9}
\]

\[
m_{i'} = (14.5 \pm 1.0) + (1.5 \pm 0.6) \log t_2 \tag{5.10}
\]

The scatter in the final MMRD fits are \( \sim 0.7 \) and \( \sim 0.8 \) magnitudes for the \( r' \) and \( i' \) datasets respectively, comparable to the mean error size. Again the MMRD data were analysed in the linear region of the “S-shaped” curve (\( 0.5 \leq \log[200d/t_2] \leq 1.5 \)) yielding:
5.3. Maximum magnitude, rate of decline

Figure 5.6: Plot showing the relationship between the $r'$ brightness at maximum light and the decay rate ($v_2(r') = \log(200d/t_2(r'))$) of the 16 POINT-AGAPE CNe with well defined maximum lights and decay rates. The range of the error bars represents the maximum estimated range of the combination of the extinction, maximum light and observational uncertainties. The red line indicates an un-weighted fit performed on all the data (Equation 5.9) while the blue line shows an un-weighted fit performed on the data in the range $0.5 \leq \log(200d/t_2(r')) \leq 1.5$ (see Equation 5.11). The vertical dashed line represents the “slow” boundary of the linear region of the MMRD ($\log(200d/t_2(r')) = 0.5$). The grey shaded region represents the best fit Galactic “S-shaped” MMRD (see Subsection 1.3.2), the black solid line shows the best fit Galactic linear MMRD - both these Galactic MMRD are derived for $V$ data and have been transformed to the M31 distance.
Figure 5.7: As Figure 5.6, but for the $i'$ data.
5.4. The $t_{15}$ relationship

\[ m_{r'} = (13.0 \pm 2.2) + (2.5 \pm 1.4) \log t_2 \quad (5.11) \]

\[ m_{i'} = (11.0 \pm 2.4) + (3.9 \pm 1.6) \log t_2 \quad (5.12) \]

with a scatter of $\sim 0.7$ magnitudes about the fits for both the $r'$ and $i'$ data, which is again comparable to the mean error.

All four of the MMRD relationships calculated (Equations 5.9-5.12) are shown in Figures 5.6 and 5.7 along with a recent Galactic calibration of the MMRD relationship (Equation 1.2, Downes & Duerbeck (2000)). The Downes & Duerbeck (2000) calibration has been translated to the distance of M31 using a distance modulus of 24.3 magnitudes (Welch et al., 1986), yielding:

\[ m_V = (12.98 \pm 0.44) + (2.55 \pm 0.32) \log t_2 \quad (5.13) \]

It is clear that the $r'$ and $i'$ MMRD relationships that are solely fitted to data within the linear region of the “S-shaped” MMRD provide a better fit than those using the full decline rate range of the CN catalogue. As such, we will refer to these relationships (Equations 5.11 and 5.12) as the $r'$ and $i'$ MMRDs for M31.

5.4 The $t_{15}$ relationship

Like the MMRD, the $t_{15}$ relationship has been empirically defined. It states that all CNe reach approximately the same absolute magnitude 15 days after maximum light (Buscombe & de Vaucouleurs, 1955). The $t_{15}$ relationship is discussed in more detail in Section 1.3.5 and it may also be useful in calculating the distance to a CN population. The majority of previous $t_{15}$ calibrations have been carried out using $V$-band data. However, due to the restrictions of the POINT-AGAPE catalogue, we can only attempt calibration using $r'$ and $i'$ data.
Using these data we can make an initial calibration of the $t_{15}$ relationship for the POINT-AGAPE catalogue:

\[ m_{15,r'} = 18.7 \pm 0.8 \]  \hspace{1cm} (5.14)

\[ m_{15,i'} = 18.7 \pm 0.9 \]  \hspace{1cm} (5.15)

As was found for the MMRD relationship, the photometric errors alone do not account for the extent of the scatter of magnitudes at 15 days following maximum light.

### 5.4.1 Maximum magnitude and extinction uncertainties

As was attempted for the MMRD data, we can try to decrease or at least explain the scatter in these data by taking into account the line-of-sight extinction for, and that we may have missed the maximum light of, each nova. Using the data in Table 5.2 to recalibrate each light-curve, we therefore reassessed the both the $r'$ and $i'$ $t_{15}$ relationships for the POINT-AGAPE novae catalogue.

\[ m_{15,r'} = 18.0 \pm 0.9 \]  \hspace{1cm} (5.16)

\[ m_{15,i'} = 18.0 \pm 1.0 \]  \hspace{1cm} (5.17)

Figures 5.8 and 5.9 show a superposition of the 16 $r'$ and 14 $i'$ re-calibrated light-curves that have well defined maximum light magnitudes. The light-curves are all plotted in units of time since maximum light. Each plot shows the light-curve behaviour for the first 50 days following each eruption. There is clearly little or no convergence of these light-curves at time around 15 days.
Figure 5.8: A superposition of the re-calibrated $r'$ light-curves of 16 of the POINT-AGAPE CNe. The light-curves have been time-shifted so that the times of their observed maximum light are coincident. Each line represents the linear interpolation of the light-curves between observations.
5.4. The $t_{15}$ relationship

Figure 5.9: As Figure 5.8, but for the $i'$ data.
The inclusion of extinction and maximum light uncertainties has actually slightly increased the scatter of the $t_{15}$ values. This implies that the scatter in magnitudes 15 days after peak is not solely due to uncertainties in the luminosity of the nova, hence indicating that any $t_{15}$ relationship may not be valid for these pass bands.

### 5.4.2 Comparison with previous results

By assuming a distance modulus for M31 of 24.3 magnitudes (Welch et al., 1986) our computed $t_{15}$ values (see Equations 5.16 and 5.17) might be compared with those found previously (see Table 1.2).

\[ M_{15,r'} = -6.3 \pm 0.9 \]  \hspace{1cm} (5.18)

\[ M_{15,i'} = -6.3 \pm 1.0 \]  \hspace{1cm} (5.19)

However, direct comparison between our results and previous results can not be easily made. All calibrations of the $t_{15}$ relationship to-date have been in “blue” bands, whereas our calibration is done in “red” bands. However, given that CNe become bluer with time, the result that our $t_{15}$ luminosities are fainter than all but the most recent of the previous “blue” calibrations (see Table 1.2) is not surprising. The scatter in our results is very large, and larger than those found in previous surveys. For instance, in a recent HST study of M49 (Ferrarese et al., 2003) the $V$-band $t_{15}$ relationship was found to have $\sigma = 0.43$ magnitudes, it should also be noted that, as an elliptical galaxy, M49 does not suffer from large extinction problems. The large degree of the scatter in the POINT-AGAPE data can not be solely explained by the combination of maximum light and extinction uncertainties, whose mean error is $\sim 0.7$ magnitudes for both the $r'$ and $i'$ data.

As a final test, if the $t_{15}$ relation is valid, then we would expect a minimum in the scatter of the light-curves at or around 15 days after maximum light. Figure 5.10
shows a plot of the scatter between the POINT-AGAPE light-curves over a large range of time following maximum light for the $r'$ and $i'$ data. From inspection of this plot it is quite clear that the light-curves of the POINT-AGAPE sample do not exhibit behaviour consistent with the existence of a $t_{15}$ relationship. However, the $r'$ scatter does seem exhibit a minimum at $\sim 30$ days after maximum light and the $i'$ scatter is minimised $\sim 35$ days following maximum. However, these minima are coincident with the end of the data for a number of the light-curves, so may just be indicative of the temporal coverage of the POINT-AGAPE light-curves themselves.

5.5 Summary and discussion

In this Chapter we have described our methods of estimating the internal extinction of M31 and of reassessing the decline rate and speed class of each of the 20 POINT-AGAPE CNe. We have used these data to calibrate and assess the reliability of both the MMRD and $t_{15}$ relationships for the POINT-AGAPE nova catalogue. However, the calibration of the MMRD relationships was dominated by the extinction uncertainties, whilst we produced evidence disproving the existence of the $t_{15}$ relationship within $r'$ and $i'$ data.

5.5.1 The MMRD relationship

The two POINT-AGAPE MMRD relationships (see Equations 5.11 and 5.12) are consistent with the existence of an MMRD relationship for the $r'$ and $i'$ filters. In fact, the observed scatter in both relationships, although higher than that of recent Galactic calibrations, can be accounted for solely by extinction and maximum light uncertainties. We were able to show that, for the speed classes used for the MMRD calibration, “missing” the maximum light of a nova by up to a week is not the dominating factor in the MMRD scatter. However, it is clear that a better understanding of the extinction affecting the POINT-AGAPE
Figure 5.10: Plot of the distribution of $r'$ magnitude scatter (green line) and the $i'$ magnitude scatter (red line) between observed nova magnitudes for a range of times following maximum light.
novae is required in order to make more robust statements about the validity and calibration of the MMRD within M31. Little more can be said about the comparison between previous MMRD relationship calibrations and the POINT-AGAPE calibrations as the Galactic MMRD (and previous M31 relations) are calibrated using bluer filter bands than the POINT-AGAPE filters. In fact these calibrations constitute the first attempt to do so using Sloan filters. Given that CNe become bluer as they decline, we would naively expect the POINT-AGAPE \( r' \) and \( i' \) slopes to be steeper than the galactic \( V \)-band slope, whereas we find that the \( r' \) slope is remarkably similar, with the \( i' \) slope being much steeper, as expected. However, it should also be noted that the \( r' \) filter contains the H\( \alpha \) emission line (see Figure 2.3). As CNe are known to remain bright in H\( \alpha \) long after the visible light-curve has diminished, this may be adversely increasing our measured \( r' \) decline times. It is also known that the decline of the H\( \alpha \) emission of a CN is not well correlated with its H\( \alpha \) at maximum (Shafter, 2005). As such, this could potentially detract from the usefulness of any \( r' \) MMRD relationship (Shafter, private communication).

The uncertainties in our calibration of the MMRD relationship are dominated by M31’s internal extinction and the small sample size (12 and 9 novae within the linear region for the \( r' \) and \( i' \) data respectively). It seems clear that a greater understanding of the extinction experienced by the light of each nova, perhaps calculated using a suitable “van den Bergh - Younger” relationship, coupled with a larger sample size, would allow a much more robust calibration of the relationship within M31. An extended sample that also contains a number of very fast novae would allow the fitting of an “S-shaped” MMRD relationship to the data. We can conclude that the POINT-AGAPE nova catalogue does adhere to the MMRD relationship and that we see some evidence of an “S-shaped” relationship as we move from the linear region into the slow/very slow region of the distribution. Any uncertainty in the \( t_{2} \) assignment of each nova is strongly dependant upon the sampling at maximum light and when the nova luminosity has diminished by two magnitudes. As most of the novae have good sampling (\( \sim 1 \) or 2 days) around
maximum light, the sampling two magnitudes below maximum is the dominating factor for these novae. However, for all but a few of the novae, this sampling is also good. Except for about a quarter of the novae, the uncertainty in the $t_2$ assignment is small ($\sim 1$ or 2 days). However, for the remaining novae the poor sampling coupled with the often erratic behaviour of a CN’s light-curve makes estimating the $t_2$ uncertainties for these novae difficult. However, for extreme cases, the $t_2$ uncertainties are still small compared to the extinction uncertainties, so a more robust treatment of this error source would lead to little (if any) change in the MMRD result.

The MMRD relationship may be used as a tool to measure the relative distance between two populations of novae. However, given that our calibrations are the first to be carried out for the Sloan $r'$ and $i'$ bands, it would be inappropriate to attempt to estimate the M31 distance by comparison with Galactic $V$ and $B$ band relationships.

### 5.5.2 The $t_{15}$ relationship

The analysis of the $r'$ and $i'$ $t_{15}$ relationships within the POINT-AGAPE catalogue is, like the MMRD relationship, dominated by the extinction uncertainties within the data. However, the extent of the scatter observed in both the $r'$ and $i'$ data cannot be accounted for by the extinction and maximum light uncertainties alone. A comparison of our $t_{15}$ values with those for bluer bands are however, consistent with a CN becoming bluer following maximum light. As with the MMRD calibration, there have been no previous $t_{15}$ calibrations in the Sloan filters, so we can not yet use our calibrations to attempt to make a reliable distance determination to M31.

Figure 5.10 shows the distribution of $t_n$ scatter, $n$ days after maximum light. This plot clearly indicates that the scatter between the light-curves is large over the entire period sampled. Also it is clear that there is no evidence of a minimum in the scatter for times around 15 days. The small minima at $\sim 30$ days in the $r'$
data and $\sim 35$ days for the $i'$ are related to the sampling of the surveys.

To some extent, the $t_{15}$ analysis is limited by the temporal sampling of the POINT-AGAPE survey. Unlike the MMRD relationship that requires good sampling around the peak of the light-curve and some good sampling of the subsequent decline, to test the $t_{15}$ relationship one also requires good sampling of the light-curve specifically at $\sim 15$ days after peak. Due to the make up of the survey, the light-curves were generally constructed from short periods of good sampling, followed by regions with no data (see Figure 2.4). As such, a relatively large amount of extrapolation was required to estimate each nova’s flux between observations. Given the rather erratic behaviour of a CN’s light-curve, the estimation of the errors induced by linearly interpolating over large periods with no data is a far from trivial task. The $r'$ data are again likely to be adversely affected by the H$\alpha$ emission. We can conclude that the POINT-AGAPE CN catalogue shows no evidence of a $t_{15}$ relationship, nor strong evidence of convergence at another timescale. We would require nova light-curves with much more uniform sampling than the POINT-AGAPE novae to be able to make a more definite statement regarding the $t_n$ relationship’s overall validity in the $r'$ and $i'$ filters and its potential usefulness.
Chapter 6

Parent Stellar Population and the Overall Nova Rate

6.1 Introduction

In this chapter we present our statistical analysis of the CN population within M31. We discuss our technique for seeding the POINT-AGAPE data with generated novae to allow us to compute the pipeline completeness. We then go on to present a number of processes that allow us to evaluate the nova distribution within M31, including the modelling of M31’s galactic light. Using this analysis we compute the expected nova rate in M31.

6.2 Seeding the data

To test the completeness of the CN catalogue produced by our detection pipeline, we seeded the raw POINT-AGAPE data with re-samples of our 20 detected CNe. We then re-ran the entire CN detection pipeline on these seeded data to allow us to compute the proportion of recovered light-curves.
6.2.1 Creating test light-curves

The seeded light-curves were positioned on a grid within the aligned image data stack, with a grid spacing of 15 pixels (5 arcmin). This grid spacing was chosen to allow the closest possible spacing of seeded objects, whilst minimising overlap of each star’s PSF. Each light-curve was seeded at a random eruption epoch, such that at least one point of the light-curve occurred between the first observational epoch and the final epoch.

In order to seed the detected novae at any random time we linearly interpolated their light-curve fluxes between successive observations. To do this we assumed that the light-curves behaved linearly between successive observations. Whilst this worked well when the timescale between observations was small it became less reliable when the gaps were larger. The largest gaps in the observations were usually of order 2 weeks, but in a few cases when light-curves were followed across two seasons these were up to 6 months. The two light-curves affected by this were PACN-00-02 and PACN-00-05 (see Chapter 4), these light-curves were linearly interpolated across the seasonal gaps. Given the form of the light-curve of PACN-00-02 we expected this method to be relatively reliable as an estimate of the flux. However, given the predicted transition phase minimum for PACN-00-05, this estimation was much less reliable.

6.2.2 Seeding the raw POINT-AGAPE data

The generated light-curves consisted of a position and magnitude for each observation epoch. These were added to both the raw data and the PSF-matched data (see Section 3.3.2) using the IRAF mkobjects package which scaled the relevant image’s PSF profile to the correct magnitude, then added the scaled PSF profile to the data, recalculated the Poisson errors and combined these with the data.
6.2.3 Re-running the nova detection pipeline

The entire CN detection pipeline was re-run on the seeded data; however a number of stages of the pipeline are not used. As both the raw and the PSF-matched data were seeded independently\(^1\), the image alignment, trimming, PSF-matching and background estimate stages are not required.

The seeded PSF-matched data were run though the aperture photometry pipeline (see Section 3.4) to produce the preliminary list of recovered light-curves. However, the object detection section of the software was disabled and instead the code was given the known locations of the seeded novae. It then simply checked these locations for “10σ objects” and re-centred these objects. In order to speed up this process only the locations of seeded novae that were actually visible in at least one observation were given to the pipeline. We were able to do this as the initial run of the pipeline, carried out when detecting the novae in our catalogue, could be considered an exhaustive test of the “non-detection” of CNe. Consequently, if we already knew that no CN was previously detected at one of the seed points, seeding a CN that was not able to be observed at any epoch at that point could not cause a new detection from the pipeline. Although removed from the seeding process, the light-curve type, position and epoch of the “undetectable” novae were recorded for later use in the completeness computations (see Section 6.3).

The seeded raw data were then passed to the PSF-fitting photometry pipeline (see Section 3.5 for a detailed description of this part of the pipeline), where PSF-fitting photometry was first performed at the position of each of the seeded novae recovered from the aperture photometry stage. These nova light-curves were then passed back through the “peak detection” stages of the pipeline. However, all of the pipeline stages that were related to the colour light-curves were ignored. We were able to ignore the colour criteria as these were solely introduced to distinguish CN light-curves from the light-curves of other objects that may have

\(^1\)In order to maintain consistency between the seedings in the raw and PSF-matched data, the same random seed was used to re-generate the Poisson noise for both CN seedings.
passed through the previous stages of the pipeline. However, as we knew that all 20 of the seeded light-curves were those of CN discovered in the POINT-AGAPE data, they had already passed the colour criteria.

A seeded CN light-curve may have “failed” the pipeline for any of the following reasons:

1. The object was seeded at a location in the M31 field where, due to the brightness of the background, and/or surrounding objects, it was impossible to make a $10\sigma$ detection of the object at any epoch.

2. There were not five consecutive detections, either because the object was too faint to detect, or because it had been seeded such that there were not five observations in which the nova was visible.

3. The observed “peak” of the seeded nova was not significant enough to pass the primary peak test. This would have been due to either the galactic background or because the nova was seeded “low down” in its light-curve, i.e. the actual peak was not seeded in any of the observations.

4. A seeded CN light-curve could fail the periodicity test, the secondary peak height test or the “< 90% of points in peaks” test, if the nova had been seeded close to a region of the image that also varied significantly with time. This may have been due to a nearby variable star, a region of bad pixels or a saturated object. Again, it was possible for a light-curve to fail this test if data around the actual peak of the nova had not been seeded.

“Stray” objects could not filter through the pipeline, as we knew that these objects did not pass through the initial pipeline run. Therefore the only objects that were recovered were the detectable seeded novae. In fact, the recovered light-curve for each seeded nova was expected to be essentially identical to the seeded light-curve, within the errors of the process.

---

2The make-up of the POINT-AGAPE observation strategy makes it impossible to seed $i'$ and $g'$ band data across observing seasons as there is minimal $i'$ band data available for the 1st season and no $g'$ band data available for the 2nd or 3rd.
6.3 Completeness distribution

Using this knowledge we were able to greatly speed up the re-running of the pipeline on the seeded data as we were able to essentially ignore the $i'$ and $g'$ data and just re-process the $r'$ data. Hence it follows that the efficiency of the pipeline was only dependent upon a nova’s $r'$ behaviour.

The numerical results of the completeness run of the CN pipeline are shown in Table 6.1.

6.3 Completeness distribution

Using the results of the completeness run of the CN pipeline we were able to calculate the completeness distribution of the pipeline. In order to do this we subdivided each CCD into 1 arc-min grid squares, with each grid square containing 144 novae seed points. Depending upon the size of the trimmed CCDs (see Section 3.3.1), the CCDs contained between 200 and 242 grid squares.

We first computed the completeness distribution of the CN pipeline; this distribution told us the probability of the pipeline detecting a CN – of a type originally detected by the pipeline – at any position in the POINT-AGAPE fields, given that the CN in question was “visible” at least once between (and including) the first and last observations. This completeness calculation took account of many of the different factors that affected the completeness of the detection pipeline, including the temporal distribution of the POINT-AGAPE observations, the galactic surface brightness, the variety of CN light-curve forms and any interference by foreground objects.

The generated completeness map is shown in Figure 6.1. This illustrates that the completeness is relatively flat across both fields, within the noise, at a value between about 30% – 40%. However the completeness does decline towards the centre of the galaxy, as the galactic background begins to increase significantly.
### 6.3. Completeness distribution

<table>
<thead>
<tr>
<th>Pipeline stage</th>
<th>North-field</th>
<th>South-field</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seeded objects</td>
<td>35,239</td>
<td>35,376</td>
<td>35,244</td>
</tr>
<tr>
<td>Objects seeded within data</td>
<td>18,291</td>
<td>18,886</td>
<td>18,314</td>
</tr>
<tr>
<td>10σ objects</td>
<td>16,519</td>
<td>17,569</td>
<td>17,339</td>
</tr>
<tr>
<td>Pipeline 1st pass – aperture photometry</td>
<td>13,457</td>
<td>14,982</td>
<td>14,945</td>
</tr>
<tr>
<td>5 consecutive detections</td>
<td>13,078</td>
<td>14,768</td>
<td>14,660</td>
</tr>
<tr>
<td>≥ 1 primary peak</td>
<td>12,979</td>
<td>14,676</td>
<td>14,550</td>
</tr>
<tr>
<td>Periodicity test</td>
<td>12,859</td>
<td>14,564</td>
<td>14,477</td>
</tr>
<tr>
<td>Primary peak height</td>
<td>11,011</td>
<td>11,642</td>
<td>12,460</td>
</tr>
<tr>
<td>Secondary peak height</td>
<td>8,169</td>
<td>10,433</td>
<td>10,994</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pipeline 2nd pass – PSF-fitting photometry</th>
<th>North-field</th>
<th>South-field</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 consecutive detections</td>
<td>9,981</td>
<td>11,549</td>
<td>12,330</td>
</tr>
<tr>
<td>≥ 1 primary peak</td>
<td>9,083</td>
<td>11,056</td>
<td>11,907</td>
</tr>
<tr>
<td>Periodicity test</td>
<td>9,083</td>
<td>11,056</td>
<td>11,907</td>
</tr>
<tr>
<td>Primary peak height</td>
<td>8,868</td>
<td>10,805</td>
<td>10,965</td>
</tr>
<tr>
<td>Secondary peak height</td>
<td>8,169</td>
<td>10,433</td>
<td>10,994</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Further candidate elimination stages</th>
<th>North-field</th>
<th>South-field</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 90% of points in peaks</td>
<td>8,141</td>
<td>10,403</td>
<td>10,968</td>
</tr>
<tr>
<td>5 g′ or i′ points</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Colour evolution</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rate of decline</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Colour–magnitude criteria</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Final candidates</td>
<td>8,141</td>
<td>10,403</td>
<td>10,968</td>
</tr>
</tbody>
</table>

Table 6.1: The effect of each stage of our selection pipeline upon the synthetic CN catalogue. These steps are described in Chapter 3.
Figure 6.1: The POINT-AGAPE CN detection pipeline completeness distribution. The white circles represent the positions of the 20 detected novae.
### 6.4 Probability distribution

If we adopt the simplest assumption, that the nova distribution in M31 follows the light distribution (Ciardullo et al., 1987). Then the probability of a CN erupting at a particular point within M31 is proportional to the flux at that position:

\[ p_i \propto f_i \]  

(6.1)

where \( p_i \) is the probability of a CN erupting in a particular grid square containing a flux \( f_i \). By requiring that a given CN erupts within one of the two POINT-AGAPE fields, we can compute the probability of a CN erupting at a particular point within M31:

\[ p_i = \frac{f_i}{\sum_{j=1}^{N_{\text{bins}}} f_j} \]  

(6.2)

However, from our completeness calculations, we also know the probability of detecting a CN in each grid square, given that a nova erupts within that square. Hence we can use this to calculate the probability of detecting a CN within the POINT-AGAPE fields, given that a nova erupts within them. This detection probability is given by:

\[ P_i = \frac{f_i}{\sum_{j=1}^{N_{\text{bins}}} f_j} \cdot \epsilon_i \]  

(6.3)

where \( \epsilon_i \) is the computed pipeline efficiency in the grid square in question. This probability distribution is shown in Figure 6.2. This plot clearly shows that the detection probability closely resembles the galactic light. However, as the completeness drops slightly towards the galactic centre, this distribution has a slightly weaker central dependence than the flux.

If M31 consisted solely of a single population of stars, then the “nova follows the
Figure 6.2: The POINT-AGAPE CN detection probability distribution map. The white circles represent the positions of the 20 detected novae.
light” distribution would be a good model of the CN distribution. However, this is not the case, with recent evidence pointing towards separate bulge and disk populations of novae (see Section 2.6) it is likely that the eruption probability model (Equation 6.2) needs to be modified. The detection probability (Equation 6.3) can be written more generally given a normalised eruption probability of $p'_i$, as:

$$P_i = p'_i \cdot \varepsilon_i \quad (6.4)$$

### 6.4.1 Testing the probability distribution – Wilcoxon-Mann-Whitney Test

We have modified the basic assumption, i.e. that the nova rate in a galaxy follows the galactic light, to a more general formulation, that the eruption probability can be represented as a power law of the galactic light:

$$p'_i \propto f_i^\alpha \quad (6.5)$$

where $\alpha$ is a constant. The initial hypothesis that the CN distribution follows the galactic light is represented by $\alpha = 1$, where $\alpha > 1$ this would describe a distribution that would favour the bulge light and $\alpha < 1$ would favour that of the disk. A value of $\alpha = 0$ would represent a completely flat distribution i.e. that the CNe do not actually arise from M31. Values of $\alpha < 0$ are completely un-physical, as are values of $\alpha \gtrsim 2$. Figure 6.3 shows graphical representations of the probability model for a range of different values of $\alpha$.

In order to test the initial hypothesis that the nova distribution follows the galactic light (Equation 6.2), we can use the Wilcoxon-Mann-Whitney Rank Test (Mann-Whitney Test, see Appendix B). Given that a CN is detected within the two POINT-AGAPE fields, the probability that it is detected at a given
Figure 6.3: Plots showing the CN eruption probability model (see Equation 6.5) for a range of values of $\alpha$. The top left plot shows $\alpha = -1$, a hyperbolic distribution. The top right plot shows $\alpha = 0$, a flat distribution. The bottom left plot is $\alpha = 1$, the CNe follow the light. The bottom right plot shows $\alpha = 2$, a parabolic distribution.
position is simply:

\[ P_i = \frac{\sum_{j=1}^{N_{\text{bins}}} f_i^\alpha \cdot \varepsilon_i}{\sum_{i=1}^{N_{\text{bins}}} f_i^\alpha \cdot \varepsilon_j} \] (6.6)

We can therefore use Equation 6.6 to generate a random set of CN events. The Mann-Whitney Test can then be used to determine whether the two CN samples (the detected sample of 20 CNe and the generated sample) are consistent with being drawn from the same parent population. By varying the value of \( \alpha \) we can also use the Mann-Whitney Test to eliminate regions of “\( \alpha \)-space” that produce inconsistent CN samples.

To use the Mann-Whitney Test it is required that the two samples are independent. Hence we required that there was a maximum probability that two generated novae lay in the same grid cell of 5%. The size of an acceptable generated sample was dependant on \( \alpha \). For instance, given that there were \( \sim 1,600 \) grid cells, the maximum size of our generated sample was limited to 80 members for the flat (\( \alpha = 0 \)) distribution. The fact that we were dealing with Gaussian statistics limited the minimum sample size to five members. These requirements limited the range of \( \alpha \) that could be investigated directly to \( -4.35 \leq \alpha \leq 1.90 \).

To test our hypothesis we used the Mann-Whitney Test to compare the projected disk semi-major axis positions (see Section 6.5) of our two samples. The distribution of \( \alpha \) against the Mann-Whitney z-ratios is shown in Figure 6.4. As can be seen from the distribution, values of \( \alpha \) in the range \( -4.35 \leq \alpha \leq 0.8 \) can be ruled out at the 99% confidence level or beyond, with a value of \( \alpha \simeq 1.5 \) appearing strongly favoured.

As \( \alpha \) becomes more negative, the probability distribution begins to favour more greatly the outer regions of the galaxy. Eventually \( \alpha \) is negative enough that the generated sample is distributed such that it lies completely “outside” the detected sample. When this occurs, and for all values of \( \alpha \) beyond this critical value, the ranking of the combined sample remains constant, hence the z-ratio
Figure 6.4: A plot showing the distribution of $\alpha$ against the z-ratios of the normal distribution for the Mann-Whitney Test. The solid black line represents the 95% confidence limit of rejecting the null hypothesis, red - 97.5%, green - 99% and blue - 99.5%.
becomes constant. This behaviour can be seen occurring in Figure 6.4, in the range $-4.35 \leq \alpha \leq -4$ the z-ratio appears to be "settling" at a constant value of $z \sim 3.6$. Using this knowledge we also ruled out values of $\alpha < -4.35$.

The opposite of this argument can be applied for large positive values of $\alpha$. As $\alpha$ becomes large, the probability distribution begins to strongly favour the centre of the galaxy. Once $\alpha$ becomes large enough, all of the generated sample lies at the centre of the galaxy, within the detected sample. Hence again the ranking of the combined sample becomes constant, leading to a constant z-ratio.

From our Mann-Whitney comparison of our model probability distribution (Equation 6.6) we were able to draw the following conclusions: All $\alpha \lesssim 0.8$ can be strongly ruled out, as can "large" positive values of $\alpha$. However, the model was not ruled out for $0.8 \lesssim \alpha \leq 1.90$, i.e. ranging from a distribution less centrally clustered than the light to an almost parabolic dependence on the flux.

### 6.4.2 Testing the probability distribution – Kolmogorov-Smirnov Test

In order to try to further constrain the allowed $\alpha$-space for the probability distribution shown in Equation 6.6, we employed the Kolmogorov-Smirnov Test (K-S Test) to investigate the same null hypothesis, i.e. that a generated sample of CNe (again produced from the probability distribution shown in Equation 6.6) and the detected nova sample are both drawn from the same overall population.

Like the Mann-Whitney Test, the K-S Test also requires that the two samples are independent; this again limited us to the range $-4.35 \leq \alpha \leq 1.90$. To test our hypothesis, we used the K-S Test in a similar manner to the way in which we previously used the Mann-Whitney Test. We compared the projected disk semi-major axis positions of the detected and generated samples. The K-S Test generates the probability that the null hypothesis, i.e. that both samples were drawn from the same population, is true. Shown in Figure 6.5 are the
distribution of disk semi-major axis positions for our detected sample of 20 CNe and the positions for a generated sample of novae for a range of values of $\alpha$.

Shown in Figure 6.6 is a plot of the distribution of K-S probabilities against $\alpha$ for the entire range tested. From an initial inspection of the distribution it is quite clear that all values in the range $-4.35 \leq \alpha \leq 0.9$ can immediately be eliminated. Further regions of $\alpha$-space may be ruled out by examining the trend of the distributions of novae positions from both samples at large positive or negative $\alpha$ values (see Figure 6.5) and by applying the same arguments used for the Mann-Whitney Test regarding the distribution of the generated samples for these $\alpha$ values. In this way it is possible to rule out all values of $\alpha < 0.9$ and all large positive values of $\alpha$. Again, the results from the K-S tests implied that a value of $\alpha \approx 1.5$ is the most favoured.

The K-S Test allowed us to completely rule out all but small positive values of $\alpha$ and hence eliminated all the unphysical CN distribution models. The K-S Test also ruled out very large values of $\alpha$, i.e. those distributions that were essentially $\delta$-functions at the galactic centre. As can be seen from both Figures 6.4 and 6.6, $\alpha < 1$ is much less favoured than $1 \leq \alpha \leq 1.90$, with $\alpha \approx 1.5$ appearing to be the most favoured. This would imply that the CN distribution is more centrally clustered than the total galactic light. From this we can infer that the CN eruption rate per unit $r^\prime$ flux is higher in the bulge than it is in the disk.

### 6.4.3 The $\alpha$ probability model

The Mann-Whitney and K-S testing of the initial distribution model had reasonable success, although either test alone would have produced the same result. All “un-physical” ($\alpha < 0$ and large $+ve\ \alpha$) models were completely ruled out. The favoured range of $1 \leq \alpha \leq 1.90$ included the initial “light following” hypothesis ($\alpha = 1$). However, a value of $\alpha$ in this range implies that the underlying CN distribution is more centrally clustered than the galactic light. This points towards two possible solutions: that of separate bulge and disk novae populations, with
Figure 6.5: Plots showing the projected disk semi-major axis position against cumulative number of the 20 POINT-AGAPE CNe (red) and the CNe seeded for the K-S testing (black). Each plot corresponds to a different value of $\alpha$. The top left plot shows the distributions for $\alpha = -1$, i.e. a hyperbolic probability distribution. The top right plot shows $\alpha = 0$, i.e. a flat distribution. The bottom left plot is $\alpha = 1$, i.e. the CNe follow the light. The bottom right plot shows $\alpha = 1.9$ an almost parabolic distribution, the highest value of $\alpha$ testable.
6.4. Probability distribution

Figure 6.6: A plot showing the distribution of $\alpha$ against the confidence probabilities of the K-S Test.
the eruption rate per unit flux of the bulge novae being greater than that of the
disk novae; or that all, or the majority of, the 20 detected CNe erupted within
the bulge.

In order to test the “two population” model and the “bulge-only” model, we
needed to separate the bulge and disk flux from the total flux of M31. This was
achieved by producing a simple model of the galactic light.

6.5 Modelling M31’s galactic light

Whereas the calculated probability distribution (Equation 6.6) allowed us to de-
terminate the probability of a CN erupting at a particular point within the POINT-
AGAPE fields, in order to calculate the overall CN rate of M31 or to investigate
the possibility of separate bulge and disk CN populations, we needed to compute
both the bulge and disk component of the light at any given point within the
galaxy. In order to do this, we attempted to model the flux distribution of the
galaxy. To perform this modelling we subdivided each CCD using the one arc-
min square grid system that we had employed for the completeness calculations.
We assumed that the flux in each grid square was the total flux contained within
that cell.

In order to try to fit the disk or bulge components of the M31 light, we first had
to define a region of the galaxy within which either the bulge or the disk light
could be unambiguously defined. In the outer regions of a spiral galaxy such as
M31, the visible light arises almost completely from the disk. So it is possible to
model the disk in these regions and extend the model to the inner regions of the
galaxy.

The light from a galactic disk can often be modelled using a simple exponential
law (Freeman, 1970):
6.5. Modelling M31’s galactic light

\[ I_d(r) = I_0 e^{-r/r_0} \]  

(6.7)

where \( I_d(r) \) is the surface brightness of the disk at a given radius \( r \). To greatly simplify the disk, we made the assumption that it was a thin-disk with an inclination of 77° (de Vaucouleurs, 1958) and that the flux distribution was smooth across the disk. Another simplification we made was to essentially collapse the disk into a one-dimensional system. Each position within the disk was transformed to the semi-major axis of the ellipse that passed through that point. The disk flux at any point within M31 could then be defined as:

\[ f_d(a_d) = f_0 d e^{-a_d/a_0^d} \]  

(6.8)

where \( f_d(a_d) \) is the disk flux at a position within the disk with semi-major axis \( a_d \).

As it was not possible to unambiguously separate disk light from bulge light, a fit was performed to the total flux data for \( a_d \geq 40 \) arcmin in order to have minimal contamination from the bulge light to the total galactic light. The best-fit values found for the two parameters were, \( f_0^d = 3,676 \) adu/pixel and \( a_0^d = 43.1 \) arcmin. A plot of M31 flux versus the disk semi-major axis, showing the computed model fit, is shown in Figure 6.7.

In order to attempt to fit the bulge flux, we extended the disk model across the whole galaxy and then subtracted the modelled disk light from the galactic light to leave just the bulge light and the residuals to the disk model. The light from galactic bulges can often be modelled using a standard \( r^{1/4} \) law (de Vaucouleurs, 1948, 1953):

\[ \log[I_b(r)/I_e] = -3.33[(r/r_e)^{1/4} - 1] \]  

(6.9)

where \( I_b(r) \) is the surface brightness of the bulge at a given radius \( r \). We modelled
Figure 6.7: A plot of M31 flux against disk-semi-major axis. The solid portion of the red line ($a_d \geq 40$ arcmin) represents the best-fit to the linear disk light using a standard exponential law (see Equation 6.8). The dashed portion of the line shows the extrapolation of the disk model over the whole galaxy. The strong deviation from the disk model seen for $a_d \leq 20$ clearly marks the point where the bulge light begins to dominate the overall galactic light. The contribution to the overall galactic light from M32 can be seen at around $a_d = 70$ arcmin. Some structure - mainly from the dust lanes - can also be seen within the disk across most of the outer galaxy.
the bulge with elliptical isophotes with an axis ratio $b/a = 0.6^{(3)}$ (Ciardullo et al.,
1987) and a smooth flux distribution across the bulge we again transformed the
spatial positions of each point within the bulge to the semi-major axis of the
ellipse on which that point lies. We produced the following bulge model using
the expected $R^{1/4}$ law:

$$\log\left[\frac{f_b(a_b)}{f_b^0}\right] = -3.33[(a_b/a_b^0)^{1/4} - 1] \quad (6.10)$$

where $f_b(a_d)$ is the bulge flux at a position within the bulge with semi-major axis
$a_b$. A fit was performed to the bulge flux data for $a_b \leq 15$ arcmin so that the fit
was not influenced by the disk fit residuals. The best-fit values were $f_b^0 = 6,914$
adu/pixel and $a_b^0 = 5.1$ arcmin. Figure 6.8 is a plot of the difference between the
total M31 flux and the computed disk model, showing the computed bulge light
model.

By combining the disk and the bulge models it was possible to produce a model of
M31. However, as both the disk and bulge models were defined using two separate
distance scales, it was not possible to unambiguously define a transformation
between these two scales. The models had therefore to be transformed back into
a two-dimensional system in order to be combined:

$$f(x, y) = f_d^0 \exp\left(\frac{x^2}{\cos^2 77^\circ} + \frac{y^2}{a_d^0}\right) + f_b^0 \exp\left\{-7.67\left[\left(\frac{x^2}{\cos^2 53^\circ} + \frac{y^2}{a_b^0}\right)^{1/4} - 1\right]\right\} \quad (6.11)$$

Figure 6.9 shows a graphical representation of the computed galactic model,
whereas Figure 6.10 shows the computed galactic model over-plotted with the
M31 flux data.

\footnote{This model of the bulge is equivalent to a thin-disk with an inclination of 53°.}
6.5. Modelling M31’s galactic light

Figure 6.8: A plot of the difference between the M31 surface brightness and the computed M31 disk model (see Equation 6.8) against the bulge-semi-major axis. The solid portion of the red line ($a_b \leq 15$ arcmin) represents the best-fit to the bulge light using a standard $r^{-1/4}$ law. The dashed portion of the line shows the extrapolation of the bulge model over the whole of the flux. The contribution to the light from M32 can be seen at around $a_b = 35$ arcmin and again some residual structure from the disk model subtraction - mainly from the dust lanes - can be seen within the outer regions of the galaxy.
Figure 6.9: The modelled CN eruption probability distribution of M31.
Figure 6.10: The modelled CN eruption probability distribution of M31 overlapped with the computed probability data.
6.6 Testing the bulge or disk-only distributions

The previous CN distribution tests led us to the conclusion that the CNe follow the galactic light or that they may be slightly more centrally clustered that the light. Whilst this may imply that there are two distinct populations (bulge and disk) of CNe, with the eruption rate of the bulge novae per unit \( r' \) flux being greater than that of the disk novae, it does not rule out the possibility that the vast majority of the M31 CNe are in the bulge\(^4\). Using the disk and bulge models calculated in Equations 6.8 and 6.10 respectively, we were able to test the two special cases of bulge or disk only populations.

As we were only testing the bulge model, we used the K-S Test to determine whether the flux model and the CN distribution were drawn from the same parent population. Figure 6.11 shows the cumulative distribution of bulge detection probability with increasing disk semi-major axis \( (a_d) \) compared with the cumulative detected CN distribution with increasing disk semi-major axis. The K-S Test produced a probability that the two distributions were drawn from the same parent population of 0.43. Hence, it is clear that the bulge alone can give rise to the observed distribution of CNe.

We also tested the disk-only model. Figure 6.12 shows the cumulative distribution of disk detection probability with increasing disk semi-major axis \( (a_d) \) compared with the cumulative detected CN distribution with increasing disk semi-major axis. The probability that these two distributions were drawn from the same population is \( 4.2 \times 10^{-6} \). It is therefore quite clear that the disk alone cannot account for the observed distribution of CNe.

For completeness, we also tested the “galactic light model”. Figure 6.13 shows the cumulative distribution of detection probability with increasing disk semi-major axis \( (a_d) \) again compared with the cumulative detected novae distribution with increasing disk position. There is a probability of \( 1.2 \times 10^{-3} \) that these

\(^4\)The distribution of the 20 detected CNe shown in Figure 4.6 gives the impression that it is unlikely that all the detected CNe are within the bulge.
Figure 6.11: Comparison of the distribution of POINT-AGAPE novae with the bulge detection probability model. The black line represents the M31 bulge-only CN detection probability model. The red line represents the distribution of the 20 POINT-AGAPE novae.
Figure 6.12: Comparison of the distribution of POINT-AGAPE novae with the disk detection probability model. The black line represents the M31 disk-only CN detection probability model. The red line represents the distribution of the 20 POINT-AGAPE novae.
distributions were drawn from the same population.

It is clear from this investigation that the bulge-only model is sufficient to model the observed CN distribution. It is also clear that the disk-only model and the galactic light model are insufficient to model the observed CN distribution. However, as the distance from the centre is increased, the bulge-only model becomes less satisfactory. Hence it seems clear that a combination of novae arising from bulge and disk populations is required to fully explain the observed CN distribution.

6.7 The two population model

Following the results of the testing of the probability distribution shown in Equation 6.5 and the testing of the bulge or disk-only models, it seemed clear that the “best” probability model description would be made using a combination of both disk and bulge populations, with each population potentially having a different eruption rate per unit $r'$ flux. To test this new model, we first made the assumption that the nova eruption probability in the disk or the bulge was proportional to the disk or bulge luminosity respectively:

$$p_i \propto \sigma_d \cdot f_i^d + \sigma_b \cdot f_i^b$$ \hfill (6.12)

where the disk flux, $f^d$, and the bulge flux, $f^b$, are defined in Equations 6.8 and 6.10 respectively and $\sigma_d$ and $\sigma_b$ are the number of CN eruptions per unit time per unit $r'$ flux, for the disk and bulge populations respectively.

Consequently, the probability that a CN is detected at a particular position, given that a CN erupts within the two POINT-AGAPE fields, can be represented as:

$$P_i = \frac{\theta f_i^d + f_i^b}{\theta \sum_{j=1}^{N_{\text{bins}}} f_j^d + \sum_{j=1}^{N_{\text{bins}}} f_j^b} \cdot \varepsilon_i$$ \hfill (6.13)
Figure 6.13: Comparison of the distribution of POINT-AGAPE novae with the galactic light detection probability model. The black line represents the M31 galactic light CN detection probability model. The red line represents the distribution of the 20 POINT-AGAPE novae.
The two population model

where \( \theta \) is the ratio of disk and bulge population eruption rates per unit \( r' \) flux and is defined as:

\[
\theta = \frac{\sigma_d}{\sigma_b}, \quad \theta \geq 0 \quad (6.14)
\]

A graphical representation of the probability model, evaluated for a number of \( \theta \) values, is shown in Figure 6.14.

In order to test this new hypothesis we again defined a second probability distribution (equivalent to that defined in Equation 6.6) given that a CN both erupts, and is detected within one of the two POINT-AGAPE fields:

\[
P_i' = \frac{(\theta f_d^i + f_b^i) \cdot \varepsilon_i}{\theta \sum_{j=1}^{N_{bins}} f_d^j \cdot \varepsilon_j + \sum_{j=1}^{N_{bins}} f_b^j \cdot \varepsilon_j} \quad (6.15)
\]

This probability distribution was then probed, over a range of \( \theta \)-space, in the same manner as the previous distribution. We again used both the Mann-Whitney and K-S Tests to locate a set of the most likely values of \( \theta \).

The Mann-Whitney Test was used to test whether the 20 POINT-AGAPE CNe and a number of artificial CNe, generated using Equation 6.15, were drawn from the same parent population. Unlike the previous Mann-Whitney Test, where the testable values of \( \alpha \) were limited by the often unphysical spatial distributions generated, we were no longer bound by such limits as our new model was “physical” for all values of \( \theta \). As such, we chose to test the distribution for values in the range \( 0.001 \leq \theta \leq 1,000 \), where \( \theta = 0.001 \) is essentially a bulge-only distribution, \( \theta = 1 \) is the original galactic light distribution and \( \theta = 1,000 \) is strongly disk dominated.

The distribution of Mann-Whitney z-ratios for the range of \( \theta \) values tested is shown in Figure 6.15. As we saw from the earlier Mann-Whitney Test (see Figure 6.4), there is a large scatter, due mainly to our relatively small sample of CNe. Using the Mann-Whitney test we were able to eliminate values of \( \log \theta \geq 0 \), i.e.
6.7. The two population model

Figure 6.14: Plots showing the CN eruption probability model (see Equation 6.12) for a range of values of $\theta$. The top left plot shows $\theta = 0.1$ in which the probability essentially follows the bulge light alone. The top right plot shows $\theta = 1$, which is the original “CNe follow the galactic light” model. The bottom left model represents $\theta = 10$ in which the eruption probability contained within the POINT-AGAPE fields is approximately the same for the disk and the bulge. Finally the bottom right plot is the disk dominated model, with $\theta = 100$. 
all models in which the disk eruption rate per unit flux is greater than that of the bulge. The tests also indicate a favoured value of $\theta \simeq 0.2$ and show that all “bulge favoured” models ($\log \theta < 0$) are permitted.

In order to try to further constrain the range of potential $\theta$ values, we again utilised the K-S Test this time to compare the projected disk semi-major axis positions of our detected and generated samples of CNes. Figure 6.16 shows the distribution of projected positions for both our detected and generated samples of novae for a range of values of $\theta$.

Figure 6.17 shows the distribution of K-S Test probabilities for the range of $\theta$ values tested. As for the three previous Mann-Whitney and K-S Test plots, there is a large inherent scatter, introduced mainly by the relatively small sample sizes of the two nova samples. However, it is clear from the plot that negative values of $\log \theta$ are much more strongly favoured than positive values and again a value of $\theta \simeq 0.2$ is favoured. We can apply this result to the original definition of $\theta$ (Equation 6.14) to derive the following statement:

$$\sigma_b > \sigma_d$$

(6.16)

In other words, the global CN eruption rate per unit $r'$ flux is greater for the bulge than it is for the disk.

6.8 Maximum likelihood testing

As noted above, both the Mann-Whitney and K-S tests of the separate bulge and disk population model produced the result that the CN eruption rate per unit $r'$ flux was greater in the bulge than it was in the disk. Both tests also indicated that a value of $\theta \sim 0.2$ was favoured. However, in order to better constrain the favoured value of $\theta$ we employed a maximum likelihood test. The likelihood function chosen is shown in Equation 6.17 below. This function is derived from a
Figure 6.15: A plot showing the distribution of $\theta$ against the z-ratios of the normal distribution for the Mann-Whitney Test. The solid black line represents the 95% confidence limit of rejecting the null hypothesis, red - 97.5%, green - 99% and blue - 99.5%.
Figure 6.16: Plots showing the projected disk semi-major axis distribution of the 20 POINT-AGAPE CNe (red) and the CNe seeded for the K-S testing (black). Each plot corresponds to a different value of $\theta$. The top left plot shows $\theta = 0.1$ in which the probability essentially follows the bulge light alone. The top right plot shows $\theta = 1$, the original “CNe follow the galactic light” model. The bottom left model represents $\theta = 10$ in which the POINT-AGAPE fields contain equal eruption probability for the disk and bulge. Finally, the bottom right plot is the disk dominated model, with $\theta = 100$. 
Figure 6.17: A plot showing the distribution of $\theta$ against the confidence probabilities of the K-S Test. The red dashed line represents $\theta = 1$, the transition between the bulge and the disk having the dominating nova eruption rate per unit flux.
simple Poisson analysis of our nova detection model, for a given underlying mean number of expected detections, evaluated over all possible underlying means,

\[
P_{\text{model}} = \int_0^\infty \frac{\mu^N}{N!} e^{-\mu} \prod_{i=1}^{N_{\text{bins}}} \lambda_i^{n_i} e^{-\lambda_i} d\mu
\]  

(6.17)

where \(\mu\) is the underlying mean number of expected detections, \(N\) is the total number of CN detected by the POINT-AGAPE survey (20), \(n_i\) is the number of CN detected in each data bin and \(\lambda_i\) is the expected number of CN detected in each bin, given by:

\[
\lambda_i = \mu \cdot \frac{(\theta f_i^d + f_i^b) \cdot \varepsilon_i}{\theta \sum_{j=1}^{N_{\text{bins}}} f_j^d \cdot \varepsilon_j + \sum_{j=1}^{N_{\text{bins}}} f_j^b \cdot \varepsilon_j}
\]  

(6.18)

In order to confine the range over which the likelihood function was investigated we changed variables from \(\theta\) to the bulge fraction \(\Phi\). Where \(\Phi\) is defined as the fraction of the eruption probability within the POINT-AGAPE field due to the M31 bulge:

\[
\Phi = \frac{\sum_{j=1}^{N_{\text{bins}}} f_j^b}{\theta \sum_{j=1}^{N_{\text{bins}}} f_j^d + \sum_{j=1}^{N_{\text{bins}}} f_j^b}, \quad \theta = \frac{1 - \Phi}{\sum_{j=1}^{N_{\text{bins}}} \varepsilon_j f_j^b}
\]  

(6.19)

Figure 6.18 shows a plot of the normalised likelihood function over the entire range of bulge fractions. By evaluating the distribution of the likelihood function we can derive the most likely value of \(\Phi\) and, by assuming a linear prior in \(\Phi\), we can evaluate confidence limits about the most likely value. As such, we find that the 95% confidence interval of \(\Phi\) is:

\[
\Phi = 0.67^{+0.27}_{-0.39}
\]  

(6.20)

using Equation 6.19, this equates to a favoured value of \(\theta = 0.18\) with the 95% confidence interval bounded by \(\theta = 0.91\) and \(\theta = 0.02\). The favoured value is
consistent with those implied by both the Mann-Whitney and K-S testing of the two population model. This result also allows us to rule out models with $\sigma_d \geq \sigma_b$ at the 95% level, lending strong support to the existence of separate bulge and disk CN populations.

6.9 Fast and slow populations

The analysis of the distribution of the complete CN catalogue carried out in Sections 6.2 - 6.7 can be repeated using just the fast novae or just the slow novae. Using the speed class data (shown in Table 5.1) for each CN, we separated the seeded novae into two groups; fast novae – which include both the fast and moderately fast novae \(^5\) ($t_2 \leq 80$), and slow novae – including slow and very slow novae ($t_2 \geq 81$). The completeness distributions were then re-computed firstly using only the fast novae and then the slow novae.

6.9.1 Fast novae

Figure 6.19 shows the CN completeness map (the top plot) and the “CNe follow the light” detection probability map (bottom) computed for the 14 fast novae only. The fast nova completeness map is relatively flat across both fields, within the noise, the completeness decreases slightly near the centre of the galaxy as the galactic surface brightness begins to rise rapidly. By comparing this completeness map with the full completeness map (Figure 6.1) it is clear that a randomly seeded fast nova is less likely to be detected than a randomly seeded nova from the complete catalogue. From this we can infer that in general a randomly seeded slow CN is more likely to be detected than a randomly seeded fast nova. The deficiency in the fast CN completeness can simply be explained by the short time-scales of these nova eruptions in conjunction with the temporal coverage of

\(^5\)The very fast nova (PACN-99-07) was not included in either group due to the large uncertainty regarding its speed class assignment.
Figure 6.18: A plot showing the distribution of normalised likelihood probabilities over the full range of bulge fractions. The dashed line represents position of the maximum likelihood ($\theta = 0.18$), with the dotted lines indicating the 95% confidence interval.
the POINT-AGAPE survey (see Figure 2.4). The period of visibility for many of the fast novae was around the same size as the time gaps within each season of observations (around two weeks). Hence it is entirely possible that a number of seeded CNe have been completely “missed” even though they erupted within one of the three observation seasons. Furthermore, it is highly likely that only a very small number of fast CNe erupting between the observation seasons were detected.

The fast nova “CNe follow the light” detection probability map was similar to the overall detection probability map (Figure 6.2). This was as expected. However, due to the lower completeness, the fast nova detection probability distribution is generally slightly lower and is slightly more centrally clustered than that of the complete catalogue.

The results of the Mann-Whitney and K-S testing for the value $\alpha$ for the fast novae only were also similar to the results from the complete catalogue. Figure 6.20 shows the distribution of the Mann-Whitney z-ratios for the range of $\alpha$ tested (top plot) and the K-S probabilities against $\alpha$ (bottom plot). The Mann-Whitney Tests allowed values in the range $-1.5 \leq \alpha \leq 1.95$, with high values of $\alpha$ again ruled out. The K-S Test further refined $\alpha$ to be within the range $-0.5 \leq \alpha \leq 1.95$. This also ruled out large positive $\alpha$; the range $1.3 \leq \alpha \leq 1.95$ was most strongly favoured. These results indicate that the distribution of the fast CNe is more centrally clustered than the galactic light. This again points to these CNe predominantly erupting within the bulge and also that the bulge has a higher fast nova rate per unit $r'$ flux than the disk.

Figure 6.21 shows the results of the Mann-Whitney testing for $\theta$ (top plot) and the K-S testing (bottom plot). The Mann-Whitney testing of $\theta$ for the fast CNe was just as inconclusive as the tests for the entire POINT-AGAPE catalogue. However, the K-S testing indicated that values of log $\theta \lesssim 0.2$ are favoured. This result indicated that, for fast CNe, all $\theta < 1$ regimes were allowed, as was the “CNe follow the light” model, as they were for the entire catalogue. However, unlike the results from the complete catalogue, a small range of disk favoured
Figure 6.19: The top box shows the completeness distribution of the fast CNe. The bottom box shows the detection probability distribution of fast CNe.
Figure 6.20: Plots showing the distribution of $\alpha$ for fast CNe. The top plot shows the distribution of $\alpha$ against $z$-ratios of the normal distribution for the Mann-Whitney Tests for fast novae. The lower plot shows the distribution of $\alpha$ against the confidence probabilities of the K-S Tests for fast novae.
models were also allowed.

### 6.9.2 Slow novae

Figure 6.22 shows the CN detection completeness map (top) and the “CNe follow the light” detection probability map (bottom) computed for the 4 slow novae only. As with the overall completeness map (Figure 6.1) and the fast nova completeness map (Figure 6.19 - upper plot), the completeness is, within the constraints of the noise, essentially flat across both fields. However the completeness diminishes significantly more for the slow novae towards the centre of the galaxy than does for the full catalogue or the fast novae only. This behaviour was expected due to the lower intrinsic luminosity of slow novae compared with their faster counterparts. The overall completeness of the slow novae is also around twice that of the fast novae, this arises as slow novae remain visible for a much greater time than their faster counterparts. Hence, given the temporal distribution of the POINT-AGAPE survey (see Figure 2.4), slow novae are much less likely to remain undetected because of the observational gaps within each season. In fact, it is highly likely that many slow CNe that erupted in the gaps between seasons were still detected once the following season began.

The results of the Mann-Whitney and K-S Tests run solely on the slow nova population unfortunately are highly unreliable due to the very small sample size tested. However, Figure 6.23 shows the results of the Mann-Whitney Tests (top plot) and the K-S Tests (bottom plot) on the $\alpha$ eruption model. This shows that a broader region of $\alpha$ space is allowed than was permitted for the full and fast catalogue and again, due to the small sample size, the excluded regions are not as strongly ruled out. The K-S Tests allow values in the range $-2 \lesssim \alpha \lesssim 2$ with the region $0 \lesssim \alpha \lesssim 2$ being more favoured.

Figure 6.24 shows the results of the Mann-Whitney Test (top) and the K-S Test (bottom) on the $\theta$ eruption model. Again these tests were severely limited by the small sample size. The Mann-Whitney results are completely inconclusive,
Figure 6.21: Plots showing the distribution of $\theta$ for fast CNe. The top plot shows the distribution of $\theta$ against $z$-ratios of the normal distribution for the Mann-Whitney Tests for fast novae. The lower plot shows the distribution of $\theta$ against the confidence probabilities of the K-S Tests for fast novae.
Figure 6.22: The top box shows the completeness distribution of the slow CNe. The bottom box shows the detection probability distribution of slow CNe.
Figure 6.23: Plots showing the distribution of $\alpha$ for slow CNe. The top plot shows the distribution of $\alpha$ against z-ratios of the normal distribution for the Mann-Whitney Tests for slow novae. The lower plot shows the distribution of $\alpha$ against the confidence probabilities of the K-S Tests for slow novae.
as they essentially permit all values of $\theta$. The K-S Tests appear to indicate a favoured region of $\theta$-space to be in the range of $-1 \lesssim \theta \lesssim 1.5$. These results imply that the slow nova population may arise from both stellar populations, although they yield little information to indicate the relative weighting of the two populations.

### 6.10 The M31 nova rate

The CN eruption probability models can be used, in conjunction with the detection completeness data, to compute an estimate of the global nova rate in M31. The total number of CNe observed within the POINT-AGAPE fields must be proportional to the total probability of detecting a CN within those fields, hence we can derive the following statement:

$$\xi \sum_{\text{i}=1}^{N_{\text{bins}}} \varepsilon_{\text{i}} \cdot \Psi_{\text{i}} = n$$  \hspace{1cm} (6.21)

where $\varepsilon_{\text{i}}$ is the probability of detecting an erupted CN at a particular location, $\Psi_{\text{i}}$ is the probability of a CN erupting at that location, $n$ is the number of novae detected within the POINT-AGAPE dataset (20), and $\xi$ is an unknown constant relating the detection probability to the recovered number of novae. The definition of the eruption probability given in Equation 6.12 is used to define $\Psi_{\text{i}}$, such that:

$$\Psi_{\text{i}} = \frac{\theta f_{\text{i}}^d + f_{\text{i}}^b}{\theta \sum_{\text{j}=1}^{N_{\text{bins}}} f_{\text{j}}^d + \sum_{\text{j}=1}^{N_{\text{bins}}} f_{\text{j}}^b}$$  \hspace{1cm} (6.22)

The value of the multiplier $\xi$ can be computed for a number of different values of $\theta$, thus producing a range of M31 nova rates. However, we chose to restrict the values of $\theta$ examined to those that related to specific physical situations: $\theta = 0$, the bulge-only system; $\theta = 1$, the galactic light scenario; $\theta \rightarrow \infty$, the disk-only
Figure 6.24: Plots showing the distribution of θ for slow CNe. The top plot shows the distribution of θ against z-ratios of the normal distribution for the Mann-Whitney Tests for slow novae. The lower plot shows the distribution of θ against the confidence probabilities of the K-S Tests for slow novae.
6.10. The M31 nova rate

Table 6.2: The computed values of \( \xi \), the bulge:disk probability ratio, \( \varphi \) and \( N \) for a range of different CN eruption probability models.

<table>
<thead>
<tr>
<th>( \theta )</th>
<th>( \xi )</th>
<th>Bulge:disk probability ratio</th>
<th>( \varphi )</th>
<th>( N )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>92.62</td>
<td>1:0</td>
<td>0.59</td>
<td>158</td>
</tr>
<tr>
<td>0.18</td>
<td>86.03</td>
<td>2.5:1</td>
<td>0.51</td>
<td>167</td>
</tr>
<tr>
<td>1.00</td>
<td>77.99</td>
<td>1:3.3</td>
<td>0.44</td>
<td>178</td>
</tr>
<tr>
<td>( \rightarrow \infty )</td>
<td>72.73</td>
<td>0:1</td>
<td>0.39</td>
<td>185</td>
</tr>
</tbody>
</table>

The global M31 CN number can now be computed as follows:

\[
N = \frac{\xi}{\varphi}
\]  (6.23)

where \( N \) is the global nova number and \( \varphi \) is a constant multiplier that accounts for the proportion of the total galactic eruption probability that has been sampled by the POINT-AGAPE survey. \( \varphi \) is defined as follows:

\[
\varphi = \frac{\sum_{i=1}^{\infty} (\theta f_i^d + f_i^b)}{\sum_{i=1}^{N_{\text{max}}} (\theta f_i^d + f_i^b)}
\]  (6.24)

In order to evaluate the sum over the entire galaxy (the numerator of Equation 6.24) we extended the 1 arcmin grid (which was initially used to model the completeness) over all space. We evaluated the sum out to a distance from the centre of M31 such that a further increase in distance by one grid square resulted in a \(< 0.1\%\) increase in the total probability. Table 6.2 shows the computed values of \( \varphi \) for the models tested. From this we were able to compute the global number of CNe that erupted in M31 during the POINT-AGAPE observing baseline, \( N \). These values are also shown in Table 6.2 for the five model examples.
### Table 6.3: The computed values of the M31 bulge nova rate ($\dot{N}_{\text{bulge}}$), the disk nova rate ($\dot{N}_{\text{disk}}$) and the global nova rate ($\dot{N}$) for a range of different CN eruption probability models.

<table>
<thead>
<tr>
<th>$\theta$ (year$^{-1}$)</th>
<th>$\dot{N}_{\text{bulge}}$ (year$^{-1}$)</th>
<th>$\dot{N}_{\text{disk}}$ (year$^{-1}$)</th>
<th>$\dot{N}$ (year$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>56 ± 12</td>
<td>-</td>
<td>56 ± 12</td>
</tr>
<tr>
<td>0.18</td>
<td>42 ± 9</td>
<td>17 ± 4</td>
<td>59 ± 13</td>
</tr>
<tr>
<td>1.00</td>
<td>15 ± 3</td>
<td>48 ± 11</td>
<td>63 ± 14</td>
</tr>
<tr>
<td>$\to \infty$</td>
<td>-</td>
<td>65 ± 15</td>
<td>65 ± 15</td>
</tr>
</tbody>
</table>

However, to calculate the global M31 CN rate, we first needed to take account of the finite observable lifespan (as defined solely by our observations) of each of the detected novae. As we did not require that a nova’s light-curve should be completely contained within our data, our effective baseline for each CN is extended by the visible period of that particular CN. As the novae were seeded uniformly over the POINT-AGAPE fields with each seeded nova selected randomly, the baseline of observations was extended, on average, by the mean lifetime of all 20 novae:

$$ T = T_{\text{baseline}} + \bar{t}_{\text{nova}} $$  \hspace{1cm} (6.25)

where, $T_{\text{baseline}}$ is the time between the first and last POINT-AGAPE observation (2.472 years) and $\bar{t}_{\text{nova}}$ is the mean lifetime of the 20 POINT-AGAPE novae (0.359 years). The effective baseline, $T$, for the POINT-AGAPE survey was therefore 2.830 years. The nova rate, $\dot{N}$, for M31 is then given by:

$$ \dot{N} = \frac{\xi}{\varphi T} $$  \hspace{1cm} (6.26)

The computed M31 global CN rates for our four model scenarios are given in Table 6.3. This illustrates that the predicted overall nova rate is dependent upon the galactic model. However, the separate bulge and disk novae rates show a great dependence upon $\theta$. 
The errors shown for the nova rates in Table 6.3 are generated solely from the Poisson errors related to the size of our nova catalogue. Given the small size of this catalogue, this source of error (∼ 22%) is expected to dominate over all others. The other main sources of error are expected to be from the completeness calculations, the lack of fast novae in the catalogue, the possible misidentification of novae and the modelling of the surface brightness. In addition, our limited knowledge of the internal extinction of M31 makes it difficult to estimate the errors introduced into the completeness by its exclusion. However, we expect these errors to be small. As is shown in Figure 5.1 the maximum $r'$ extinction expected in the disk is ∼ 0.7 magnitudes; as all the POINT-AGAPE novae were followed through at least one magnitude it is expected that few, if any, novae were missed due to extinction problems. Should a non-CN have been wrongly included within the nova catalogue, this would directly result in a 5% reduction of the nova rate (see Equation 6.21), coupled, indirectly, with a further maximum decrease of 5% from the completeness model. Hence, the misidentification of a single nova generates a maximum absolute error of ∼ 7%, however the errors induced into the completeness through misidentification are highly likely to be much less than 5%. Likewise, a single CN which is “missed”, due to extinction would induce a maximum increase of ∼ 7% of the global nova rate. Although there is some error in our modelling of the M31 surface brightness within the POINT-AGAPE fields, a much greater error is introduced by our extrapolation of this model over the entire galaxy. Without further observations to measure the extended $r'$ surface brightness and further surveys to investigate the “missing” very fast novae, it is somewhat difficult to assign appropriate error estimates to these effects.

Taking the above error discussion into account, we can use the value of $\theta = 0.18$ deduced from the likelihood analysis of the two population model to produce a model constrained estimate of the true nova rate of M31. By evaluating the error on the bulge fraction determination we were able to show that the Poisson errors were still the dominant error source. Hence we arrive at the following estimate of the true nova rate of M31:
\[ \dot{N} = 59 \pm 13 \text{ year}^{-1} \]  

6.11 Summary and discussion

In this Chapter we have presented our analysis of the completeness of the POINT-AGAPE CN catalogue. We have also reported the subsequent analysis of the M31 nova distribution, showing that novae arise from separate disk and bulge populations, with the bulge nova rate per unit \( r' \) flux favoured by a factor of five. These analyses have lead to a prediction of a global M31 nova rate of \( 59 \pm 13 \) year\(^{-1} \).

6.11.1 Completeness

Overall, the method employed to evaluate the completeness of the POINT-AGAPE CN catalogue generated by the nova pipeline allowed us to obtain a very good understanding of the CN detection efficiency of both the survey and the pipeline. The completeness analysis took into account a variety of possible selection effects preventing us from detecting novae. These selection effects included the strongly varying surface brightness of M31, the range of morphologies exhibited by CN light-curves and the temporal sampling of the POINT-AGAPE survey.

We are confident that the completeness of our catalogue is understood to a much greater extent than that of even the most recent surveys of M31 and the majority of all previous extragalactic nova surveys. Until very recently the detection of novae relied solely upon visual detection, often by the “blinking” of images. Even the most recent surveys (Shafter & Irby, 2001, for example) have relied on blinking to some extent, particularly to aid in the detection of the faintest novae. The majority of past novae surveys have also relied upon visual inspection of light-curves to determine the likelihood that an object was a CN (e.g Ferrarese et al., 2003). Our confidence in the completeness stems from the fact that our pipeline
6.11. Summary and discussion

uses much more robust methods and objective selection criteria to both detect and classify potential CNe. Whilst the POINT-AGAPE CN catalogue may not be as complete as various others\(^6\), we believe that we can be much more confident about the number of novae that have not been detected than any other survey.

There were, however, a number of factors that have not been taken into account by the completeness analysis. As was discussed in Sections 5.2.2 and 6.10, our knowledge of the internal extinction of M31 is limited and these extinction uncertainties have not been built into the completeness computations. Whilst the extinction may have diminished our ability to detect novae, especially fainter CNe, its relative small magnitude (see Figure 5.1) should not have been too troublesome. There are no very fast novae (\(t_2 \leq 10\) days) within the POINT-AGAPE catalogue\(^7\), whilst this may simply be indicative of our small sample size, there may also be additional selection effects – due to the temporal sampling of the POINT-AGAPE survey – that have prevented us from detecting novae of this class. Both of these effects potentially prevented us from observing novae erupting during the survey. Consequently, the computed completeness is likely to be an over-estimate. Given the form of the extinction within M31 it is likely that the completeness was over-estimated to a greater extent within the disk (due to its generally greater extinction) than within the bulge. However, Shafter & Irby (2001) used observations of the planetary nebula population of M31 to conclude that (in H\(\alpha\)) the observed CN population is not significantly affected by extinction. As it is expected that fast novae are more likely to be observed within the disk of a galaxy (see Section 2.6), the probable exclusion of very fast novae from the catalogue would again lead us to conclude that we had over estimated the completeness, especially within the disk.

\(^6\)A number of CN candidates contained within the POINT-AGAPE dataset are known not to be contained within our catalogue (An et al., 2004; Feeney et al., 2005).

\(^7\)PACN-99-07, had a great uncertainty in its speed class assignment. Although initially classified as a very fast nova, it is thought more likely to be a moderately fast or slow nova.
6.11.2 CN population of M31

The analysis of the observed CN distribution within M31 allowed us to develop a basic model of the underlying CN distribution. Within the two POINT-AGAPE fields we have shown that M31 CNe are unlikely to arise exclusively from either bulge or disk stellar populations. Instead a combination of the two is required to reproduce the observed distribution. Our results show that the CN distribution is more centrally clustered than the surface brightness, which indicates a bulge eruption rate per unit $r'$ flux that is perhaps as much as an order of magnitude greater than that of the disk. This result is consistent with previous findings (Ciardullo et al., 1987; Capaccioli et al., 1989; Shafter & Irby, 2001) which reported that the M31 novae are primarily associated with the bulge. Shafter & Irby also reported an eruption rate per unit $B$ flux within the bulge of up to an order of magnitude greater than that of the disk. The maximum likelihood analysis of the two population model (see Section 6.8) indicated that a value of $\theta = 0.18$ was favoured.

The range of bulge:disk eruption rate ratios that are consistent with the range of allowed CN distributions ($0.02 \leq \theta \leq 0.91$, from the maximum likelihood analysis), leads to a range of expected bulge:disk nova ratios. The global bulge:disk CN ratios range from 4.8 : 1 for a bulge dominant population ($\theta = 0.1$) through to 1 : 3.2 for the distribution following the surface brightness ($\theta = 1$). The expected novae ratios within the POINT-AGAPE fields themselves range from 23.3 : 1 ($\theta = 0.1$) to 2.3 : 1 ($\theta = 1$). However, the POINT-AGAPE survey of M31 covers a much greater surface area of M31 than all previous nova surveys (see Shafter, 2005, for a summary) which have concentrated mainly on the bulge. The POINT-AGAPE survey has given us much better coverage of the M31 disk and its CN population. As a result, these previous surveys will have all observed a distribution (for all of our permitted eruption models) that appears to be much more bulge dominated than that of the POINT-AGAPE catalogue.

The analysis of the M31 CN distribution is, however, limited by a number of
considerations. These are mainly the small size of the POINT-AGAPE CN catalogue, the simplistic nature of the M31 surface brightness models and the uncertainties arising from the completeness modelling. The large range of “permitted” eruption rate ratios generated by the eruption model is indicative of the limited size of the observed distribution; hopefully the inclusion of the fourth year of POINT-AGAPE data will increase the size of the catalogue sufficiently to enable us to make more robust statements about the M31 CN distribution. Further, the CN distribution analysis relies upon the modelling of the M31 surface brightness. However, this modelling only includes the “normal” disk component and the bulge component of the surface brightness. Other components, such as the spiral arm structure, the dust lanes (and extinction within M31 in general) and M32, were not taken into account. As with the completeness analysis, these effects are expected to have greater affect within the disk than the bulge. Thus, the inclusion of the dust lanes and spiral structure within the models may have lead to an increase in the expected number of disk novae.

### 6.11.3 M31 nova rate

Using the maximum likelihood analysis we were able to produce a two population model constrained global nova rate for M31. This nova rate was dominated by Poisson uncertainties from the small sample size of detected nova. The favoured value of $\theta = 0.18$ generates a global nova rate of $59 \pm 13 \text{ year}^{-1}$. This rate is at the limit of being consistent with that of the most robust previous calibration, which found a global rate of $37^{+12}_{-8} \text{ year}^{-1}$ (Shafter & Irby, 2001). However, our deduced rate is much higher than all previous results including the Shafter & Irby determination and those of Hubble (1929) ($\sim 30 \text{ year}^{-1}$), Arp (1956) ($24 \pm 4 \text{ year}^{-1}$) and Capaccioli et al. (1989) ($29 \pm 4 \text{ year}^{-1}$). The favoured $\theta$ value generates a bulge novae rate of $42 \pm 9 \text{ year}^{-1}$ and a disk rate of $17 \pm 4 \text{ year}^{-1}$. Although this is much higher than those found by Shafter & Irby, who determined the bulge rate to be $\sim 25 \pm 4 \text{ year}^{-1}$, we find a ratio between the bulge and disk nova rate that is remarkably similar to Shafter & Irby’s (computed from
As was discussed in Section 6.11.1, we believe that we have a greater understanding of the completeness of our catalogue than that of previous surveys. As such, we suggest that our elevated nova rate for M31 is solely indicative of our more robust analysis of the data. As discussed above, the main sources of concern regarding our evaluation of the global nova rate arise from extinction, the lack of very fast novae in the catalogue, uncertainties in the surface brightness modelling of M31 and the potential misclassification of novae within our catalogue. However, the uncertainties in the extinction and the lack of very fast novae (see Section 6.11.1) all point to our evaluation of the completeness being an overestimate, especially within the disc. Hence, taking the extinction and very fast novae into account would cause a further increase in the global nova rate; in particular the disk nova rate. The misidentification of a single CN within the catalogue would lead to a maximum decrease in the global nova rate of $\sim 7\%$ (see Section 6.10). However, with the possible exception of PACN-00-07, we believe that the POINT-AGAPE catalogue contains very strong CN candidates. Without further analysis of the surface brightness and in particular the extended surface outside the POINT-AGAPE fields, it is difficult to estimate the errors induced by the surface brightness modelling.

There are a number of potential consequences of our elevated nova rate. Given that our completeness estimation is much more robust than those of previous surveys, we would naively expect to measure an elevated nova rate in most galaxies, including, perhaps, our own. As was already mention in Section 1.2, CNe are thought to make a substantial contribution to the abundances of a number of elemental isotopes. The increased nova rate ($\sim 50\%$ greater) would thus increase the significance of novae as producers of these isotopes. Such an increase in isotope abundance could have ramifications to the understanding of star formation processes. However, most star formation models are normalised to our own Galaxy, in which the nova rate is still poorly known, although given the similarities between M31 and the Milky Way a higher nova rate in M31 could
imply a higher nova rate in the Galaxy.
Chapter 7

Classical Novae in Other Galaxies

7.1 Introduction

In this chapter we discuss the extension of the techniques developed for the exploitation of the POINT-AGAPE data into a number of other, more distant, galaxies (M81, NGC 2403 and M64), using data taken specifically for this purpose from the Liverpool Telescope (LT). We also present some of the results of a brief pilot project conducted on M81 using data from the INT and the Jacobus Kapteyn Telescope (JKT) on La Palma.

The main aims of this survey are similar to those of the POINT-AGAPE CN project. We aim to analyse the MMRD and $t_{15}$ relationships (see Sections 1.3.4 and 1.3.5) within these galaxies and hopefully tighten these relationships. We will also perform an analysis of the nova distribution within these galaxies in an attempt to resolve the current debate about the dependence of nova rate with galaxy and stellar population type and attempt to determine whether there are indeed two distinct nova populations (see Section 2.6).

The full initial stage of this project began with the LT in late October 2004. Following this initial one year programme, it is planned to extend the survey to three years. During this survey it is expected that a very large sample of novae
will be discovered, containing more novae than discovered in our Galaxy to-date. A by-product of this survey will be the discovery of a varied catalogue of other luminous variables.

The CN detection pipeline developed for this work (see Chapter 3) can be easily adapted to work in conjunction with the LT data on these galaxies. As the database of detected novae grows, we envisage further refinement and development of the pipeline, hopefully with the development of an alert method for CNe, such that (for example spectroscopic) follow-ups may be undertaken from other (large) facilities.

7.2 The Liverpool Telescope

The recently commissioned Liverpool Telescope, situated at the Observatorio del Roque de Los Muchachos, La Palma, is, at 2m, the world’s largest fully robotic telescope that is used primarily for research (Bode et al., 2000). The primary scientific goals of the LT are: the monitoring of variable objects on all timescales from years to seconds; rapid reaction to unpredictable phenomena and their systematic follow up; simultaneous or coordinated with other facilities, both ground based and from space, and small scale surveys and serendipitous source follow up. The observations are being conducted using the telescope’s “RATCam” optical CCD camera which contains a single $2048 \times 2048$ pixel EEV detector. The RATCam has a field of view of $4.6 \times 4.6$ arcmin giving a resolution of 0.135 arcsec/pixel. Data acquisition is being conducted in the Sloan $r'$ and $g'$ broadband filters as well as the H$\alpha$ filter. Guaranteed time has been approved for our extragalactic CNe survey. Data acquisition began on $7^{th}$ October 2004 for NGC 2403 and $26^{th}$ October 2004 for M81 (Appendix C contains tables showing all LT CN programme observations to-date). The current LT CN observing schedule, for both M81 and NGC 2403, is as follows:
7.3 LT extragalactic CN survey target galaxies

- $r'$-band observations - 4×180 second exposures every 2 nights - the $r'$ data will be primarily used for light-curve creation and the subsequent study of MMRD and $t_{15}$ relationships. The $r'$ data can also be used for candidate selection in the manner described in Chapter 3.

- $g'$-band observations - 4×180 second exposures every 7 nights - these data will be used to facilitate candidate selection using CN colour criteria, such as those laid down in Chapter 3 and also exploration of extinction corrections. Due to the temporal sampling of the $g'$ data, it may not be possible to use it the MMRD or $t_{15}$ studies.

- Ha observations - 6×200 second exposures every 7 nights - the Hα data are included solely to facilitate initial candidate detection. The use of Hα specifically, rather than $r'$ data (that also includes the Hα emission), will provide a more robust candidate identification method and should aid us in the detection of novae in their decline.

7.3 LT extragalactic CN survey target galaxies

There are three target galaxies selected for the LT extragalactic nova survey, the two primary targets M81 and NGC 2403, and a secondary target, M64. These galaxies were selected by via the following criteria:

- Accessibility - the target galaxies should be visible to the LT.

- Inclination - they should be as close to face-on as possible.

- Distance - they should be close enough such that novae of all speed classes can be detected at peak and for at least two magnitudes below this.

- Angular size - the targets should be of an angular size that can be covered in, at most, a few RatCAM frames.
7.3. *LT extragalactic CN survey target galaxies*

- Nova rate - the expected nova rate should be high enough so that a good sample of CNe can be detected.

The three galaxies that passed these selection criteria are of differing Hubble types, allowing us to also probe with this survey any dependence of the nova rate upon Hubble type (see Section 2.6). The Hubble type of the primary targets differ greatly, with M81 being a bulge dominated early-type and NGC 2403 an almost bulge-less late-type. As such we would expect the nova rate (per unit $K$ flux) to be $\sim 3$ times higher for NGC 2403 than M81 (della Valle, 2002).

### 7.3.1 M81

M81 is also commonly referred to as “Bode’s Galaxy” after J.E. Bode who discovered it in 1774. It is a spiral galaxy, dominating the nearby M81 group (see Section 2.5.5). This galaxy is the primary target of the LT CN survey project as it is close enough so that CNe of all speed classes and morphologies can be followed using the LT through at least two magnitudes below maximum light. In addition, the angular size of M81 requires four LT fields to cover significantly the bulge and the disk. However, a single field, centred on the galaxy, covers the majority of the starlight. The mass of M81 is high enough to be expected to be a significant producer of CNe, with a nominal rate of $\sim 30$ year$^{-1}$. The LT M81 CN survey will potentially produce the best multi-colour light-curves of novae in M81 to-date. The combination of H$\alpha$ observations and the good temporal sampling of the survey will enable us to investigate the population and rate of M81 much more thoroughly than past surveys have allowed. A short nova pilot project was undertaken in M81 using $R$-band and H$\alpha$ observations from the INT and JKT as part of the “Excitement of Science 2003” project (see Section 7.4).

---

1. The nova rate of M81 has previously been determined to be $24 \pm 8$ year$^{-1}$ (Moses & Shafter, 1993) and $33^{+13}_{-8}$ year$^{-1}$ (Neill & Shara, 2004).
7.3.2 NGC 2403

NGC 2403 is an 8th-magnitude spiral galaxy in Camelopardalis. It is of Hubble Type Scd III and is situated around 3 Mpc away. Like M81, NGC 2403 is close enough such that nova of all speed classes can be followed through peak to at least two magnitudes into the decline. Again, it is massive enough to have an expected CNe eruption rate of \( \geq 5 \text{ year}^{-1} \) and it has a low inclination, i.e. it is relatively “face-on”. The angular size of NGC 2403 is large enough that the CN distribution can be studied, but small enough that it is covered by the LT’s field of view. There have been no previous published nova studies of NGC 2403.

7.3.3 M64

Known by many names: the “Black Eye”, the “Evil Eye” or the “Sleeping Beauty” galaxy, M64 is one of the most interesting galaxies in the sky, famous for its conspicuous dark structure which is a prominent dust feature obscuring the stars behind. This face-on spiral is of Hubble Type Sab II and lies at a distance of 3.7Mpc. Thought to have been formed by the collision of two galaxies it has been found to have two counter-rotating systems of gas in its disk (Braun et al., 1992) thought to have been caused by the collision. Like both M81 and NGC 2403, M64 is again close enough to allow novae of all types to be followed through two magnitudes below peak. Its expected nova rate is high enough to make M64 a worthy candidate to study, it is essentially “face-on” and its angular size is comparable with the field of view of the LT. Like NGC 2403, there have been to-date no CNe surveys of M64. However, due to the highly complex structure of M64 this galaxy has not been given as high a priority in the LT survey as M81 and NGC 2403.
7.4 The initial pilot - The Excitement of Science project

“The Excitement of Science” is a collaboration between The Royal Institution of Great Britain, the Great Britain and Ireland division of Rotary International and the National Schools’ Observatory. As well as being an educational project, it was a test-bed for the LT extragalactic CN survey also described in this chapter. The 2003 project was to determine the distance to M81. The distance was to be calculated by an application of the MMRD relationship to CNe discovered, as part of the project, within M81. This simple application involved comparing M81 novae to POINT-AGAPE M31 novae of similar types, to determine the relative distance of the two galaxies, by use of the inverse-square law. Given the distance to M31, the distance of M81 could then be inferred.

A total of 14 epochs or $R$-band data of M81, along with a number of H$\alpha$ epochs were taken using both the WFC on the INT and the JAG-CCD camera on the JKT from the end of April to the beginning of June 2003. The observation time needed to carry out this work was kindly donated by a number of observers at the Isaac Newton Group at the time. The project required the production of aligned, trimmed and median-filtered H$\alpha$ images, a task for which aspects of the POINT-AGAPE CN detection pipeline were utilised. The reduced H$\alpha$ data were then sent to a number of schools nationally, who used software developed for the project, to “blink” the images in an attempt to locate CNe and other variables. A number of transient H$\alpha$ “objects” were detected, the majority of them spurious events such as cosmic ray hits. However, four good CN candidates were discovered and their $R$ light-curves are shown in Figure 7.1. Another two potential novae were found, however it was not possible to produce light-curves for these events, hence their classification as CNe is not as certain.

The project culminated at a live event, in which the light-curves were then compared to a number of the POINT-AGAPE light-curves by the audience. One
Figure 7.1: The light-curves of four M81 novae discovered during the The Excitement of Science project in 2003. The blue dashed line represents a linearly interpolated extrapolation of the light-curve between observations.
7.5. Progress to date with LT CN programme

As was mentioned briefly in Section 7.2, data acquisition for the LT CN programme began on 7th October 2004 for NGC 2403 and 26th October 2004 for M81. A full list of the observations taken to-date is given in Appendix C. So far 16 epochs have been taken for M81 and 19 for NGC 2403, a breakdown of the observations, by filter, is shown in Table 7.1.

Unfortunately, the LT CN programme has experienced a number of problems since it began. Many of these are due to the LT still undergoing commissioning as a scientific instrument. The start of the programme was itself delayed by a number of years due to difficulties installing the telescope and the enclosure on the La Palma site.

<table>
<thead>
<tr>
<th>Target</th>
<th>Filter</th>
<th>Epochs</th>
</tr>
</thead>
<tbody>
<tr>
<td>M81</td>
<td>r′</td>
<td>16</td>
</tr>
<tr>
<td>M81</td>
<td>g′</td>
<td>7</td>
</tr>
<tr>
<td>M81</td>
<td>Hα</td>
<td>7</td>
</tr>
<tr>
<td>NGC 2403</td>
<td>r′</td>
<td>19</td>
</tr>
<tr>
<td>NGC 2403</td>
<td>g′</td>
<td>8</td>
</tr>
<tr>
<td>NGC 2403</td>
<td>Hα</td>
<td>6</td>
</tr>
<tr>
<td>NGC 2403</td>
<td>Hα-50</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 7.1: The break down the the LT CN programme observations to-date by galaxy and filter. The Hα-50 filter was a narrow Hα filter with width ~ 50Å, later replaced by a Hα filter with width ~ 100Å (see Section 7.5).

of the M81 light-curves was deemed to be most similar to one from POINT-AGAPE, having similar form and decline rate. The audience were introduced to the MMRD relation. Hence, they were able to compute the distance modulus between M31 and M81 and, being given the distance to M31, evaluate the distance to M81. The computed distance was, within the errors, the same as that determined by Freedman et al. (2001) who found M81 to have a distance modulus of 27.67 ± 0.07.

7.5 Progress to date with LT CN programme

As was mentioned briefly in Section 7.2, data acquisition for the LT CN programme began on 7th October 2004 for NGC 2403 and 26th October 2004 for M81. A full list of the observations taken to-date is given in Appendix C. So far 16 epochs have been taken for M81 and 19 for NGC 2403, a breakdown of the observations, by filter, is shown in Table 7.1.

Unfortunately, the LT CN programme has experienced a number of problems since it began. Many of these are due to the LT still undergoing commissioning as a scientific instrument. The start of the programme was itself delayed by a number of years due to difficulties installing the telescope and the enclosure on the La Palma site.
Figure 7.2: False-colour image of M81, created from the INT Excitement of Science data.
Once data acquisition began, an early problem was experienced with the Hα filter in the RatCAM. The initial Hα filter installed on the telescope had a width of $\sim 50\text{Å}$. The narrowness of the filter, coupled with a slight offset in the maximum transmission wavelength and a further offset due to its position in the optical path meant that this filter’s throughput was severely reduced and thus, insufficient to observe the Hα emission of the target galaxies. The original Hα filter was replaced with a filter with a width of $\sim 100\text{Å}$ which allowed us to resolve the Hα emission of both target galaxies.

Full robotic operation of the LT began in mid-December 2004; however, since then the observing schedule has been subject to significant interruptions due to poor weather. In December, the LT was only able to observe on three nights (27.6 hours of observing for all programmes, 195.3 hours lost to the weather). In January the weather was slightly better, with the LT able to observe to some degree on 15 nights (93.7 hours of observing, 133.4 hours lost to the weather and 102.5 hours lost due to technical problems). However, the entire month of February and the beginning of March (up to the time of writing) were lost due to the weather conditions at the observatory (a total of 313.3 hours of potential observing time). Due to these weather interruptions, the temporal coverage of the LT CN data taken to-date has been less than optimal for the project.

Additional problems have arisen with the LT CN programme due to tracking and pointing problems. The pointing problems of the telescope have now been all but eradicated. In order to try and minimise the LT’s tracking issues, the original LT proposal was altered to allow for a greater number of shorter observations (the revised schedule is shown in Section 7.2). However, many of the observations still suffer from a slight elongating of the image PSFs. The tracking problems are currently still under investigation, although the tracking has improved significantly since the telescope first entered operation. A number of instrumental upgrades took place in January 2005, with the anticipation of improving the tracking. But, due to the poor weather, they have yet to be tested. The implementation of autoguided tracking later this year will alleviate any remaining tracking anomalies.
7.5. Progress to date with LT CN programme

The data received from the LT to-date, has already been preprocessed (de-biased and flat fielded) by the LT data reduction pipeline. To-date, only the Hα data have been processed further. In order to evaluate the LT data received so far, the Hα data from each night have been aligned and stacked. The stacking process combines a number of images taken at essentially the same time (six images were taken in Hα for each galaxy) to produce a single image whose signal-to-noise ratio is a factor $\sqrt{N}$ greater than each of the $N$ single images. The combining of images in this way can also eradicate transient events, such as cosmic rays, from the data. From a visual analysis of the M81 and NGC 2403 data, there appear to have been no transient Hα sources observed to-date. However, a much more thorough reduction and analysis of the data (including the Hα data) needs to be performed before we can begin the nova detection process properly.

Once observing using the LT becomes possible again, the LT CN programme will continue to take data. However, the $r'$ filter will now be replaced with observations taken in the V-band. The $r'$ data were primarily being taken to generate CN light-curves and to calibrate the MMRD and $t_{15}$ relationships. However, it is now known that the Hα “contamination” of the $r'$ filter can affect the reliability of these relationships (Shafter, private communication). The V-band observations will also be conducted every night (as opposed to every second night for the $r'$ data) to increase the temporal sampling of the survey.

The following chapter summarises the results of this thesis and discusses future work. The LT extragalactic CN survey forms a significant part of this discussion.
Chapter 8

Summary and Further Work

8.1 Summary of results to-date

8.1.1 CN detection pipeline

We have developed a fully self-contained data reduction and analysis system with the sole aim of detecting CNe within broadband optical data with good temporal sampling, producing and analysing the light-curves of detected novae. The pipeline was described in full within Chapter 3 and details have been published in Darnley et al. (2004).

8.1.2 POINT-AGAPE CN catalogue

The CN detection pipeline was primarily developed for use on the data taken by the POINT-AGAPE micro-lensing collaboration. The subsequent analysis of these data produced a catalogue of 20 CNe which exhibited light-curves of varying morphologies, from fast through very slow. The CN catalogue was presented in Chapter 4 which also provides the $r'$, $r' - i'$ and $g' - r'$ (where available) light-curves of each nova. The POINT-AGAPE CN catalogue has also been published in Darnley et al. (2004). By comparison with nova candidates from An
8.1. Summary of results to-date

et al. (2004) we drew the preliminary conclusion that the pipeline is successful in recognising CN within the boundaries of the defined criteria. A brief visual evaluation of the observed CN distribution was carried out at this stage. This yielded some evidence of spatial concentration around the bulge, but also potentially an extended (disk) population of novae. Both the catalogue completeness and observed distribution were evaluated much more rigorously, with the results presented in Chapter 6.

Within Chapter 4 we also presented the light-curves of two non-novae that were identified (and later eliminated as potential nova candidates) by various stages of the pipeline. The first source was an extremely long period Mira, exhibiting a period of either $\sim 700$ or $\sim 1,400$ days. The second was a high signal-to-noise micro-lensing event (PA-99-N2) previously discovered by the POINT-AGAPE collaboration (Paulin-Henriksson et al., 2003).

8.1.3 Novae as distance indicators

Chapter 5 reported the calibration of both the MMRD and $t_{15}$ relationships using the POINT-AGAPE CN catalogue, which included a recalibration of each nova’s decay rate and speed class and assessments of the uncertainties in the maximum light and line of sight extinction to each nova. The results from this Chapter will be reported in a follow up paper, currently in preparation and to be submitted for publication in a referred journal.

We were able to show that the basic premise of the MMRD relationship, that the brighter novae decline faster, held for the POINT-AGAPE catalogue. By analysing the possible uncertainties of the maximum light calibration of each nova and the line of sight extinction to each nova, we were able to produce reasonable MMRD fits, within the linear portion of the relationship, to both the $r'$ and $i'$ data. Although these fits were dominated by the extinction uncertainties, these uncertainties seemed to account for the majority of the scatter in both calibrations. Given that this was the first MMRD calibration for the Sloan $r'$
and $i'$ bands, direct comparison with previous calibrations was not possible, which prevented us from using our fits to produce reliable distance estimates to M31. However, we can conclude that the MMRD relationship is both valid within M31 and for the $r'$ and $i'$ regions of a nova’s emission within the linear region of the MMRD, although the usefulness of the $r'$ relationship is compromised by the Hα emission within the $r'$ passband. We also see evidence for the slow end of the “S-shaped” form. Our calibrated $r'$ and $i'$ MMRD relationships are:

$$m_{r'} = (11.8 ± 2.2) + (2.6 ± 1.4) \log t_2$$ (8.1)

$$m_{i'} = (10.2 ± 2.4) + (3.9 ± 1.6) \log t_2$$ (8.2)

We then proceeded to evaluate the $t_{15}$ relationship. As was done for the MMRD calibration, each of the catalogue nova’s light-curves was reassessed to take account of maximum-light and extinction uncertainties. However, following this analysis, no evidence of a $t_{15}$ relationship was seen. Given that our calibration is dominated by uncertainties from the extinction and temporal sampling of the POINT-AGAPE survey, we can not make any robust statements about the general validity of the $t_{15}$ relationship. However, our results can only add to the growing body of evidence against the existence of the $t_{15}$ relationship. In order to thoroughly exhaust the testing of the $t_{15}$ relationship, a large sample of (preferably) extragalactic novae would be required, with light-curves that have good and uniformly distributed temporal sampling, a sample in which the extinction is also preferably well defined.

### 8.1.4 M31’s CNe population

In Chapter 6 we presented the full statistical analysis we conducted of the completeness of the POINT-AGAPE survey and the CN pipeline, the M31 nova distribution, parent population and nova rate.
8.1. Summary of results to-date

To evaluate the combined completeness of the survey and the pipeline, we employed a method which seeded generated novae (using the 20 POINT-AGAPE novae as templates) within the POINT-AGAPE data, on which the pipeline was re-run to determine the proportion of recovered novae. Determining the completeness in this way, combined with the objective selection criteria employed in the pipeline, has provided us with a much better knowledge of the true completeness than has been possible in previous surveys. Our completeness analysis is limited however by the exclusion of extinction effects internal to M31 and due to the lack of the very fast class of novae within the catalogue. These effects indicate that our calculated completeness may be an over-estimate, particularly within the M31 disk.

By developing a number of simple models of the CN eruption distribution within M31 we were able to conduct an analysis of the observed nova distribution and the underlying parent population of those novae. The first basic analysis indicated that the observed distribution was slightly more centrally clustered than the galactic luminosity. Following the deconvolution of the disk and bulge through modelling of the surface brightness, we were able to show that it was highly unlikely that the observed distribution was drawn from solely a bulge or a disk population, that a combination of both was required. Further analysis showed that the observed distribution could be explained if the nova rate per unit $r'$ flux within the bulge was greater, by up to an order of magnitude, than that of the disk. The maximum likelihood analysis of the two population model produced a favoured value of $\theta = 0.18$ and allowed us to rule out the single population model at the 95% level. We also conclude however, that the strong bulge domination of the nova population of M31, reported by a number of previous surveys, is likely to be a selection effect of these surveys which often concentrated on a small field centred on the bulge. The limitations of this analysis are drawn from the small size of the input catalogue, uncertainties in the surface brightness modelling and the survey/pipeline completeness. The conclusions drawn from this analysis are that there are separate disk and bulge nova populations in M31, with the majority
8.1. Summary of results to-date

of observed novae arising from the bulge, but that there is also a significant disk contribution.

8.1.5 The M31 nova rate

By extending the M31 CN eruption model over the whole galaxy we were able to produce an estimate of the global nova rate. The computed global CN rate of M31 is $59 \pm 13$ year$^{-1}$, with a bulge rate of $42 \pm 9$ year$^{-1}$, a result that is significantly higher than all previous results. Although it is also noted that our bulge to disk nova rate ratios are consistent with previous results. Despite its apparent high value, we are confident that our computed nova rate is a true evaluation of the nova production rate of M31. Our robust completeness analysis and objective selection criteria lead us to believe that the completeness of previous surveys may have been greatly over estimated. Also, given their bulge-centric nature, many previous surveys are likely to have underestimated the contribution from disk novae. Sources of concern in our estimated rate arise again from the extinction uncertainties and the lack of very fast novae in the catalogue. However, both these factors would only lead to a further increase in the predicted rate, so we are led to conclude that the true global CNe rate of M31 is much higher than was previously thought. In fact it is at least 50% greater.

8.1.6 Surveys for CN in other galaxies

As part of a pilot programme conducted for the LT project, four strong CN candidates were discovered in M81 using data from the INT and JKT. To-date, 16 epochs of M81 data and 19 epochs of NGC 2403 data have been taken as part of the the LT extragalactic CN programme. These data have been taken in three bands, $r'$, $g'$ and H$\alpha$. The H$\alpha$ data has been fully reduced. However, an initial evaluation of these data did not reveal any transient H$\alpha$ sources (indicative of CN) in either galaxy.
8.2 Further work

Parts or all of the nova detection techniques presented in this thesis can be applied to various other projects including further study of the novae in M31, CN surveys in other galaxies and to variable star surveys in general. A few avenues of further work are described below in more detail.

8.2.1 The POINT-AGAPE dataset

A further year of POINT-AGAPE data has recently become available. Combining this with the existing three years of data would produce an improved resource for the study of CNe. The longer the baseline of a CN survey the less likely any catalogue is to be contaminated by periodically varying objects. The added year of data would also help us to further refine both the MMRD and $t_{15}$ relationships and CN population analyses by providing a larger sample of CNe with which to work. The limited size of the current catalogue is, along with the extinction uncertainties, the main stumbling block in the evaluation of the MMRD and $t_{15}$ relationships and severely limits the determination of the true relationship between the underlying bulge and disk populations.

8.2.2 The Liverpool Telescope CN survey

The Liverpool Telescope will be used to systematically survey three galaxies (M81, NGC 2403 and M64) in a similar way to the POINT-AGAPE survey, primarily as a search for novae. The survey is being conducted in two broadband filters, Sloan $r'$ and $g'$, supplemented with Hα data to aid nova detection. A pilot of this project was completed in 2003 and data acquisition began in earnest with the LT towards the end of 2004. The main aims of the LT CN survey are to analyse the MMRD and $t_{15}$ relationships within a number of galaxies and to study the CN distribution within these galaxies in an attempt to resolve the current debate.

\footnote{Future observations will replace the $r'$ filter with a $V$-band filter (see Section 7.5).}
8.2. Further work

about the dependence of nova rate upon galaxy and stellar population type. Using the early data from the LT programme we also aim to develop an alert system for extragalactic CN eruptions, which will hopefully facilitate rapid spectroscopic follow up observations. It may also be possible, in the future, to extend this survey as a “RoboNet-1.0” project. RoboNet-1.0 will utilise the LT and its two identical sister telescopes, the Faulkes North (Maui) and the Faulkes South (Siding Spring, Australia), potentially giving any CN survey greater temporal sampling and sky coverage.

8.2.3 The Angstrom project

The Andromeda Galaxy sub-stellar robotic micro-lensing (Angstrom) project is a UK-Korean-US collaboration that aims to use stellar micro-lensing events to trace the structure and composition of the inner regions of M31 (Kerins et al., 2005). The Angstrom project will use difference imaging techniques to aid in the detection of micro-lensing events. However, the temporal sampling of the project is unique. By employing three telescopes worldwide, The LT in the Canaries, the 1.8m Doyak Telescope in Korea and the 2.4m Hiltner in Arizona, upwards of 3 Sloan $r'$ and $i'$ epochs will be obtained per 24 hour period. This resolution will enable the the survey to be sensitive to short-duration stellar micro-lensing events due to low mass stars and brown dwarfs, missed by current surveys. The high temporal sampling also makes the Angstrom data potentially a powerful resource for the study of novae and other bright variable stars. The CN pipeline employed in this study can be adapted and combined with the difference image software to potentially create a pipeline capable of detecting, classifying and analysing a vast range of variable objects. It is hoped that this study will also lead to the development of an alert system for micro-lensing and CN events amongst others. The data acquisition for the Angstrom Project has already begun, with the first LT observation taking place on 16th August 2004. To-date ~ 50 epochs have been taken from the LT alone. The data are currently undergoing initial reduction.
Bibliography


An, J. H., Evans, N. W., Kerins, E., Baillon, P., Calchi Novati, S., Carr, B. J.,
Crézé, M., Giraud-Héraud, Y., Gould, A., Hewett, P., Jetzer, P., Kaplan, J.,
Paulin-Henriksson, S., Smartt, S. J., Tsapras, Y., & Valls-Gabaud, D. 2004,


Aurière, M., Baillon, P., Bouquet, A., Carr, B. J., Crézé, M., Evans, N. W.,
Giraud-Héraud, Y., Gould, A., Hewett, P. C., Kaplan, J., Kerins, E., Lastennet,
E., Le Du, Y., Melchior, A.-L., Paulin-Henriksson, S., Smartt, S. J., & Valls-

A. Evans (Chichester: Wiley), 61–72


Belokurov, V., An, J., Evans, N. W., Hewett, P., Baillon, P., Novati, S. C., Carr,
B. J., Crézé, M., Giraud-Héraud, Y., Gould, A., Jetzer, P., Kaplan, J., Kerins,
E., Paulin-Henriksson, S., Smartt, S. J., Stalin, C. S., Tsapras, Y., & Weston,

Bertaud, C. 1948, Annales d’Astrophysique, 11, 3

University Press)


Bode, M. F., & Evans, A., eds. 1989, Classical novae (Chichester: Wiley)


Buscombe, W., & de Vaucouleurs, G. 1955, The Observatory, 75, 170


de Vaucouleurs, G. 1948, Annales d’Astrophysique, 11, 247


—. 1990, Lecture Notes in Physics, Berlin Springer Verlag, 369, 34


Flamsteed, J. 1725, HISTORIA Coelestis Britannicae, tribus Voluminibus contenta (1675-1689), (1689-1720), vol. 1, 2, 3 (London : H. Meere; in folio; DCC.f.9, DCC.f.10, DCC.f.11)


Grotrian, W. 1937, Zeitschrift fur Astrophysics, 14, 129


Hernanz, M., & José, J., eds. 2002, Classical Nova Explosions

Hind, J. R. 1848a, MNRAS, 8, 146
—. 1848b, MNRAS, 8, 155
—. 1848c, MNRAS, 8, 192

Holwerda, B. W., Gonzalez, R. A., Allen, R. J., & van der Kruit, P. C. 2004,
astro-ph/0411663 - Accepted for publication in AJ


Jacoby, G. H., Branch, D., Ciardullo, R., Davies, R. L., Harris, W. E., Pierce,

& J. José, 104–113

Joshi, Y. C., Pandey, A. K., Narasimha, D., Giraud-Héraud, Y., Sagar, R., &

Kato, T., Uemura, M., Haseda, K., Yamaoka, H., Takamizawa, K., Fujii, M., &
Kiyota, S. 2002a, PASJ, 54, 1009

Kato, T., Yamaoka, H., & Ishioka, R. 2002b, Informational Bulletin on Variable
Stars, 5309, 1

Kerins, E., Carr, B. J., Evans, N. W., Hewett, P., Lastennet, E., Le Du, Y.,

Kerins, E., Darnley, M. J., Duke, J., Gould, A., Han, C., Jeon, Y. B., Newsam, A.,


McLaughlin, D. B. 1939, Popular Astronomy, 47, 410

—. 1941, PASP, 53, 102

—. 1943, Publications of Michigan Observatory, 8, 149

—. 1945, PASP, 57, 69


—. 1979, A&A, 72, 192


Ritchey, G. W. 1917a, PASP, 29, 257

—. 1917b, PASP, 29, 210

Robinson, E. L. 1975, AJ, 80, 515

Rosino, L. 1964, Annales d’Astrophysique, 27, 498

—. 1973, A&AS, 9, 347
Schmidt, T. 1957, Zeitschrift fur Astrophysics, 41, 182
Sharov, A. S. 1972, Soviet Astronomy, 16, 41
—. 1993, Astronomy Letters, 19, 7


—. 1999, Physics Reports, 311, 371


Starrfield, S., Truran, J. W., & Sparks, W. M. 2000, New Astronomy Review, 44, 81


Trumpler, R. J. 1930, Lick Observatory Bulletin, 14, 154

van den Bergh, S. 1988, PASP, 100, 8

van den Bergh, S., & Younger, P. F. 1987, A&AS, 70, 125


Wolf, B. 1977, in IAU Colloq. 42: The Interaction of Variable Stars with their Environment, 151–+
Appendix A

Colour System Transformation

To compute the colour transformations from the Sloan-like filters of the POINT-AGAPE survey to the more commonly used Johnson-Cousins filter system we assumed that a simple linear relationship existed allowing us to transform between the two systems (Fukugita et al., 1996):

\[
V = g' + \Gamma_V + \beta_V(g' - r') \\
R = r' + \Gamma_R + \beta_R(g' - r') \\
R = r' + \Gamma_R + \beta_R(r' - i') \\
I = i' + \Gamma_I + \beta_I(r' - i')
\] (A.1) (A.2) (A.3) (A.4)

In these equations, \(r', i'\) and \(g'\) correspond to the photometrically corrected \(r', i'\) and \(g'\) instrumental magnitudes, respectively, and \(V, R\) and \(I\) are the Johnson-Cousins apparent magnitudes to be calculated. The \(\Gamma\) and \(\beta\) parameters are constants that depend upon the specific characteristics of each CCD in the WFC. The \(\Gamma\) terms represent the difference in each CCD’s zero-point magnitude between the two systems, whilst the \(\beta\) terms describe the difference in response of each CCD between photons of different wavelengths. The best-fit parameter values for each CCD are computed from fits using the selected standards from the Magnier
catalogues.

Unfortunately we were not able to implement these colour transformations to convert the light-curves of the POINT-AGAPE novae to the Johnson-Cousins filter system. The simple linear transformations rely upon the objects in question having essentially a well behaved black body spectrum, i.e. that the intrinsic colour differences between filters can in theory be calculated. Whilst the fitting of the parameters of the transformations using stars in the M31 field was relatively successful, applying the transformations to the nova data would not be prudent. The spectra of novae, although at times through their evolution they are comparable with the black body-like spectra of stars, can vary greatly from this, as seen through various filters, at times during their evolution.
Table A.1: Best-fit $\Gamma$ and $\beta$ coefficients for colour equations (A.1–A.4)

<table>
<thead>
<tr>
<th></th>
<th>CCD1</th>
<th>CCD2</th>
<th>CCD3</th>
<th>CCD4</th>
<th>CCD1</th>
<th>CCD2</th>
<th>CCD3</th>
<th>CCD4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_V$</td>
<td>0.0460</td>
<td>-0.801</td>
<td>-0.548</td>
<td>-0.424</td>
<td>-0.363</td>
<td>-0.304</td>
<td>-0.412</td>
<td>-0.311</td>
</tr>
<tr>
<td>$\Gamma_{R_g}$</td>
<td>-0.0184</td>
<td>-1.04</td>
<td>-0.642</td>
<td>-0.643</td>
<td>-0.715</td>
<td>-0.593</td>
<td>-0.706</td>
<td>-0.517</td>
</tr>
<tr>
<td>$\Gamma_{R_i}$</td>
<td>-0.141</td>
<td>-0.991</td>
<td>-0.689</td>
<td>-0.639</td>
<td>-0.701</td>
<td>0.116</td>
<td>-0.725</td>
<td>-0.592</td>
</tr>
<tr>
<td>$\Gamma_I$</td>
<td>-0.716</td>
<td>-1.42</td>
<td>-1.35</td>
<td>-1.16</td>
<td>-1.13</td>
<td>0.201</td>
<td>-1.12</td>
<td>-1.03</td>
</tr>
<tr>
<td>$\beta_V$</td>
<td>-0.644</td>
<td>-0.637</td>
<td>-0.610</td>
<td>-0.607</td>
<td>-0.603</td>
<td>-0.710</td>
<td>-0.663</td>
<td>-0.603</td>
</tr>
<tr>
<td>$\beta_{R_g}$</td>
<td>-0.196</td>
<td>-0.191</td>
<td>-0.190</td>
<td>-0.164</td>
<td>-0.217</td>
<td>-0.248</td>
<td>-0.221</td>
<td>-0.173</td>
</tr>
<tr>
<td>$\beta_{R_i}$</td>
<td>-0.303</td>
<td>-0.300</td>
<td>-0.302</td>
<td>-0.243</td>
<td>-0.327</td>
<td>1.00</td>
<td>-0.344</td>
<td>-0.0852</td>
</tr>
<tr>
<td>$\beta_I$</td>
<td>-0.175</td>
<td>-0.197</td>
<td>-0.338</td>
<td>-0.340</td>
<td>-0.101</td>
<td>2.77*</td>
<td>-0.259</td>
<td>-0.314</td>
</tr>
</tbody>
</table>

<p>| | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$r'$ &amp; $i'$ stars</td>
<td>122</td>
<td>42</td>
<td>11</td>
<td>44</td>
<td>16</td>
<td>3</td>
<td>84</td>
<td>3</td>
</tr>
<tr>
<td>$r'$ &amp; $g'$ stars</td>
<td>176</td>
<td>101</td>
<td>13</td>
<td>74</td>
<td>22</td>
<td>6</td>
<td>202</td>
<td>56</td>
</tr>
</tbody>
</table>
Appendix B

The Wilcoxon-Mann-Whitney Rank Test

We consider a problem in which a random sample of $m$ observations, $X_1, ..., X_m$, is taken from a continuous distribution for which the distribution function, $F(x)$, is unknown, and an independent random sample of $n$ observations, $Y_1, ..., Y_n$, is taken from another continuous distribution for which the distribution function, $Gx$, is also unknown. We desire to test the following hypothesis:

\[ H_0 : \quad F = G \]  \hspace{1cm} (B.1)
\[ H_1 : \quad F \neq G \]  \hspace{1cm} (B.2)

Although this hypothesis can often be tested using the Kolmogorov-Smirnov Test, another procedure that may be employed is the Wilcoxon-Mann-Whitney Rank Test (M-W Test), developed independently by Wilcoxon, Mann and Whitney in the 1940s.

To perform the M-W Test the $m+n$ observations from both samples are arranged in sequence from the smallest value to the largest. Each observation is assigned
a rank, from 1 to \(m + n\), corresponding to its position in the ordering.

If the null hypothesis \(H_0\) is true then the observations \(X_1, \ldots, X_m\) will tend to be dispersed throughout the ordering of all \(m + n\) observations, rather than concentrated in a group within the combined sample. In fact, if \(H_0\) is true, the ranks assigned to the \(m\) observations \(X_1, \ldots, X_m\) will be the same as if they were a random sample of \(m\) ranks drawn at random, without replacement, from a box containing all \(m + n\) ranks of the combined sample.

If \(S\) denotes the sum of the ranks assigned to the \(m\) observations \(X_1, \ldots, X_m\) then, when \(H_0\) is true, the expectation value of \(S\) is given by:

\[
E(S) = \frac{m(m + n + 1)}{2} \quad (B.3)
\]

and the variance of \(S\) is thus:

\[
\sigma^2(S) = \frac{mn(m + n + 1)}{12} \quad (B.4)
\]

When the sample sizes \(m\) and \(n\) are both large and \(H_0\) is true, then the distribution of \(S\) will be approximately that of a Gaussian distribution whose mean and variance are given by Equations B.3 and B.4 respectively.

The M-W Test will reject \(H_0\) if the value of \(S\) deviates far from its mean value (given by Equation B.3). \(H_0\) will be rejected if:

\[
|S - (1/2)m(m + n + 1)| \geq c \quad (B.5)
\]
## Appendix C

### LT extragalactic CN Programme

Observing Schedule To-date

<table>
<thead>
<tr>
<th>Observation date and time</th>
<th>Filter</th>
<th>Exposure time (secs)</th>
<th>Seeing (arcsec)</th>
<th>Airmass</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004-10-27 04:22:18</td>
<td>r'</td>
<td>180.0</td>
<td>2.1</td>
<td>1.7200</td>
</tr>
<tr>
<td>2004-10-27 04:25:38</td>
<td>r'</td>
<td>180.0</td>
<td>68.9</td>
<td>1.7100</td>
</tr>
<tr>
<td>2004-10-27 04:28:59</td>
<td>r'</td>
<td>180.0</td>
<td>57.2</td>
<td>1.7000</td>
</tr>
<tr>
<td>2004-10-27 04:32:19</td>
<td>r'</td>
<td>180.0</td>
<td>65.7</td>
<td>1.6900</td>
</tr>
<tr>
<td>2004-12-02 01:18:59</td>
<td>r'</td>
<td>180.0</td>
<td>11.5</td>
<td>1.9000</td>
</tr>
<tr>
<td>2004-12-02 01:22:16</td>
<td>r'</td>
<td>180.0</td>
<td>11.8</td>
<td>1.8800</td>
</tr>
<tr>
<td>2004-12-02 01:25:33</td>
<td>r'</td>
<td>180.0</td>
<td>13.7</td>
<td>1.8700</td>
</tr>
<tr>
<td>2004-12-02 01:28:51</td>
<td>r'</td>
<td>180.0</td>
<td>11.3</td>
<td>1.8500</td>
</tr>
<tr>
<td>2004-12-09 04:40:36</td>
<td>r'</td>
<td>180.0</td>
<td>10.7</td>
<td>1.3400</td>
</tr>
<tr>
<td>2004-12-09 04:43:54</td>
<td>r'</td>
<td>180.0</td>
<td>10.9</td>
<td>1.3400</td>
</tr>
<tr>
<td>2004-12-09 04:47:11</td>
<td>r'</td>
<td>180.0</td>
<td>11.2</td>
<td>1.3300</td>
</tr>
<tr>
<td>2004-12-09 04:50:28</td>
<td>r'</td>
<td>180.0</td>
<td>12.8</td>
<td>1.3300</td>
</tr>
<tr>
<td>2004-12-18 23:55:14</td>
<td>r'</td>
<td>180.0</td>
<td>26.6</td>
<td>1.9800</td>
</tr>
<tr>
<td>2004-12-18 23:58:32</td>
<td>r'</td>
<td>180.0</td>
<td>13.3</td>
<td>1.9600</td>
</tr>
</tbody>
</table>

Continued on next page
<table>
<thead>
<tr>
<th>Observation date and time</th>
<th>Filter</th>
<th>Exposure time (secs)</th>
<th>Seeing (arcsec)</th>
<th>Airmass</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004-12-19 00:01:49</td>
<td>r'</td>
<td>180.0</td>
<td>23.7</td>
<td>1.9500</td>
</tr>
<tr>
<td>2004-12-19 00:05:06</td>
<td>r'</td>
<td>180.0</td>
<td>25.3</td>
<td>1.9300</td>
</tr>
<tr>
<td>2004-12-19 00:10:21</td>
<td>Hα</td>
<td>200.0</td>
<td>9.2</td>
<td>1.9100</td>
</tr>
<tr>
<td>2004-12-19 00:13:58</td>
<td>Hα</td>
<td>200.0</td>
<td>9.8</td>
<td>1.8900</td>
</tr>
<tr>
<td>2004-12-19 00:17:35</td>
<td>Hα</td>
<td>200.0</td>
<td>2.4</td>
<td>1.8700</td>
</tr>
<tr>
<td>2004-12-19 00:21:12</td>
<td>Hα</td>
<td>200.0</td>
<td>9.4</td>
<td>1.8600</td>
</tr>
<tr>
<td>2004-12-19 00:24:49</td>
<td>Hα</td>
<td>200.0</td>
<td>5.6</td>
<td>1.8400</td>
</tr>
<tr>
<td>2004-12-19 00:28:26</td>
<td>Hα</td>
<td>200.0</td>
<td>7.8</td>
<td>1.8200</td>
</tr>
<tr>
<td>2004-12-19 00:32:54</td>
<td>g'</td>
<td>180.0</td>
<td>18.3</td>
<td>1.8000</td>
</tr>
<tr>
<td>2004-12-19 00:36:11</td>
<td>g'</td>
<td>180.0</td>
<td>17.0</td>
<td>1.7900</td>
</tr>
<tr>
<td>2004-12-19 00:39:27</td>
<td>g'</td>
<td>180.0</td>
<td>15.8</td>
<td>1.7800</td>
</tr>
<tr>
<td>2004-12-19 00:42:45</td>
<td>g'</td>
<td>180.0</td>
<td>16.1</td>
<td>1.7600</td>
</tr>
<tr>
<td>2004-12-20 23:51:41</td>
<td>r'</td>
<td>180.0</td>
<td>23.3</td>
<td>1.9600</td>
</tr>
<tr>
<td>2004-12-20 23:54:58</td>
<td>r'</td>
<td>180.0</td>
<td>15.6</td>
<td>1.9400</td>
</tr>
<tr>
<td>2004-12-20 23:58:14</td>
<td>r'</td>
<td>180.0</td>
<td>13.0</td>
<td>1.9300</td>
</tr>
<tr>
<td>2004-12-21 00:01:31</td>
<td>r'</td>
<td>180.0</td>
<td>24.2</td>
<td>1.9100</td>
</tr>
<tr>
<td>2004-12-31 02:34:50</td>
<td>r'</td>
<td>180.0</td>
<td>13.4</td>
<td>1.3800</td>
</tr>
<tr>
<td>2004-12-31 02:38:07</td>
<td>r'</td>
<td>180.0</td>
<td>14.4</td>
<td>1.3700</td>
</tr>
<tr>
<td>2004-12-31 02:41:24</td>
<td>r'</td>
<td>180.0</td>
<td>12.6</td>
<td>1.3700</td>
</tr>
<tr>
<td>2004-12-31 02:44:41</td>
<td>r'</td>
<td>180.0</td>
<td>14.1</td>
<td>1.3700</td>
</tr>
<tr>
<td>2004-12-31 02:49:54</td>
<td>Hα</td>
<td>200.0</td>
<td>9.9</td>
<td>1.3600</td>
</tr>
<tr>
<td>2004-12-31 02:53:31</td>
<td>Hα</td>
<td>200.0</td>
<td>9.8</td>
<td>1.3600</td>
</tr>
<tr>
<td>2004-12-31 02:57:07</td>
<td>Hα</td>
<td>200.0</td>
<td>10.0</td>
<td>1.3500</td>
</tr>
<tr>
<td>2004-12-31 03:00:45</td>
<td>Hα</td>
<td>200.0</td>
<td>10.6</td>
<td>1.3500</td>
</tr>
<tr>
<td>2004-12-31 03:04:21</td>
<td>Hα</td>
<td>200.0</td>
<td>22.0</td>
<td>1.3500</td>
</tr>
<tr>
<td>2004-12-31 03:07:58</td>
<td>Hα</td>
<td>200.0</td>
<td>3.7</td>
<td>1.3400</td>
</tr>
<tr>
<td>2004-12-31 03:12:26</td>
<td>g'</td>
<td>180.0</td>
<td>14.7</td>
<td>1.3400</td>
</tr>
</tbody>
</table>

Continued on next page
<table>
<thead>
<tr>
<th>Observation date and time</th>
<th>Filter</th>
<th>Exposure time (secs)</th>
<th>Seeing (arcsec)</th>
<th>Airmass</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004-12-31 03:15:43</td>
<td>g'</td>
<td>180.0</td>
<td>13.9</td>
<td>1.3400</td>
</tr>
<tr>
<td>2004-12-31 03:18:59</td>
<td>g'</td>
<td>180.0</td>
<td>14.4</td>
<td>1.3300</td>
</tr>
<tr>
<td>2004-12-31 03:22:17</td>
<td>g'</td>
<td>180.0</td>
<td>14.1</td>
<td>1.3300</td>
</tr>
<tr>
<td>2005-01-02 22:55:50</td>
<td>r'</td>
<td>180.0</td>
<td>149.3</td>
<td>1.9800</td>
</tr>
<tr>
<td>2005-01-02 22:59:07</td>
<td>r'</td>
<td>180.0</td>
<td>13.7</td>
<td>1.9700</td>
</tr>
<tr>
<td>2005-01-02 23:02:24</td>
<td>r'</td>
<td>180.0</td>
<td>15.6</td>
<td>1.9500</td>
</tr>
<tr>
<td>2005-01-02 23:10:51</td>
<td>Hα</td>
<td>200.0</td>
<td>2.8</td>
<td>1.9100</td>
</tr>
<tr>
<td>2005-01-02 23:14:28</td>
<td>Hα</td>
<td>200.0</td>
<td>4.4</td>
<td>1.8900</td>
</tr>
<tr>
<td>2005-01-02 23:18:04</td>
<td>Hα</td>
<td>200.0</td>
<td>6.7</td>
<td>1.8700</td>
</tr>
<tr>
<td>2005-01-02 23:21:41</td>
<td>Hα</td>
<td>200.0</td>
<td>4.8</td>
<td>1.8600</td>
</tr>
<tr>
<td>2005-01-02 23:25:17</td>
<td>Hα</td>
<td>200.0</td>
<td>3.0</td>
<td>1.8400</td>
</tr>
<tr>
<td>2005-01-02 23:28:54</td>
<td>Hα</td>
<td>200.0</td>
<td>3.9</td>
<td>1.8300</td>
</tr>
<tr>
<td>2005-01-02 23:33:19</td>
<td>g'</td>
<td>180.0</td>
<td>12.9</td>
<td>1.8100</td>
</tr>
<tr>
<td>2005-01-02 23:36:36</td>
<td>g'</td>
<td>180.0</td>
<td>2.7</td>
<td>1.7900</td>
</tr>
<tr>
<td>2005-01-02 23:39:53</td>
<td>g'</td>
<td>180.0</td>
<td>16.9</td>
<td>1.7800</td>
</tr>
<tr>
<td>2005-01-02 23:43:10</td>
<td>g'</td>
<td>180.0</td>
<td>12.4</td>
<td>1.7700</td>
</tr>
<tr>
<td>2005-01-03 22:52:38</td>
<td>r'</td>
<td>180.0</td>
<td>10.8</td>
<td>1.9800</td>
</tr>
<tr>
<td>2005-01-03 22:55:55</td>
<td>r'</td>
<td>180.0</td>
<td>12.3</td>
<td>1.9600</td>
</tr>
<tr>
<td>2005-01-03 22:59:12</td>
<td>r'</td>
<td>180.0</td>
<td>11.5</td>
<td>1.9500</td>
</tr>
<tr>
<td>2005-01-03 23:02:30</td>
<td>r'</td>
<td>180.0</td>
<td>11.2</td>
<td>1.9300</td>
</tr>
<tr>
<td>2005-01-07 23:17:37</td>
<td>r'</td>
<td>180.0</td>
<td>9.8</td>
<td>1.7900</td>
</tr>
<tr>
<td>2005-01-07 23:20:54</td>
<td>r'</td>
<td>180.0</td>
<td>11.1</td>
<td>1.7800</td>
</tr>
<tr>
<td>2005-01-07 23:24:10</td>
<td>r'</td>
<td>180.0</td>
<td>10.4</td>
<td>1.7600</td>
</tr>
<tr>
<td>2005-01-08 22:35:17</td>
<td>Hα</td>
<td>200.0</td>
<td>5.1</td>
<td>1.9700</td>
</tr>
<tr>
<td>2005-01-08 22:38:54</td>
<td>Hα</td>
<td>200.0</td>
<td>2.4</td>
<td>1.9500</td>
</tr>
<tr>
<td>2005-01-08 22:42:30</td>
<td>Hα</td>
<td>200.0</td>
<td>2.4</td>
<td>1.9300</td>
</tr>
<tr>
<td>2005-01-08 22:46:07</td>
<td>Hα</td>
<td>200.0</td>
<td>3.9</td>
<td>1.9100</td>
</tr>
</tbody>
</table>

Continued on next page
<table>
<thead>
<tr>
<th>Observation date and time</th>
<th>Filter</th>
<th>Exposure time (secs)</th>
<th>Seeing (arcsec)</th>
<th>Airmass</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005-01-08 22:49:44</td>
<td>Hα</td>
<td>200.0</td>
<td>3.0</td>
<td>1.9000</td>
</tr>
<tr>
<td>2005-01-08 22:53:20</td>
<td>Hα</td>
<td>200.0</td>
<td>4.9</td>
<td>1.8800</td>
</tr>
<tr>
<td>2005-01-08 22:57:52</td>
<td>g′</td>
<td>180.0</td>
<td>15.4</td>
<td>1.8600</td>
</tr>
<tr>
<td>2005-01-08 23:01:09</td>
<td>g′</td>
<td>180.0</td>
<td>6.2</td>
<td>1.8400</td>
</tr>
<tr>
<td>2005-01-10 23:18:36</td>
<td>r′</td>
<td>180.0</td>
<td>12.1</td>
<td>1.7400</td>
</tr>
<tr>
<td>2005-01-10 23:27:13</td>
<td>Hα</td>
<td>200.0</td>
<td>2.7</td>
<td>1.7100</td>
</tr>
<tr>
<td>2005-01-10 23:30:50</td>
<td>Hα</td>
<td>200.0</td>
<td>11.3</td>
<td>1.7000</td>
</tr>
<tr>
<td>2005-01-10 23:34:26</td>
<td>Hα</td>
<td>200.0</td>
<td>3.2</td>
<td>1.6800</td>
</tr>
<tr>
<td>2005-01-10 23:38:03</td>
<td>Hα</td>
<td>200.0</td>
<td>10.4</td>
<td>1.6700</td>
</tr>
<tr>
<td>2005-01-10 23:52:38</td>
<td>g′</td>
<td>180.0</td>
<td>3.5</td>
<td>1.6200</td>
</tr>
<tr>
<td>2005-01-12 22:49:56</td>
<td>r′</td>
<td>180.0</td>
<td>15.4</td>
<td>1.8200</td>
</tr>
<tr>
<td>2005-01-12 22:53:13</td>
<td>r′</td>
<td>180.0</td>
<td>16.5</td>
<td>1.8100</td>
</tr>
<tr>
<td>2005-01-12 22:56:30</td>
<td>r′</td>
<td>180.0</td>
<td>15.4</td>
<td>1.8000</td>
</tr>
<tr>
<td>2005-01-12 22:59:46</td>
<td>r′</td>
<td>180.0</td>
<td>15.7</td>
<td>1.7800</td>
</tr>
<tr>
<td>2005-01-14 22:22:01</td>
<td>r′</td>
<td>180.0</td>
<td>11.7</td>
<td>1.9200</td>
</tr>
<tr>
<td>2005-01-14 22:25:19</td>
<td>r′</td>
<td>180.0</td>
<td>12.0</td>
<td>1.9000</td>
</tr>
<tr>
<td>2005-01-14 22:28:35</td>
<td>r′</td>
<td>180.0</td>
<td>11.0</td>
<td>1.8900</td>
</tr>
<tr>
<td>2005-01-14 22:31:51</td>
<td>r′</td>
<td>180.0</td>
<td>10.9</td>
<td>1.8700</td>
</tr>
<tr>
<td>2005-01-21 22:03:02</td>
<td>r′</td>
<td>180.0</td>
<td>10.4</td>
<td>1.8800</td>
</tr>
<tr>
<td>2005-01-21 22:06:20</td>
<td>r′</td>
<td>180.0</td>
<td>6.6</td>
<td>1.8600</td>
</tr>
<tr>
<td>2005-01-21 22:09:36</td>
<td>r′</td>
<td>180.0</td>
<td>10.1</td>
<td>1.8500</td>
</tr>
<tr>
<td>2005-01-21 22:12:52</td>
<td>r′</td>
<td>180.0</td>
<td>10.5</td>
<td>1.8300</td>
</tr>
<tr>
<td>2005-01-21 22:18:02</td>
<td>Hα</td>
<td>200.0</td>
<td>4.6</td>
<td>1.8100</td>
</tr>
<tr>
<td>2005-01-21 22:21:38</td>
<td>Hα</td>
<td>200.0</td>
<td>22.2</td>
<td>1.7900</td>
</tr>
<tr>
<td>2005-01-21 22:25:15</td>
<td>Hα</td>
<td>200.0</td>
<td>2.0</td>
<td>1.7800</td>
</tr>
<tr>
<td>2005-01-21 22:28:52</td>
<td>Hα</td>
<td>200.0</td>
<td>29.6</td>
<td>1.7700</td>
</tr>
<tr>
<td>2005-01-21 22:32:29</td>
<td>Hα</td>
<td>200.0</td>
<td>17.4</td>
<td>1.7500</td>
</tr>
</tbody>
</table>

Continued on next page
<table>
<thead>
<tr>
<th>Observation date and time</th>
<th>Filter</th>
<th>Exposure time (secs)</th>
<th>Seeing (arcsec)</th>
<th>Airmass</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005-01-21 22:36:05</td>
<td>Hα</td>
<td>200.0</td>
<td>2.0</td>
<td>1.7400</td>
</tr>
<tr>
<td>2005-01-21 22:40:29</td>
<td>g'</td>
<td>180.0</td>
<td>2.0</td>
<td>1.7200</td>
</tr>
<tr>
<td>2005-01-21 22:43:46</td>
<td>g'</td>
<td>180.0</td>
<td>15.5</td>
<td>1.7100</td>
</tr>
<tr>
<td>2005-01-21 22:47:03</td>
<td>g'</td>
<td>180.0</td>
<td>13.5</td>
<td>1.7000</td>
</tr>
<tr>
<td>2005-01-21 22:50:20</td>
<td>g'</td>
<td>180.0</td>
<td>19.1</td>
<td>1.6900</td>
</tr>
<tr>
<td>2005-01-22 21:59:36</td>
<td>Hα</td>
<td>200.0</td>
<td>9.6</td>
<td>1.8700</td>
</tr>
<tr>
<td>2005-01-22 22:03:13</td>
<td>Hα</td>
<td>200.0</td>
<td>5.5</td>
<td>1.8600</td>
</tr>
<tr>
<td>2005-01-22 22:06:50</td>
<td>Hα</td>
<td>200.0</td>
<td>5.0</td>
<td>1.8400</td>
</tr>
<tr>
<td>2005-01-22 22:10:26</td>
<td>Hα</td>
<td>200.0</td>
<td>5.1</td>
<td>1.8300</td>
</tr>
<tr>
<td>2005-01-22 22:14:03</td>
<td>Hα</td>
<td>200.0</td>
<td>9.9</td>
<td>1.8100</td>
</tr>
<tr>
<td>2005-01-22 22:17:40</td>
<td>Hα</td>
<td>200.0</td>
<td>9.2</td>
<td>1.7900</td>
</tr>
<tr>
<td>2005-01-22 22:22:15</td>
<td>g'</td>
<td>180.0</td>
<td>14.9</td>
<td>1.7800</td>
</tr>
<tr>
<td>2005-01-22 22:25:31</td>
<td>g'</td>
<td>180.0</td>
<td>14.3</td>
<td>1.7600</td>
</tr>
<tr>
<td>2005-01-22 22:28:48</td>
<td>g'</td>
<td>180.0</td>
<td>12.5</td>
<td>1.7500</td>
</tr>
<tr>
<td>2005-01-22 22:32:05</td>
<td>g'</td>
<td>180.0</td>
<td>13.2</td>
<td>1.7400</td>
</tr>
<tr>
<td>2005-01-23 22:18:09</td>
<td>r'</td>
<td>180.0</td>
<td>37.4</td>
<td>1.7800</td>
</tr>
<tr>
<td>2005-01-23 22:21:26</td>
<td>r'</td>
<td>180.0</td>
<td>27.0</td>
<td>1.7600</td>
</tr>
<tr>
<td>2005-01-23 22:24:42</td>
<td>r'</td>
<td>180.0</td>
<td>8.7</td>
<td>1.7500</td>
</tr>
<tr>
<td>2005-01-23 22:27:58</td>
<td>r'</td>
<td>180.0</td>
<td>7.3</td>
<td>1.7400</td>
</tr>
</tbody>
</table>

Table C.1: M81 LT observation schedule to date.

<table>
<thead>
<tr>
<th>Observation date and time</th>
<th>Filter</th>
<th>Exposure time (secs)</th>
<th>Seeing (arcsec)</th>
<th>Airmass</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004-10-07 02:54:55</td>
<td>r'</td>
<td>180.0</td>
<td>11.9</td>
<td>1.8200</td>
</tr>
<tr>
<td>2004-10-07 02:58:12</td>
<td>r'</td>
<td>180.0</td>
<td>11.8</td>
<td>1.8100</td>
</tr>
<tr>
<td>2004-10-07 03:01:30</td>
<td>r'</td>
<td>180.0</td>
<td>11.9</td>
<td>1.7900</td>
</tr>
<tr>
<td>2004-10-07 03:04:47</td>
<td>r'</td>
<td>180.0</td>
<td>13.0</td>
<td>1.7700</td>
</tr>
</tbody>
</table>

Continued on next page
<table>
<thead>
<tr>
<th>Observation date and time</th>
<th>Filter</th>
<th>Exposure time (secs)</th>
<th>Seeing (arcsec)</th>
<th>Airmass</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004-10-07 03:10:13</td>
<td>Hα-50</td>
<td>200.0</td>
<td>6.1</td>
<td>1.7500</td>
</tr>
<tr>
<td>2004-10-07 03:13:41</td>
<td>Hα-50</td>
<td>200.0</td>
<td>9.0</td>
<td>1.7300</td>
</tr>
<tr>
<td>2004-10-07 03:17:10</td>
<td>Hα-50</td>
<td>200.0</td>
<td>4.6</td>
<td>1.7200</td>
</tr>
<tr>
<td>2004-10-07 03:20:39</td>
<td>Hα-50</td>
<td>200.0</td>
<td>5.7</td>
<td>1.7000</td>
</tr>
<tr>
<td>2004-10-07 03:24:07</td>
<td>Hα-50</td>
<td>200.0</td>
<td>7.6</td>
<td>1.6900</td>
</tr>
<tr>
<td>2004-10-07 03:27:36</td>
<td>Hα-50</td>
<td>200.0</td>
<td>7.5</td>
<td>1.6800</td>
</tr>
<tr>
<td>2004-10-07 03:31:56</td>
<td>g'</td>
<td>180.0</td>
<td>11.7</td>
<td>1.6600</td>
</tr>
<tr>
<td>2004-10-07 03:35:15</td>
<td>g'</td>
<td>180.0</td>
<td>16.0</td>
<td>1.6500</td>
</tr>
<tr>
<td>2004-10-07 03:38:34</td>
<td>g'</td>
<td>180.0</td>
<td>15.1</td>
<td>1.6300</td>
</tr>
<tr>
<td>2004-10-07 03:41:51</td>
<td>g'</td>
<td>180.0</td>
<td>15.8</td>
<td>1.6200</td>
</tr>
<tr>
<td>2004-10-23 04:10:48</td>
<td>r'</td>
<td>180.0</td>
<td>16.5</td>
<td>1.3800</td>
</tr>
<tr>
<td>2004-10-23 04:14:06</td>
<td>r'</td>
<td>180.0</td>
<td>14.3</td>
<td>1.3700</td>
</tr>
<tr>
<td>2004-10-23 04:17:23</td>
<td>r'</td>
<td>180.0</td>
<td>16.7</td>
<td>1.3700</td>
</tr>
<tr>
<td>2004-10-23 04:20:40</td>
<td>r'</td>
<td>180.0</td>
<td>13.9</td>
<td>1.3600</td>
</tr>
<tr>
<td>2004-10-23 04:53:15</td>
<td>Hα-50</td>
<td>200.0</td>
<td>9.1</td>
<td>1.3100</td>
</tr>
<tr>
<td>2004-10-23 04:56:43</td>
<td>Hα-50</td>
<td>200.0</td>
<td>11.8</td>
<td>1.3100</td>
</tr>
<tr>
<td>2004-10-23 05:00:11</td>
<td>Hα-50</td>
<td>200.0</td>
<td>9.8</td>
<td>1.3000</td>
</tr>
<tr>
<td>2004-10-23 05:03:39</td>
<td>Hα-50</td>
<td>200.0</td>
<td>12.7</td>
<td>1.3000</td>
</tr>
<tr>
<td>2004-10-23 05:07:08</td>
<td>Hα-50</td>
<td>200.0</td>
<td>9.5</td>
<td>1.3000</td>
</tr>
<tr>
<td>2004-10-23 05:10:36</td>
<td>Hα-50</td>
<td>200.0</td>
<td>9.2</td>
<td>1.2900</td>
</tr>
<tr>
<td>2004-10-23 05:14:42</td>
<td>g'</td>
<td>180.0</td>
<td>17.5</td>
<td>1.2900</td>
</tr>
<tr>
<td>2004-10-23 05:17:59</td>
<td>g'</td>
<td>180.0</td>
<td>19.7</td>
<td>1.2900</td>
</tr>
<tr>
<td>2004-10-23 05:21:16</td>
<td>g'</td>
<td>180.0</td>
<td>19.8</td>
<td>1.2800</td>
</tr>
<tr>
<td>2004-10-23 05:24:33</td>
<td>g'</td>
<td>180.0</td>
<td>16.7</td>
<td>1.2800</td>
</tr>
<tr>
<td>2004-10-25 02:47:21</td>
<td>r'</td>
<td>180.0</td>
<td>13.6</td>
<td>1.5700</td>
</tr>
<tr>
<td>2004-10-25 02:50:37</td>
<td>r'</td>
<td>180.0</td>
<td>13.4</td>
<td>1.5600</td>
</tr>
<tr>
<td>2004-10-27 02:16:35</td>
<td>r'</td>
<td>180.0</td>
<td>12.0</td>
<td>1.6500</td>
</tr>
</tbody>
</table>

Continued on next page
<table>
<thead>
<tr>
<th>Observation date and time</th>
<th>Filter</th>
<th>Exposure time (secs)</th>
<th>Seeing (arcsec)</th>
<th>Airmass</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004-10-27 02:19:57</td>
<td>r'</td>
<td>180.0</td>
<td>9.1</td>
<td>1.6300</td>
</tr>
<tr>
<td>2004-10-27 02:26:42</td>
<td>r'</td>
<td>180.0</td>
<td>10.4</td>
<td>1.6100</td>
</tr>
<tr>
<td>2004-12-02 01:45:34</td>
<td>r'</td>
<td>180.0</td>
<td>9.9</td>
<td>1.3600</td>
</tr>
<tr>
<td>2004-12-02 01:48:52</td>
<td>r'</td>
<td>180.0</td>
<td>10.0</td>
<td>1.3500</td>
</tr>
<tr>
<td>2004-12-02 01:52:09</td>
<td>r'</td>
<td>180.0</td>
<td>8.5</td>
<td>1.3500</td>
</tr>
<tr>
<td>2004-12-02 01:55:26</td>
<td>r'</td>
<td>180.0</td>
<td>11.0</td>
<td>1.3400</td>
</tr>
<tr>
<td>2004-12-08 22:18:12</td>
<td>r'</td>
<td>180.0</td>
<td>9.2</td>
<td>1.9800</td>
</tr>
<tr>
<td>2004-12-08 22:21:28</td>
<td>r'</td>
<td>180.0</td>
<td>12.3</td>
<td>1.9600</td>
</tr>
<tr>
<td>2004-12-08 22:24:44</td>
<td>r'</td>
<td>180.0</td>
<td>9.0</td>
<td>1.9400</td>
</tr>
<tr>
<td>2004-12-08 22:28:01</td>
<td>r'</td>
<td>180.0</td>
<td>12.9</td>
<td>1.9200</td>
</tr>
<tr>
<td>2004-12-18 22:10:13</td>
<td>r'</td>
<td>180.0</td>
<td>22.6</td>
<td>1.8100</td>
</tr>
<tr>
<td>2004-12-18 22:13:30</td>
<td>r'</td>
<td>180.0</td>
<td>23.6</td>
<td>1.7900</td>
</tr>
<tr>
<td>2004-12-18 22:16:47</td>
<td>r'</td>
<td>180.0</td>
<td>19.4</td>
<td>1.7800</td>
</tr>
<tr>
<td>2004-12-18 22:20:04</td>
<td>r'</td>
<td>180.0</td>
<td>17.1</td>
<td>1.7600</td>
</tr>
<tr>
<td>2004-12-18 22:25:14</td>
<td>Hα</td>
<td>200.0</td>
<td>20.0</td>
<td>1.7400</td>
</tr>
<tr>
<td>2004-12-18 22:28:51</td>
<td>Hα</td>
<td>200.0</td>
<td>20.0</td>
<td>1.7200</td>
</tr>
<tr>
<td>2004-12-18 22:32:28</td>
<td>Hα</td>
<td>200.0</td>
<td>21.3</td>
<td>1.7100</td>
</tr>
<tr>
<td>2004-12-18 22:36:05</td>
<td>Hα</td>
<td>200.0</td>
<td>19.5</td>
<td>1.6900</td>
</tr>
<tr>
<td>2004-12-18 22:39:42</td>
<td>Hα</td>
<td>200.0</td>
<td>17.6</td>
<td>1.6800</td>
</tr>
<tr>
<td>2004-12-18 22:43:18</td>
<td>Hα</td>
<td>200.0</td>
<td>16.6</td>
<td>1.6700</td>
</tr>
<tr>
<td>2004-12-18 22:47:44</td>
<td>g'</td>
<td>180.0</td>
<td>21.7</td>
<td>1.6500</td>
</tr>
<tr>
<td>2004-12-18 22:51:01</td>
<td>g'</td>
<td>180.0</td>
<td>21.8</td>
<td>1.6400</td>
</tr>
<tr>
<td>2004-12-18 22:54:18</td>
<td>g'</td>
<td>180.0</td>
<td>20.9</td>
<td>1.6200</td>
</tr>
<tr>
<td>2004-12-18 22:57:35</td>
<td>g'</td>
<td>180.0</td>
<td>22.9</td>
<td>1.6100</td>
</tr>
<tr>
<td>2004-12-20 22:01:09</td>
<td>r'</td>
<td>180.0</td>
<td>21.7</td>
<td>1.8200</td>
</tr>
<tr>
<td>2004-12-20 22:04:25</td>
<td>r'</td>
<td>180.0</td>
<td>20.4</td>
<td>1.8000</td>
</tr>
<tr>
<td>2004-12-20 22:07:42</td>
<td>r'</td>
<td>180.0</td>
<td>20.1</td>
<td>1.7800</td>
</tr>
</tbody>
</table>

Continued on next page
<table>
<thead>
<tr>
<th>Observation date and time</th>
<th>Filter</th>
<th>Exposure time (secs)</th>
<th>Seeing (arcsec)</th>
<th>Airmass</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004-12-20 22:10:59</td>
<td>$r'$</td>
<td>180.0</td>
<td>22.1</td>
<td>1.7700</td>
</tr>
<tr>
<td>2004-12-30 21:06:19</td>
<td>Hα</td>
<td>200.0</td>
<td>15.3</td>
<td>1.9000</td>
</tr>
<tr>
<td>2004-12-30 21:09:56</td>
<td>Hα</td>
<td>200.0</td>
<td>18.1</td>
<td>1.8800</td>
</tr>
<tr>
<td>2004-12-30 21:13:34</td>
<td>Hα</td>
<td>200.0</td>
<td>16.9</td>
<td>1.8600</td>
</tr>
<tr>
<td>2004-12-30 21:17:10</td>
<td>Hα</td>
<td>200.0</td>
<td>14.7</td>
<td>1.8400</td>
</tr>
<tr>
<td>2004-12-30 21:20:47</td>
<td>Hα</td>
<td>200.0</td>
<td>13.2</td>
<td>1.8200</td>
</tr>
<tr>
<td>2004-12-30 21:24:23</td>
<td>Hα</td>
<td>200.0</td>
<td>18.3</td>
<td>1.8000</td>
</tr>
<tr>
<td>2004-12-30 21:28:48</td>
<td>$g'$</td>
<td>180.0</td>
<td>18.7</td>
<td>1.7800</td>
</tr>
<tr>
<td>2004-12-30 21:32:04</td>
<td>$g'$</td>
<td>180.0</td>
<td>19.3</td>
<td>1.7700</td>
</tr>
<tr>
<td>2004-12-30 21:35:21</td>
<td>$g'$</td>
<td>180.0</td>
<td>18.6</td>
<td>1.7500</td>
</tr>
<tr>
<td>2004-12-30 21:38:38</td>
<td>$g'$</td>
<td>180.0</td>
<td>20.7</td>
<td>1.7400</td>
</tr>
<tr>
<td>2005-01-02 20:41:51</td>
<td>$r'$</td>
<td>180.0</td>
<td>20.5</td>
<td>1.9700</td>
</tr>
<tr>
<td>2005-01-02 20:51:40</td>
<td>$r'$</td>
<td>180.0</td>
<td>23.1</td>
<td>1.9100</td>
</tr>
<tr>
<td>2005-01-02 20:56:52</td>
<td>Hα</td>
<td>200.0</td>
<td>23.0</td>
<td>1.8800</td>
</tr>
<tr>
<td>2005-01-02 21:00:29</td>
<td>Hα</td>
<td>200.0</td>
<td>22.0</td>
<td>1.8700</td>
</tr>
<tr>
<td>2005-01-02 21:04:05</td>
<td>Hα</td>
<td>200.0</td>
<td>18.3</td>
<td>1.8500</td>
</tr>
<tr>
<td>2005-01-02 21:07:41</td>
<td>Hα</td>
<td>200.0</td>
<td>16.2</td>
<td>1.8300</td>
</tr>
<tr>
<td>2005-01-02 21:11:18</td>
<td>Hα</td>
<td>200.0</td>
<td>18.7</td>
<td>1.8100</td>
</tr>
<tr>
<td>2005-01-02 21:14:55</td>
<td>Hα</td>
<td>200.0</td>
<td>19.9</td>
<td>1.7900</td>
</tr>
<tr>
<td>2005-01-02 21:19:19</td>
<td>$g'$</td>
<td>180.0</td>
<td>23.1</td>
<td>1.7700</td>
</tr>
<tr>
<td>2005-01-02 21:22:35</td>
<td>$g'$</td>
<td>180.0</td>
<td>23.1</td>
<td>1.7600</td>
</tr>
<tr>
<td>2005-01-02 21:25:52</td>
<td>$g'$</td>
<td>180.0</td>
<td>19.1</td>
<td>1.7400</td>
</tr>
<tr>
<td>2005-01-02 21:29:08</td>
<td>$g'$</td>
<td>180.0</td>
<td>26.6</td>
<td>1.7300</td>
</tr>
<tr>
<td>2005-01-03 21:05:57</td>
<td>$r'$</td>
<td>180.0</td>
<td>10.8</td>
<td>1.8200</td>
</tr>
<tr>
<td>2005-01-03 21:09:13</td>
<td>$r'$</td>
<td>180.0</td>
<td>9.6</td>
<td>1.8000</td>
</tr>
<tr>
<td>2005-01-03 21:12:30</td>
<td>$r'$</td>
<td>180.0</td>
<td>9.4</td>
<td>1.7900</td>
</tr>
<tr>
<td>2005-01-03 21:15:46</td>
<td>$r'$</td>
<td>180.0</td>
<td>12.3</td>
<td>1.7700</td>
</tr>
</tbody>
</table>

Continued on next page
<table>
<thead>
<tr>
<th>Observation date and time</th>
<th>Filter</th>
<th>Exposure time (secs)</th>
<th>Seeing (arcsec)</th>
<th>Airmass</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005-01-12 21:36:50</td>
<td>g′</td>
<td>180.0</td>
<td>14.2</td>
<td>1.5500</td>
</tr>
<tr>
<td>2005-01-12 21:40:07</td>
<td>g′</td>
<td>180.0</td>
<td>17.8</td>
<td>1.5400</td>
</tr>
<tr>
<td>2005-01-12 21:43:23</td>
<td>g′</td>
<td>180.0</td>
<td>13.5</td>
<td>1.5300</td>
</tr>
<tr>
<td>2005-01-12 21:46:39</td>
<td>g′</td>
<td>180.0</td>
<td>13.3</td>
<td>1.5200</td>
</tr>
<tr>
<td>2005-01-12 20:29:03</td>
<td>r′</td>
<td>180.0</td>
<td>13.7</td>
<td>1.8200</td>
</tr>
<tr>
<td>2005-01-12 20:32:21</td>
<td>r′</td>
<td>180.0</td>
<td>16.0</td>
<td>1.8100</td>
</tr>
<tr>
<td>2005-01-13 01:44:21</td>
<td>r′</td>
<td>180.0</td>
<td>12.4</td>
<td>1.2500</td>
</tr>
<tr>
<td>2005-01-13 01:47:38</td>
<td>r′</td>
<td>180.0</td>
<td>12.8</td>
<td>1.2500</td>
</tr>
<tr>
<td>2005-01-13 01:50:55</td>
<td>r′</td>
<td>180.0</td>
<td>11.8</td>
<td>1.2500</td>
</tr>
<tr>
<td>2005-01-13 01:54:12</td>
<td>r′</td>
<td>180.0</td>
<td>9.9</td>
<td>1.2600</td>
</tr>
<tr>
<td>2005-01-12 20:59:26</td>
<td>r′</td>
<td>180.0</td>
<td>18.7</td>
<td>1.6900</td>
</tr>
<tr>
<td>2005-01-12 21:02:43</td>
<td>r′</td>
<td>180.0</td>
<td>18.8</td>
<td>1.6700</td>
</tr>
<tr>
<td>2005-01-12 21:06:00</td>
<td>r′</td>
<td>180.0</td>
<td>19.0</td>
<td>1.6600</td>
</tr>
<tr>
<td>2005-01-12 21:09:16</td>
<td>r′</td>
<td>180.0</td>
<td>20.6</td>
<td>1.6500</td>
</tr>
<tr>
<td>2005-01-12 21:14:22</td>
<td>Hα</td>
<td>200.0</td>
<td>23.9</td>
<td>1.6300</td>
</tr>
<tr>
<td>2005-01-12 21:17:59</td>
<td>Hα</td>
<td>200.0</td>
<td>21.3</td>
<td>1.6200</td>
</tr>
<tr>
<td>2005-01-12 21:21:35</td>
<td>Hα</td>
<td>200.0</td>
<td>22.9</td>
<td>1.6000</td>
</tr>
<tr>
<td>2005-01-12 21:25:12</td>
<td>Hα</td>
<td>200.0</td>
<td>22.8</td>
<td>1.5900</td>
</tr>
<tr>
<td>2005-01-12 21:28:48</td>
<td>Hα</td>
<td>200.0</td>
<td>19.4</td>
<td>1.5800</td>
</tr>
<tr>
<td>2005-01-12 21:32:25</td>
<td>Hα</td>
<td>200.0</td>
<td>14.9</td>
<td>1.5700</td>
</tr>
<tr>
<td>2005-01-14 20:20:23</td>
<td>Hα</td>
<td>200.0</td>
<td>14.4</td>
<td>1.8300</td>
</tr>
<tr>
<td>2005-01-14 20:27:37</td>
<td>Hα</td>
<td>200.0</td>
<td>10.0</td>
<td>1.7900</td>
</tr>
<tr>
<td>2005-01-14 20:31:14</td>
<td>Hα</td>
<td>200.0</td>
<td>16.2</td>
<td>1.7800</td>
</tr>
<tr>
<td>2005-01-14 20:34:51</td>
<td>Hα</td>
<td>200.0</td>
<td>8.5</td>
<td>1.7600</td>
</tr>
<tr>
<td>2005-01-14 20:42:57</td>
<td>g′</td>
<td>180.0</td>
<td>12.3</td>
<td>1.7200</td>
</tr>
<tr>
<td>2005-01-15 02:42:49</td>
<td>r′</td>
<td>180.0</td>
<td>14.7</td>
<td>1.3000</td>
</tr>
<tr>
<td>2005-01-15 02:46:06</td>
<td>r′</td>
<td>180.0</td>
<td>9.1</td>
<td>1.3000</td>
</tr>
</tbody>
</table>

Continued on next page
<table>
<thead>
<tr>
<th>Observation date and time</th>
<th>Filter</th>
<th>Exposure time (secs)</th>
<th>Seeing (arcsec)</th>
<th>Airmass</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005-01-15 02:49:23</td>
<td>$r'$</td>
<td>180.0</td>
<td>11.1</td>
<td>1.300</td>
</tr>
<tr>
<td>2005-01-15 02:52:40</td>
<td>$r'$</td>
<td>180.0</td>
<td>9.4</td>
<td>1.3100</td>
</tr>
<tr>
<td>2005-01-21 19:51:49</td>
<td>$r'$</td>
<td>180.0</td>
<td>8.4</td>
<td>1.8300</td>
</tr>
<tr>
<td>2005-01-21 19:55:06</td>
<td>$r'$</td>
<td>180.0</td>
<td>14.0</td>
<td>1.8200</td>
</tr>
<tr>
<td>2005-01-21 19:58:22</td>
<td>$r'$</td>
<td>180.0</td>
<td>1.9</td>
<td>1.8000</td>
</tr>
<tr>
<td>2005-01-21 20:01:39</td>
<td>$r'$</td>
<td>180.0</td>
<td>10.2</td>
<td>1.7900</td>
</tr>
<tr>
<td>2005-01-21 20:06:47</td>
<td>$H\alpha$</td>
<td>200.0</td>
<td>11.7</td>
<td>1.7600</td>
</tr>
<tr>
<td>2005-01-21 20:10:24</td>
<td>$H\alpha$</td>
<td>200.0</td>
<td>6.6</td>
<td>1.7500</td>
</tr>
<tr>
<td>2005-01-21 20:14:00</td>
<td>$H\alpha$</td>
<td>200.0</td>
<td>8.0</td>
<td>1.7300</td>
</tr>
<tr>
<td>2005-01-21 20:17:37</td>
<td>$H\alpha$</td>
<td>200.0</td>
<td>2.0</td>
<td>1.7100</td>
</tr>
<tr>
<td>2005-01-21 20:21:13</td>
<td>$H\alpha$</td>
<td>200.0</td>
<td>10.4</td>
<td>1.7000</td>
</tr>
<tr>
<td>2005-01-21 20:24:50</td>
<td>$H\alpha$</td>
<td>200.0</td>
<td>3.3</td>
<td>1.6800</td>
</tr>
<tr>
<td>2005-01-21 20:29:12</td>
<td>$g'$</td>
<td>180.0</td>
<td>14.3</td>
<td>1.6700</td>
</tr>
<tr>
<td>2005-01-21 20:32:29</td>
<td>$g'$</td>
<td>180.0</td>
<td>14.7</td>
<td>1.6500</td>
</tr>
<tr>
<td>2005-01-21 20:35:46</td>
<td>$g'$</td>
<td>180.0</td>
<td>13.8</td>
<td>1.6400</td>
</tr>
<tr>
<td>2005-01-21 20:39:02</td>
<td>$g'$</td>
<td>180.0</td>
<td>14.4</td>
<td>1.6300</td>
</tr>
<tr>
<td>2005-01-23 01:45:19</td>
<td>$r'$</td>
<td>180.0</td>
<td>10.5</td>
<td>1.2700</td>
</tr>
<tr>
<td>2005-01-23 01:48:36</td>
<td>$r'$</td>
<td>180.0</td>
<td>10.2</td>
<td>1.2700</td>
</tr>
<tr>
<td>2005-01-23 01:51:54</td>
<td>$r'$</td>
<td>180.0</td>
<td>9.9</td>
<td>1.2800</td>
</tr>
<tr>
<td>2005-01-23 01:55:10</td>
<td>$r'$</td>
<td>180.0</td>
<td>8.1</td>
<td>1.2800</td>
</tr>
<tr>
<td>2005-01-25 02:33:30</td>
<td>$r'$</td>
<td>180.0</td>
<td>10.4</td>
<td>1.3300</td>
</tr>
<tr>
<td>2005-01-25 02:36:47</td>
<td>$r'$</td>
<td>180.0</td>
<td>13.2</td>
<td>1.3400</td>
</tr>
<tr>
<td>2005-01-25 02:40:04</td>
<td>$r'$</td>
<td>180.0</td>
<td>13.6</td>
<td>1.3400</td>
</tr>
<tr>
<td>2005-01-25 02:43:21</td>
<td>$r'$</td>
<td>180.0</td>
<td>9.6</td>
<td>1.3500</td>
</tr>
</tbody>
</table>

Table C.2: NGC 2403 LT observation schedule to date.
Appendix D

Journal Papers