Accrete, accrete, accrete… Bang! (and repeat):
The Remarkable Recurrent Novae

Matt Darnley
Liverpool John Moores University

With thanks to: Mike Bode (LJMU), Rebekah Hounsell (UCSC) Tim O’Brien (Manchester),
Valério Ribeiro (Radboud), Allen Shafter (SDSU), Steve Williams (Lancaster),
and Martin Henze (CSIC-IEEC)
Novae: “Vital Statistics”

- **Primary: White Dwarf**
  - 0.5 – ~1.4 Solar Masses (Chandrasekhar mass)
  - CO or ONe(Mg)
  - Plus He and H layers

- **Secondary: ‘Late Type’ MS star**
  - Typically Solar-ish composition
  - Orbital period 1.5 – 8 hrs – Roche lobe filling

- **Mass Accretion:**
  - Solar material – Hydrogen rich
  - Accretion rate: $10^{-9}$ Solar masses / year

- **Luminosity:**
  - Quiescence: ~ Solar Luminosity
  - Eruption: ~$10^{4}$ Solar – Eddington luminosity

- **Ejected Mass:**
  - $10^{-5}$ – $10^{-4}$ Solar Masses
  - Composition: depleted H, enhanced He/N
  - Possible Ne enhancement in ONe WD

- **Recurrence Period:**
  - 1,000 – 1,000,000 years
  - 1,000s of eruptions per system

- **Recurrent Novae:**
  - >1 observed eruption
  - Secondary: Evolved
  - Orbital period: >1 day
  - High accretion rate (up to $10^{-7}$ $M_{\text{sun}}$ / yr)
  - High mass WD (>1.2 $M_{\text{sun}}$)
Novae among the transients
Nova mechanism – just big photon convertors
Time Domain Astronomy: Novae: X-ray properties

- The SSS turn-on occurs when the ejecta becomes optically thin

- The less massive the ejecta the sooner the SSS is unveiled

- The SSS turn-off occurs around the time that the nuclear burning ceases

- This timescale depends primarily on the WD mass – the higher the WD mass the lower the ignition mass – the less fuel there is to ‘burn’
## Classical vs Recurrent Novae

### Classical Novae
- Only one observed eruption
- Recurrence timescales few thousand – million years (predicted)
- Secondaries – main sequence stars
- Low mass transfer/accretion rates
- Range of WD masses
- Range of evolution speeds
- Range of ejection velocities
- Mix of Fe II and He/N spectra
- 400 Galactic systems (1000 M31)
- WD mass decreasing

### Recurrent Novae
- >1 observed eruption
- Recurrence timescales 10 – 100 years
- Secondaries – sub-giants (U Sco) or red giants (RS Oph)
- High mass transfer/accretion rates
- High WD Masses
- Rapid eruption evolution
- High ejection velocities
- He/N spectra
- 10 Galactic systems (18 M31, 3 LMC)
- WD mass increasing ➔ SN Ia (?)
Classical Novae

- Only one observed eruption
- Recurrence timescales few thousand – million years (predicted)
- Secondaries – main sequence stars
- Low mass transfer/accretion rates
- Range of WD masses
- Range of evolution speeds
- Range of ejection velocities
- Mix of Fe II and He/N spectra
- 400 Galactic systems (1000 M31)
- WD mass decreasing

Recurrent Novae

- >1 observed eruption
- Recurrence timescales 10 – 100 years
- Secondaries – sub-giants (U Sco) or red giants (RS Oph)
- High mass transfer/accretion rates
- High WD Masses
- Rapid eruption evolution
- High ejection velocities
- He/N spectra
- 10 Galactic systems (18 M31, 3 LMC)
- WD mass increasing → SN Ia (?)
Nova as SN Ia progenitors

- Growing consensus: there are many viable SN Ia progenitor pathways

- *Just* need to grow a CO WD to ~1.4 $M_{\text{sun}}$

- Novae have long been poised as a ‘leading’ single-degenerate pathway

- RNe contain massive WDs and accrete at high rates – the prime candidates

- Novae are the most luminous SN Ia progenitor – we can measure their populations… can we measure their contribution?
Nova Populations

- The Milky Way nova rate has been estimated to be $34 \pm 14$/year
- But we see only a handful
- Our position within the Milky Way prohibits observations of most Galactic nova systems
- To study population statistics, e.g. spatial distribution, speed classes, or spectral types – we need to look to other galaxies
  - SMC and LMC are too small/big
  - The nova rate of M33 is too low
- So we turn to M31...
M31 Novae

- Novae in M31 studied since Hubble
- Nova rate measured at ~30/40 per year
- Many surveys were photographic early/small CCDs focused mainly on the bulge
- Spectroscopically confirmed occasionally – but rare
- Rate calculations often depended on blinking completeness estimates, etc

- *Nightly* $r'/i'$-band INT/WFC 2 pointings covering >50% of the M31 light
- Automated nova detection and classification pipeline – discovered 20 M31 novae

- Nova rate determined to be $65\pm16$ /yr
- Bulge rate: $38\pm13$ /yr
- Disk rate: $27\pm17$ /yr
M31 Nova – Two populations?

- Most novae split into two spectroscopic classes Fe II vs He/N
- Proposed that there are 2 distinct populations: bulge (old?) and disk (young?) [Duerbeck 90]
- Galactically, tendency for fast novae to be nearer to the plane than slow novae [Della Valle 92]
- Darnley+ 2006 determined bulge nova rate (per unit light) 2.5 – 12.5 greater than disk nova rate (mean 5)
The Liverpool Telescope – The World’s Largest *Fully Robotic* Telescope

- One of the first extragalactic (M31) novae to be observed in optical, UV and X-rays, and spectroscopically confirmed
- Initially thought to be recurrent due to positional “coincidence” with 1969-08a
- X-ray observations and optical spectra consistent with recurrent nova
- HST archival data revealed progenitor system – red giant secondary
- First recovery of a nova progenitor beyond the Milky Way

- One of the first extragalactic (M31) novae to be observed in optical, UV and X-rays, and spectroscopically confirmed
- Initially thought to be recurrent due to positional “coincidence” with 1969-08a
- X-ray observations and optical spectra consistent with recurrent nova
- HST archival data revealed progenitor system – red giant secondary
- First recovery of a nova progenitor beyond the Milky Way
Galactic Progenitors – Darnley+ 2012

- The problem with Galactic nova studies is the distance ... the problem with extragalactic studies is the distance(!)
- Can we carry out a statically significant survey of extragalactic progenitors
- Assumption: the colour & magnitude of a quiescent nova can be used to determine secondary type
- Colour-mag position is determined by the secondary – accretion disk shifts emission blue-wards and luminosity upwards
- Blue – MS-novae (CNe); Green – SG-novae; Red – RG-novae
Galactic Progenitors – Darnley+ 2012

- The problem with Galactic nova studies is the distance ... the problem with extragalactic studies is the distance(!)
- Can we carry out a statically significant survey of extragalactic progenitors
- Assumption: the colour & magnitude of a quiescent nova can be used to determine secondary type
- Colour-mag position is determined by the secondary – accretion disk shifts emission blue-wards and luminosity upwards
- Blue – MS-novae (CNe); Green – SG-novae; Red – RG-novae
Extragalactic Progenitors – Darnley+ 2013
Extragalactic Progenitors – Darnley+ 2013
M31 Nova Survey – Shafter & Darnley et al. (2011), Williams & Darnley et al. (2014, 2016)

- Extensive follow-up survey of M31 novae: August 2006 – ?? (Shafter+2011)
- Lead facilities: Liverpool Telescope (phot+spec), HET (spec), HST (archive)
- Photometric, spectroscopic, astrometric follow-up survey of almost 100 novae (3x the spectroscopically confirmed sample)
- As with M31N 2007-12b, utilising the HST archive for quiescent detection
M31 Quiescent Nova Survey – Williams & Darnley et al. (2014)

- In principle all novae with red giant donors visible in M31

- Survey to determine the M31 ‘red giant’ nova population

- Galactically these are the high mass accretion systems... and predominantly known recurrences

- Input catalogue of 38 spectroscopically confirmed novae – with astrometry
M31 Quiescent Nova Survey – Williams & Darnley et al. (2014)
11 of 38 novae found to have red giant donors (29%)  

Chance of coincidence <5%  

Galactic red giant nova population ~3%  

If this sample is representative of M31 population...  

Up to 16% (5 sigma lower limit) of M31 novae may have red giant donors
M31 Quiescent Nova Survey – Williams & Darnley et al. (2016)

- Nine of the eleven novae are consistent with SED of red giant donor
- Two are consistent with a luminous accretion disk – high mass accretion rate
- Undertook a large Monte Carlo simulation of the survey to estimate completeness
- Biases including spatial distribution, observability, astrometry, chance alignments, detection efficiency, spectroscopy, HST availability, all (painstakingly) accounted for
M31 Quiescent Nova Survey – Williams & Darnley et al. (2016)

- 30±12% of M31 nova eruptions occur in RG-nova systems (>10% at 99%)
- The traditional Galactic proportion is ~3%
- ~Order of magnitude increase in the RG-nova population size – same affect to their SN Ia contribution(?)
- RG-novae are associated with the disk (young) stellar population of M31
- Result is consistent with all the RG-novae being disk novae
- No nova SN Ia contribution from novae in early-type galaxies(?)
• 30±12 % of M31 nova eruptions occur in RG-nova systems (>10% at 99%)
• The traditional Galactic proportion is ~3 %
• ~Order of magnitude increase in the RG-nova population size – same affect to their SN Ia contribution(?)
• RG-novae are associated with the disk (young) stellar population of M31
• Result is consistent with all the RG-novae being disk novae
• No nova SN Ia contribution from novae in early-type galaxies(?)
• Can the RN population really be this large? Only 10 Galactic systems known...
• Shafter+ 2015 – 16 RNe in M31 – prediction that up to 1/3 of all M31 nova eruptions could be due to RNe
• Pagnotta & Schaefer 2014 – 25±10 % of Galactic novae may be RNe
• Nova rates may be higher then first thought (Shafter 2016, Shara+ 2016)
RNe / RG-novae → SNe Ia (?)

- Some models now show RN WD mass is growing with time (Hillman+ 2016)
- He-flashes on high mass WDs may not cause significant mass loss
- High mass WD and high accretion rate drive shorter recurrence times
- And! Short recurrence times drive WD mass growth rates
- Predictions limit recurrence periods to ~50 days as approach Chandrasekhar limit
- Minor question about the WD composition – CO vs. ONe
- But we need to find the extreme system(s)

RNe / RG-novae → SNe Ia (?)

- **Galactically (Schaefer 2010)**
  - RG-nova: RS Oph – 20 yrs
  - SG-nova: U Sco – 10 yrs

- **LMC**
  - LMCN 1968-12a – 6 years (Kuin+ in prep)

- **M31 (Shafter+ 2015)**
  - M31N 2007-11f – 9 yrs (Sin+ 2016)
  - M31N 1990-10a – 8/9 yrs (Henze+ 2016)
  - M31N 1984-07a – 8 yrs (Pietsch+ 2007)
  - M31N 2006-11c – 8 yrs
  - M31N 1963-09c – 5 yrs (Henze+ in prep)
  - M31N 1997-11k – 4 yrs
RNe / RG-novae → SNe Ia (?)

• But wouldn't it be nice to find something more extreme?!

M31N 1966-08a (Shafter+ 2015)

- Two eruptions:
  - M31N 1966-08a: August 11 1966
  - M31N 1968-10c: October 24 1968
- Very rapid evolution
- Never seen again!

- A two(.2) year RN? Surely not?
- A foreground dwarf nova outburst?
- Coincident novae? Very low probability
M31N 2008-12a – The remarkable recurrent nova!

2008  M31 transient discovered
2009  Eruption announced
       (PTF; Tang+ 2014)
2010  Eruption recovered
       (Henze+ 2015)
2011  Erupted again
2012  Spectroscopically confirmed
2013  iPTF discover eruption (Darnley+/Tang+ 2014)
2014  LT detects predicted eruption (Darnley+ 2015)
2015  LCOGT detects predicted eruption (Darnley+ 2016)

M31N 2008-12a – The remarkable recurrent nova in M31 (Darnley+ 2016)

• Eruptions every year for the last nine years!
• The fastest evolving nova ever observed \( (t_3 = 2.5 \text{ days}) \)
• Some of the highest ejection velocities seen in a nova \( \sim 13,000 \text{ km/s} \)

• All powered by the highest mass accreting WD known \( 1.38 \, M_{\odot} \) (Kato+ 2015)
• With the highest accretion rate known \( \sim 2 \times 10^{-7} \, M_{\odot}/\text{yr} \) (Kato+ 2015)
• Ejecting \( \sim 6 \times 10^{-8} \, M_{\odot}/\text{yr} \) (Kato+ 2015)

The leading pre-explosion SN Ia candidate?
Remarkable Recurrent Nova

- RNe driven by high mass WD and high mass accretion rate
- RG novae – high accretion rates – comprise upto 1/3 of M31 novae?
- Rapid RNe probe the extremes of WD mass and accretion rate
- Provide compelling pre-explosion SN Ia candidate systems beyond Milky Way
- Discovering new RNe at a rate of knots...
- But are they rare, or have we just uncovered the tip of the iceberg?
The European Week of Astronomy and Space Science (EWASS) 2018

Liverpool, UK – 3 to 6 April 2018