Classical Novae:
(Brief) New Life for Old Stars

Dr Matt Darnley
Liverpool John Moores University
Classical Novae: 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]

• Whereas, Wikipedia says: A nova is a cataclysmic nuclear explosion originating on the surface of a white dwarf
Canonical nova light curve
Darnley, 2005
Classical Novae: SMEI

- SMEI – Solar Mass Ejection Imager
- On board the Coriolis Satellite (USAF/NASA)
- Re-observes the whole sky every ~100 minutes
- Unintentionally – a unique source of Classical Nova lightcurves
SMEI: Nova Lightcurve

SMEI light curve of RS Oph
Contents

• Stellar Evolution
• Evolution of close binary systems
• The Cataclysmic Variables
• Nova outbursts
• Nova remnants
• The importance of novae

The evolution of the remnant of RS Oph
Close to Home: The Sun

- Relatively normal ‘main sequence’ star
- Diameter: 1,392,000 km (109 times the Earth’s)
- Mass: 1,989,100,000,000,000,000,000,000,000,000 kg (1,300,000 times Earth)
The Sun: Red Giant

• Eventually the Sun will exhaust its Hydrogen fuel supply
• In an attempt to prolong its life the centre/core of the Sun contracts and heats up.
• As a consequence the Sun will swell up and the surface cool
• Diameter: >150,000,000 km
The Sun: Planetary Nebula

- After another 100 million years or so, the Sun will exhaust its Helium fuel supply.
- Again the Sun will expand significantly.
- However this time the expansion is terminal and the Sun will eject the majority of its mass.
- Becoming – briefly – a glorious planetary nebula.
The Sun: White Dwarf

• One the nebula has dissipated all that is left behind is the dense hot extinguished core of the Sun – a white dwarf

• A quarter to a half of the Sun’s mass packed into an object the size of the Earth

• Carbon-Oxygen ‘degenerate’ matter
The Sun: An Unusual Star?

- 90% of stars are less luminous and less massive
- The only star (known) to support life
- Most stars are binary stars:
  - Single stars: 1/3
  - Binary stars: 1/2
  - Triple stars: 1/8
  - Multiple: 1/24
Binary Stars

- Sirius – the brightest star in the night sky – is actually a binary system
- Both stars are the same age – formed together
- The more massive star evolved quicker and is already a white dwarf
- The least massive (‘Sirius’) is still like the Sun
- Separation 20 times Earth-Sun distance
Binary Stars: Close Binaries

• Occasionally binary systems are formed such that the two stars are particularly close.

• When the more massive star evolves into a red giant the two stars may come into contact, or the massive star may fully encompass its companion.
Binary Stars: Common Envelope

- Important but poorly understood binary evolutionary stage
- Drag forces within the envelope causes the stars to lose energy
- The stars move much closer together
- Common envelope phase ends when most massive star becomes a planetary nebula

Matt Darnley - Merseyside Astronomy Day 4th June 2011
Binary Stars: (Very) Close Binaries

• Common envelope leaves a white dwarf – main sequence binary
• Orbital separation a few Solar radii
• Gravity severely distorts the shape of the main sequence star
• Orbital period a few hours
• Orbital velocity a few thousand km/s (1% the speed of light)
Classical Novae: Mass Transfer

• As the MS star and the WD are so close any material ‘lost’ by the MS star can be easily captured by the WD

• Mass transfer from the MS star to the WD is what ultimately powers the Classical Nova outburst
Classical Novae: Accretion Disk

• Material lost by the MS star doesn’t fall directly on to the WD
• The material spirals inwards in ever decreasing orbits
• This ‘accreted’ material forms a disc around the white dwarf
Cataclysmic Variables

- This model of close binary systems was developed in the 1960s by Crawford and Kraft.
- The wider CV group containing:
  - Classical Novae
  - Dwarf Novae
  - Polars
  - Type Ia Supernova?
  - Many others!
- Very similar to X-ray binaries.
Classical Novae: White Dwarf

• Hydrogen rich material from MS star eventually – via the disc – falls on to the surface of the white dwarf
• This ‘accreted’ material is compressed and heated by the intense gravitational field of the WD
• The accreted material reaches temperatures similar to that of the Sun’s core – and the material becomes degenerate
Degeneracy

Classical Matter
• Pressure is coupled to temperature
• The pressure of a gas is due to the molecules of that gas colliding with each other and the gasses container
• If we increase the temperature we give more energy to the molecules – so they move faster
• The faster they move, the bigger the collisions, so the higher the pressure

Degenerate Matter
• Pressure is uncoupled from temperature
• Quantum mechanical effect – a consequence of the ‘Pauli Exclusion Principle’
• Arises as two (identical) particles cannot occupy the same space at the same time
• Only applies at extremely high pressures and densities – higher than those at the centre of the Sun
Classical Novae: TNR

- When the accreted hydrogen reaches about 10 million Celsius nuclear fusion reactions begin.
- The reactions use Carbon from the WD as a catalyst to fuse four Hydrogen nuclei into Helium.
- As the material is degenerate – pressure cannot regulate the reactions – hence a ‘thermonuclear runaway’ ensues.
Classical Novae: Mushroom Cloud?

Hydrogen Bomb

Nova Model

Simulation of the outburst of U Sco
Classical Novae: Outburst

• The TNR powers the nova outburst
• A large amount of the accreted material is ejected from the surface of the WD
• The system increases in luminosity significantly, for a short time becoming up to 1 million times brighter than the Sun
Classical Novae: Lightcurve II

SMEI light curve of RS Oph
Classical Novae: X-Rays

- X-ray radiation is part of the EM spectrum – just like light – albeit much higher frequency / shorter wavelength
- X-rays are produced naturally by hot bodies – between 1 and 100 million Celsius
- Nuclear burning during a nova outburst should produce copious amounts of X-ray emission

Evolution of a nova’s spectral energy distribution
Swift

- Swift is a space-based observatory dedicated to the detection & study of Gamma Ray Bursts
- Swift is also equipped with an X-Ray Telescope (XRT) – which has been invaluable in the study of recent nova outbursts
Classical Novae: X-Ray Lightcurve

RS Oph X-ray light curve
Classical Novae: Remnant

- After the nuclear burning has ceased the system essentially returns to how it was before the outburst
- The WD and MS star remain unscathed
- Mass transfer from the MS star to the WD will continue
- The accretion disc will re-establish around the WD
- For a brief time a spectacular remnant of the outburst will remain
Classical Novae: Remnants

RS Oph remnant
Why are Novae Important?

• Allow us to study in great detail many extreme areas of physics over relatively short timescale
  – Accretion physics
  – Massive explosions
  – Thermonuclear reactions
  – Binary star evolution
Importance: Distance Indicators

- In 1929 Edwin Hubble noted that the brighter a nova the faster it diminished.
- Once calibrated, such a relationship can be used to determine the distance to any nova.
- Unfortunately, large scatter means this is only really useful when one has a large population of novae.

Nova MMRD relationship
Importance: Dust

- Galaxies are predominately made from three (four) things: stars, gas and dust (dark matter)
- ‘Cosmic’ dust is nothing like its Earth-based namesake
- Consists mainly of Carbon or Silicon ‘grains’
- Whilst novae are not prolific producers of dust they do provide a unique opportunity to study its production
Importance: ISM Enrichment

- Most stable Carbon, Nitrogen and Oxygen in the Universe contain an equal number of protons and neutrons
- Novae are the main produces of stable isotopes of C, N & O that contain an extra neutron ($^{13}\text{C}$, $^{15}\text{N}$, $^{17}\text{O}$)
- Particularly important in nuclear magnetic resonance imaging (MRI scans)
Important: Recurrence

• After outbursts the nova system settles down and the WD begins to accumulate more material
• Typically after 10,000 – 100,000 years they will erupt again
• However, a small group of novae – the recurrents – exist with intra-outburst times of 10 – 100 years

RS Oph over the last 100 years
AAVSO - www.aavso.org
Importance: Type Ia Supernovae

- Unlike other classes of Supernovae – Type Ia SNe are thermonuclear detonations of white dwarfs
- SNe Ia are up to 5 billion times more luminous than the sun (5,000 times brighter than a CN)
- Essentially all the same luminosity hence are extremely useful distance indicators – “standard candles”
- Progenitor system – uncertain – possibly Recurrent Novae
Recurrent Novae: RS Ophiuchi

- Unusual system – rather than a MS star and WD contains a red giant and WD
- Orbital period is a year rather than a few hours
- 2006 outburst probably the best studied nova outburst to date

The evolution of the radio remnant of RS Oph
Recurrent Novae: U Scorpii

- 2010 outburst became first successful prediction of a (recurrent) nova outburst
- U Sco contains a very high mass WD and has a very high mass transfer rate
- Prime candidate for a Type Ia progenitor system

Simulation of the outburst of U Sco
Recurrent Novae: T Pyxidis

- ‘Last’ erupted in 1996, following outbursts in 1890, 1902, 1920 & 1944
- Was not expected to erupt again for 100s – 1000s of years
- Erupted 14th April 2011
Summary

• Novae are bright – relatively common – transient objects
• At outburst ~1 million times brighter than the sun – occasionally reaching naked eye brightness
• All novae are ‘close’ binary systems – cataclysmic variables
• Cause: thermonuclear runaway within accreted material at the surface of a white dwarf

• Novae expected to undergo outbursts every 10,000 – 100,000 years
• Recurrent novae erupt every 10-100 years
• Novae can be used as distance indicators
• Can be used as laboratories to study a large array of physics
• Novae may be the progenitors of Type Ia supernovae