Binary Evolution
Novae, Supernovae, and X-ray Sources

http://apod.nasa.gov/apod/
The Algol Mystery

• Algol is a double-lined eclipsing binary system with a period of about 3 days (very short). The two stars are:

  Star A: B8, 3.4M\(_\odot\) main-sequence star
  Star B: G5, 0.8M\(_\odot\) `subgiant’ star

What is wrong with this picture?
Algol

• The more massive star (A) should have left the main sequence and started up the RGB before the less massive star (B).
• What is going on here?
• The key is the short-period orbit and the evolved state of star B.
Mass Transfer in Binaries

• In the case of Algol, Star B transferred $2.2M_\odot$ of material to Star A.

  Star A:  $1.2M_\odot \rightarrow 3.4M_\odot$

  Star B:  $3.0M_\odot \rightarrow 0.8M_\odot$
Binary Star Evolution

[(a) detached binary]

[(b) semidetached binary]

surface of equal total potential energy – including rotation

“Roche Lobe”
Mass exchange can greatly alter stellar evolution. It can change the composition we see on the surface of a star and can alter the lifetime and luminosity of both stars. Also …

- When a massive star becomes a red giant, it may spill its H-envelope onto its companion changing the evolution of both. E.g.
  
  **Type Ib supernova**

- After the (initially) more massive star has died, interesting systems can be created in which one “star” is a white dwarf, neutron star, or black hole, with another more ordinary star spilling matter onto it.

  **Classical novae**

  **Type Ia supernovae**

  **X-ray binaries**
CLASSICAL NOVAE

- Classical novae are thought to occur about 30 to 60 times a year in the Milky Way, but only about 10 are discovered each year.

- $L \sim 10^{38}$ erg s$^{-1}$ for several days to months. About $10^5$ times the luminosity of the sun, but $\sim 10^5$ times less luminous than the brightest supernova.

- Recur – in theory - but the recurrence time scale may be very long - typically tens of thousands of years.

- Some mass is ejected, but the amount is small $10^{-6}$ - $10^{-4}$ solar masses. The velocities are slower than supernovae – 100’s to perhaps 1000 km s$^{-1}$.

- Show emission lines of H, He, C, N, O, Ne, and Mg.
V1500 Cygni

Discovery Aug 29, 1975
Magnitude 3.0

A “fast” nova

V1500 Cygni

Nova Cygni 1975

Graph showing the visual magnitude over time:
- 4 Sept.
- 24 Sept.
- Time (days)
Novae

- Nova Vel 1998 (3rd magnitude)
Novae

- Nova Persei became one of the brightest stars in the sky in 1901. Look there now and see the expanding shell from the explosion. The velocity of the material is $\approx 2000\text{km s}^{-1}$.
Novae

- The expanding shell of the nova could be seen a few years later with HST.
Nova Cygni 1992

Visible magnitude at peak was 4.3. Photo at left is from HST in 1994. Discovered Feb. 19, 1992. Spectrum showed evidence for ejection of large amounts of neon, oxygen, and magnesium.

“Naked eye” novae occur roughly once per decade.

2.5 light days across ejected mass $\sim 2 \times 10^{-4}$ solar masses
The companion star is typically a low mass (K or M) main sequence star. The orbital period is short < 1 day.
An earth mass or so is ejected at speeds of 100s to 1000s of km s$^{-1}$. Years later the ejected shells are still visible. The next page shows images from a ground-based optical survey between 1993 and 1995 at the William Herschel Telescope and the Anglo-Australian Telescope.
Nova Persei (1901)  
GK Per

Nova Hercules (1934)  
DQ - Her

Nova Pictoris (1927)  
RR Pic

Nova Cygni (1975)  
V1500 Cygni

Nova Serpentis (1970)  
FH Ser

http://www.jb.man.ac.uk/~tob/novae/
MODEL FOR CLASSICAL NOVAE

• A carbon-oxygen white dwarf accretes at a slow rate of about $10^{-10}$ - $10^{-8}$ solar masses per year from a binary companion. Hydrogen and helium accumulate on the surface (at higher accretion rates can get SN Ia).

• This material is initially too cool for nuclear reactions, but as accretion continues, it is compressed and heated. At about $10^4$ g cm$^{-3}$, hydrogen burning ignites ("hot" CNO cycle; temperature over 100 Million K)

• Initially the material is degenerate. Burning is also unstable because it happens in a thin shell on the WD surface. Hydrogen burns explosively. Not all of the hydrogen burns because the material is not very tightly bound to the white dwarf
Binding energy per gm for a $1 \, M_\odot$ white dwarf

$$\frac{GM}{R} = \left( \frac{(6.67 \times 10^{-8})(2 \times 10^{33})}{5 \times 10^8} \right)$$

$$\approx 3 \times 10^{17} \, \text{erg} \, \text{g}^{-1} \ll 6.8 \times 10^{18} \, \text{erg} \, \text{g}^{-1} = q_H$$

- The hydrogen continues to burn for several months as the entire accreted layer is driven off the star in a powerful wind. None of the accreted material is left behind.

- Accretion then resumes and the cycle repeats
nb. Novae can repeat!

accrete
explode
accrete
explode

Typical peak hydrogen explosion temperatures are 200 million K at densities of 10,000 g/cm³.

About 5000 trillion megatons/sec
Nucleosynthesis from novae – not much, but a couple of isotopes that can’t be made elsewhere

$^{15}\text{N}$, $^{17}\text{O}$

The more common isotopes of nitrogen and oxygen – $^{14}\text{N}$ and $^{16}\text{O}$ are made elsewhere in planetary nebulae and supernovae respectively.

Novae also make some radioactive $^{22}\text{Na}$ (half life 2.6 years which has been searched for but not discovered yet.

Generally novae actually decrease slightly with mass as a consequence of repeated outbursts, but at higher accretion rates the burning shell becomes stable and the mass of the white dwarf can actually grow.
Type Ia Supernovae
Type Ia supernovae are the biggest thermonuclear explosions in the universe.

Thirty billion, billion, billion megatons.

For several weeks their luminosity rivals that of a large galaxy.
**Observational facts**

- Very bright, regular events, peak $L \sim 10^{43}$ erg s$^{-1}$

- Associated with an old stellar population (found in ellipticals, no clear association with spiral arms when in spiral galaxies)

- No hydrogen in spectra; strong lines of Si, Ca, Fe

- Total kinetic energy $\sim 10^{51}$ erg (nothing left behind)

- Higher speed, less frequent than Type II
Spectra of three Type Ia supernovae near peak light – courtesy Alex Filippenko
The Phillips Relation
(post 1993)

Broader = Brighter

Can be used to compensate for the variation in observed SN Ia light curves to give a “calibrated standard candle”.

Note that this makes the supernova luminosity at peak a function of a single parameter – e.g., the width.
Possible Type Ia Supernovae in Our Galaxy

<table>
<thead>
<tr>
<th>SN</th>
<th>D(kpc)</th>
<th>m_V</th>
</tr>
</thead>
<tbody>
<tr>
<td>185</td>
<td>1.2+-0.2</td>
<td>-8+-2</td>
</tr>
<tr>
<td>1006</td>
<td>1.4+-0.3</td>
<td>-9+-1</td>
</tr>
<tr>
<td>1572</td>
<td>2.5+-0.5</td>
<td>-4.0+-0.3</td>
</tr>
<tr>
<td>1604</td>
<td>4.2+-0.8</td>
<td>-4.3+-0.3</td>
</tr>
</tbody>
</table>

Expected rate in the Milky Way Galaxy about 1 every 200 years, but dozens are found in other galaxies every year. About one SN Ia occurs per decade closer than 5 Mpc. SN 2014J was at 3.5 Mpc and is being extensively studied.
(A) Leading Model*

Accretion and growth to the Chandrasekhar Mass (1.38 solar masses) *Degenerate thermonuclear explosion.* (Hoyle and Fowler, 1960).

Explains:

- Lack of H in spectrum
- Association with old population
- Regularity
- Large production of $^{56}\text{Ni}$ and a light curve dominated by radioactivity.

* well, until recently….
<table>
<thead>
<tr>
<th>The progenitor of a Type Ia supernova</th>
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<tbody>
<tr>
<td><img src="image.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>

- Two normal stars are in a binary pair.
- The more massive star becomes a giant...
- ...which spills gas onto the secondary star, causing it to expand and become engulfed.
- The secondary, lighter star and the core of the giant star spiral toward within a common envelope.
- The common envelope is ejected, while the separation between the core and the secondary star decreases.
- The remaining core of the giant collapses and becomes a white dwarf.
- The aging companion star starts swelling, spilling gas onto the white dwarf.
- The white dwarf's mass increases until it reaches a critical mass and explodes...
- ...causing the companion star to be ejected away.

Evolutionary scenario
Another Possibility
Merging White Dwarfs

0.9 + 0.9 solar mass WD still make subluminous event

1.1 + 0.9 can make a more typical SN Ia like 2011fe
In order for the white dwarf to grow and reach the Chandrasekhar Mass the accretion rate must be relatively high (to avoid the nova instability). In the case of the “single degenerate model” this must be maintained for millions of years.

\[ \dot{M} \sim 10^{-7} \, M_{\text{sun}} / \text{yr} \]
**Progenitor**

Ignition occurs carbon fusion in the center of the white dwarf begin to generate energy faster than convection and neutrino losses can carry it away.

\[
\text{As } \rho \rightarrow 2 \times 10^9 \text{ gm cm}^{-3}; \ T \approx 3 \times 10^8 \text{ K}
\]

\[
M \approx 1.38 M_\odot
\]
P is independent of T, but 
\[ \varepsilon_{\text{nuc}} \propto T^{26} \] for carbon burning

\[ \Rightarrow \] BANG
Ignition at $\rho_c \sim 3 \times 10^9$ because:

1) Neutrino loss rates decline at very high density

2) Carbon fusion reaction enhanced at high density by “electron screening”

3) Central regions compressed and heated by accretion of matter on surface.

Once carbon ignites, the core begins to convect. Energy is generated too fast for conduction or diffusion to get it to the surface fast enough.
Explosion preceded by about a century of convection. The convection is asymmetric.
The Explosion - Burning and Propagation

0.7 $M_\odot$ of $^{56}\text{Ni}$

0.94 $M_\odot$ of $^{56}\text{Ni}$

SN Ia probably make about 2/3–3/4 of the iron group elements found in nature
Qualitative Type Ia Supernova Light Curve

$^{56}\text{Ni} + ^{56}\text{Co}$ decay

Entirely due to radioactivity

Diffusion and expansion time scales approximately equal

Optical light curve

gamma-ray escape
Radioactivity

\[ ^{56}\text{Ni} + e^- \rightarrow ^{56}\text{Co} + \nu \]

\[ \tau_{1/2} = 6.1 \text{ days} \]

\[ q = 3.0 \times 10^{16} \text{ erg/gm} \]

\[ ^{56}\text{Co} + e^- \rightarrow ^{56}\text{Fe} + \nu \]

\[ \tau_{1/2} = 77.1 \text{ days} \]

\[ q = 6.4 \times 10^{16} \text{ erg/gm} \]

0.6 solar masses of radioactive Ni and Co can thus provide 1.1 $\times$ $10^{50}$ erg at late times after adiabatic expansion is essentially over.
SN 2003 du vs Model
**Supernova**  
(Death of a star)

### Type Ia
- No hydrogen
- Thermonuclear explosion of a white dwarf star
- No bound remnant
- $\sim 10^{51}$ erg kinetic energy
- $v \sim 5,000 - 30,000$ km s$^{-1}$
- No neutrino burst
- $E_{\text{optical}} \sim 10^{49}$ erg
- $L_{\text{peak}} \sim 10^{43}$ erg s$^{-1}$ for 2 weeks
- Radioactive peak and tail ($^{56}$Ni, $^{56}$Co)
- 1/200 yr in our Galaxy
- Makes about 2/3 of the iron in the Galaxy

### Type II
- Hydrogen in spectrum
- $M > 8$ solar masses
- Iron core collapses to a neutron star or black hole
- $\sim 10^{51}$ erg kinetic energy
- $v \sim 2,000 - 30,000$ km s$^{-1}$
- Neutrino burst $\sim 3 \times 10^{53}$ erg
- $E_{\text{optical}} \sim 10^{49}$ erg
- $L_{\text{peak}} \sim 3 \times 10^{42}$ erg s$^{-1}$ for about 3 months (varies from event to event)
- Radioactive tail ($^{56}$Co)
- 2/100 yr in our Galaxy
- Makes about 1/3 iron and all the oxygen plus many other elements

*There are also Type Ib and Ic supernovae that share many of the properties of Type II but have no hydrogen in their spectra*
Binary X-Ray Sources
The bright x-ray sky – mostly point sources (AGN, SNR, black holes and neutron stars)

HEAO survey completed 1978
  841 sources mostly binary systems containing a neutron star or a black hole.

Also Giaconni - rockets in 60’s
UHURU = SAS 1 1970 - 1973
50,000 sources. By 1999
over 150,000 sources had been catalogued. Many are “normal stars”.

red > 100,000 K
white ~ 20 million K
luminosities ~ $10^{36} - 10^{38}$ erg s$^{-1}$
<table>
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<tr>
<th>Active Galaxies</th>
<th>Binary Star Systems</th>
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<tr>
<td>Black Holes</td>
<td>Cataclysmic Variables</td>
</tr>
<tr>
<td>Dark Matter??</td>
<td>Diffuse Background</td>
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<tr>
<td>Gamma-ray Bursts</td>
<td>Neutron Stars</td>
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<tr>
<td>Pulsars</td>
<td>Stars</td>
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<tr>
<td>The Sun</td>
<td>Supernovae and their Remnants</td>
</tr>
<tr>
<td>White Dwarfs</td>
<td>X-ray Transients</td>
</tr>
</tbody>
</table>
X Ray Binaries

• Two classes based upon mass of companion star that is feeding the x-ray emitting compact object

• High mass donors (over about 5 solar masses) are found in the disk of the galaxy and are Population I. The donor star is typically a B-type main sequence star or a blue supergiant. Roughly 300 are estimated to exist in our galaxy. Lifetime $< 10^8$ years. Long period. High accretion rate.

• Low mass x-ray binaries contain a donor star of $< 1$ solar mass which may be a main sequence star. Population II. Found in Galactic center, globular clusters, in and above disk. Roughly 300 estimated to exist.

• Luminosities in X-rays for both are $\sim 10^{36} - 10^{38}$ erg s$^{-1}$. Spectra are approximately black bodies.
MODELS

- The persistent emission of all x-ray binaries is due to the gravitational energy released by the accreted matter as it impacts the surface of the neutron star (black holes are a special case of this where the energy is released in a disk outside the event horizon).

- Typical accretion rates are $10^{-8} \, M_\odot \, y^{-1}$ (or $6 \times 10^{17} \, g \, s^{-1}$)

\[
L = \frac{G M \dot{M}}{R} = \frac{(6.67 \times 10^{-8})(1.4)(2 \times 10^{33})(6 \times 10^{17})}{1.0 \times 10^6} = 1 \times 10^{38} \, \text{ergs}^{-1}
\]
This is still approximately blackbody radiation, so

\[ T_{\text{eff}} \approx \left( \frac{L}{4\pi R^2 \sigma} \right)^{1/4} \]

\[ = 2 \times 10^7 \text{ K} \]

which corresponds to x-rays.

\[ \lambda_{\text{max}} = \frac{0.289 \text{ cm}}{T_{\text{eff}}} = \frac{2.89 \times 10^7}{T_{\text{eff}}} \text{ Angstroms} \]

\[ \approx 3 \text{ Angstroms (X-rays)} \]
Accreting neutron star or black hole

Companion star

Accretion disk
$\sim 10^{10}$ cm

$\sim 10^6$ cm
NS or black hole

$\sim 10^{11}$ cm
Binary separation

Luminosity $\sim 10^{36} - 10^{38}$ erg s$^{-1}$ = 200 - 50,000 $L_{\odot}$

Temperature of disk $\sim 10^{7}$K $\Rightarrow$ primarily X-rays
High Mass X-Ray Binary Formation

<table>
<thead>
<tr>
<th>$M_1(M_\odot)$</th>
<th>$M_2(M_\odot)$</th>
<th>$P_b(d)$</th>
</tr>
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<tbody>
<tr>
<td>25.0</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>25.0</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>17.5</td>
<td>17.5</td>
<td>5.4</td>
</tr>
<tr>
<td>7.1</td>
<td>27.9</td>
<td>20.4</td>
</tr>
<tr>
<td>1.4</td>
<td>27.9</td>
<td>30.7</td>
</tr>
</tbody>
</table>

transfer all H envelope leaving only helium core

Supernova

e = 0.19, $v_s = 39.2$ km/s

$100R_\odot$
Cyg X-1 in X-Rays

exosat Observatory
cma1 detector
Exposure time: 4351 seconds
Field name: CYGNUS X-1
21 arcsec
Artist’s Rendition of Cyg X-1
<table>
<thead>
<tr>
<th>Source</th>
<th>Companion</th>
<th>P (days)</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cygnus X-1</td>
<td>B supergiant</td>
<td>5.6</td>
<td>6-15</td>
</tr>
<tr>
<td>LMC X-3B</td>
<td>main sequence</td>
<td>1.7</td>
<td>4-11</td>
</tr>
<tr>
<td>A0620-00 (V616 Mon)</td>
<td>K main sequence</td>
<td>7.8</td>
<td>4-9</td>
</tr>
<tr>
<td>GS2023+338 (V404 Cyg)</td>
<td>K main sequence</td>
<td>6.5</td>
<td>&gt; 6</td>
</tr>
<tr>
<td>GS2000+25 (QZ Vul)</td>
<td>K main sequence</td>
<td>0.35</td>
<td>5-14</td>
</tr>
<tr>
<td>GS1124-683 (Nova Mus 1991)</td>
<td>K main sequence</td>
<td>0.43</td>
<td>4-6</td>
</tr>
<tr>
<td>GRO J1655-40 (Nova Sco 1994)</td>
<td>F main sequence</td>
<td>2.4</td>
<td>4-5</td>
</tr>
<tr>
<td>H1705-250 (Nova Oph 1977)</td>
<td>K main sequence</td>
<td>0.52</td>
<td>&gt; 4</td>
</tr>
<tr>
<td>+ 2 more</td>
<td></td>
<td></td>
<td></td>
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</table>

Fraknoi, Morrison, and Wolff  p. 328