Nuclear Astrophysics

IV: Novae, x-ray bursts and thermonuclear supernovae

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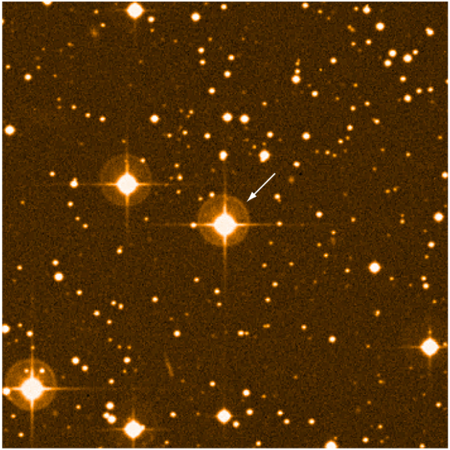
Stars in binaries

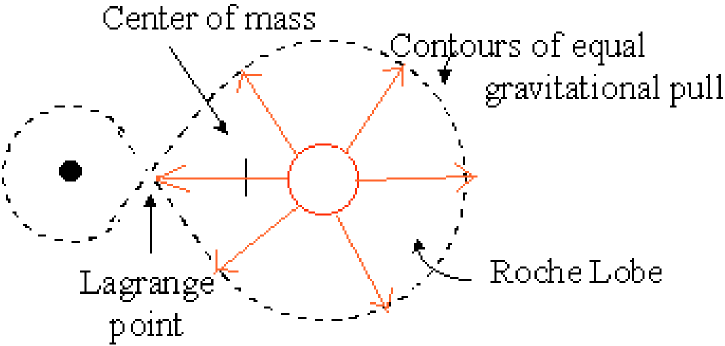


The Lead-Star HD 196944

ESO PR Photo 26a/01 (22 August 2001)

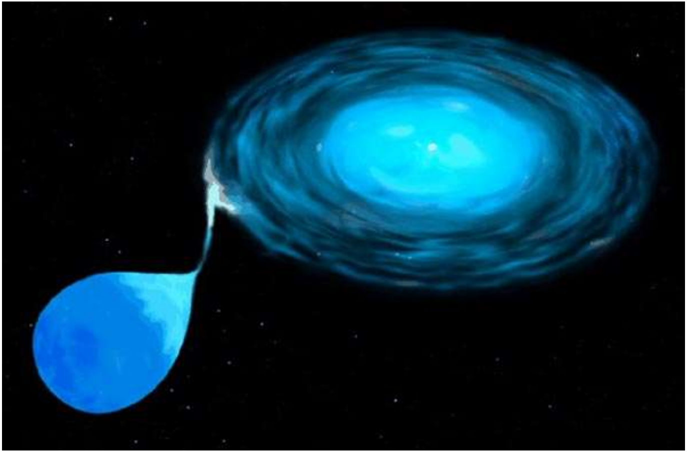
About 50% of all stars exist in binaries

Roche lobe

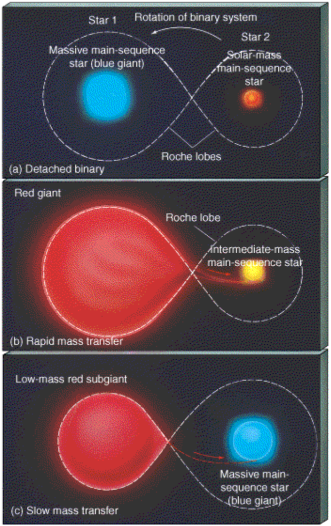


Mass transfer from one to the other star can occur if the gas of the star overflows the Roche lobe. The gas can then escape through the inner Lagrangian point towards the compagnion.

Accretion disk surrounding a compact object



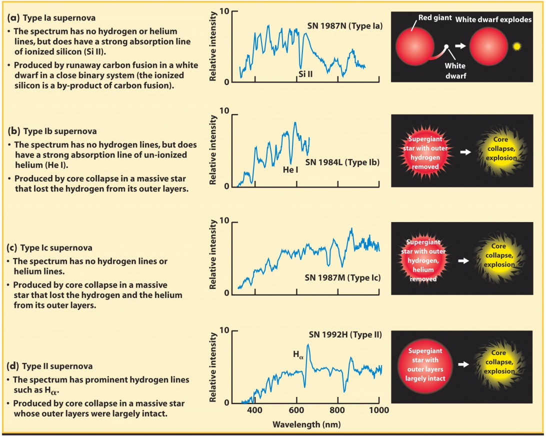
Binary star evolution



A **cataclysmic variable** is a touching ('semidetached') binary system with a white dwarf and a late-stage main-sequence star. When the later star becomes a Red Giant, mass flow sets in. The fate of the white dwarf then depends on the mass flow $\dot{M}$:

- If $\dot{M}$ is about $10^{-8} - 10^{-10}$ $M_\odot$/y, the white dwarf will experience an explosion of its surface layers (**nova**).
- If $\dot{M}$ is about $10^{-6} - 10^{-8}$ $M_\odot$/y, the entire white dwarf will be destroyed in a **type Ia supernova**.
- At even higher $\dot{M}$, an extended H-rich red giant envelope should form around the white dwarf so that the debris of the explosion could not be seen.

Supernova classes

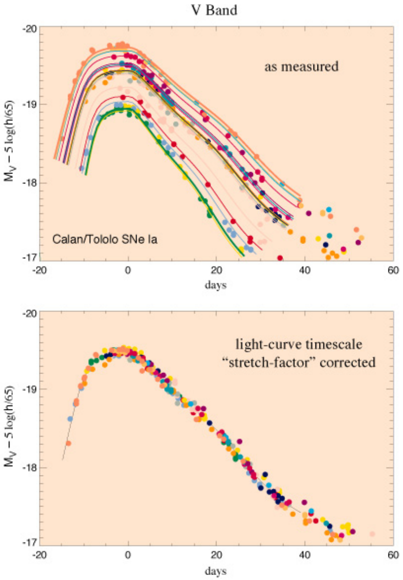


Type Ia supernovae: general properties

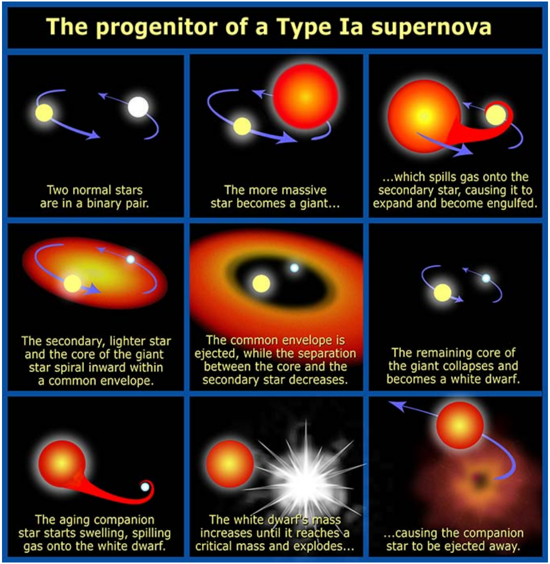
- there are no hydrogen lines in the spectra, but prominent Si lines
- the spectra are dominated by intermediate-mass elements (early: Si, Ca, Mg, S, O; later: Fe, Co)
- typical velocities of the ejecta are a few 10^4 km/s
- there are no neutron star remnants
- they produce a few tenth of $M_\odot$ of ^{56}Ni which powers the lightcurve
- there is not much variations between different type Ia's

Correlations and standard candles

Inhomogeneities among type Ia observables are strongly intercorrelated. The most important one is the correlation between the width of the light curve around maximum and the peak brightness (Phillips relation). This makes type Ia's to **standard candles**.



Progenitor evolution of a type Ia supernova



Progenitor system

It is generally assumed that Type Ia supernovae are the results of the thermonuclear disruption of white dwarfs. The favored progenitor models are carbon/oxygen white dwarfs which have a Chandrasekhar mass at explosion. Obviously the C/O ratio has to be known throughout the white dwarf, which depends on

- the still uncertain ^{12}C$(\alpha,\gamma)^{16}$O rate
- the metallicity content of the ZAMS star
- the main sequence mass.

Besides the favored progenitor model, also low-mass C+O white dwarf cores, embedded in a shell of helium, are discussed.

Ignition

In the standard scenario, there is mass flow from the H-rich (or He-rich) envelope of the donor star onto the surface of the white dwarf. The mass flow is large enough to establish a layer of hydrogen and helium burning on the white dwarf, which produces additional ^{12}C. Thus the core of the white dwarf grows. When it reaches masses close to the Chandrasekhar mass ($\sim 1.4 M_\odot$), the condition becomes explosive and carbon is ignited in the core.

Thermonuclear runaway

- carbon burning is ignited in the core, probably at several off-center sites
- the ignition occurs in extremely degenerate environment (densities of a few 10^9 g/cm^3)
- thus, the energy generated by the nuclear reaction is initially not used in mechanical work (expansion), but for increasing the temperature
- this accelerates the C+C fusion ($\sim T^{12}$ at $T_{10} = 1$); the rate is tremendously enhanced due to screening effects
- finally the degeneracy gets lifted, a burning front ('flame') moves outwards

Explosion

- due to the strong T-dependence of the nuclear reaction rate, nuclear burning is confined to a rather thin layer which moves outwards at subsonic speed (deflagration)
- the temperature is sufficiently high so that burning occurs instantaneously compared to the fluid motion; a thin reaction zone forms between burnt and unburnt material
- at the beginning, the flame moves subsonically
- the burnt products create heat and pressure; the increase in the later forms a shock wave which can ignite the fuel by compressional heating (combustion)
- the combustion front propagates supersonically; the unburnt medium has no time to expand before it is burnt
- finally the white dwarf entirely explodes

Energetics

A white dwarf has a radius of about 2000 km and a mass of order 1.4 $M_\odot$. Then its gravitational binding energy is about

$$E_g \approx \frac{GM^2}{2R} \approx 10^{51} \mathrm{ergs}$$

Burning of an entire white dwarf from ^{12}C or ^{16}O to ^{56}Ni, releases close to 1 MeV nuclear binding energy per nucleon. This results in about 2×10^{51} ergs for a mass of $1.4 M_\odot$.

Thus the nuclear burning is sufficient to overcome the gravitational binding energy. Simulations show that the disruption occurs on timescales of seconds.

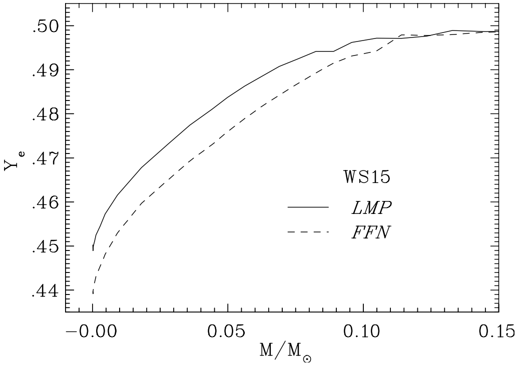
Type Ia nucleosynthesis

Despite the complexity of the explosion, nucleosynthesis is rather simple.

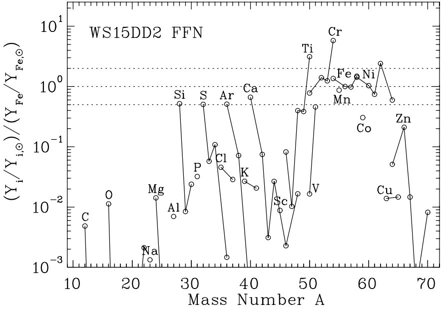
- At $\rho \geq 2 \times 10^7$ g/cm^3, the temperature exceeds 5×10^9 K and all matter burns to Nuclear Statistical Equilibrium. As the matter had $Y_e = 0.5$ prior to explosion, the most abundant nucleus is ^{56}Ni.
- At $\rho \geq 4 \times 10^6$ g/cm^3, the matter undergoes incomplete silicon burning producing mainly S and Si.
- At $\rho \geq 1 \times 10^6$ g/cm^3, the matter undergoes explosive oxygen burning producing mainly Ne, Mg, and O.

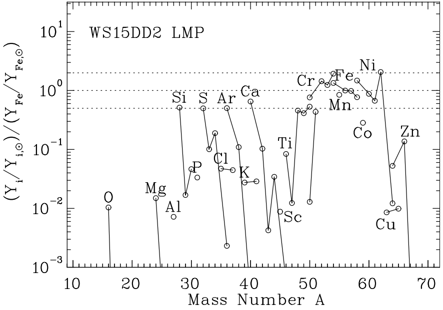
Electron captures behind the flame

The burning flames moves slow enough at the beginning that electron captures occur behind the flame. These captures reduce the Y_e value and hence change the nucleosynthesis abundances. The neutrinos produced by the capture also cool the core.

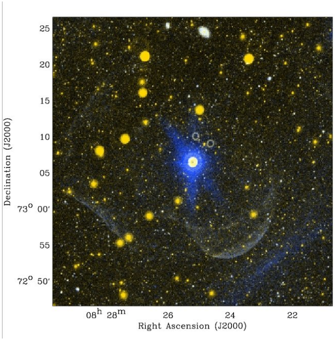


Type 1a supernova abundances





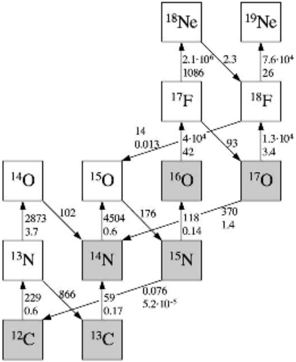
Novae facts



- it is a quite common phenomenon; there are about 30 ± 10 novae every year in our galaxy
- the energy output of a nova reaches to $\geq 10^4 \ L_\odot$
- the mass ejection in a nova is about $10^{-5} - 10^{-4} \ M_\odot$
- the mean velocity of the ejecta is about $10^2 - 10^3$ km/s
- models predict that novae recur with periodicities of order $10^4 - 10^5$ y
- spectra show production of medium-mass elements, but not beyond calcium

The two nuclear timescales

Nuclear hydrogen burning occurs within the CNO cycle. There are really two nuclear timescales:



β-lifetimes and reaction lifetimes at $T_8 = 1$ and $T_8 = 2$ are given.

- β-decays: there are several β^+-unstable nuclei with very short halflives (^{13}N, ^{14,15}O, ^{17}F). Under nova conditions, the β timescale τ_β is independent on temperature and density
- proton captures: the rates depend strongly on temperatures; the reaction lifetime is $\tau_p = [\rho X_H / A_H N_A \langle \sigma v \rangle]^{-1}$

The importance of convection

In the early evolution of the runaway, $\tau_\beta < \tau_p$ and the CNO cycle operates in equilibrium. But once T has increases to 10^8 K, $\tau_\beta > \tau_p$ and the CNO cycle is β-limited.
Further, the nuclear burning produces now more energy than can be transported by radiation. Convection sets in.
The β-unstable nuclei are transported to the outer cooler regions where their decays initiate the nova outburst. The release of energy in the β-decays increase the temperature of the matter, the degeneracy of the envelope is lifted, expansion sets in allowing the ejection of matter.
Convection also brings unburnt material to the burning shell which has effects on the nucleosynthesis.

General remark to nova nucleosynthesis

The total amount of material produced by novae during the history of our galaxy is:

$$M_{Nova} = N_{rate} \times M_{ejec} \times \tau_{Gal} \approx 6 \times 10^6 M_\odot$$

assuming $N_{rate} \sim 30$ as the nova rate per year, $M_{eject} \approx 2 \times 10^{-5} M_\odot$ as the average ejected mass per nova and $\tau_{Gal} = 10^{10}$ y as the age of our Galaxy.

The total matter produced by novae is much smaller than the mass content of the Galaxy. Hence novae are minor contributors to the overall Galactical chemical abundance evolution. However, they are important for specific nuclides. Those must then be overproduced with respect to solar abundances by a factor 1000 or more.

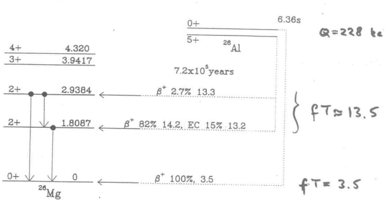
Modern nova nucleosynthesis calculations involve spherical hydrodynamical models coupled to extended nuclear networks. First studies in 2D or 3D have been attempted, however, covering only small portions of the star and assuming quite restricted nuclear networks.

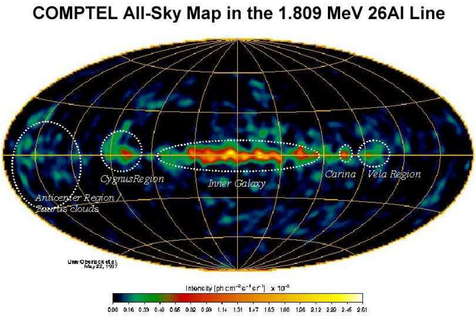
γ-ray emission from novae

Several of the nuclides produced in nova nucleosynthesis are β-unstable and their lifetimes are long enough that the γ-rays produced by the decay can become observable. Measuring the γ-emission from novae has been and is the goal of several satellites, including BATSE (wide-field instrument on board of the Compton Gamma-Ray Observatory), the TGRS spectrometer on board of the WIND satellite and, more recently, by two instruments as part of INTEGRAL.

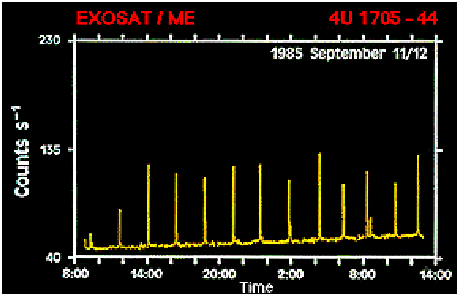
Observing the γ-lines and their fluxes allows to test nova models and nucleosynthesis. The most interesting lines come from the decay of ^{13}N ^{17}F, ^{7}Be, ^{22}Na, and ^{26}Al.

γ-lines from ^{26}Al





X-ray bursts



X-ray bursts are thermonuclear explosions on the surface of an accreting neutron star.

X-ray burst properties

- mass transfer from companion star $\dot{M} = 10^{-8} - 10^{-10} M_\odot/y$
- duration 10-100 s with typical luminosities of order 10^{39-40} ergs
- X-ray flux originates from thermal emission of the neutron star photosphere which is dramatically heated during the burst
- the bursts recur with periodicities of hours to days; long sequences of bursts can be observed
- recently ms oscillations of the x-ray flux have been observed during the burst; they are likely related to the spin of the rotating neutron star
- about 60 bursters are known in the Galaxy

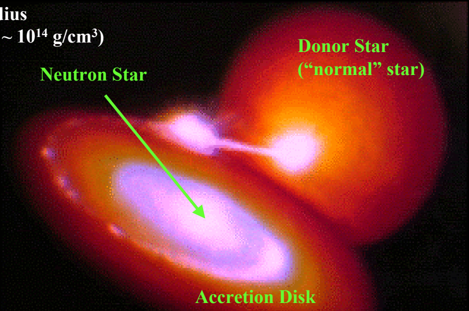
Why is nuclear physics important?

- The energy source of x-ray bursts are nuclear reactions occuring on the protonrich side of the nuclear chart
- the energy generation is up to 7 MeV/nucleon (6.7 MeV for the pp-chain)
- however, the gravitational potential of the neutron star is so strong that 200 MeV/nucleon are required for the matter to be released
- thus, nuclear networks occuring during x-ray bursts do not contribute to the nucleosynthesis in the Galaxy

X-ray burst model

The Model

Neutron stars:
1.4 M_o, 10 km radius
(average density: ~ 10^{14} g/cm^3)



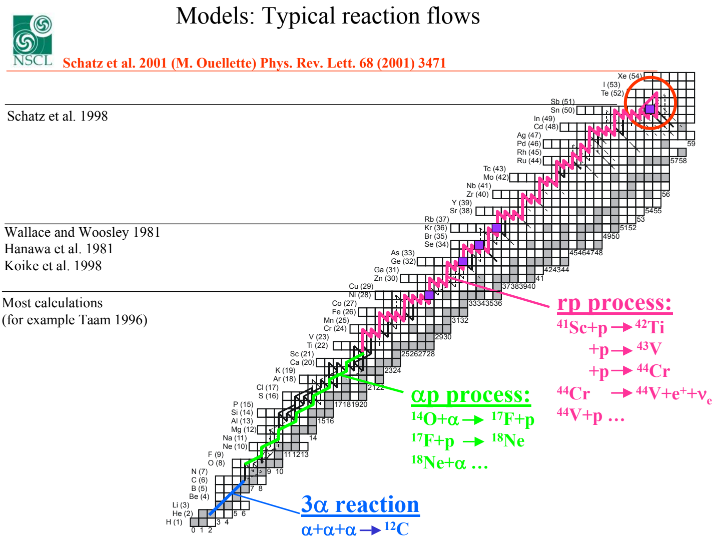
Typical systems:

- accretion rate $10^{-8}/10^{-10}$ M_o/yr (0.5-50 kg/s/cm^2)
- orbital periods 0.01-100 days
- orbital separations 0.001-1 AU's

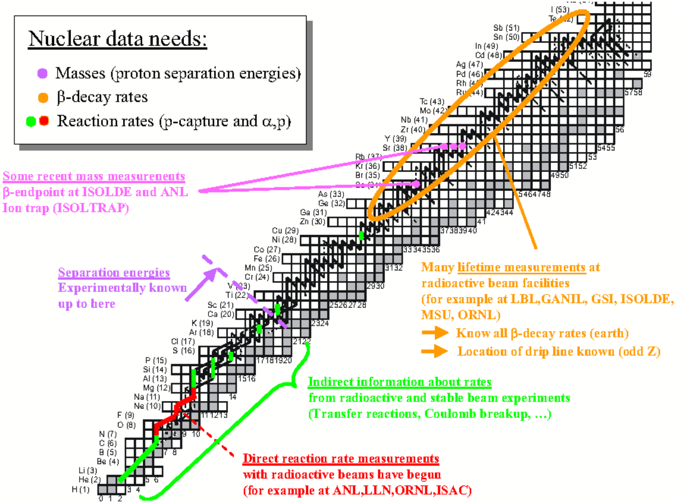
X-ray burst model

- the accreted matter is a mix of hydrogen, helium and some heavier elements
- this matter is accumulated on the neutron star surface for hours or days
- the matter is compressed and heated
- if $T_8 > 2$, helium is ignited by the triple-alpha reaction
- this occurs in a very thin shell where the heating from the nuclear burning cannot be compensated by readjusting the stellar structure or by cooling through the surface (shell instability)
- the consequence is a thermonuclear runaway with increasing temperatures until the accreted matter is burnt

The x-ray burst mass flow



Nuclear needs for rp-process models



Crust processes in binaries with x-ray bursts