Accretion onto Compact Stars: TUM and MPA/MPE Workshop

Nuclear Burning on White Dwarfs: Novae, Supersoft Sources

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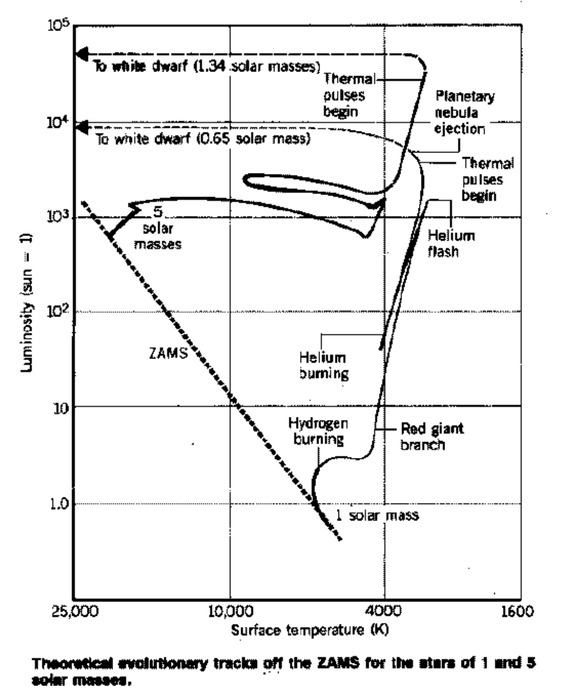
Main Contents:

- White Dwarfs (WD) in Binary Systems
- Types of Nuclear Burnings on the WD Surface
- Novae
  (classical novae, recurrent novae)
- Luminous X-ray Supersoft Sources (SSS)

Formation of WDs

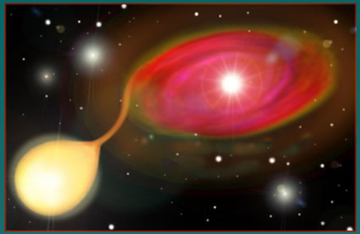
They are the final evolution states of the low and intermediate mass of stars.



Theoretical evolutionary tracks off the ZAMS for the stars of 1 and 5 solar masses.

initial mass (M_{sun})	final state
$M<0.08$	brown dwarfs, planets
$0.08<M<0.25$	He WDs
$0.25<M<8$	C-O WDs
$8<M<12$	O-Ne-Mg WDs
$M>12$	neutron stars (NS)
$M>40$	black holes (BH)

WDs in binary systems



- WD + low mass main-sequence stars in close binaries:

Cataclysmic Variables (CV, Roche lobe outflow, low accretion rate, no evolution in donor stars)

- Magnentic WDs (B>10^6 G)
  Intermediate polars (DQ Her stars) B=(1-10)*10^6 G
  Polars (AM Her stars) B=(10-100)*10^6 G
- Non-magnetic WDs
  dwarf novae, nova-like objects (accretion disk instability)

Hydrogen–rich matter transferring from donors to the surface of WDs accumulates until it reaches hydrogen ignition conditions, which leads to a thermonuclear runaway: novae.

- WD + (1.3-2.5)M_{sun} main-sequence stars in close binaries: (Roche lobe outflow, relatively high accretion rate, no evolution)
- WD + red giants in wide binaries: symbiotic systems (winds, relatively high accretion rate, evolved donors)
- CO WD + CO WD (merger) → Type Ia supernovae
- NS/BH + low mass WD → Low mass X-ray binaries

Nuclear burning types on the WD surface

Eddington critical rate for hydrogen

For very high accretion rate, a red-giant-like envelope will form, the matter burns steadily in [illegible] around [illegible]

The steady nuclear burnings occur within [illegible] (1-4)*10^{-7} M_{sun}/yr

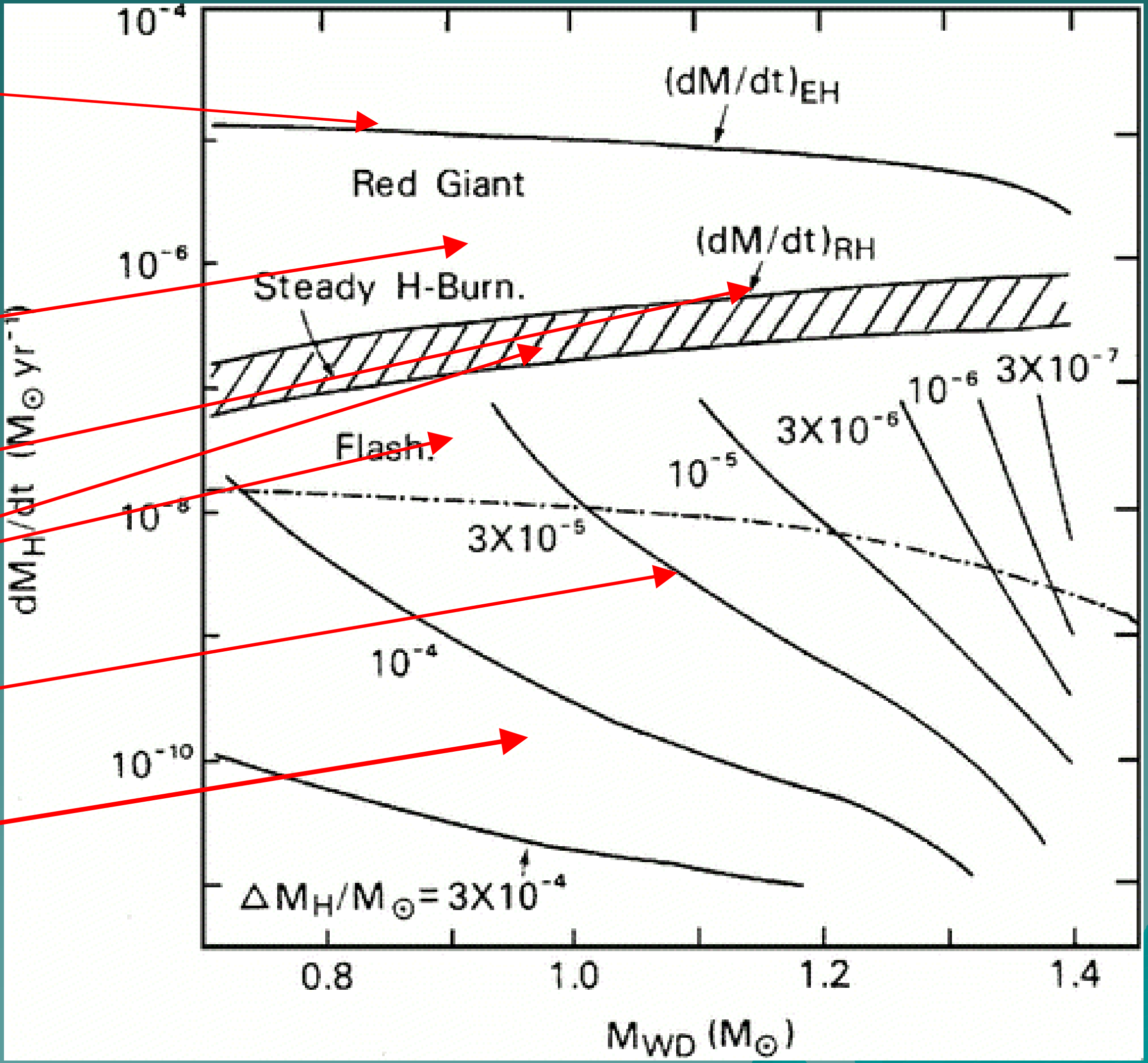
The growth rate of the degenerate core in red giants

For lower accretion rate, the matter burns in flashes

Solid lines: the envelope mass at which burning is ignited

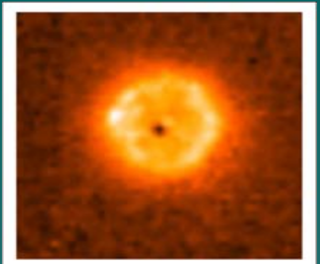
Lower accretion rate, flashes become more and more violent.

Nova explosion and typical CVs lie in the region below the dot-dashed line.



(Kahabka & van den Heuvel ARA&A, 1997)

Novae

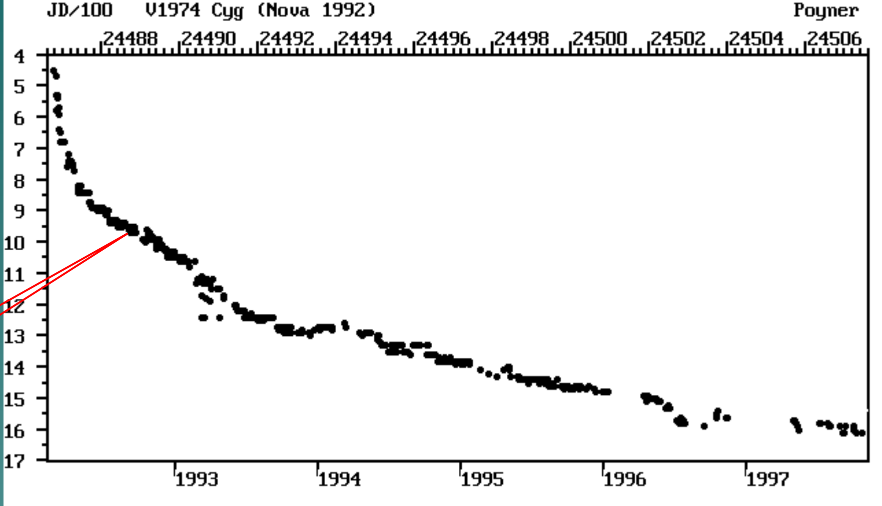


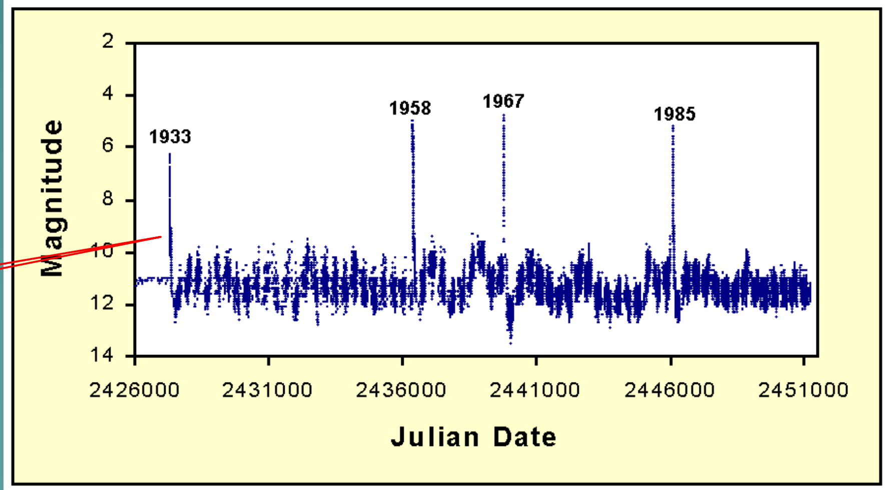
Nova QUVul (Univ. of Wyoming / Space Telescope Science Institute)

- Observations:

Novae are the transient phenomena, and their optical light curves show an increase in luminosity which corresponds to a decrease of the apparent visual magnitude of more than 5 magnitudes (even more than 9 magnitudes for a typical classical nova).

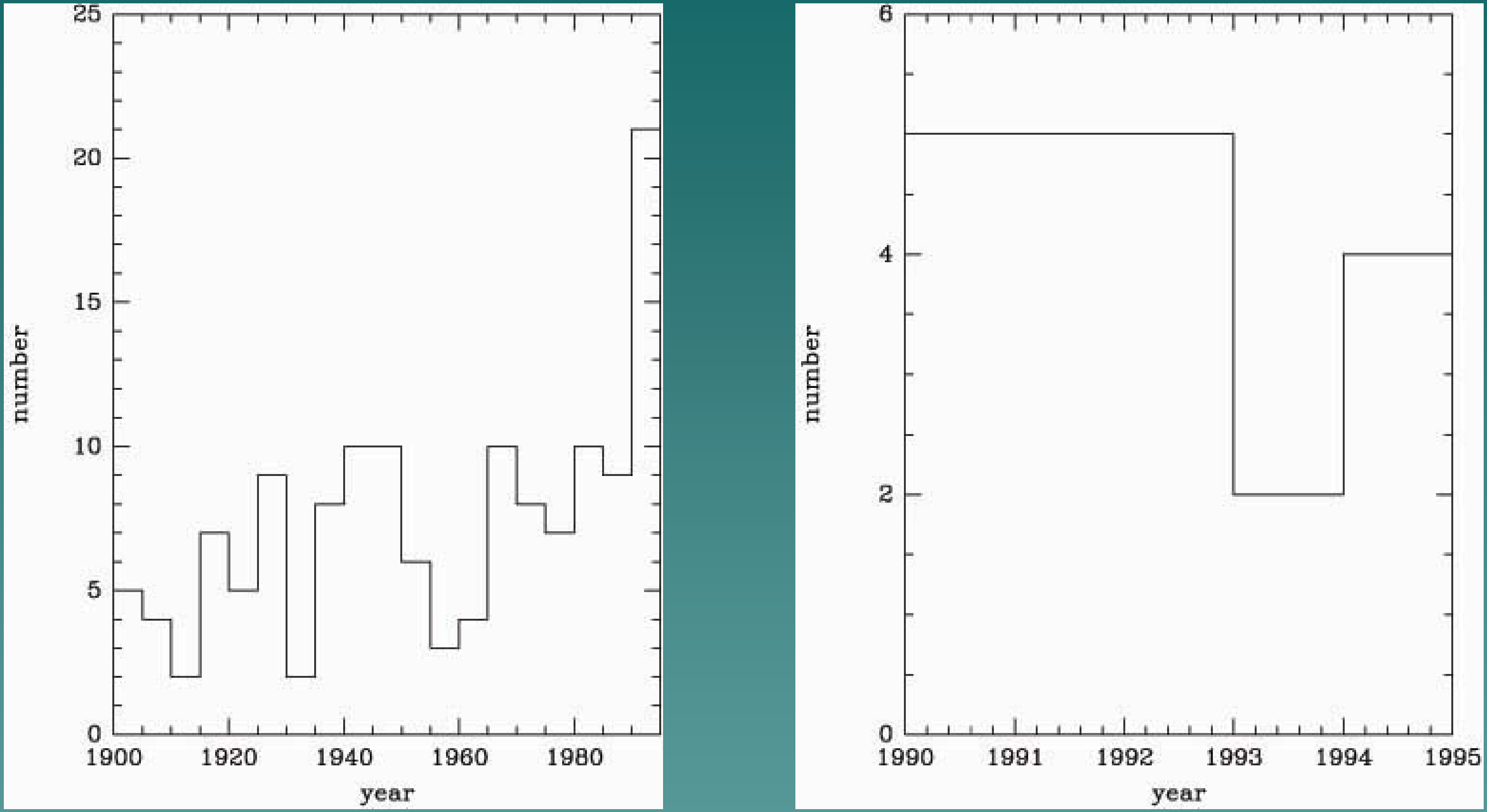
The outbursts repeat every several or several-tens of years, which are called recurrent novae.





RS Ophiuchi

Novae: observations



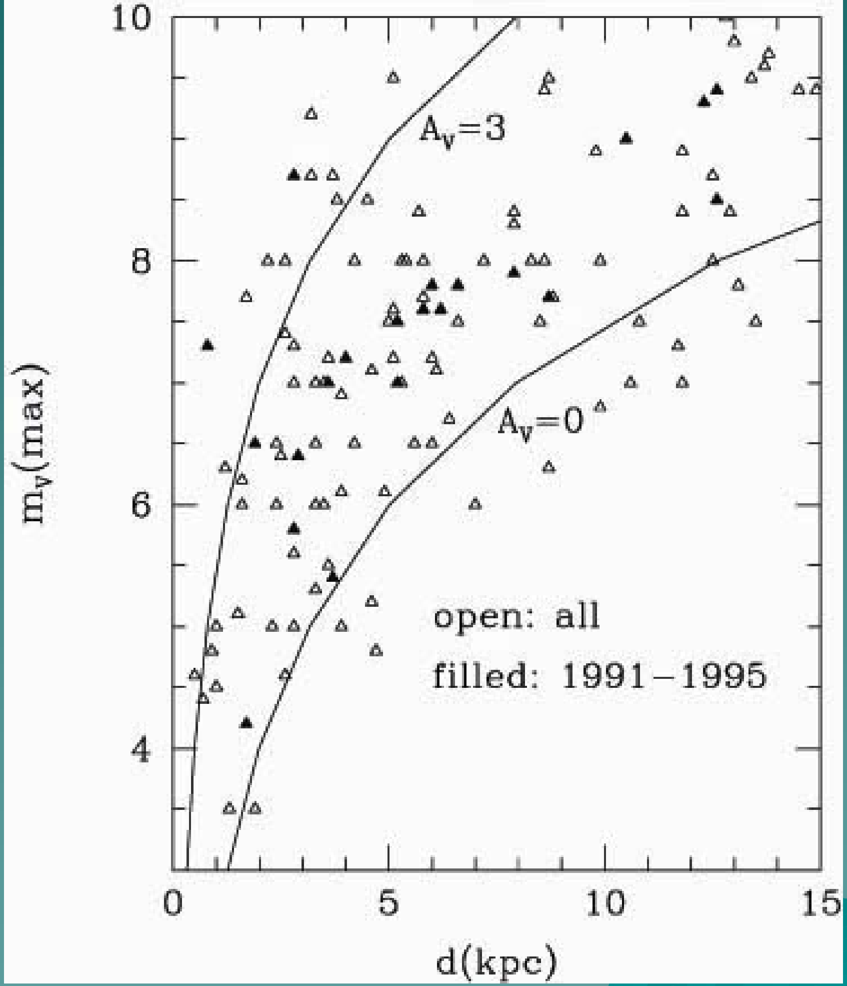
(Hernanz 2004, astro-ph/0412333)

Number of novae discovered during the last century.
At most 5 novae are discovered every year in the Galaxy.

Novae: observations

Apparent magnitude m_V at maximum versus distance, including novae from 1901-1995.

The empirical relation corresponding to visual extinction $A_V=0$ and $A_V=3$ is also shown.

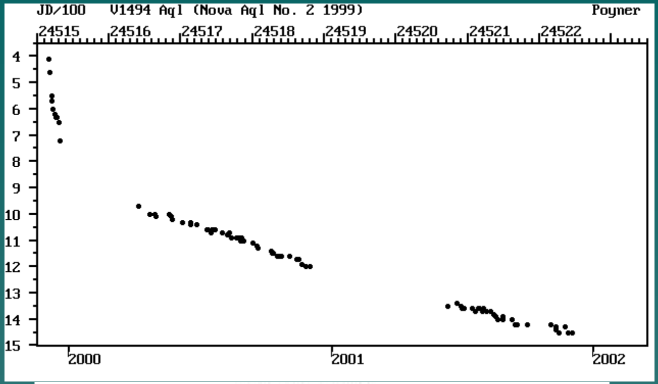


(Hernanz 2004, astro-ph/0412333)

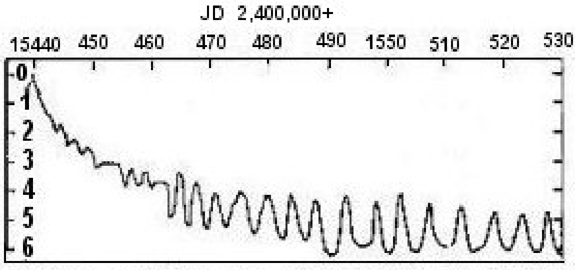
Novae: light curves

Nova light curves are classified according to the speed class, e.g. defined from t_2 which is the time needed to decay by 2 visual magnitudes from maximum. Speed classes range: very fast ($t_2<10$ d), fast (11-25 d), slow (26-150 d), very slow ($t_2>150$ d).

very fast

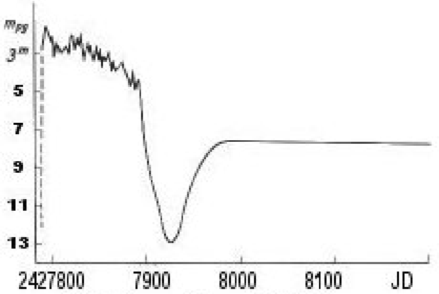


fast



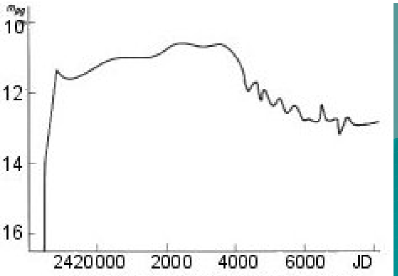
Light Curve of GK Persei from Feb 24, 1901 to May 25, 1901

slow



Light Curve of Nova DQ Her from Dec 28, 1934 to Feb 1, 1936

very slow



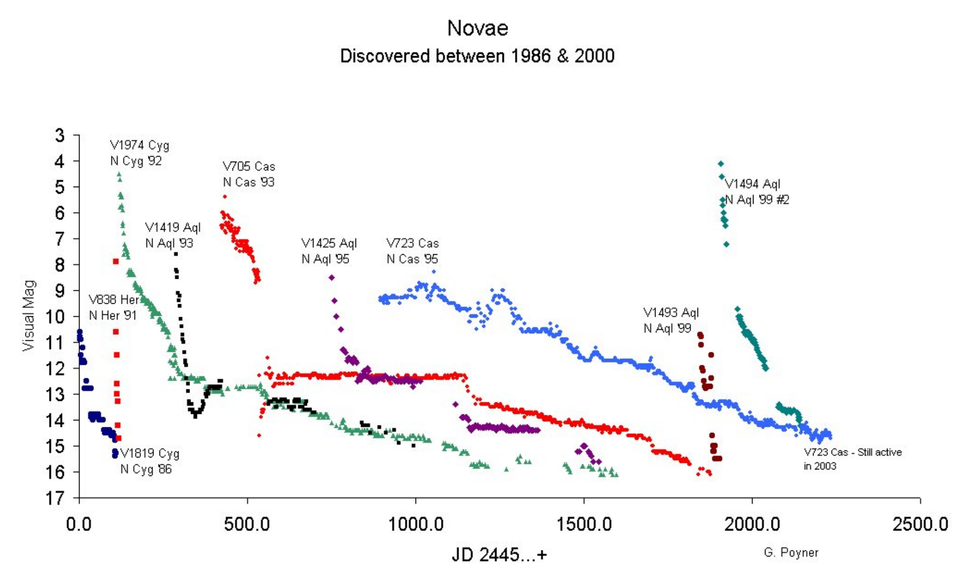
Light Curve of Nova RT Ser from the beginning of 1908 to July 16, 1935

Novae: light curves

There is a relationship between the absolute magnitude at maximum M_V and the speed class of novae: brighter novae have shorter decay times.

In Theory,

Nova duration is determined by the strong wind mass-loss which depends only on the white dwarf mass. Fast novae correspond very massive white dwarfs and very slow novae correspond almost lower mass limit of white dwarfs. This relation is shown in both classical novae and recurrent novae.



Light curves of novae discovered between 1986 and 2000.

Comparison between classical and recurrent novae

	Classical novae	recurrent novae
Recurrent period	around ten thousand of years	several or several-tens of years
Ejecta components	enhancement of carbon and oxygen or other WD material	no enhancement of WD material
WD masses from light curves	wide mass range from low limits to massive WDs	relatively massive WDs (near 1.4 M_{sun})

Theorist suggests they are candidates of Type Ia supernova progenitors (for accreting CO WDs).

Classical novae in the Galaxy

Two distinct nova populations (Della Valle 1992):

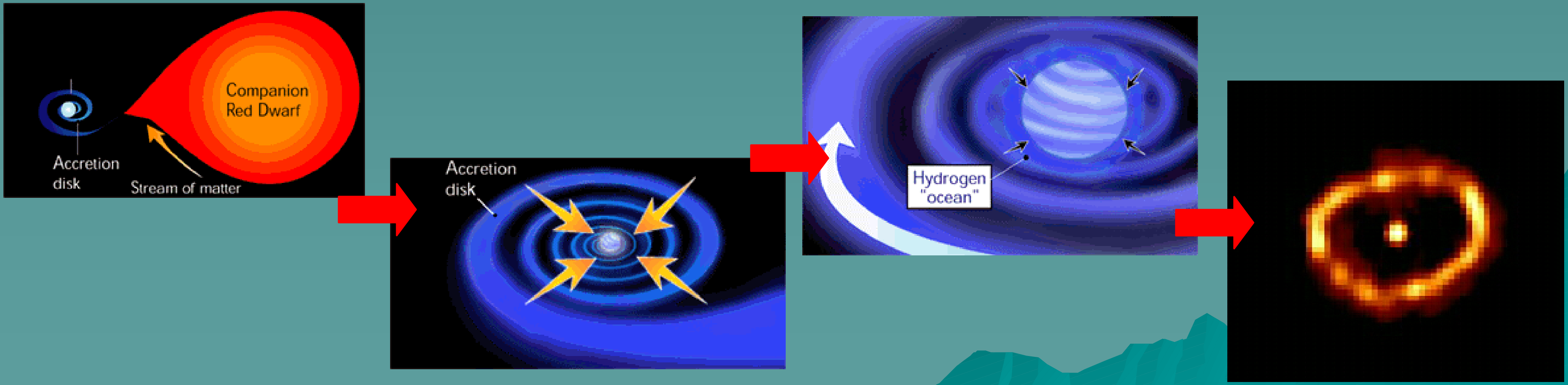
- Disk novae: they are in general fast and bright, the maximum absolute magnitude $M_{v,max}$=-8;
- Bulge novae: slower and dimmer, $M_{v,max}$=-7.

The classification may be according to their early post-outburst spectra (Williams 1992) based on the group of emission lines (either Fe II lines or He and N lines): Fe II-type novae evolve more slowly and have a low level of ionization; He/N-type novae have larger expansion velocities and a higher level of ionization. It is deduced that the faster and brighter He/N novae are concentrated closer to the galactic plane than the slower and dimmer Fe II ones which would preferentially belong to the bulge (Della Valle 2002).

Nucleosynthesis in classical novae

The scenario of classical nova explosions:

A low luminosity WD accretes hydrogen-rich matter in a cataclysmic binary system, as a result of Roche lobe outflow of its main sequence companion. For accretion rates low enough, 10^{-9}-10^{-10} M_{sun}/yr, accreted hydrogen is compressed up to degenerate conditions until ignition, thus leading to thermonuclear burning without control. Explosive hydrogen burning synthesizes some short-life β^+ unstable nuclei (e.g. ^{13}N, $^{14,15}O$, ^{17}F), which are transported by convection to the outer envelope where they are preserved from destruction. The decays of these unstable nuclei lead to a huge energy release in the outer shells which causes the nova outburst, i.e. a visual luminosity increase, accompanied by mass ejection with typical velocities $10^2 - 10^3$ km/s.

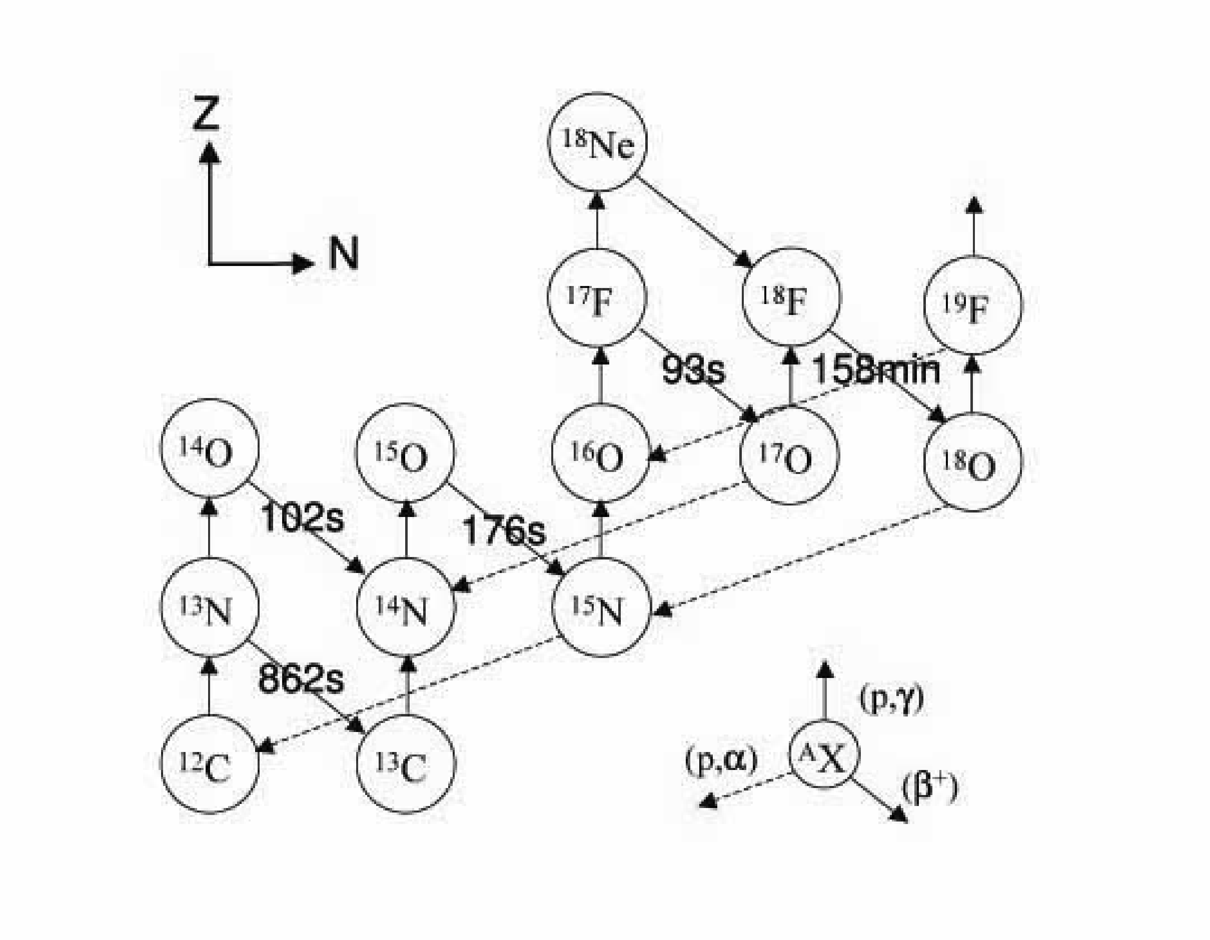


Nova explosion mechanism:

Some relative timescales (Starrfield 1989):

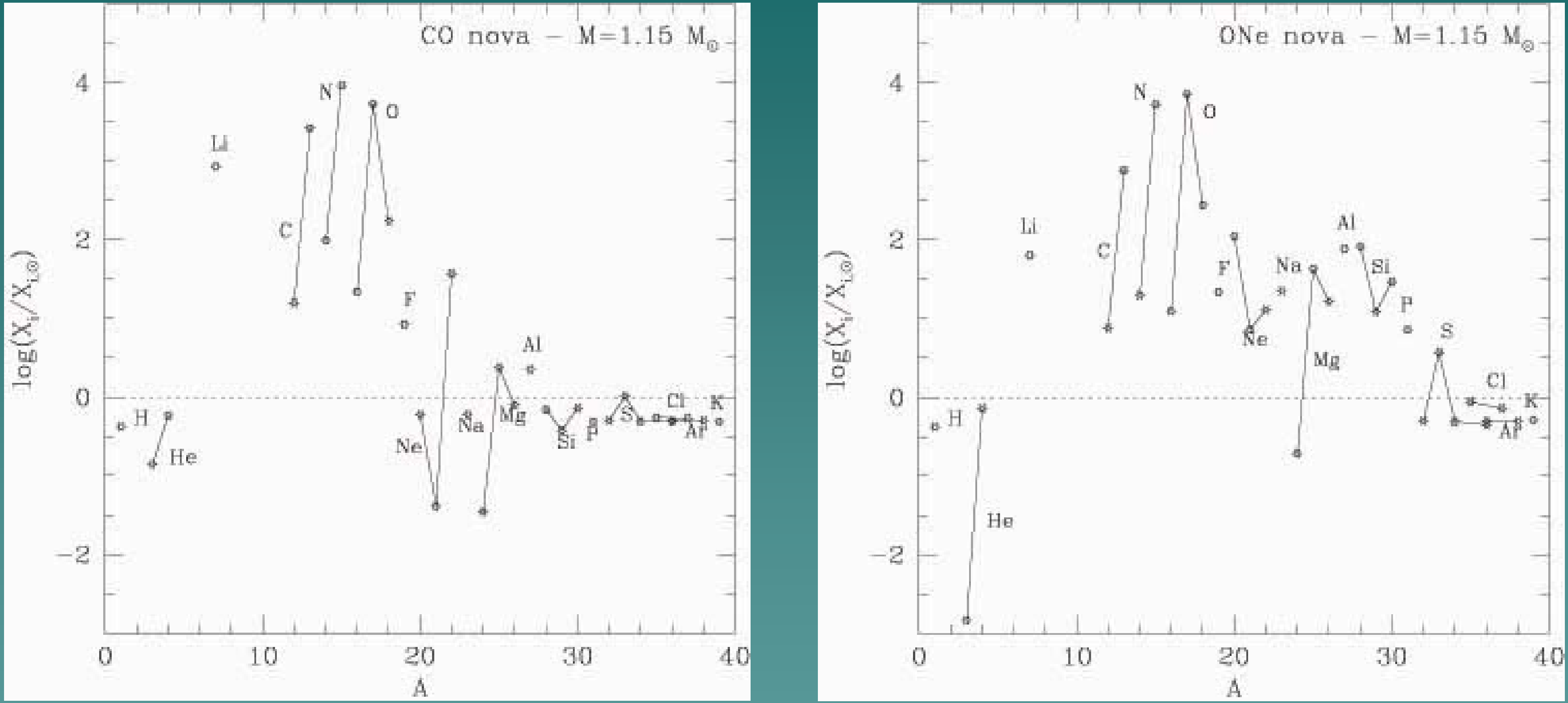
- Accretion timescale: $\tau_{\mathrm{acc}} \sim \mathrm{M}_{\mathrm{acc}}/\dot{\mathrm{M}}$, is of the order of 10^{4-5} yr.
- Nuclear timescale: $\tau_{\mathrm{nuc}} \sim C_{\mathrm{p}}T/\epsilon_{\mathrm{nuc}}$, a few seconds at peak burning, C_p is the specific heat, ϵ_{nuc} is the nuclear energy generation rate.
- Dynamical timescale: $\tau_{\mathrm{dyn}} \sim H_{\mathrm{p}}/c_{\mathrm{s}} \sim (1/g)\sqrt{P/\rho}$, H_p is the pressure scale height, c_s the local sound speed.

During the accretion phase, $\tau_{\mathrm{acc}} \leq \tau_{\mathrm{nuc}}$, accretion proceeds and the envelope mass increases. When degenerate ignition conditions are reached, degeneracy prevents envelope expansion, the thermonuclear runaway occurs, $\tau_{\mathrm{nuc}} \ll \tau_{\mathrm{dyn}}$, temperature increases, specially if the envelope is enriched in CNO elements, enhancing the contribution of the CNO cycle to hydrogen burning. Since the envelope cannot readjust itself through expansion, temperature and nuclear energy generation rate continue to increase without control.



Scheme of the carbon-nitrogen-oxygen (CNO) cycle of the hydrogen burning which operates out of equilibrium in nova outbursts.

The main goal of the theoretical models of nucleosynthesis in novae is to reproduce the observed abundances in nova ejecta.



Logarithmic overproduction factors with respect to solar abundance versus mass number of elements (Jose & Hernanz 1998). Left panel: CO nova of 1.15 M$_{sun}$; right panel: ONe nova of 1.15 M$_{sun}$.

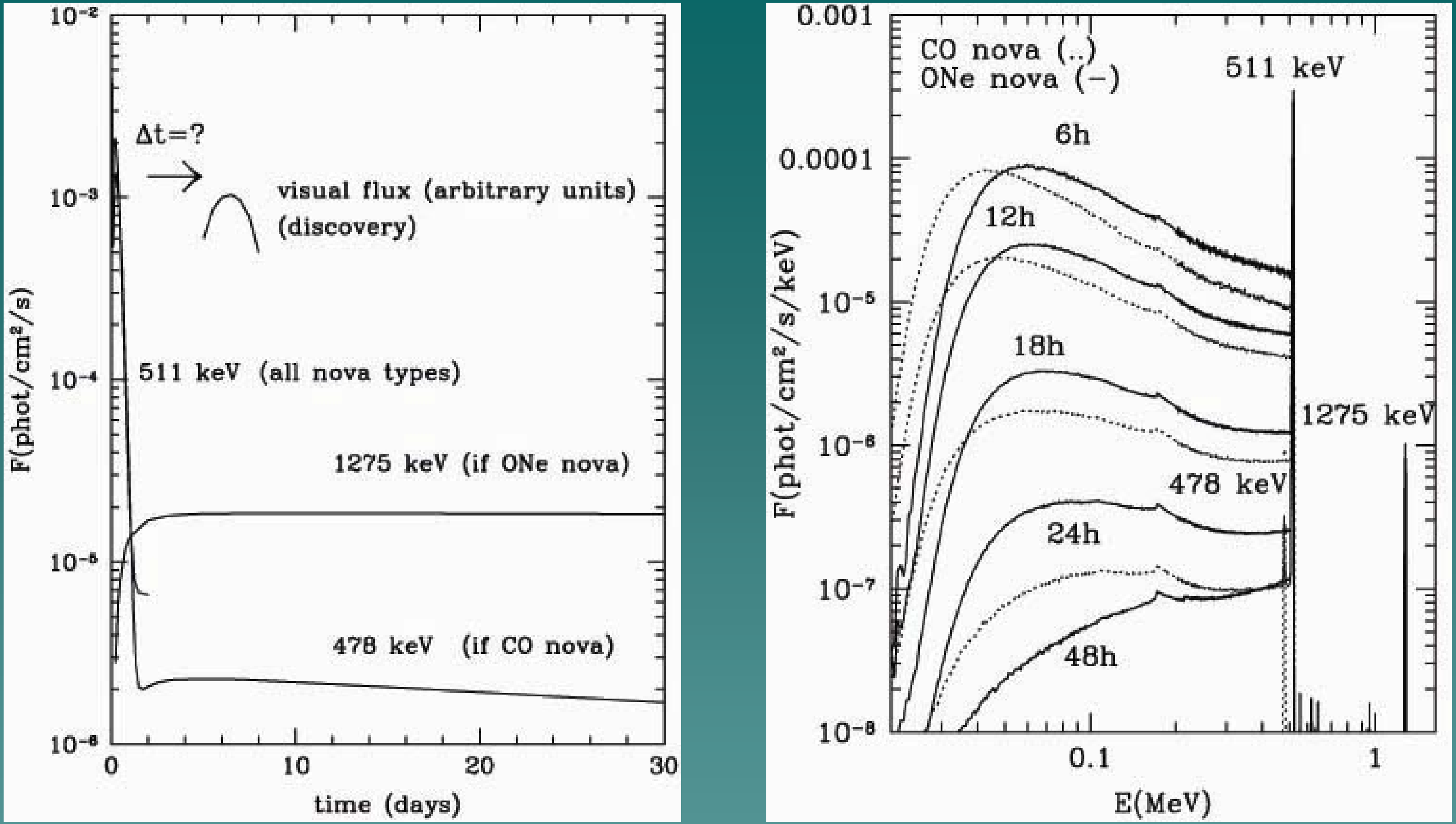
High energy emission from novae

- Gamma-rays

An important property of nova ejecta is the presence of radioactive nuclei, so novae are potential gamma-ray emitters. The very short-lived isotopes are responsible for the nova explosion, other long-lived nuclei have some relavance to the radioactivity of the Galaxy and the gamma-ray emission of individual novae.

Short-lived nuclei ^{13}N (t=862 s) and ^{18}F (t=158 min) are produced in similar quantities in all nova types, whereas ^{7}Be (t=77 d) is mainly produced in CO novae, ^{22}Na (t=3.75 yr) and ^{26}Al (t=10^6 yr) are produced in appreciable amounts only in ONe novae.

The short-lived nuclei (i.e. ^{13}N and ^{18}F) produce an intense burst of gamma-ray emission, with duration of some hours, which consists of 511 keV annihilation line and a continuum between 20 and 511 keV. But the emission occurs before the nova visual maximum, it may requires a 'posteriori' analyses, with large field-of-view instruments monitoring the whole sky within the energy range.



(Gomez-Gomer et al. 1998; Hernanz et al. 1999)

Left panel: gamma-ray light curves of three possible lines as compared with visual light curve.
Right panel: early temporal evolution of gamma-ray spectra of a CO nova (dotted) and an ONe (solid) nova at a distance of 1 kpc.

X-rays

The nova GQ Mus was first detected by the EXOSAT satellite as a soft X-ray emitter (0.04-2 keV), 460 days after optical maximum (Ogelman et al. 1983). ROSAT (0.1-2.4 keV) detected again the source even 9 years after the explosion (Ogelman et al. 1993). Nova Cyg 1992 was also detected by ROSAT as a bright soft X-ray source, the emission lasted 18 months (Krauther et al. 1996).

The soft X-ray emission is interpreted as the photospheric emission of the hot white dwarf, hosting a remaining hydrogen burning shell, which becomes visible when the expanding envelope is transparent. The luminosity in soft X-rays is close to L_{Edd} (10^{38} erg/s), possibly contributing to a population of luminous supersoft sources.

The turn-off times of novae deduced from soft X-ray and ultraviolet observations, range from 1-5 years, which is much shorter than expected from the nuclear burning timescale of the generally accepted mass of the remaining envelope. Thus, some extra and unknown mechanism should remove mass after or during the nova outburst.

Luminous supersoft sources

- Discovery

The luminous supersoft X-ray sources (SSS) were discovered in the Large and Small Magellanic Clouds (LMC, SMC) with Einstein satellite around 1980 (Long et al. 1981; Seward & Mitchell 1981).

The first four SSS: CAL 83 and CAL87 in the LMC;
1E0035.4-7230 and 1E0056.8-7154 in the SMC

The luminous SSS were recognized as an important new class of intrinsically bright X-ray sources based on ROSAT observations (Trumper et al. 1991; Greiner et al. 1991). The X-ray luminosities are of the order of the Eddington limit (generally $L_X = 10^{36-38}$ erg/s) with the extremely soft X-ray spectra, peaking at energies in the range of 15-100 eV, on average of order 30-40 eV which are below the energy limit of ROSAT detectors. The temperature is two orders of magnitude lower than that of the classical X-ray binaries (containing NS or BH).

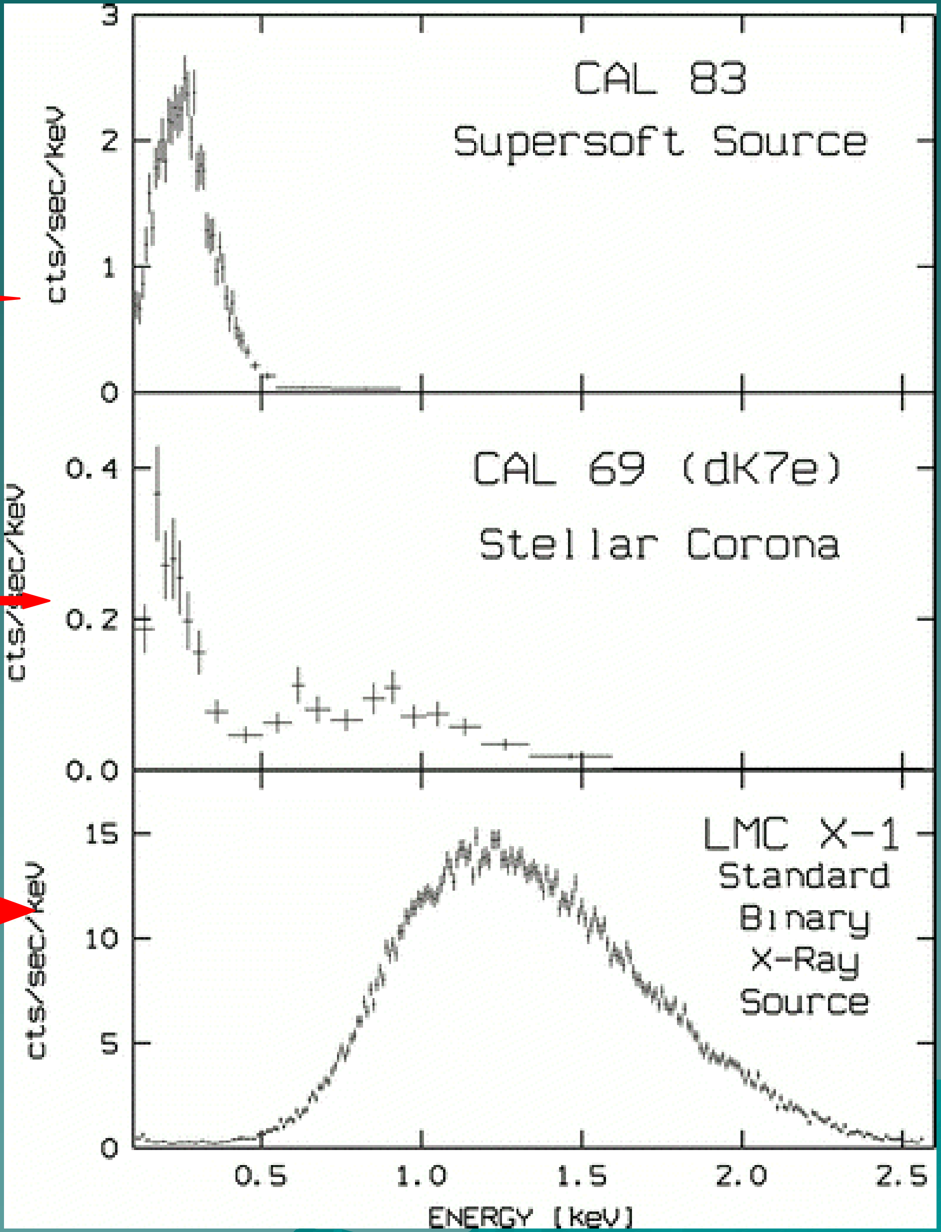
ROSAT PSPC count spectra Of three objects in the LMC Field:

The SSS CAL 83

The foreground star CAL 69

The black hole candidate LMC X-1

(Trumper et al. 1991)

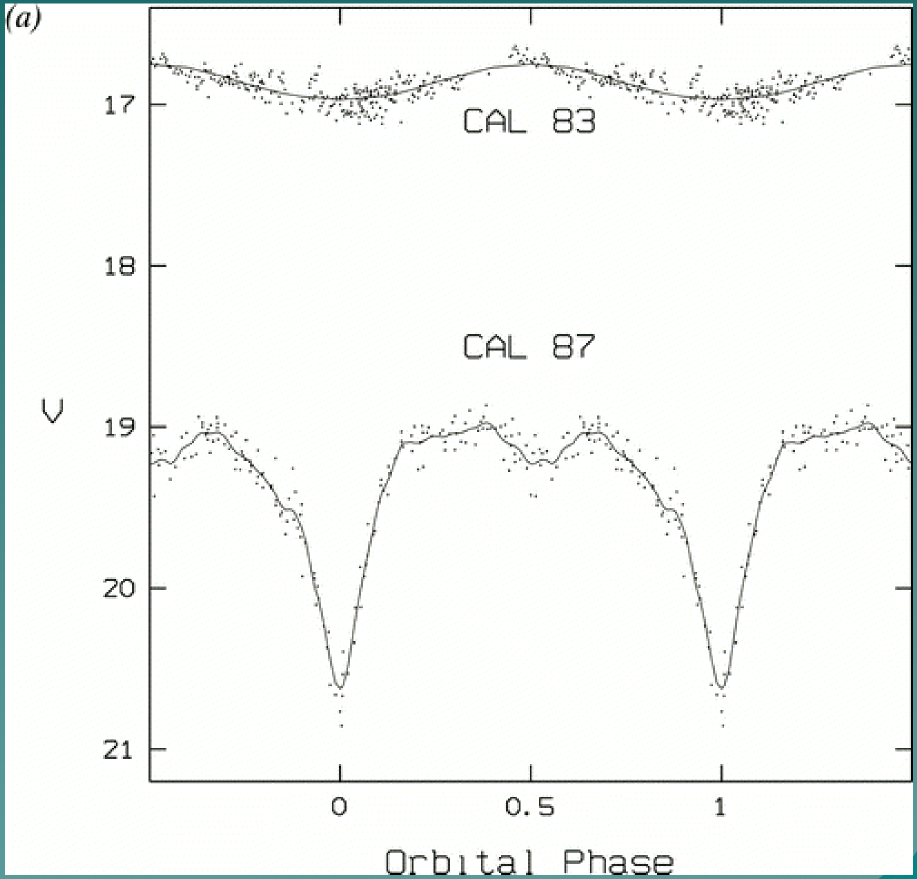


The binary nature of SSS

The regular photometric variations with a orbit period were discovered.

CAL 83: P=1.04 d
(Smale et al. 1988)

CAL 87: P=10.6 h
(Cowley et al. 1990;
Schmidtke et al. 1993)



Optical V-band light curves of CAL 83
And CAL 87.

SSS: nuclear burning on the surface of a WD?

First, using Stefan-Boltzman's law: $L = 4\pi R^2 \sigma T^4$,

then we find: $R = 7\times10^8 (L_{37})^{1/2} (T_{eff}/40\ \mathrm{eV})^{-2}$ cm , similar to a WD radius.

Energy gain of accretion to 1 M_{sun} BH, NS, WD compared with that of hydrogen nuclear burning

Compact object	energy release	
	accretion	nuclear burning
BH	(0.1-0.42) mc^2	-
NS	0.15 mc^2	0.007 mc^2
WD	0.00025 mc^2	0.007 mc^2

For BH/NS systems, the nuclear fusion is negligible, but in the case of a WD, the energy release by accretion is 30 times smaller than the energy release by nuclear fusion with the same amount of matter.

WD models for SSS

- WD + (1.3-2.5)M_{sun} main-sequence stars in close binaries:

  Accretion rate is in the range of (1-4)x10^{-7} M_{sun}/yr;

  steady nuclear burning provides the stable soft X-rays, and in this accretion rate, soft X-rays can escape;

  CAL 83 and CAL 87 lie in this case.

- WD in symbiotic systems:

  Accretion rate is around 10^{-7} M_{sun}/yr, steady nuclear burning on the WD can take place. The SSS phase could last about 1 million years.

- Novae (classical and recurrent novae)

  Some novae appear as transient luminous SSS in a limited period, generally up to 10 years, after the nova outbursts. Soft X-rays could be observed only after the envelope becomes transparent enough.

Selection of luminous SSS in X-ray surveys

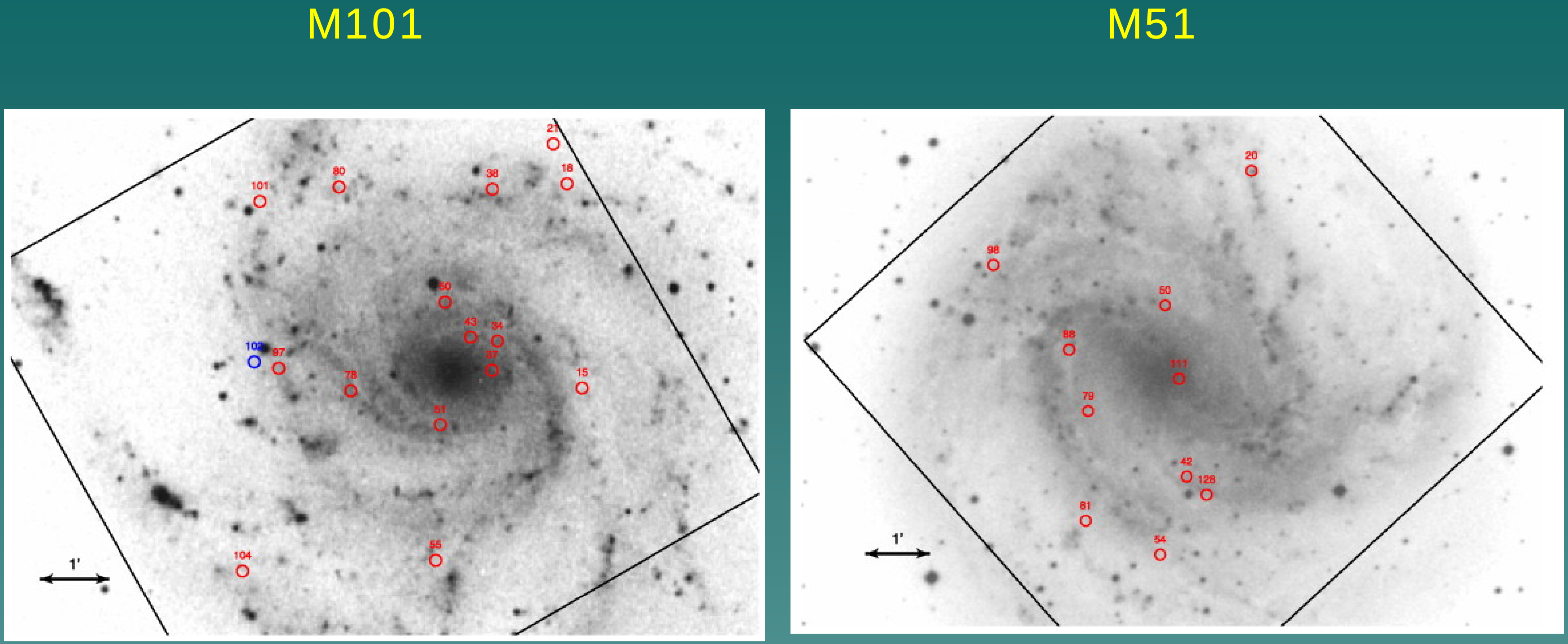
ROSAT all sky survey identified about 35 SSS in the Galaxy, LMC, SMC, M31, NGC 55 (Greiner 1996). Chandra studies also detected more SSS in the Galaxy, M31, LMC/SMC, and SSS in other nearby galaxies: M101, M51, M83, NGC 4697 (Di Stefano et al 2003, 2004).

Selection of luminous SSS (>10^{36} erg/s) if one of following conditions is met: (see Di Stefano & Kong astro-ph/0311374)

- The spectrum is well fit by a blackbody model with kT<175 eV;
- The spectrum is well fit by a power-law model with a index α >3.5;
- Whatever the best fit model, less than 10% of the energy is carried by photons with energy greater than 1.5 keV.

Contamination of other sources:

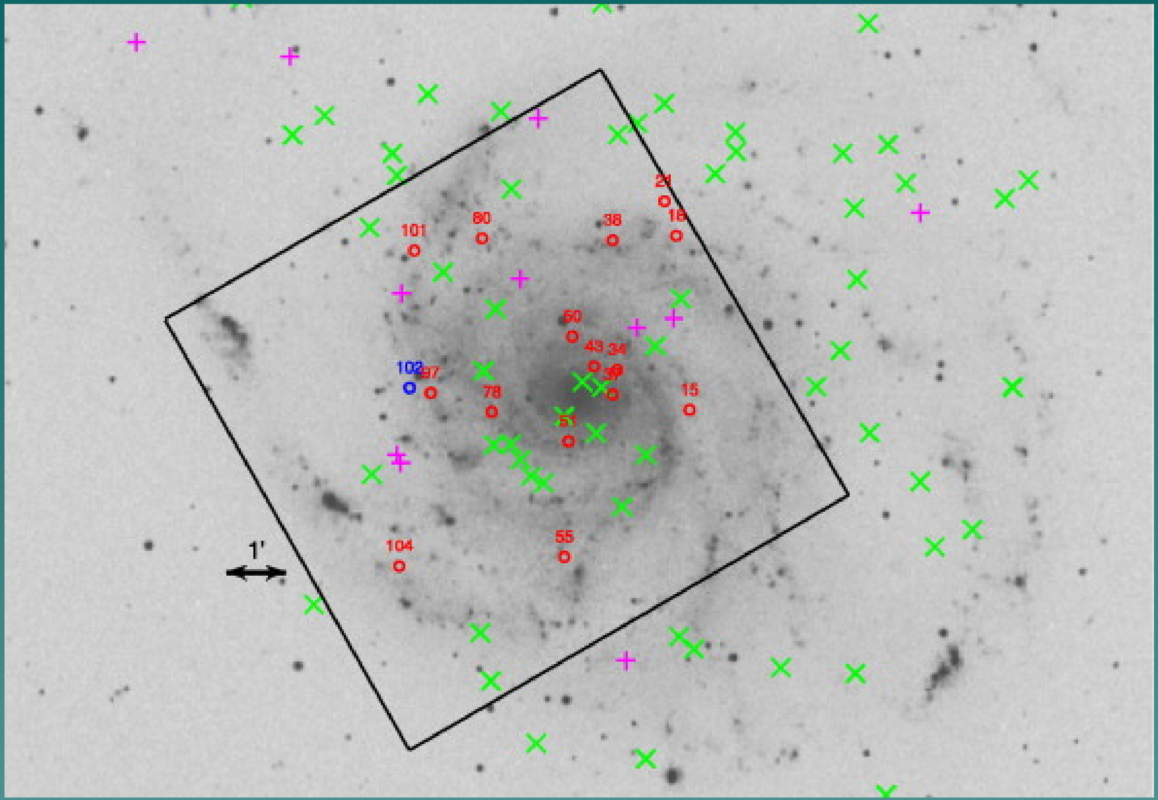
Transient X-ray pulsars in outburst
Intermediate mass black holes
Stripped cores of tidally disrupted stars in the galactic center region
Supernova remnants (SNR)
Foreground stars
Distant soft active galactic nuclei (AGN)



Chandra field of view overlaid with the SLOAN survey images of M101 and M51 (Di Stefano & Kong 2003). The red circles are the selected SSS candidates.

SSS candidates probably show a spiral distribution in the galaxies.

The positions of planetary nebulae (PNe, green crosses) and novae (purple crosses) overlaid on the SLOAN image of M101.
The red circles are the selected SSS candidates.



M101 (Di Stefano & Kong 2003)

As expected, novae and PNe cover the disk of the galaxy. But some of them located away from the arms and also away from regions with bright blue clumps.

In contrast, the 16 SSS candidates are largely absent from these open spaces and tend to be located within 10” of bright blue clumps. SSSs probably associate with the young population.

Summary

- Nuclear burning could occur after the hydrogen-rich matter is accreted from donor stars to the surface of white dwarfs. The nuclear burning in a steady or unstable state depends on the accretion rates.

- Two important applications:

  Novae

  Luminous X-ray supersoft sources

Thank you for your attention!

All the references can be found in the ADS
http://adswww.harvard.edu/
and the astro-ph preprint server
http://www.arxiv.org/