ASTROPHYSICS OF INTERACTING BINARY STARS

Lecture 7

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Close Binary Stars

- Existence Of Accretion Disks In Close Binary Systems
- The zoo of close binary systems
- Cataclysmic Variables (CVs)
- Low-Mass X-ray Binaries (LMXBs)
- High-Mass X-ray Binaries (HMXB)
- Contact Binaries
- Symbiotic Stars, etc

Existence Of Accretion Disks In Close Binaries

- Members of close binary systems might undergo mass transfer at different stages in their evolution.
- In an evolution which starts with both components on the main sequence, it is always the more massive star evolves faster and thus fills its critical Roche lobe first and starts transferring mass to its companion.
- In many cases, the primary's remnant after the first mass transfer will later become a compact star.
- If in such a system at a later time the secondary starts transferring mass back to the now compact primary, this will almost invariably result in the formation of an accretion disk around it.

Existence Of Accretion Disks In Close Binaries

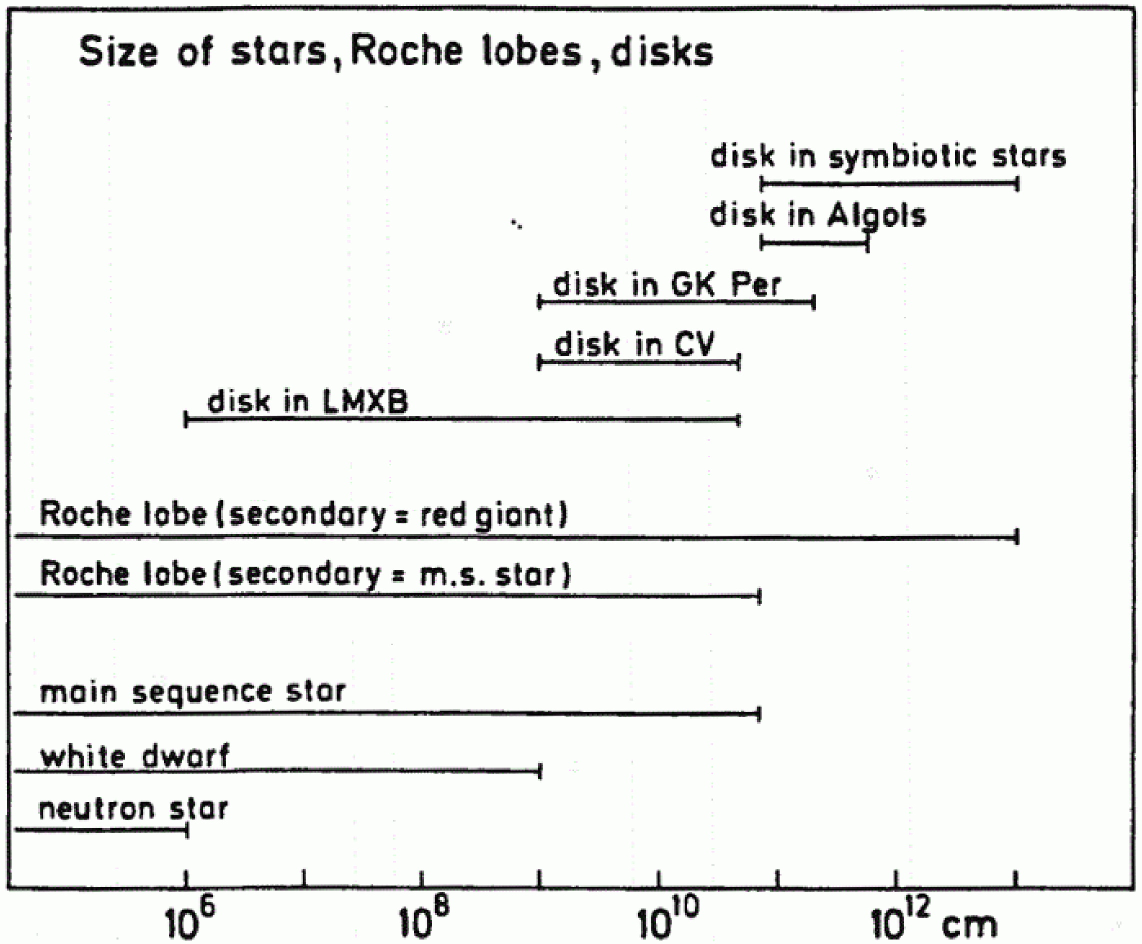
- We expect the formation of an accretion disk wherever the specific angular momentum of material flowing towards a star is so high that it cannot directly fall on it.
- The more compact and therefore the smaller this star, the better is the chance for the formation and persistence of an accretion disk.
- Apart from the frequent combination compact star/main sequence star we find also binaries with a larger separation containing a compact star and a star which has reached a more advanced evolutionary stage (e.g. GK Per or some long-period low-mass X-ray binaries).
- The closest systems are the ones which consist of two compact stars.
- Besides the accretion via Roche lobe overflow there is also the possibility of accretion from a stellar wind. This is particularly relevant for detached systems consisting of an O/B star and a neutron star or a black hole (massive X-ray binaries).

The zoo of close binary systems

secondary / primary	main-sequence star *)	evolved star **)	white dwarf	neutron star or black hole
main-sequence star *)	[binary T Tauri stars] [RS CVn stars] Algols (AD) (TAD) {W UMa stars = contact systems}	symbiotic stars Type I as e.g. CI Cyg, Z And, AR Pav (AD) Algols (AD), (TAD)	*) main-sequence star or slightly evolved **) evolved star, but not yet a compact star [ ] detached systems	
evolved star **)	[Wolf-Rayet binaries] [binary planetary nebulae]		(AD) evidence for an accretion disk (TAD) evidence for a transient accretion disk	
white dwarf	[pre-cataclysmic binaries] non-magnetic CVs: UX UMa stars (AD) dwarf novae (AD) DQ Her stars (AD) AM Her stars	long period CVs as GK Per (AD) recurrent nova (AD) symbiotic stars (AD) symbiotic novae (AD)	[double white dwarfs] AM CVn stars (AD)	
neutron star or black hole	massive X-ray binaries (AD) (wind accretion) low mass X-ray binaries (AD) HZ Her/Her X-1 (AD) SS 433 (AD)	long period low mass X-ray binaries (AD)	[binary pulsars] 4U1820-30 (AD)	[binary pulsars]

Comments: in semi-detached systems the mass gaining star is listed as the primary
in detached systems the more evolved star is listed as the primary

Accretion Disks In Close Binaries



Accretion Disks In Close Binaries

- **HMXBs:**
  - The donor stars are O or B giants or supergiants, $L_{opt} \sim 10^{37} - 10^{38}$ erg/s, much higher than the UV and optical luminosity of the disks.
- **LMXBs and CVs:**
  - The donor stars are late type, low-mass, faint stars, the accreting compact stars are neutron stars (black holes) and white dwarfs respectively.
  - The processes of mass transfer are similar in these two types of systems, but $L_{opt,LMXB} \geq 100\ L_{opt,CV}$
  - This means that re-absorption of X-rays in LMXB disks is very important.
- **CVs are the best candidates for testing the theory of steady (and unsteady) thin disks.**

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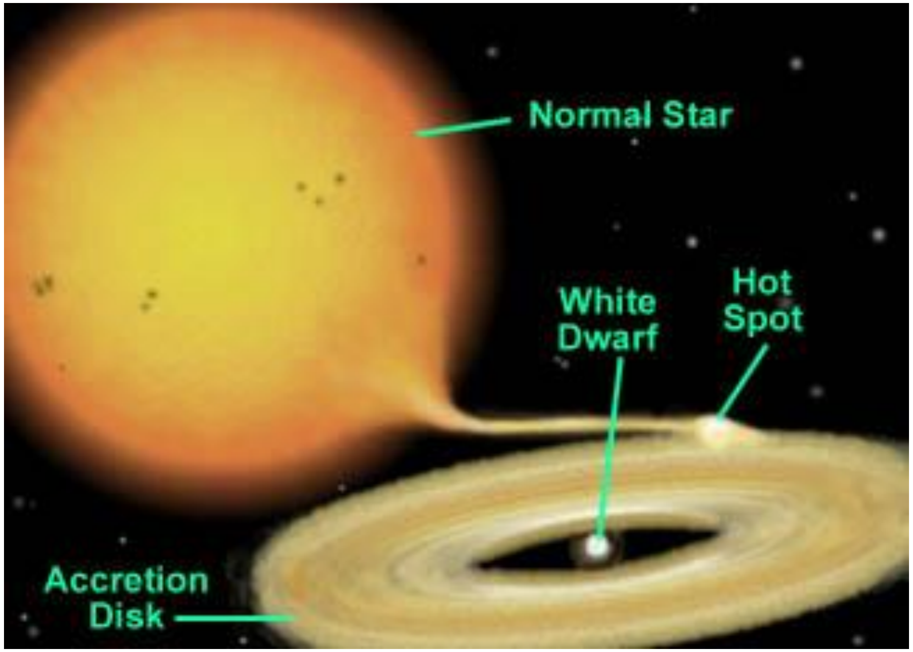
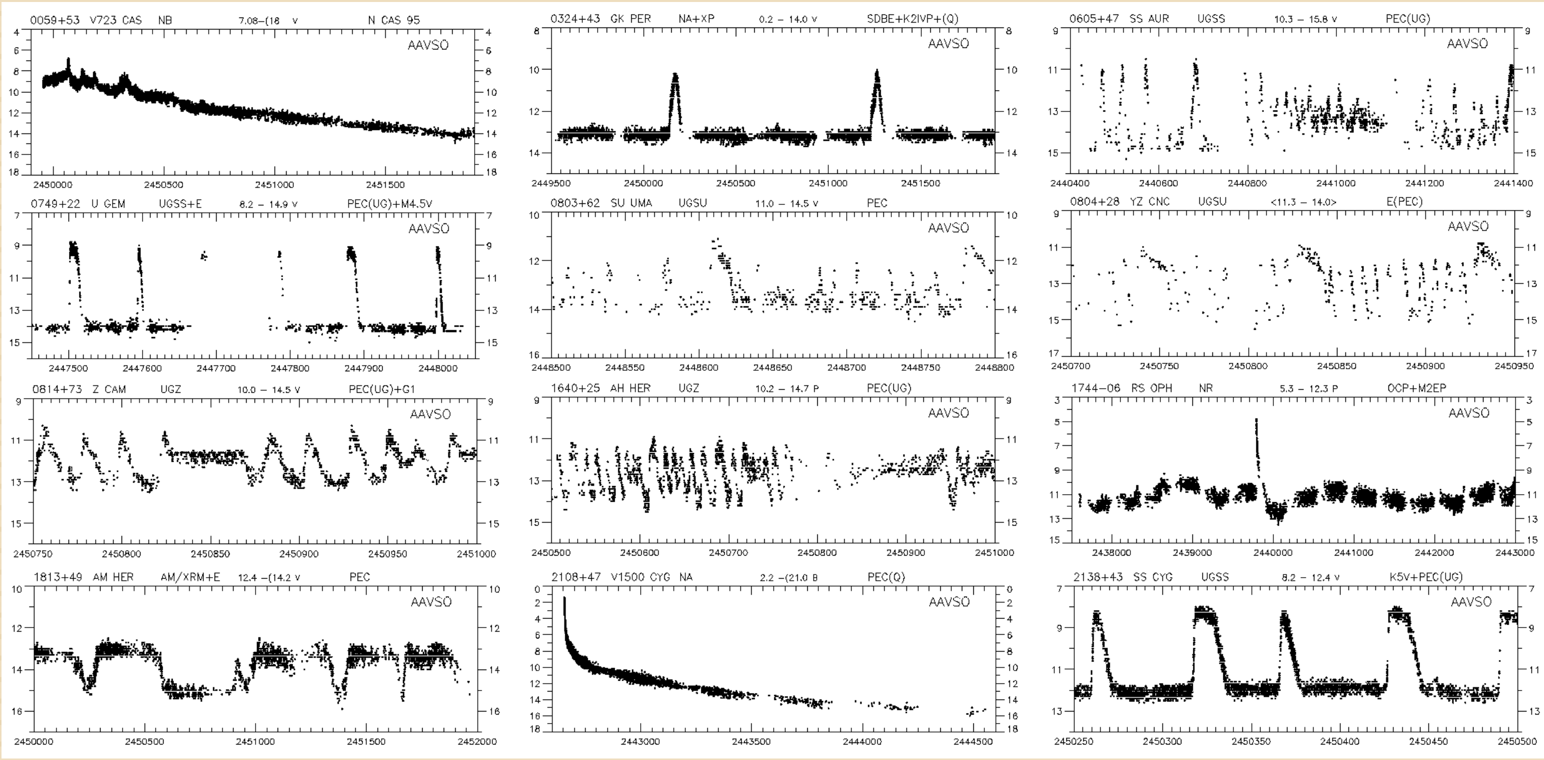
Cataclysmic Variables

Cataclysmic Variables

- Compact close binary systems;
- Red dwarf-type (Sun-like) star – secondary, and a white dwarf – primary;
- Due to evolution, the red star is losing matter to the white dwarf star via an accretion disk (usually but not always);
- Thousands of CVs are known.

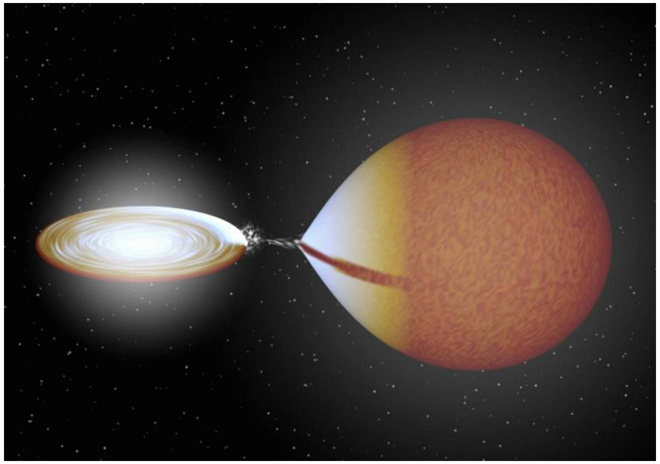


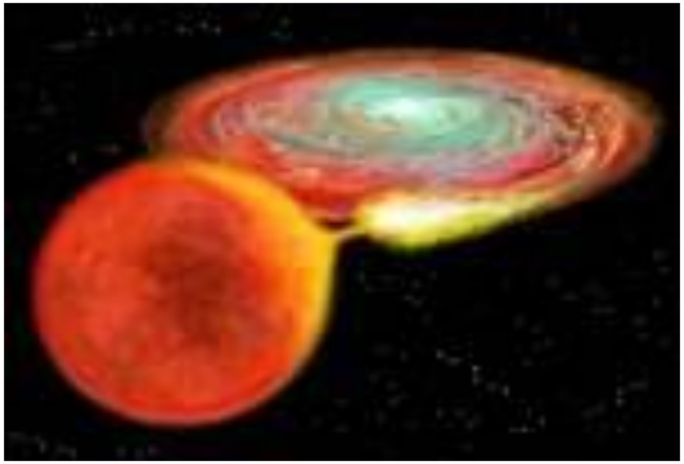


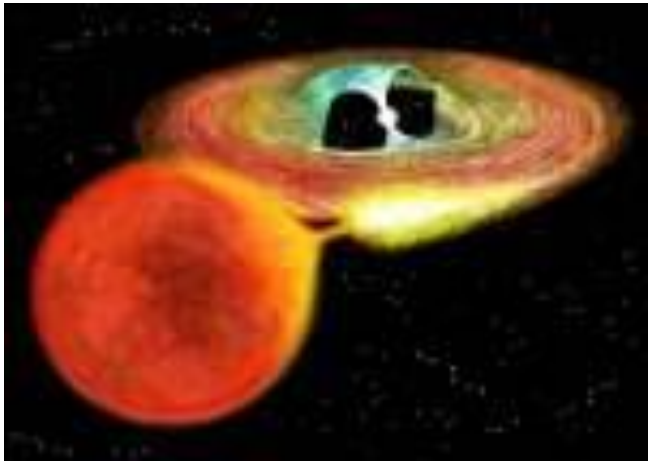
The Many Faces of Cataclysmic Variables

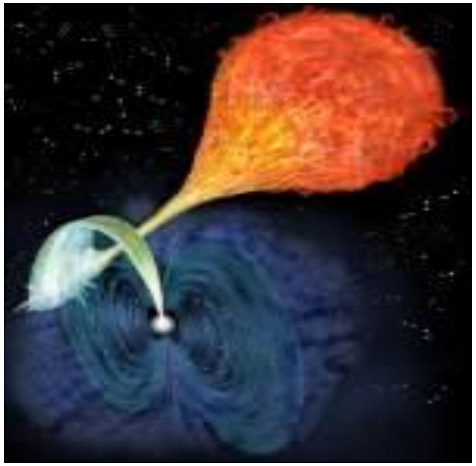
The classification of CVs is rooted in the historical observations of these objects, which concentrated, for obvious reasons, on the spectacular outbursts that characterise these stars and lend them their name.

Classification of CVs









Classification of CVs

- The fundamental observational characteristic of CVs is their variability.
- CVs vary on many different time scales, from long-term variations of years, down to short-term variability of seconds:
  - Long-term variability
    - Classical Nova Eruptions
    - Dwarf Nova Eruptions
  - Variability on orbital timescales
    - Orbital variability
    - Superhumps
  - Short-term variability
    - White Dwarf Spin Period
    - QPO
    - Non-Radial Pulsations
    - Flickering

Classical Novae Eruptions

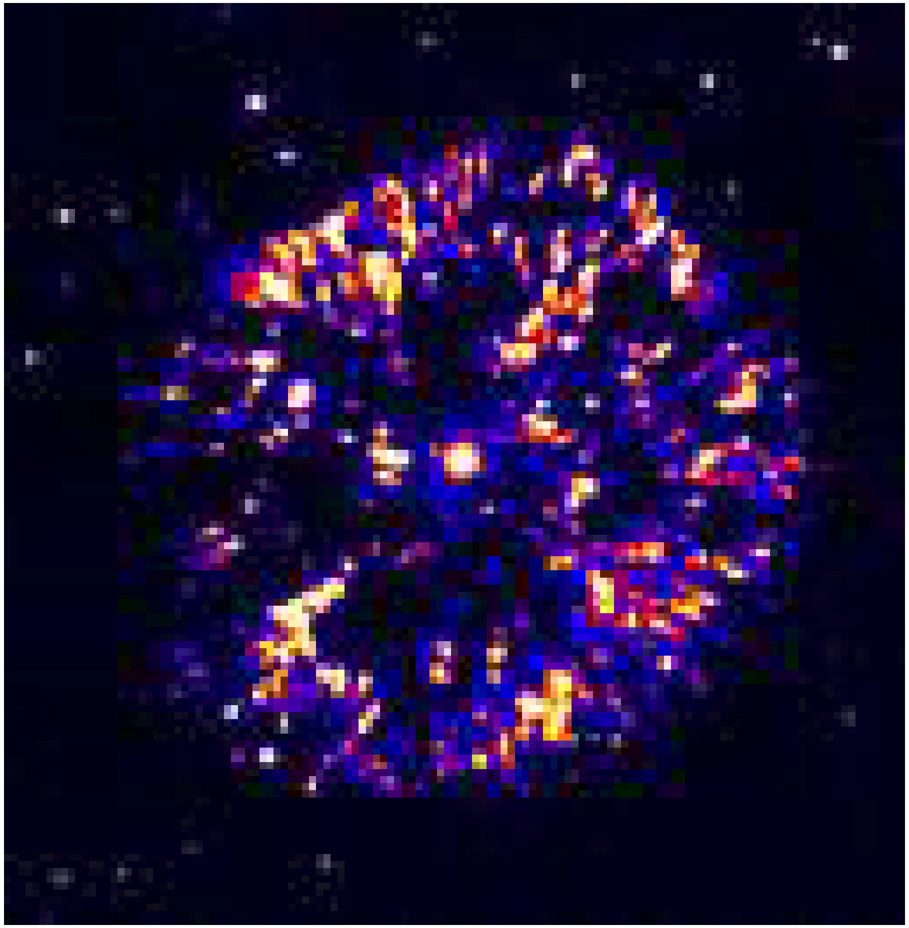
- **Classical novae (CN)** have, *by definition*, only one observed eruption. The range from pre-nova brightness to maximum brightness is from 6 to greater than 19 magnitudes and is strongly correlated with the rate at which the nova fades after maximum.
- **Recurrent novae (RN)** are, *by definition*, previously recognized CN that are found to repeat their eruptions, implying a nova recurrence time scale of approximately 10 years – 100 years.

Classical Novae Eruptions

- Observationally, CN with more massive WDs are brighter during the eruptions, but decline faster, compared to CN with lower WD masses. They are therefore divided into classes depending on how fast they fade.
- The speed class usually being defined by the quantity t_2, which is defined as the time it takes for the nova to decline 2 mag below maximum brightness.
  - The largest amplitude eruptions, of shortest duration, are in very **fast novae** ($t_2 < 10$ days). They decline with a rate up to 0.2 mag d^{-1}.
  - The lowest amplitudes, in eruptions that may last for years (a decline rate of 0.008 – 0.013 mag d^{-1}), are in the **slow novae** ($t_2 > 150$ days).

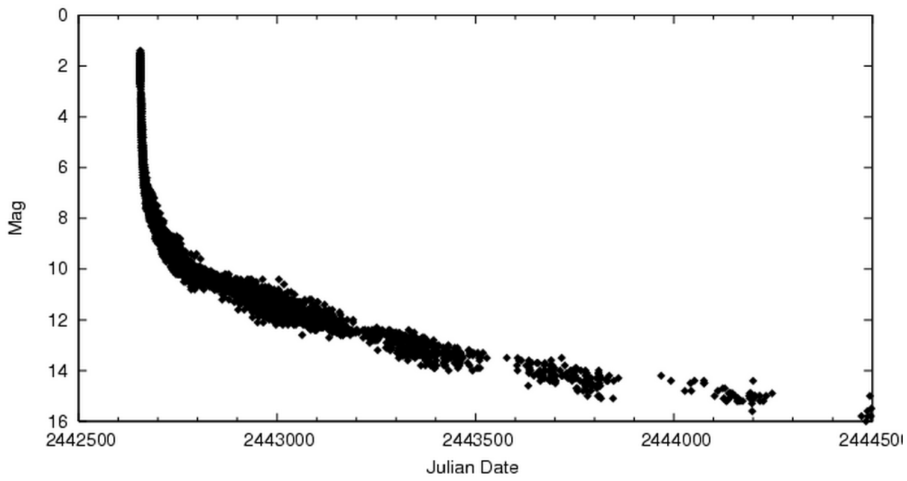
Classical Novae Eruptions

- The nova eruption is due to the accumulation of hydrogen-rich material from the secondary star on the surface of the white dwarf.
- As material is accumulated, the temperature and density of this layer eventually become high enough to start nuclear fusion in a runaway manner.



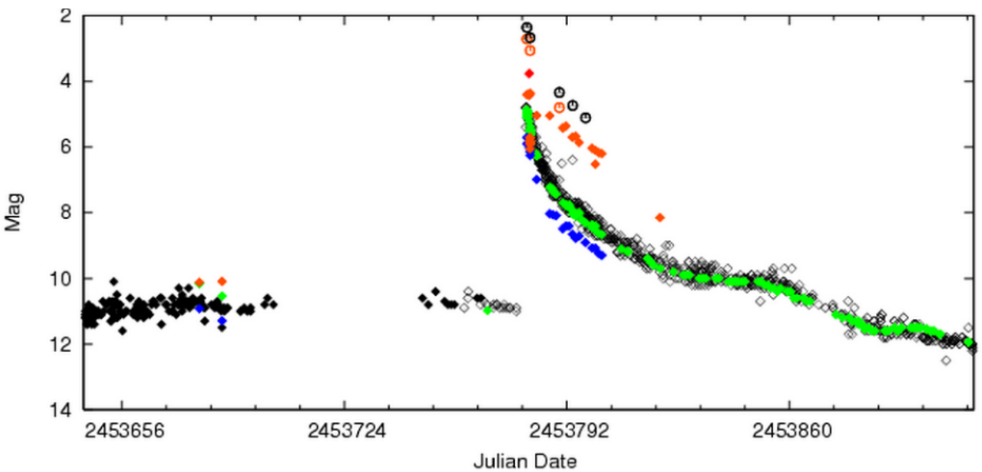
Classical and Recurrent Novae

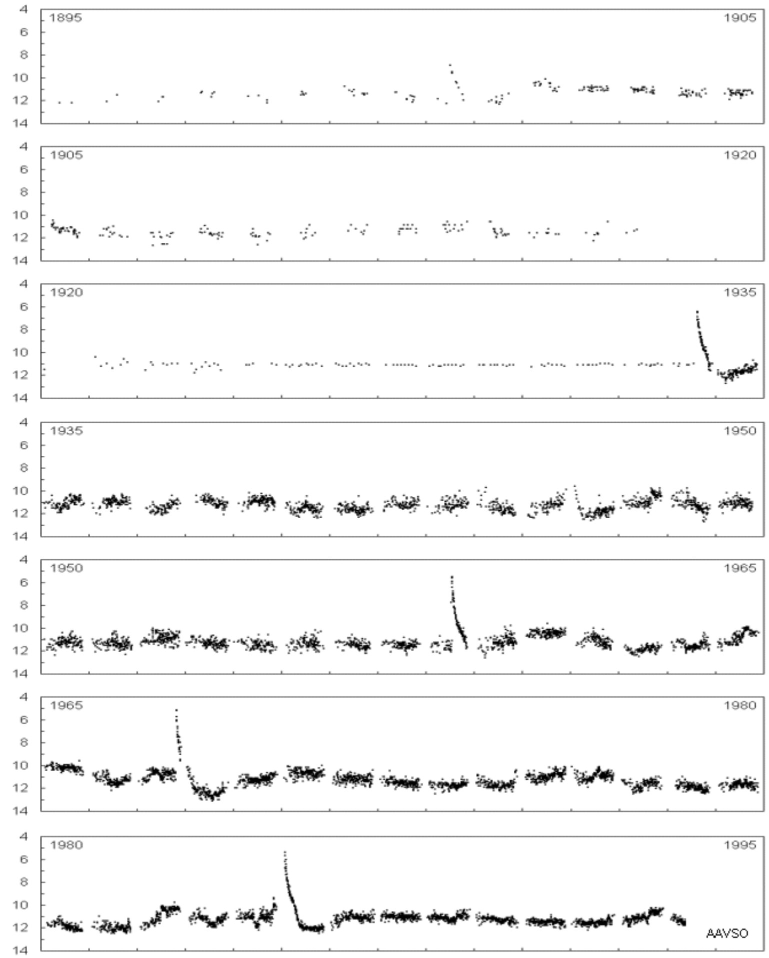
- **V1500 Cygni** or **Nova Cygni 1975** was a bright nova occurring in 1975. It had the second highest intrinsic brightness of any nova of the 20th Century, exceeded only by CP Puppis in 1942.
- V1500 Cyg was discovered on August 29 and reached 1.7 mag on the next day. It remained visible to the naked eye for about a week, and 680 days after maximum the star had dimmed by 12.5 magnitudes.



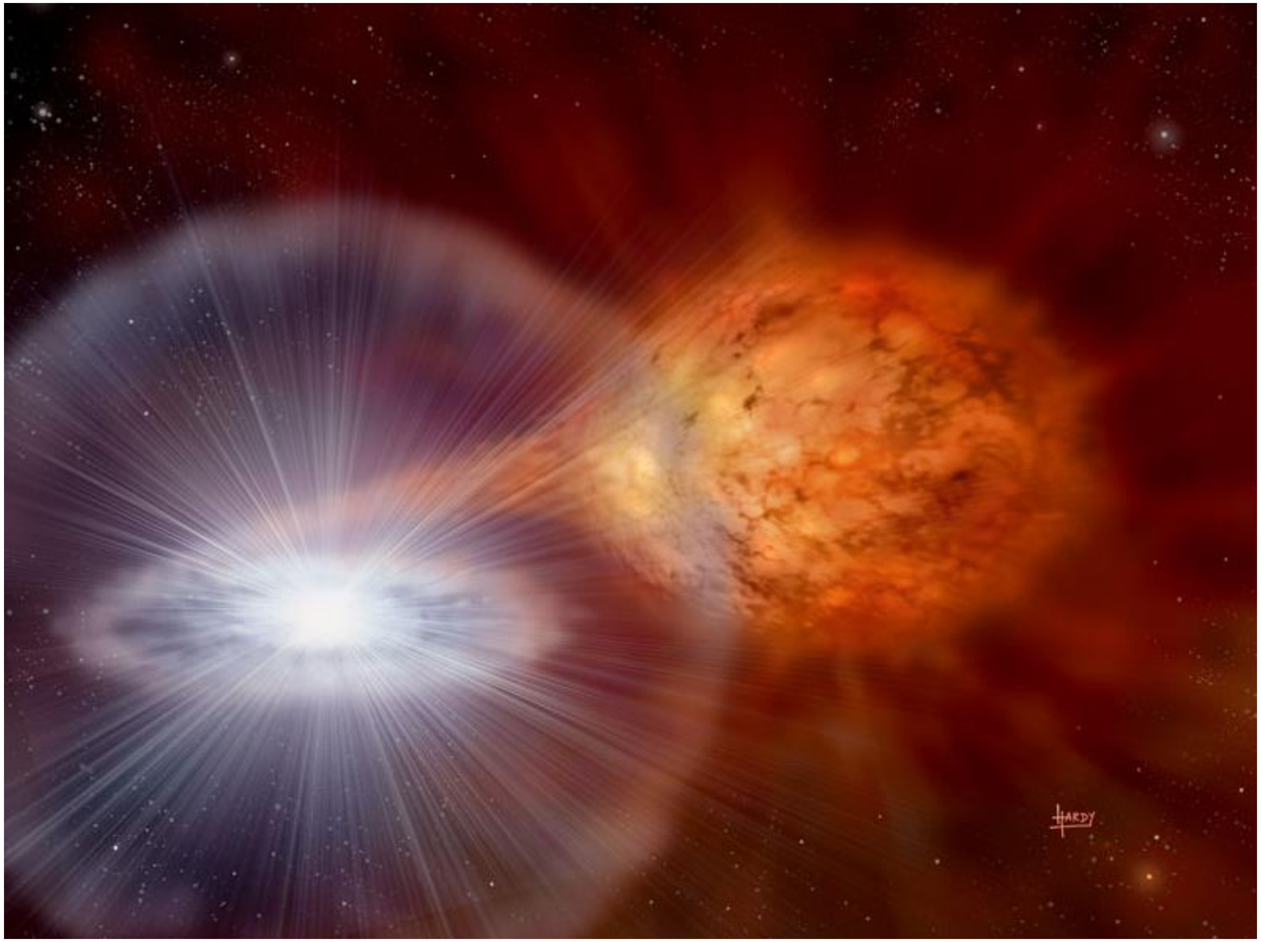
Classical and Recurrent Novae

- **RS Ophiuchi** (*RS Oph*) is a **RN** erupted in 1898, 1933, 1958, 1967, 1985, and 2006 and reached about 5 mag on average.
- In its quiet phase it has an apparent magnitude of about 12.5.





Classical and Recurrent Novae



Explosions from White Dwarf Star RS Oph
Illustration Credit & Copyright: David A. Hardy & PPARC

Classical and Recurrent Novae

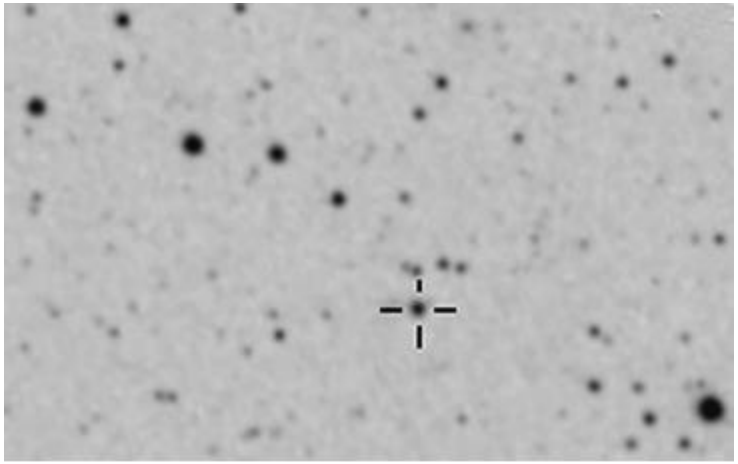
- In theory, the expected mass required to ignite the hydrogen layer on the WD surface should be roughly equal to the total mass of the expelled nova shell. A WD of mass 1 $M_\odot$ will need to accumulate $\approx 10^{-4}$ $M_\odot$, before ignition.
- Assuming an accretion rate of $\dot{M} \sim 10^{-9}$ $M_\odot$ yr^{-1}, the time scale between two such eruptions is about $\sim 10^4 - 10^5$ years.
- A nova recurrence time scale of <100 years can only occur for systems which have a high accretion rate (of order 10^{-7} $M_\odot$ yr^{-1}) and a massive WD ($M_1 > 1M_\odot$).
- In RNe, theWD is expected to gain more mass between eruptions than it ejects during them. This could make the already high WD mass exceed the Chandrasekhar limit ($M_{CH} \approx 1.4$ $M_\odot$). Therefore, RNe are considered as candidate supernova Type 1a progenitors.

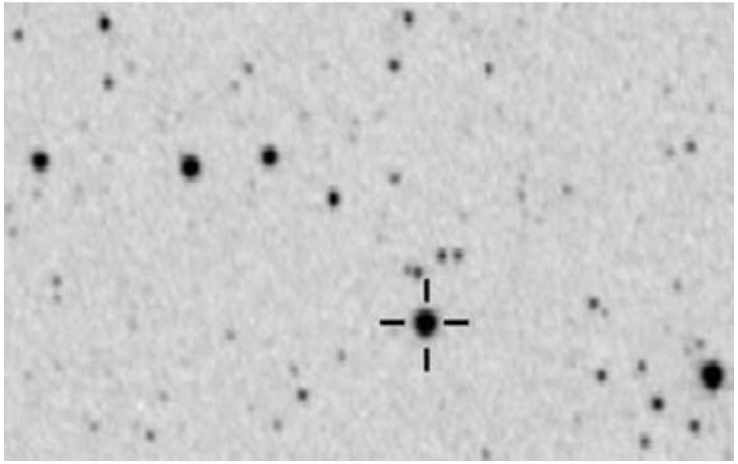
Dwarf Nova Outbursts

- **Dwarf nova (DN)** eruptions are less violent than the CN eruptions. DNe have outbursts of typically 2-5 mag, with some rare objects (e.g., WZ Sge) with up to 8 mag range.
- However, they occur more frequently: the interval between outbursts is from ~10 d to tens of years with a well-defined time scale for each object; the duration of normal outbursts is ~2-20 d, correlated with interval between outbursts.
- The DN outburst is reasonably well understood as a release of gravitational energy, caused by a temporary large increase in mass transfer rate through the disk.

Dwarf Nova Outbursts

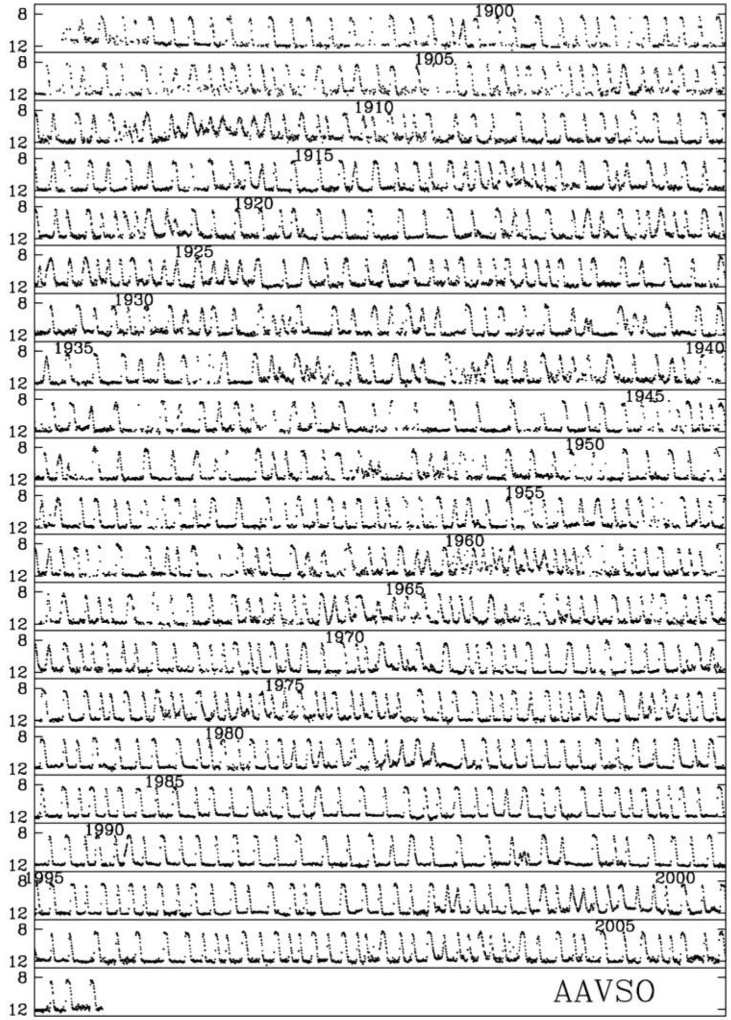
- Since its discovery in 1896, **SS Cygni** has undoubtedly been one of the most observed variable stars in the night sky.
- It undergoes frequent and regular brightness outbursts every 7-8 weeks, rising from 12th magnitude to 8th magnitude for, typically, 1–2 days.





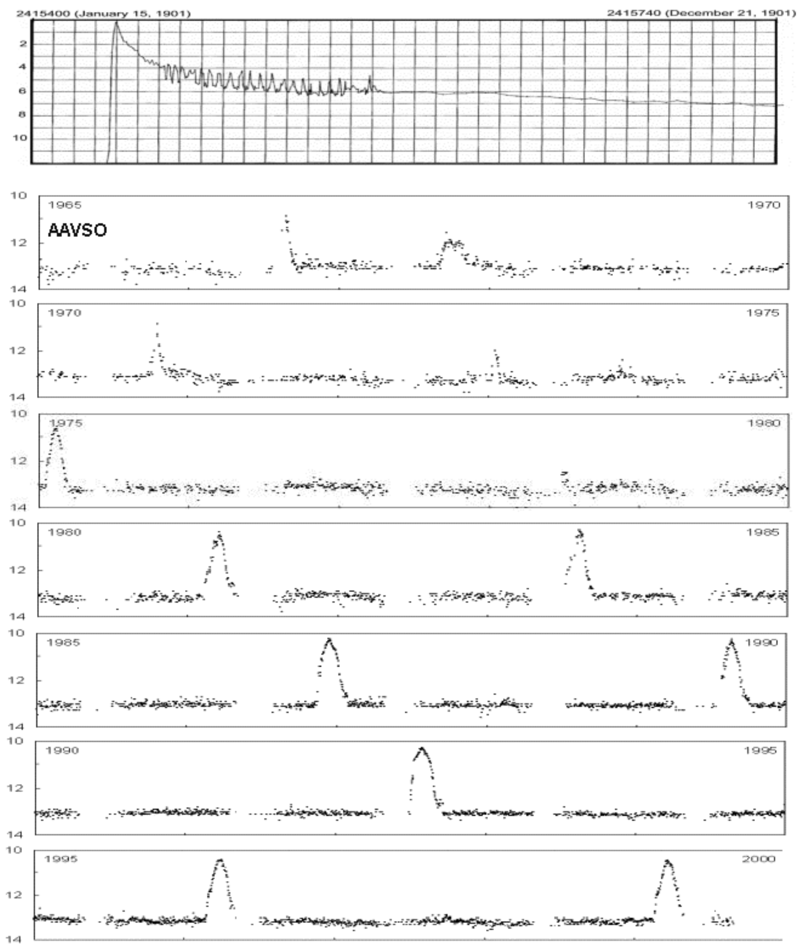
Dwarf Nova Outbursts

- The 1896 discovery of SS Cyg proved to be only the second star of the dwarf nova type, with U Gem being the first of the class with its discovery in 1855.
- In the past century, not a single outburst of SS Cyg has been missed.



SS Cyg (27 Sep 1896–30 July 2006)

Dwarf Nova Outbursts



- A few CNe also show DN outbursts.
- **GK Persei** (**Nova Persei 1901**) was a bright nova occurring in 1901 (max ~0.2 mag). After fading into obscurity at about 12 mag, GK Per began displaying infrequent outbursts of 2-3 mag, occurring about every three years. Thus, GK Persei has changed from a CN to a typical DN.

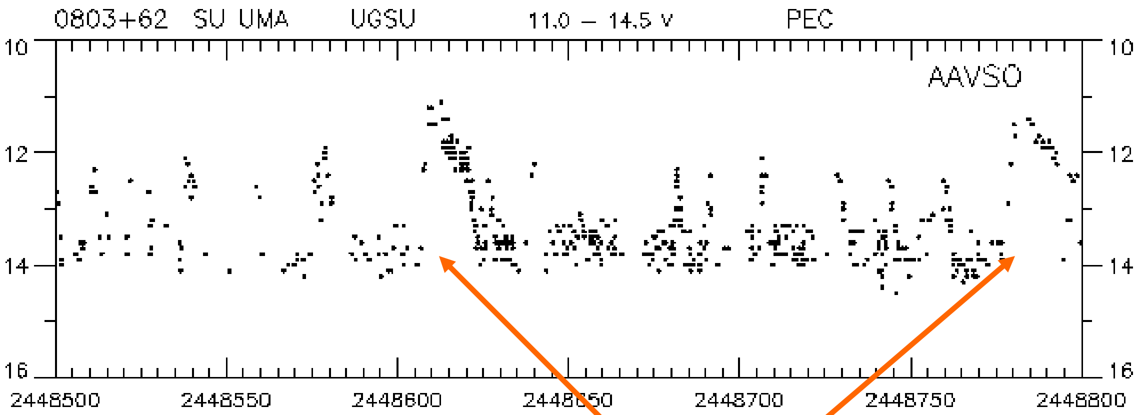
Dwarf Novae

- There exist three distinct subtypes of dwarf novae:
- **SU Ursae Majoris** stars exhibit superoutbursts in addition to regular outbursts;
- **Z Camelopardalis** stars show protracted standstills about 0.7 mag below maximum brightness, during which outbursts cease for intervals of tens of days to years;
- **U Geminorum** stars are the dwarf novae that are neither Z Cam nor SU UMa stars.

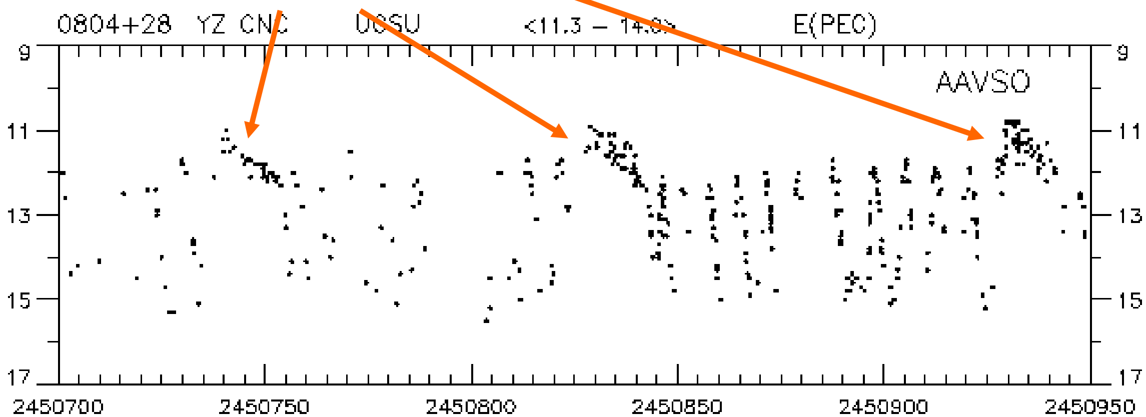
Dwarf Novae: SU UMa stars

- Narrow outbursts of about 1-2 days;
- The superoutbursts are approximately 0.7 mag brighter than normal outbursts and of longer duration (for ~5 times the duration of an ordinary outburst);
- The superoutbursts often appear to be triggered by normal outbursts, as a pause before maximum superoutburst brightness is achieved.
- Superhumps seen during superoutbursts;
- Subtype: WZ Sagittae

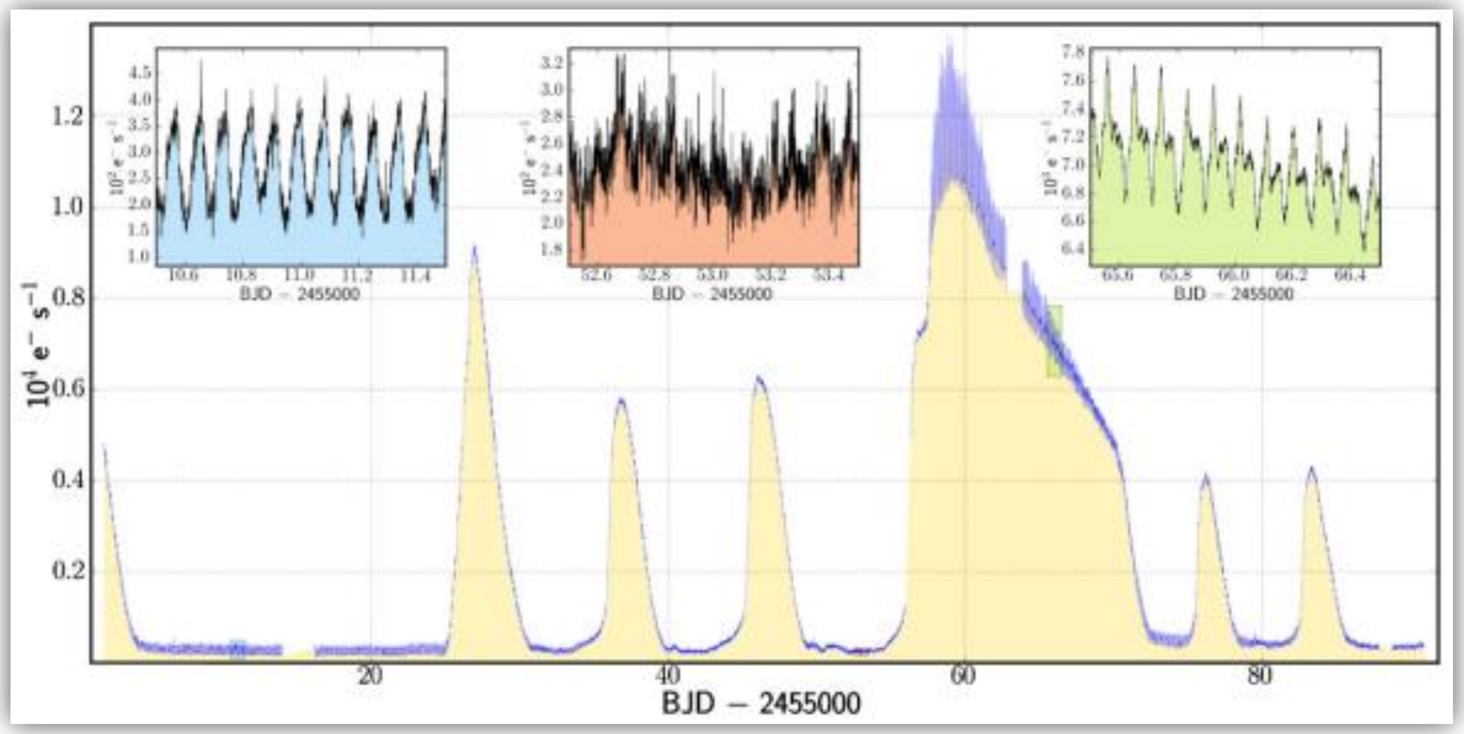
Dwarf Novae: SU UMa stars



Superoutbursts

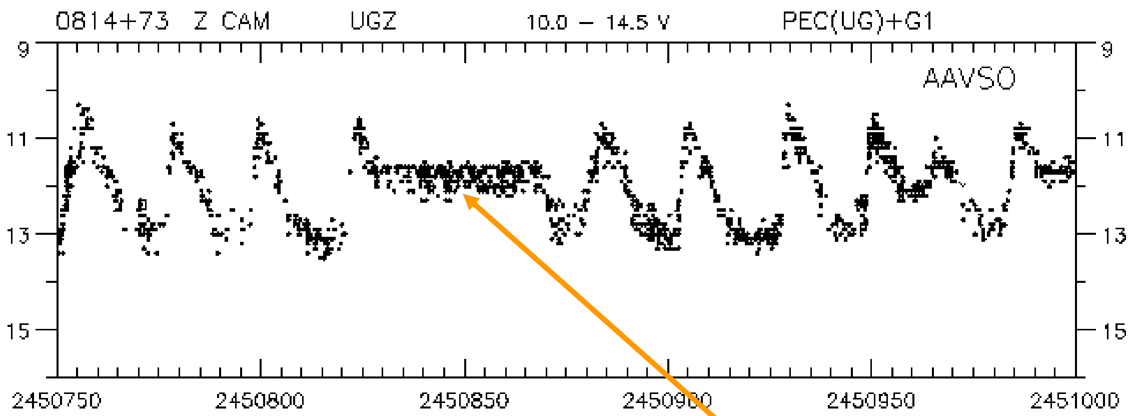


Dwarf Novae: SU UMa stars

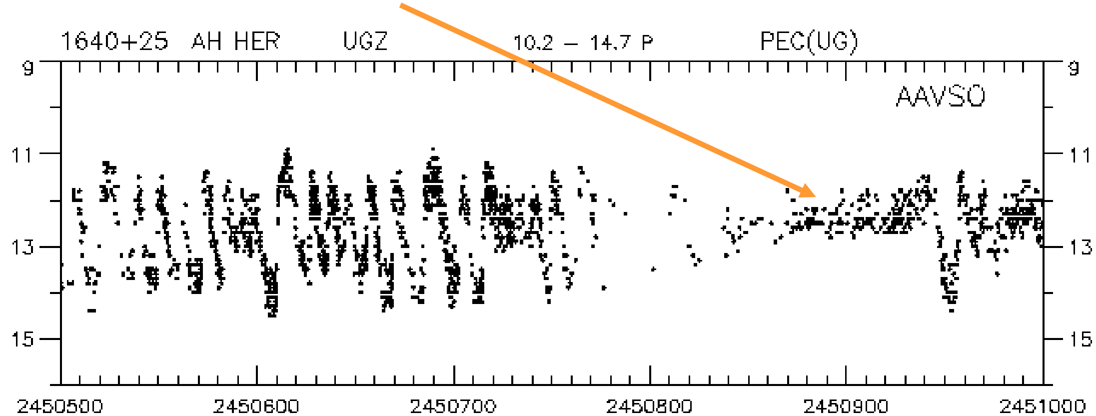


Kepler light curve of V344 Lyrae showing several normal outbursts and one superoutburst (from Still et al. 2010).

Dwarf Novae: Z Cam stars

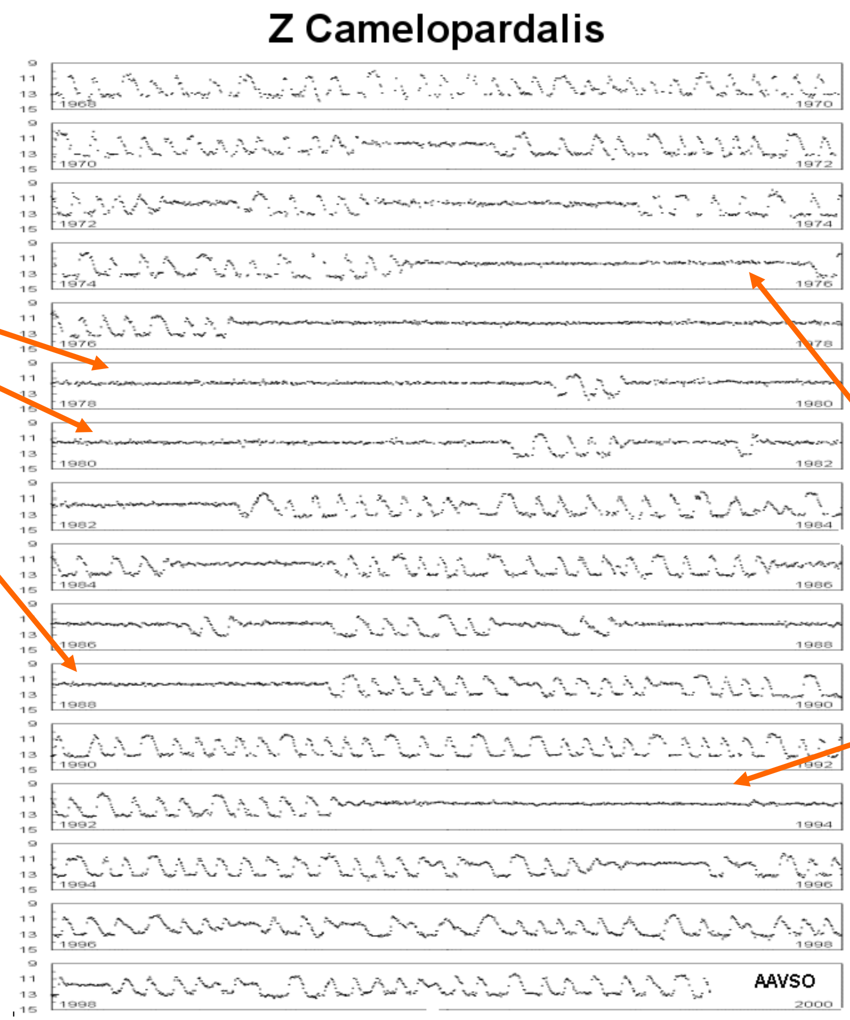


Standstill



Dwarf Novae: Z Cam stars

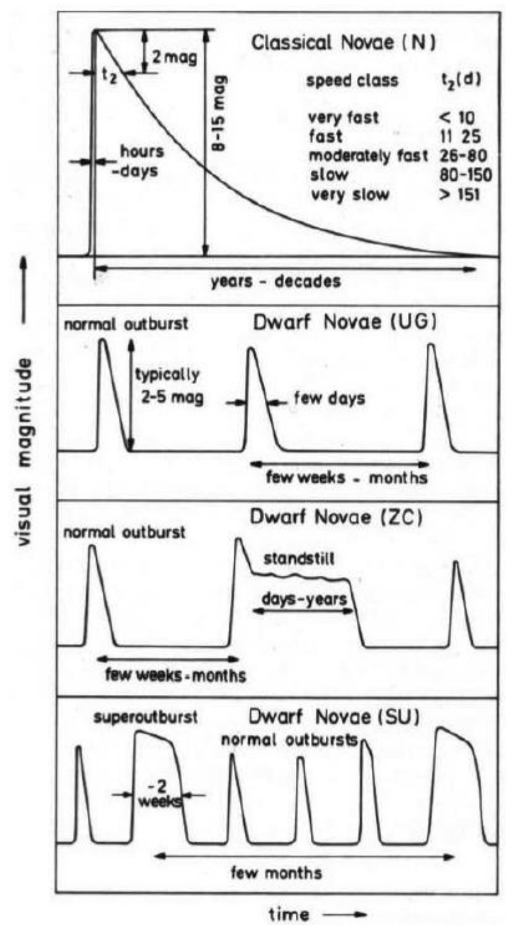
Standstill



Standstill

Outbursts of CNe and DNe

The eruption behaviour of CNe and DNe.



Dwarf Nova Outbursts

- Several CNe also show DN outbursts.

- The distinction between RN and DN is made spectroscopically: in RN and CN a substantial shell is ejected at high velocities; in DN no shell is lost.

GK Persei: Nova of 1901.