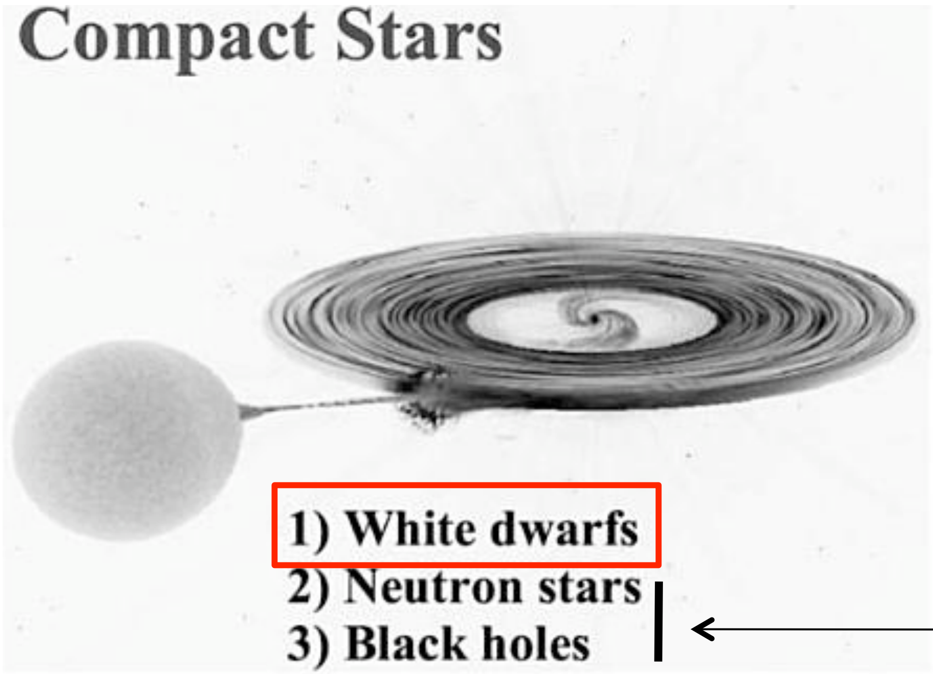
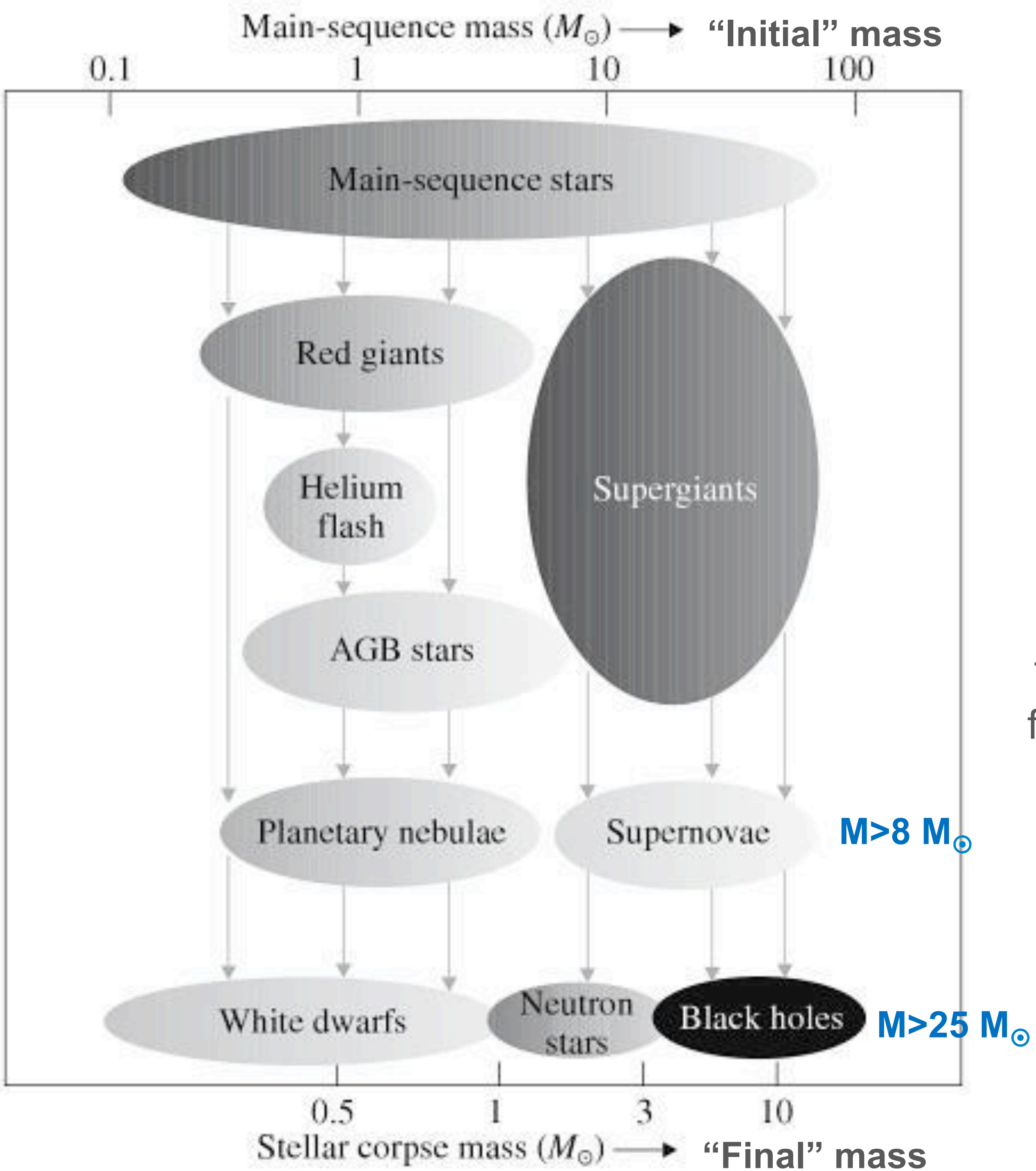
Cataclysmic variables

Cataclysmic variable: main properties

- **Mass-transfer binaries**, in which the white dwarf is the accretor and the secondary is typically a normal star with H-rich envelope or another WD (double-degenerate case) or a giant star (symbiotic CV)
- The energy is released in the gravitational field of the accreting WD + nuclear processing of the accreted material ➔ bursts
- CV already known in the optical before Sco-X1 was detected
- Many different classes of CV. At first order, non-magnetic vs. magnetic WDs (accretion disc vs. accretion column…)
- P_{orb}≈5 m-8 hr mostly, but there are periods >200 d (symbiotic stars, where the WD is orbiting in the wind of a supergiant)



X-ray binaries



Initial mass fundamental for the stellar history

The CV zoo

Table 12.1 Subdivision of CVs according to the nature of donor and accretor

Accretor	Synchro-nized ($P_{orb}=P_{wd}$)	Total number	X-ray discov. (%)	Donor Star: MS-Star/Brown Dwarf Subclass	MS-Star/Brown Dwarf F_X/F_V	White Dwarf Subclass	White Dwarf F_X/F_V
Non-magn.	No	400	~10	non-mag CV	0.01–1	AM CVn	0.1–5
Magnetic	No	35	65	IP/DQ Her	0.1–10	?	
Magnetic	Yes	80	75	polar/AM Her	1–100	?	

Situation as ~2008

Non-magnetic WD: accretion via an accretion disc

X-rays from the boundary layer (BL) between the disc and the WD

disc sometimes as origin of X-ray absorption

majority discovered in optical surveys (e.g., SDSS)

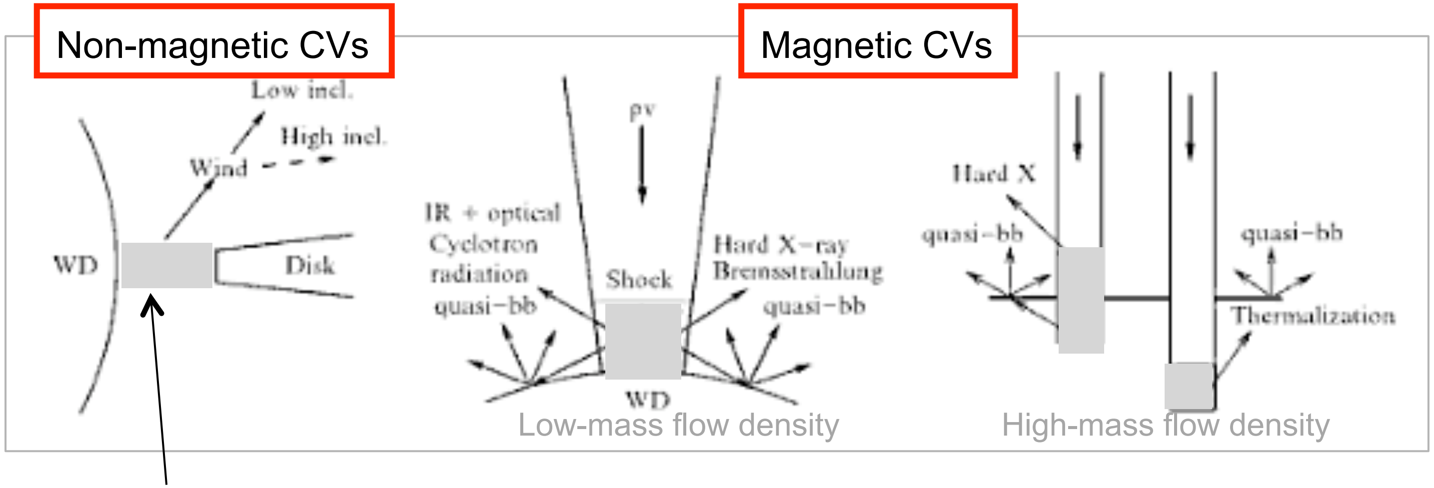
Magnetic WD: *polars (AM Her stars)* and *intermediate polars (IPs/DQ Her stars)*

accretion disk (truncated) only in IPs ("magnetic stresses")

accretion columns to the magnetic pole

$P_{orb}=P_{WD}$ in polars due to the strong coupling with the magnetic field

up to 75% discovered by means of X-ray/UV surveys (mostly RASS)



Boundary Layer: the disc material is breaked from the Keplerian angular velocity to the stellar angular velocity.
Absorption and scattering in the wind may be important (depending on the inclination wrt the line of sight).
Multiple shocks may occur in the flow.

Truncation of the accretion disk in magnetic CV at a distance where

Ram pressure ≈ magnetic pressure

$$\rho v^2 \approx B^2 / 8\pi \rightarrow R_M \propto B^{4/7} \dot{M}^{-2/7}$$

Magnetospheric radius

In short-period binaries and with large magnetic fields, R_M is larger than the binary separation, hence the disc is prevented from forming.

Truncation of the disc in magnetic CVs

The suppression of the disc in magnetic CVs is related to the strength of the magnetic field and the period of the binary system (i.e., the separation of the two stars).

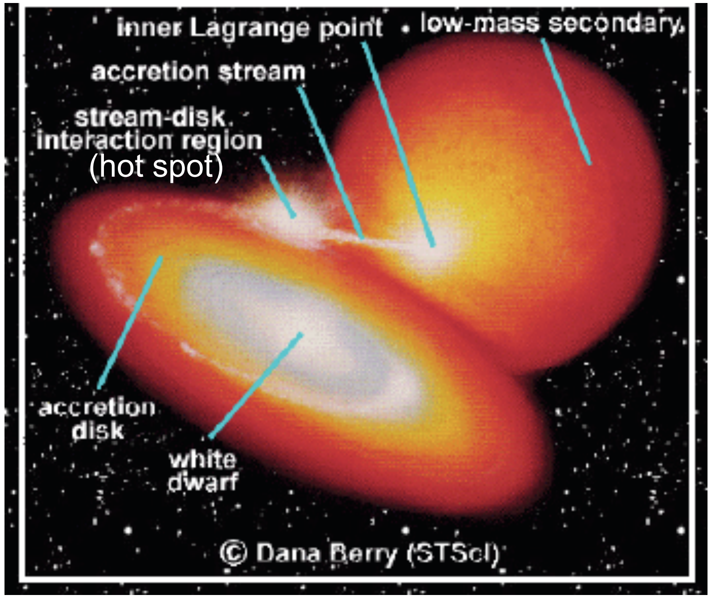
There will be a point at which the magnetic field of the WD takes control of the accreting material. The radial distance of such point can be determined by balancing the **ram pressure of the accreting gas** (**ρv^2**) with the **magnetic pressure** (**$B^2/8\pi$**) ➔ *magnetospheric radius* (described in the lessons on binaries)

$$R_M \propto B^{4/7} \dot{M}^{-2/7}$$

For short-period binaries (low separation) and powerful magnetic fields R_M may exceed the binary separation and the disc is prevented from forming

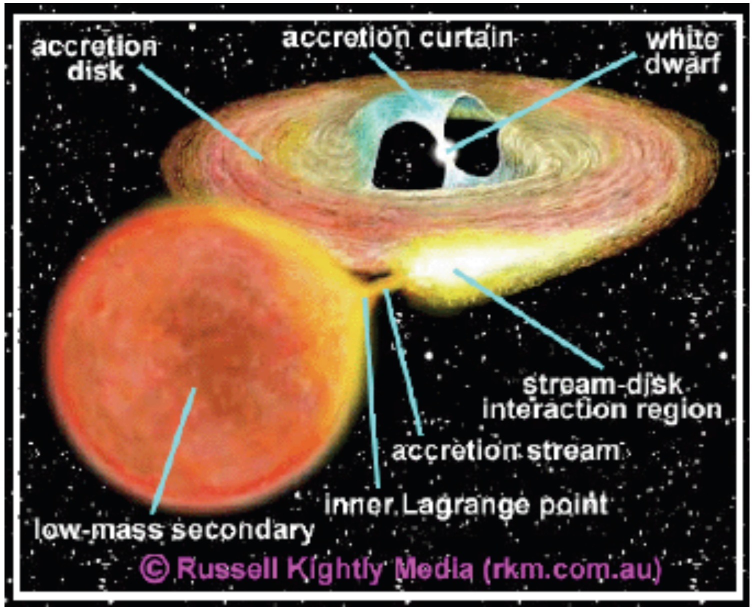
Example: $M=0.85\ M_\odot$, $R=0.01R_\odot$, and $M_{dot}=2\times10^{-10}\ M_\odot/yr$, this occurs at $B\approx10^7$ G

Increasing role of shocks in producing X-rays from systems with an AD to Polars

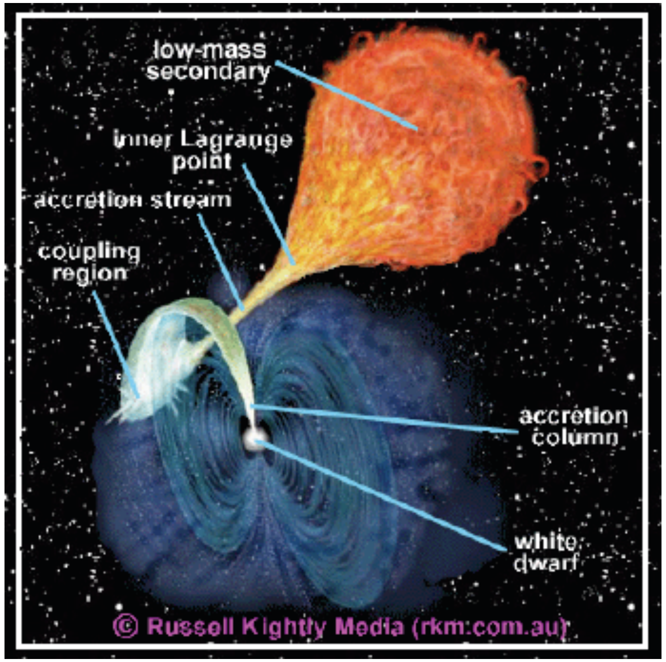


Non-magnetic WD
(B<10^{4-6} G)

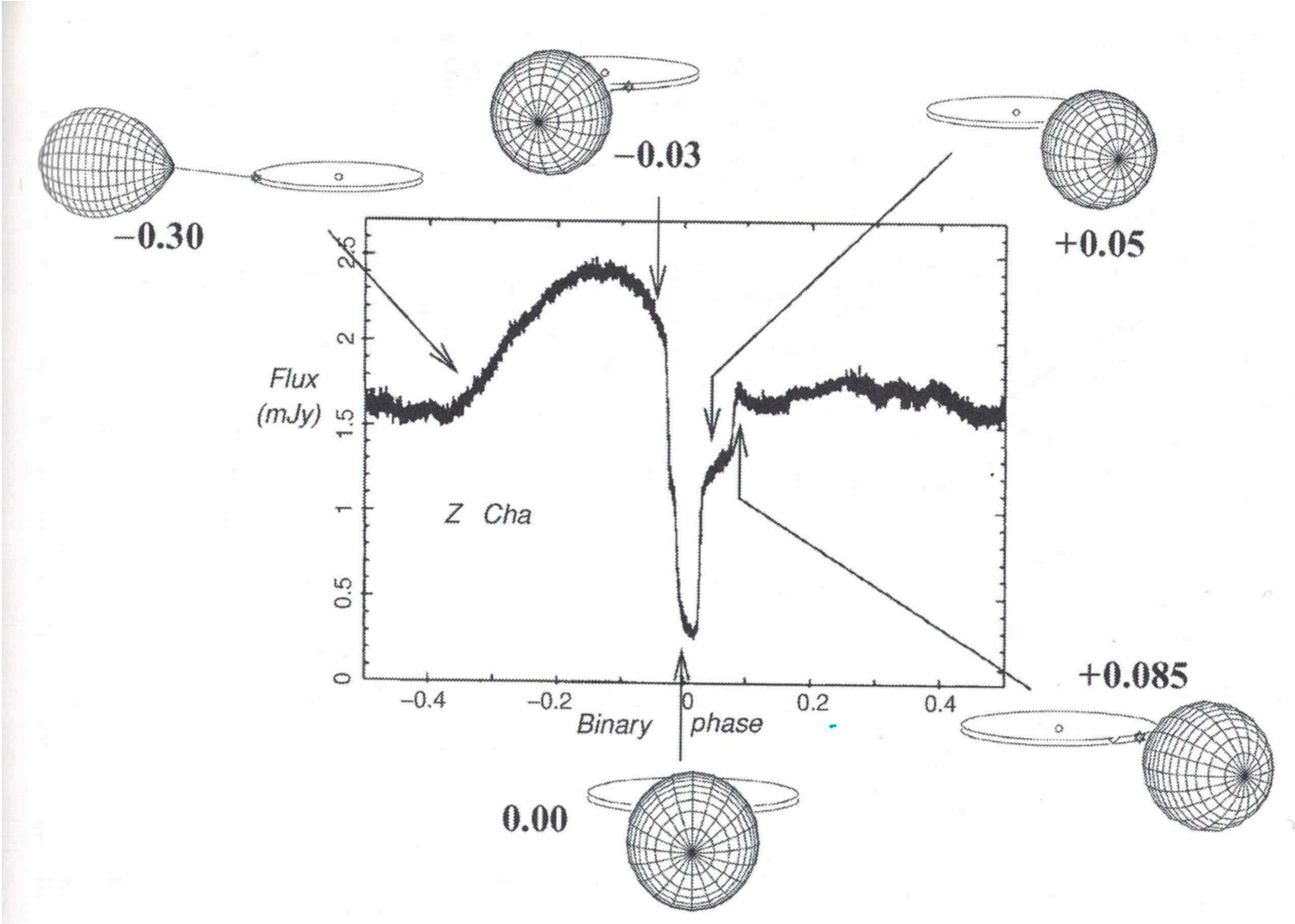
Intermediate polar (IP)
(B=1−10 ×10^6 G)



Polar
(B=10−100 ×10^6 G)



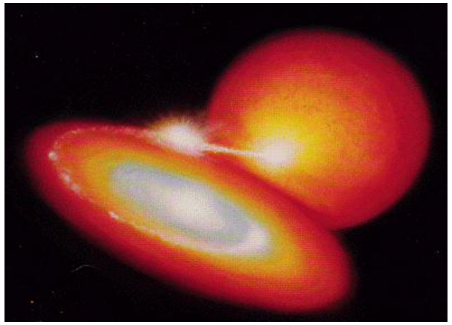
Geometry of a CV



Disc accretors (mainly, non-magnetic CVs)

- In non-magnetic CV, the accretion is governed by the disc.
- Basic theory predicts that half of the gravitational energy potential is liberated through the viscosity in the disc, while the remaining half in the boundary layer between the disc and the surface of the WD

$$L_{disc} \approx L_{BL} \approx \frac{1}{2} G M_{WD} \dot{M} / R_{WD}$$



$$M_{WD} = 1 M_{sun};\ R_{WD} = 10^{9}\,\mathrm{cm};\ \dot{M} = 10^{-10} M_{sun}/\mathrm{yr}$$

→ $L \sim 4 \times 10^{32}$ erg/s

If BB: T~30000 K (UV)

- The disc is generally too cool (kT<1 eV) to emit X-rays (mostly UV radiation)
- BL mostly radiates in EUV + X-rays
- BL thin for low M_{dot}, thick for high M_{dot} (the kinetic energy of the flow is thermalized, resulting in a *BB-like emission*) ➔ the shock-heated plasma in the BL must cool from kT≈10 keV to kT≈2.5 eV (photospheric WD temp.)

As we will see in other accreting systems (e.g., in X-ray binaries) each annulus is assumed to radiate as a blockbody with Temperature=f(r=radius of the annulus), i.e., with decreasing T at increasing distances from the accreting object

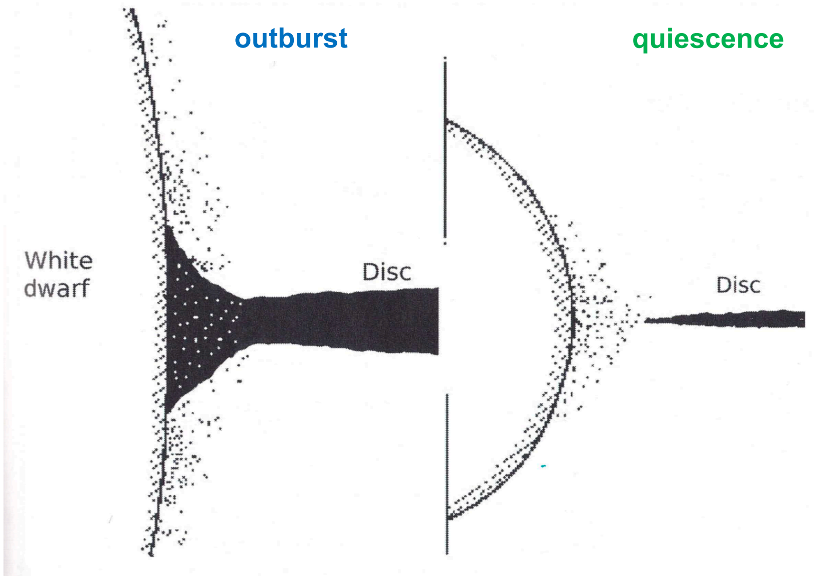
$$T(r)^4 = T_{\rm max}^4 (r/R_{\rm wd})^{-3}\ [1 - (R_{\rm wd}/r)^{1/2}]$$

$$T_{\rm max} = 41000\ (\dot{M} M_{\rm wd}/R_{\rm wd}^3)^{1/4} {\rm K}$$

$$\text{where } \dot{M} = [10^{16} {\rm g/s}], M_{\rm wd} = [M_\odot], R_{\rm wd} = [10^4\ {\rm km}]$$

Pringle (1991)

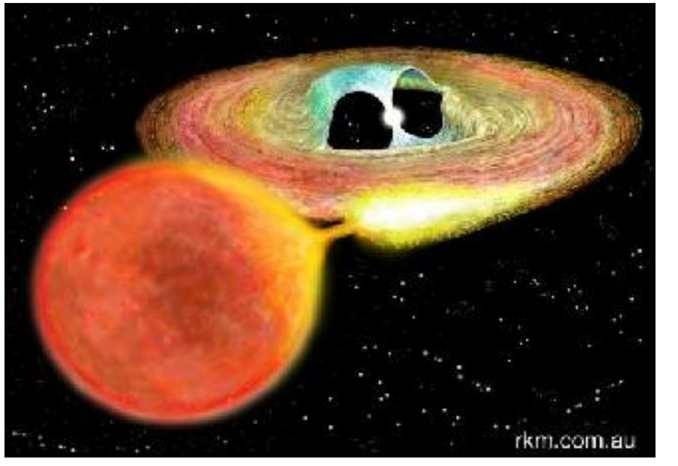
Outburst vs. quiescence phase



Much higher accretion rate and viscosity in the disc
Mostly optically thick flow

Hot and optically thin flow,
Mostly hard X-rays

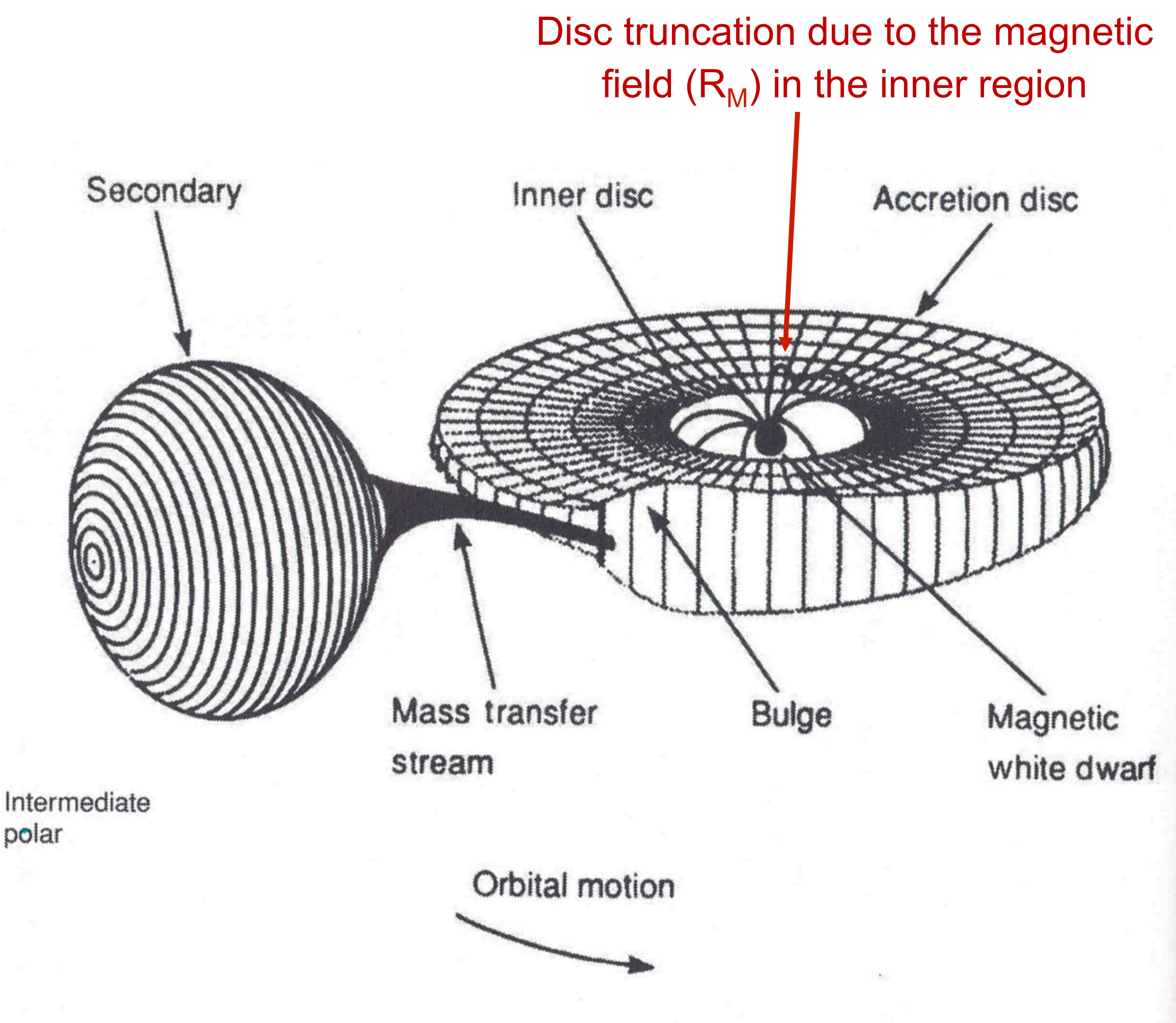
Intermediate polars



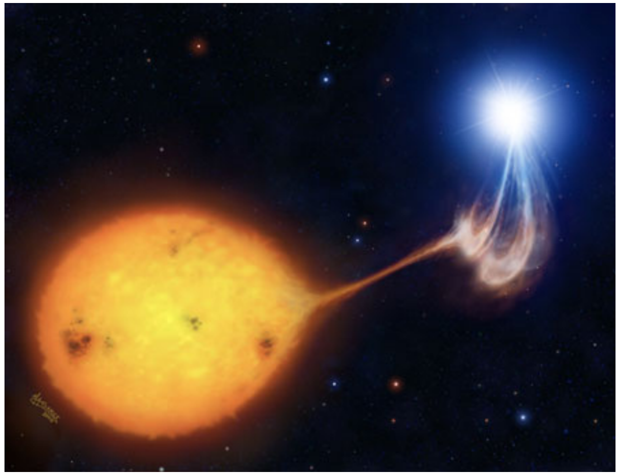
- In intermediate polars, the accretion disc is disrupted at small radii by the WD magnetosphere (inner edge of AD=magnetospheric radius); the accreting material then leaves the disc and follows the magnetic field lines down to the WD surface in the vicinity of the magnetic poles.

- As the accreting material ‘rains’ down onto the WD surface, it passes through a *strong shock* where its free-fall kinetic energy is converted into thermal (*bremsstrahlung*) energy. The shock temperature is ≈ 10^8 K (10 keV), so the post-shock plasma is a strong source of hard X-rays.

- The X-ray, UV, and optical radiation is pulsed at the spin period P_{spin} of the WD.

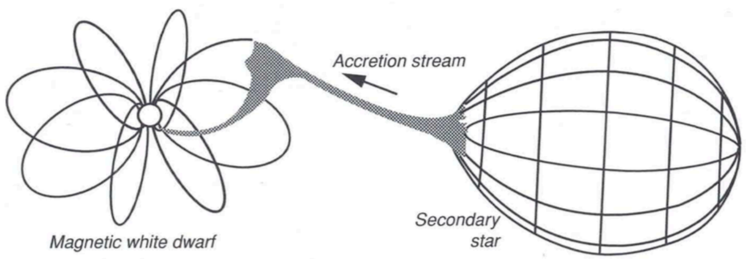

Disc truncation due to the magnetic field (R_M) in the inner region
Secondary
Inner disc
Accretion disc
Mass transfer stream
Bulge
Magnetic white dwarf
Intermediate polar
Orbital motion

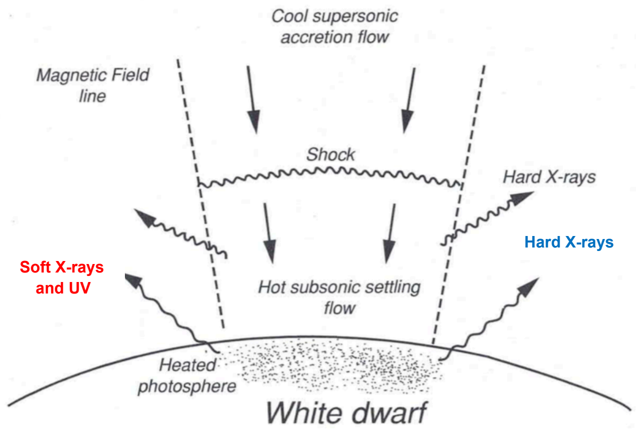
Polars (AM Her)

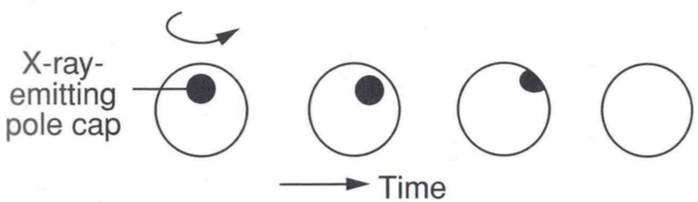


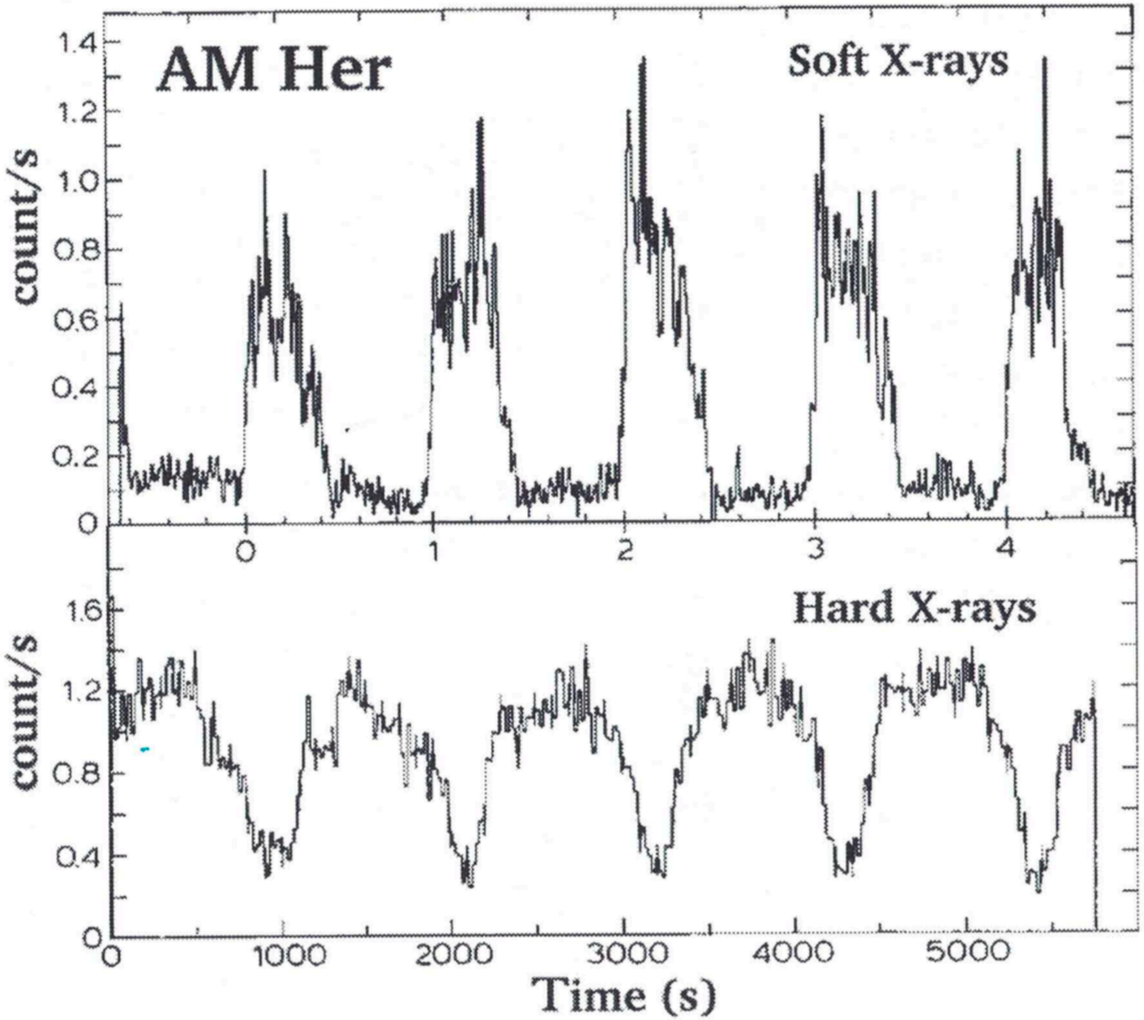
- In polars, the WD is spin-synchronized with the binary (P_{spin}=P_{orb})
- No disc is forming because of the effect of magnetic field: accretion takes place directly into the WD magnetosphere
- Like intermediate polars, also polars are strong X-ray sources; the X-ray, UV and optical emission is pulsed at the binary orbital period. Modulation due to occultation of the X-ray emitting pole by the WD itself
- *Thermal bremsstrahlung* (free-fall, v~5000 km/s) matter which termalizes + *cyclotron* (polarized) *emission* (IR/UV) → heating of the surface → BB soft X-ray emission
- Limited absorption due to the narrow accretion streams in polars

Matter is almost in free-fall in Polars







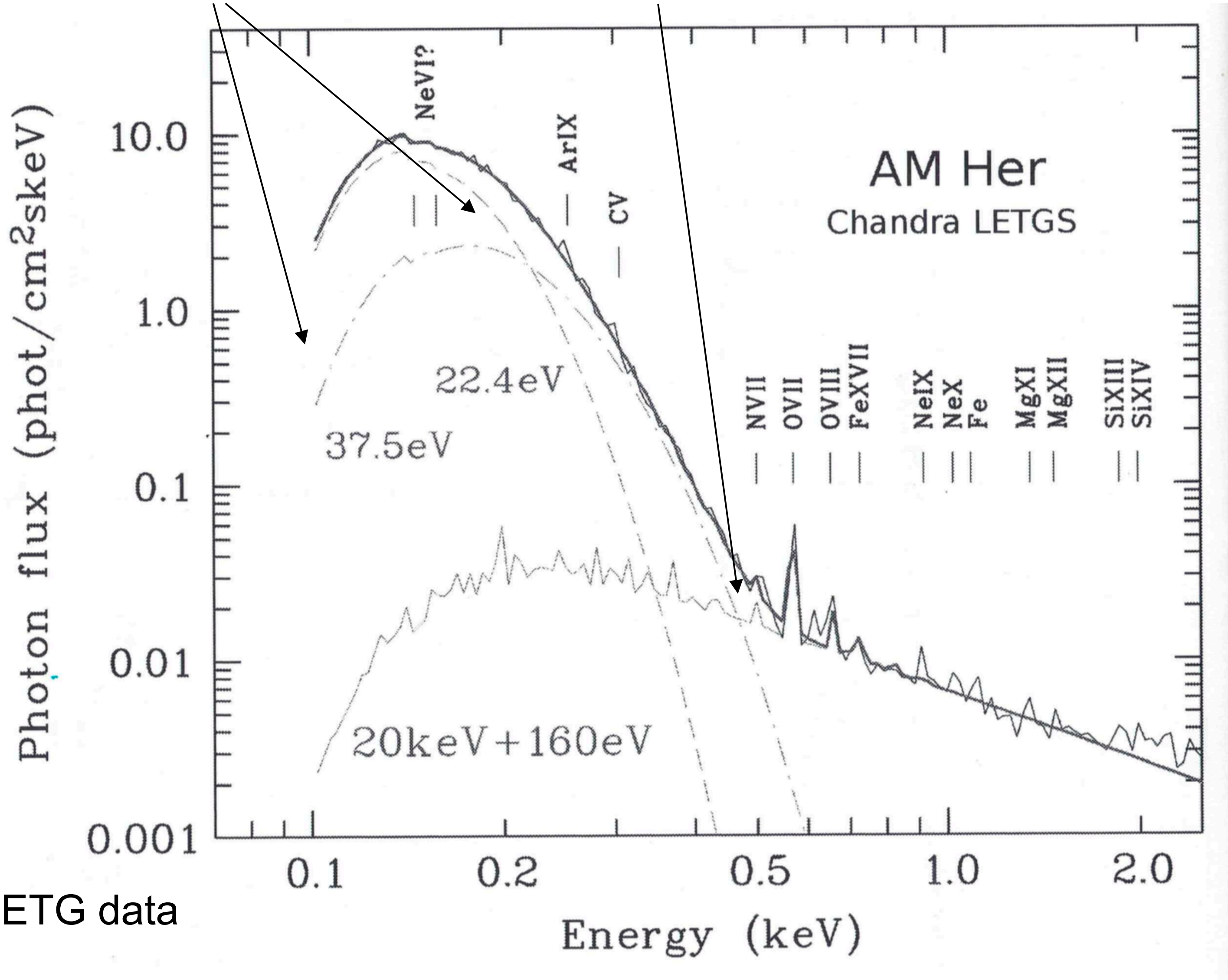


EXOSAT data

Heise et al. (1995)

Both poles are activated and produce soft+hard X-ray emission in anti-phase → the emission is a complex function of viewing geometry and accretion column density geometry (Cropper et al. 2000). The flow is probably ‘clumpy’

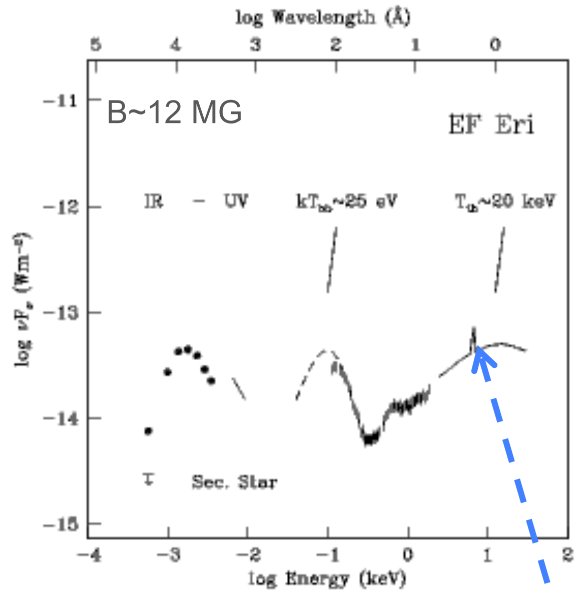
2 BB emission + hard continuum + ~160 eV coronal-type plasma

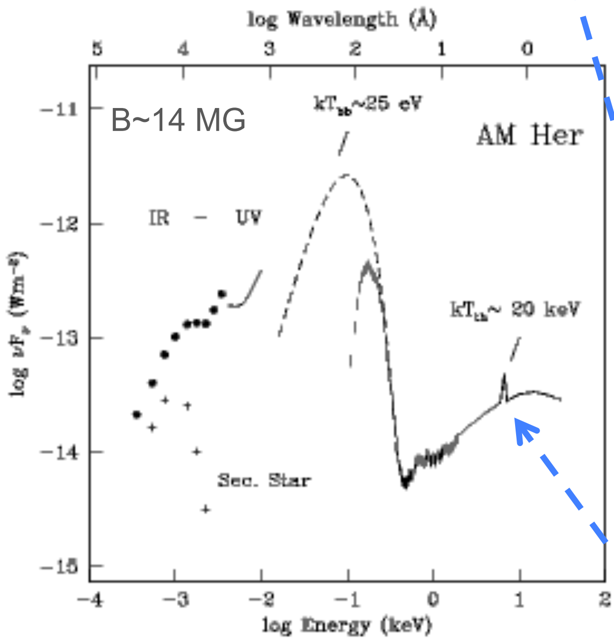


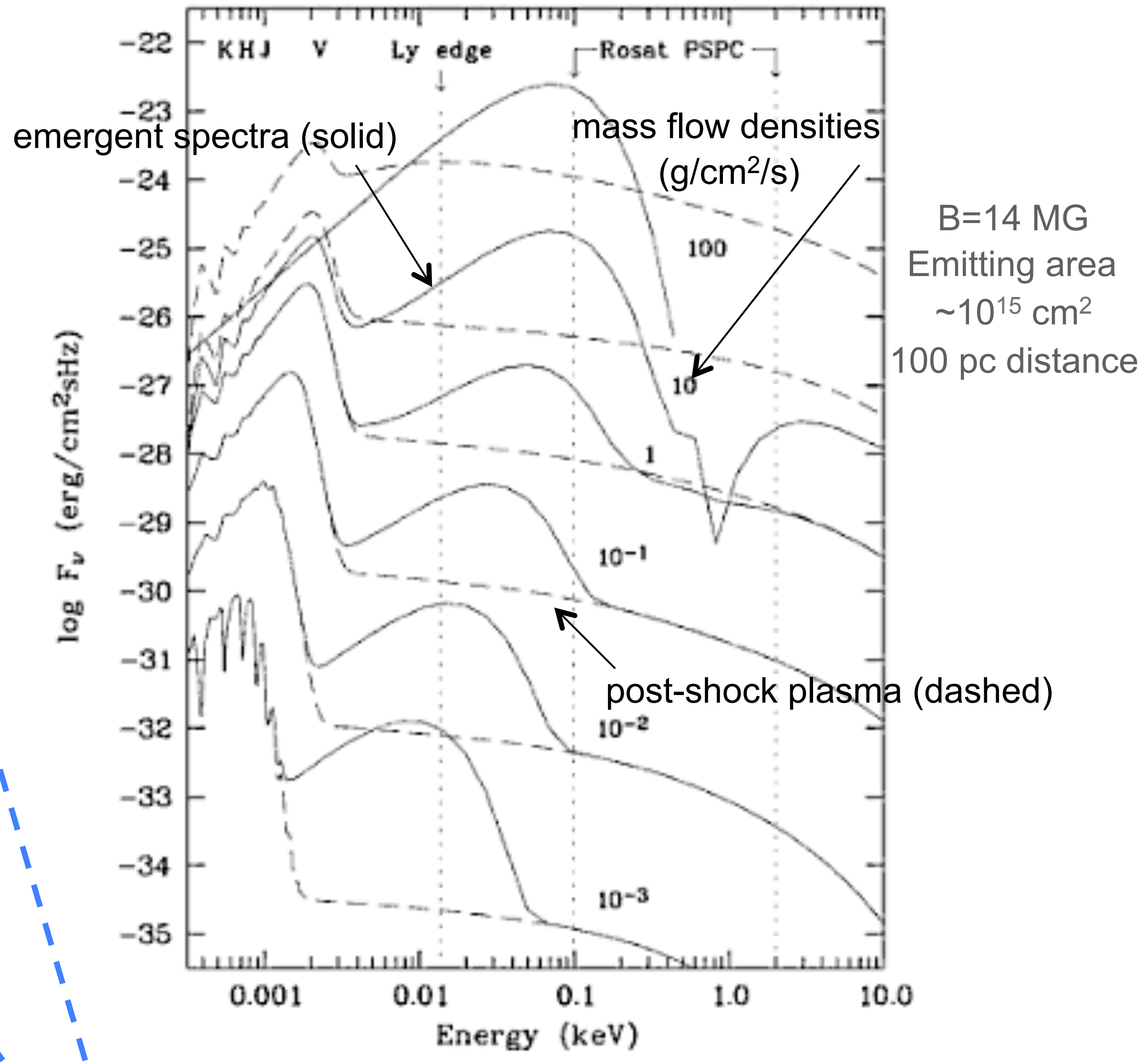
Chandra/LETG data

Polar spectral energy distributions

Emergent spectra include absorption and reprocessed component from the WD photosphere







Iron line? Cyclotron line? E_{cycl}=11.6 (B/10^{12} G) keV → Answer: iron line (E_{cycl}<<X-ray band here and the energy is the same)

X-ray emission from CV in burst

White dwarfs in binary systems

Accretion-dominated phase

Non-magnetic WD/dwarf novae
Intermediate polars/Polars

Fusion-dominated phase

Classical novae – sporadic burning
Supersoft sources (SSS) – steady burning

- In **novae**, after the **thermo-nuclear runaway** in a H-burning shell at the bottom of the accreted layer on the WD, a *shock* and/or a *wind* may develop. 10-90% of the accreted material may remain on the WD

➔ If the accreted material is not burned or blown away (as a nova shell), the mass of the WD may increase toward the Chandrasekhar limit, leading to a SNIa

- H-burning produces soft X-rays, while shocks in the hot circumstellar material can produce hard X-ray emission. Shocks may originate in interacting winds or may be due to *interaction between ejecta and pre-existing material*

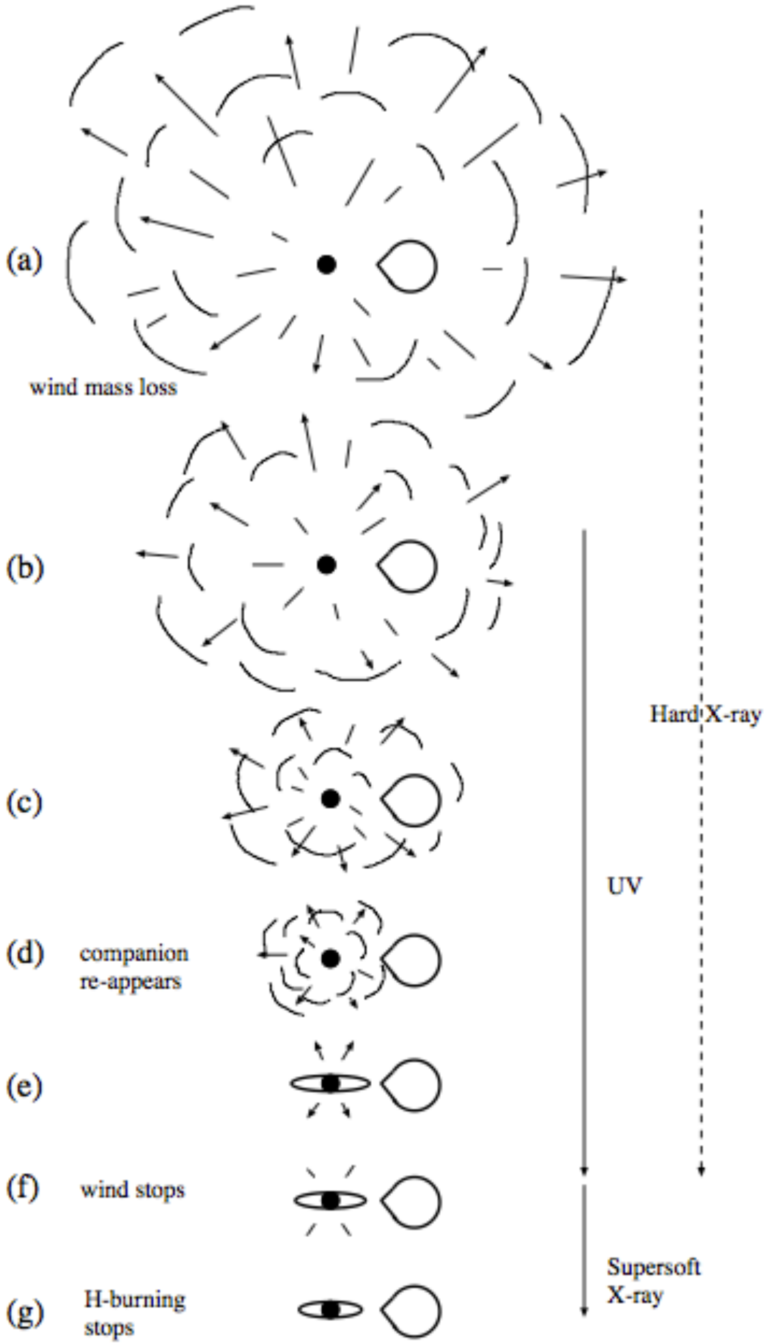
Classical Novae

- The matter begins a thermonuclear fusion reaction on the WD surface. Matter is accumulated at small rates, so low-level of X-ray emission (10^{33-34} erg/s) between novae explosions (× thousands/millions)
- Weak X-ray emission from shock-heating of the circumstellar envelope in the WD's environment from the material expelled from the nova explosion
- On-going accretion is traced by hard X-ray emission

Supersoft sources (SSS)

- T≈200,000-800,000, $L_X \approx 10^{38}$ erg/s, 90% of the X-ray emission below 0.5 keV (BB with kT≈100 eV) ➔ $10^{-7}-10^{-8}$ $M_\odot$/yr needed to sustain nuclear burning
- PG1159 stars (hot stars) + WDs which have experienced a late He shell flash ("borne-again" scenario)
- Progenitors of SNIa?
- Some properties similar to those of LMXBs (hosting NS/BH)
- Few known in the Galaxy (soft X-ray emission, easily depressed by Galactic absorption

Evolution of a nova outburst



Hachisu & Kato (2006)

The photospheric radius moves inward with time due to **strong wind losses**

Presence of **shocks**

The optically thick wind stops, and an accretion disc may re-establish again

Emission is mostly in the very soft band

Classical Novae

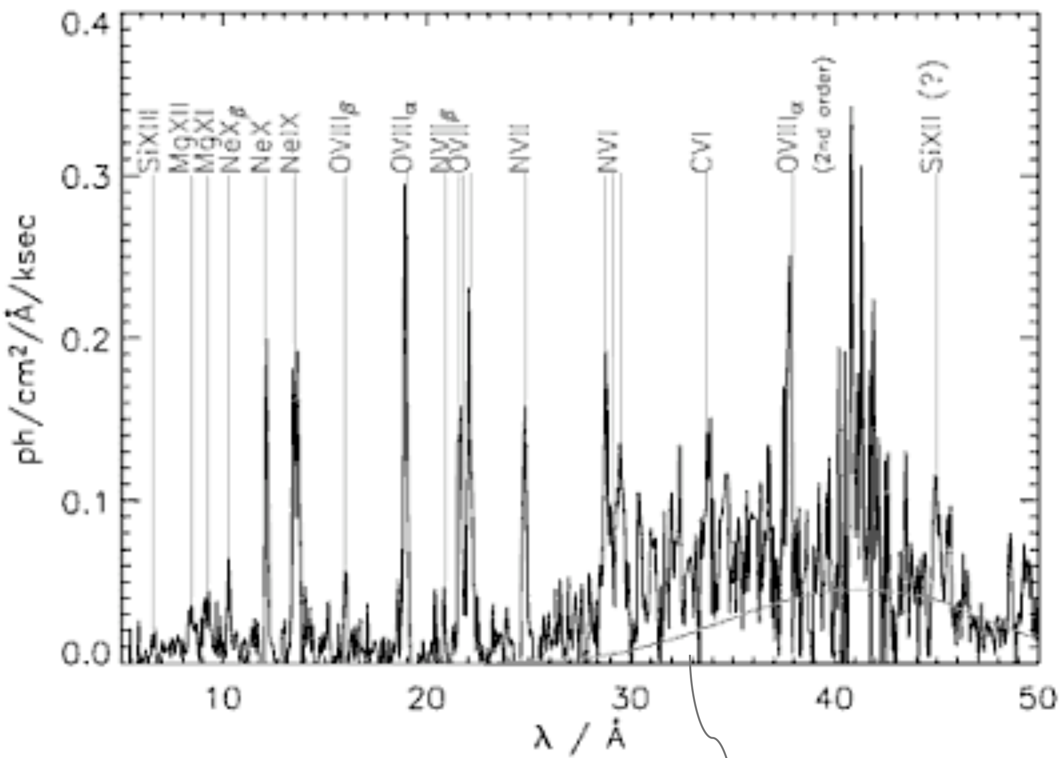
• $P>P_{crit}$ at the bottom of the accreted H-rich material ➔ thermonuclear runaway, i.e., burning of the H via the CNO cycle ($T \geq 10^8$ K)
• The thermonuclear fusion depends upon the mass and luminosity of the WD, the mass accretion rate and the chemical composition of the accreted layer
• ≈25% of all novae have strong over-abundances of O, Ne, and Mg (from the WD with an ONeMg core)
• Total energy up to 10^{45} erg
• Strong *soft X-rays* with SED of a hot stellar atmosphere
• Ejection of the nova shell ➔ the expanding envelope becomes opaque to X-rays (fireball phase)
• Not all the ejected material is lost, some re-fuels the CNO cycle
• In a second phase, the radius of the stellar photosphere shrinks, temperature increases, and the peak of emission moves from optical to UV and X-rays
• Strong shocks between different layers are found and produce *bremsstrahlung* emission

V382 Vel (ONeMg **nova**)

the abundances of the elements in the ejected material are enhanced

continuum by BB emission with kT≈2.7×10^5 K

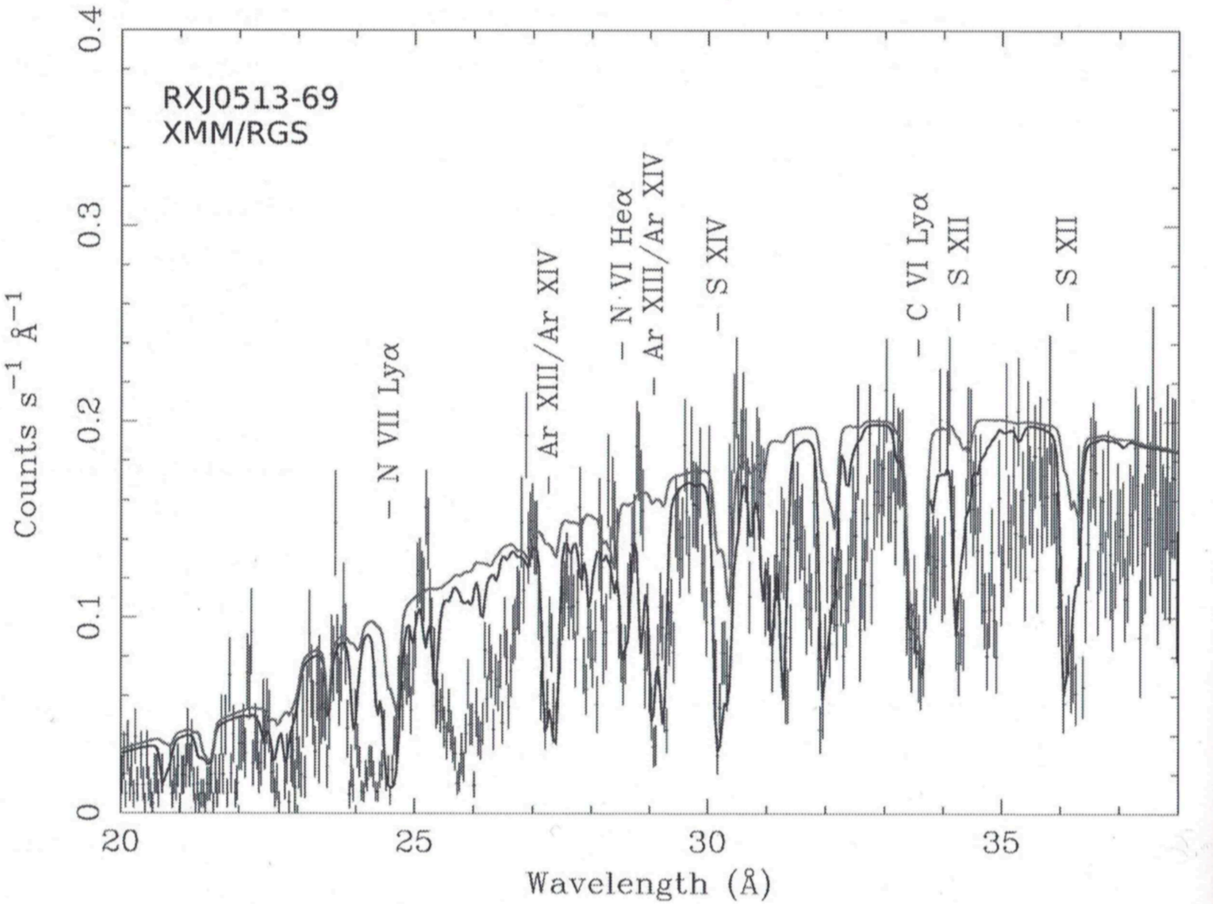
Broadening of the lines ➔ 1200 km/s expansion



BB

SSS RXJ0513.9-6951

70 eV BB underlying continuum absorbed through the an outflowing, partially ionized wind [modelled with solar (dotted line, top) and modified (solid line, bottom) abundances (McGowan et al. 2005)



Requirements for nuclear burning

Let's consider an envelope (where H is ignited) with a critical mass for nuclear burning: ΔM_{crit} (critical mass of the envelope where H is converted into He) to sustain $T \approx 10^8$ K and $P \geq 10^{18-20}$ g/cm/s^2 for nuclear (mainly CNO cycle) burning

$$Log\left(\frac{\Delta M_{crit}}{M_{sun}}\right) \approx A + B\left(\frac{M_{wd}}{M_{sun}}\right)^{-1.44} \ln\left(1.43 - \frac{M_{wd}}{M_{sun}}\right) + C\left(Log\left(\frac{\dot{M}}{M_{sun} yr^{-1}}\right) + 10\right)^{1.48}$$

A=-2.86; B=1.54; C=-0.20

The accretion rate determines the strength of the outburst: the higher M_{dot} is, the less violent outbursts are (because less material has been accumulated; C is <0)

Steady state: accretion rate similar to nuclear burning rate: the accreted material remains on the WD

$$\dot{M}_{steady} \approx 3.7 \times 10^{-7}\left(\frac{M_{wd}}{M_{sun}} - 0.4\right) \approx (1-4) \times 10^{-7}\ M_{sun}/yr$$

for a typical M_{WD}=(0.7-1.4) $M_{\odot}$

$$\dot{M}_{acc} \leq 0.25\ \dot{M}_{steady}$$

All accreted material is ejected during a nova outburst

Supersoft sources (SSS)

- L_X up to 10^{38} erg/s, i.e., 1000 × L_X of a typical WD: LMXB? BHB?
- kT≈10−75 eV

$$L = 4\pi R^2 \sigma T^4$$

if radiating as a blackbody

$$R = 10^4 \text{ km } (\text{L} / 10^{37} \text{ erg/s})^{0.5} \ (\text{T}/3\times10^5 \text{ K})$$

≈ size of a WD >> R_{NS}
or BH event horizon
(van der Heuvel+1992)

However, the high X-ray luminosity requires a high M_{dot} (≈10^{-6} $M_\odot$/yr), i.e., 100× that of a CV in outburst and 10000× of a 'normal' CV.

But accretion is just part of the story; fusion of H contribute to L_X, hence **M_{dot}≈$10^{-7÷-8}$ $M_\odot$/yr may be required** (in case of stable nuclear hydrogen burning; *still high accretion rate*) → fusion energy in WD can exceed that due to accretion per unit mass due to the low potential well compared to NSs and BHs

Unstable mass accretion in a presumably short-lived phase may alleviate the problem