The Universe in X-rays:

Overview of HW#5

a) Energy of incoming photons = 6.0 KeV

Energy required to produce one ion/electron pair for argon gas is say 25 eV

Hence, number of ion/electron pairs produced is

$$\frac{6000\ eV}{25\ eV} = 240 \text{ pairs}$$

let N = 240

according to Poisson statistics, the standard deviation (σ) in number of ion/electron pairs is $\sqrt{N} = \sqrt{240} = 15.49$

Relative fluctuation in N is $\frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}} = 0.0645$

According to assumption, number of ion $/e^-$ pairs produced are proportional to incident photon energy. so relative fluctuation in energy should be equal to relative fluctuation in N . Hence,

$\frac{\sigma_E}{E} = 0.0645$ or, standard deviation in energy (σ_E) = 6.0 x 0.0645 = 0.39 KeV

FWHM occurs at 2.36σ so 0.065 x 2.36 = 0.153 or 15.3 %

The Universe in X-rays:

Overview of HW#5

b) FWHM for incoming photon of 2 KeV:

$$\frac{2000\ eV}{25\ eV} = 80 \text{ pairs}$$

$$\frac{\sigma_E}{E} = \frac{1}{\sqrt{80}} = 0.111 \quad \text{(follows from subpart (a))}$$

FWHM = 2.36 x 0.111 = 0.263 or 26.3%

for 30 KeV photon :

$$\frac{30000\ eV}{25\ eV} = 1200 \text{ pairs}$$

$$\frac{\sigma_E}{E} = \frac{1}{\sqrt{1200}} = 0.028$$

FWHM = 2.36 x 0.028 = 0.068 or 6.8%

Summary after 8th lecture:

8th lecture:

Solar system:

- **Sun – the main X-ray source**
- **fluorescence of X-rays**
- **solar wind**
- **charge transfer (CT) process.**

Planets, Moon, Comets:

- **Earth and geocorona**
- **aurora in X-rays**
- **Moon and it's X-ray emission**
- **spectrum of CT process**
- **Comets and their emission contours**
- **Jupiter, Mars, Venus, Saturn, Titan**

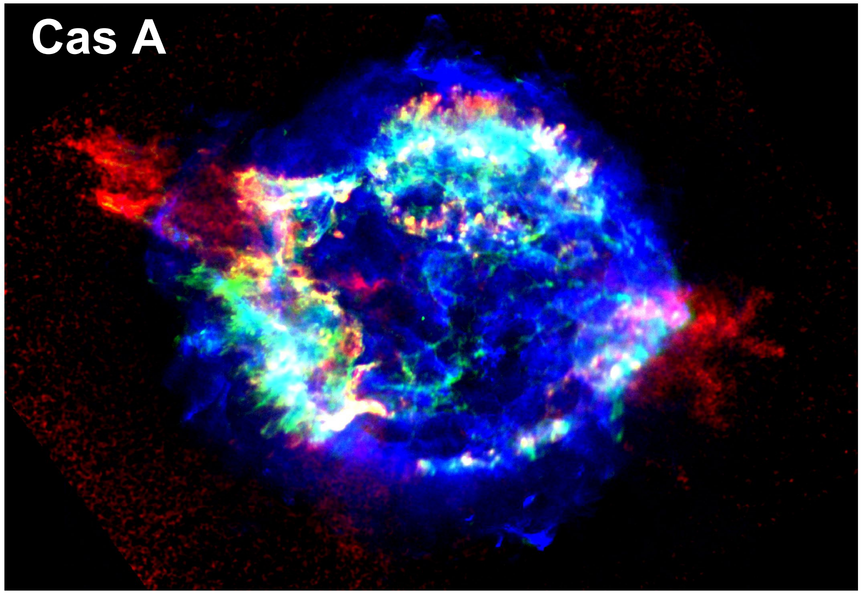
Nuclear burning stars:

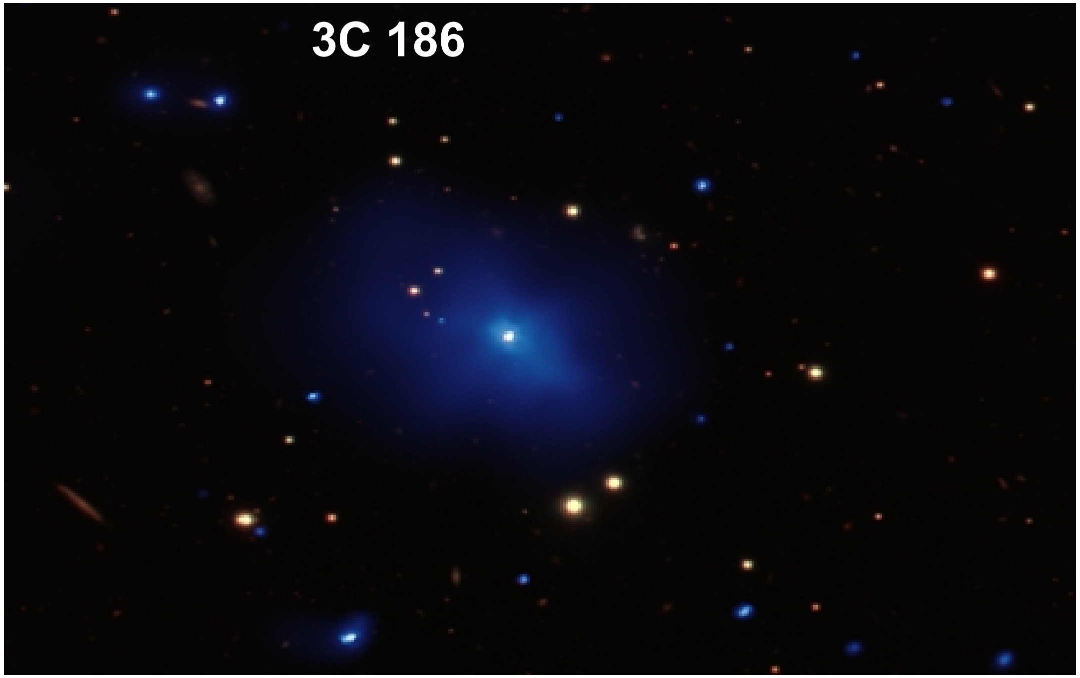
- **solar magnetic dynamo**
- **connection of X-rays with stellar parameters**
- **coronal age-activity relation**
- **binaries with rapidly rotating companions**
- **very low-mass stars and brown dwarfs**

The theory of different emission processes across astrophysical objects:

- Solar system objects
- Nuclear Burning Stars
- White Dwarfs
- Cataclysmic Variables
- Classical Novae
- Pulsars and Isolated Neutron Stars
- Accreting Neutrons Stars and Black Hole binaries
- Supernova Remnants
- Interstellar Medium
- Galactic Center

- Nearby Galaxies
- Active Galactic Nuclei
- Clusters of Galaxies
- Gamma- Ray Bursts
- Cosmic X-ray Background





X-ray Sources:

1) Most X-ray emission from the Universe comes from discrete sources.

2) In general sources can be divided into:

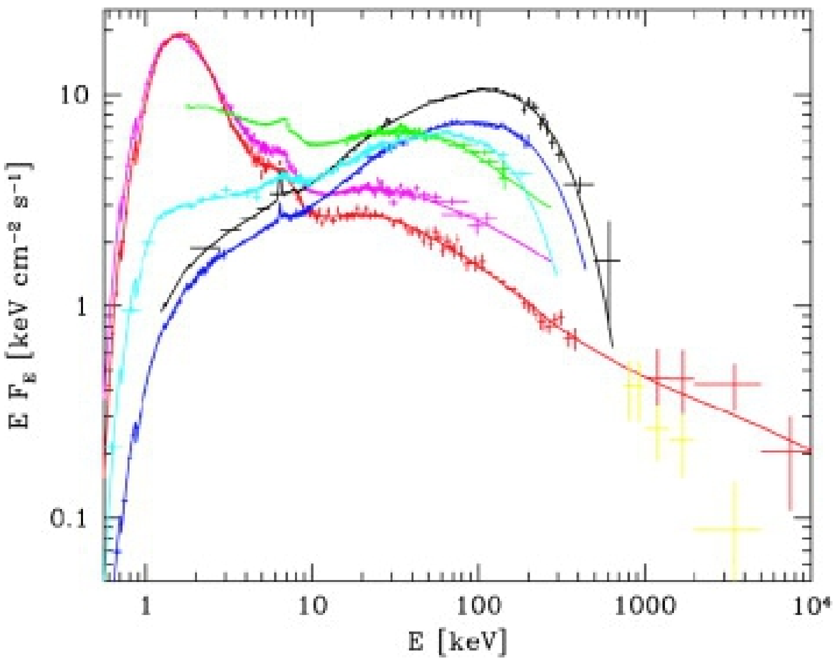
- accreting objects

  most of them

$$L_{bol} = \eta * \frac{dM}{dt} * c^2$$

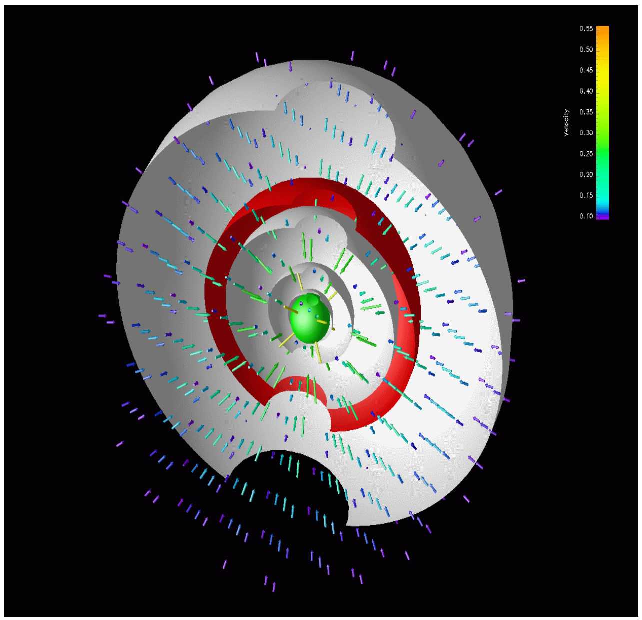
- no accreting

Cyg X-1 Zdziarski + 2002



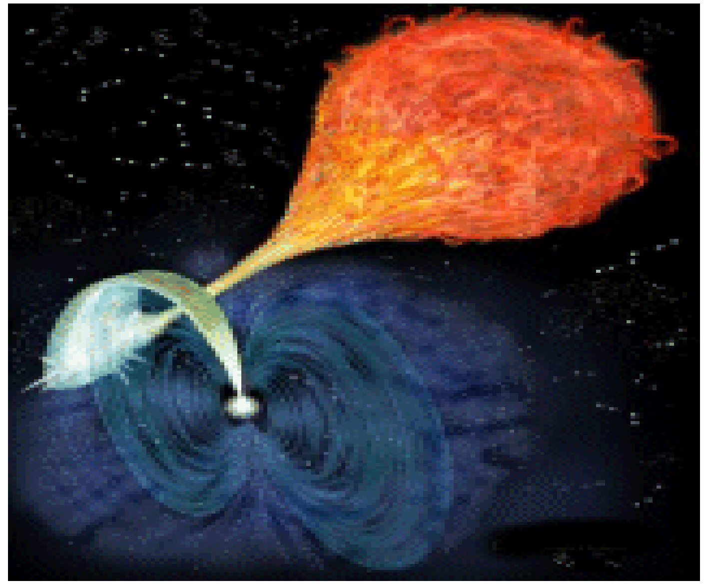
Different kind of accretion:

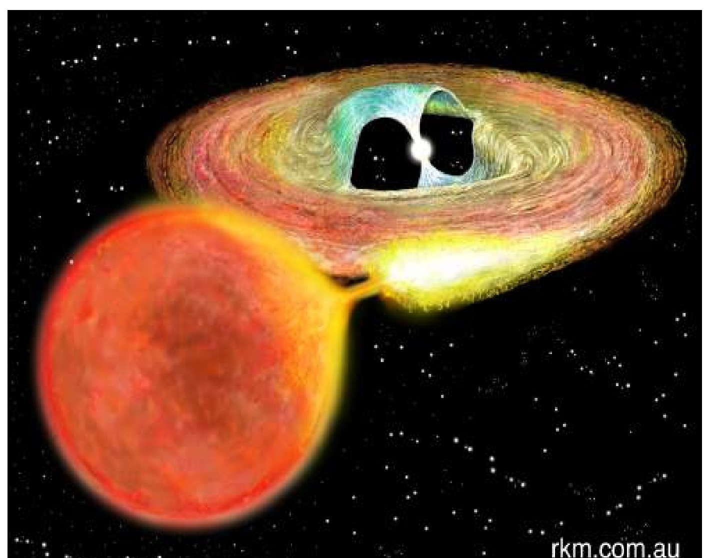
Bondi; Sag A



Adiabatic heating

Column accretion: WD, NS

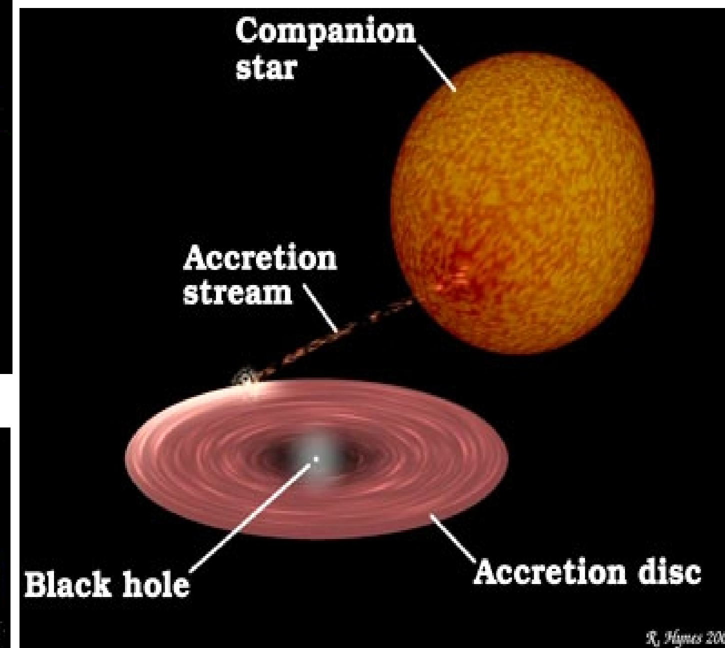




Shocks

Accretion disk:
AGN, Binary systems.

Shakura & Sunayev 1973



Viscous heating

Accretion is the way to heat gas, but to see X-rays, plasma must be cooled by radiative processes.

Radiative cooling mechanizms:

1) Thermal cooling – diffusion of radiation from inner parts of atmosphere Up to the surface and emitting spectrum is BB (black body).
This kind of process requires substantial gas density. It is realized in optically thick accretion disks with viscous heating.

$$T_{eff} \propto r^{-3/4} \qquad\qquad T \propto 4\times10^{6}\left(\frac{M_{BH}}{10\,M_{Sun}}\right)^{-1/4}$$

AGN, $M_{BH} \sim 10^{8}\ M_{№}$ $T \sim 10^{5}$ K

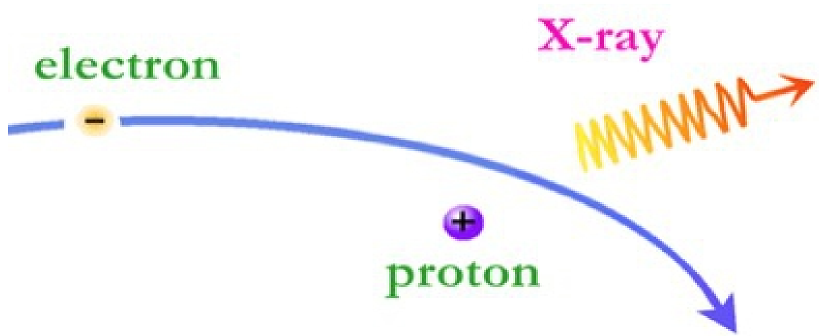
ULXs, $M_{BH} \sim 10^{2-4}\ M_{№}$? $T \sim 10^{6-7}$ K

GBHB, $M_{BH} \sim 10\ M_{№}$ $T \sim 10^{7}$ K

Geometricaly thin and optically thick disk does NOT explain hard X-ray Emission from AGN and Galactic Black Hole Binaries (GBHB).

In the gas optically thin gas regime:
I) small radiation pressure,
II) large radiation pressure,

2) Bremsstrahlung. Where Radiation pressure is small, gas optically thin and substantially ionized, electrons are decelerated in the potential field of ions.



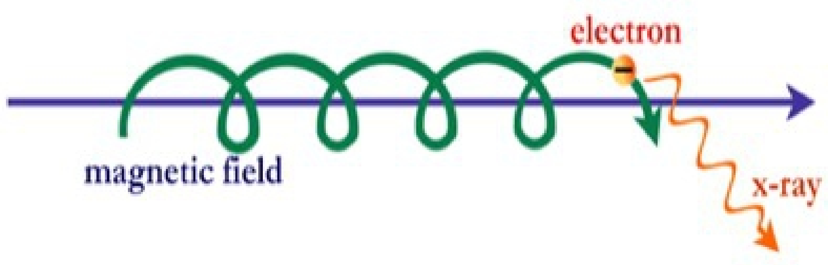
$$Q_{brems} = 6.6\times10^{20}\rho^{2}T^{1/2} \qquad erg\,s^{-1}\,cm^{-2}$$

Bremsstrahlung becomes important in the upper atmospheres of hot gas, and increases with density.

When bremsstrahlung is a dominant process responsible for continuum radiation, we can determine the gas temperature.

3) The energy lost of electrons due to the path around magnetic field lines of the magnetic field B – synchrotron/cyclotron radiation.

B small – electrons as classical particles
B large – electrons as quantum particles,
we can observe cyclotron absorption line



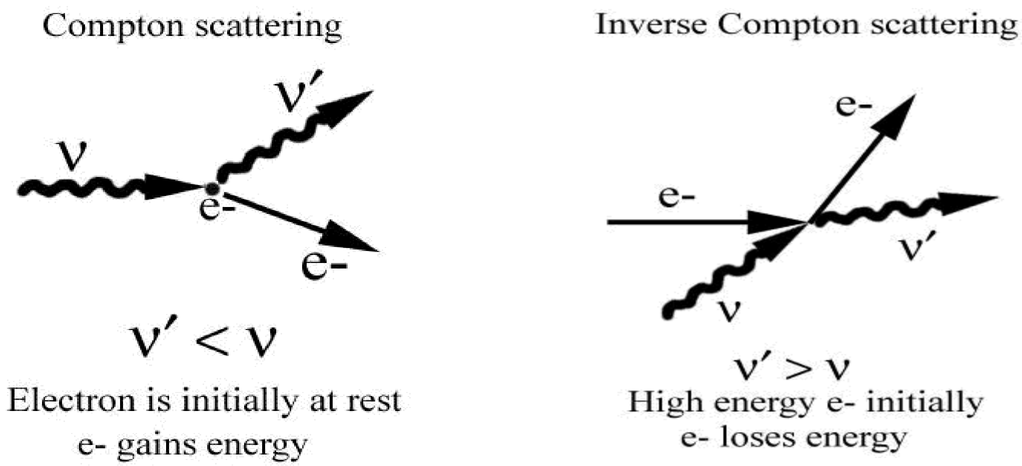
$$E_{first\ Landau\ level} = 511\left(\frac{B}{4\times 10^{13}G}\right)keV$$

Transitions between levels are possible only when there are photons which interact with electrons.

Synchrotron cooling very popular – jets , magnetic neutron stars and white dwarfs, Bondi and column accretion.

Q_(synch) is the efficient source of photons which may increase P_(rad)

4) Compton scattering – depending on the gas conditions, Compton heating or cooling can be important, but it always requires the presence of intrinsic photon field – radiation pressure has to be substantially large – case II.



T_(inverse Compton) = <E_(fotonow)> / 4 k

The temperature under which Compton heating balances Compton cooling

T_gaz < T_(inverse Compton) – Compton heating

T_gazu > T_(inverse Compton) – Compton cooling

Radiative heating increases gas temperature only to the value of T_(inverse Compton)

Premain Sequence Stars:

1). T - Tauri phase – evolved from Young stellar objects (YSOs) $M \leq 2\ M_{sun}$. Spectral type F-M.

cTTS – the remaining circumstellar material has settled into a disk, from which it is accreted onto the star.

wTTS – weak lines TTS, according to Balmer line:

$$W_{H_\alpha} < 10\ \mathring{A}$$

hard to distinguish from more evolved MS stars.

2) Herbig Ae/Be stars – HaeBe stars $M \sim 2\text{-}10\ M_{Sun}$.

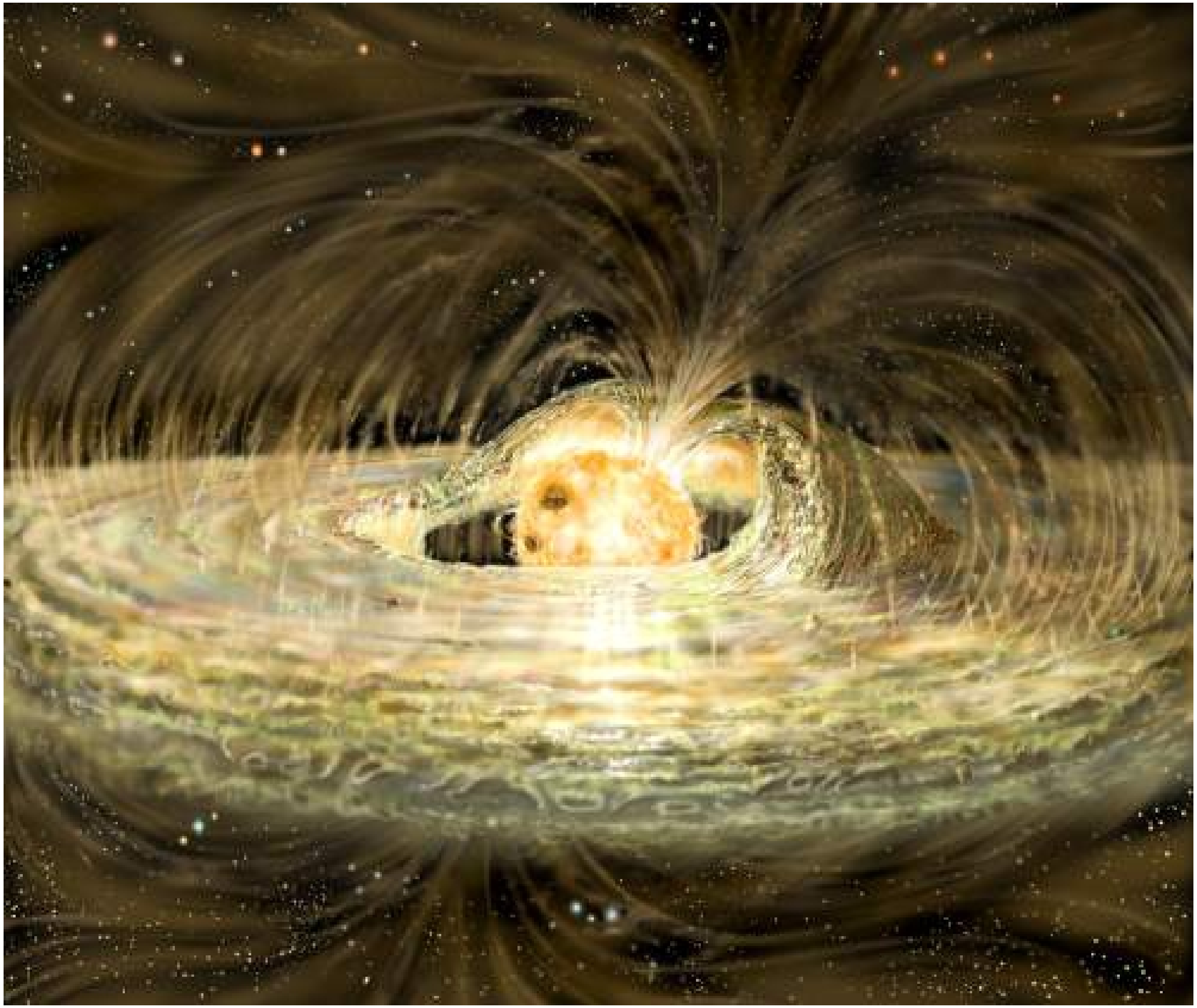
- fully convective interior, non-solar like dynamos, or turbulent dynamos

- fully radiative interiors should not drive any dynamos.

cTTS:

Accretion occurs along magnetic field lines - hot spots. Material reaches free fall velocities, and infalling gas is heated reaching 10^6 K.

X-ray emission: thermal emission by an optically thin plasma about 20 MK, L= 10^{29-30} erg/s.

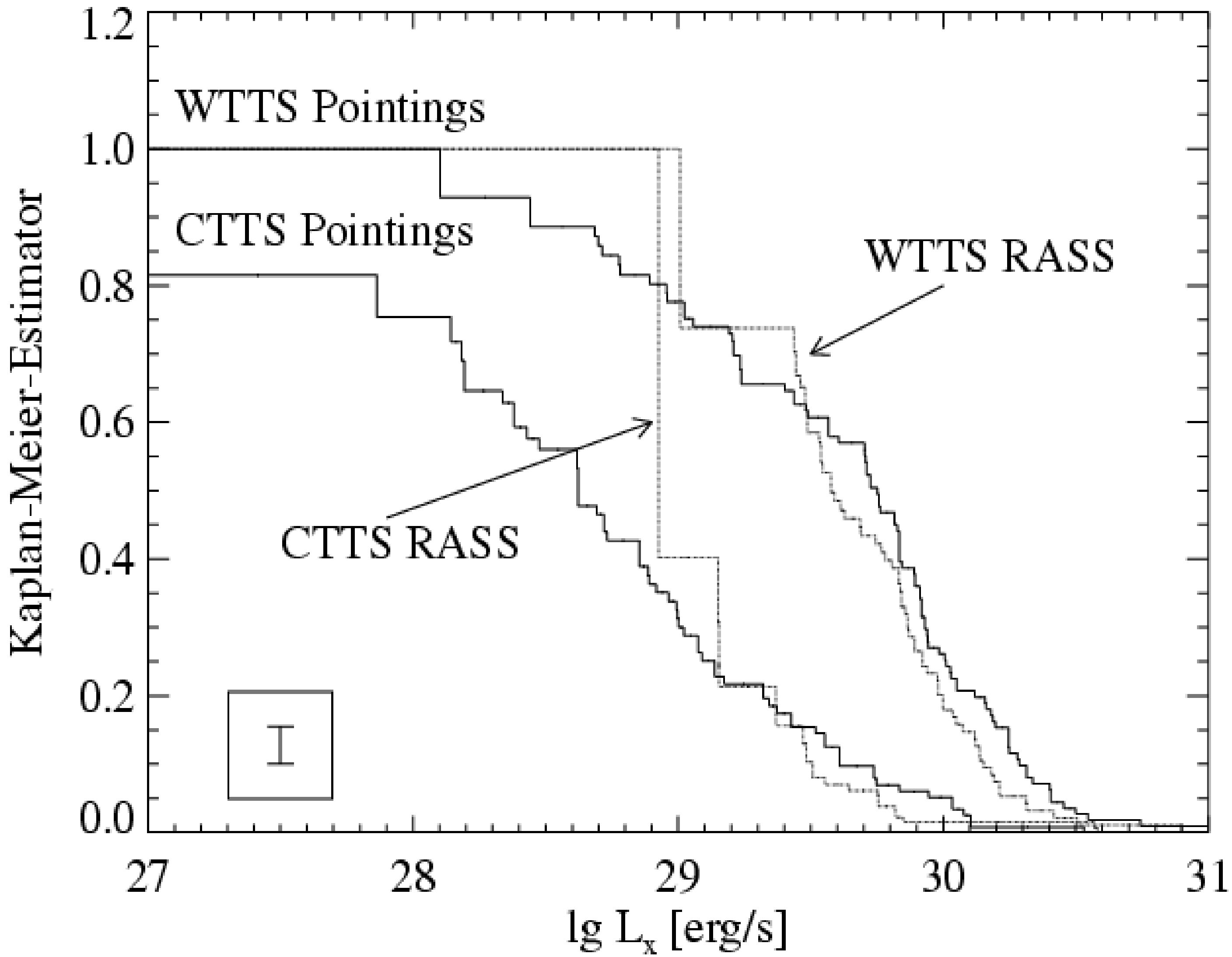


$$L_X/L_{bol}=10^{-3...-5}$$

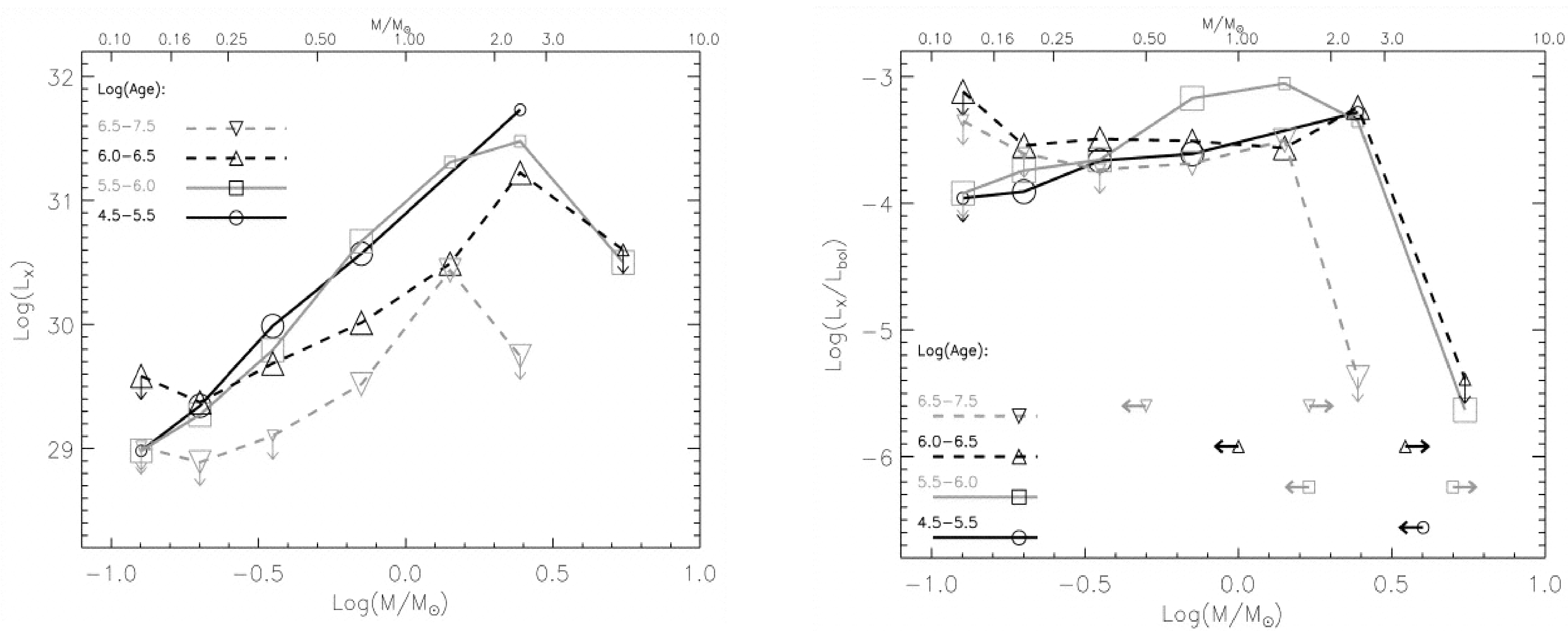
close to saturation limit

wTTS have stronger X-ray emission than cTTS:

Stelzer+2001



Dependence of Lx/Lbol on mass and age:



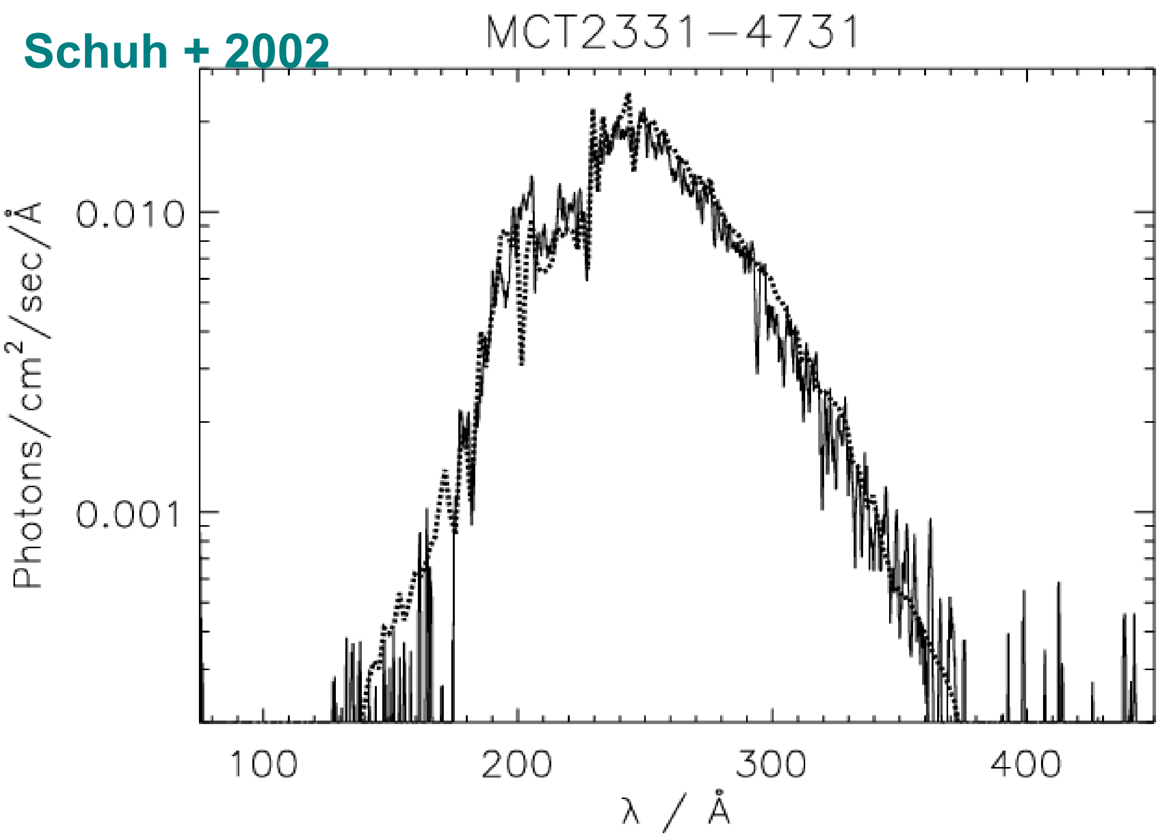
Sample of pre-main sequence stars in Orion.
Masses at which the interior structure of stars is expected to become fully convective – leftward arrows
fully radiative – rightward arrows.

White Dwarfs: 97% stars in Galaxy will become WD.

DA WD exhibit pure hydrogen Balmer line spectra,
non-DA WD exhibit pure helium line spectra.

Thermal soft X-ray emission from hot hydrogen rich atmospheres
Teff = 20000 K (DA) pure H
Teff = 200000 K (hottest WD H1504+65) - naked C-O stellar core.

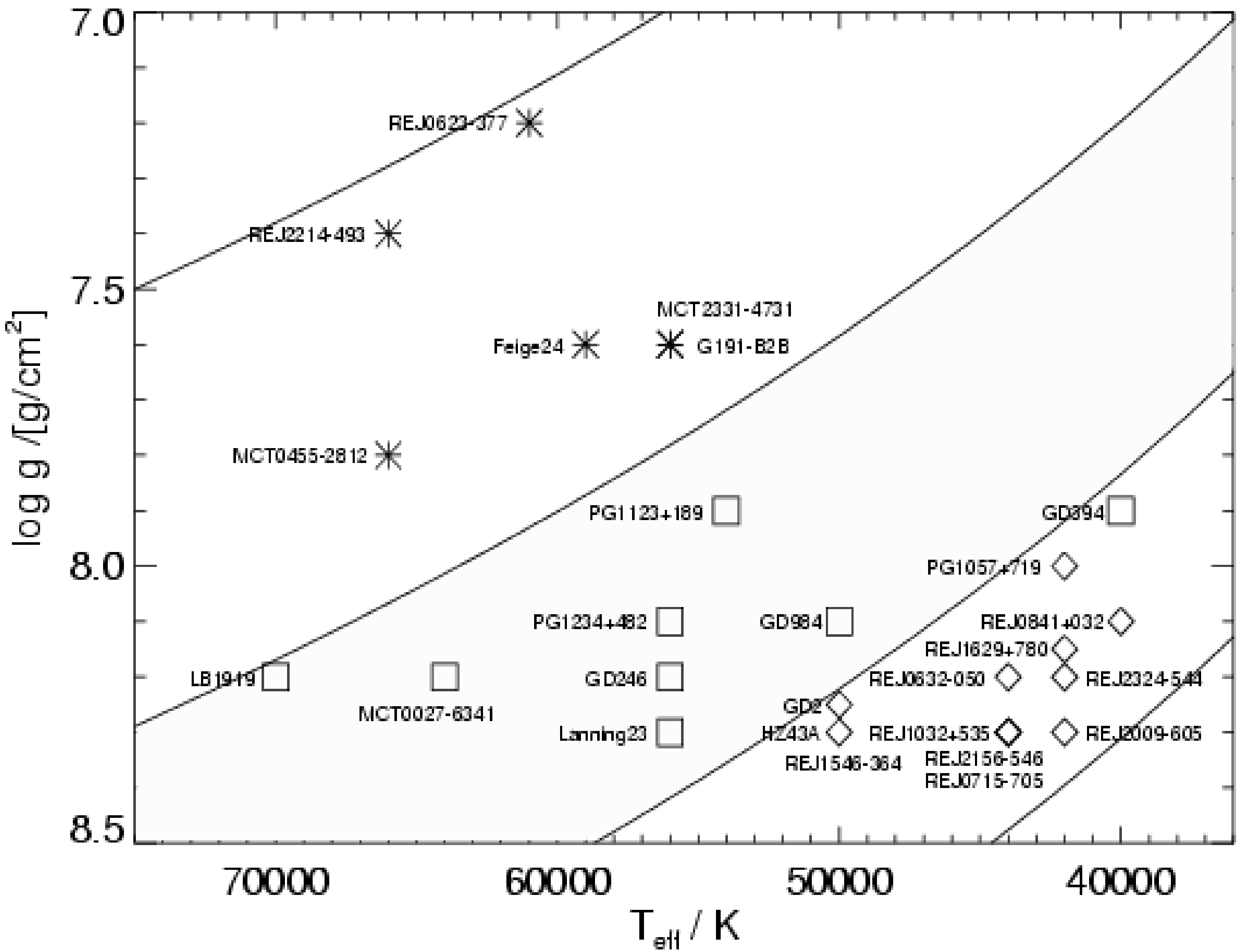
Schuh + 2002



EUVE – observations; ROSAT, EXOSAT. Emission modeled by non-LTE transfer from the atmosphere, with pure hydrogen, or some mixture of heavy elements.

White Dwarfs: 97% stars in Galaxy will become WD.

Schuh + 2002



White Dwarfs: 97% stars in Galaxy will become WD.

H1504+65

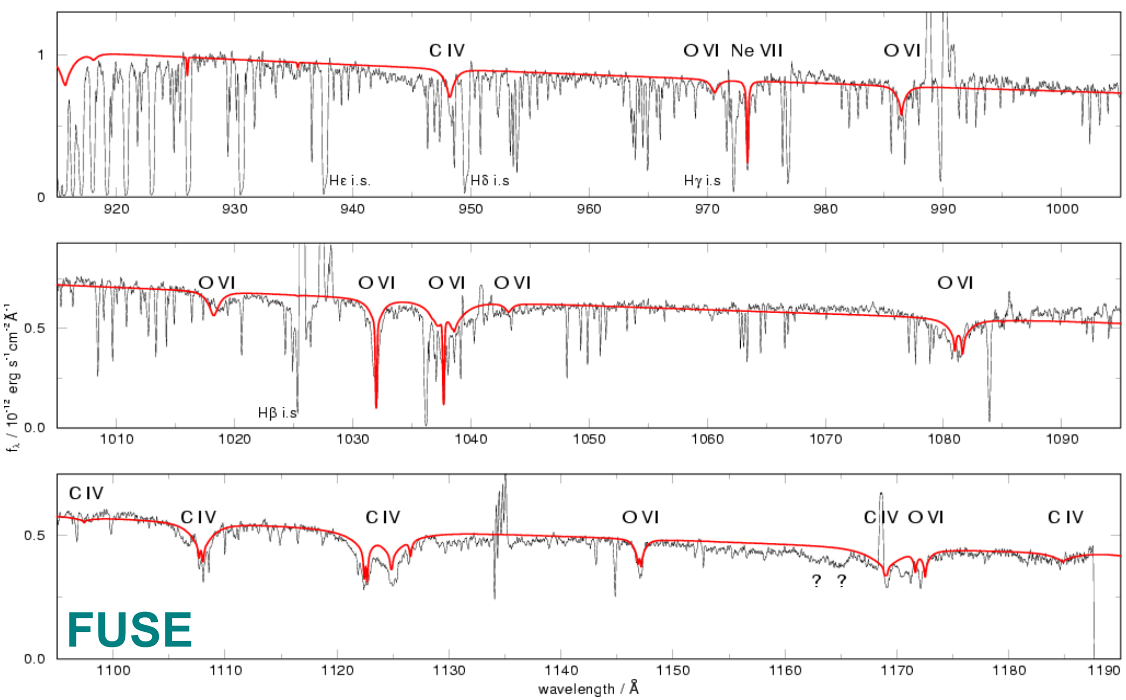
$$T_{eff}=200000\pm20000\,K$$

$$\log(g)=8\pm0.5\,cgs$$

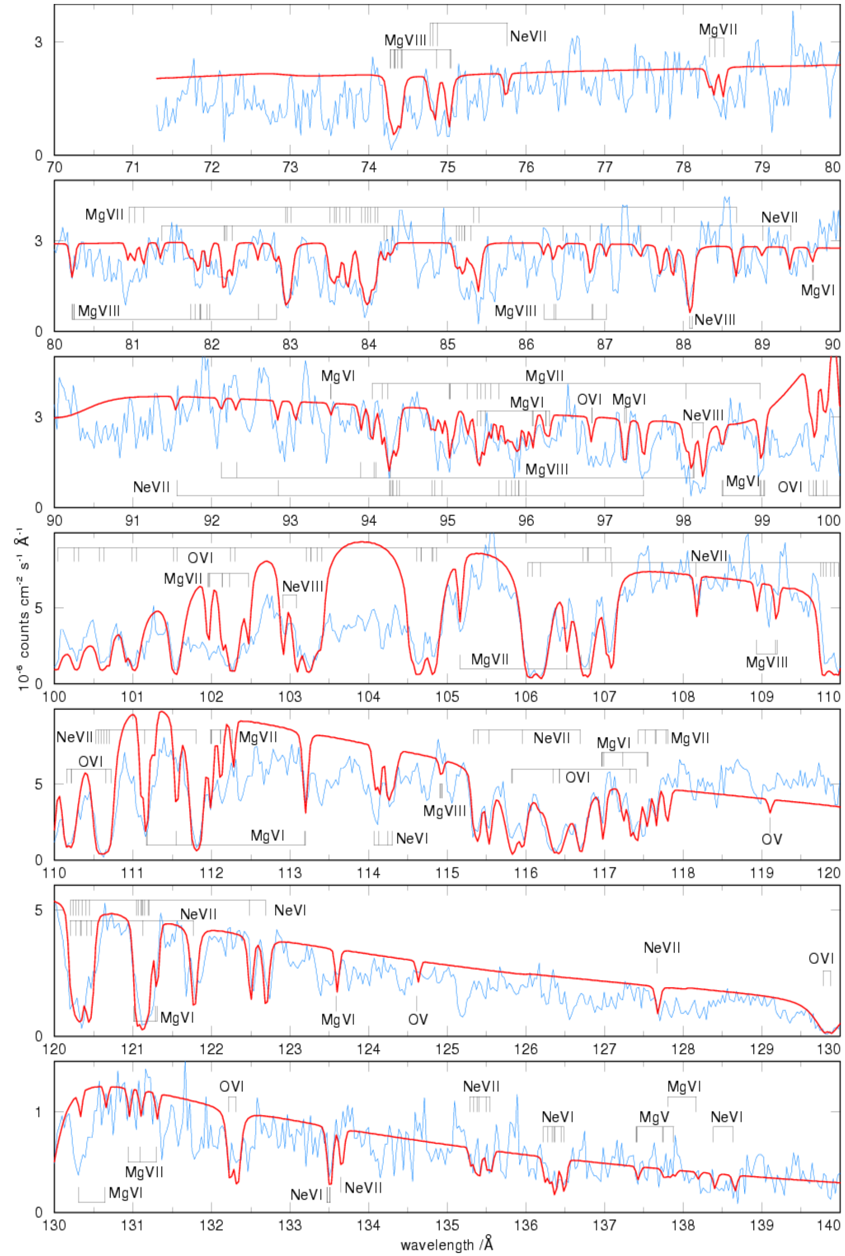
Element abundances in % mass fraction:

$$C=48\;;\quad O=48\;;\quad Ne=2\;;\quad Mg=2\;;$$

$$Fe=0.14\;;\quad Ne<1\;;\quad Na<0.1\;;\quad Al<0.1$$

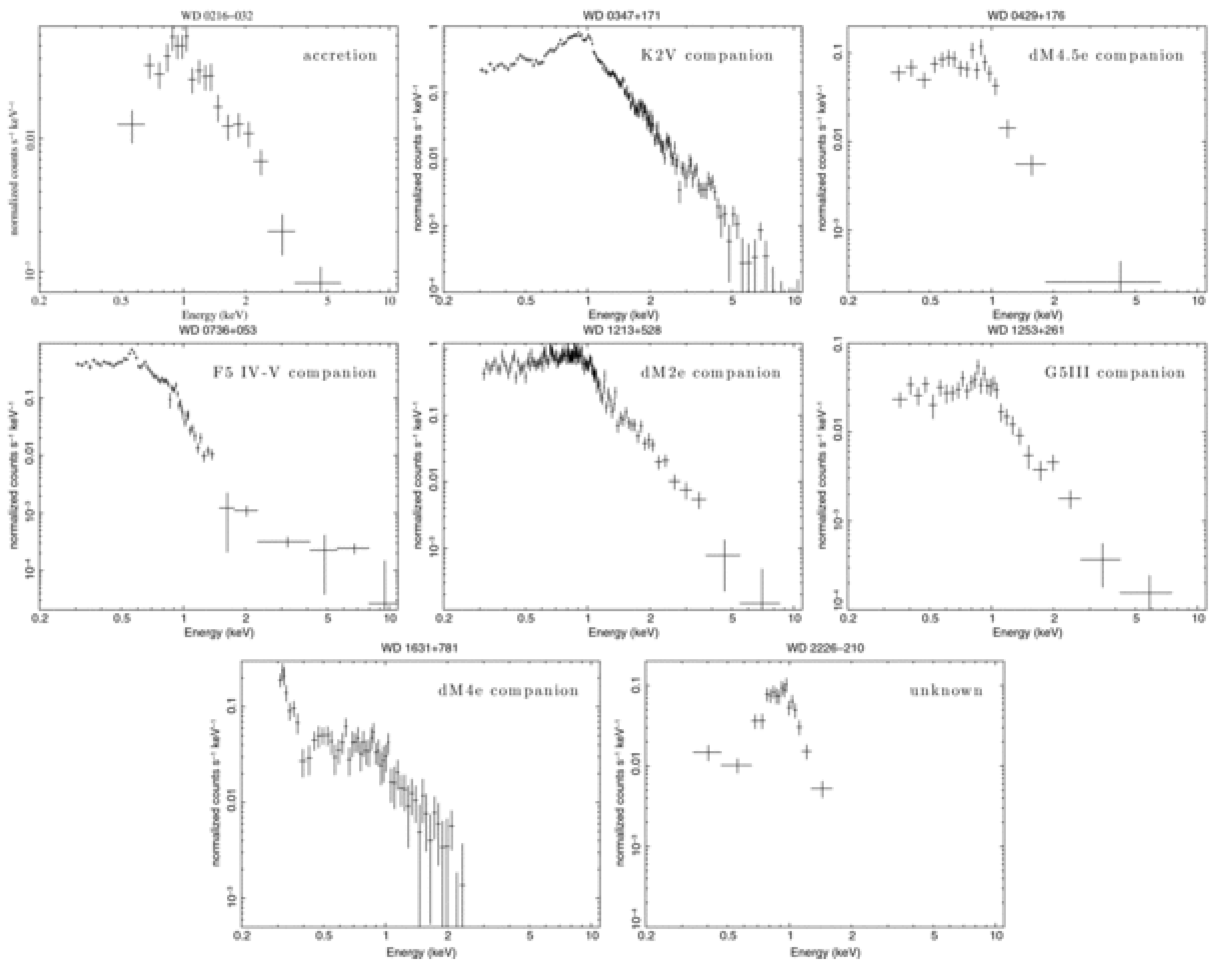


Chandra Werner+2004

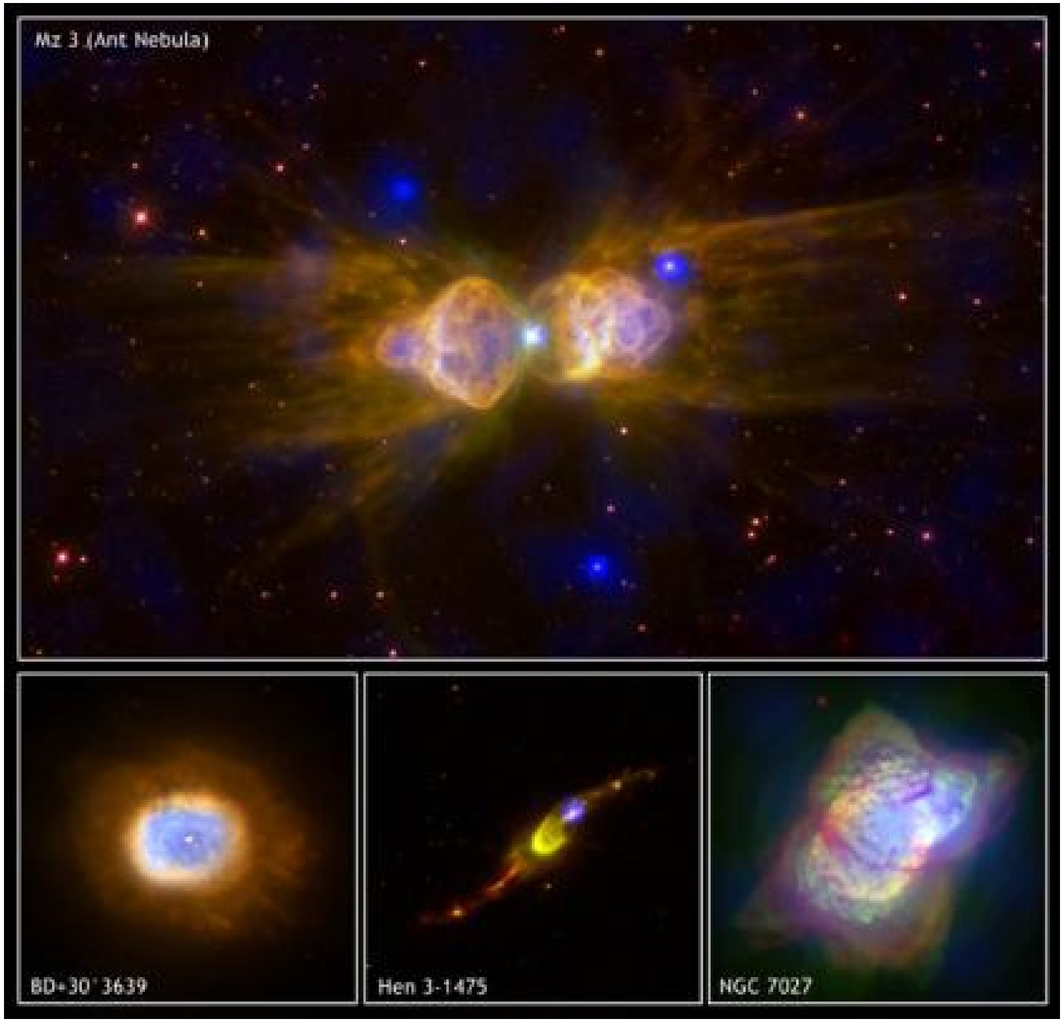


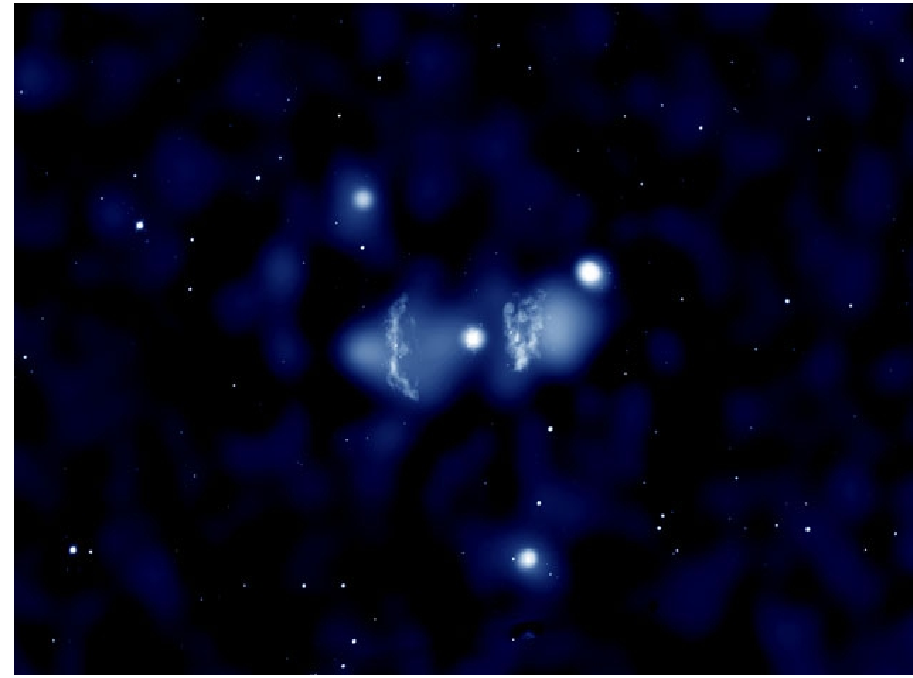
White Dwarfs: 97% stars in Galaxy will become WD.

Hard X-rays (i.e. > 1 keV) are use to diagnose the presence of late-type binary companions, mass accretion from companions, or physical processes with unknown origins Bilikova + 2010.



Imaging of planetary nebulae – fast winds:





Chandra 2004 ; Mz3

Cataclysmic Variables - CVs:

Mass-transfer binaries, primary – White Dwarf,
secondary – can be a normal star with H rich envelope
or second White Dwarf.

Subsequent nuclear processing of the accreted matter leads to various types of nova events and supersoft X-ray sources SSS. Physics similar to X-ray binaries, in which the accretor is BH or NS.

4U-catalog – 1970-73 – the nature of the bright X-ray sources was settled.

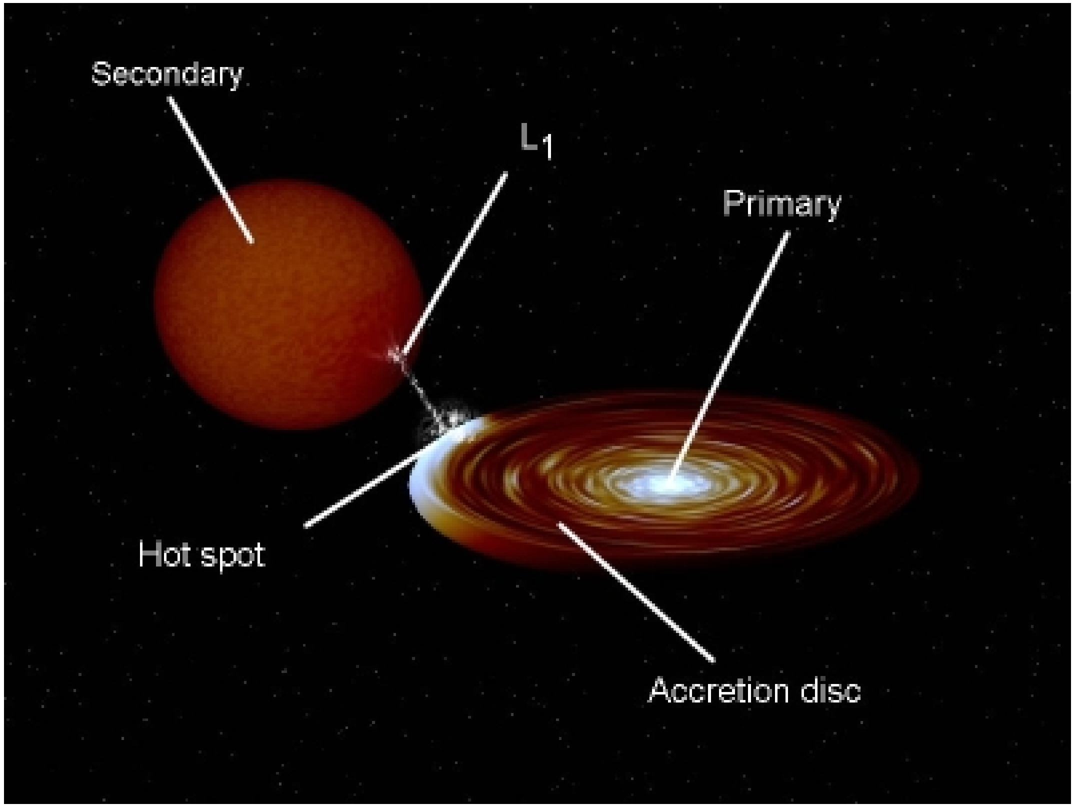
4U 1809+50 with the long-known 12-15 mag variable star AM Her and discovery that AM Her was circularly polarized. Interpreted as strong magnetic accreting WD – *polars* (Krzeminski + 1977).

The Zoo of CVs:

Accretion dominated CVs can be classified according to the mass accretor and the mass donor.

Mass donors: - i) MS-stars/Brown Dwarfs; ii) WD.

1) Dwarf Novae: 400; about 10% observed in X-rays:



Non-magnetic:

i) MS-star – CV

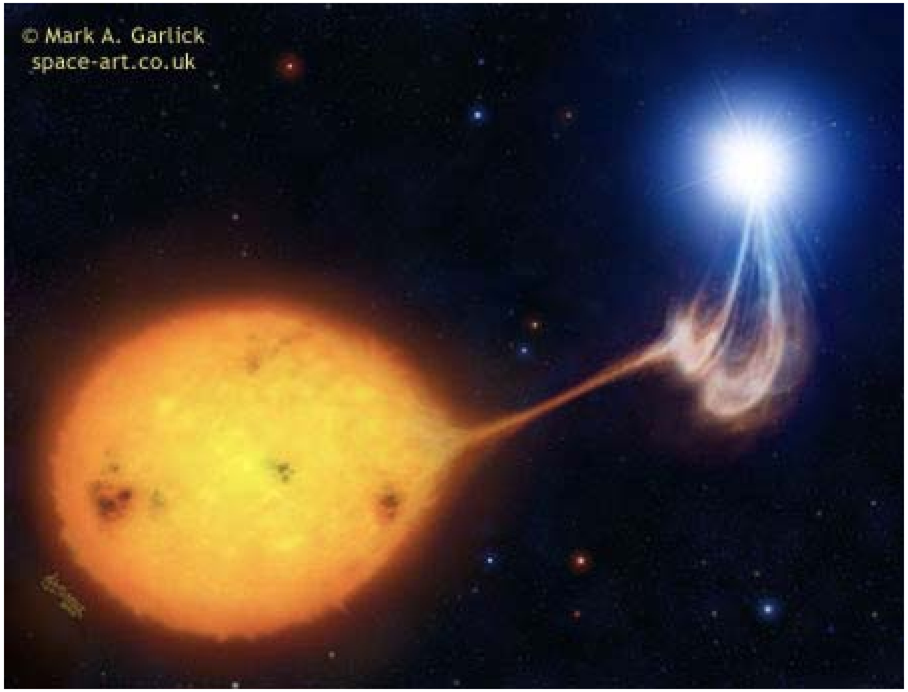
$$F_X / F_V = 0.01 - 1$$

ii) WD – AM CVn

$$F_X / F_V = 0.1 - 5$$

The Zoo of CVs:

2) Polars – mater overflow the Roche lobe. Strong magnetic field prevents disk formation. 80; 75% observed in X-rays:



i) MS star – AM Her

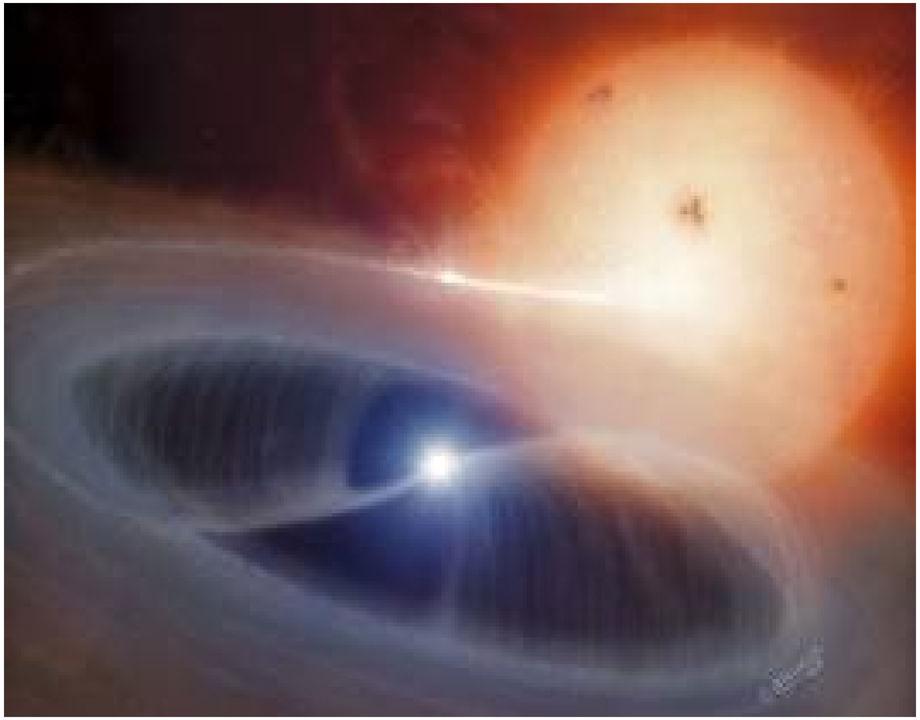
$$F_X / F_V = 1 - 100$$

ii) ?

The strong magnetic field tidally lock the orientation of the WD relative to the companion, so the orbital and rotational periods are synchronized – i.e. identical.

The Zoo of CVs:

2) Intermediate Polars – magnetic field and wide separation allow for accretion disk formation. 35; 65% observed in X-rays:



i) MS star – IP/DQ Her

$$F_X / F_V = 0.1 - 10$$

ii) ?

Longer orbital periods than polars, orbital and rotational period is not synchronized.

Accretion geometries:

CV Polars shocks:

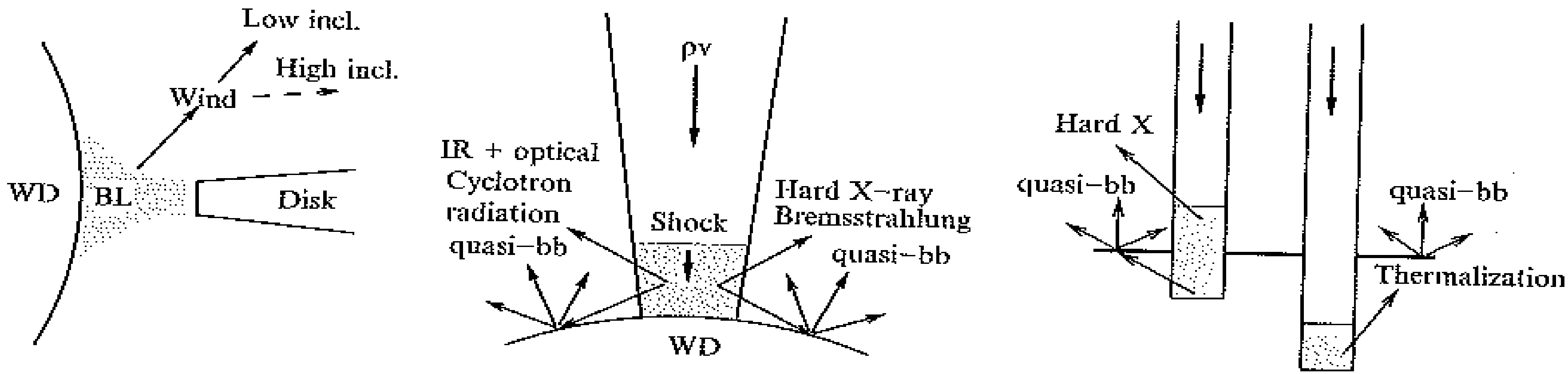


Fig. 12.1 The accretion geometry and the observed radiation components. *Left:* Boundary layer in nonmagnetic CVs. *Center:* Cooling flow behind free-standing shock for radial accretion in a magnetic CV with low mass-flow density (i.e., specific accretion rate). *Right:* Partially and completely buried shocks for intermediate and high mass flow densities, respectively

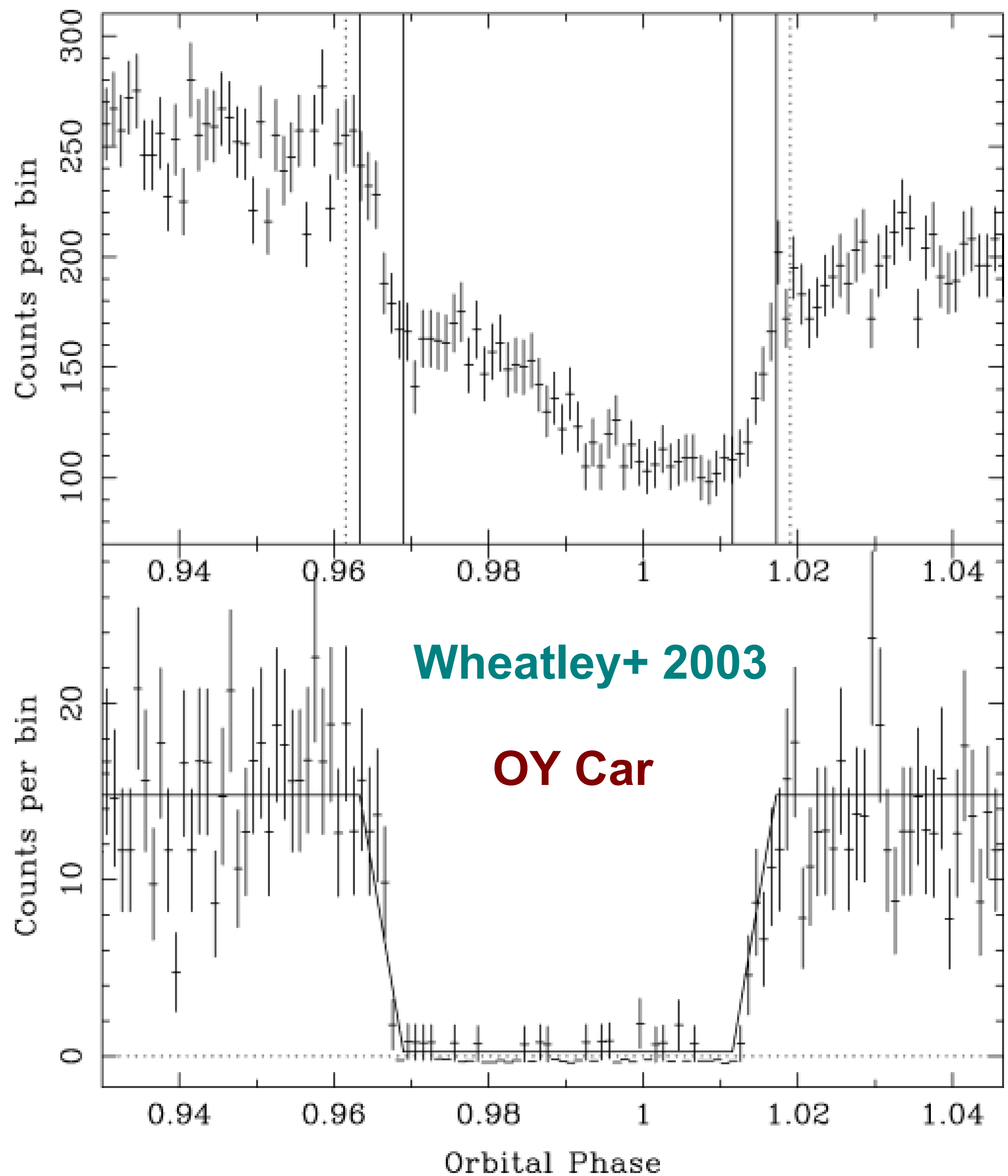
BL – boundary layer emits thermal radiation. For plasma with relatively low densities we have cases of movement of electrons in magnetic field emit cyclotron radiation, and electrons in the field of ions (Coulomb interaction) emit bremsstrahlung radiation.

X-ray and UV emission from non-magnetic CVs:

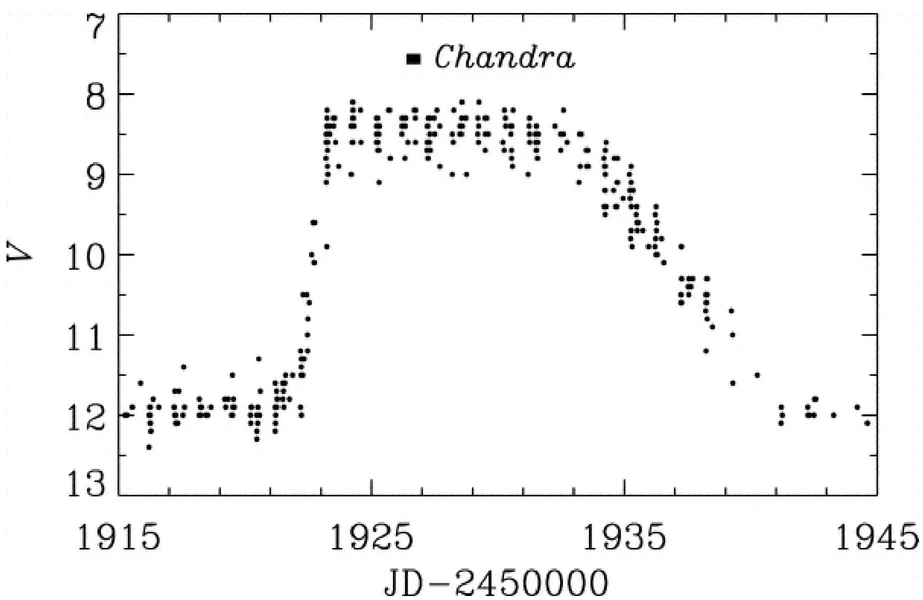
Emission from BL (boundary layer): Top – B, bottom – XMM

The length of the X-ray visibility is identical to that of the optical light of the WD, but ingress and egress times are significantly shorter than that of the WD.

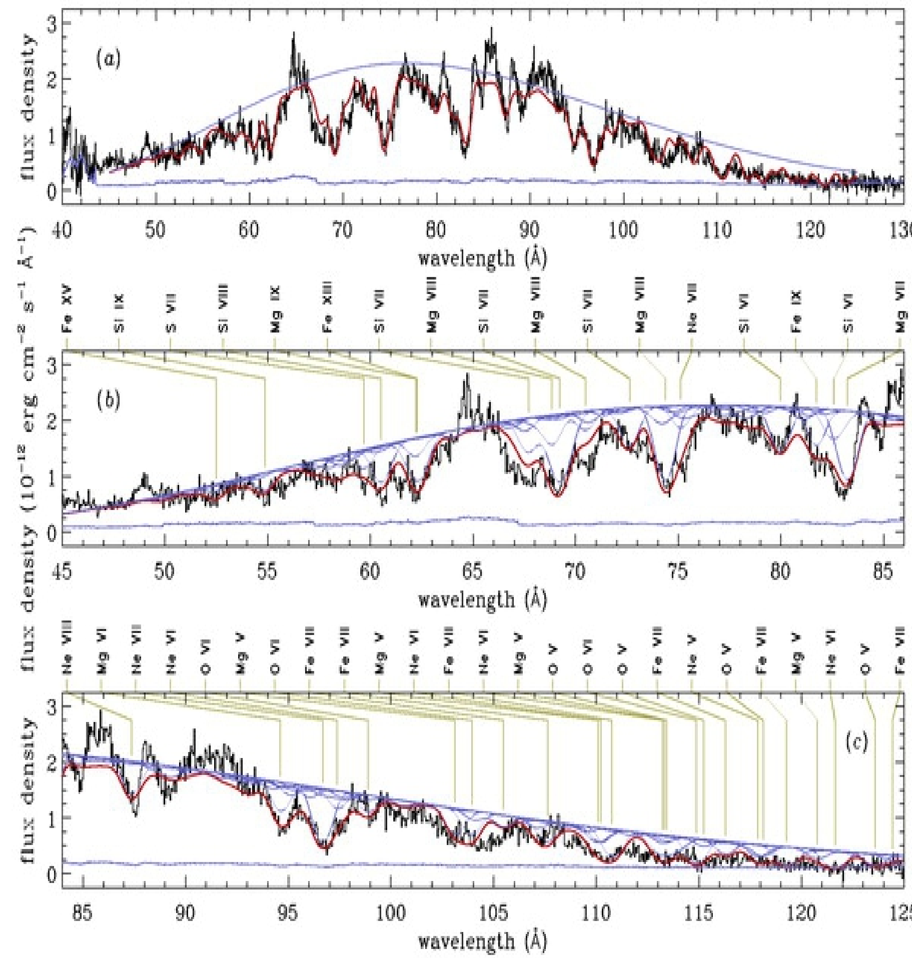
This suggest that the X-ray emission arises from the region on the white dwarf.



SS Cyg during outburst:



Chandra LETG; Mauche 2004

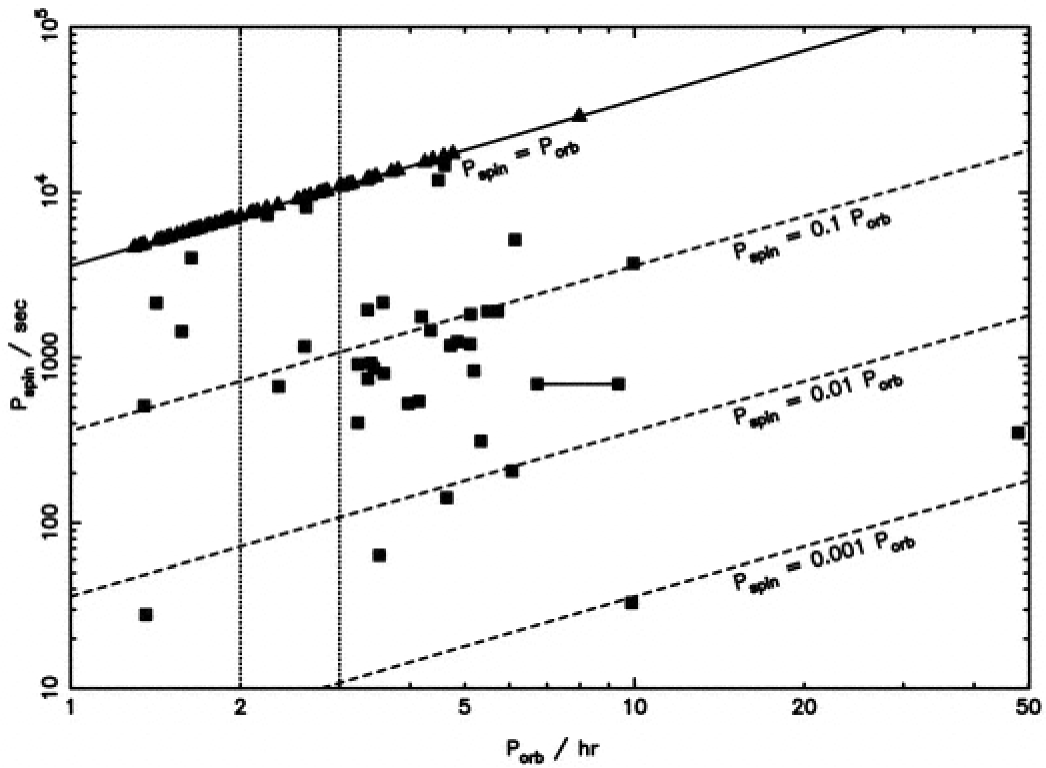


Absorbed BB continuum – blue line
Individual ion spectra by blue thin lines
Black histogram – observations
Red line – net model fitted.

X-ray from Intermediate Polars:

The defining feature of IPs is a coherent pulsation at a period P_s shorter than the orbital period P_{orb}.

P_s – spin period of the WD.

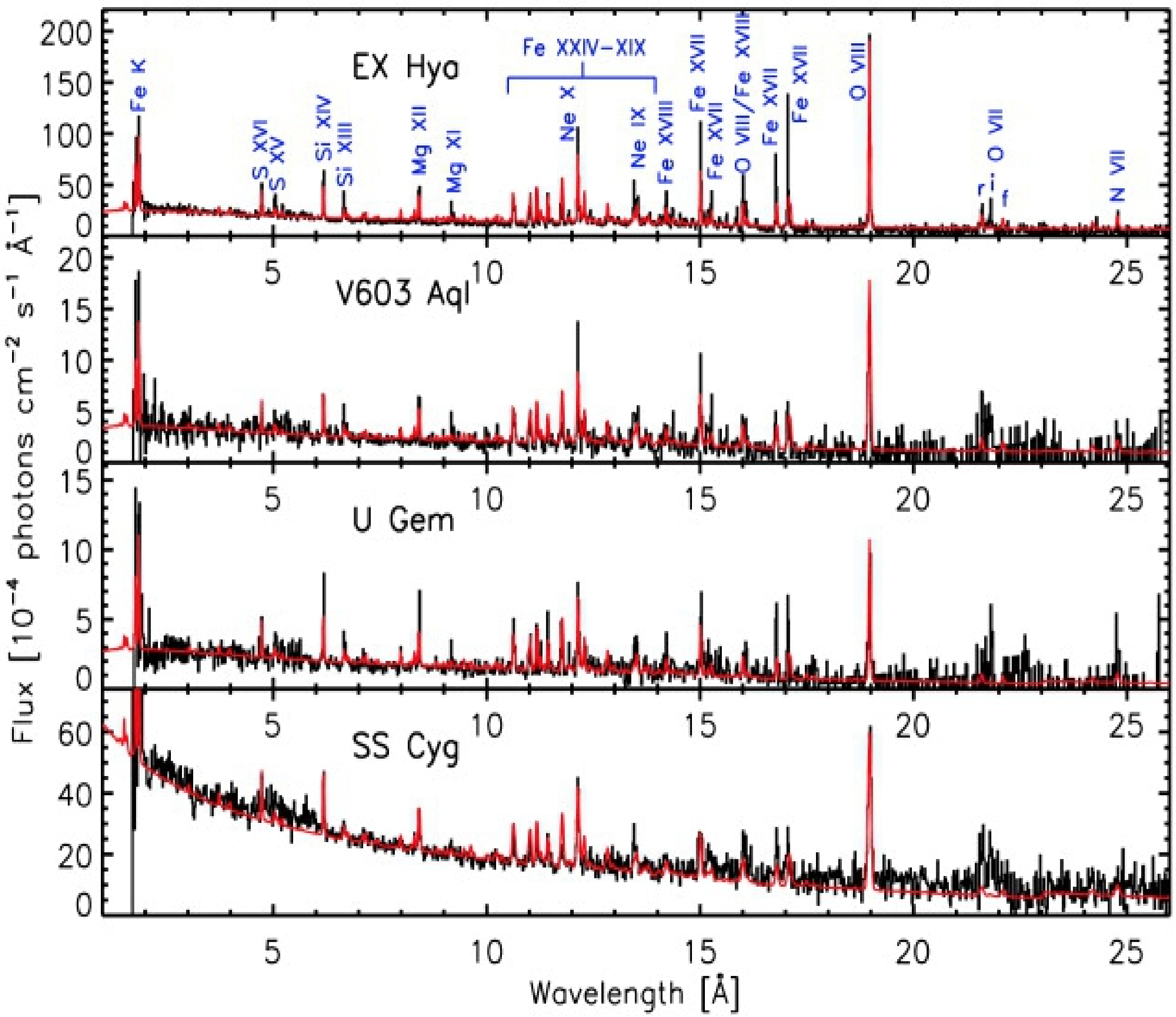


Polars by triangles
IP by squares.

Norton + 2003

X-ray from Intermediate Polars:

Chandra HETG spectra (MEG m = -+ order) Mukai+ 2003



X-rays from Polars:

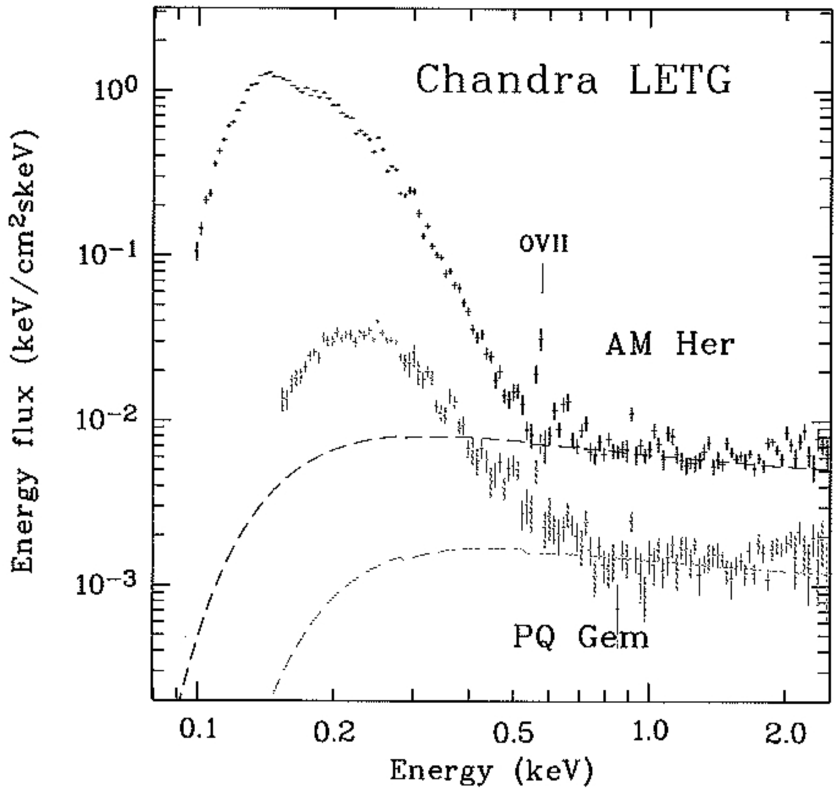


Fig. 12.6 Spectral energy distributions of AM Her and PG Gem based on Chandra LETG spectra binned into 100 bins per decade in energy. The model for the hard X-ray bremsstrahlung component is included (*dashes lines*) [8, and private communication V. Burwitz]

Accretion rates:

Accretion luminosity:

$$L_{acc} \simeq \frac{G M \dot{M}}{R}$$

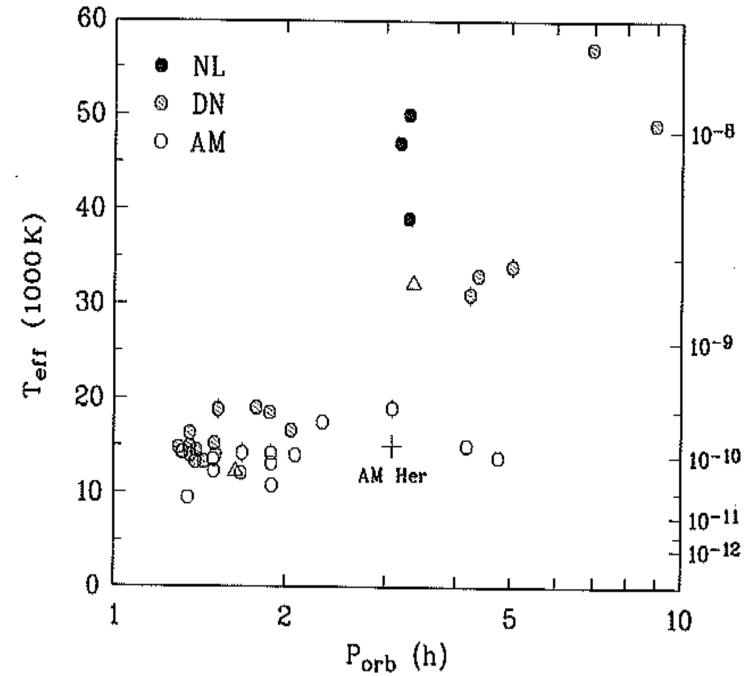


Fig. 12.8 Observed effective temperatures of white dwarfs in CVs vs. orbital period (mostly from [1]). Different subtypes of CVs are indicated by the shading of the *symbols*. Statistical error bars are typically smaller than the symbol size. The right-hand scale gives a long-term average $\langle \dot{M} \rangle$ from (12.7). Also shown is the 20-yr average $\dot{M}$ of AM Her [30] as a cross and the luminosity-derived $\dot{M}$ of EX Hya and V1223 Sgr [5,6] as *open triangles*

heating and cooling of the envelope is important; accreted mass is negligible compared to the core mass, but the geometrical thickness is not:

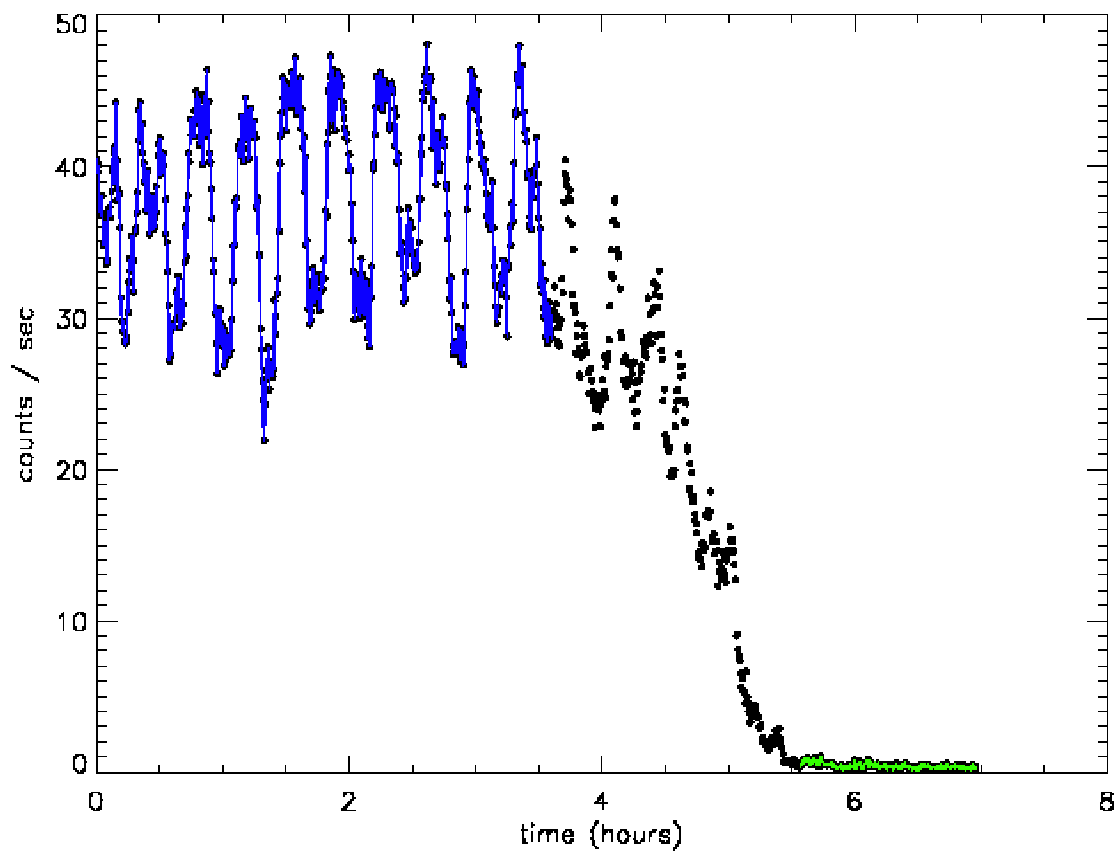
$$T_{eff} \simeq 14400\, \dot{M}_{10}^{0.27} f^{0.05}\, K$$

Classical Novae:

If the certain critical pressure is reached at the bottom of the accreted envelope, explosive thermonuclear burning of hydrogen via C-N-O cycle will start – thermonuclear runaway (TNR). Temperature of the burning H zone will grow to the value:

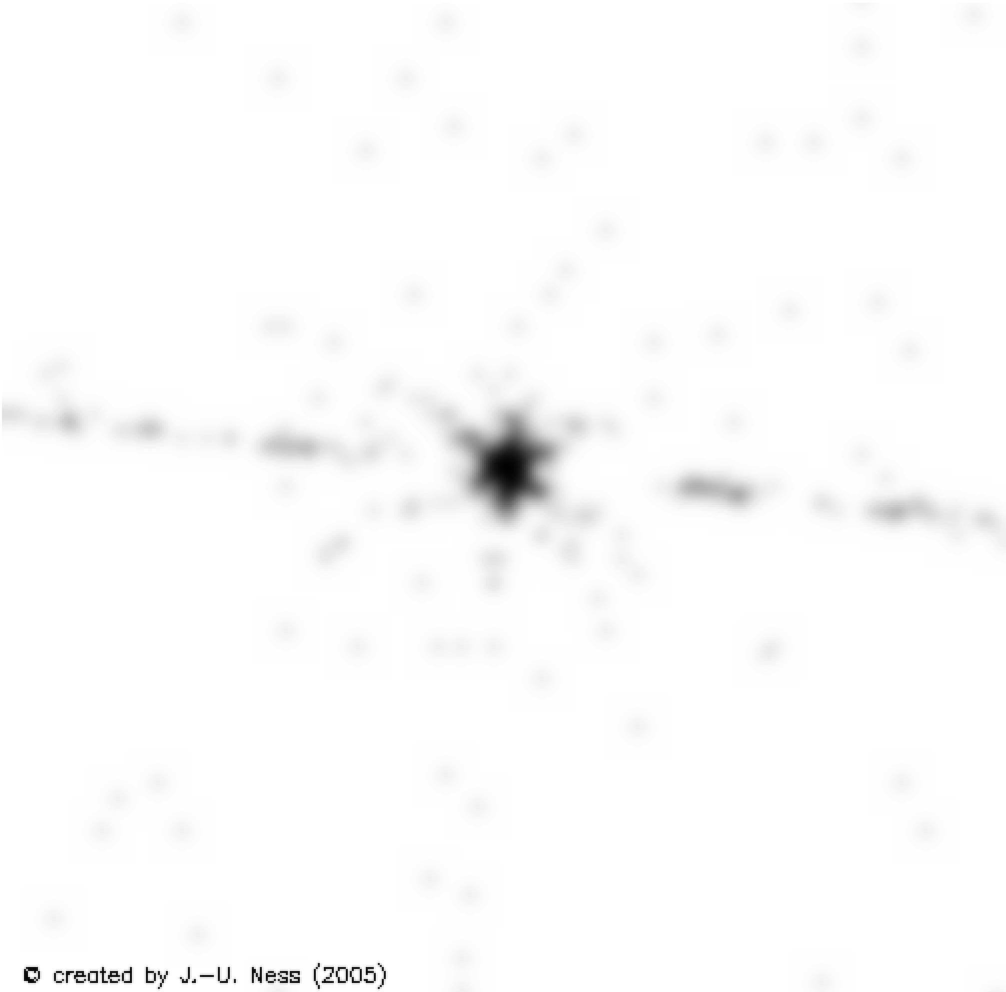
$$T = 10^8 K$$
$$L = 10^{45} erg/s$$

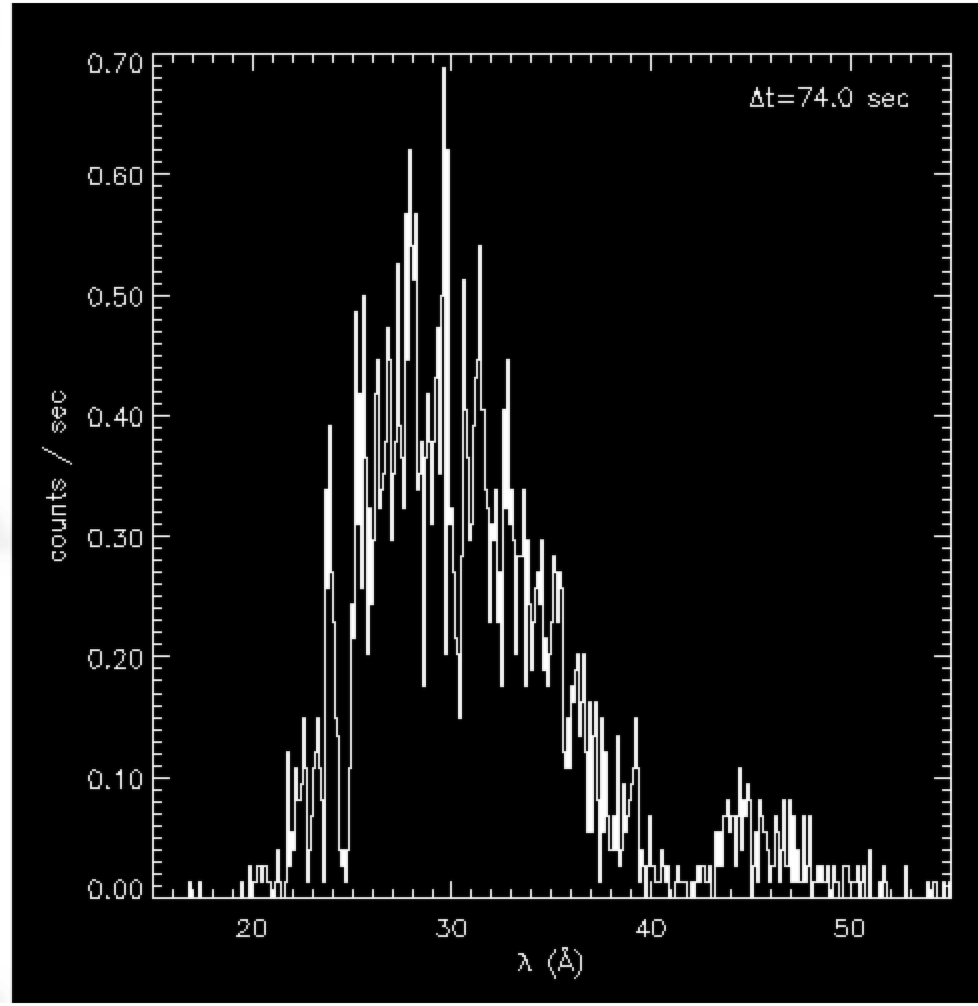
The evolution of TNR depends on the M and L of WD, mass accretion rate, and chemical composition of the accreted matter.



Chandra V4743 Sgr

Classical Novae:

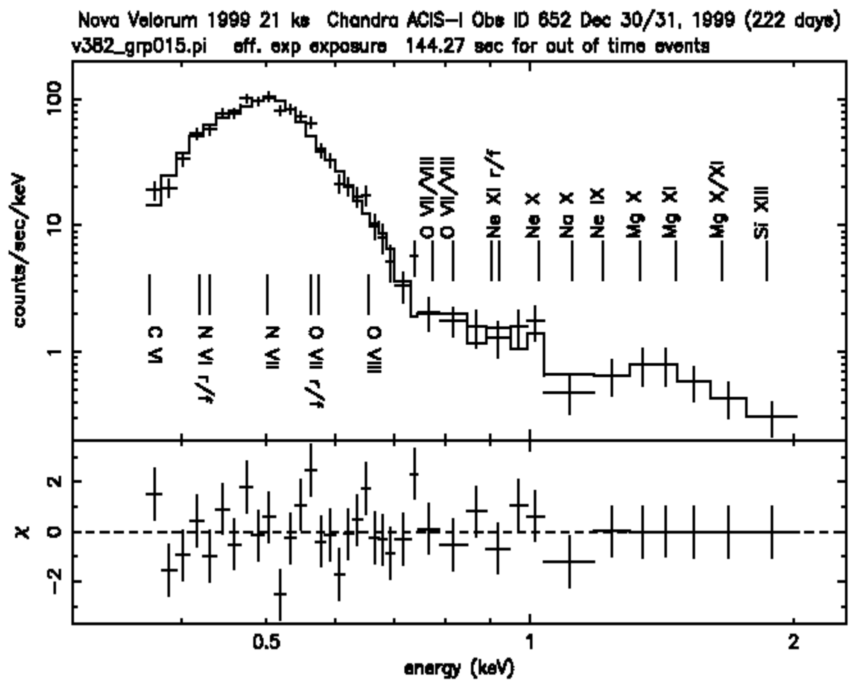




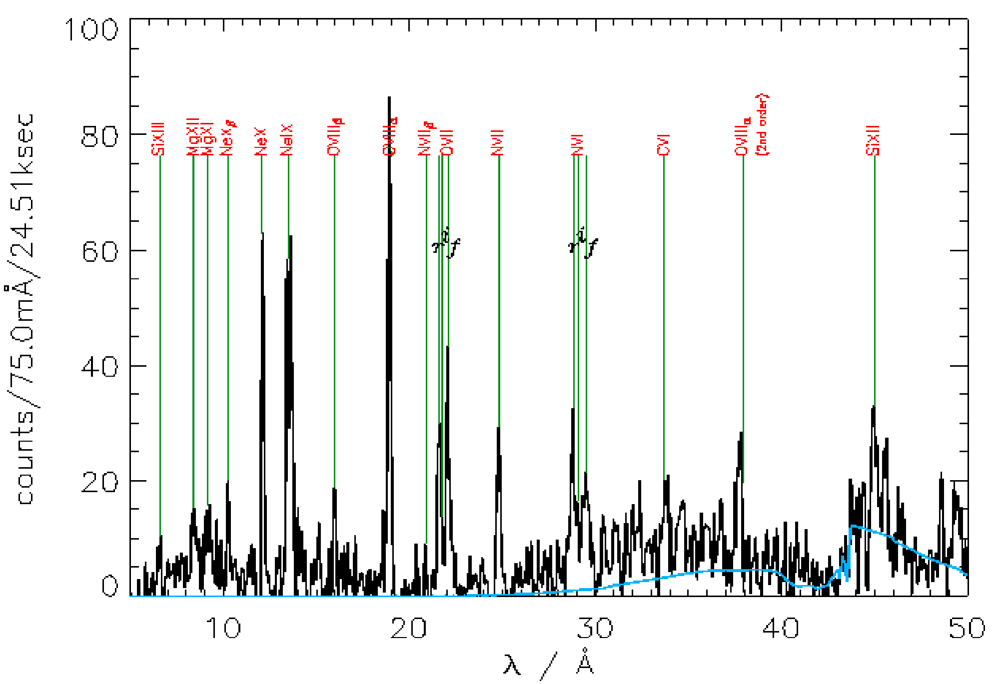
Chandra observations of Nova V4743 Sgr with evolution of brightness and spectrum. Velocities 800 – 2400 km/s

Source of X-rays in Nova stars:

Thermal radiation from the hot white dwarf with luminosity with luminosity of the order of L_{Edd}. Nova emits strong soft X-rays with the SED of a hot stellar atmosphere.
Duration of the soft X-ray emission – fireball phase is very short of the order of few hours.



ACIS during bright phase; V 382 Vel



LEGT after nuclear burning ended

Pulsars and Isolated Neutron Stars:

1750 radio pulsars have been discovered by now.

$$\rho_{nuc} \geqslant 2.8 \times 10^{14} \quad g\,cm^{-3}$$

Rapidly spinning, strongly magnetized neutron stars radiating at the expense of their rotational energy.

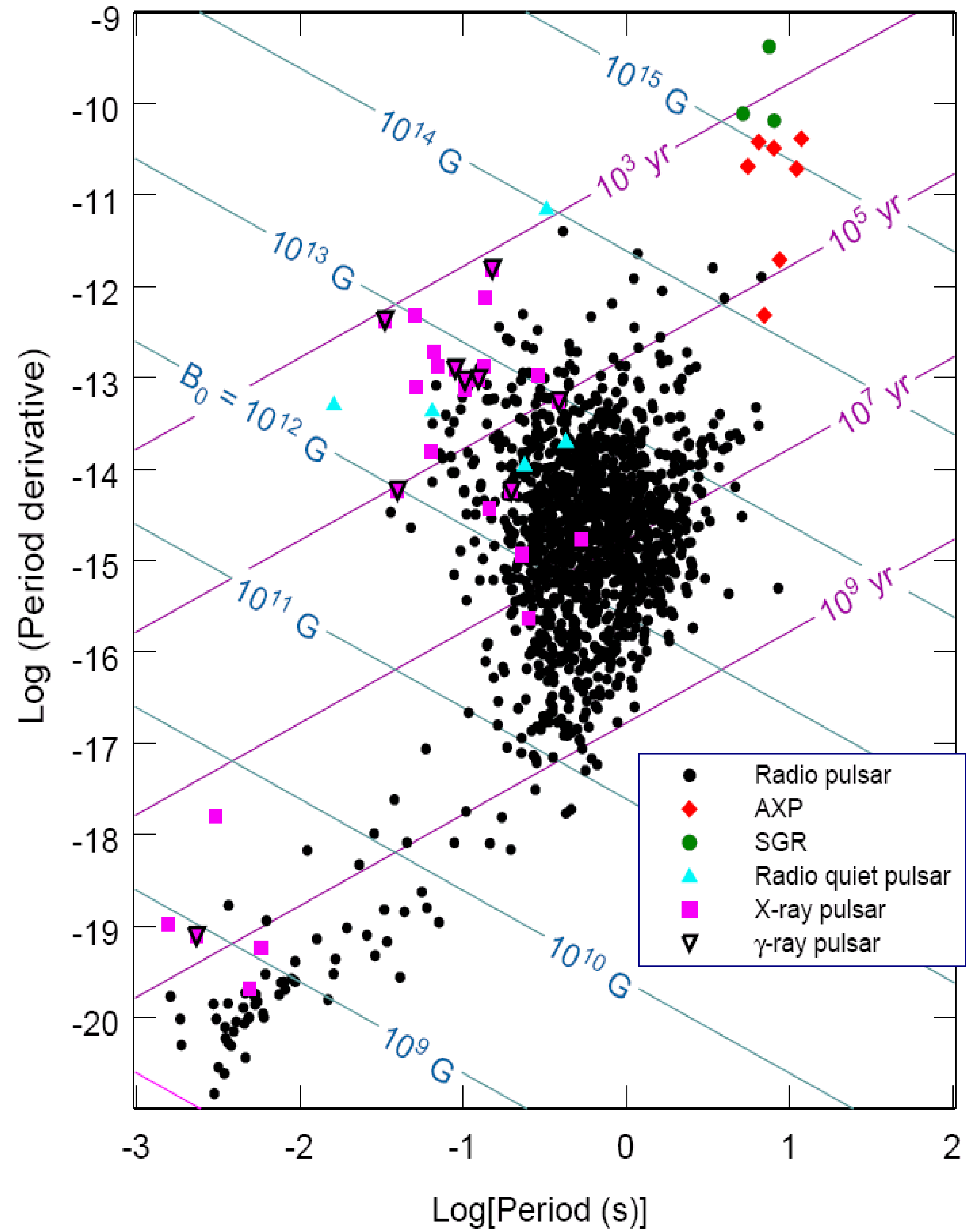
Characteristic spin down age:

$$\tau = P / (2\dot{P})$$

Minimum magnetic field strength:

$$B = 3.2 \times 10^{19} (P\dot{P})^{1/2} \, Gauss$$

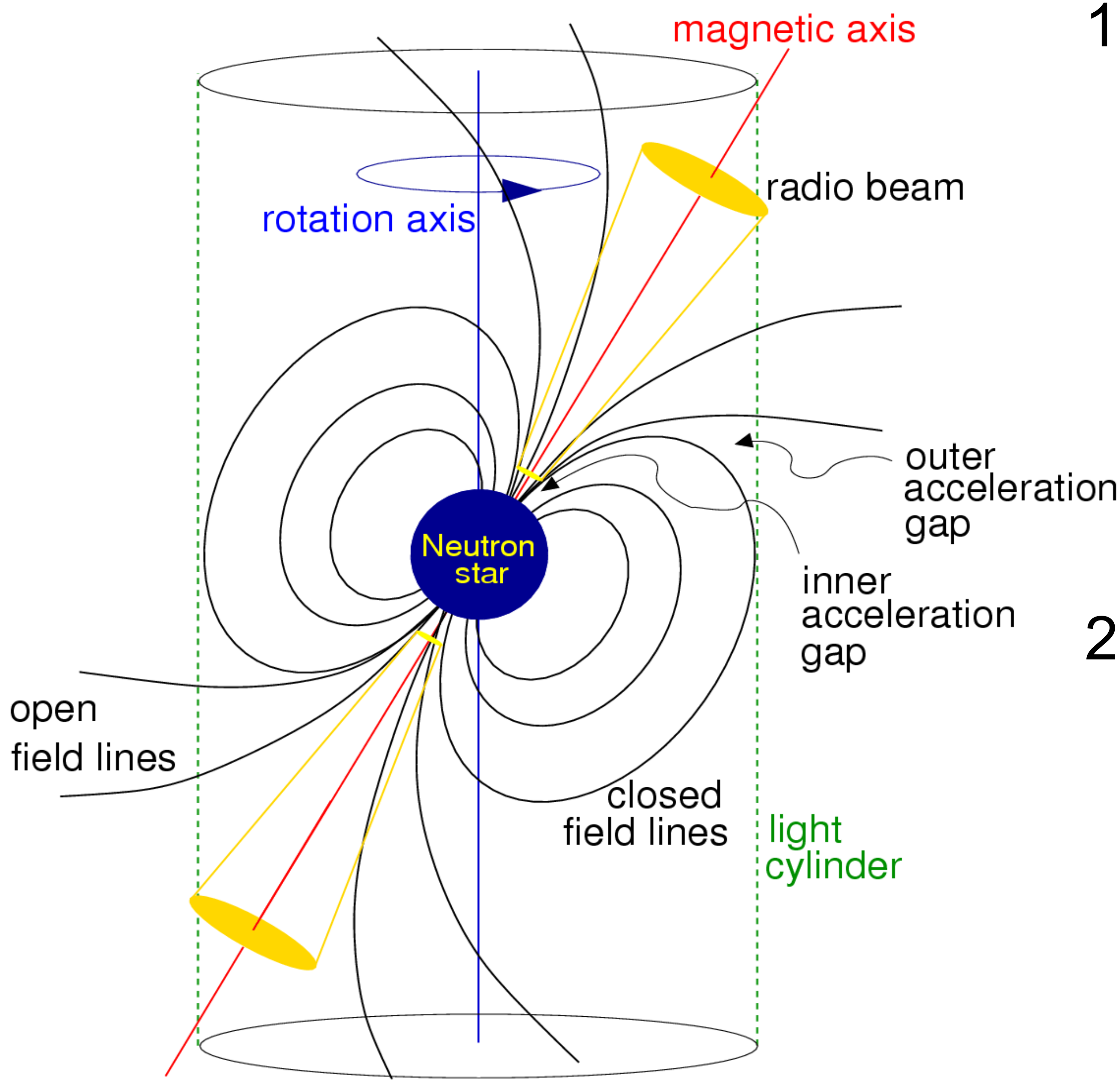
P – P dot



Pulsars and Isolated Neutron Stars:

Chandra – blue , HST – green, VLA – red
X-ray/optical/radio image of Crab Nebula.

Pulsars and Isolated Neutron Stars:



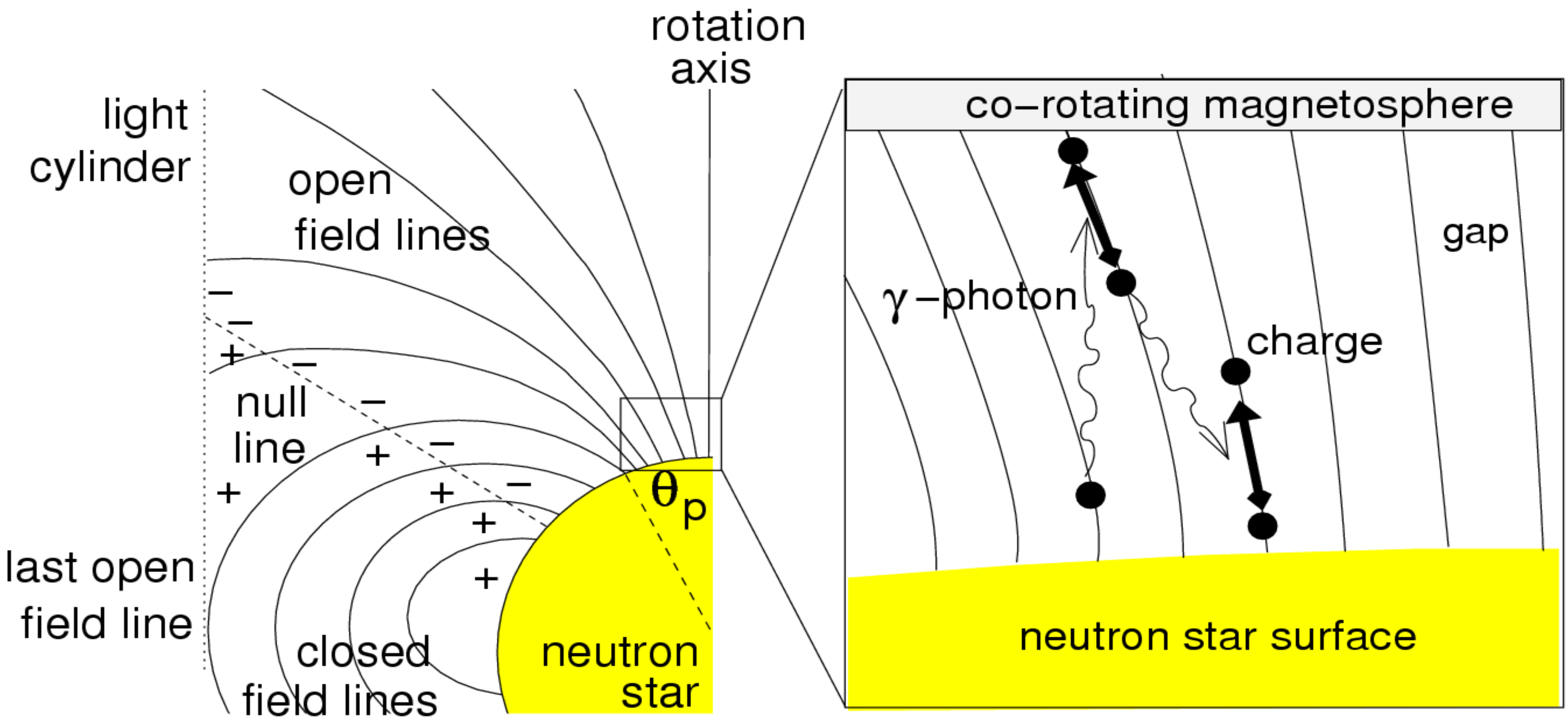
1) Photospheric emission from the hot neutron star atmosphere.
A few x 10^7 K
Modified Black Body emission.

2) Thermal soft X-ray emission from the neutron star's polar caps, heated by hot particles streaming back to the surface from pulsar magnetosphere.

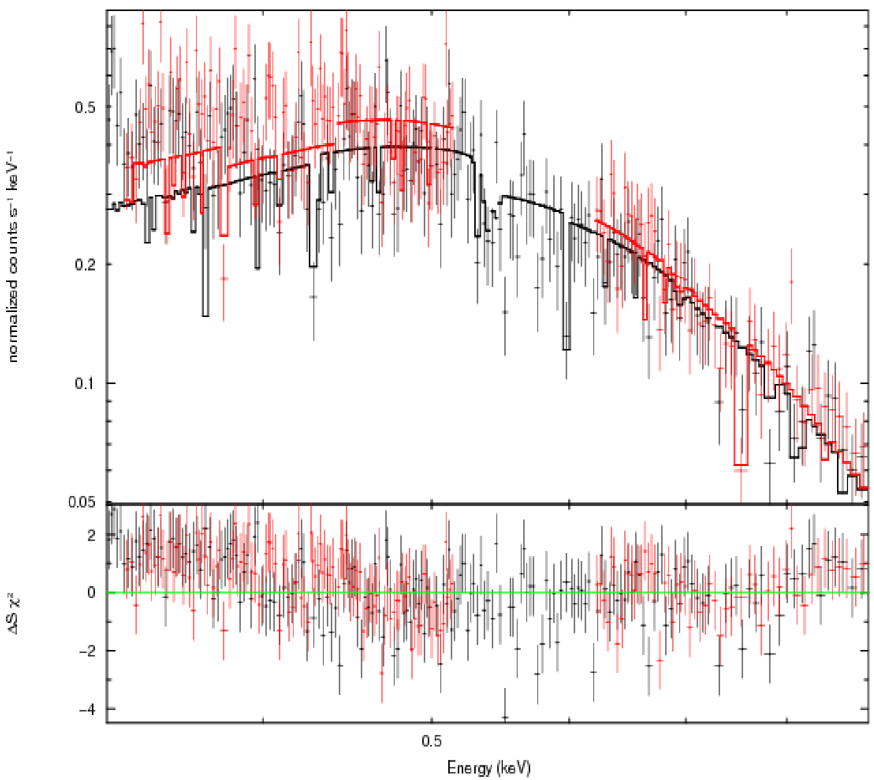
Pulsars and Isolated Neutron Stars:

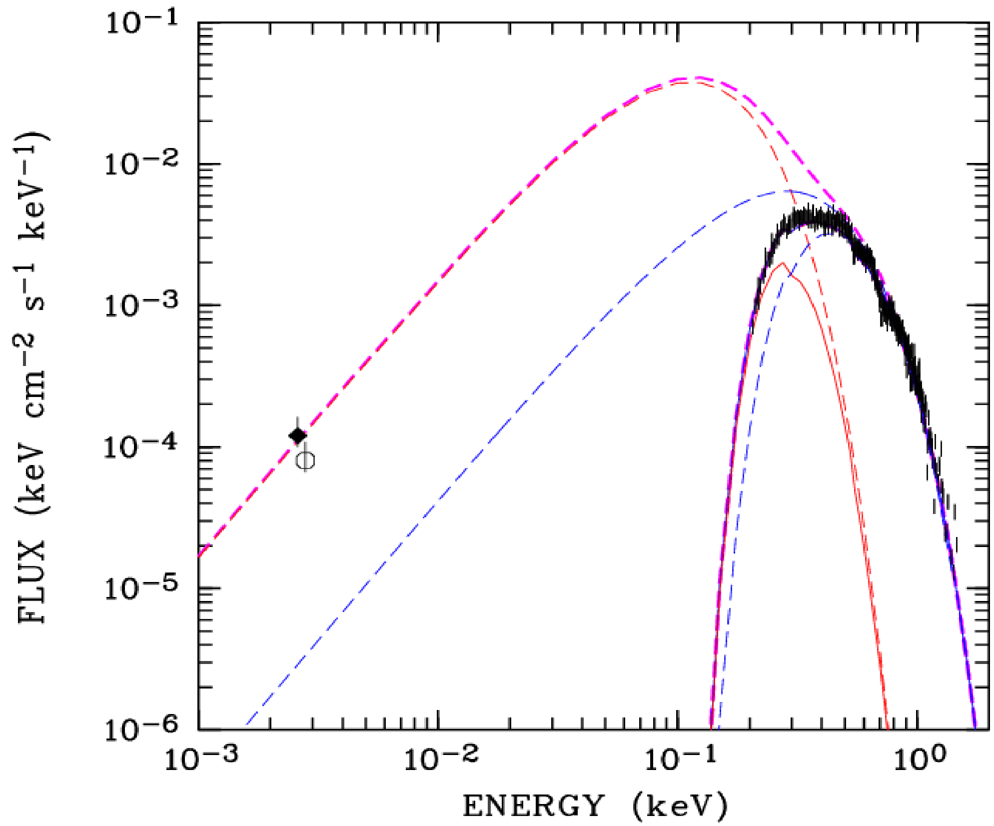
3) Nonthermal emission from charged relativistic particles: from optical to the gamma-ray band.

4) Extended emission from pulsar-driven synchrotron nebulae: from radio through hard X-ray energies.



Thermal radiation – cooling neutron stars:

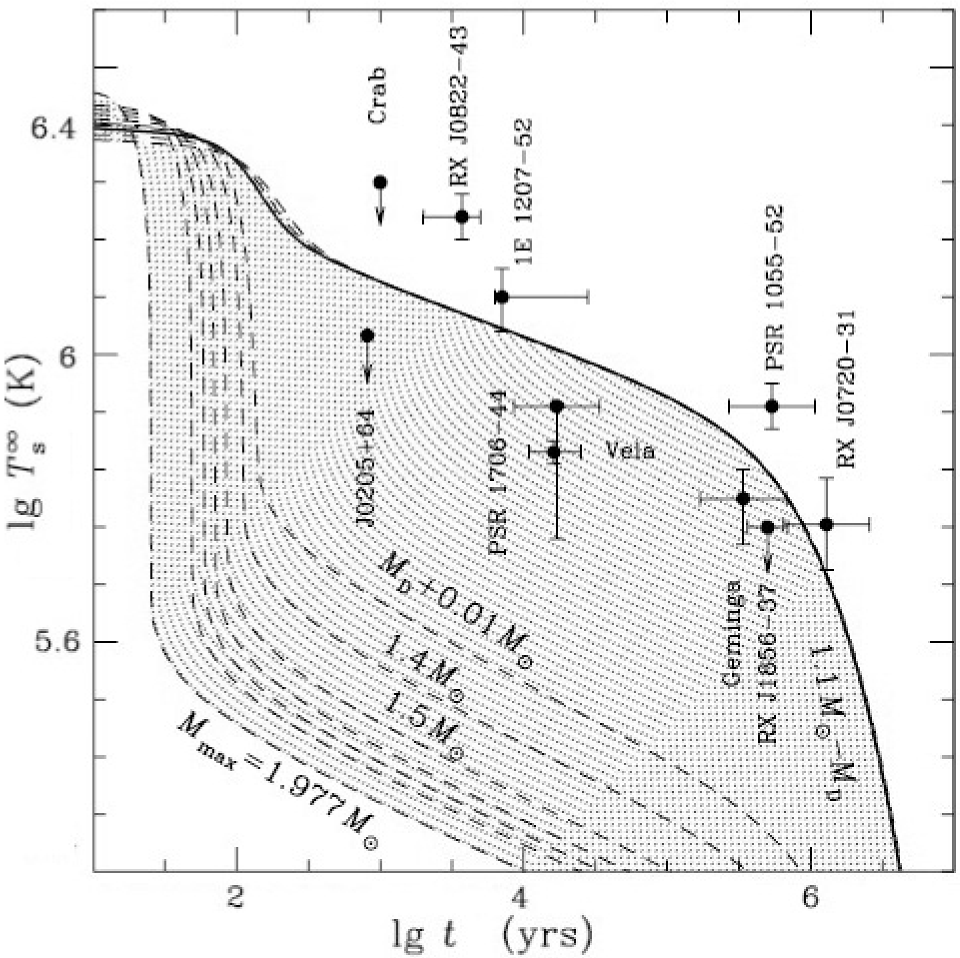


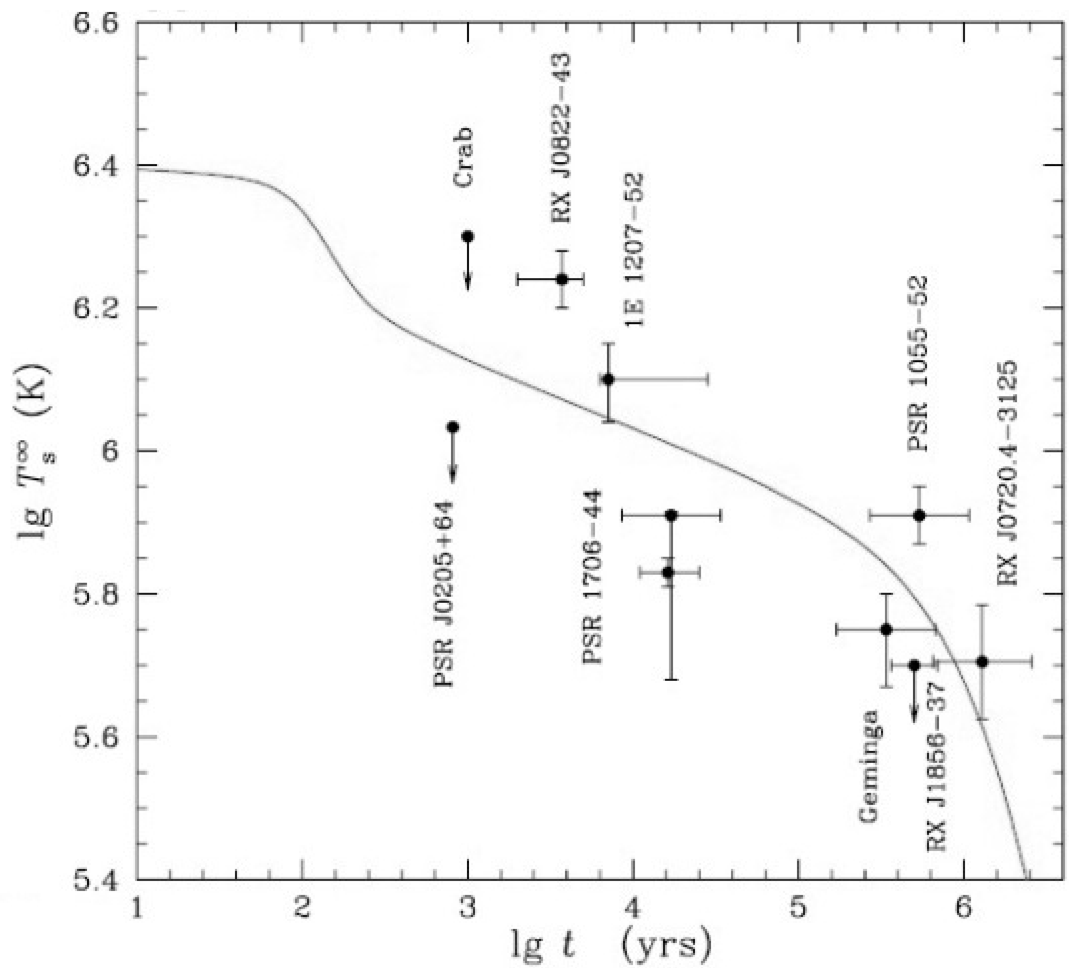


RBS1774, XMM-Newton, Schwope+ 2009

T_{eff} about 10^7 K.

Thermal radiation – cooling neutron stars:

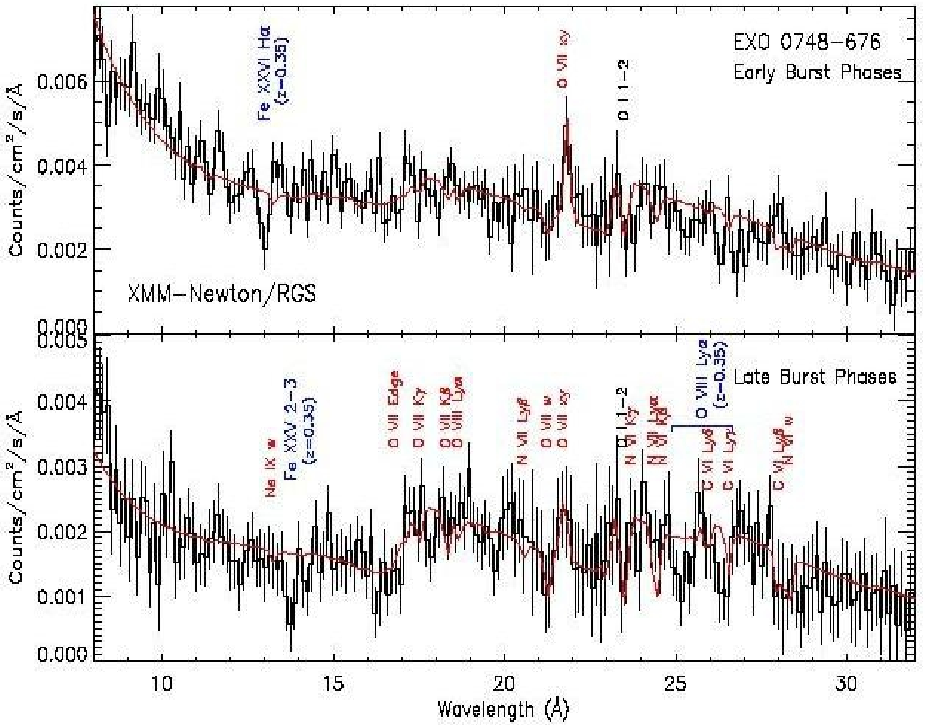




Solid line – basic theoretical cooling curve of a nonsuperfluid NS with M = 1.3 M_{Sun}.

Thermal radiation, X-ray spectroscopy:

XMM-Newton – Cottam+ 2002 Nature;   z= 0.35

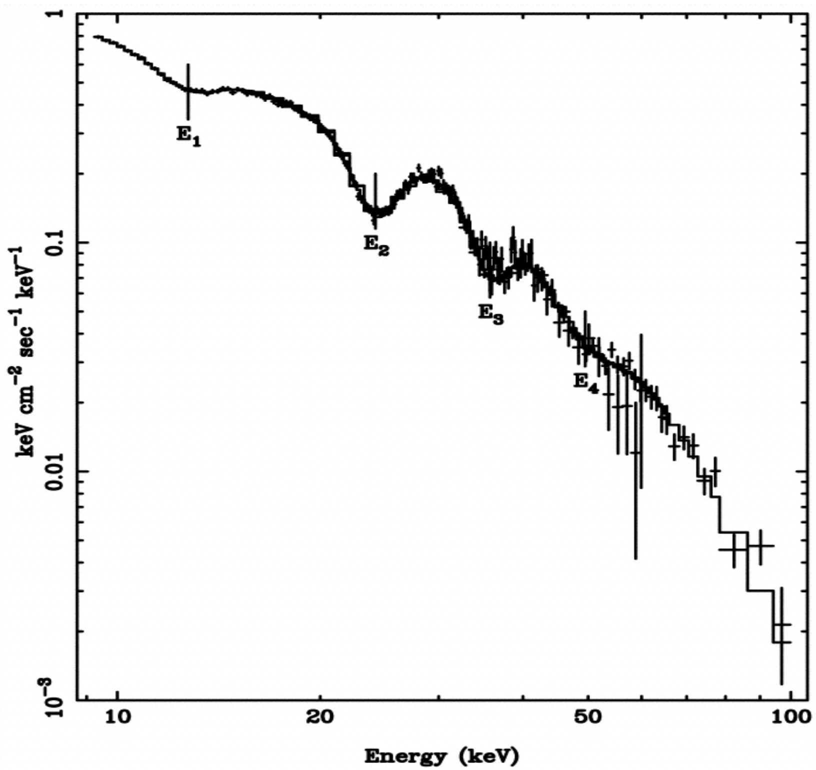


X-ray burst spectra of a neutron star

Image courtesy of J. Cottam, NASA GSFC

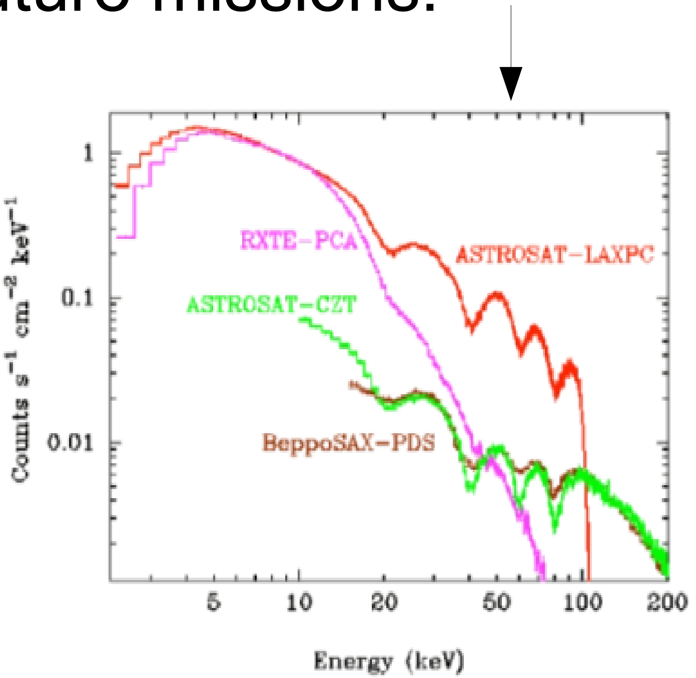
European Space Agency

X-ray spectroscopy - cyclotron lines B determination:



X0115+63
Santangelo + Bulik+ 2000

Cyclotron lines predicted by future missions:



Hands-on session – Homework#6

Download data from classic Seyfert galaxies
(e.g., NGC 3227, Fairall 9, NGC 2992, NGC 4151, Mrk 3)
and in XSPEC software fit power-law models to 2-10 keV spectrum
- Add additional absorber, esp. for Sy 2s
- Compare diskline and gaussian fits to Fe-K
- Does Fe-K EW vary between observations?

Repeat Fe-K diskline simulation shown in the "Low-resolution X-Ray Spectroscopy" presentation (http://cxc.harvard.edu/xrayschool/talks/lowres-agn-spec.pdf): how many counts are needed before diskline becomes statistically distinct from a broad Gaussian?

Simulate partial covering models at various numbers of counts (100, 500, 1000, 5000)
- Fit with a simple power law, see how "effective" photon index for a simple power-law fit varies with scattering fraction and NH of the highly absorbed component

Hands-on session – Homework#6

In XSPEC

>pl data res
>show all

Figure of the final fit plus table with parameters

The same lecture on Jan. 10rd 2023

Jan. 12th - CAMK Annual Meeting
Jan. 17th , 19th – Geneva EAS Council meeting
Jan. 24th , 26th – Amsterdam meeting

NEXT NEW LECTURE on Feb. 2nd 2023

- Overview of HW#5

- theory, but we still practice

wi-fi password: a w sercu maj
We have eduroam as well