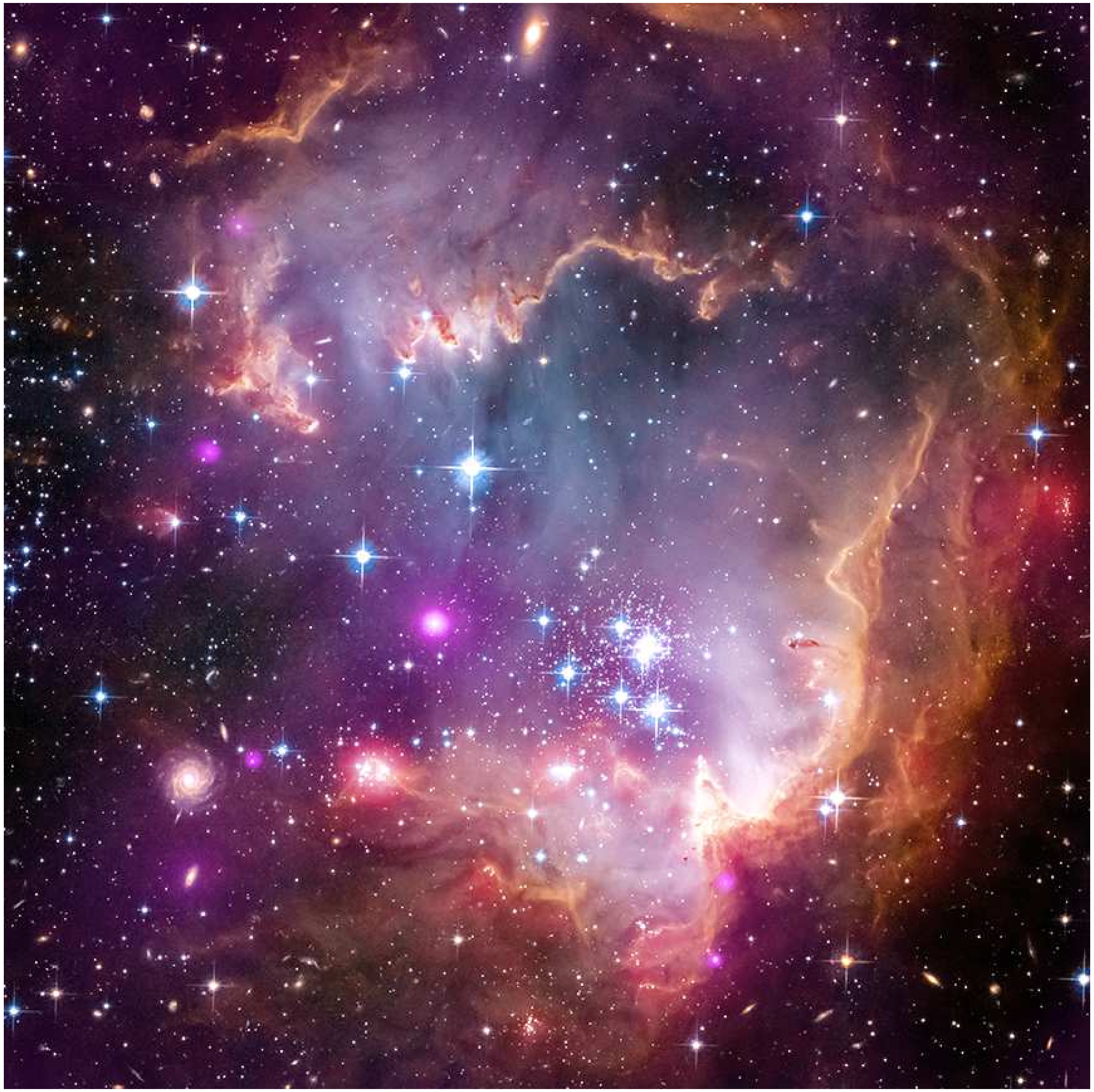
The X-Ray Universe



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~lida/vorlesungXRAYSo17.html

Chandra X-ray, HST optical, Spitzer IR
NGC602 in the SMC
d=60pc

Radiation Processses

Thermal plasma:

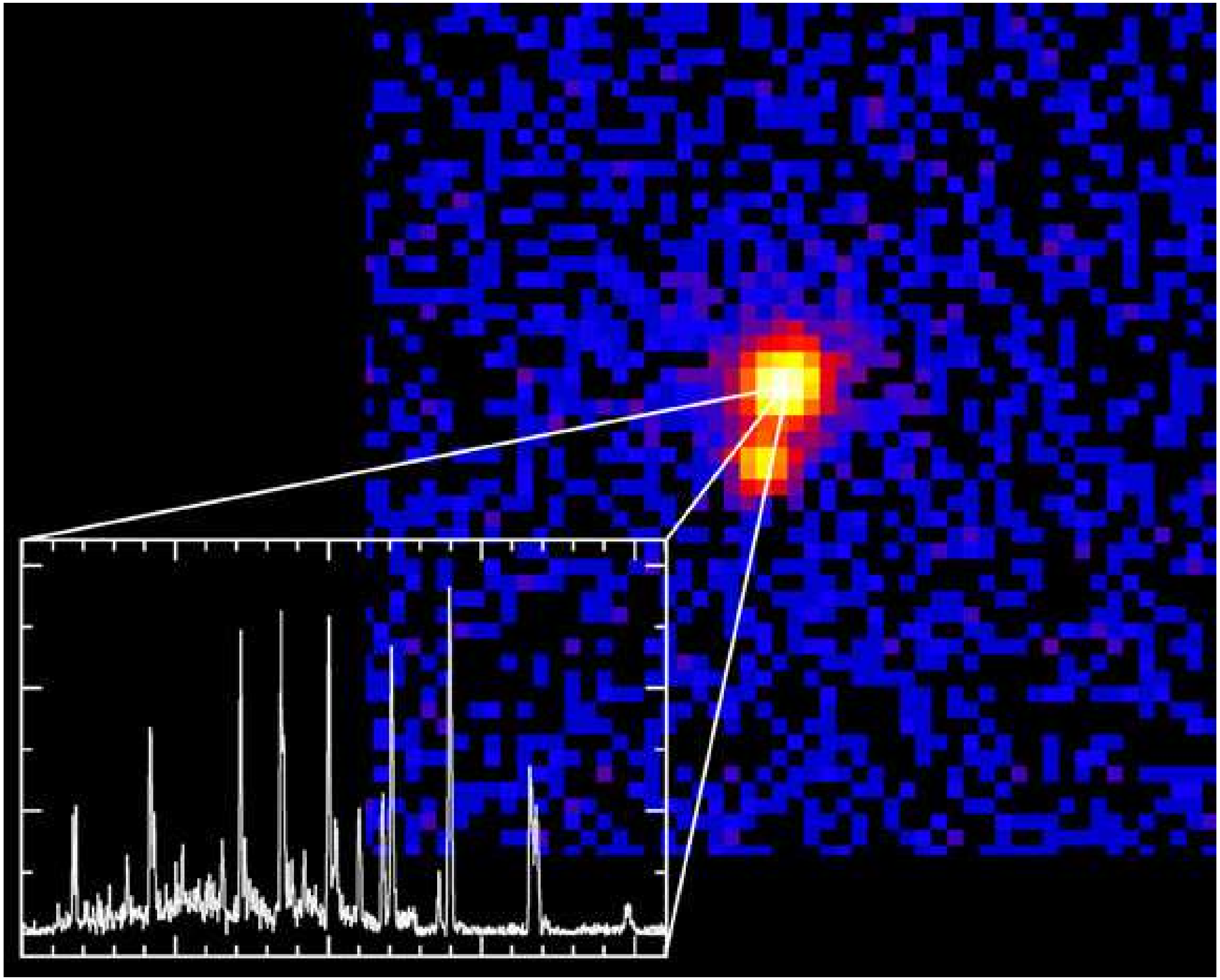
- Black-body (neutron stars and hottest WD). Continuum.
- Collisional ionized plasma (stellar coronae). Lines
- Photoionized plasma (close to BH and NS). Lines
- Thermal bremsstrahlung. Continuum

Non-thermal plasma. Mainly continuum.

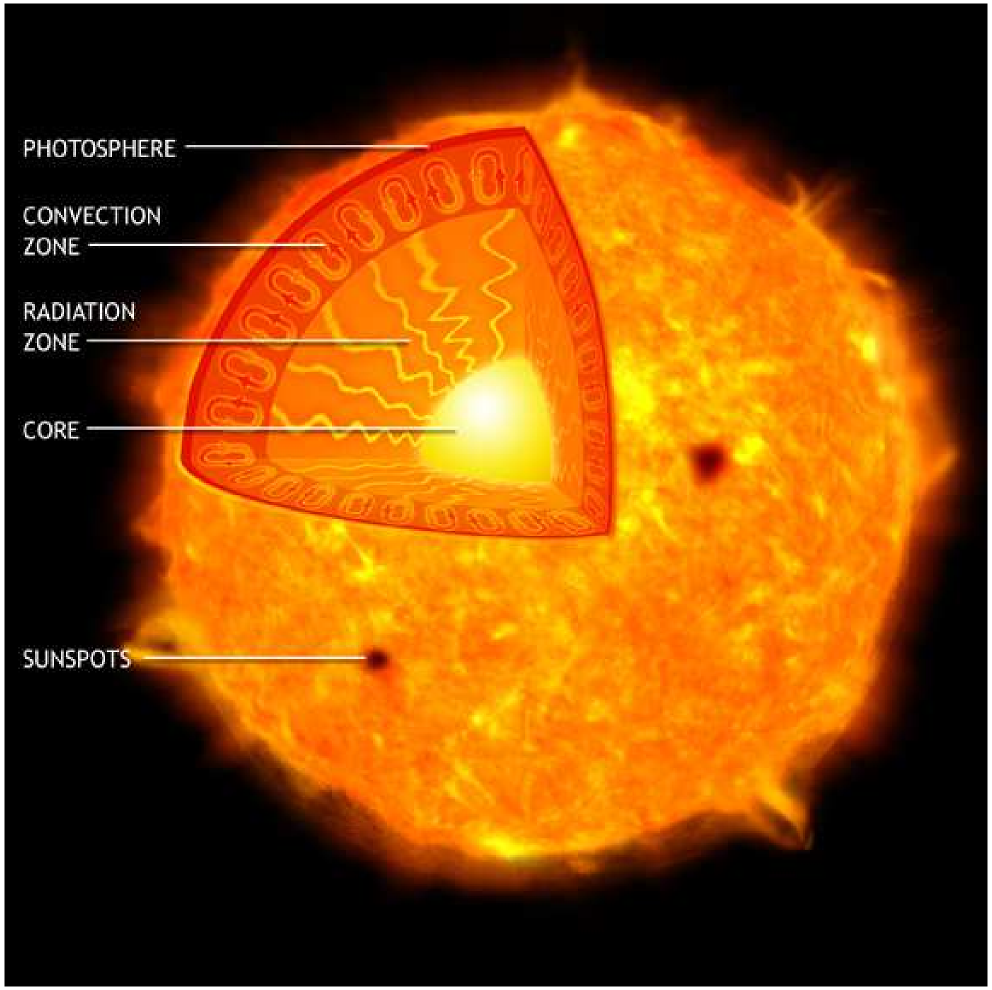
- Synchrotron.
- Inverse Compton
- Non-thermal bremsstrahlung

When X-ray radiation is produced (by any of the processes above), X-ray photons travel through the medium and interact with it. Always present: absorption in the ISM

X-rays from Stars



NASA/EIT/W.Waldron, J.Cassinelli



http://chandra.harvard.edu/photo/2005/neon/

Brief reminder: Stars

Low-mass stars on main sequence:

pp-cycle → $\varepsilon \sim T^6$

Radiative equilibrium core

Large temperature gradient outwards

Outer convection envelopes

Weak stellar winds

Massive stars on main sequence:

CNO-cycle → $\varepsilon \sim T^{15}$

Convective core

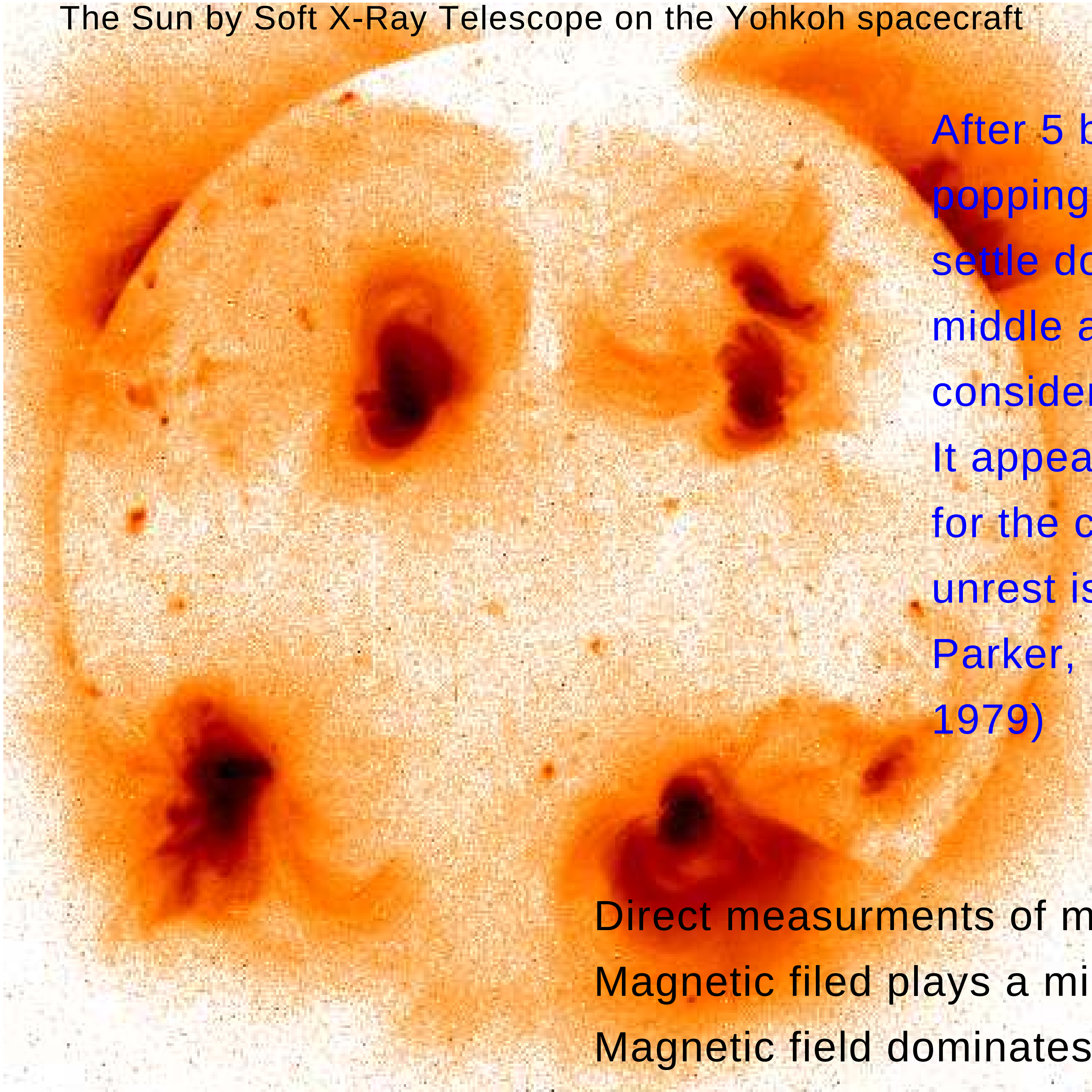
Outer radiative envelopes

Strong stellar winds

Sp	T_{eff}	Hβ	Other Features	$M/M_\odot$	$R/R_\odot$	$L/L_\odot$	T(MS)
O	>33000	weak	He^+, mb. emission	>20	>10	90,000-800,000	10-1 Myr
B	10,500-30,000K	med.	HeI absorption	3-18	3.0-8	95-52,000	400-11 Myr
A	7,500-10,000K	strong	H lines	2-3	2-3	8-55	3Gyr - 440 My
F	6,000-7,200 K	med.		1-2	1-1.5	2.0-7.0	7-3 Gy
G	5,500-6,000 K	weak, Ca+ H	K, Na "D"	0.9-1	0.8-1	0.6-1.5	15-8 Gy
K	4,000-5,250 K	v. weak	a+, Fe, CH,CN	0.6-0.8	0.6-0.80	0.10-0.4	17 Gy
M	2,600-3,850 K	TiO, mol.		0.08-0.5	0.2-0.6	0.001-0.08	56 Gy
L			Brown dwarfs	<0.08			

Magnetic fields

The Sun by Soft X-Ray Telescope on the Yohkoh spacecraft



After 5 billion years, the Sun is still popping and boiling, unable to settle down into the decadent middle age that simple theoretical considerations would suggest. (...) It appears that the radical element for the continuing thread of cosmic unrest is the magnetic field. (E N Parker, Cosmical Magnetic Fields, 1979)

Direct measurments of magnetic fileds: photosphere

Magnetic filed plays a minor role in the photosphere

Magnetic field dominates in the corona: X-rays

coronal heating, flares, CMEs, wind acceleration

http://solar.physics.montana.edu/ypop/

αΩ-Dynamo

The Parker mechanism has been mathematically formalized and generalized by mean-field theory (Krause, Rädler, Steenbeck 1966).

Evolution of a suitably averaged magnetic field in a turbulent flow of an electrically conducting fluid.

$$\frac{\partial \langle B \rangle}{\partial t} = \nabla \times (\langle u \rangle \times \langle B \rangle + \alpha \langle B \rangle) - \nabla \times [(\eta + \beta) \nabla \times \langle B \rangle$$

$\alpha \langle B \rangle$ drives a mean current parallel or anti-parallel to the mean magnetic field.

α-effect generates a meridional field from an azimuthal and vs.

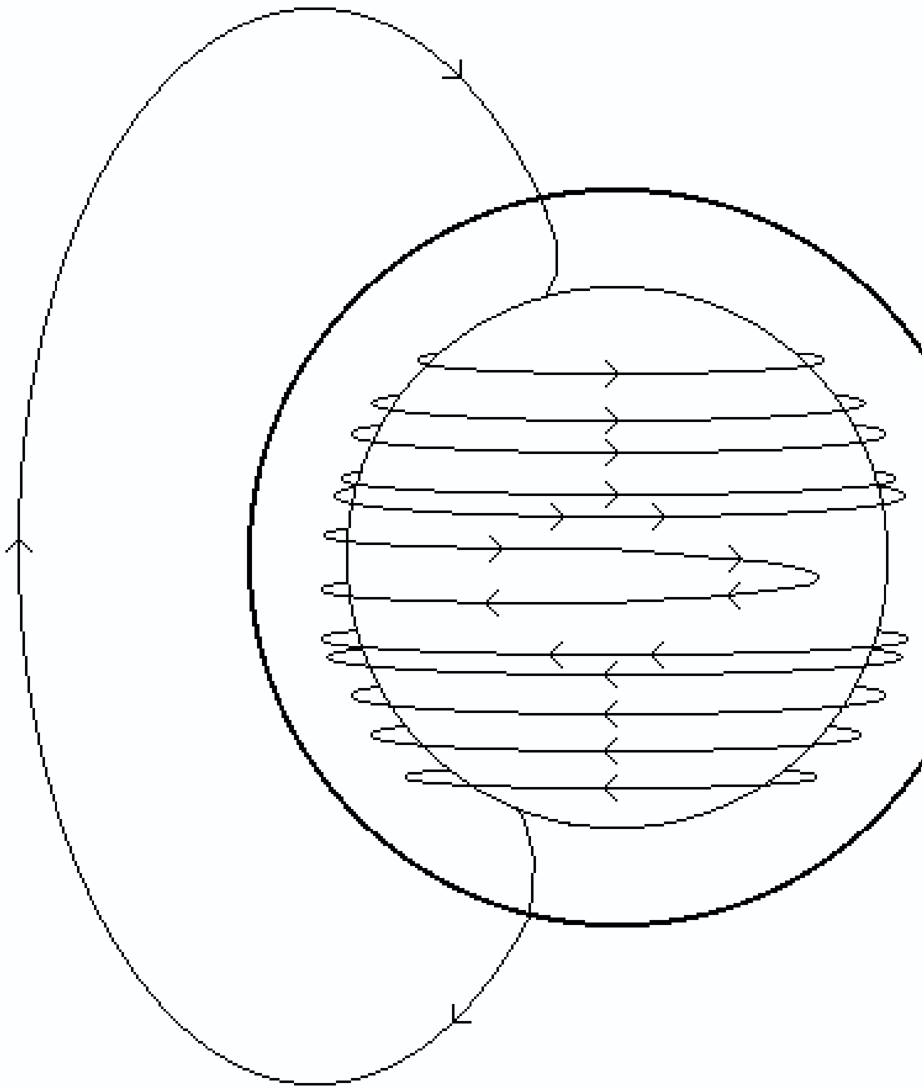
Ω-effect describbels differential rotation, Ω is angular velocity

$\alpha \frac{\partial \Omega}{\partial r}$ describes dynamo waves

Mean-field αΩ-dynamo reproduces many of the key features of the solar cycle: the periodic filed reversals, the polarity of sun-spot groups, the equatorwards drift of the activity zones.

However the equatorwards drift requires radially inward fast increase of the angular velocity. This is in direct conflict with the results of helioseismology.

Ω-effect



The ω-effect

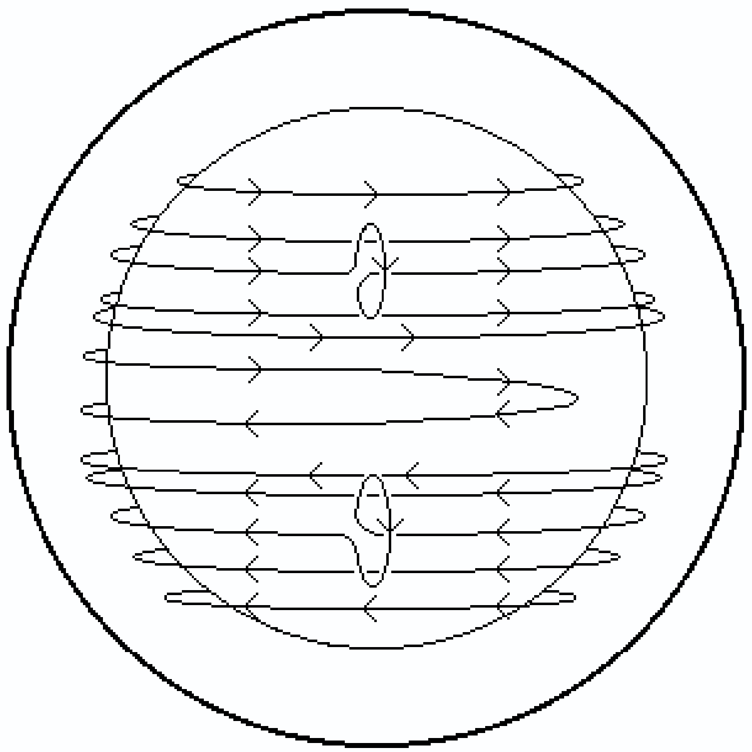
Differential rotation - the change in rotation rate as a function of latitude and radius within the Sun.

Magnetic filed is stretched out and wound around the Sun

Latitudal differential rotation can wrap magnetic field line around the Sun in about 8 months.

http://solarscience.msfc.nasa.gov/

α-effect



The α-effect

http://solarscience.msfc.nasa.gov/

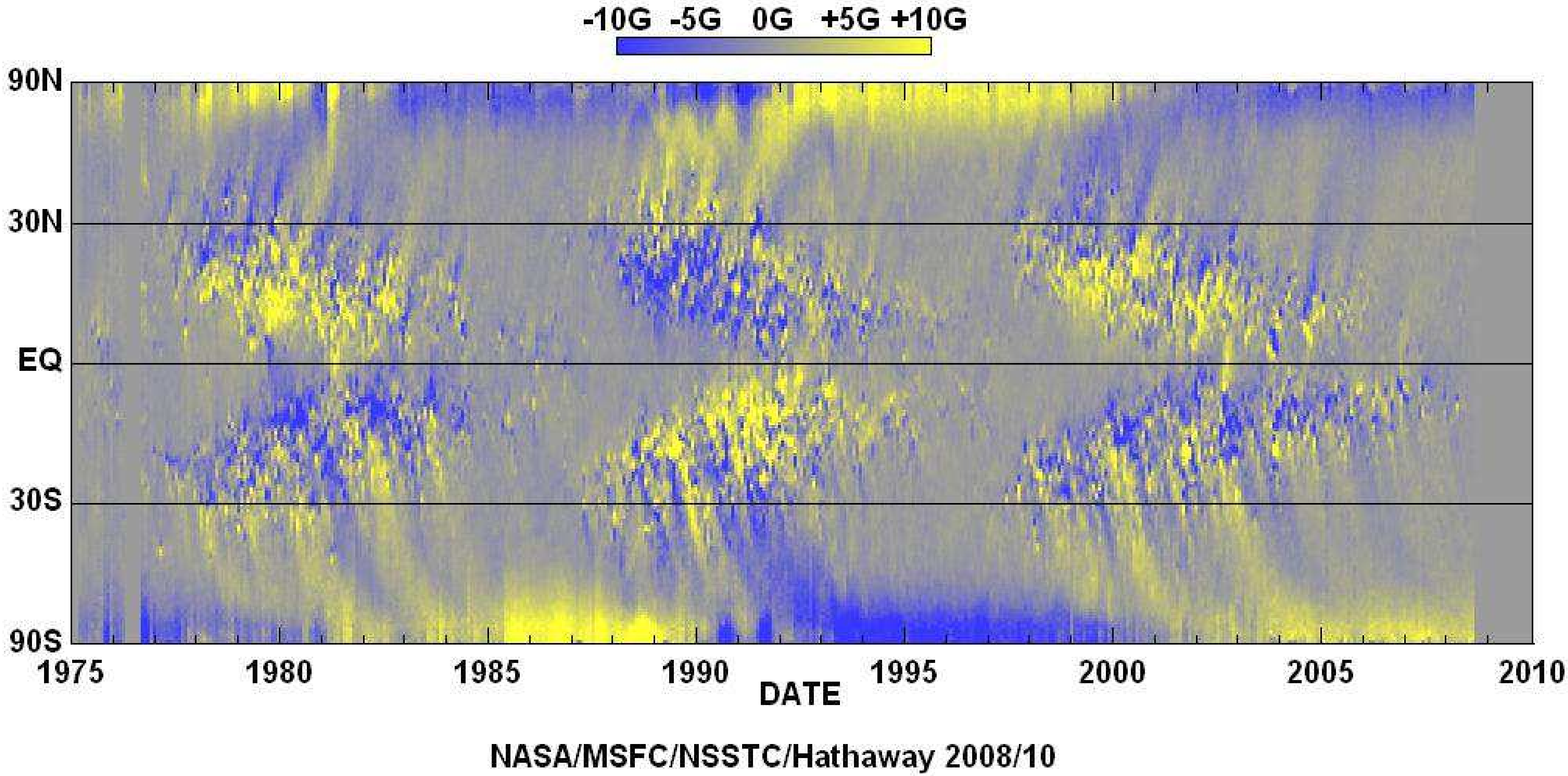
Effect of rotation on the rising "tubes" of magnetic field- loops look like letter α

α-effect governs tilt of spot groups and polarity reversal

Similar effects are observed in solar type stars, so Sun is an average star.

Dynamo operates in all low- and solar-mass stars. Activity scales with rotation rate.

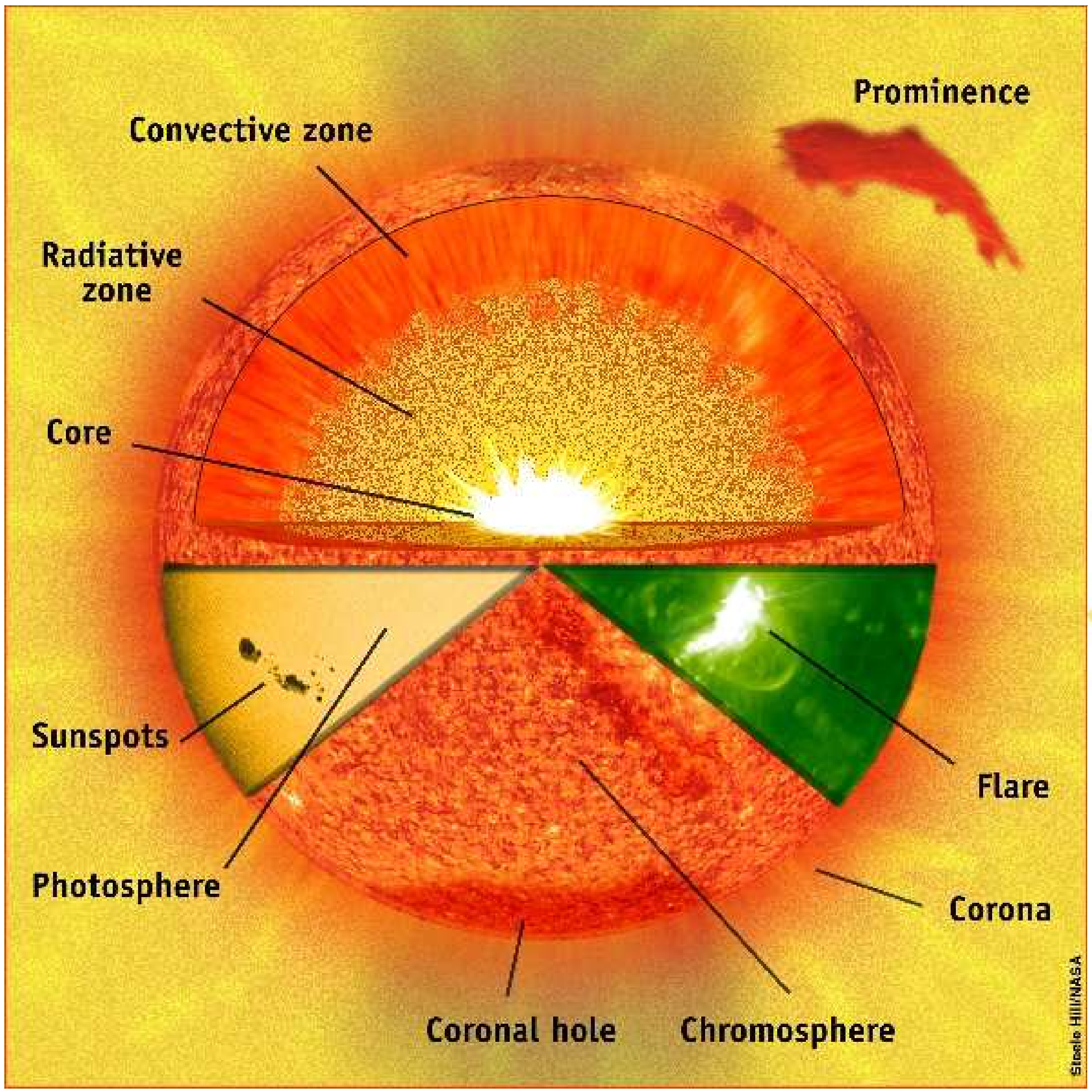
Solar dynamo

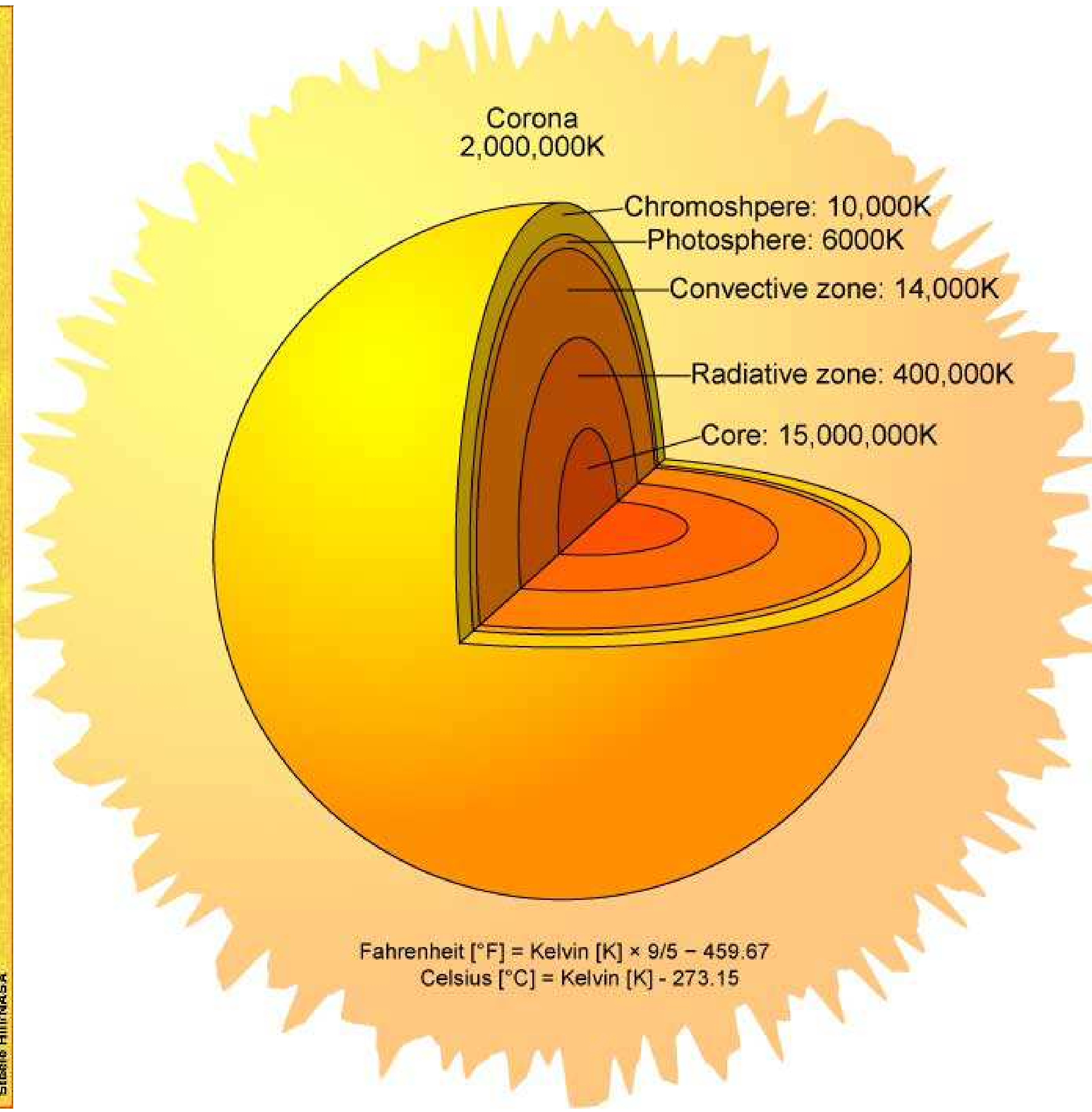


Observational laws: 1) 11-year period; 2) butterfly diagram; 3) tilt of sunspot group; 4) 22-year magnetic cycle

Magnetic fields and temperature distribution

Convection brings the magnetic field lines on the surface. Lines are always closed, the relative role of gas and magnetic field pressure changes with height

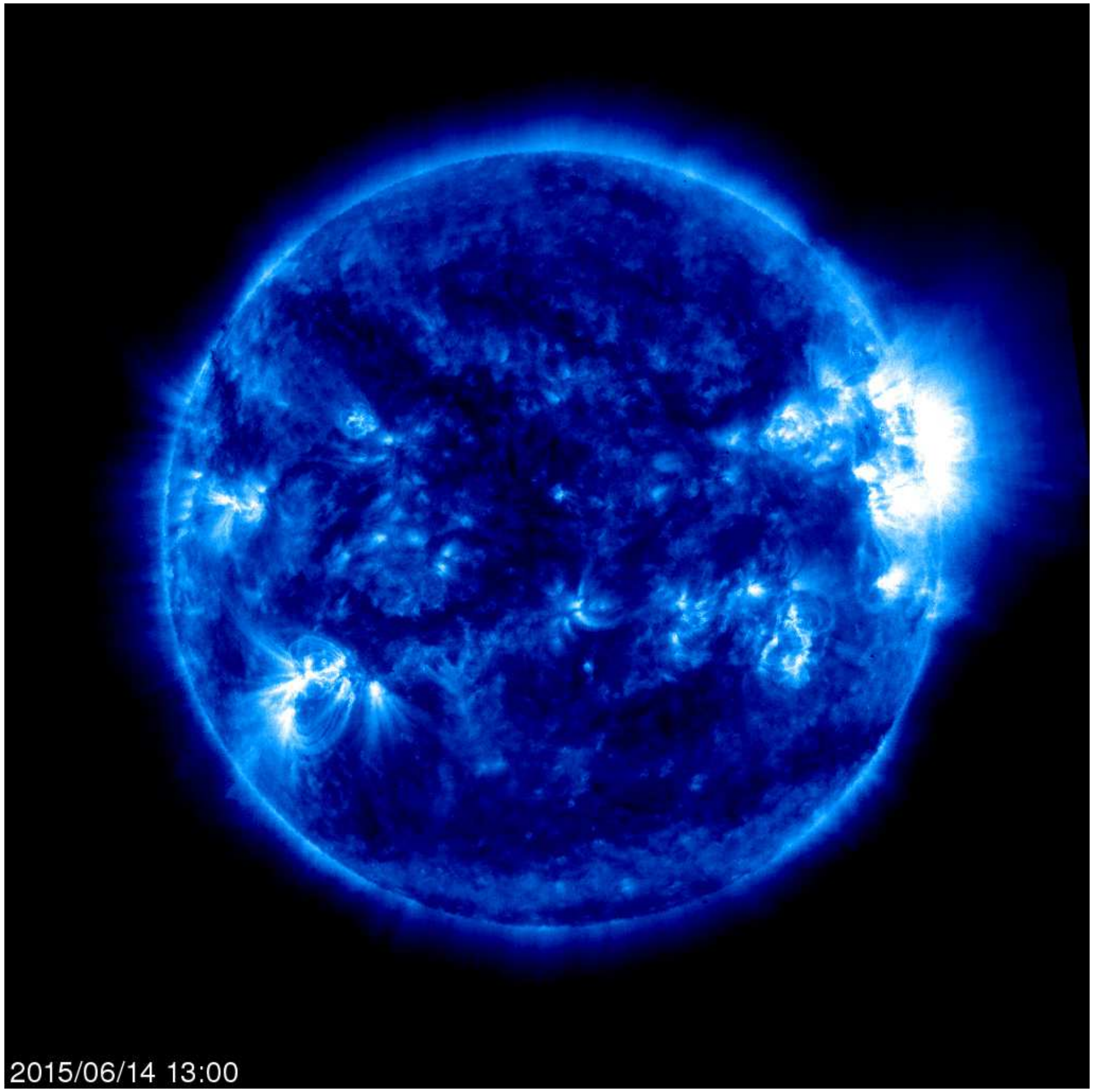


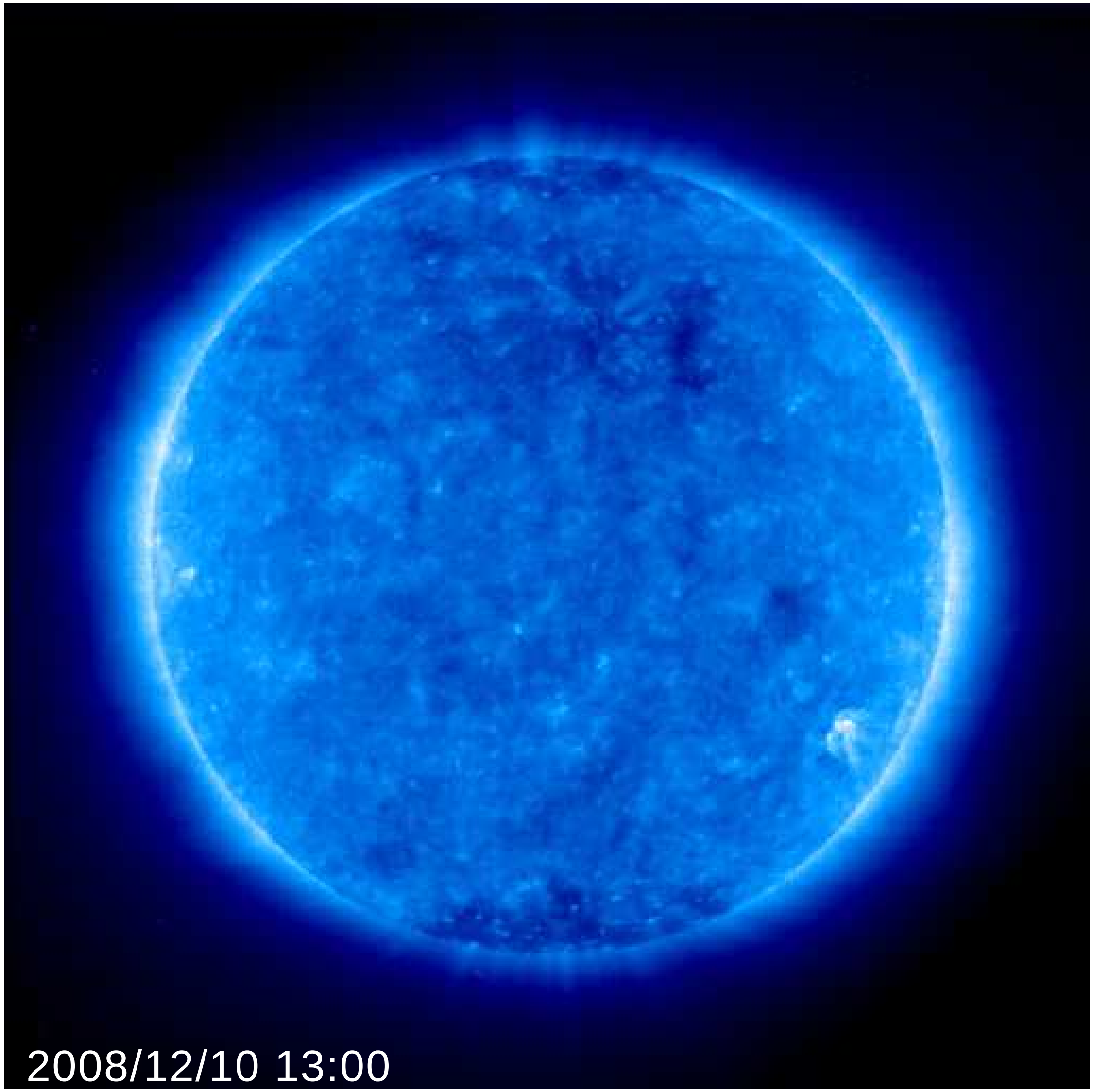


http://sohowww.nascom.nasa.gov/

Lower corona: now and then

SOHO images in Fe IX/X 171Å line. Lower corona, plasma temperature 1MK.





http://sohowww.nascom.nasa.gov/

Flares

Solar flares are an explosions in the solar atmosphere:

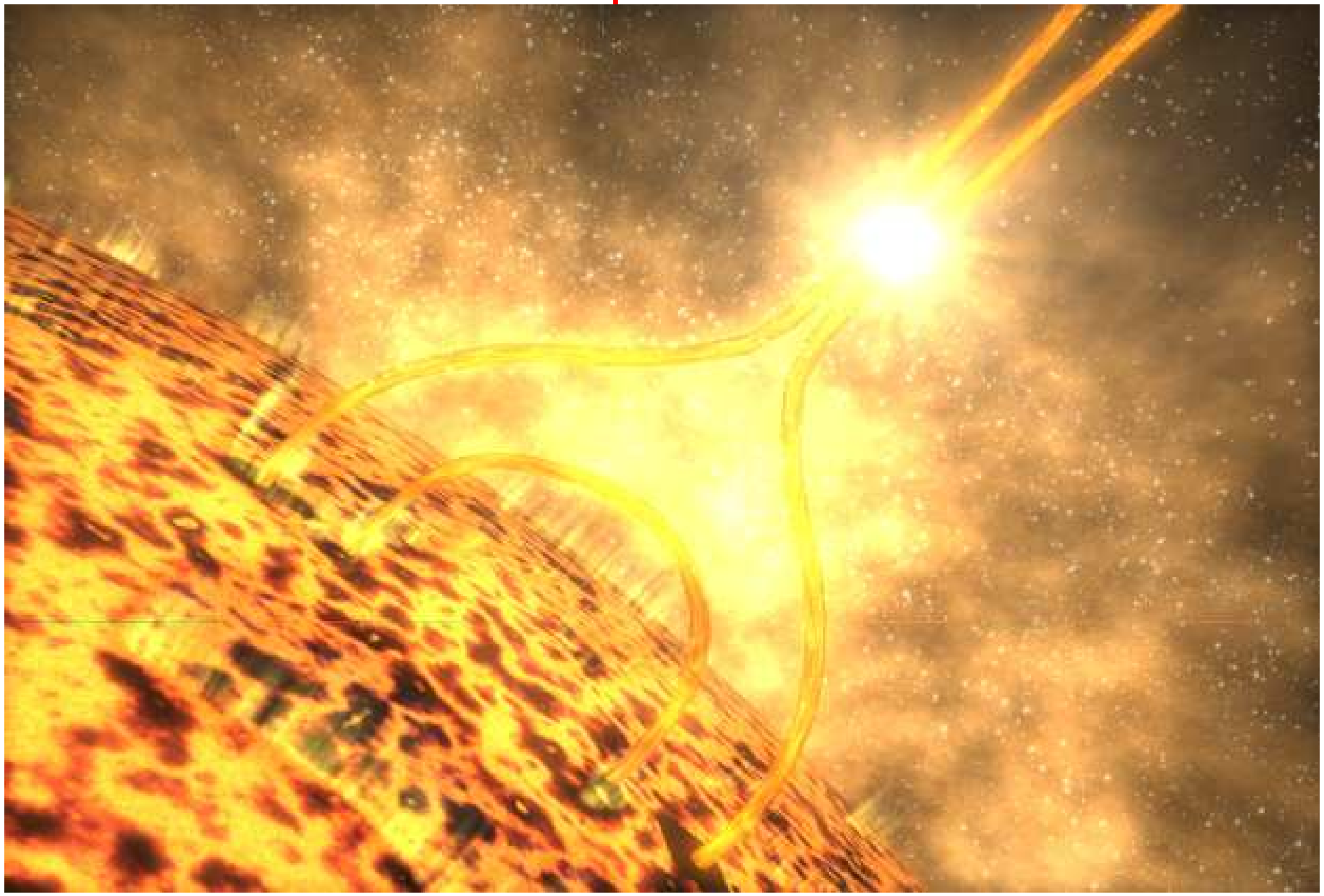
Sudden bursts of particle acceleration, plasma heating, and bulk mass motion.

Release of energy stored in the magnetic fields that thread the corona.

In the largest flares >10^{32} ergs can be released in a few minutes.

Largest flares observed around solar maximum

There is a continious spectrum of flare sizes $dN/dE=kE^{-\alpha}$, α=1.6 ... 2.6



http://svs.gsfc.nasa.gov/vis/a000000/a002700/a002750/index.html

No consistent theory of flares

Reconnection, 3D-topologies

How corona is heated?

Coronal activity scales with magnetic activity, 11 yr cycle

Corona never disappears:

$L_X = 10^{26}$ erg/s in min activity, 10^{27} erg/s in max activity (+ very strong flares)

The energy release mechanism is magnetic in origin - but, what specific heat input is dominating in a given coronal feature throughout the solar cycle?

Leading theories:

* Sound wave dissipation (Walsh & Ireland 2003)
* Differential heating by plasmakinetic processes (Vocks & Marsch 2002)
* Nanoflare heating: small scale reconnection events (Parker 1988)

Model shall describe physical conditions in the corona:

density, temperature, velocity

Corona heating and dynamo theory should be consistent

Sun offeres only a limited range of parameters.

Solar-Stellar connections

All low- and solar-type stars posses magnetic fields and are X-ray active

Is Sun an average star?

The Sun in time?

How dynamo and heating processes differ among stellar types?

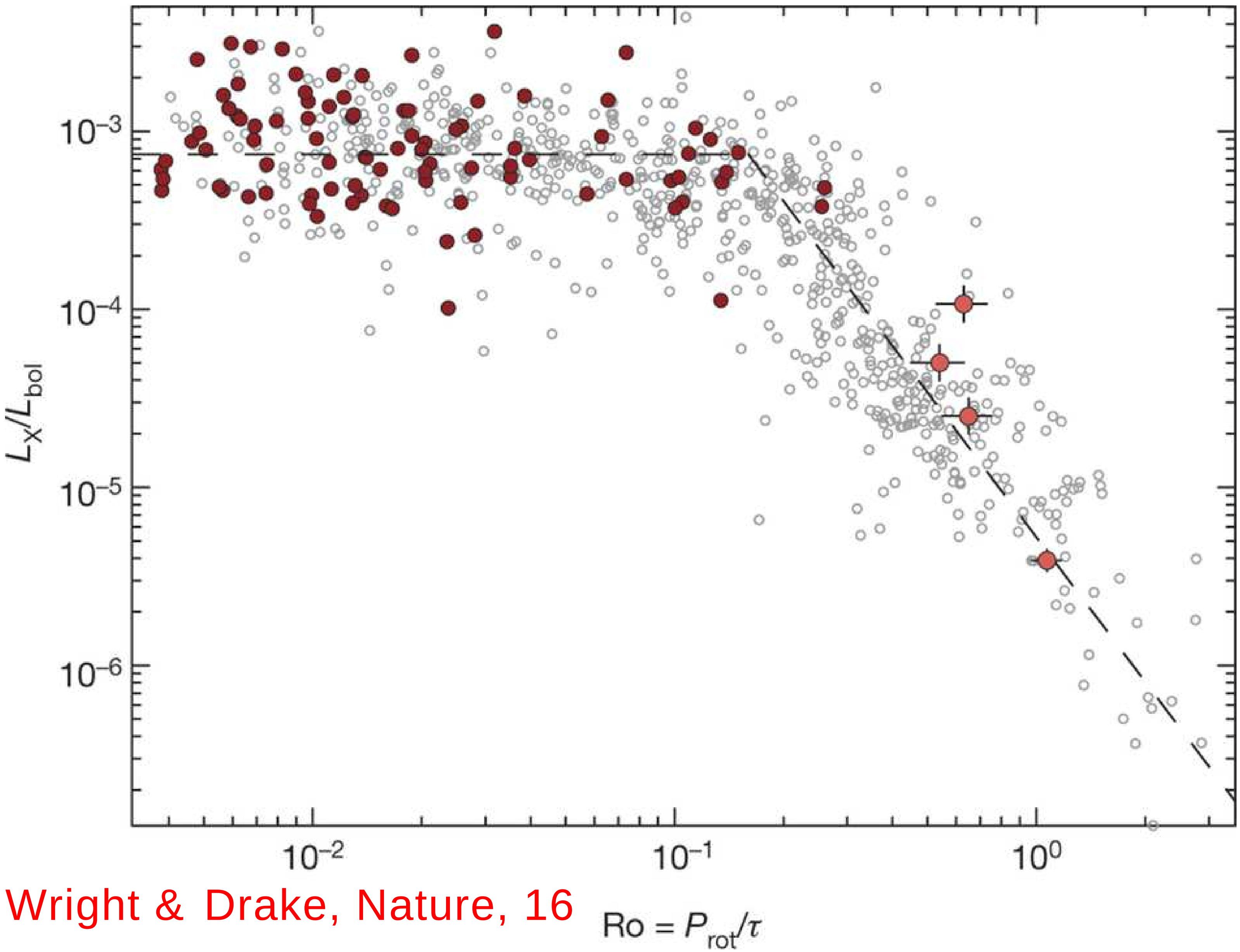
In some cases, the magnetic filed can be directly measured through the Zeeman effect, but in general X-ray emission is used to infer stellar activity.

In accordance with dynamo theory the magnetic activity of cool stars is related to their rotation rate: faster spinning stars are more active (α-effect increases with rotation rate).

For solar type stars ($M < 1.5 M_{\odot}$) and ages of > 100 Myr, angular momentum loss by a stellar wind brakes rotation: rotation nearly uniquely determined by the stellar age.

Late type stars, M and brown-dwarfs are fully convective. How their activity level differ from solar-type stars?

X-ray observations overturn accepted Dynamo models



Wright & Drake, Nature, 16

- Dynamo operates in tachocline • Fully convective stars → no tacholine
- Predicted, MV should be different in X-rays from GV • Not observed
- Ergo, dynamo operates in the convective zone

Coronal activity cycles in solar analog stars

The Sun 11-yr cycle is the global manifestation of its activity.

The behavior of HD 81809 (G2 + G9) is a simple extension of the solar case.

Two more studied stars show cyclic activity as well.

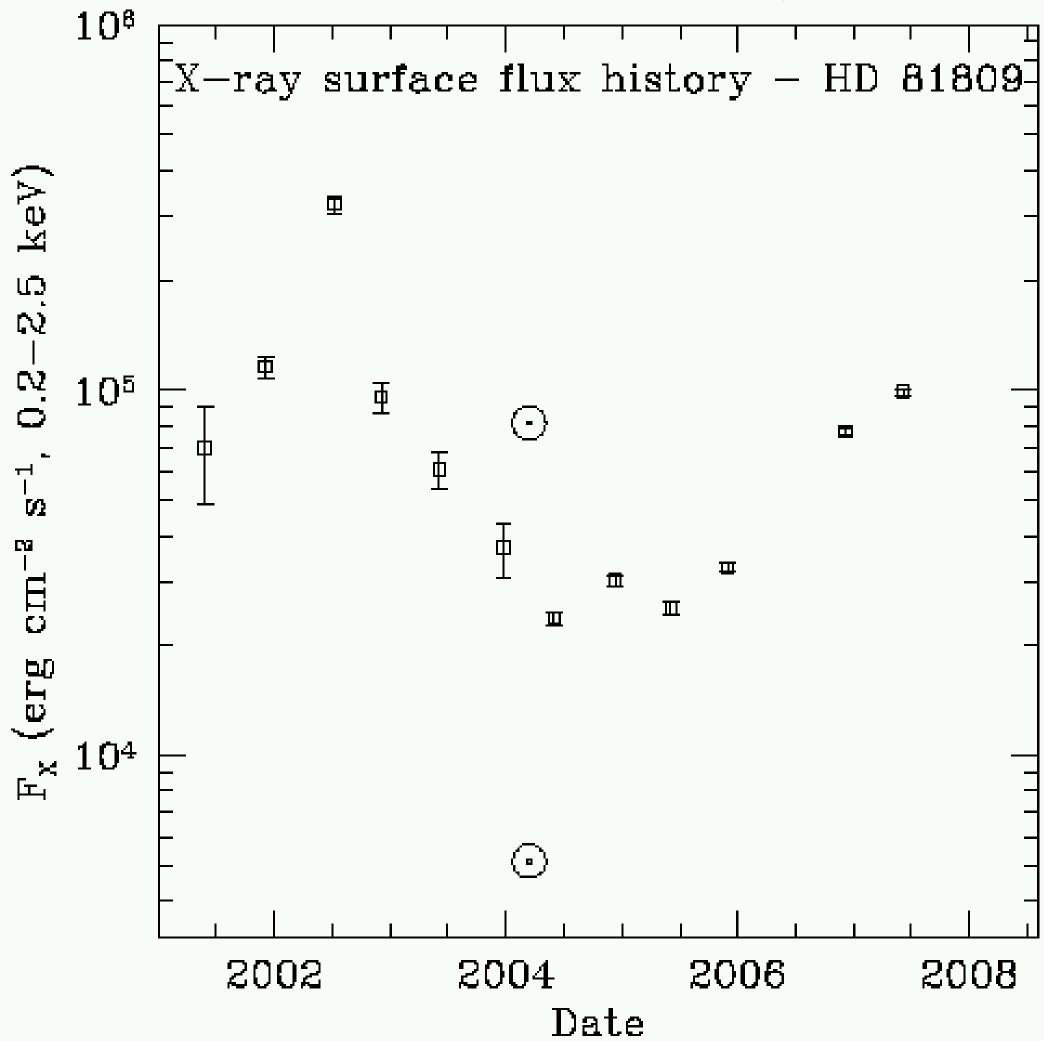


Fig. 3. Evolution of the X-ray surface flux (in the 0.2–2.5 keV band) of HD 81809 from April 2001 to May 2007. The typical X-ray surface flux of the Sun at minimum and maximum of the cycle, in the ROSAT band, is also plotted.

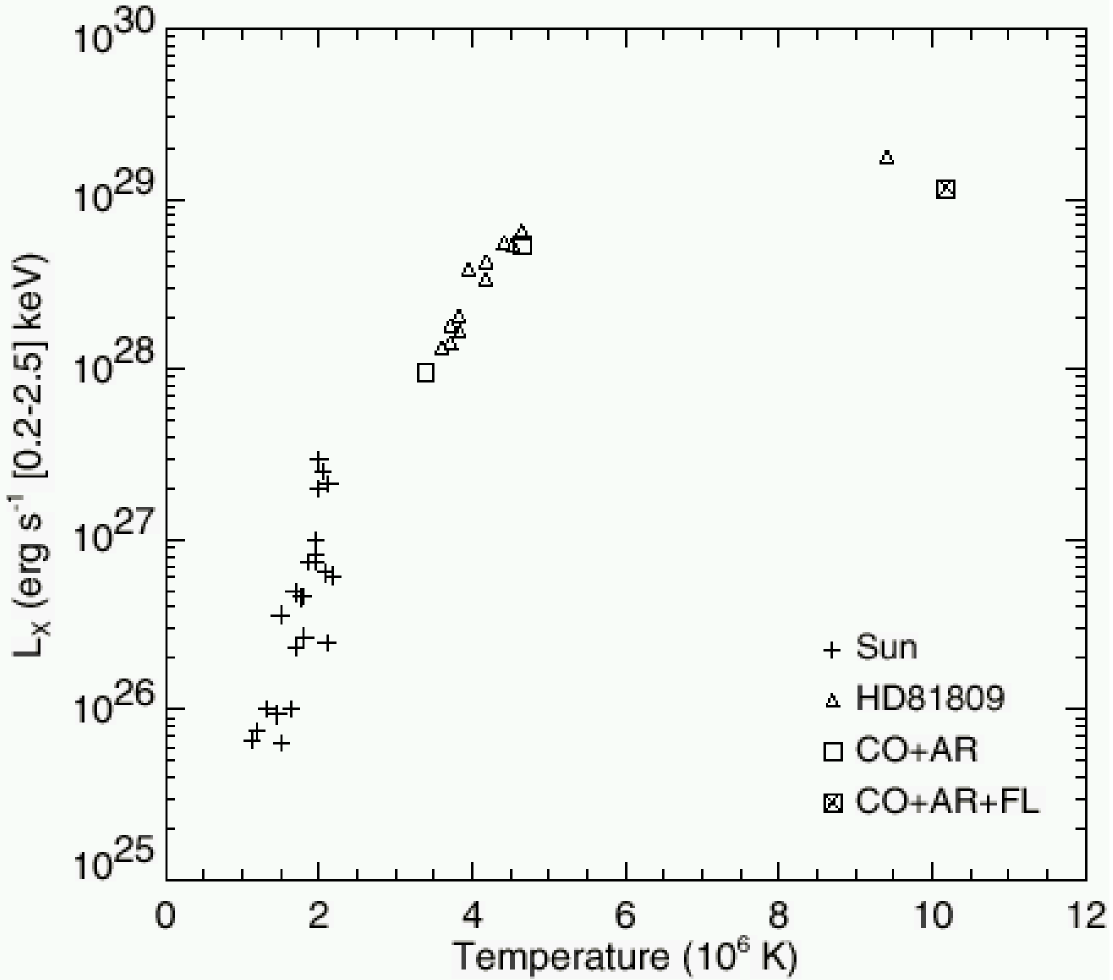
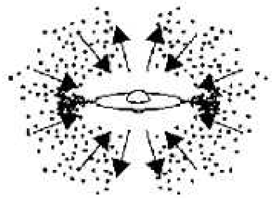
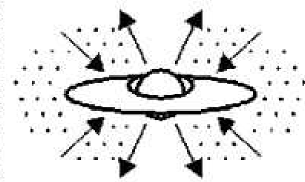
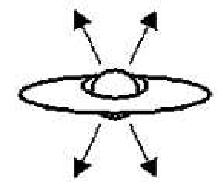
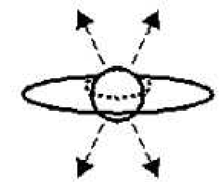
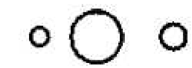


Fig.4 The evolution of the coronal X-ray temperature and luminosity along the cycle in both the Sun (crosses) and HD 81809 (triangles).

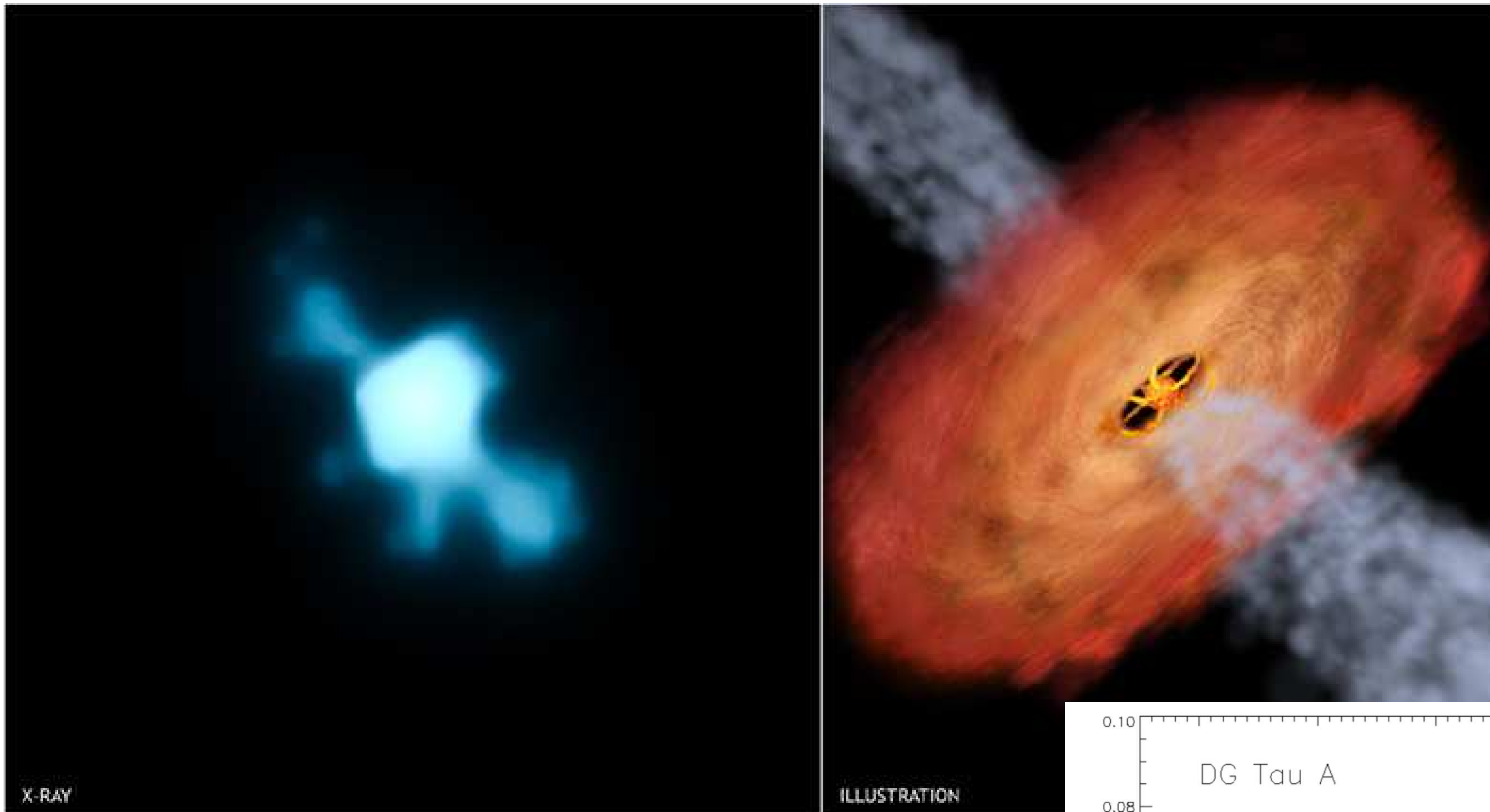
Favata etal. 2008 A&A 490, 1121

Young stars (solar type)

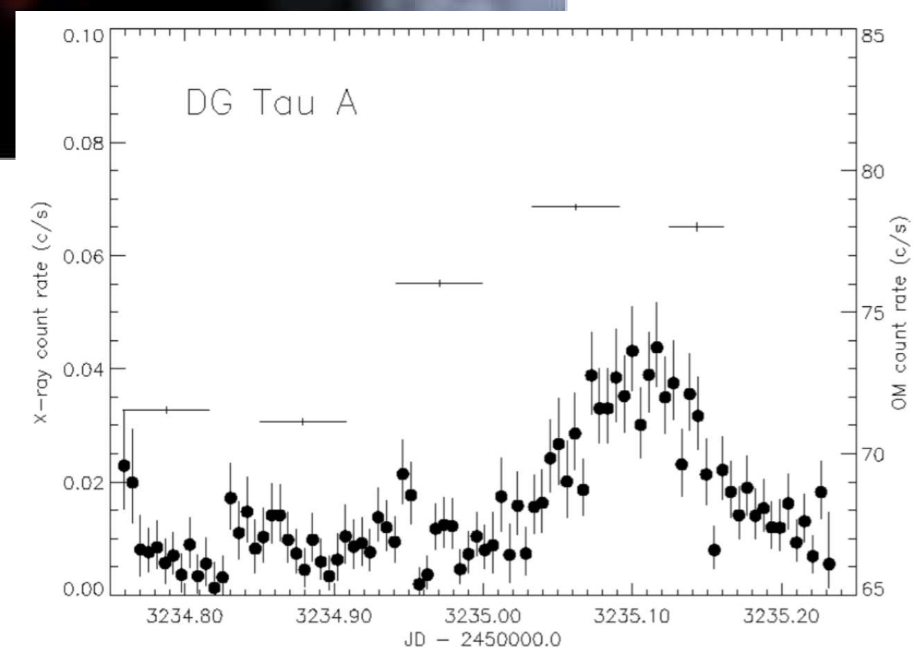
Properties	*Infalling Protostar*	*Evolved Protostar*	*Classical T Tauri Star*	*Weak-lined T Tauri Star*	*Main Sequence Star*
Sketch					
Age (years)	10^4	10^5	$10^6 - 10^7$	$10^6 - 10^7$	$> 10^7$
mm/Infrared Class	Class 0	Class I	Class II	Class III	(Class III)
Disk	Yes	Thick	Thick	Thin or Non-existent	Possible Planetary System
X-ray	?	Yes	Strong	Strong	Weak
Thermal Radio	Yes	Yes	Yes	No	No
Non-Thermal Radio	No	Yes	No ?	Yes	Yes

Feigelson & Montmerle ARAÄ 37, 363

Observations



http://chandra.harvard.edu/photo/2008/dgtau/



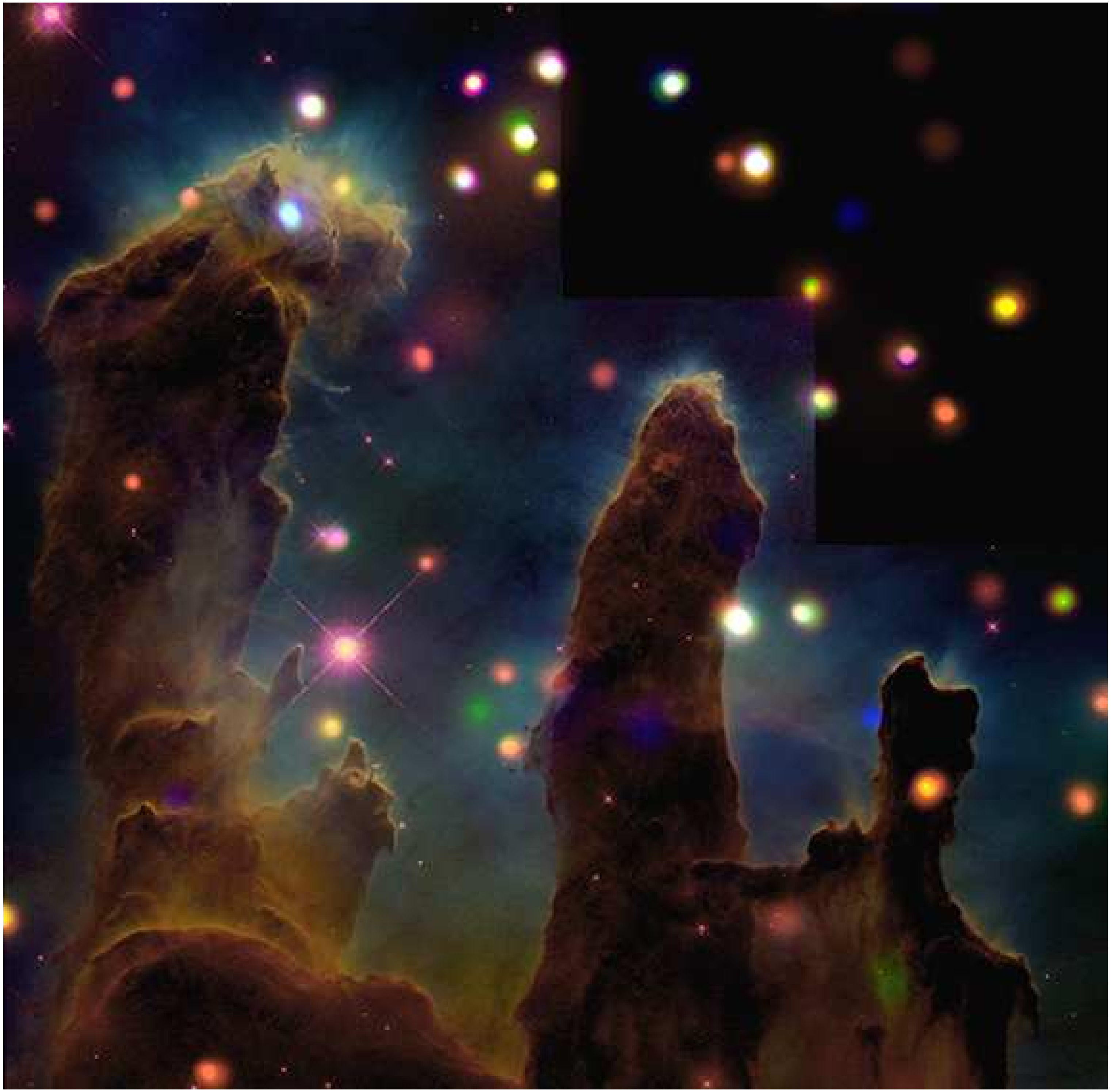
DG Tau $M=1M_{sun}$, Age=1Myr

Jets, disk absorption, flares

Accretion **and** corona (?)

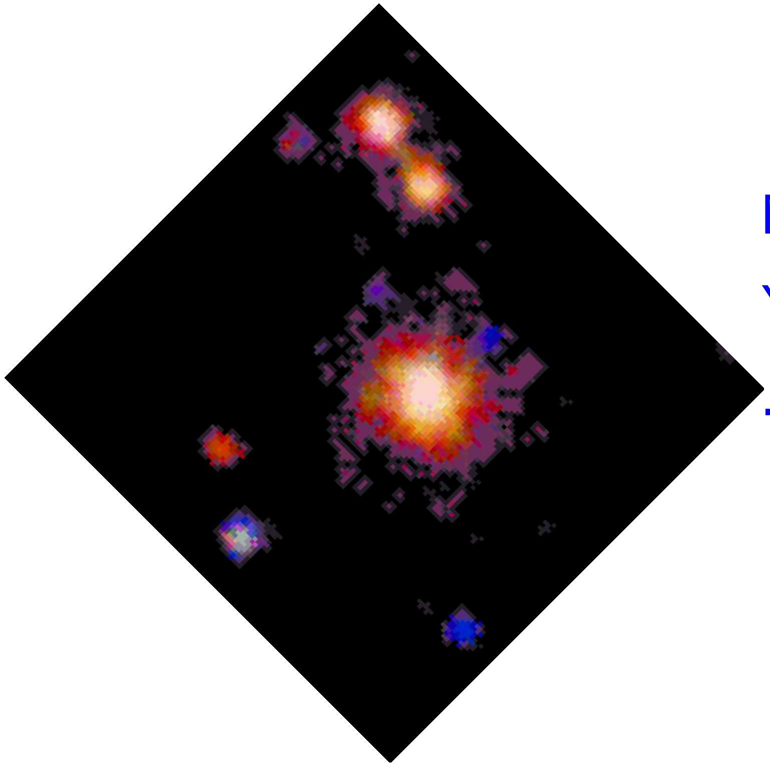
Importance for planet formation

HST & Chandra: Pillars of Creation in M2



http://chandra.harvard.edu/2007/m16/

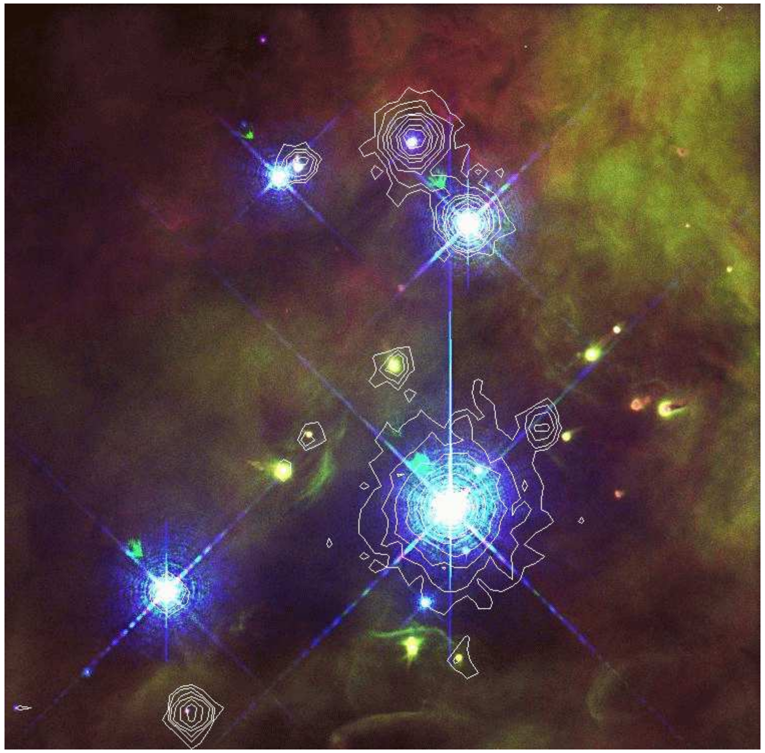
Chandra's Orion Trapezium



Massive stars in the center of Orion nebula

Young (1Myr) O type stars that ionize the nebula

... Are X-ray sources and they are hard



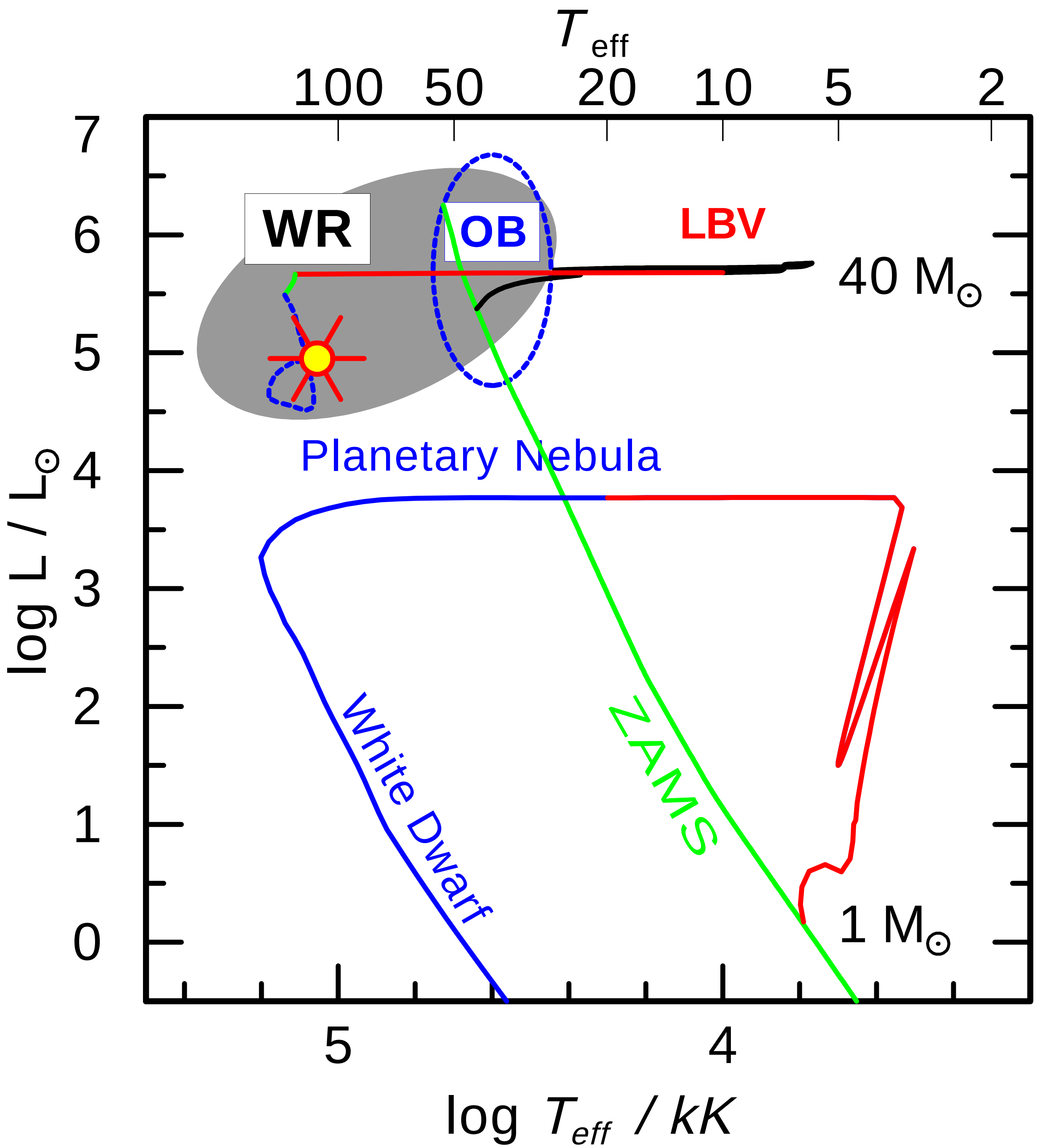
Massive stars (earlier than A-type) are fully radiative

Solar type coronae powered by $\alpha\Omega$-dynamo cannot operate there

Massive stars posses strong stellar winds

http://chandra.harvard.edu/press/00_releases/press_110900.html

The evolution of (very) massive stars



Evolution ← stellar wind (!)

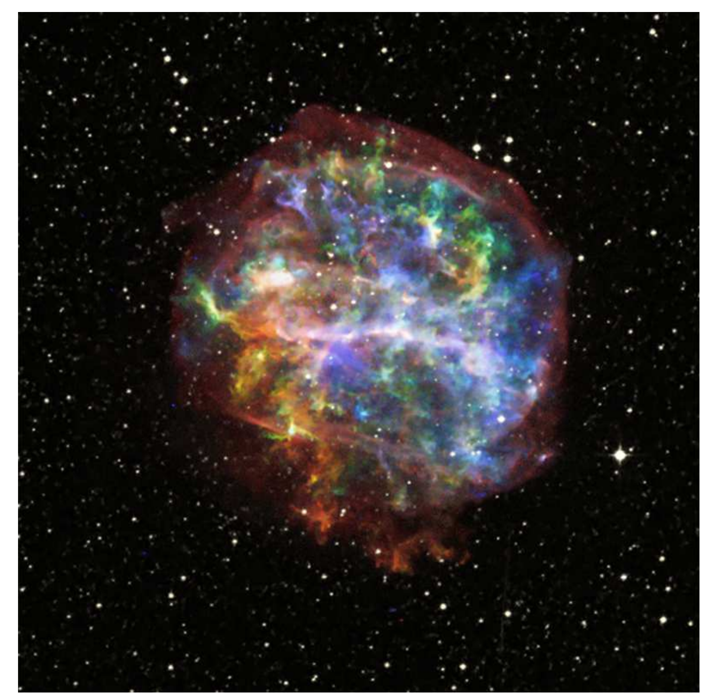
- O and B type stars
- Luminous Blue Variables
- Wolf-Rayet (WR) stars

According to dominant spectral lines

WN (nitrogen) →

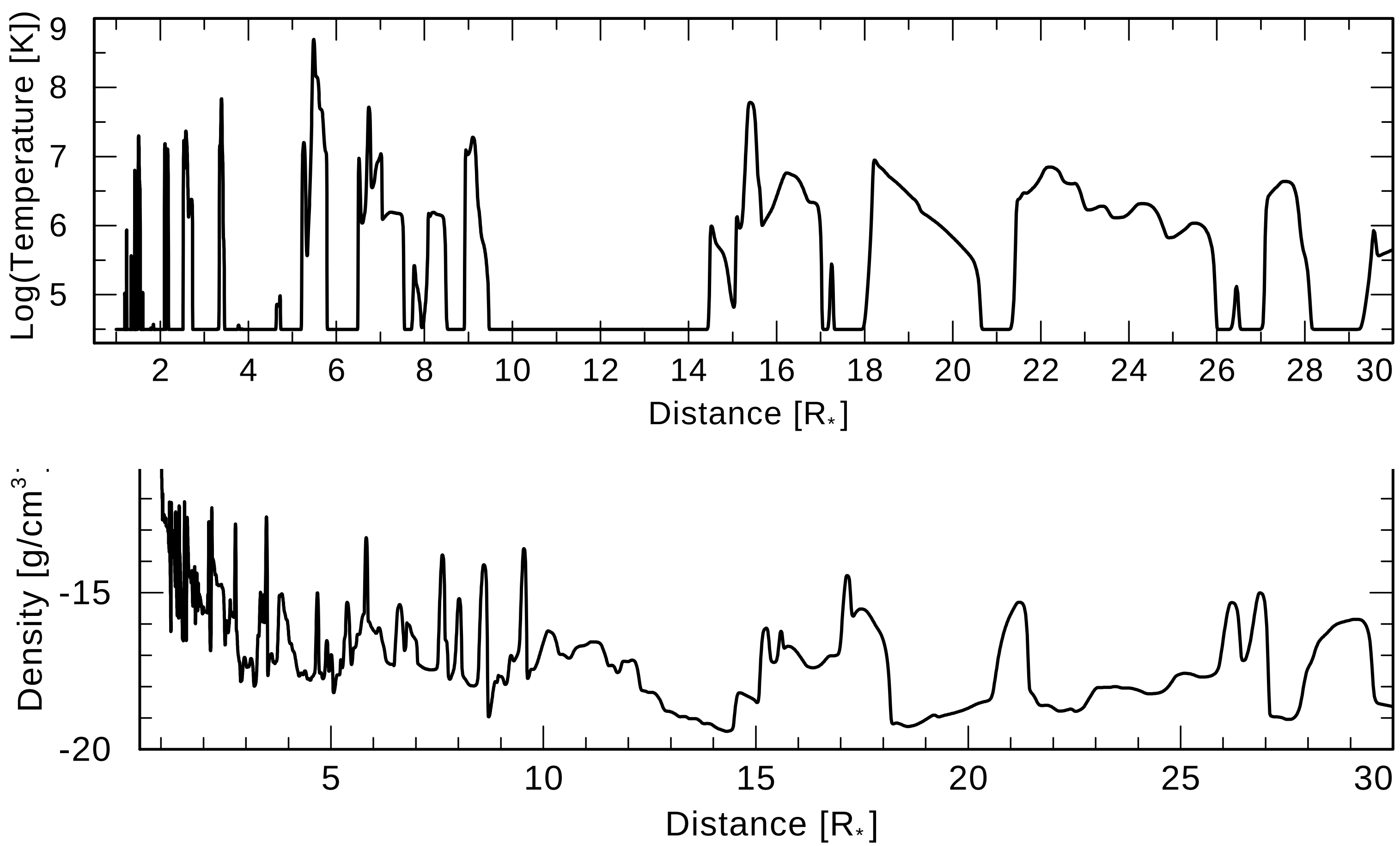
WC (carbon) →

WO (oxygen) →

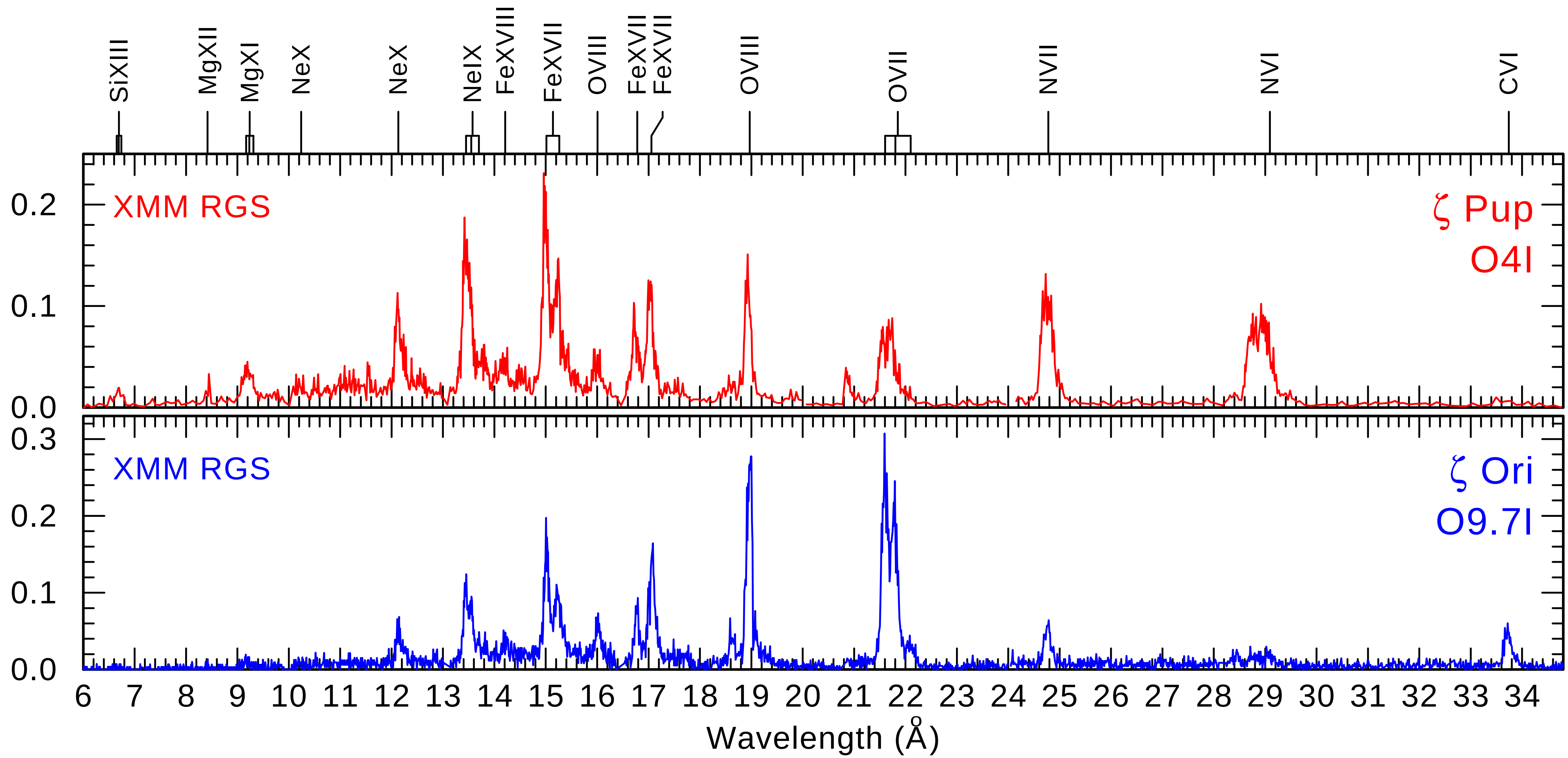


How X-rays are generated in O stars? Leading theories.

- Bow shocks around blobs (Lucy & White '80, Cassinelli etal. '08)
- Magnetically confined loops at the stellar base (Cassinelli & Swank '83)
- Wind shocks from the instabilities of radiation driving (Owocki etal. '83)
- Collisions of dense shells in deep wind regions (Feldmeier etal. '97)



High-Resolution X-ray Spectra

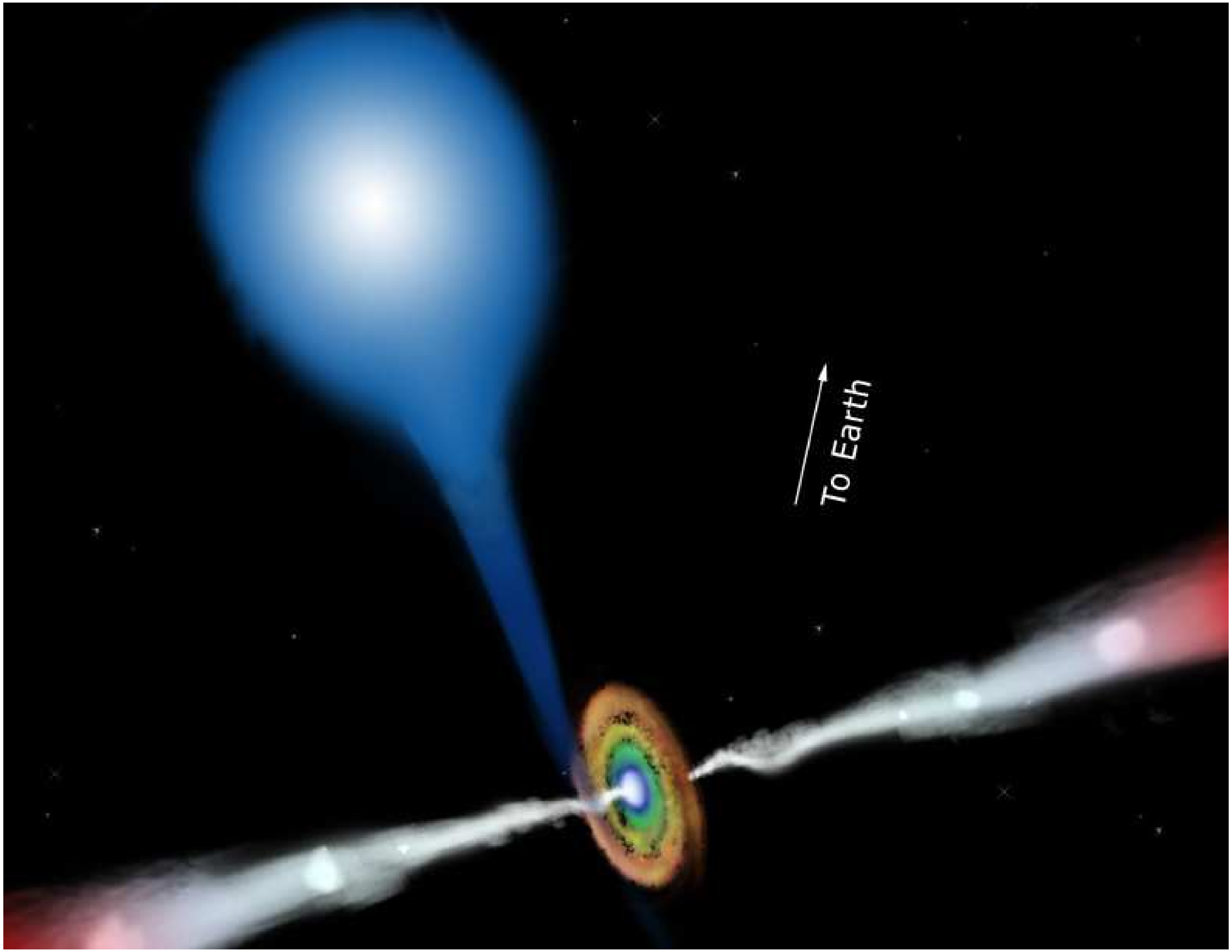


* Overall spectral fitting → plasma model, abundunces
* Line ratios → $T_X(r)$, spatial distribution
* Line profiles → velocity field, wind opacity

X-Ray from stars

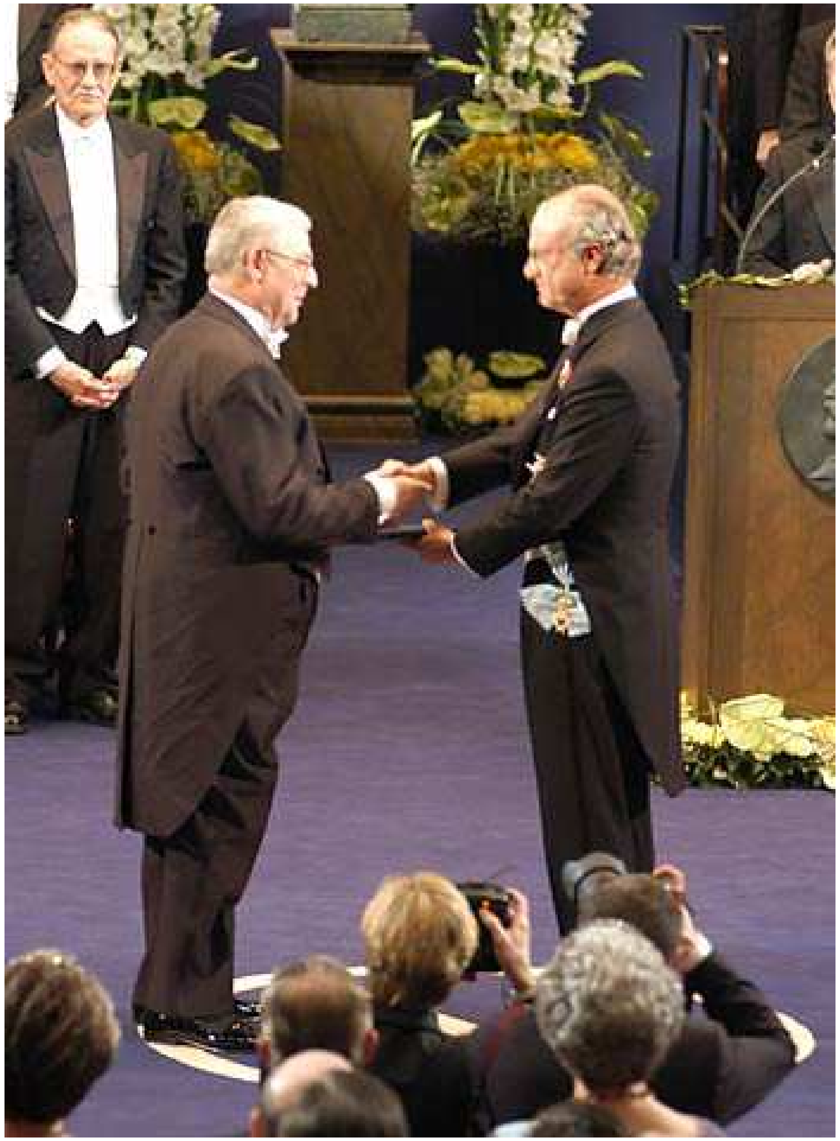
- Low and solar type stars: magnetic fields
- Magnetic fields reconnection: coronal heating → X-ray
- Young forming stars (T Tauri stars): coronae and accretion
- High-mass stars: stellar wind shocks

X-ray Binaries



http://chandra.harvard.edu/photo/2004/ss433/

53 years of X-ray astronomy



2002: Giacconi recieves NP from the king of Sweeden

1962 Bruno Rossi & Riccardo Giacconi

American Science & Engineering (AS&E)

A rocket with Geiger counter: to seach X-rays from the Moon

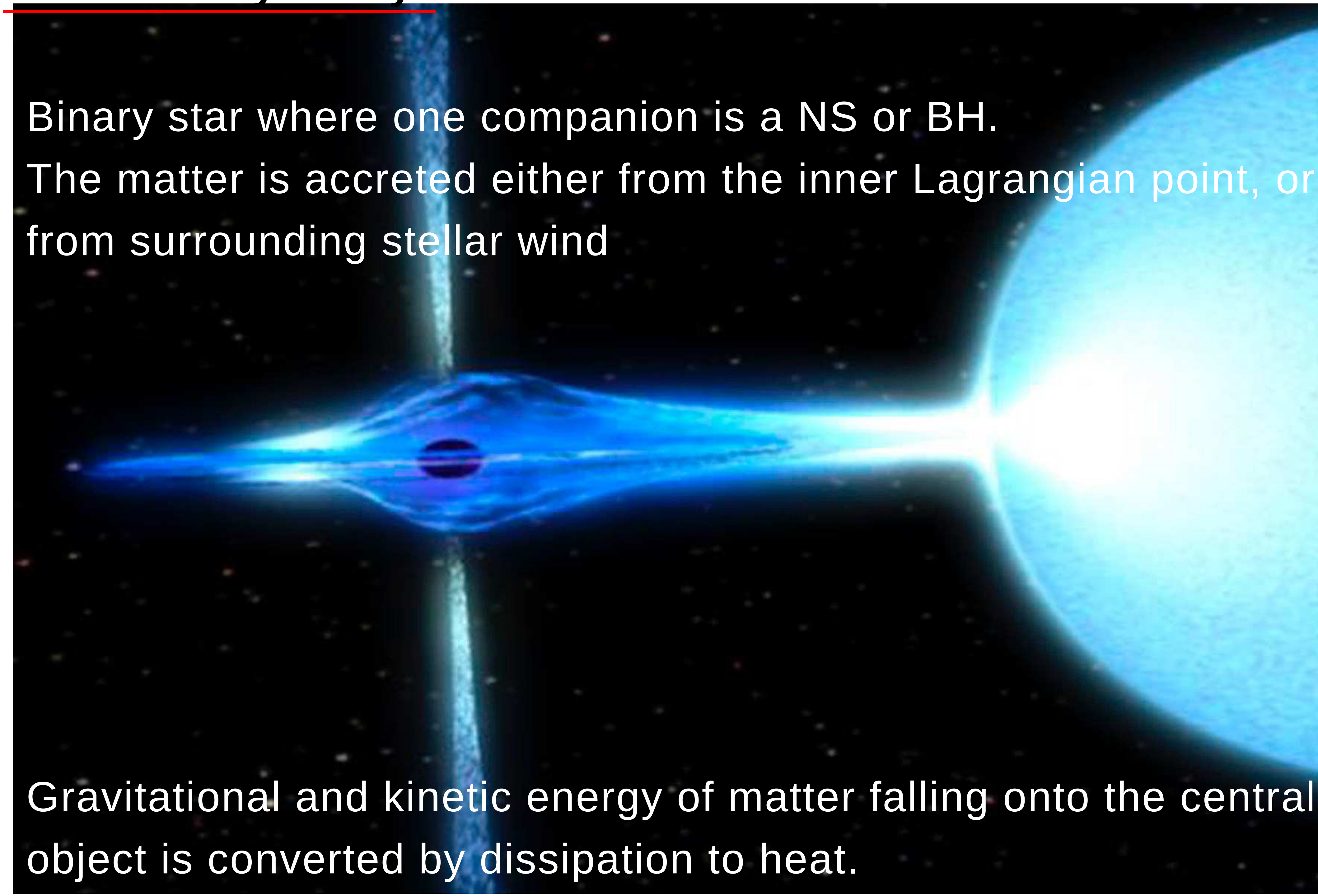
Rocket spans -
the field-of-view passed a bright source named Scorpius X-1

Sun: X-rays are 10^{-6} visible light intensity

Sco X-1: $L_X = 10^9 \ L_X^{sun}$

www.nobelprize.org/nobel_prizes/physics/laureates/2002/giacconi-lecture.html

What is X-ray binary?

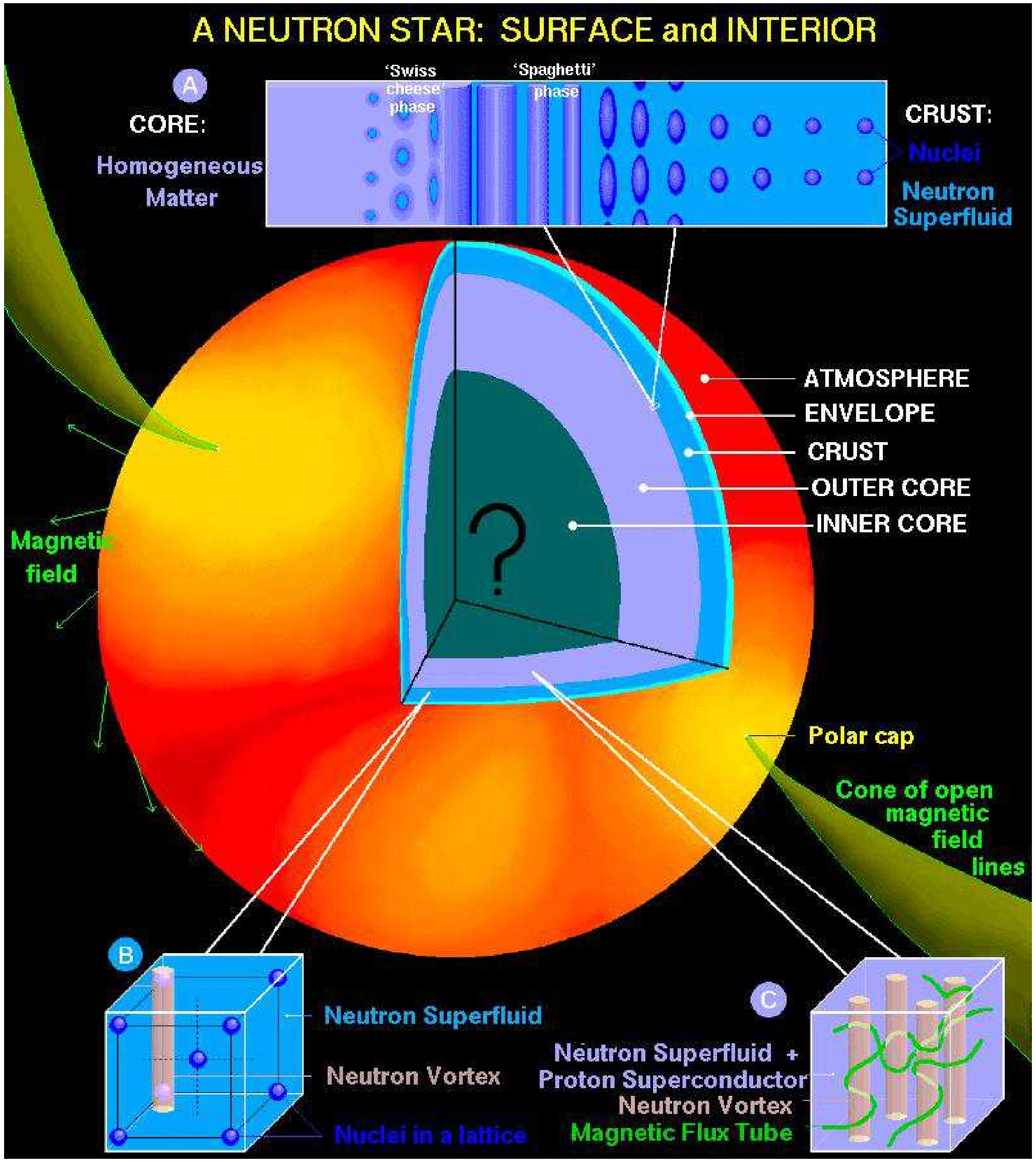


Binary star where one companion is a NS or BH.

The matter is accreted either from the inner Lagrangian point, or from surrounding stellar wind

Gravitational and kinetic energy of matter falling onto the central object is converted by dissipation to heat.

Neutron stars



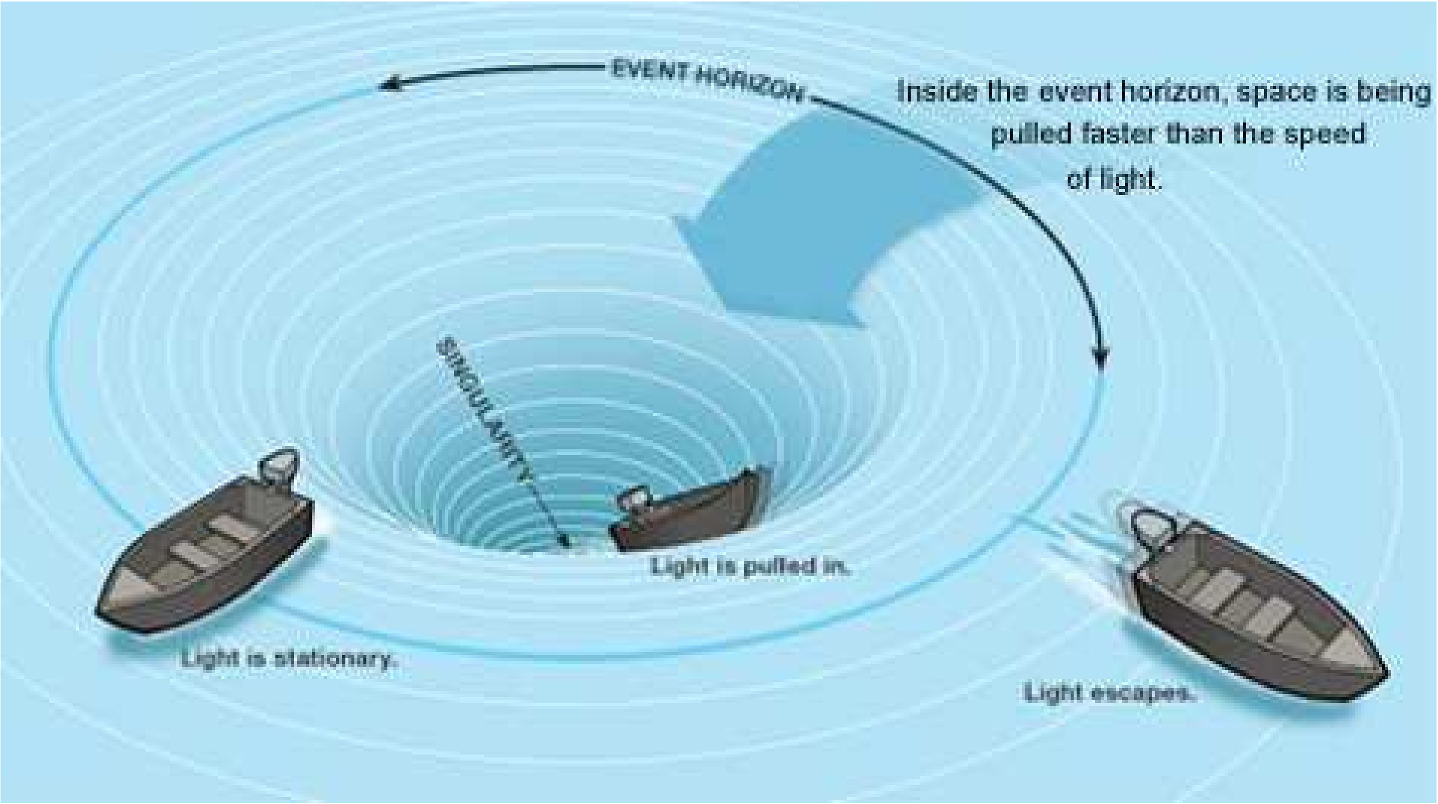
- Neutron stars are the collapsed cores of some massive stars. Mass of the Sun in r=10km. Rotation periods 0.001 sec to 2000 sec. B about 10^{12} Gs. Density 10^{14} g/cm^3 GR

- Iron core collapse → protons and electrons combine to neutrons plus neutrinos → neutron star.

- High-density, strong magnetic field: different (from 'normal') atomic structure

- Born very hot, cools by neutrino radiation in first moments. Rotation is slowed down by magnetic torque.

Black Holes



- A black hole is a region of space that has so much mass concentrated in it that there is no way for a nearby object to escape its gravitation.
- Einstein GR → Karl Schwarzschild: a mathematical solution to the GR equations that described such an object.

- In GR, gravity is a manifestation of the curvature of spacetime.
- Event horizon: the escape velocity = the velocity of light
- Inside of the horizon, spacetime is distorted so much that the coordinates describing radial distance and time switch roles.

Accretion

The depth of potential well in compact objects is large → large ammount of energy is liberated in accretion process

The process of accretion at a rate $\dot{M}$ onto an object of mass M and radius R gives a luminosity of

$$L = GM\dot{M}/R$$

Heat is partially radiated out, partially converted to work on the disc expansion and (in the case of BH accretion) partially lost inside the hole.

Mass to energy conversion efficiency $\eta = L/Mc^2 = 0.1$ → **considerably greater than the efficiency of nuclear fusion**

Eddington limit

The accretion rate is limited by the Eddington limit. Defined by the balance between outward radiation pressure and inward gravitational force.

Any phenomenon lasting more than a few dynamical scales should have $L<L_{edd}$.

Force of radiation acting on an electron

$$F_{\rm rad} = \frac{L}{4\pi R^2 h\nu}\sigma_{\rm T}\frac{h\nu}{c}$$

Force of gravity on a proton $F_{\rm grav} = \frac{GMm_{\rm p}}{R^2}$

$$L_{\rm edd} = \frac{4\pi GMm_{\rm p}c}{\sigma_{\rm T}} \approx 10^{38} M$$

Maximum accretion rate

Accretion disks

Matter's angular momentum is > than the Keplerian angular momentum → accreting matter will orbit a compact object.

Dissipation and friction: matter flattens and spreads equatorially into an accretion disk. The angular momentum is transported outward by friction and mass moves inward.

Newtonian gravity: angular momentum at a distance R from a spherical object with the mass M is $(GMR)^{1/2}$ → monotonically increasing → stability of all orbits.

Einstein gravity: angular momentum has a minimum at the radius of the innermost stable circular orbit (ISCO). Orbits above r_{ISCO} are stable, and below are unstable.

For a non- rotating black hole $r_{ISCO} = 6GM/c^2$

31 Spherically symmetrical (Bondi) accretion

- Spherical accretion onto an object occurs e.g. in a star accreting from ISM or in a compact object immersed in stellar wind.

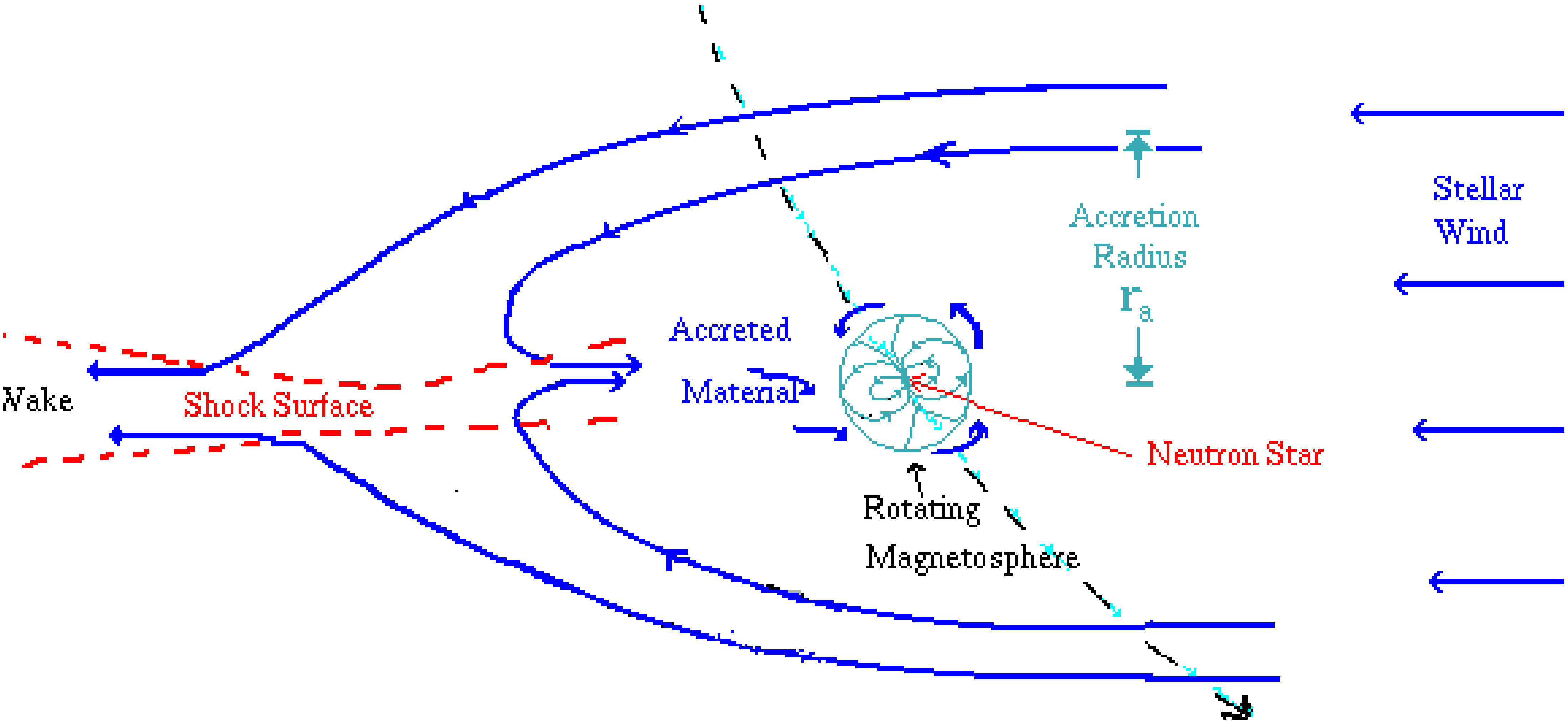
- This happening when angular momentum is not dynamically important

- Accretion rate $\dot{M}_{\mathrm{acc}} = 4\pi r_{\mathrm{A}}^2 \rho v$, velocity can be either sound speed (c_s) or motion speed of compact object through the medium.

- Accretion $E_{tot}<0$ → r_A is effective radius such that escape velocity $\sqrt{\frac{2GM}{r_{\mathrm{A}}}} = v$

- $r_{\mathrm{A}} = \frac{2GM}{v^2}$ → $\dot{M}_{\mathrm{acc}} = \frac{8\pi\rho G^2 M^2}{v^3}$

Davidson & Ostriker (1973)

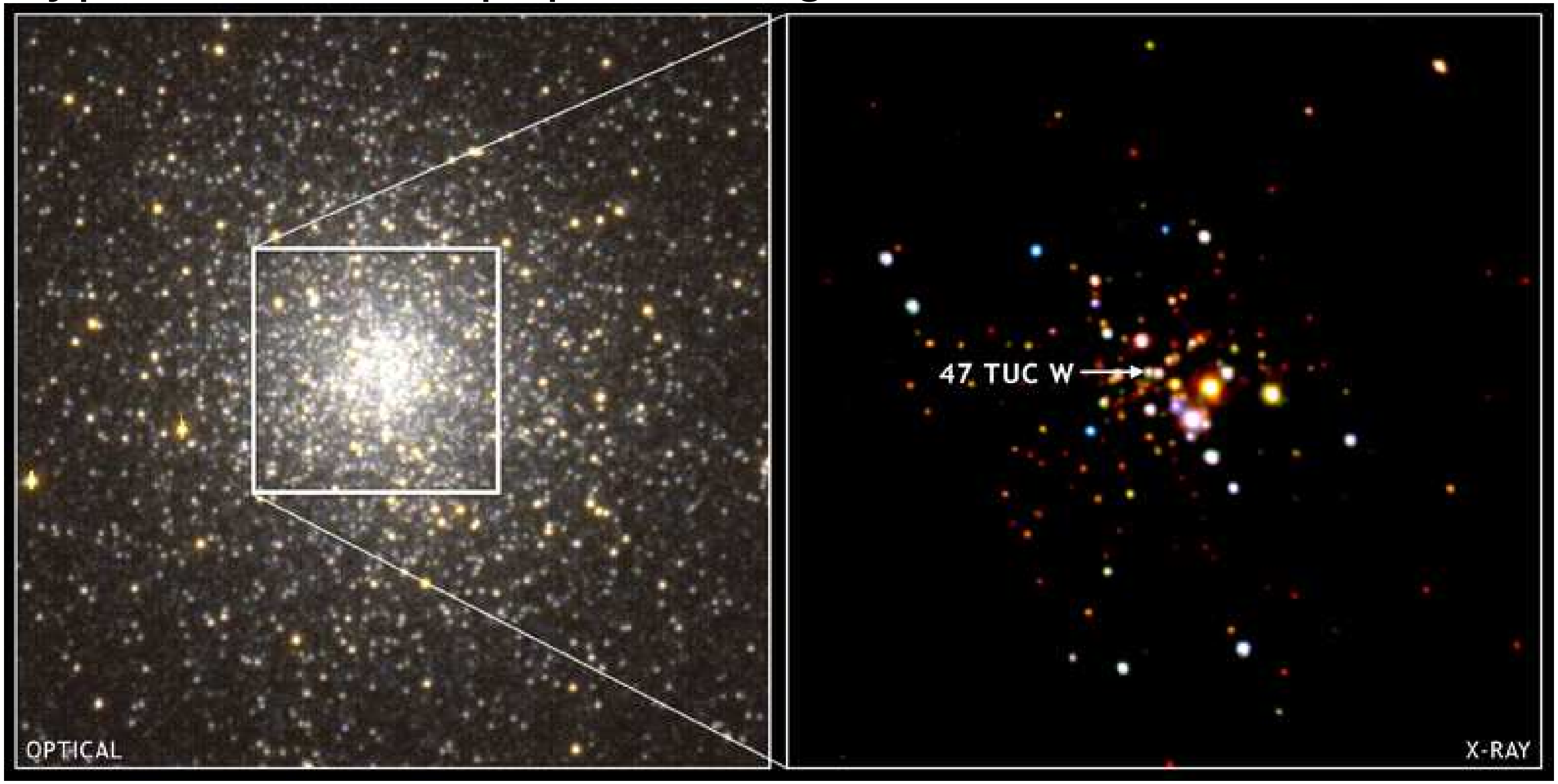


Accretion of stellar wind on a neutron star

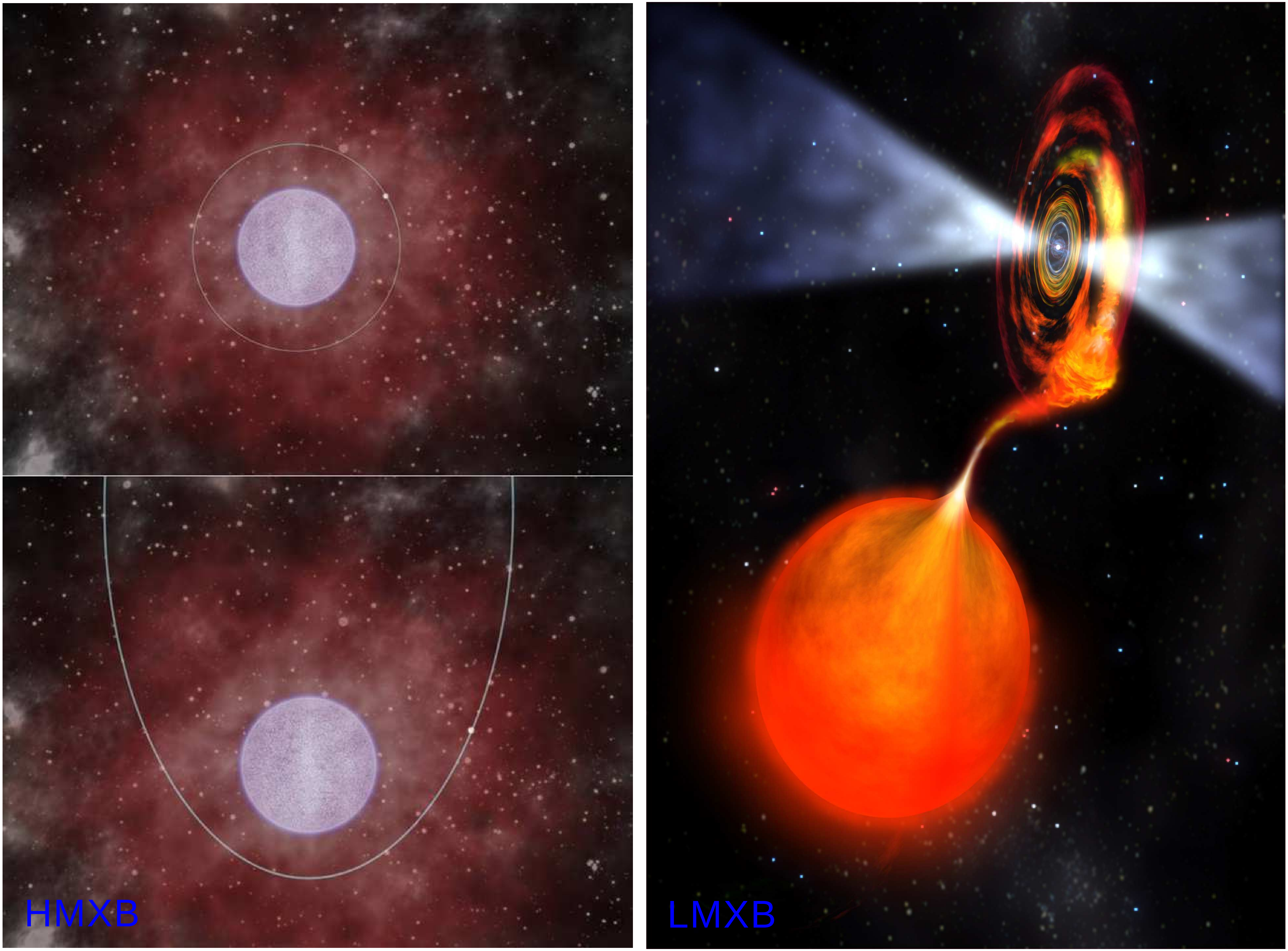
X-ray Binary Classification

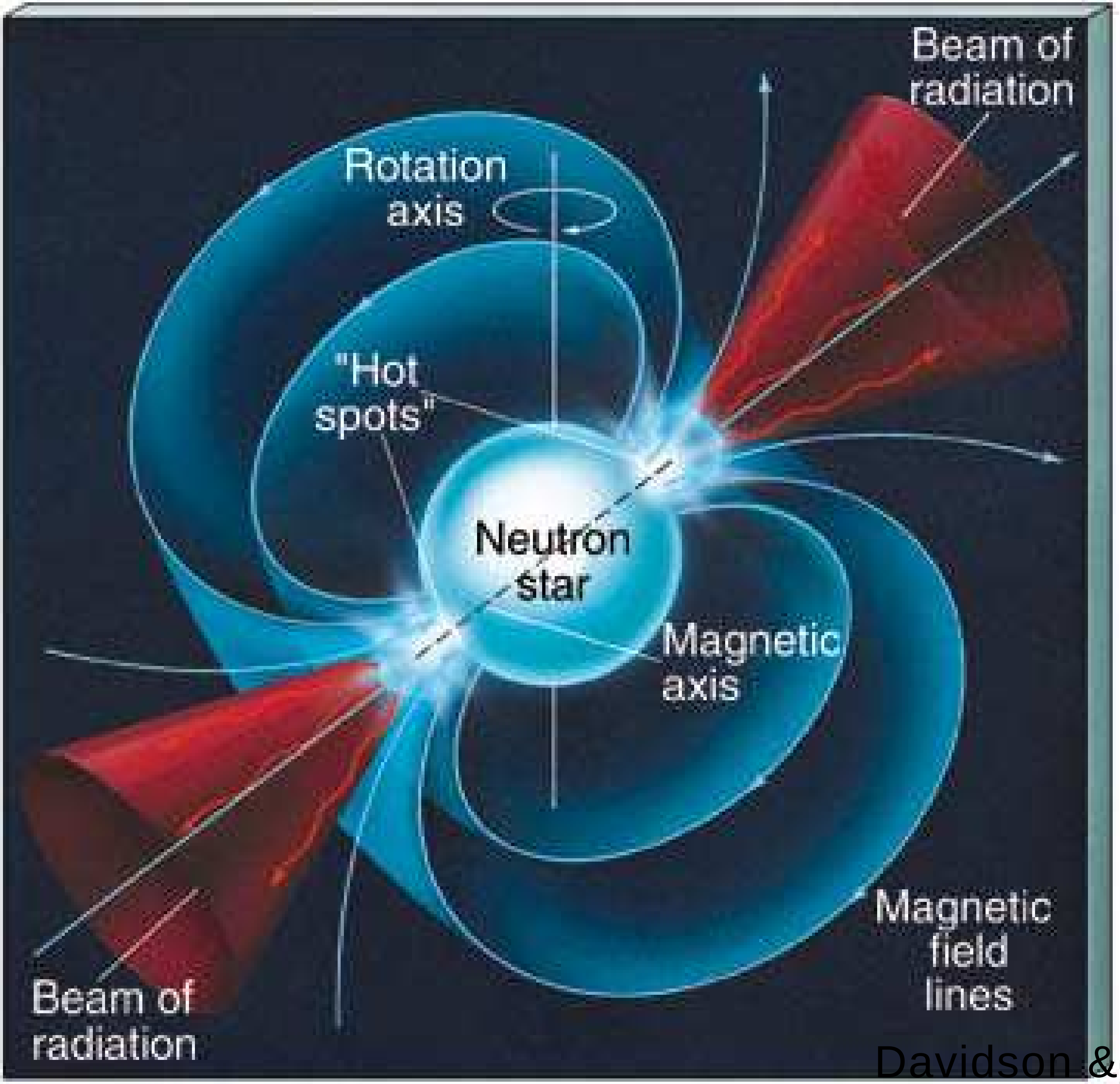
Classified according to the type of donor

- High-mass X-ray binaries (HMXB): early-type star (OB or Wolf-Rayet). Stellar wind accretion. Located in star forming regions. Cyg X-1, Vela X-1, Her X-1
- Low-mass X-ray binary (LMXB): late type stars. Mass transfer via L1. Many types. Trace old population, globular clusters. Sco X-1



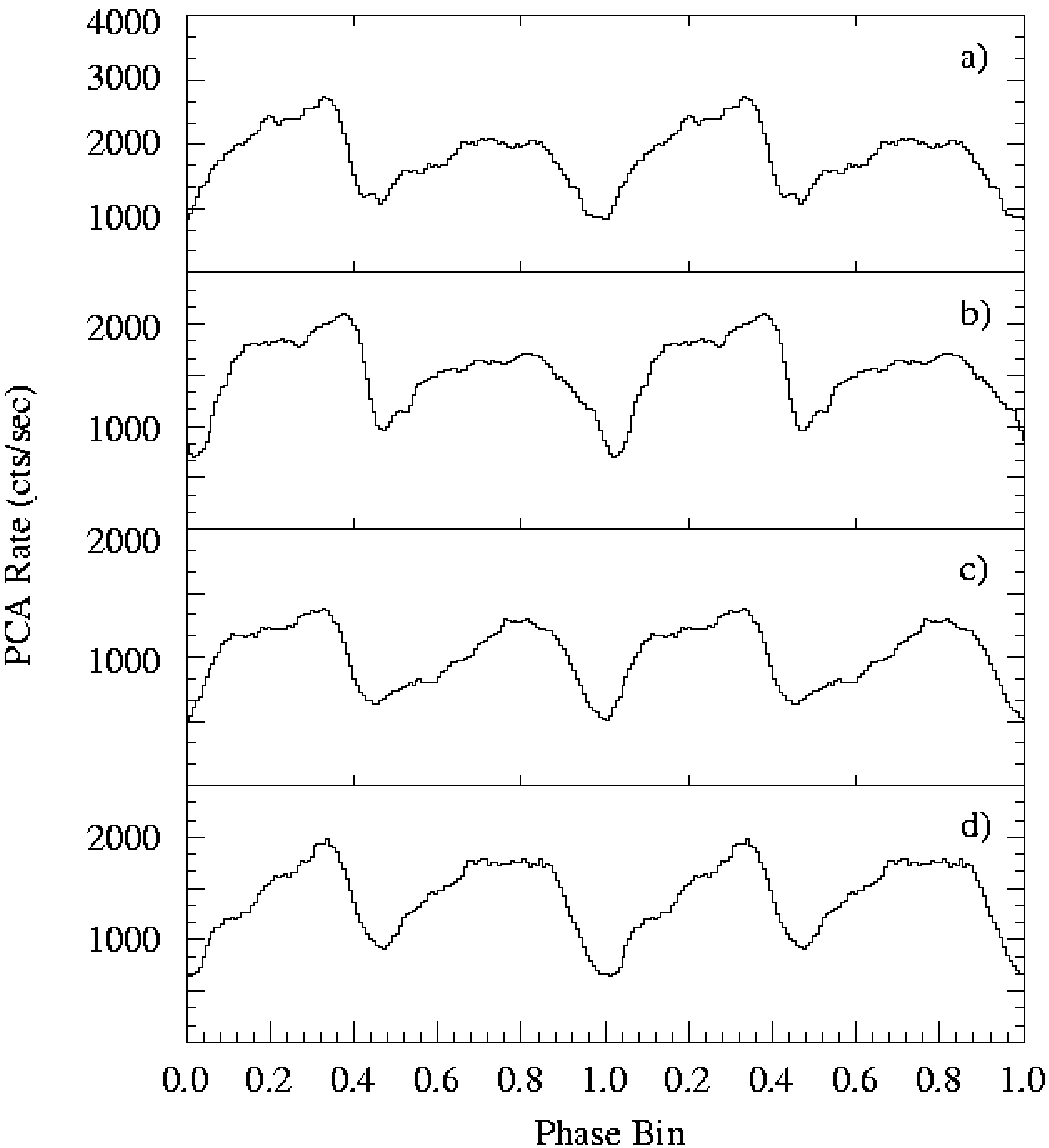
NASA/CXC/CfA/J.Grindlay C.Heinke; ESO/Danish 1.54-m/W.Keel


HMXB
LMXB



Davidson & Ostriker 1973

X-ray Pulsars



Kreykenbohm et al. A&A 341, 141 P=283.4 s

- The rotation rate of the NS is held near equilibrium, depending on the B_0 and rotation rate
- If NS is spinning too fast $R_M > R_{sy}$, matter cannot fall through the magnetosphere
- Material is flung out of the system, inducing a braking torque. **Spin-down of a pulsar** **long period pulsars**
- If is spinning too slow $R_M < R_{sy}$. Density gradient in stellar winds → a side closer to the star accretes more → a torque → **spin up** **millisecond pulsars**

Persistent HMXBs

- OB-type donor (usually a supergiant). NS is immersed in a stellar wind. Orbital separation is typically $2R_{star}$.

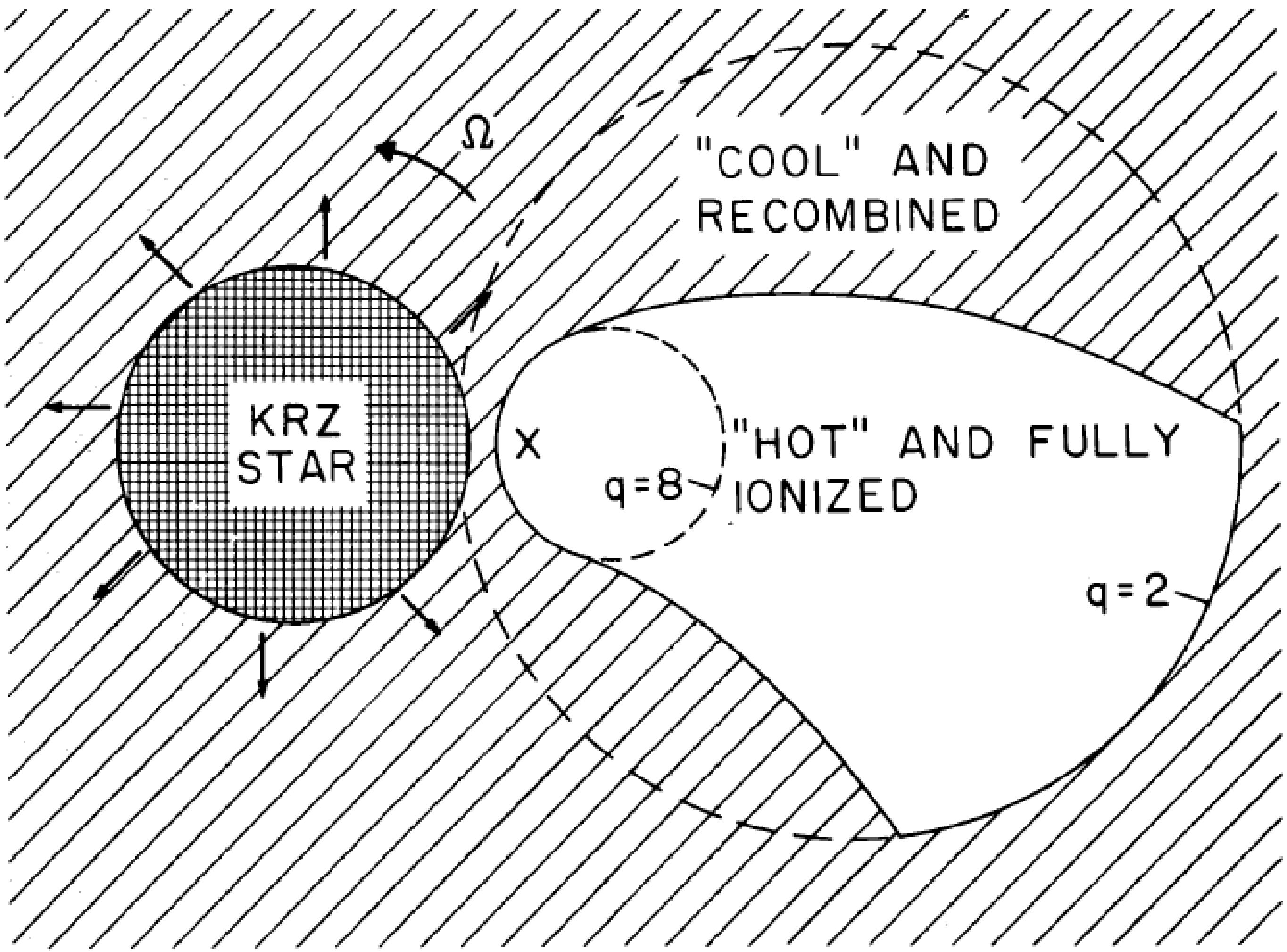
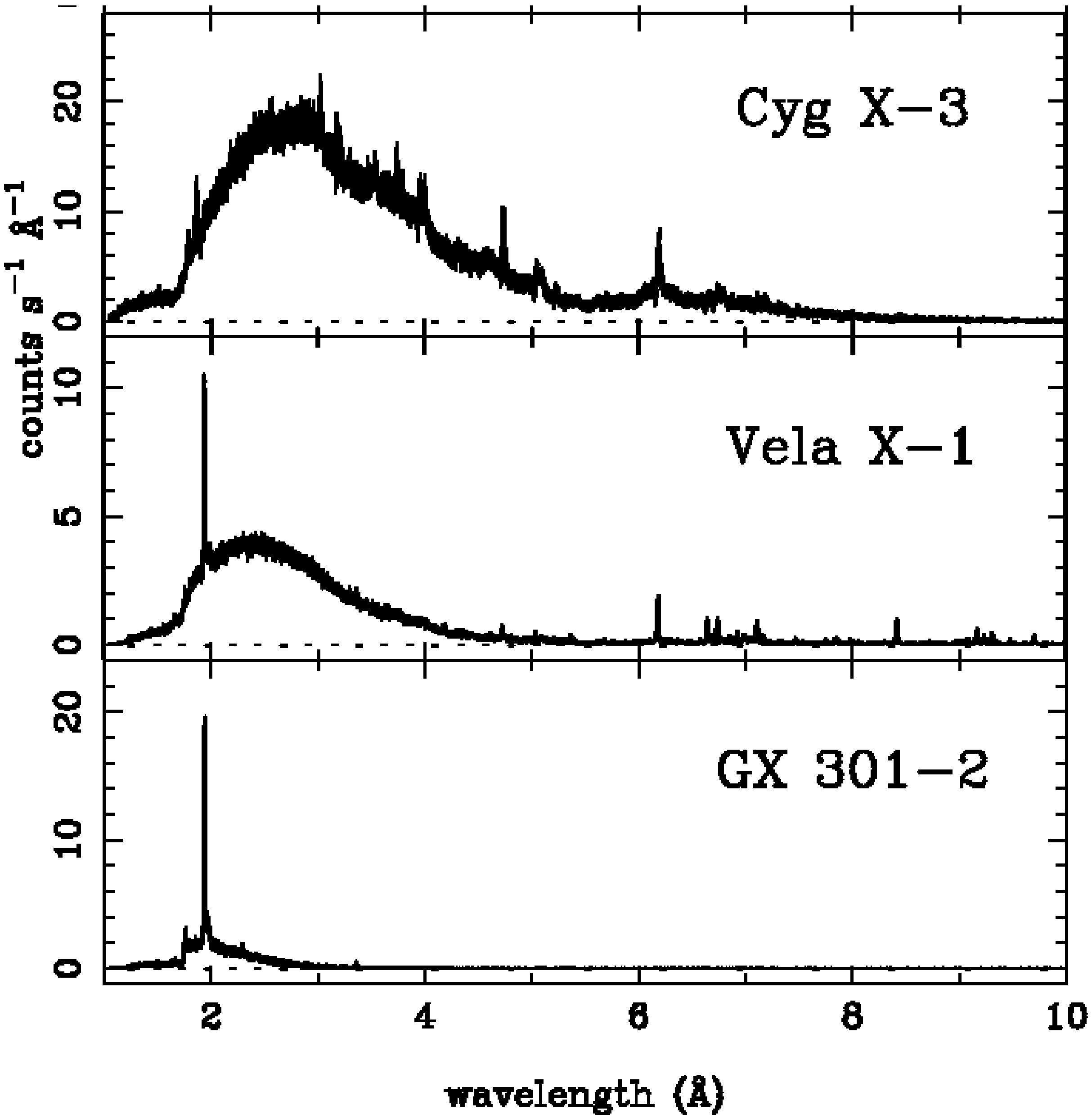


FIG. 4.—A model for the system Cen X-3/Krzeminski's star during the turn-on of 1972 July.

Hatchett & McCray 1977

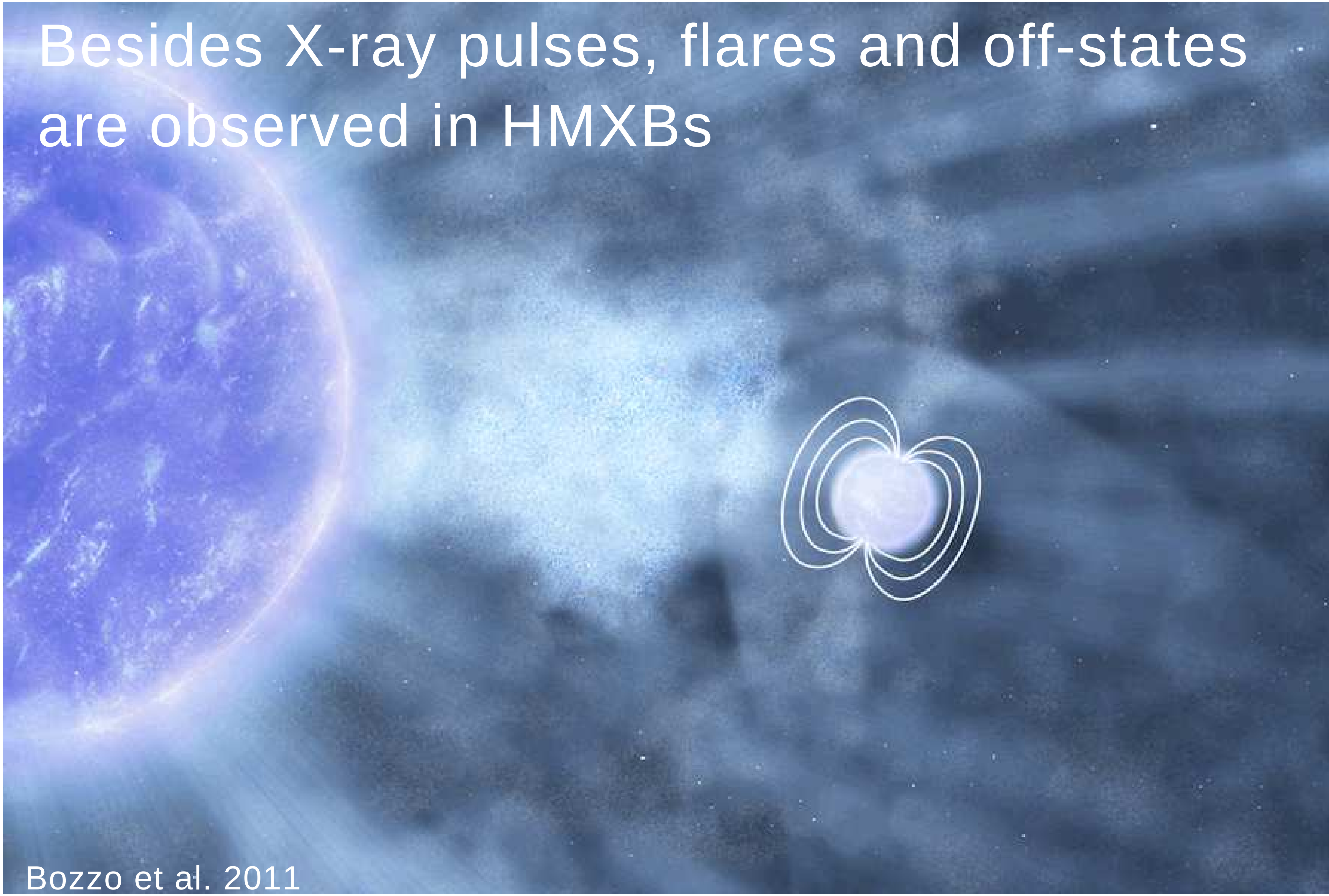
- Some host X-ray pulsars
- Sensitive to the properies of donor winds
- About a dozen known in the Galaxy

X-ray spectra



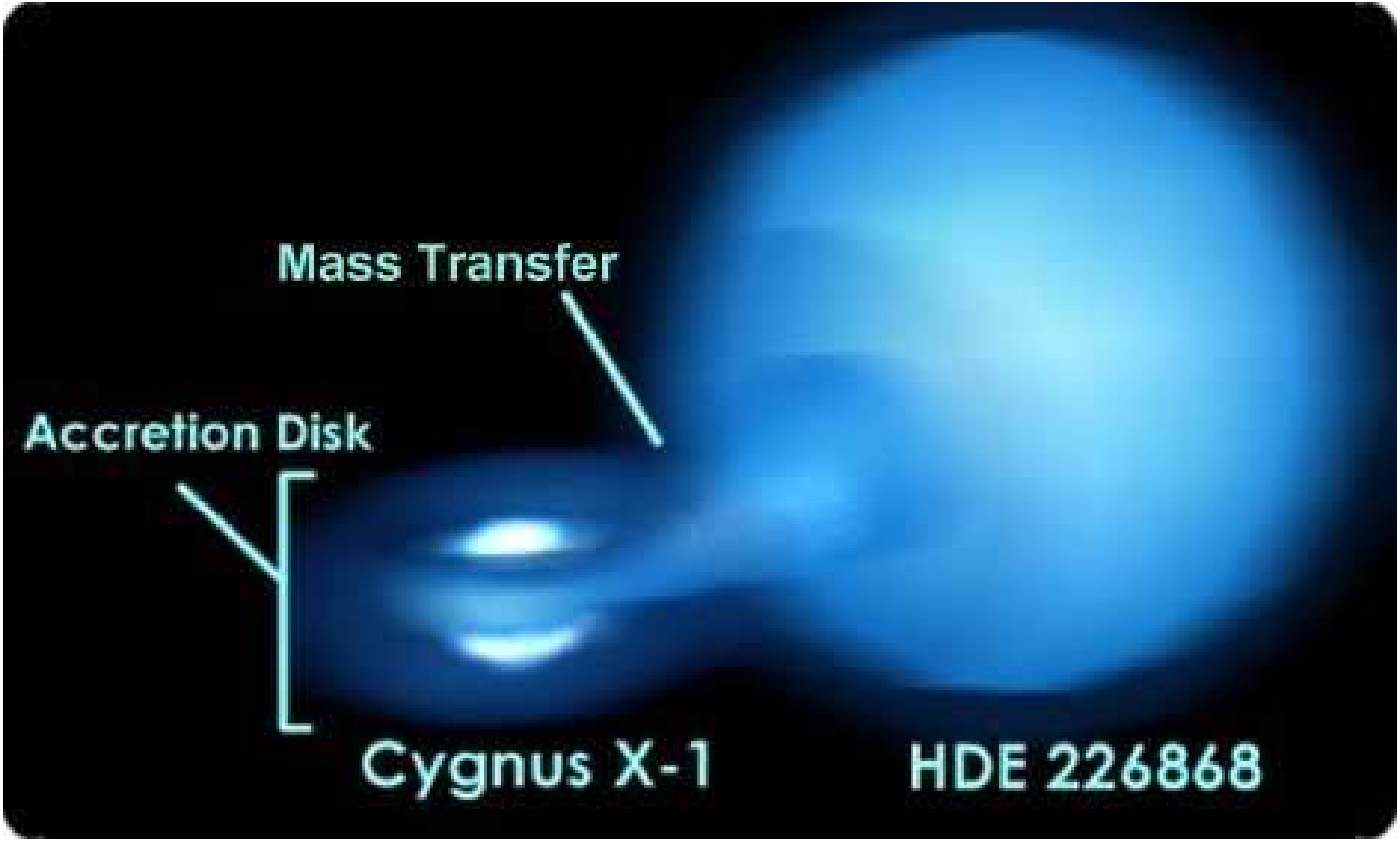
- Strongly absorbed power-law
- Absorption depends on orbital phase
- Compact object distorts wind
- X-ray field distorts the wind

Besides X-ray pulses, flares and off-states are observed in HMXBs

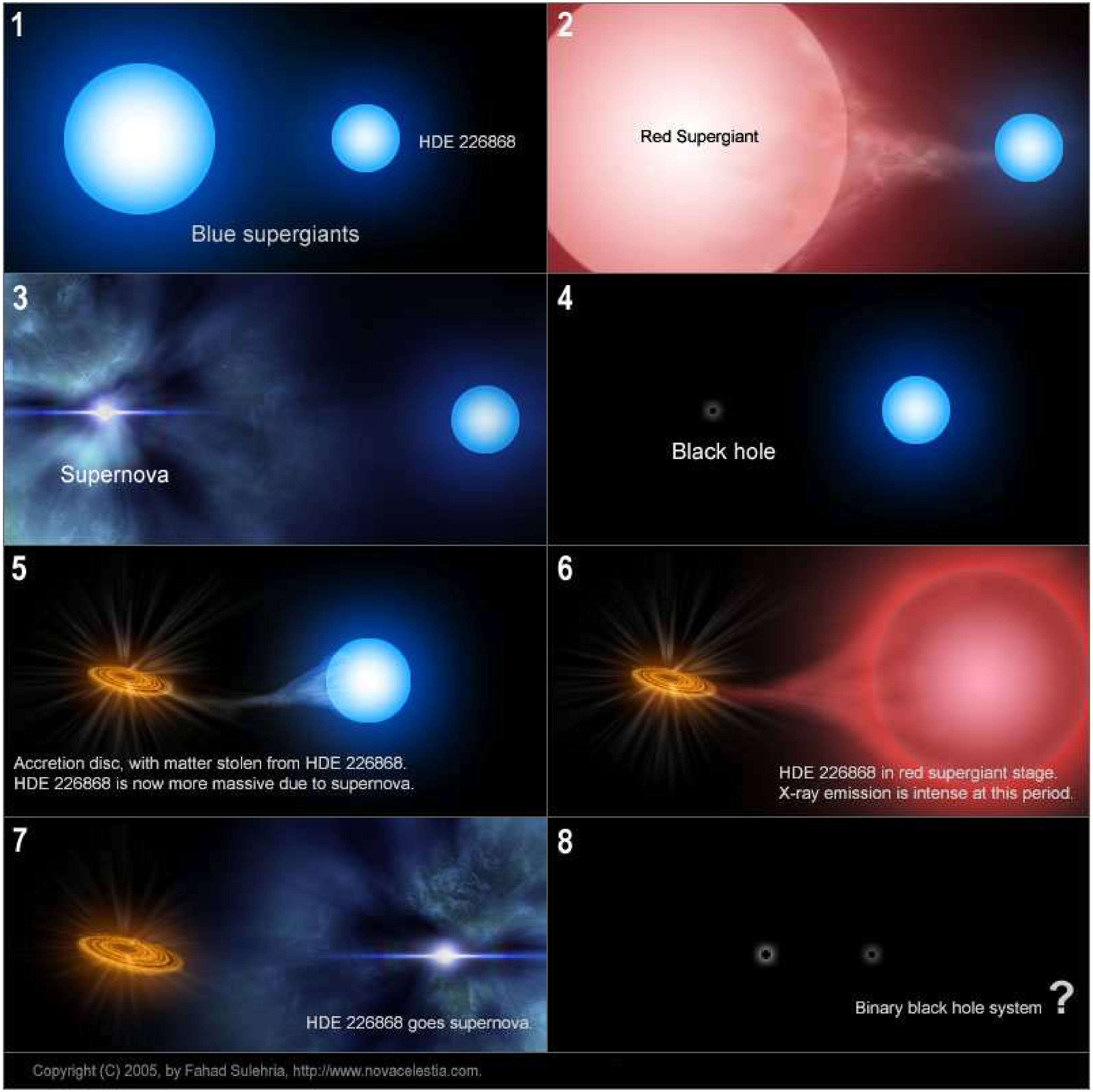


Bozzo et al. 2011

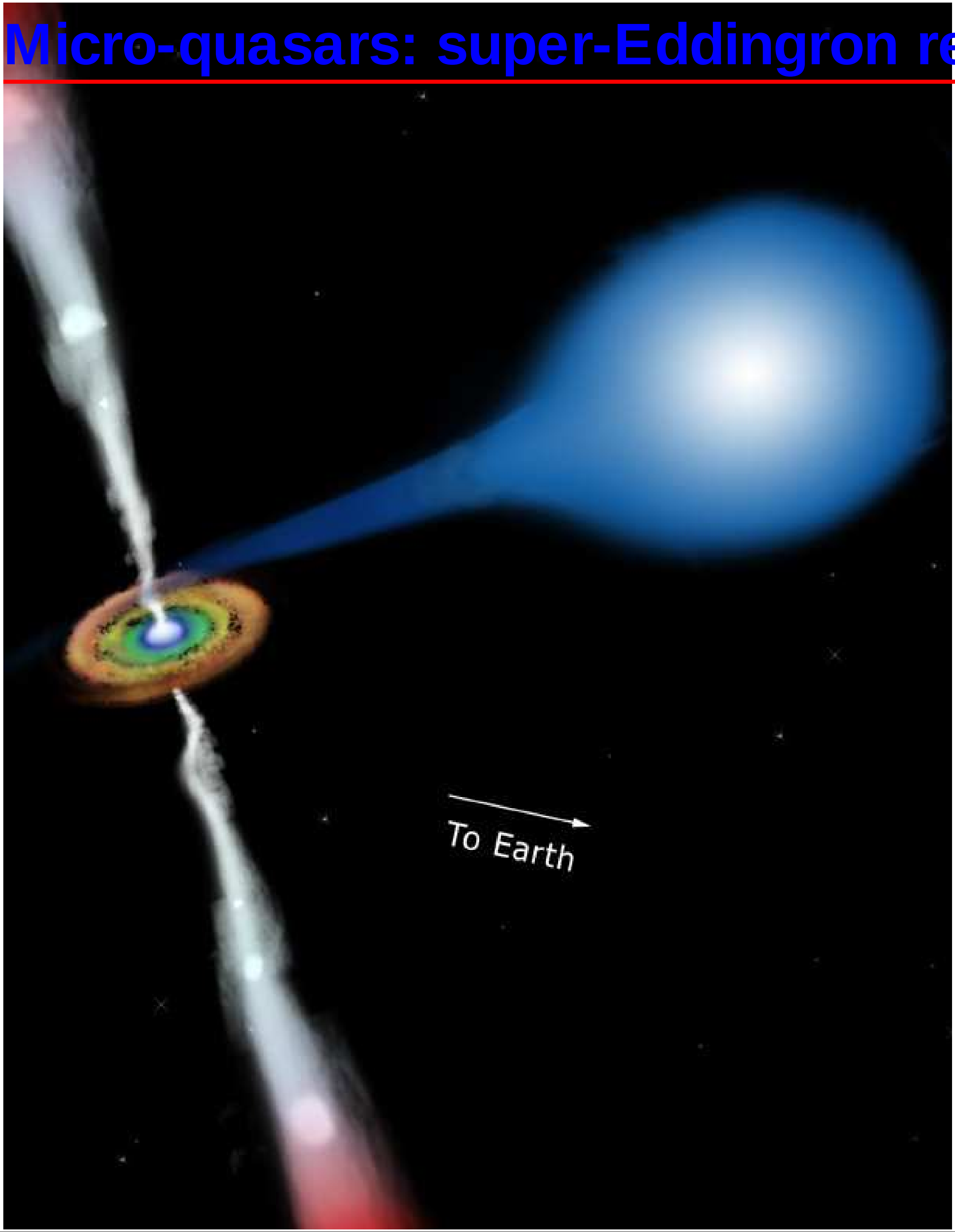
Roche Lobe filling HMXB



High $L_X > 10^{38}$ erg/s; hard and soft spectral states; Cyg X-1 black hole


1
HDE 226868
Blue supergiants
2
Red Supergiant
3
Supernova
4
Black hole
5
Accretion disc, with matter stolen from HDE 226868.
HDE 226868 is now more massive due to supernova.
6
HDE 226868 in red supergiant stage.
X-ray emission is intense at this period.
7
HDE 226868 goes supernova.
8
Binary black hole system ?
Copyright (C) 2005, by Fahad Sulehria, http://www.novacelestia.com.

Micro-quasars: super-Eddingron regime of accretion



SS 433: the central engine is obscured by the accretion disc and only jet is visible in X-rays

43 Tolman-Oppenheimer-Volkoff (TOV) limit

The Chandrasekhar limit

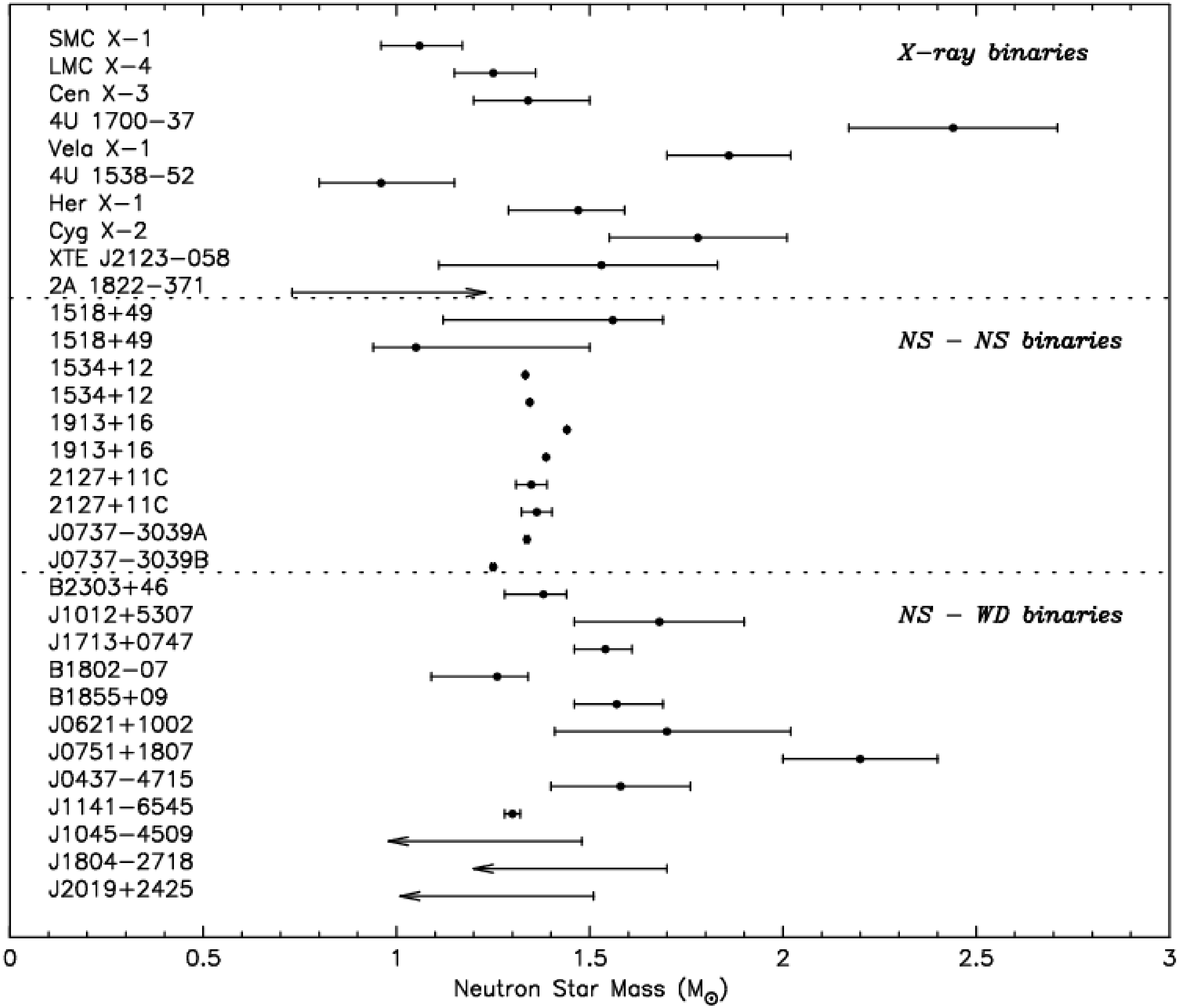
- The maximum nonrotating mass which can be supported against gravitational collapse by electron degeneracy pressure. **1.4Msun**

The Tolman-Oppenheimer-Volkoff limit

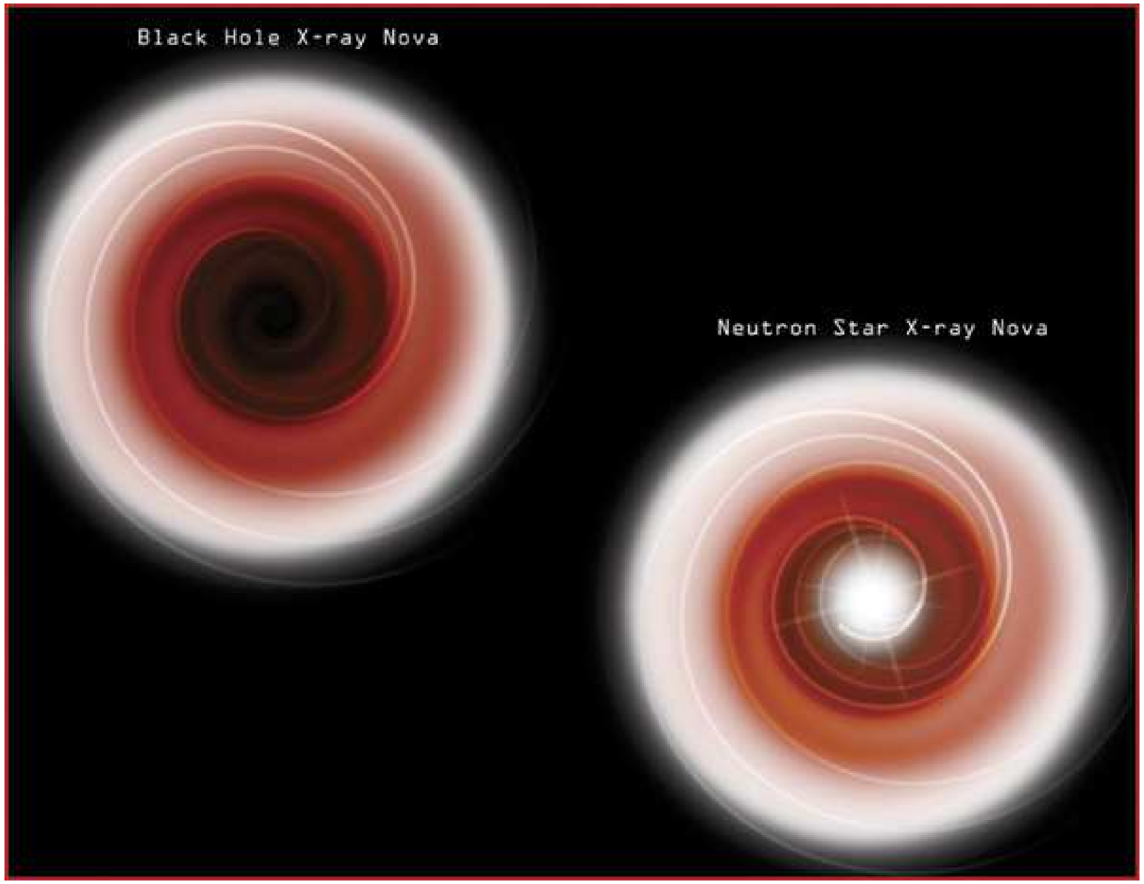
- The maximum nonrotating mass which can be supported against gravitational collapse by y short-range repulsive neutron-neutron interactions mediated by the strong force and also by the quantum degeneracy pressure of neutrons **1.5…3.0 Msun**

- Quark degeneracy: At densities greater than those supported by neutron degeneracy.
- Strange matter is a degenerate gas of quarks that contain strange quarks in addition to the usual up and down quarks.
- **Quark stars:** formed by the collapse of objects above the TOV mass limit for neutron-degenerate objects.

44 Neutron Star (NS) masses (van der Meer et al. 2007, A&A, 473, 523)

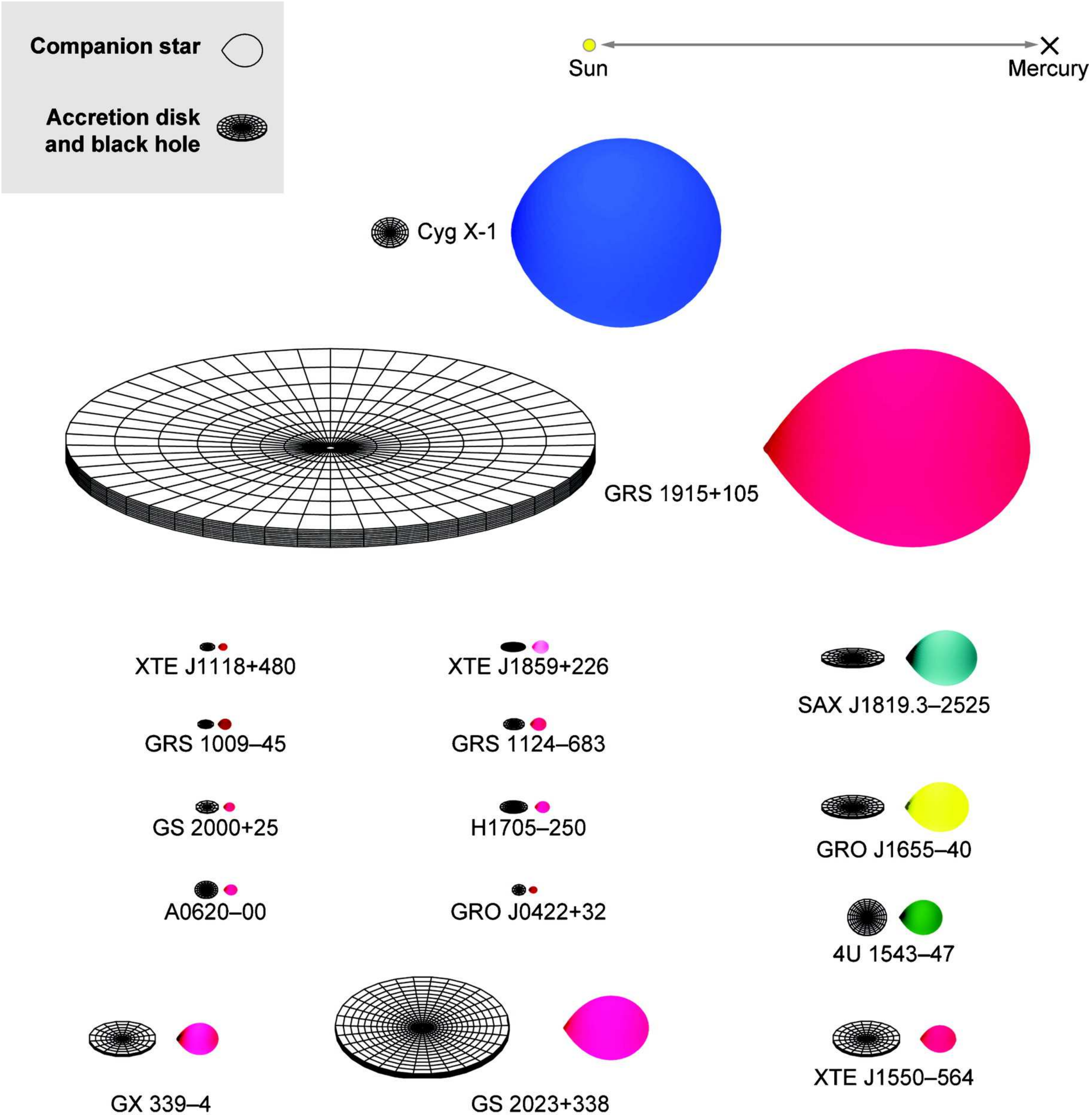


45 Black Hole X-ray Binaries



Oppenheimer & Snyder (1939): formation of a black hole.

- 20 XRBs contain a compact object with $M > 3M_\odot$. In the Galaxy $10^{8\text{-}9}$.
- A BH is specified by M (scale) and spin a=J/c M (geometry), where J is angular momentum. Or $a^* = a/R_G$. Schwarzschild BH: $a^*=0$; Kerr BH: $a^*=1$.
- Event horizon of a Schwarzschild BH $R_S = 2R_G = 30\text{km}\,(M/10M_\odot)$, the ISCO lies at $R_{ISCO} = 6R_G$, and the maximum orbital frequency is $\nu_{ISCO} = 220\text{Hz}(M/10M)^{-1}$. For Kerr BH (a* = 1), the $R_S = R_{ISCO}$ and $\nu_{ISCO} = 1615\text{Hz}(M/10M)^{-1}$.
- Radiating gas orbiting a compact object is the steady-state, thin accretion disk model (Shakura & Sunyaev 1973) → $T(R) \propto R^{-3/4}$. Luminosity of an annulus $L_X \propto R dR \sigma_{sb} T^4 \propto R^{-2}$. X-rays are the best window to the horizon of a BH.



46 Census

LMC X-3 B3V

$M_{BH}=5.9\text{-}9.2M_\odot$

LMC X-1 O7III

$M_{BH}=4.0\text{-}10.0M_\odot$

GRS1915+105 MIII

$M_{BH}=10.0\text{-}18.0M_\odot$

Cyg X--1 O9.7I

$M_{BH}=6.8\text{-}13.3M_\odot$

V404 Cyg K0III

$M_{BH}=10.1\text{-}13.4M_\odot$

XTE1118 M0V

$M_{BH}=6.5\text{-}7.2M_\odot$

steady X-ray bright

transient X-ray novae

Remillard RA, McClintock JE. 2006.
Annu. Rev. Astron. Astrophys. 44:49–92

X-ray binaries: HMXBs, (LMXBs)

Very complex systems: relativity, stellar physics, stellar and galactic evolution, hydrodynamic. etc....

- Matter in extreme conditions

- Stellar winds from massive stars

Neutron stars (X-ray pulsars) - Black Holes