Accreting neutron stars and black holes

Rudy Wijnands
Anton Pannekoek Institute for Astronomy
University of Amsterdam

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Why study accreting neutron stars and black holes?

Accreting NSs and BHs: X-ray binaries

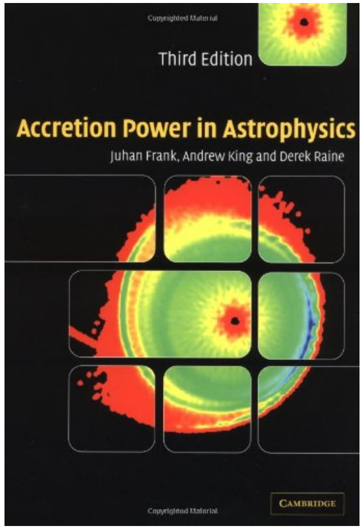
- Accretion physics
- Neutron star and black hole physics
  - Ultra-dense matter
  - Strong to very strong gravity fields
  - Super strong magnetic fields
- Binary evolution
  - Extreme end points of evolution
- Galaxy evolution

Today (Accretion physics; Neutron star and black hole physics; Ultra-dense matter)

Tomorrow (Binary evolution; Extreme end points of evolution; Galaxy evolution)

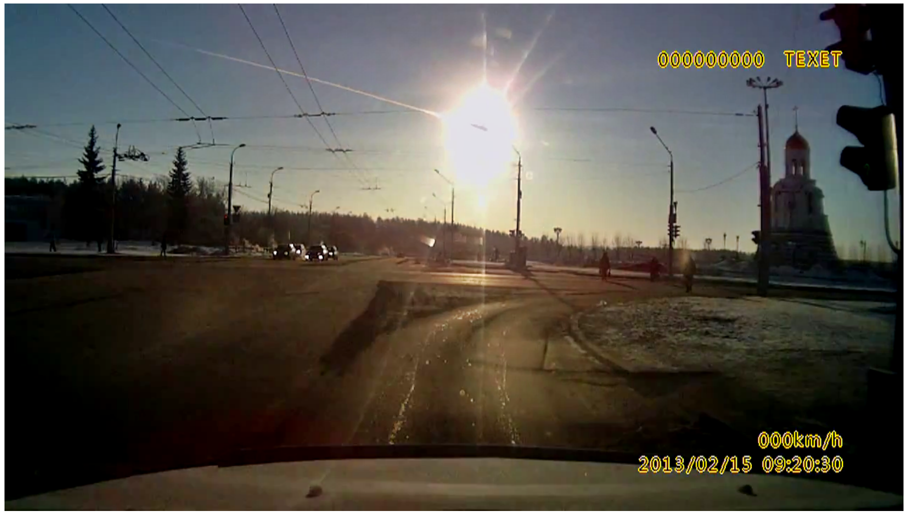
What is accretion?

- **An increase in the mass of an object by the collection of surrounding gasses or objects by gravity**
- Accretion is a very important process in astronomy!
- Accretion is an extremely powerful process to release fast amounts of energy
  – Especially for accretion NSs and BHs
- Text book: Frank, King, & Raine "Accretion Power in Astrophysics"



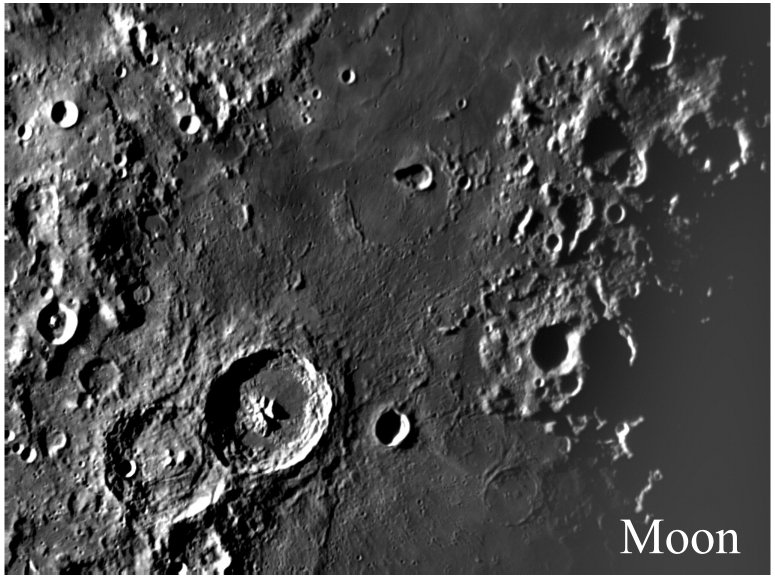
Solar system bodies

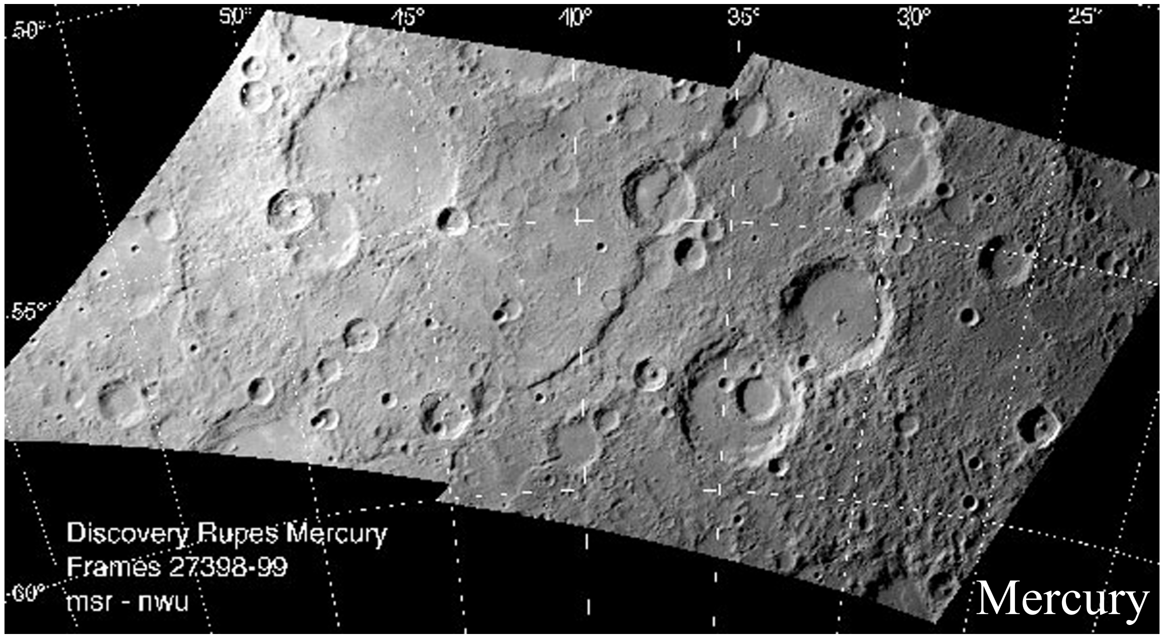
Earth

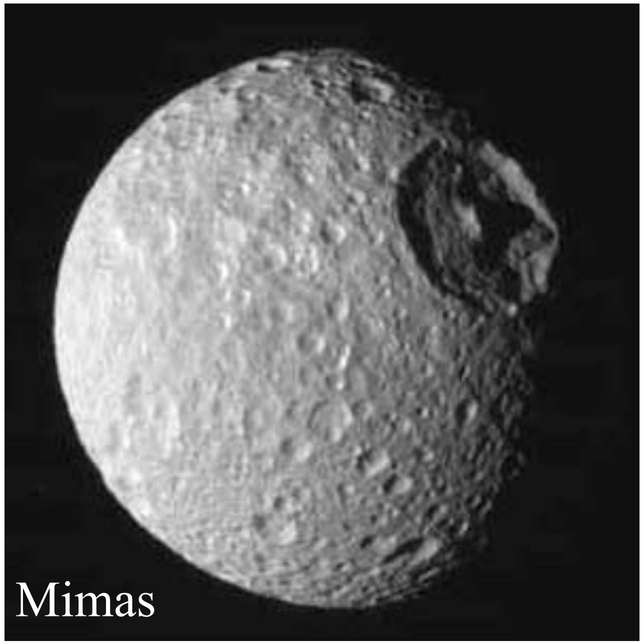


Chelaybinsk, Russia, February 15, 2013

Craters on planets and moons

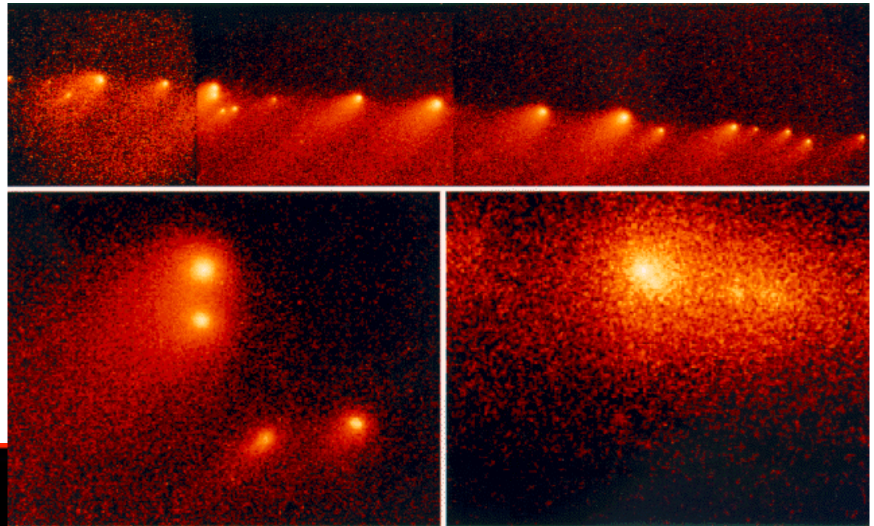


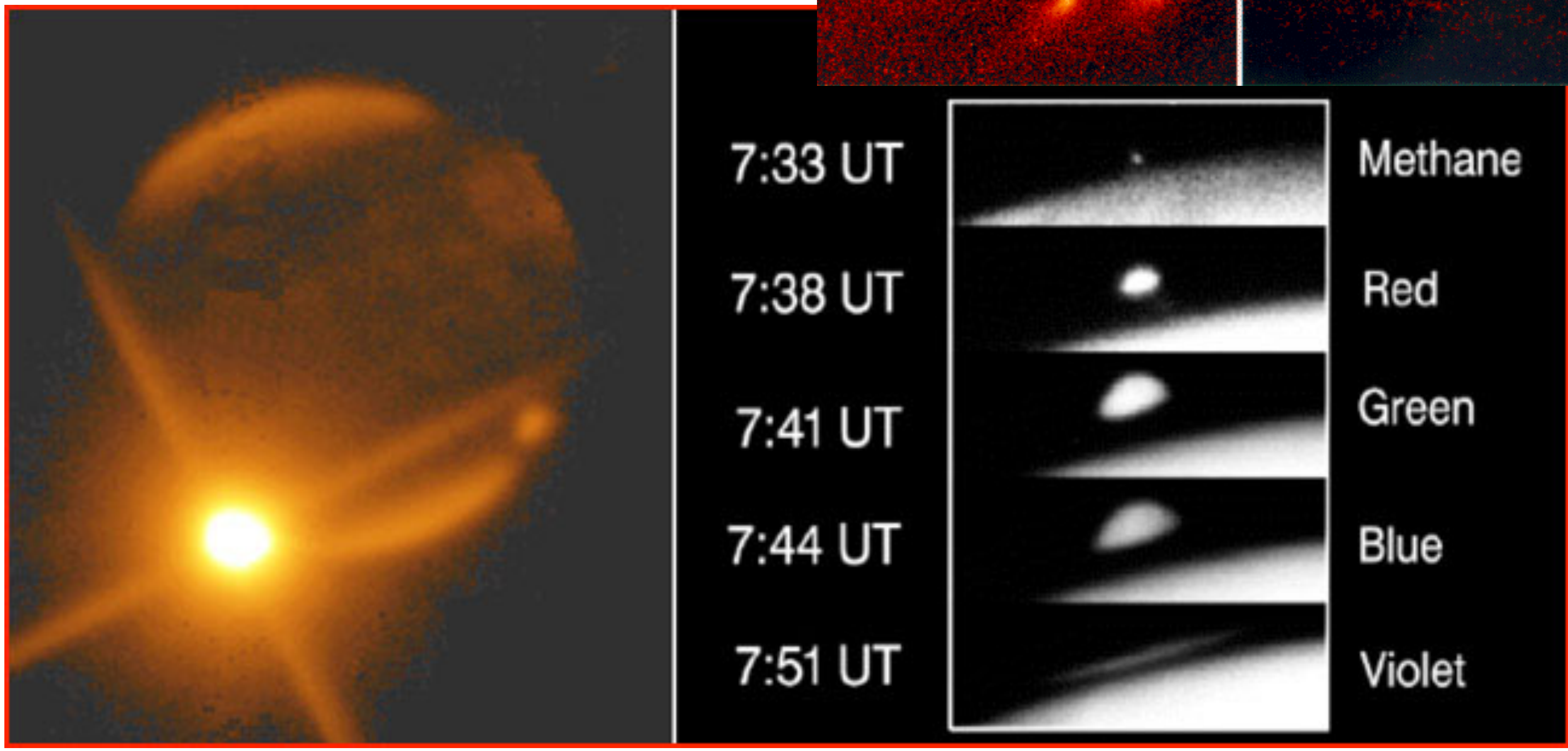




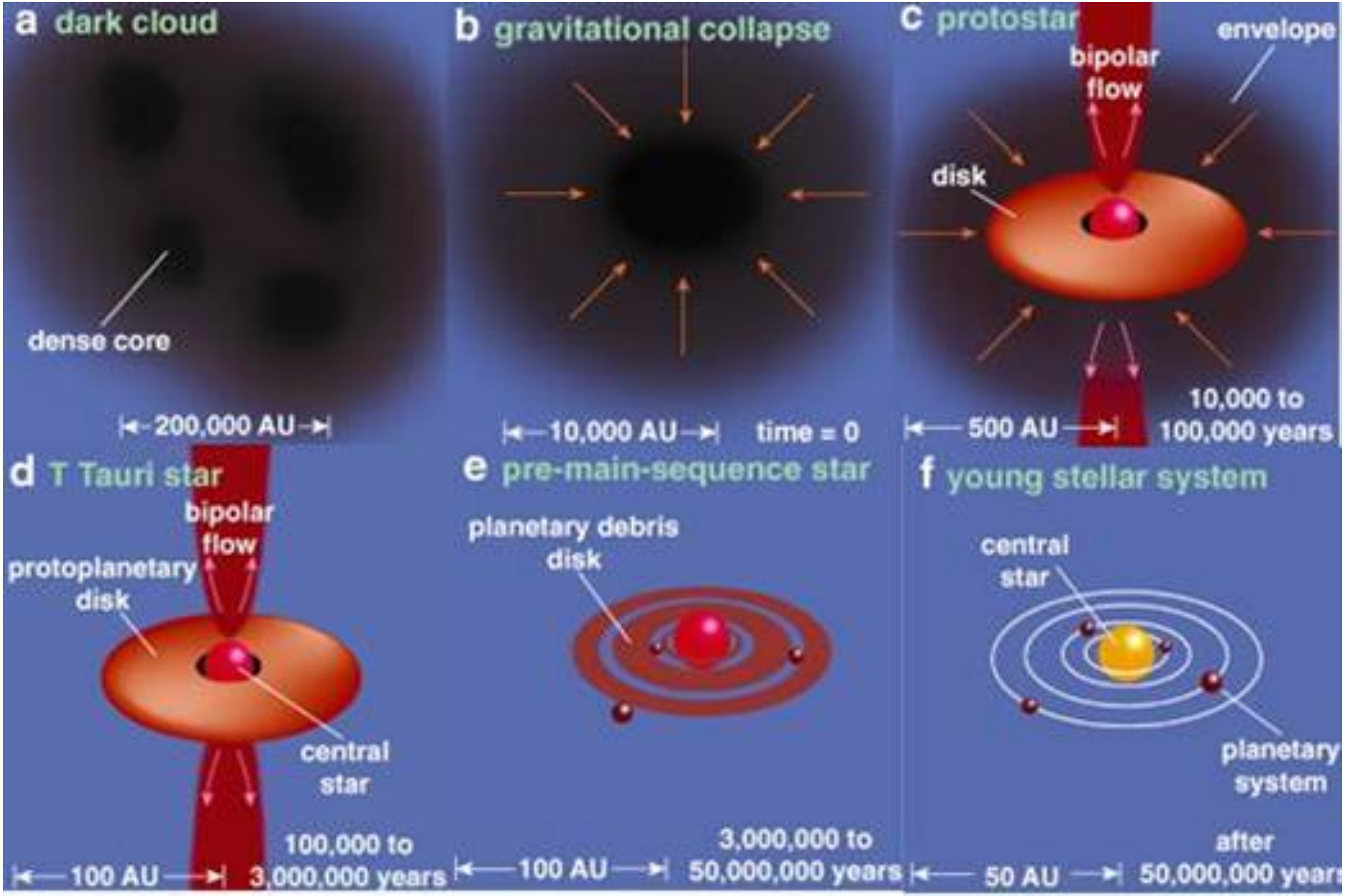
Jupiter and Shoemaker-Levy 9

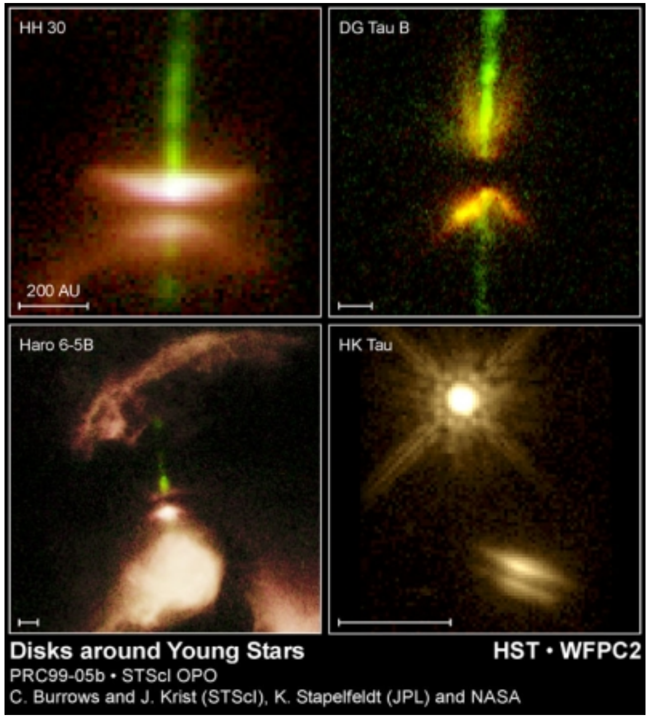
- July 16-22, 1994





Young stellar objects





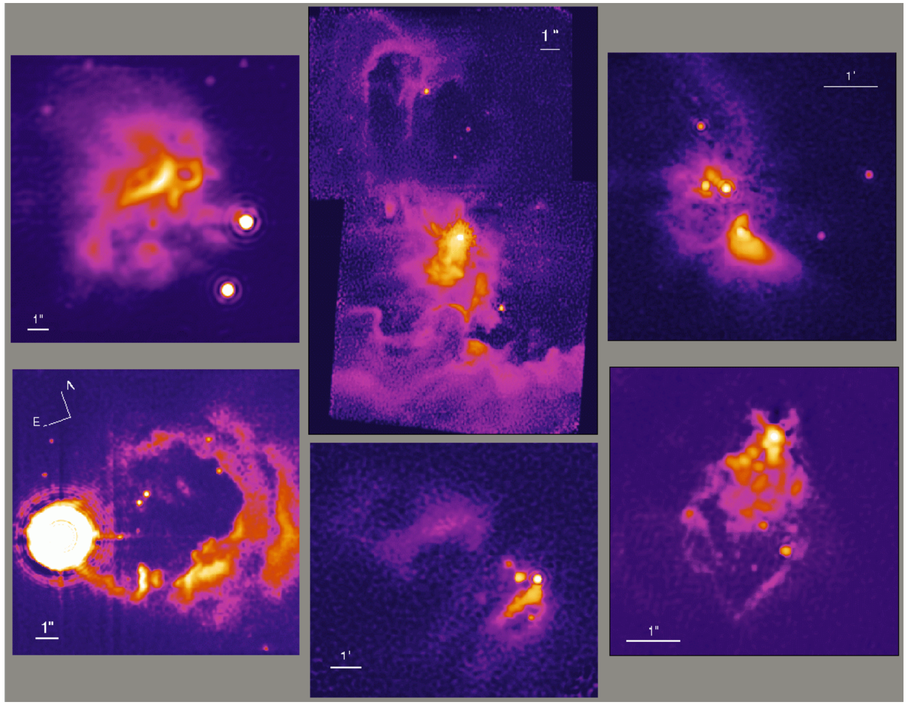
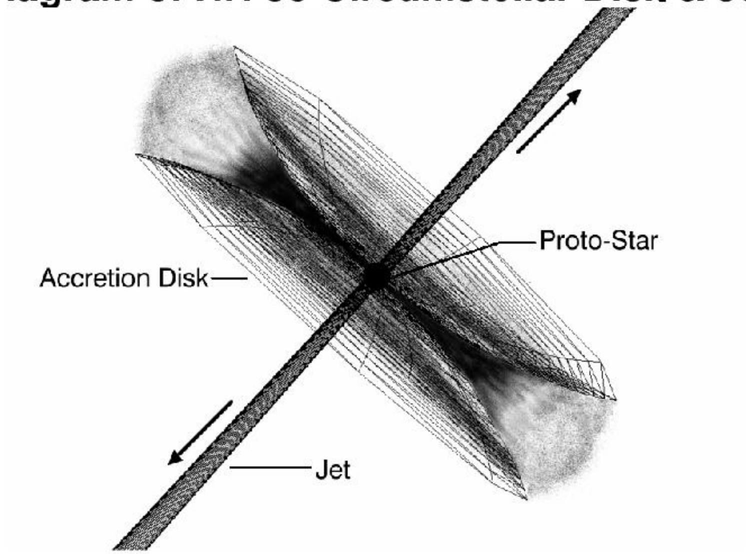
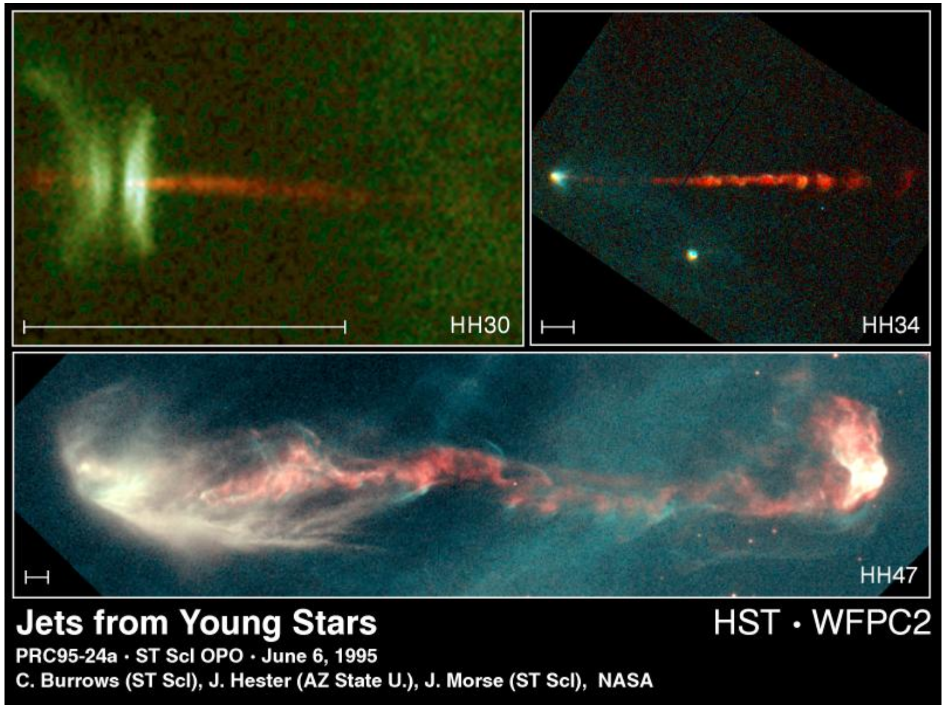


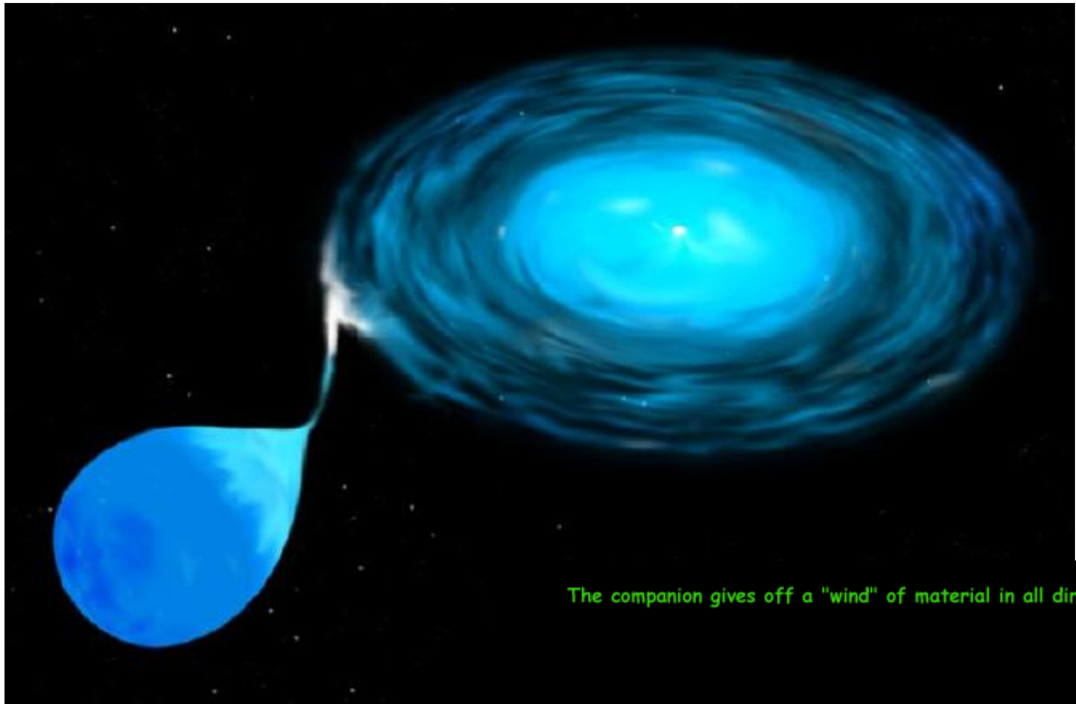
Diagram of HH 30 Circumstellar Disk & Jet

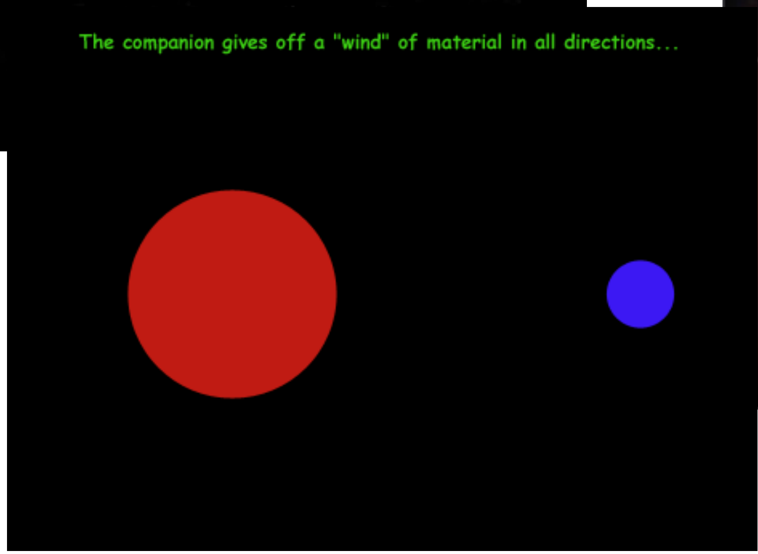




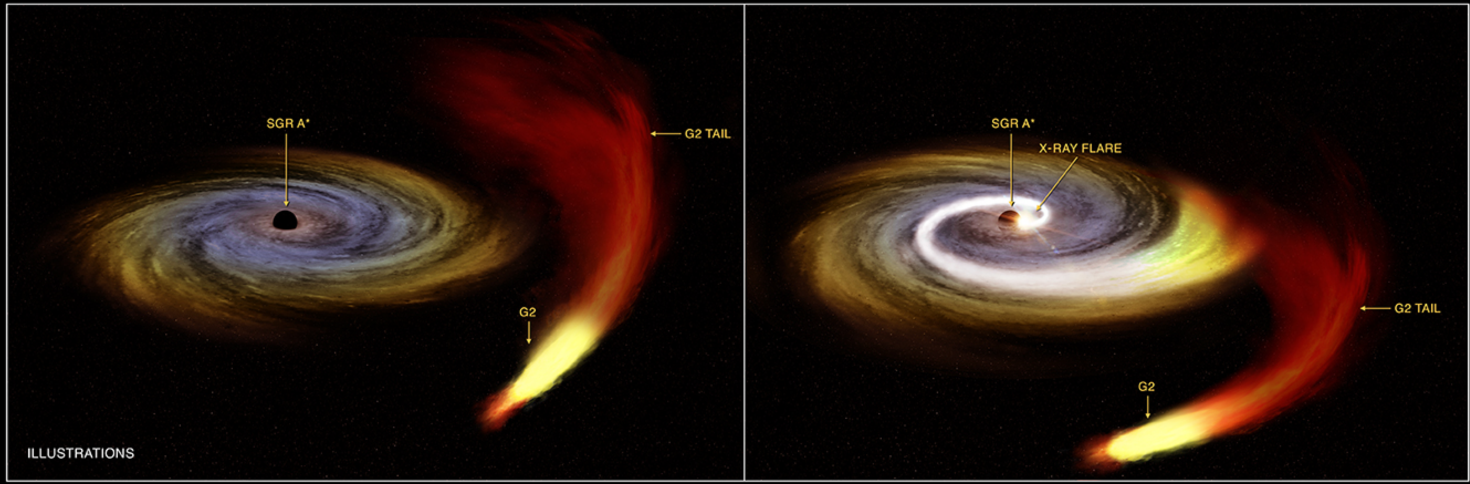
Compact stars

- White dwarfs, neutron stars, black holes





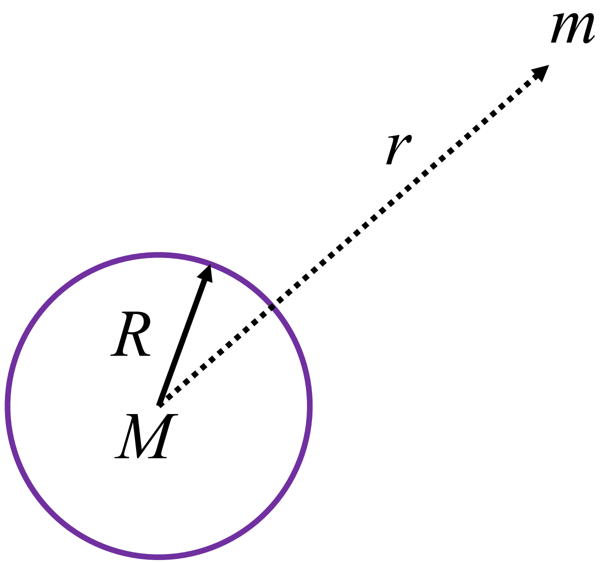
ACTIVE GALAXIES
Zooming In On A Galaxy With Jets
The long view of an active galaxy is dominated by lobes of radio emission caused by highly focused twin jets of matter streaming out from the galaxy nucleus.
Closer in, a torus of dust and gas can be seen, orbiting outside a flatter disk of swirling gas.
In an extreme close-up, the black hole in the center is surrounded by a flat accretion disk of rapidly orbiting material. The jets are emitted at right angles from the plane of the disk, driven by physics still not well understood.
http://glast.sonoma.edu
What we see depends on how we view it ...
An active galaxy is one in which a tremendous amount of energy is emitted from the nucleus. Active galaxies take many forms; some have exquisitely bright nuclei pouring forth high-energy photons, some have high-energy nuclei but appear to be surrounded by a more-or-less "normal" galaxy, while some have long, narrow jets or beams of matter streaming out from the center. Displayed here is an illustration of an active galaxy that has jets. The nucleus of this galaxy contains a supermassive black hole - the engine that powers the phenomena we see. Following its launch, the Gamma-ray Large Area Space Telescope (GLAST) will see thousands of these types of active galaxies.
All the images are artist's conceptions unless otherwise noted.
Different Angles On A Galaxy With Jets
Viewing down the jet
When we are looking down the jets, the emission is dominated by high-energy photons such as x-rays and gamma rays, In this case the active galaxy is called a blazar.
This observation of the blazar 3C279 shows gamma rays streaming from the vicinity of the central black hole. The fainter object above and to the right of 3C279 is another active galaxy, a quasar called 3C273.
Image credit: EGRET team, Compton Gamma Ray Observatory, NASA
Viewing at an angle to the jet
When seen from an angle, the linear jets are clear, and features near the galactic nucleus are more easily seen. Gamma rays are not detected, although the central source is still bright in x-rays and lower energies down to radio.
This observation of Centaurus A - a nearby active galaxy - is from Chandra, NASA's orbiting x-ray observatory. It shows x-rays from one of the jets, diffuse gas in the galaxy, and numerous point-sources near the galactic center.
Image credit: NASA/SAO/R.Kraft et al.
Viewing at 90° from the jet
When seen from the side, the relatively weak emission from the lobes becomes apparent. The jets powered by the black hole travel hundreds of thousands of light-years before billowing into huge clouds of radio-wave emitting gas.
This observation from the Very Large Array maps the radio emission from the lobes of matter in the active galaxy Cygnus A. The central region of the galaxy can be seen as just a dot, while the long jets transform into ethereal clouds over 300,000 light years from the central black hole.
Image credit NRAO/AUI
Definitions
Accretion Disk: The flattened disk of matter swirling just outside the black hole.
Active Galaxy: A galaxy with an unusually large amount of energy emitted from the nucleus.
Black Hole: An object so small and dense that the escape velocity is faster than the speed of light. In an active galaxy, the central black hole may have millions or even billions of times the Sun's mass.
Blazar: A quasar that one is viewing directly down the jet axis.
Jet: A thin, highly focused beam of matter and energy emitted from the nuclei of some active galaxies. Jets can be hundreds of thousands of light years long.
Nucleus: The central region of a galaxy.
Quasar: An active galaxy so distant it appears star-like.
Radio Lobe: A large radio wave-emitting cloud of matter located at the ends of the jets in some active galaxies, formed when the matter from the jet is slowed by intergalactic material.
Torus: A doughnut shaped object. Gas and dust outside the accretion disk in an active galaxy orbit the central black hole in a torus shaped region.
GLAST
This poster is funded by GLAST, the Gamma-ray Large Area Space Telescope, an international scientific collaboration with funding from NASA, the U.S. Department of Energy and agencies in France, Germany, Italy, Japan and Sweden
Art design by Aurore Simonnet. Text by Phil Plait.



Sgr A*

Accretion as a source of energy

- Gravitational potential energy release for an object with mass M and with radius R by accretion of a test particle with mass m



$$\left.\begin{array}{l} E_r = -\frac{GMm}{r} \\ E_R = -\frac{GMm}{R} \end{array}\right\} \Delta E = Er - E_p = -\frac{GMm}{r} + \frac{GMm}{R}$$

$$\Longrightarrow E_{acc} = \frac{GMm}{R} \text{ for } r \gg R$$

- ***M/R is the compactness of the accretor***
  - ***The more compact, the more energy can be released***

Energy in accretion

Object	Radius *R* (km)	
Nuclear fusion	- -	$0.007\ mc^2$
White dwarf	7×10^3	$10^{-4}\ mc^2$
Neutron star	10	$0.15\ mc^2$

Accretion luminosity

The accretion luminosity is given by

$$L_{acc} = \frac{dE_{acc}}{dt} = \frac{GM}{R}\frac{dm}{dt} \Rightarrow L_{acc} = \frac{GM\dot{m}}{R}$$

With M and R the mass and radius of the accreting star and $\dot{m}$ the *accretion rate*

Luminosity of the Sun: $L = 4 \times 10^{33}$ erg/s

Luminosity of an accreting white dwarf: $L = 10^{33} - 10^{34}$ erg/s

Luminosity of an accreting neutron star: $L = 10^{36} - 10^{38}$ erg/s

Accretion luminosity of a BH

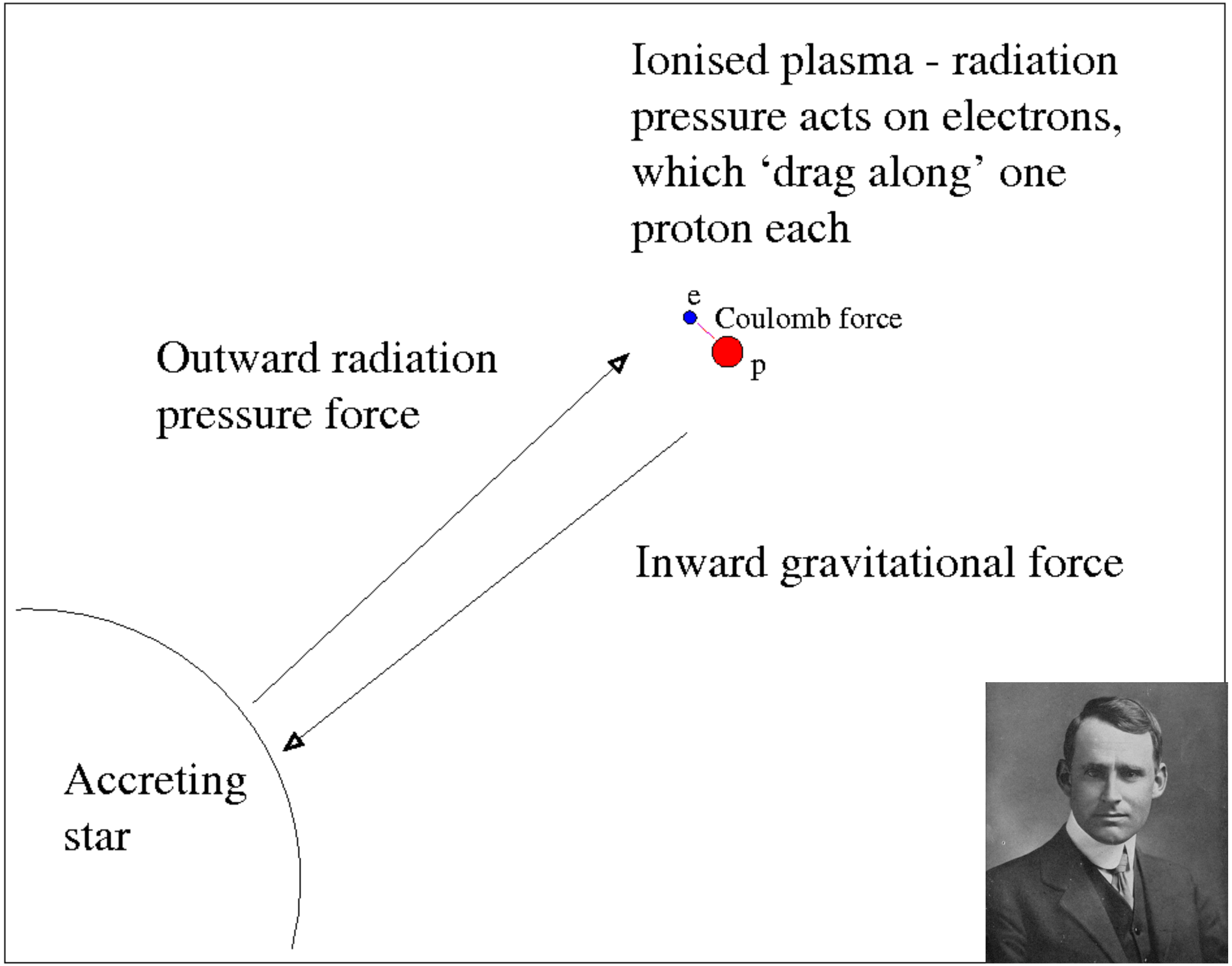
- The accretion luminosity equation assumes that all potential energy is released on impact on the star surface.
- Black holes do not have a surface and all mater will pass through the event horizon before all possible potential energy has been emitted away.
- For a black hole we can write

$$L_{acc} = \varepsilon \times L_{acc} = \varepsilon \frac{GM\dot{m}}{R_*} = 2\eta \frac{GM\dot{m}}{R_*} \Longrightarrow \boldsymbol{L_{acc,b} = \eta\, \dot{m} c^2}$$

since for a black hole $R_* = \frac{2GM}{c^2}$

- With η the efficiency factor which is ~0.1 → only ~10% of the rest mass of the accreted matter is transferred into radiation! For a neutron star $\eta \sim 0.15$ and thus a neutron star can be more efficient than a black hole!

The Eddington limit I



Arthur Eddington

The Eddington limit II

$$F_{rad} = \frac{L\sigma_T}{4\pi r^2 c} \quad \text{and} \quad F_{grav} = \frac{GM(m_p + m_e)}{r^2} \approx \frac{GMm_p}{r^2}$$

$$F_{rad} = F_{grav} \rightarrow L_{Edd} = \frac{4\pi GMm_p c}{\sigma_T} = 1.3 \times 10^{38} (M / M_{Sun}) \text{ erg/s}$$

F_{rad} = photon pressure, F_{grav} = gravtitational force, σ_T = Thomson cross section

c = speed of light, G = gravitational constant, M = mass of star, m_p = proton mass,

m_e = electron mass, r = distance from centre of the star, L = luminosity of source.

Assumptions made

Accretion flow steady + spherically symmetric: e.g. in supernovae, L_{Edd} can be exceeded by many orders of magnitude.

Material fully ionized and only hydrogen: not fully ionized heavy elements cause problems and may reduce ionized fraction (bound electrons do not scatter photons)

Reasonable assumption for most X-ray binary system!

Eddington accretion rate

- The maximum accretion rate an accreting object can have (for pure ionized hydrogen)

$$L_{acc} = L_{Edd} \rightarrow \frac{GM\dot{M}_{Edd}}{R} = \frac{4\pi GMm_p c}{\sigma_T} \rightarrow$$

$$\dot{M}_{Edd} = \frac{4\pi m_p cR}{\sigma_T}$$

Practical use of Eddington limit

- Maximum luminosity an object can have
  - Sometimes super-Eddington luminosities
- If one knows that the source is at L_{Edd} then the distance *d* towards the source can be obtained if flux *f* is measured from the source since

$$f = \frac{L}{4\pi d^2}$$

Radiation due to accretion

- Define a black-body radiation temperature of
(using the Stefan-Boltzmann law; 1879 and 1884)

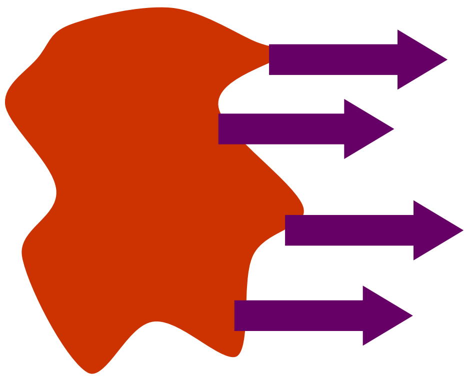
$$T_b = \left(\frac{L_{acc}}{4\pi R^2 \sigma} \right)^{\frac{1}{4}}$$

- The thermal temperature in the accreted matter is
(assuming all potential energy is turned into thermal energy)

$$\frac{GM(m_p + m_e)}{R} \approx \frac{GMm_p}{R} = 2 \times \tfrac{3}{2} kT_{th} \Rightarrow T_{th} = \frac{GMm_p}{3kR}$$

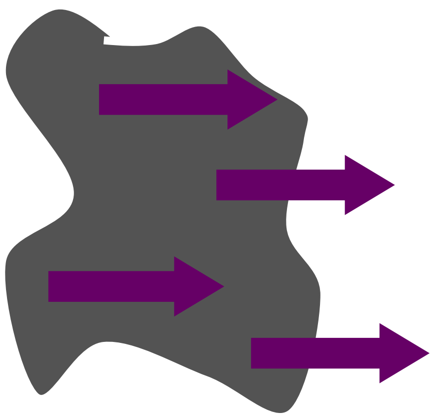
Accretion temperatures

Optically thick



$$T_{rad} \sim T_b$$

Optically thin

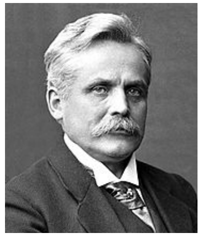


$$T_{rad} \sim T_{th}$$

Accretion energies

- In general, $T_b \leq T_{rad} \leq T_{th}$
- For a neutron star, $T_{th} \sim 5 \times 10^{11}$ K and T_b comes from assuming
  - Accretion close to the Eddington limit, $L \sim 10^{38}$ erg/s
  - $R \sim 10$ km
  - This results in $T_{b,Edd} = \left(\dfrac{10^{38}}{4\pi \times 10^{12} \times 6 \times 10^{-5}} \right)^{\frac{1}{4}} \approx 10^{7}$ K
  - If accretion is optically thick then this is the temperature of the emitted radiation

- Wien displacement law (1893) states

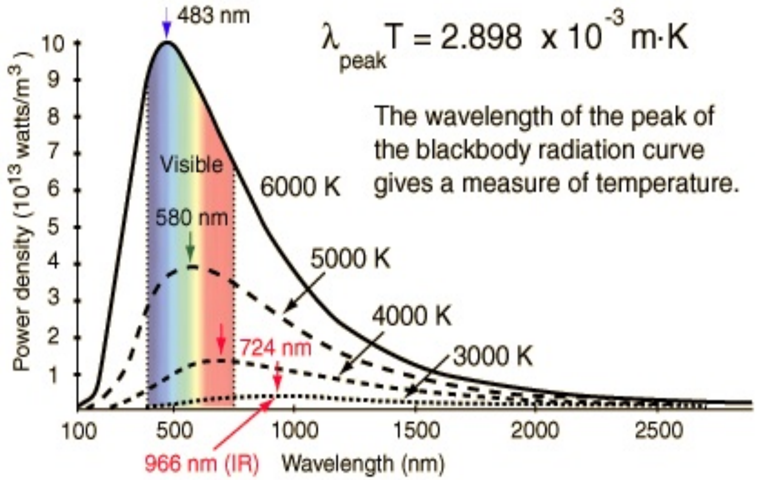


Wilhelm Wien

$$\lambda_{max} T = \text{constant} = 3 \times 10^7$$

(T in Kelvin, λ_{max} Angstroms)

$$\Rightarrow \upsilon_{max} = 6 \times 10^{10} T \text{ Hz}$$



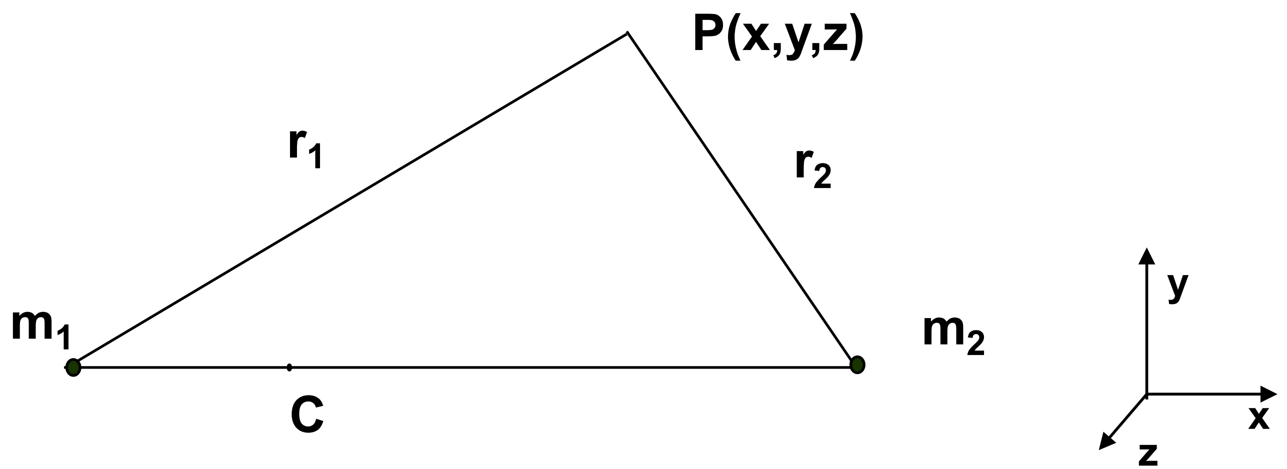
- For $T \sim 10^7$ K this gives $\nu \sim 10^{18}$ Hz ~ 3 keV
- Accreting neutron star will radiate in the X-rays!
  - E.g., as neutron-star X-ray binaries
  - Similarly: black-hole X-ray binaries
  - Accreting white dwarf are mainly visible in the optical and the UV

Different forms of accretion

- Accretion from the ISM
  - Too little material in the ISM to produce significant radiation
  - Accreting from dense molecular clouds
  - Steady, spherically symmetric accretion
    - Bondi accretion (1952)
- Accretion from a companion star
  - Matter transfer through Roche-Lobe overflow
    - Most relevant for low-mass X-ray binaries
  - Matter transfer through a stellar wind
    - Most relevant for high-mass X-ray binaries

Hermann Bondi

Potential in close binaries



- C: centre of mass
  - reference frame centred on more massive star m_1, with distance m_1 to m_2 is 1
  - rotating with angular velocity ω, same as binary system
  - circular orbit
- Potential at P(x,y,z) is then

$$\Phi = -\frac{Gm_1}{r_1} - \frac{Gm_2}{r_2} - \tfrac{1}{2}\omega^2\left[\left(x - \frac{m_2}{m_1+m_2}\right)^2 + y^2\right]$$

$$r_1^2 = x^2 + y^2 + z^2 \quad \text{and} \quad r_2^2 = (x-1)^2 + y^2 + z^2$$

1619

Johannes Kepler

$$\Phi = -\frac{Gm_1}{r_1} - \frac{Gm_2}{r_2} - \tfrac{1}{2}\omega^2\left[\left(x - \frac{m_2}{m_1+m_2}\right)^2 + y^2\right]$$

Kepler's third law and normalize to a = 1

$$\rightarrow \omega^2 = \left(\frac{2\pi}{P}\right)^2 = \frac{G(m_1+m_2)}{a^3} \quad \rightarrow \omega^2 = G(m_1+m_2)$$

Then we can define $\Phi_n = \dfrac{-2\Phi}{G(m_1+m_2)}$

- the normalized gravitational potential
- and the mass ratio

$$q = \frac{m_2}{m_1} \qquad (0 \le q \le 1)$$

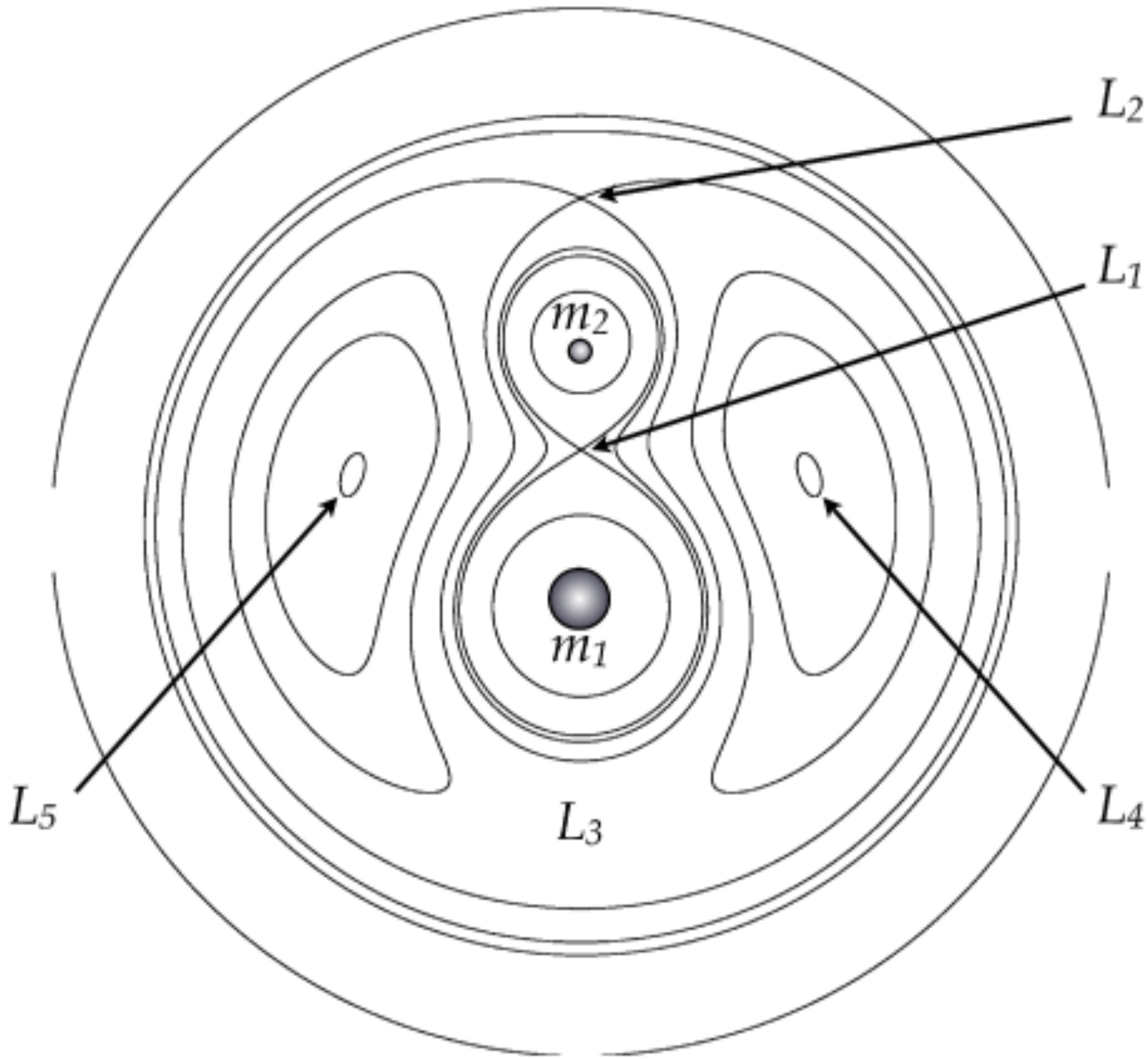
$$\Rightarrow \Phi_n = \frac{2}{(1+q)}\frac{1}{r_1} + \frac{2q}{(1+q)}\frac{1}{r_2} + \left(x - \frac{q}{(1+q)}\right)^2 + y^2$$

Equipotential surfaces

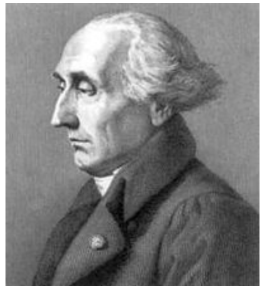
$$\Phi_n = \frac{2}{(1+q)}\frac{1}{r_1} + \frac{2q}{(1+q)}\frac{1}{r_2} + \left(x - \frac{q}{(1+q)}\right)^2 + y^2$$

- The total potential may then be calculated at any point P with respect to the binary system
- Surfaces of constant potential may be found
  - shape of stars is given by these equipotential surfaces
- Deformation from spherical depends on size relative to semi major axis, a, and mass ratio q

- Equipotential surfaces
  - Lagrange points L_1, L_2, L_3, and L_4, L_5

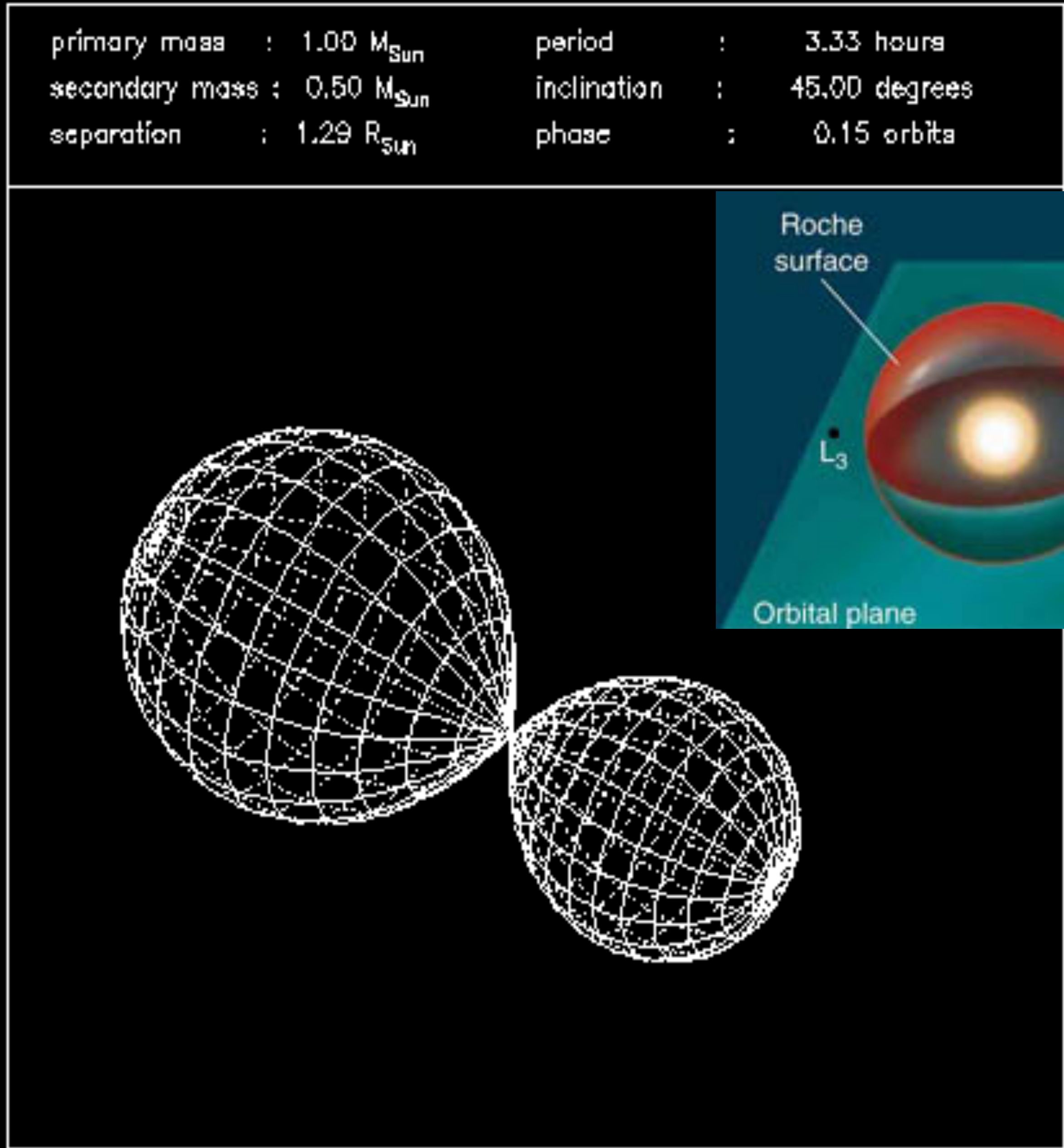


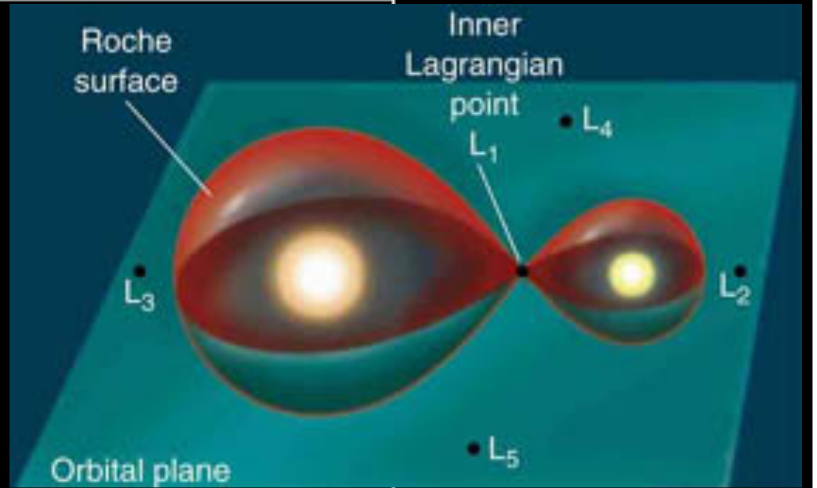
Lagrange points



Joseph-Louis Lagrange

- Points where $\nabla \Phi_n = 0$
- L_1 - *Inner Lagrange Point*
  - in between two stars
  - matter can flow freely from one star to other
  - mass exchange
- L_2 - on opposite side of secondary
  - matter can most easily leave system
- L_3 - on opposite side of primary
- L_4, L_5 - in lobes perpendicular to line joining binary
- Roche-lobes: surfaces which just touch at L_1

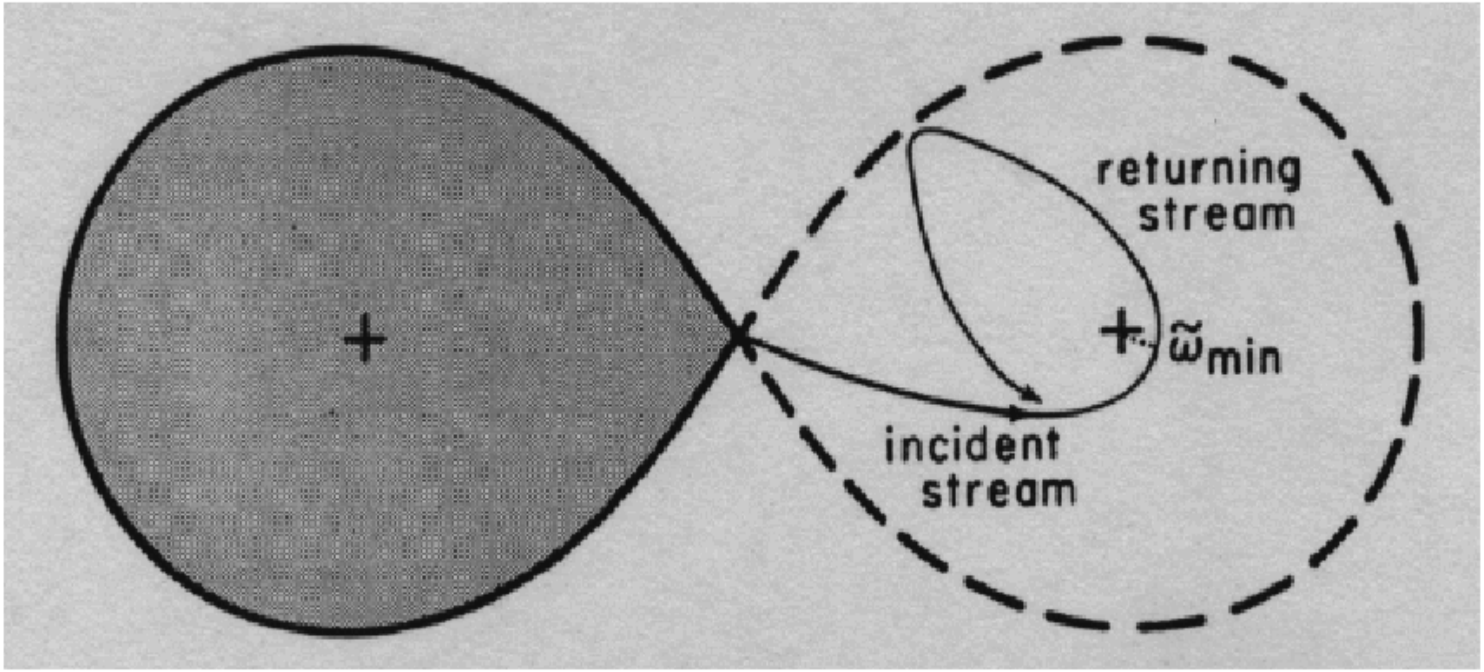




Édouard Roche

Roche lobes in three dimensions

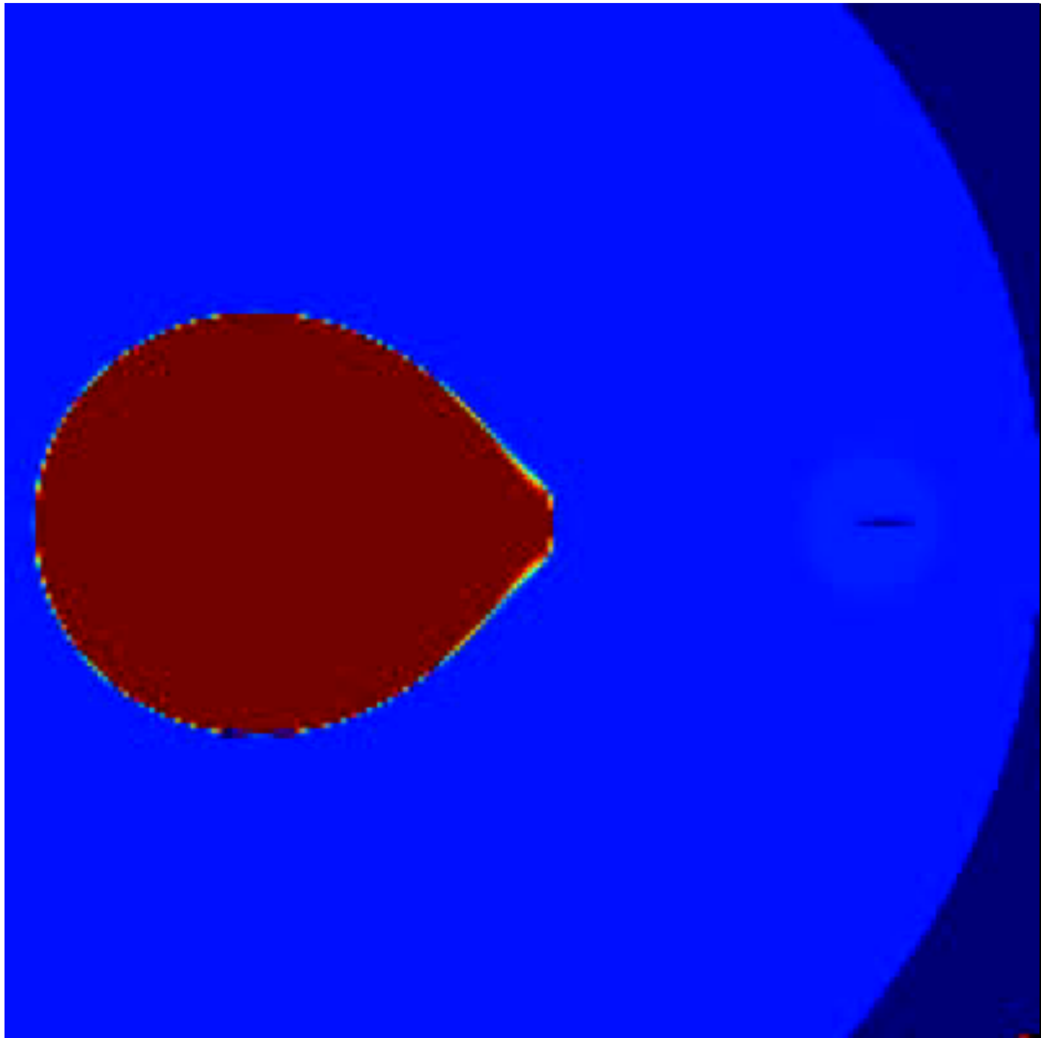
Formation of an accretion disk



- Material transferred has high angular momentum so must loose it before accreting => disk forms
- Gas loses angular momentum through collisions, shocks, and viscosity: kinetic energy converted into heat and radiated → not fully understood!

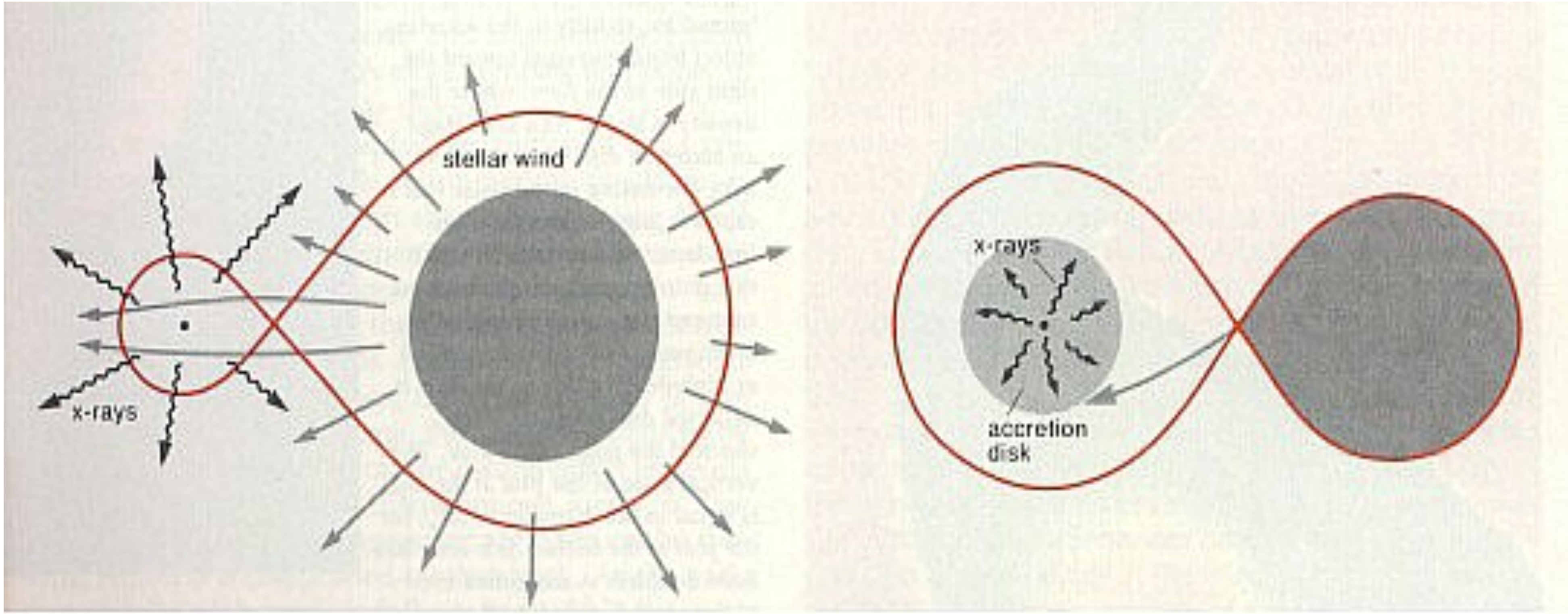
Circularization radius R_{circ}

- When leaving L_1 gas has a lot of angular momentum
- Difficult to get rid off
  - Remember: angular moment is a conserved quantity
- Gas will orbit in lowest energy orbit
  - Circular orbits
  - Kepler orbits
- Circularization radius R_{circ} = radius of the Kepler orbit with the same angular moment



http://wonka.physics.ncsu.edu/~blondin/Movies/lmxb.mpg
http://wonka.physics.ncsu.edu/~blondin/Movies/lmxb2d.mpg

Wind accretion

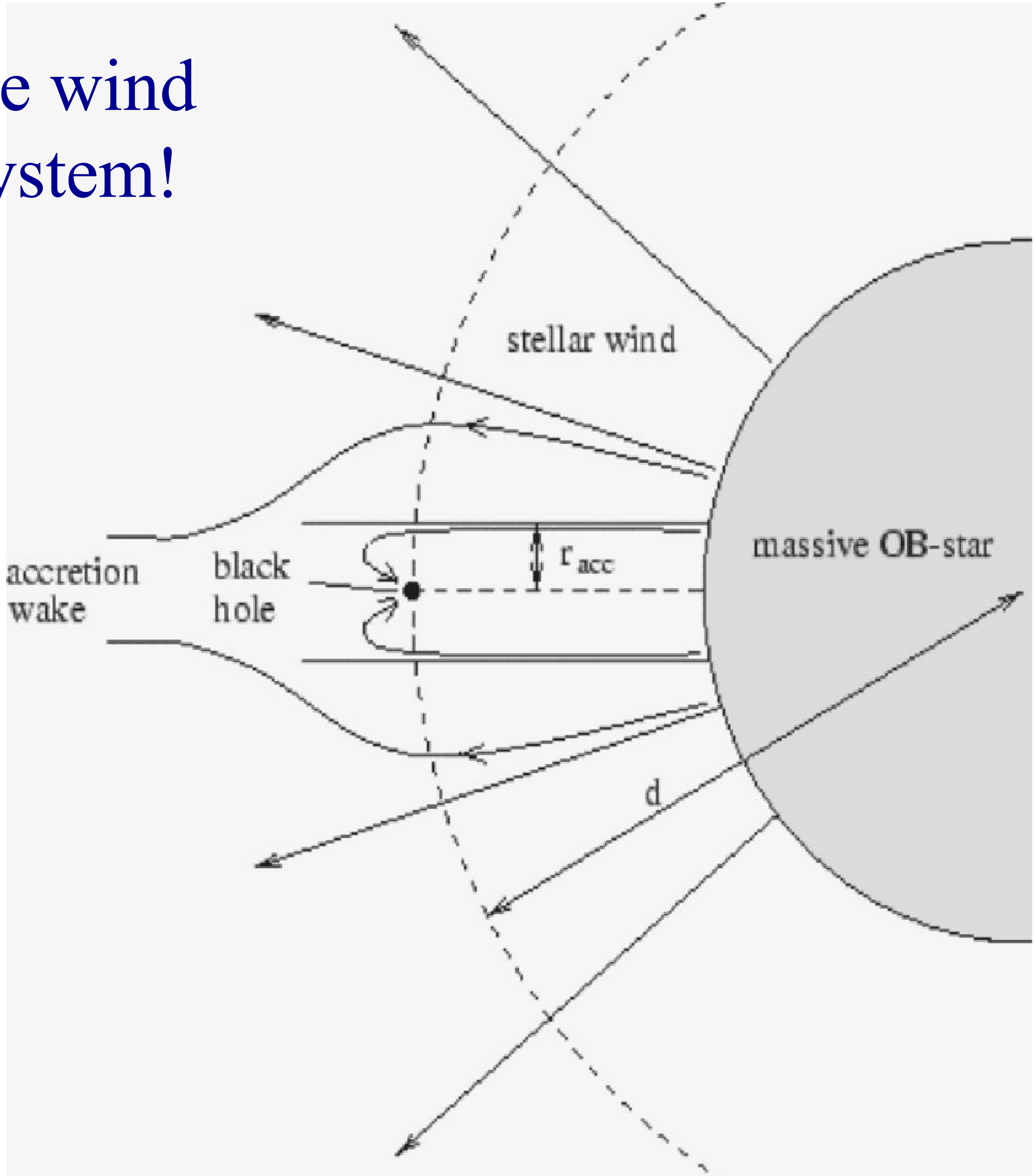


Some stars (e.g., giants and supergiants, early-type stars) have intense and highly supersonic winds. Mass loss rates can be up to 10^{-6}-10^{-4} solar masses per year.

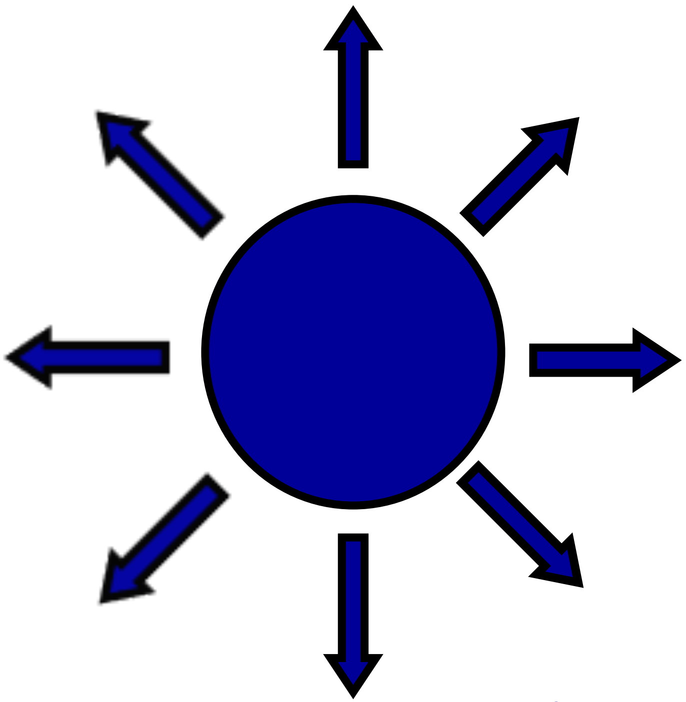
Most matter in the wind is lost from the system!

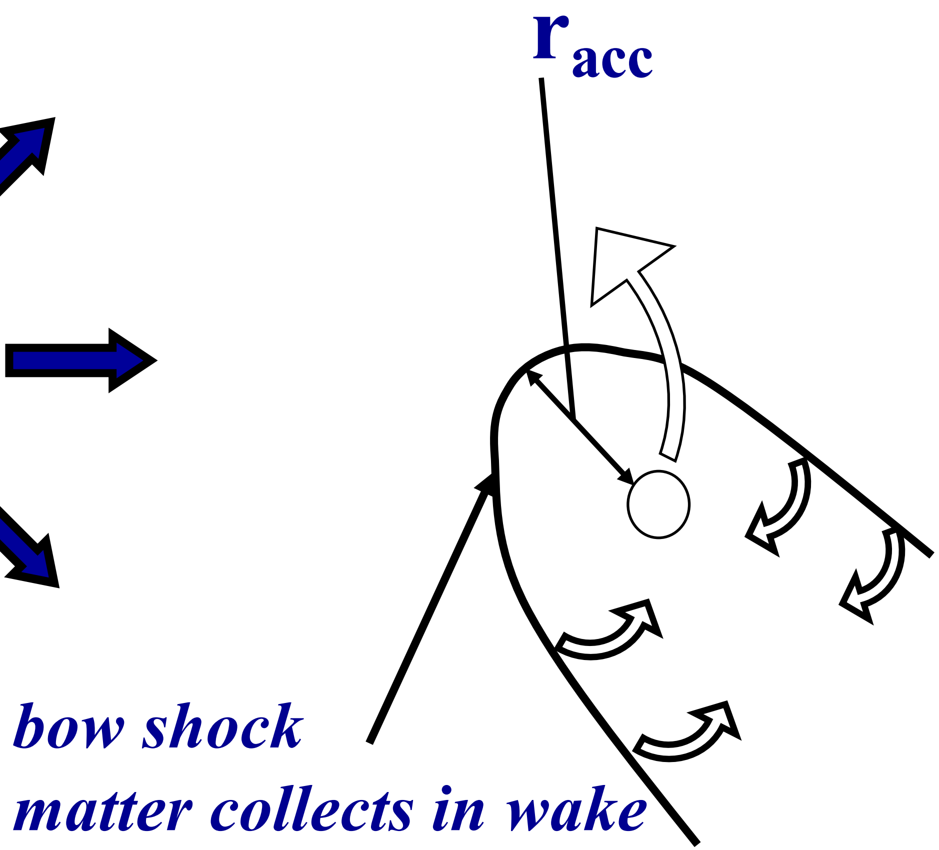
$$\frac{mv^2_{wind}}{2} \approx \frac{GMm}{r_{acc}} \Rightarrow$$

$$r_{acc} \approx \frac{2GM}{v^2_{wind}}$$

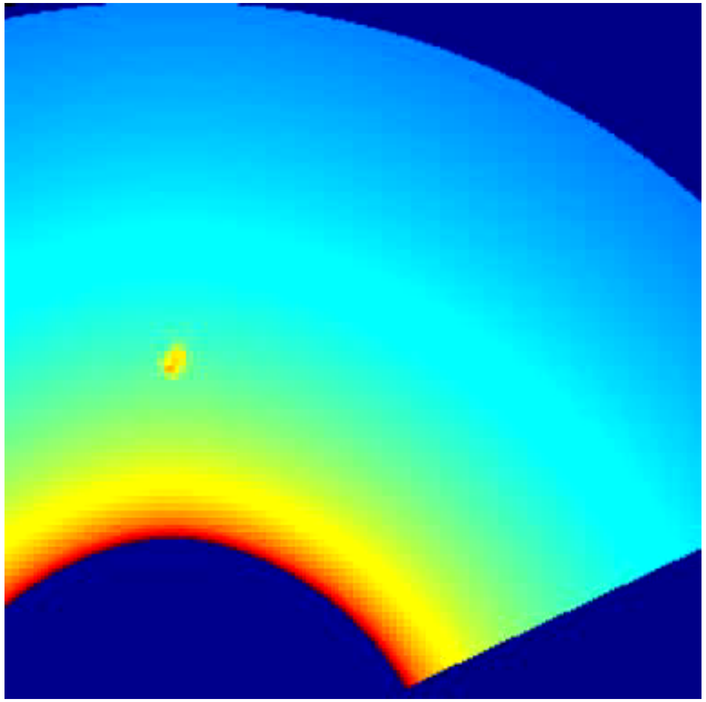


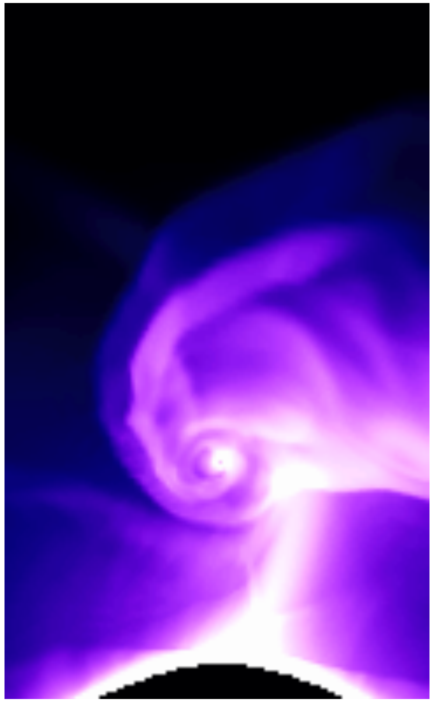
Compact star moves in binary





$$\frac{m(v^2_{wind} + v^2_{CS})}{2} \approx \frac{GMm}{r_{acc}} \Rightarrow r_{acc} \approx \frac{2GM}{v^2_{wind} + v^2_{CS}}$$





Simulation of wind accretion in HMXB

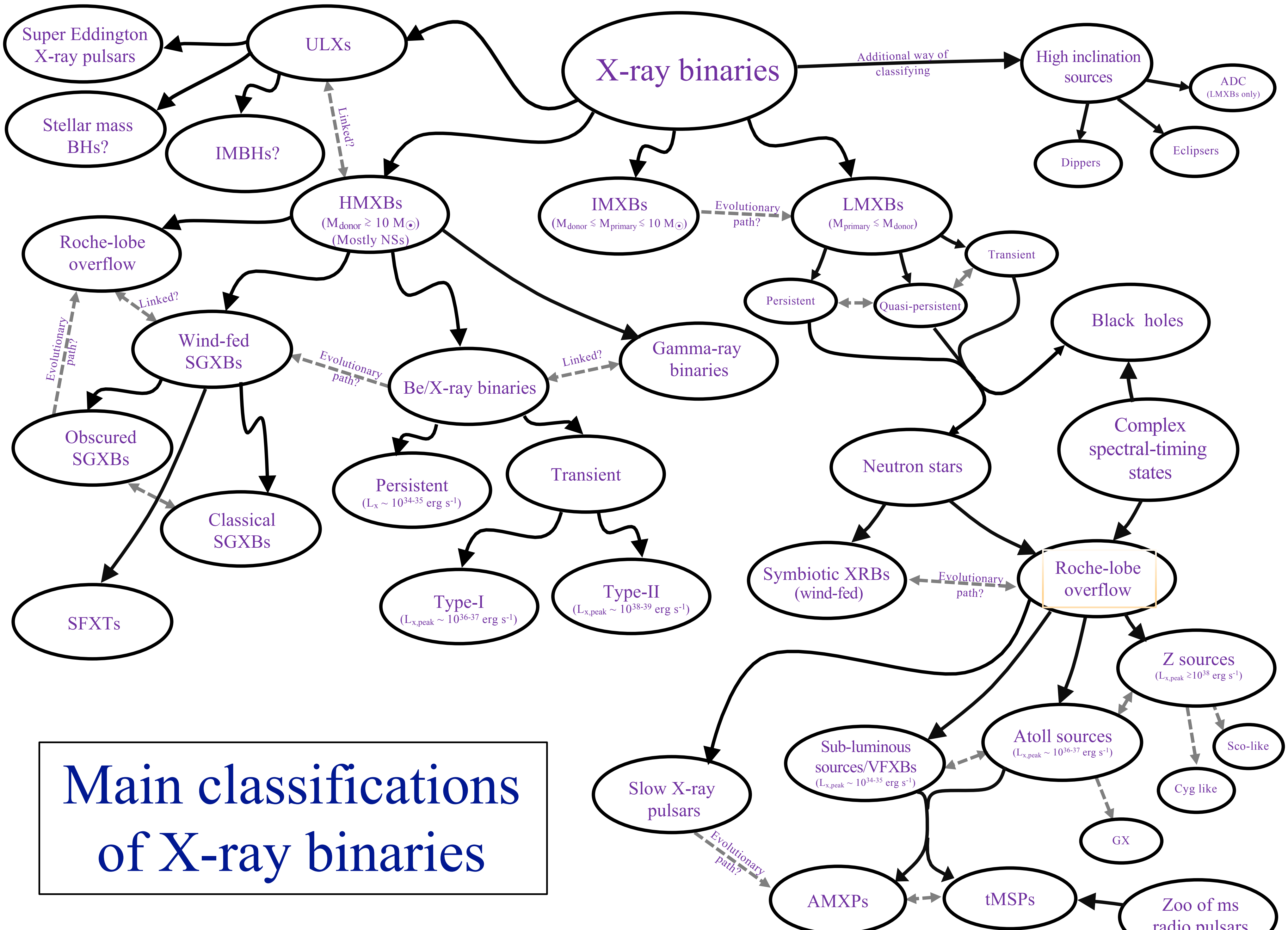
Partly Roche-lobe overflow

Blondin et al.

http://wonka.physics.ncsu.edu/~blondin/Movies/vela2d.mpg
http://csep10.phys.utk.edu/OJTA2dev/ojta/course2/binaries/accreting/blondinbinary.swf

X-ray binary classification

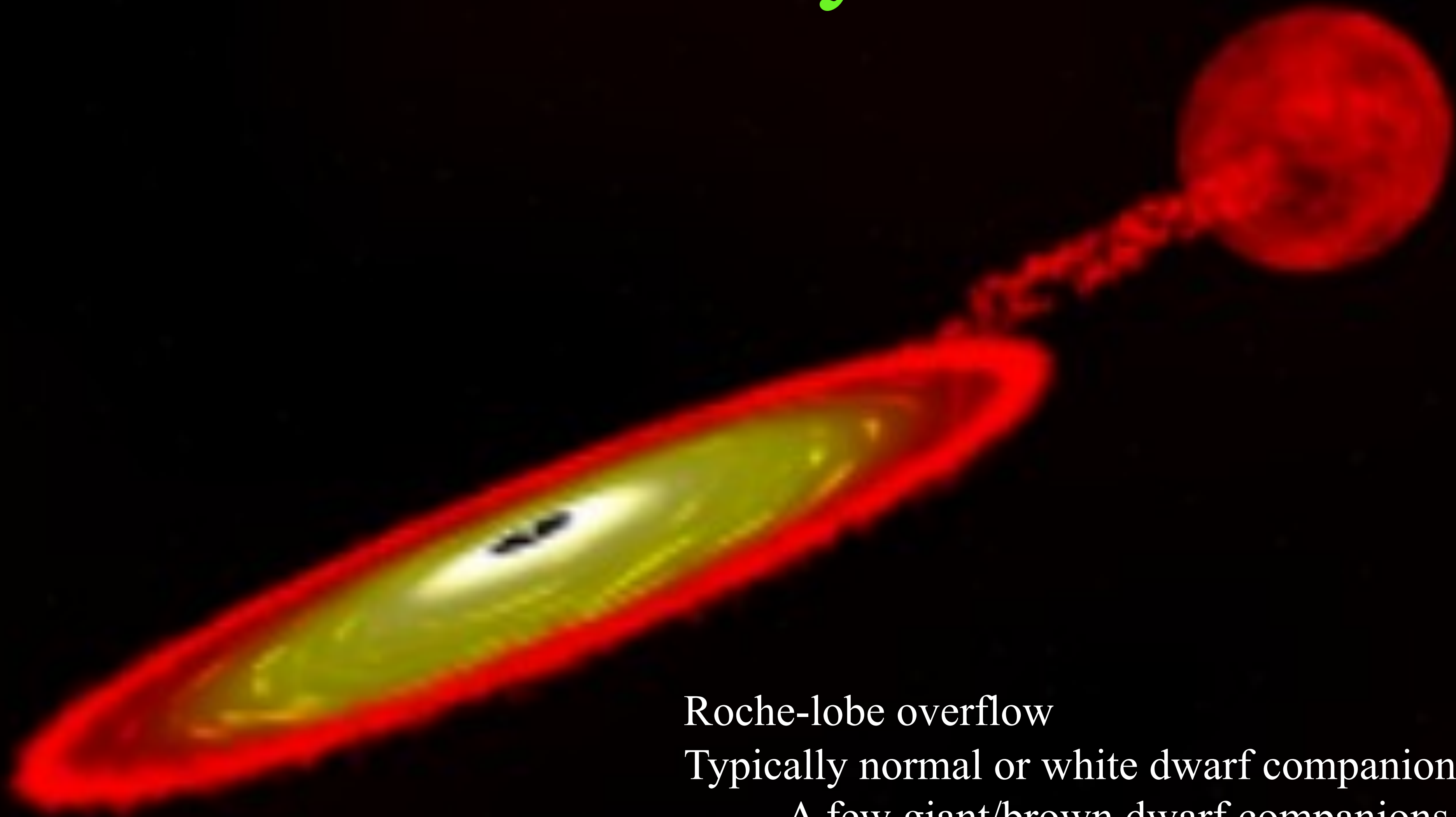
- Complex and variate ways of classifying X-ray binaries
  - Type of accretor (neutron star vs. black hole)
  - Type/mass of donor (high mass vs. low mass)
  - Persistent versus transient sources
  - Observed phenomena
- Often a hybrid way of classification is used combining different ways


Main classifications of X-ray binaries
X-ray binaries
ULXs
Super Eddington X-ray pulsars
Stellar mass BHs?
IMBHs?
Linked?
Additional way of classifying
High inclination sources
ADC (LMXBs only)
Dippers
Eclipsers
HMXBs ($M_{donor} \gtrsim 10\ M_\odot$) (Mostly NSs)
IMXBs ($M_{donor} \lesssim M_{primary} \lesssim 10\ M_\odot$)
Evolutionary path?
LMXBs ($M_{primary} \lesssim M_{donor}$)
Transient
Persistent
Quasi-persistent
Roche-lobe overflow
Linked?
Evolutionary path?
Wind-fed SGXBs
Evolutionary path?
Be/X-ray binaries
Linked?
Gamma-ray binaries
Obscured SGXBs
Classical SGXBs
SFXTs
Persistent ($L_x \sim 10^{34-35}$ erg s^{-1})
Transient
Type-I ($L_{x,peak} \sim 10^{36-37}$ erg s^{-1})
Type-II ($L_{x,peak} \sim 10^{38-39}$ erg s^{-1})
Black holes
Complex spectral-timing states
Neutron stars
Symbiotic XRBs (wind-fed)
Evolutionary path?
Roche-lobe overflow
Z sources ($L_{x,peak} \gtrsim 10^{38}$ erg s^{-1})
Sco-like
Cyg like
Atoll sources ($L_{x,peak} \sim 10^{36-37}$ erg s^{-1})
GX
Sub-luminous sources/VFXBs ($L_{x,peak} \sim 10^{34-35}$ erg s^{-1})
Slow X-ray pulsars
Evolutionary path?
AMXPs
tMSPs
Zoo of ms radio pulsars

Low- versus high-mass X-ray binaries

- Low-mass X-ray binaries
  - Traditional: companion has a mass of <1 solar mass
  - More accurate: $M_{companion} < M_{accretor}$
  - Mass transfer through Roche-lobe overflow
    - A handful of wind fed systems
- High-mass X-ray binaries
  - Traditional: $M_{companion} > 10\ M_{accretor}$
  - Mass transfer not through Roche-lobe overflow
    - Wind accretion
    - Accretion from circumstellar decretion disk

Low-mass X-ray binaries



Roche-lobe overflow

Typically normal or white dwarf companion

- A few giant/brown dwarf companions

Typically low magnetic field neutron star

- A few with strong magnetic fields

High-mass X-ray binary

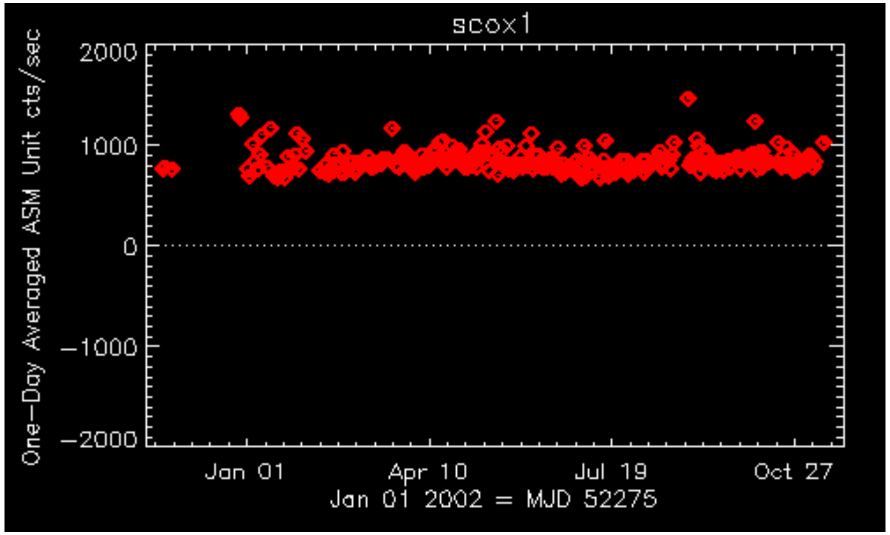
Accretion from a strong stellar wind from giant or supergiant donor
Typically a high magnetic field neutron star
Formation of small disk is possible
Some have mass transfer through Roche-lobe overflow
Be/X-ray binaries

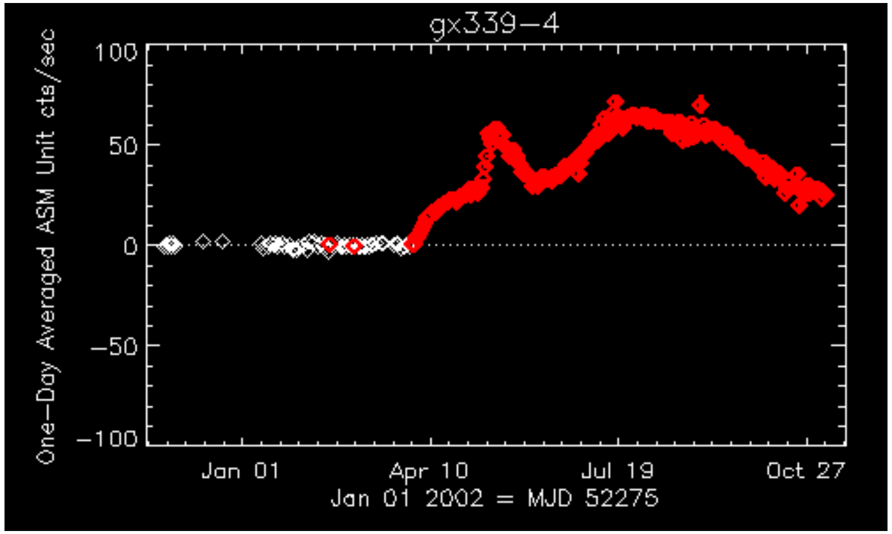
Intermediate-mass X-ray binaries?

- When $M_{companion} > M_{accretor} < 10$ solar masses
- Typically stellar wind is relatively weak
  - Very little X-rays due to accretion
  - Except possibly on the giant branch
    - But relatively massive stars thus short life span
- Roche-lobe mass transfer is unstable
  - Runaway accretion
  - Some do exist but they are rare
  - Some binary evolution models predict that many LMXBs descent from IMXBs

Persistent and transient X-ray binaries

- Most X-ray binaries are not always visible
- They are usually very dim → no or very little accretion of matter

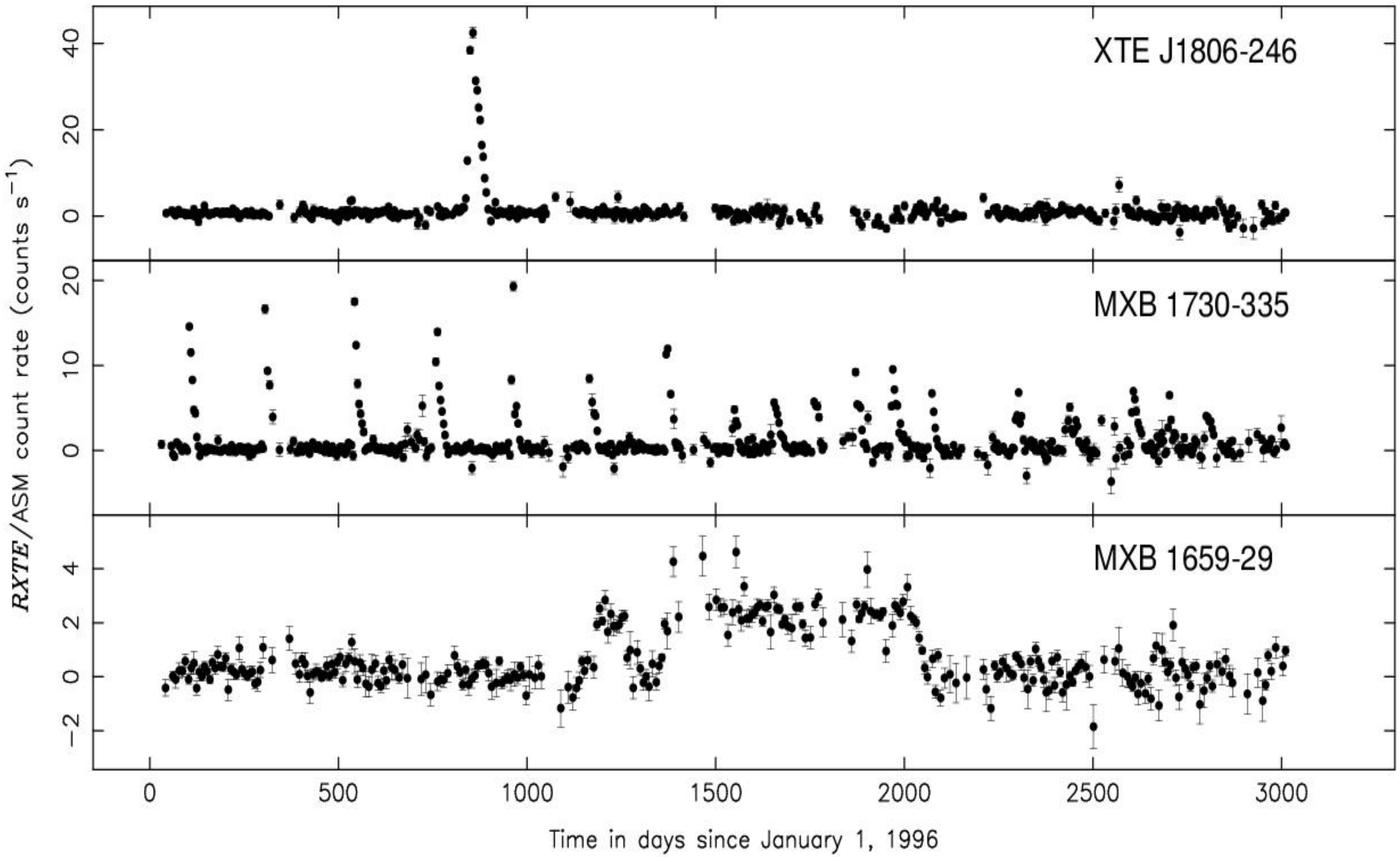




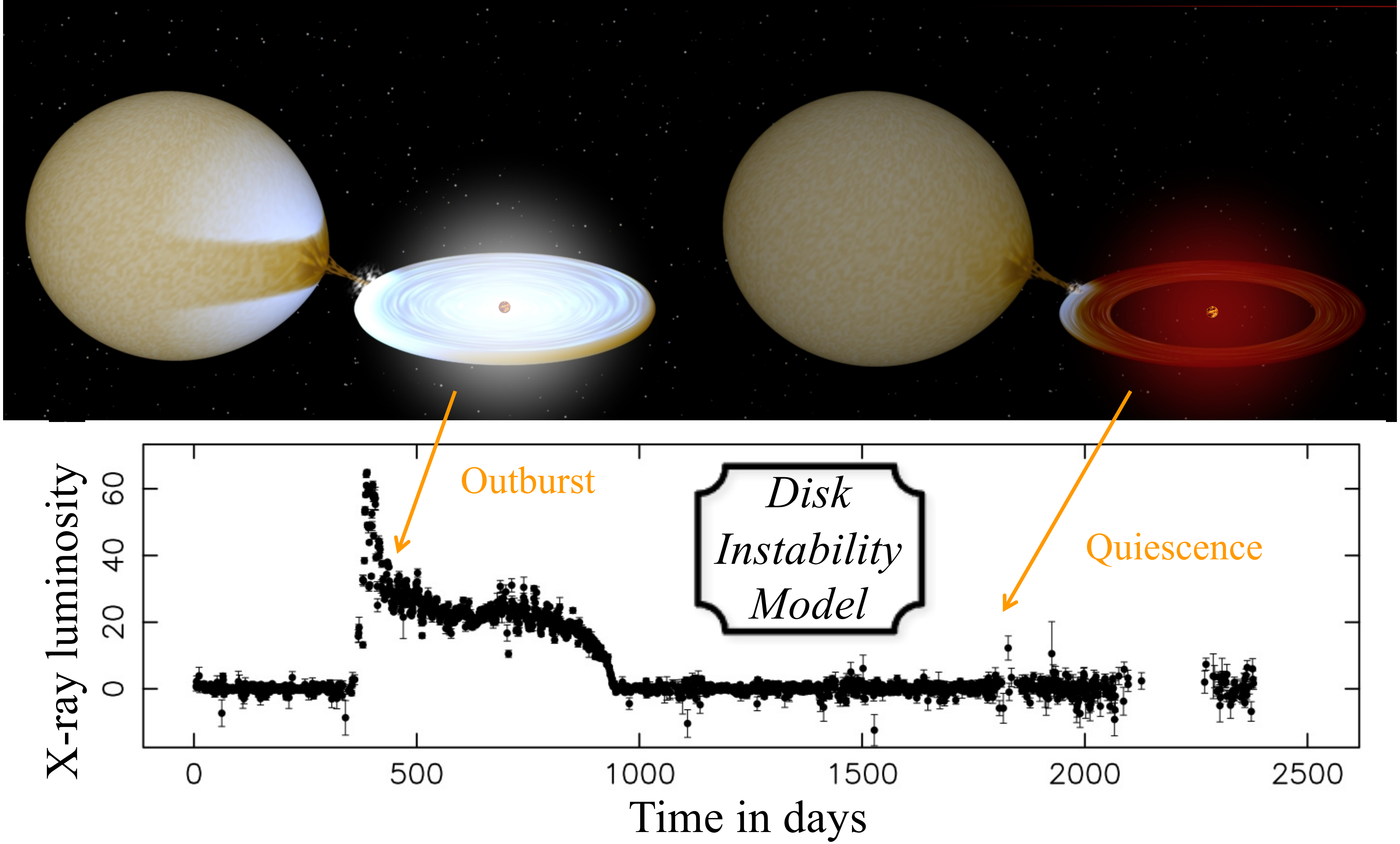
RXTE/ASM light curves

- They become occasionally very bright → huge (>10^{4-6}) increase in accretion rate
- During such ‘outbursts’ they behave in all aspects like the persistent sources
- Different models for the outburst depending on source type

Transient X-ray binaries



Transient low-mass X-ray binaries

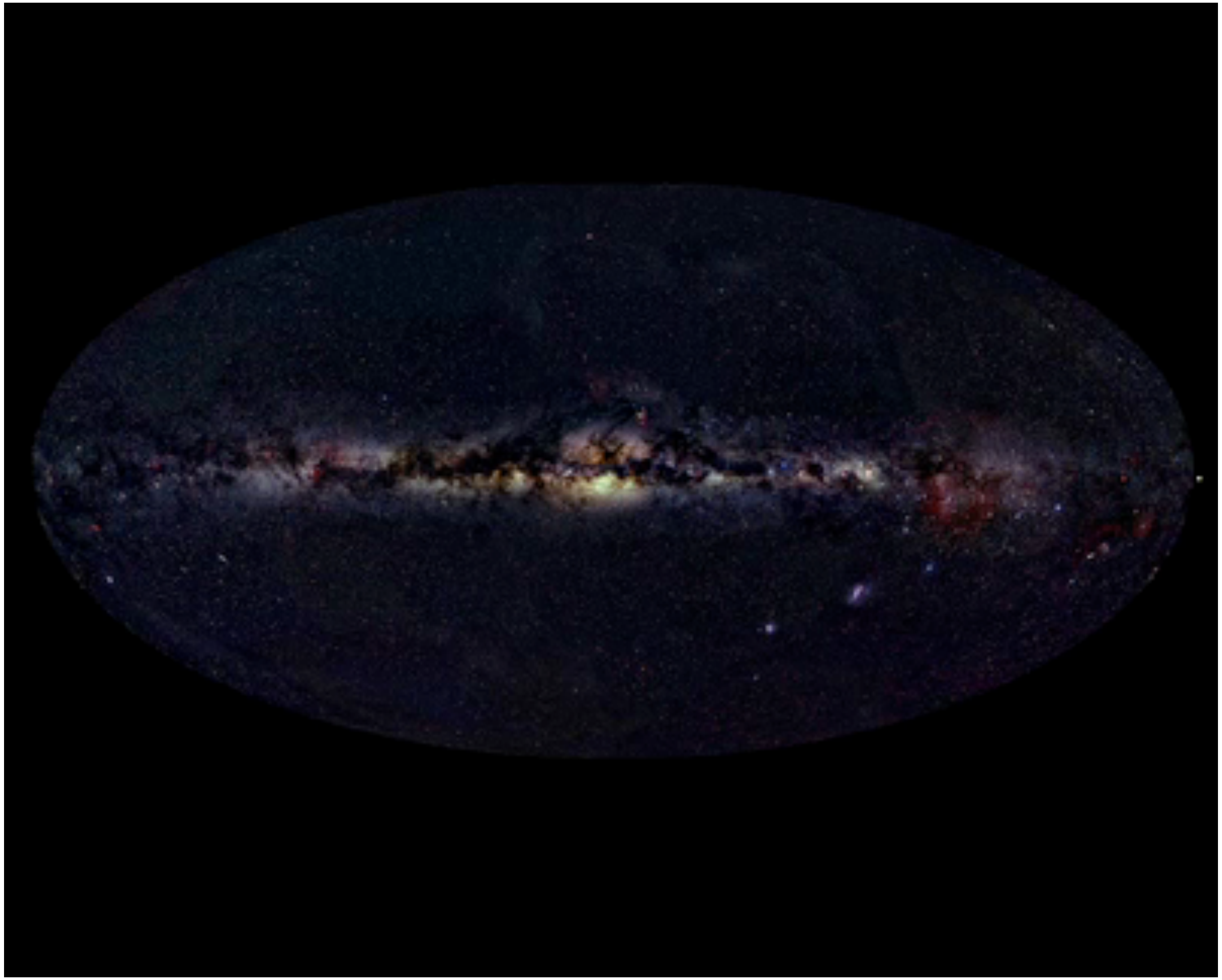


Movie of transient behavior

https://heasarc.gsfc.nasa.gov/docs/xte/Snazzy/Movies/xsky010400_mp.mov

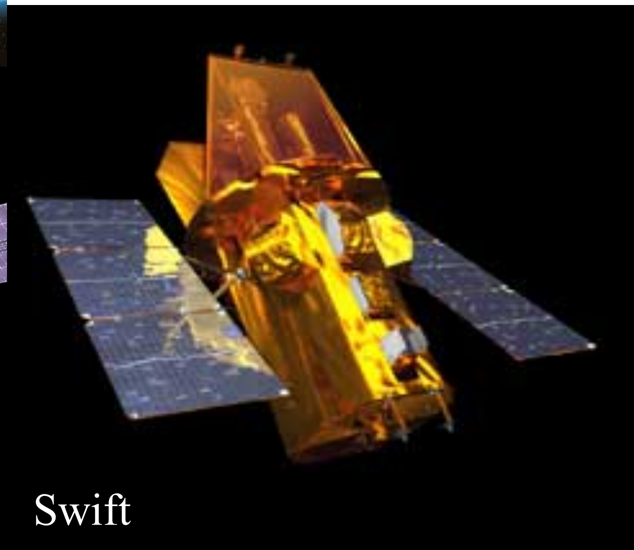
Movie of transient behavior

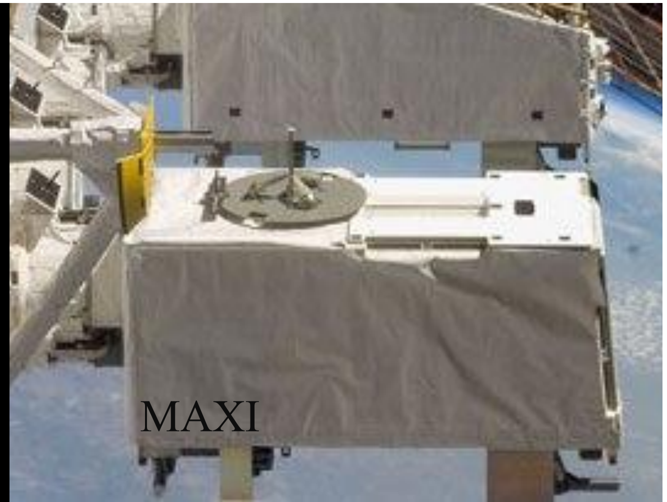
Kuulkers et al. 2007

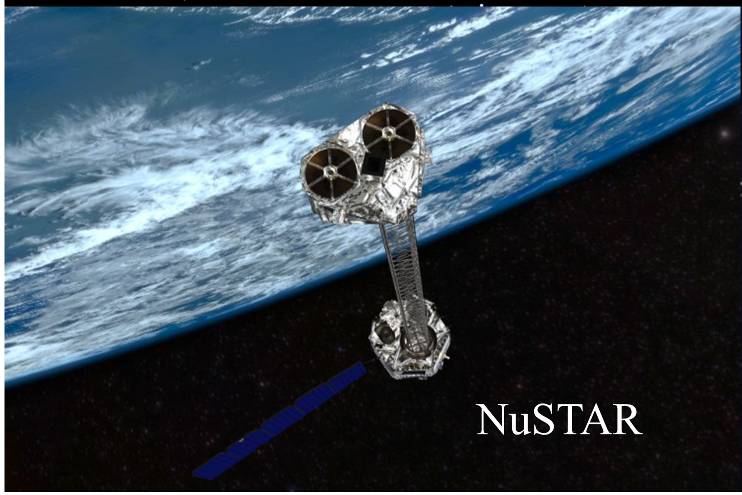


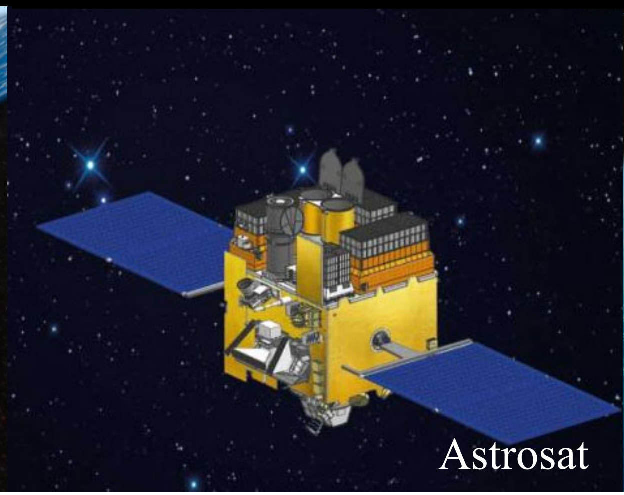
http://integral.esac.esa.int/BULGE/links/Movies.html

Current X-ray satellites



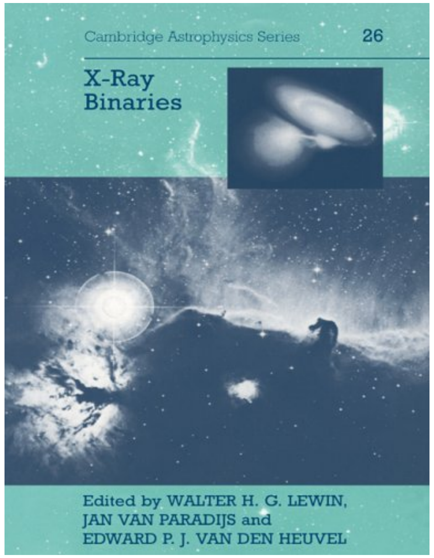






X-ray binary literature

- General X-ray binary information
  - Lewin, van Paradijs, & van den Heuvel "X-ray binaries", 1995
  - Lewin & van der Klis "Compact Stellar X-ray sources", 2010



Note: things can get quickly outdated!