1.3 Accretion power in astrophysics

Accretion power in astrophysics

The strong gravitational force of the compact object attracts matter from the companion

grav.energy ---> Accretion -----> radiation

The infalling matter have some angular momentum
(the secondary star is orbiting the compact object when the gas comes off the star, it, too will orbit the compact object)
and conservation of angular momentum prevents matter from falling directly into the black hole)

X-ray Binaries, Lewin, van Paradijs, and van den Heuvel, 1995, p. 420;
High energy astrophysics, M. Longair p.134.

Because of the friction, some of the particles rub up against each other.
The friction will heat up the gas
(dissipation of energy).

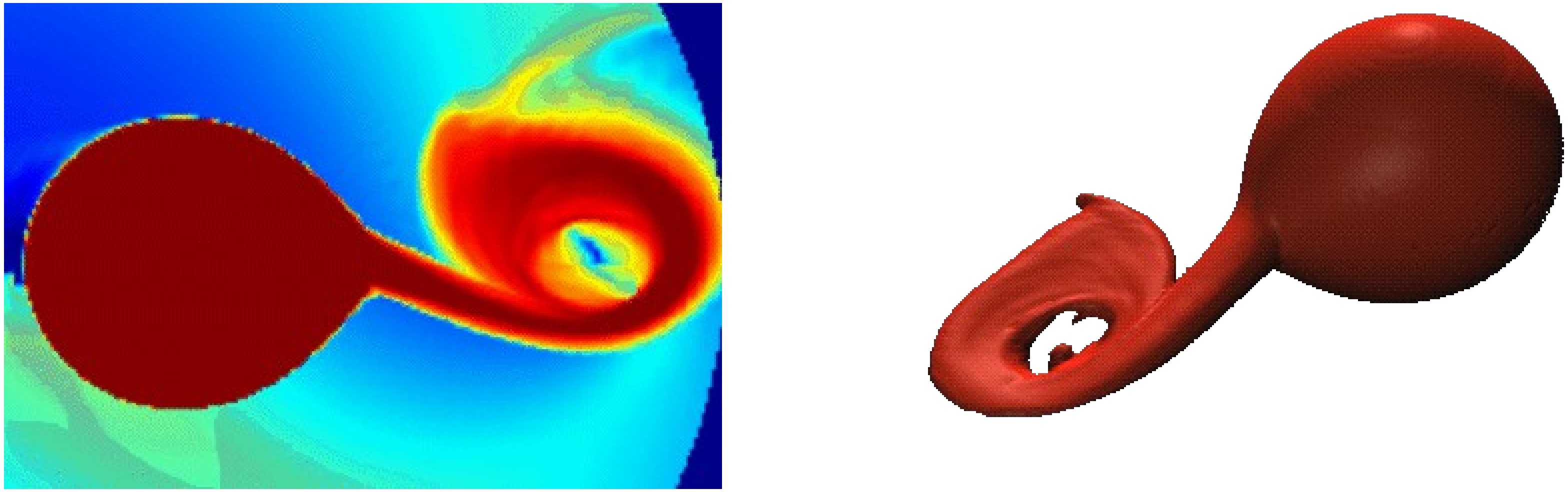
Because of the conservation of angular momentum
if some particle slows down, so that it gradually
spirals in towards the compact object, some other must expand outwards,
creating a disc from the initial ring.
The disc edge thus expands, far beyond the initial radius, most of the original
angular momentum is carried out to this edge,
(LPH, cap. 10, pag 420)

Another, external, agent of angular momentum sink is the magnetic field.

Initial ring of gas spreads into the disk due to diffusion.

To be able to accrete on the star, matter should lose angular momentum

Friction leads to heating of the disk and intense radiation

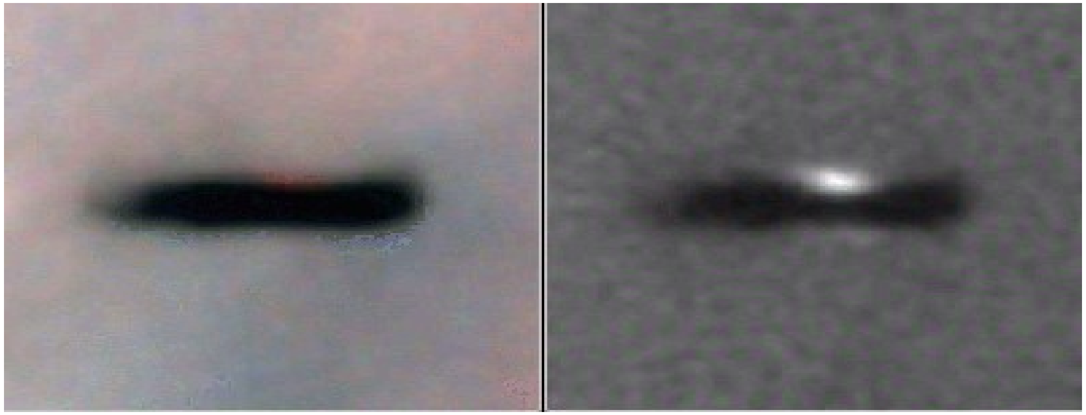


Accretion

Accretion disks are the most common mode of accretion in astrophytsics.

Examples

Accretion disk around a protostar – this is essentially the protostellar/proto-planetary disk .



Accretion disks

Suppose matter (gas) moves in a disk around a star or compact object
Then it means matter is in centrifugal equilibrium.
How can it fall onto the star or compact object?

Answer: there must be a non conservative force that "extracts" angular momentum and orbital energy from the matter in the disk

Assumption: viscous force (same meaning as friction)

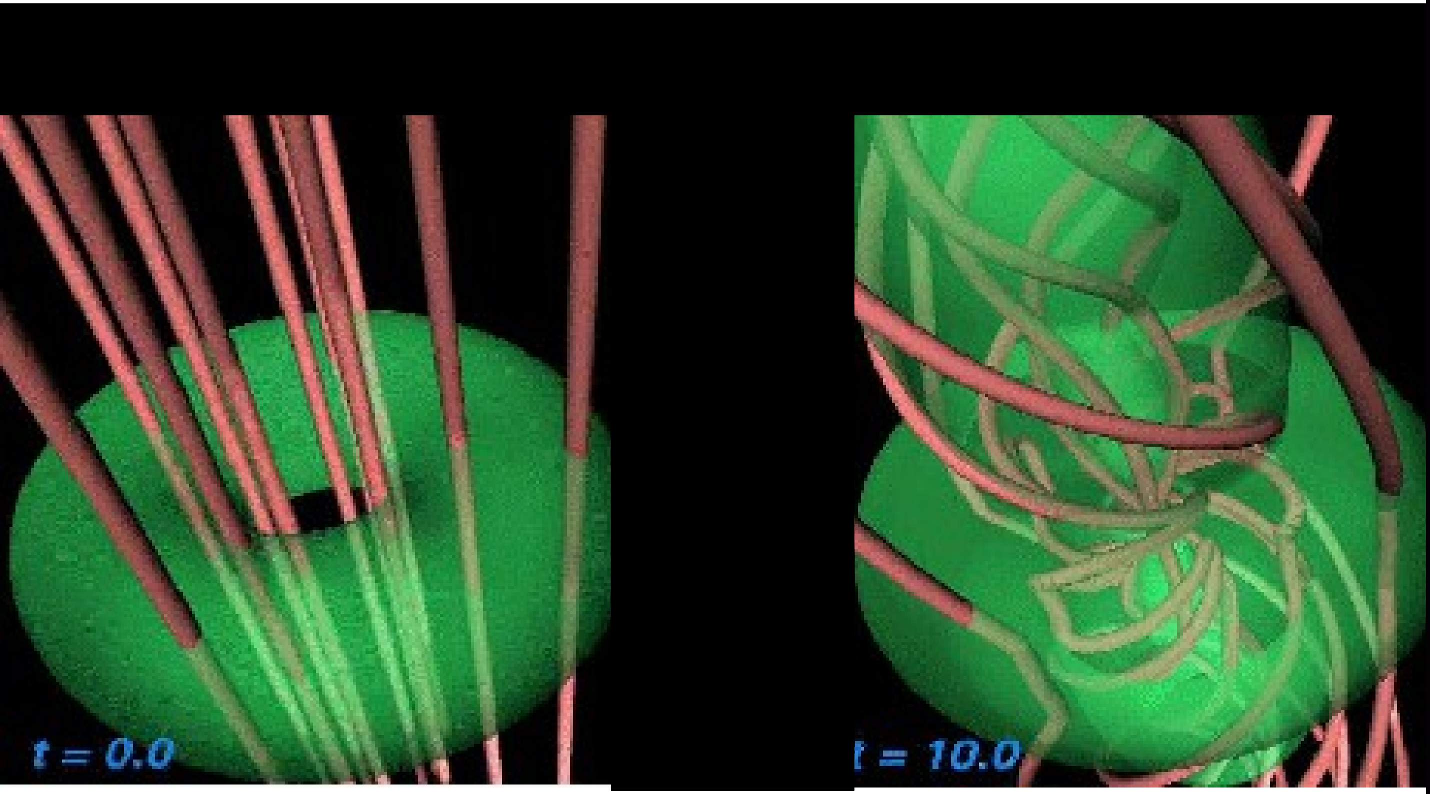
Physical mechanism behind viscous; many possible mechanisms…

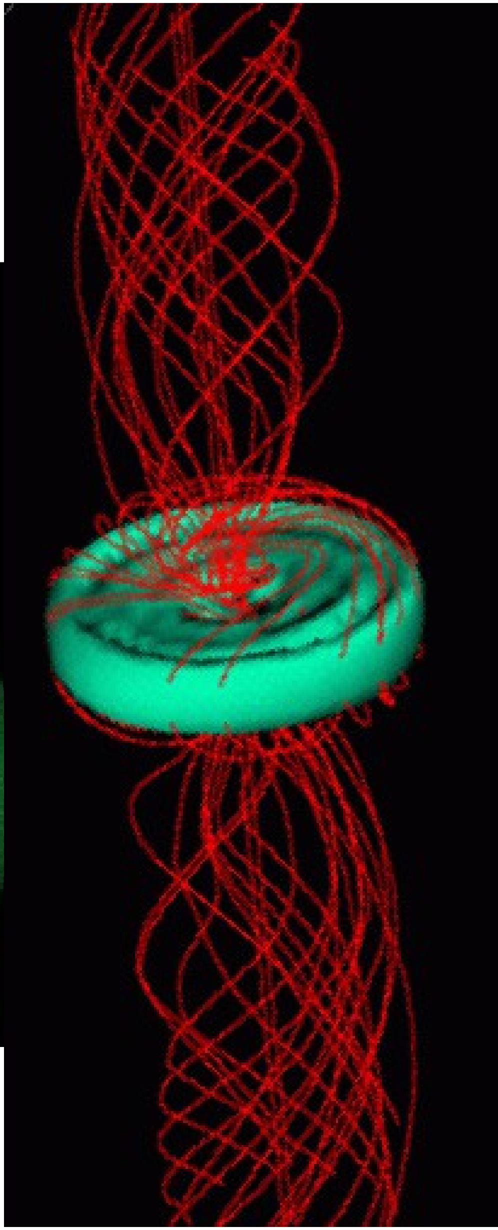
Examples
1- turbulence in a clumpy medium = medium made of clouds and clouds collide transferring energy and angular momentum

2 – magnetic field can also extract energy and angular momentum from the gas.

Jets can be produced when an accretion disk is present

"Is the disk that feeds the jet"





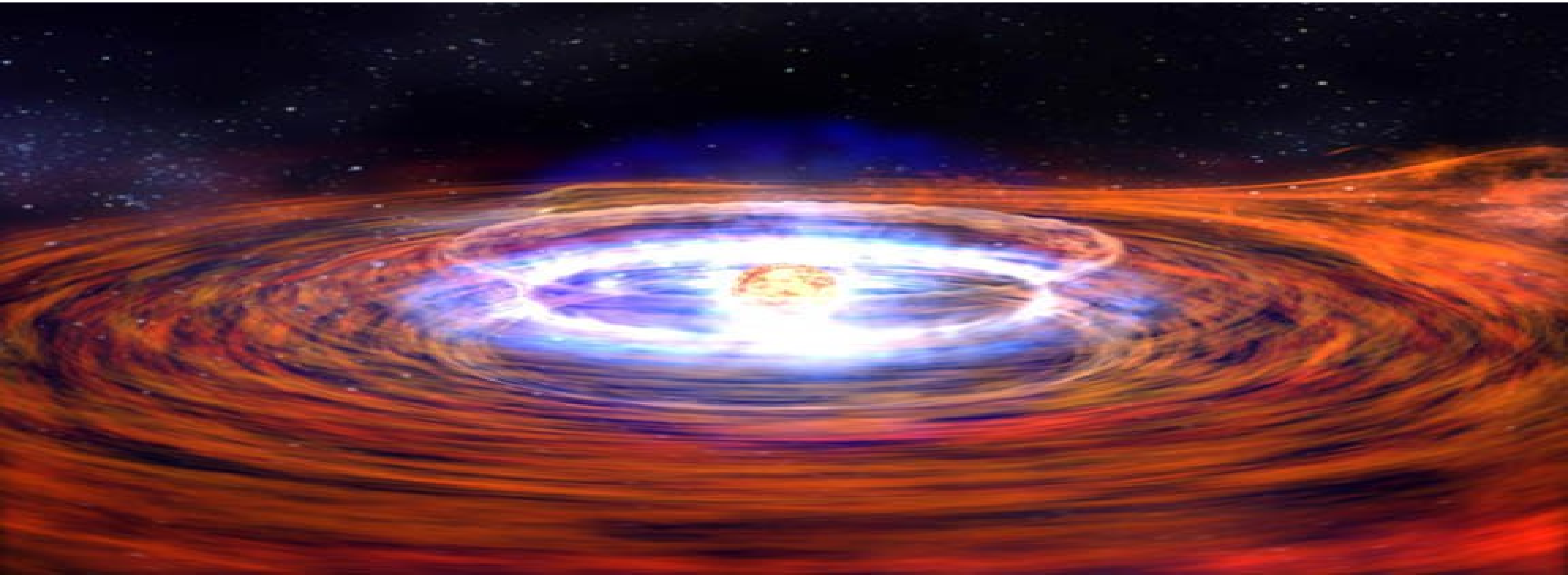
(Matsumoto et al. 1996;   Meier, Koida, Uchida 2001)

The accretion disc grows until a steady state, where the gas that reach it is equal to that falling into the black hole.

The friction will heat the gas to extremely high temperatures.
The accretion disc will glow in the x-ray portion of the spectrum.

The matter in the accretion disc drifts gradually inwards until it reaches the last stable orbit about the bh. At this point the matter spirals into the bh.

Thus the energy which can be released by accretion onto black holes is given by the energy which can be dissipated in order to reach the last stable orbit about the B.H.

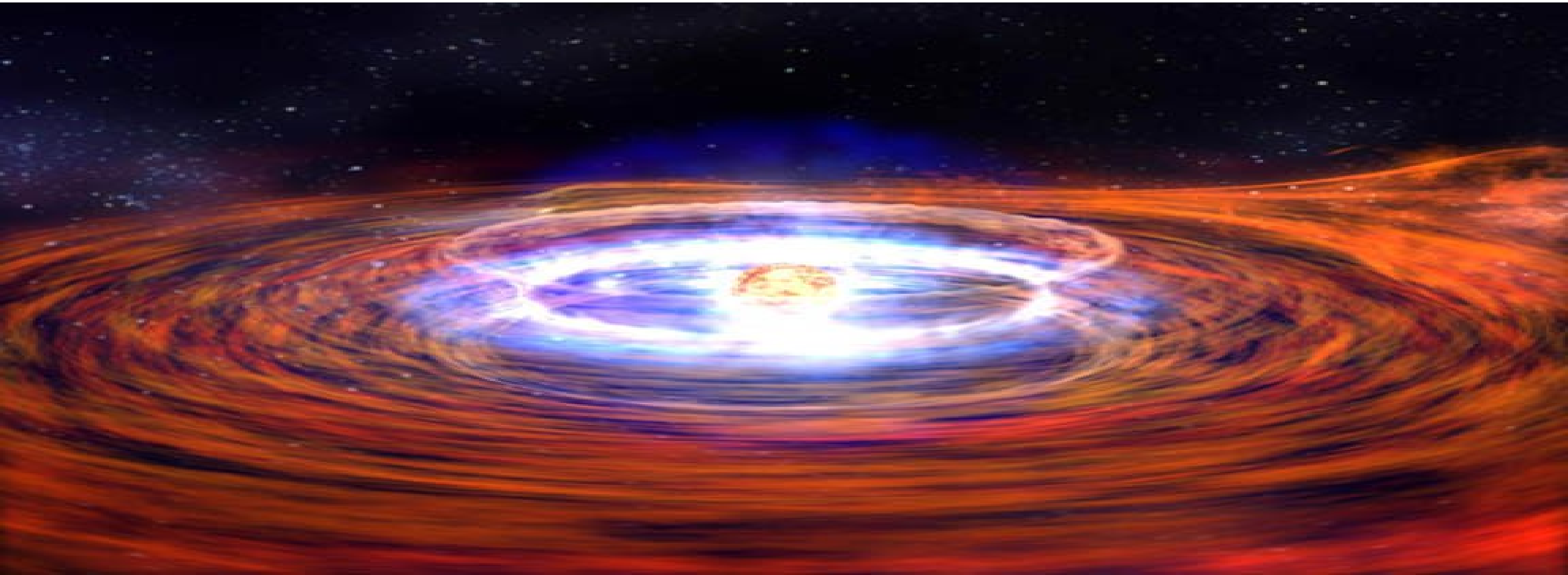


$rs = 2GM/c^2$ = 3km x M/Mo (Schwarzschild radius)
rs ~ 10 km for 3 Mo

From studying equation of motion of matter around a black hole in General Relativity one finds that radius of

<u>last stable orbit is 3rs</u>

this is the"radius" of a black hole relevant for accretion (the particle motion changes abruptly near R_{LSO} from a slow inspiral to a fast plunge).



Accretion

Let us compute the total available energy. Considering a proton falling in from infinity, we can write (Longair p. 134)

$$\frac{1}{2} m v^2_{\text{free-fall}} = \frac{G M m}{r}$$

When the matter reaches the surface of the star at r=R,

the kinetic energy of the free-fall (part of it) has to be radiated away as heat.

If the rate at which mass is accreted onto the star is d m/dt,

the rate at which kinetic energy is dissipated at the star surface is
½ dm/dt v^2,

and hence the luminosity of the source is

$$L = \tfrac{1}{2}\, dm/dt\;\; v^2_{\text{free-fall}} = \frac{G\;\; M\;\; dm/dt}{R} \qquad \frac{c^2}{c^2}$$

Accretion efficiency

$$\text{Efficiency} = \eta = GM / c^2 R$$

$$L = \eta\;\; dm/dt\;\; c^2$$

LUMINOSITY = $\mathbf{L = \eta \, dm/dt \; c^2}$

$$R_{sch} = 2GM/c^2$$

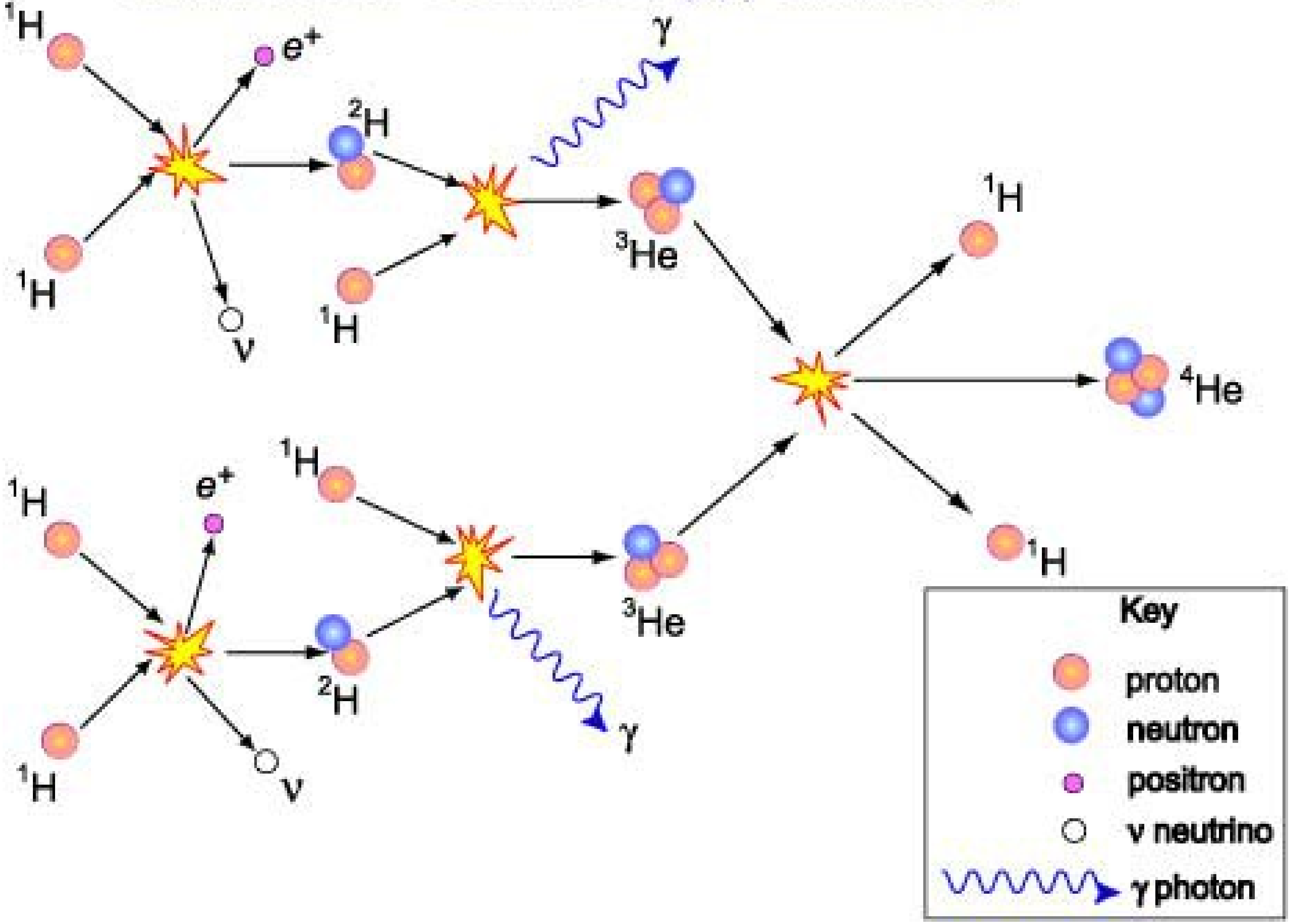
Efficiency = $\boldsymbol{\eta = GM / c^2 R = \tfrac{1}{2} \; R_{sch} / R}$

This is a remarkable formula .
It can be seen that written in this form η is the *efficiency* of conversion of the rest mass energy of the accreted matter into heat .

According to the above calculation, the efficiency of energy conversion simply depends upon how compact the star is.

Thus , accretion is a powerful source of energy. This efficiency of energy conversion can be compared with the η of nuclear energy generation.

Main Form of Proton-Proton (pp) Chain in Sun



This efficency of energy conversion can be compared with the η of nuclear energy generation.

Accretion process: Efficiency = $\eta = GM / c^2 R$

Neutron Star – $r_{in} \sim$ 10 km → $\eta = 0.1$ ----------------------------> 10%

..of the rest mass energy of the accreted matter into heat) .

Nuclear fusion process:
Efficiency = $\eta = (4\, m_p - m_\alpha) / 4\, m_p$

$$\frac{(4 \times 1.6726\ 10^{-24} - 6.642 \times 10^{-24})}{4 \times 1.6726\ 10^{-24}} = 0.007$$

For nuclear reactions in stars $\eta \sim 0.007$ ------------------------> <1% !!!

Thus , accretion is a powerful source of energy.

Accretion efficiency

Efficiency = $\eta = GM / c^2 R = \frac{1}{2} \; r_{sch} / R$

$$r_{sch} = 2\, GM/c^2$$

White dwarf M=1 M sol, R=5000 Km → $\eta = 3 \times 10^{-4}$

Neutron Star – $r_{in} \sim$ 10 km → $\eta = 0.1$

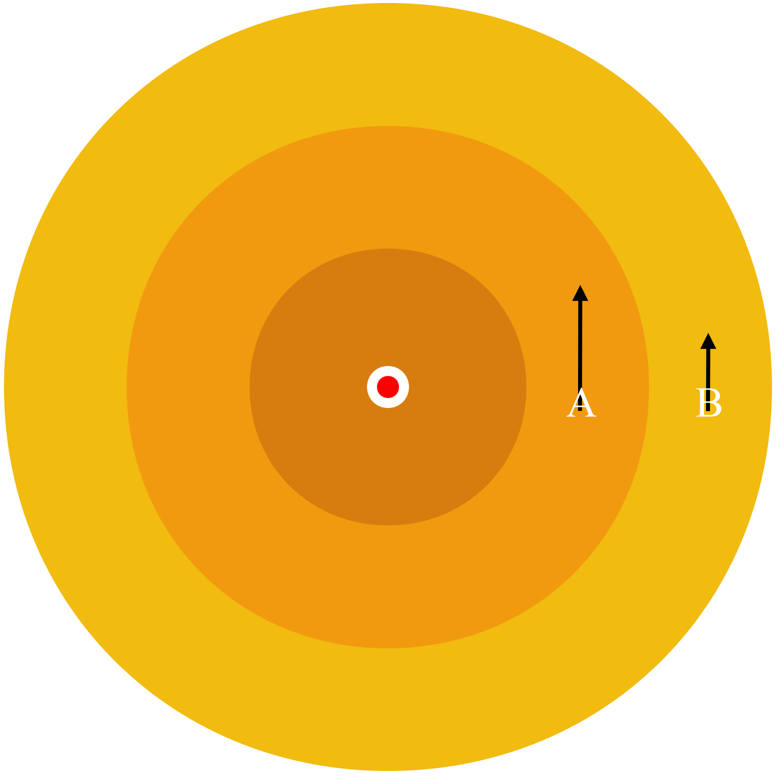
Black Hole - $r_{in} = 3rs$ → $\eta \sim 0.06$

But from GR for rotating black holes $\eta = 0.42$-------------> >40%

For nuclear reactions in stars $\eta \sim 0.007$ ----------------------> <1% !!!

Outward angular momentum transport

Ring A moves faster than ring B. Friction between the two will try to slow down A and speed up B.



Keplerian rotation

So ring A must move inward! Ring B moves outward, unless it, too, has friction (with a ring C, which has friction with D, etc.).

The “standard model”… Viscous accretion disks

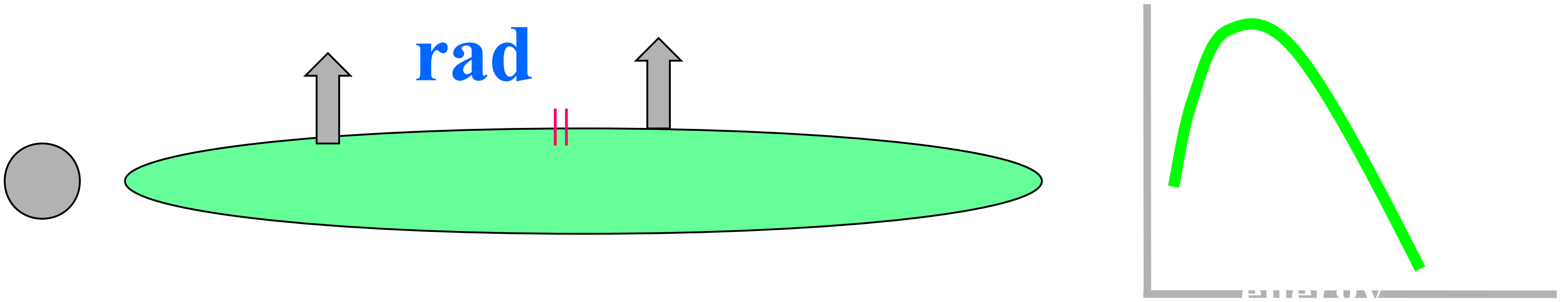
- Suppose that there is some kind of “viscosity” in the disk
  - Different annuli of the disk rub against each other and exchange angular momentum
  - Results in most of the matter moving inwards and eventually accreting
  - Angular momentum carried outwards by a small amount of material

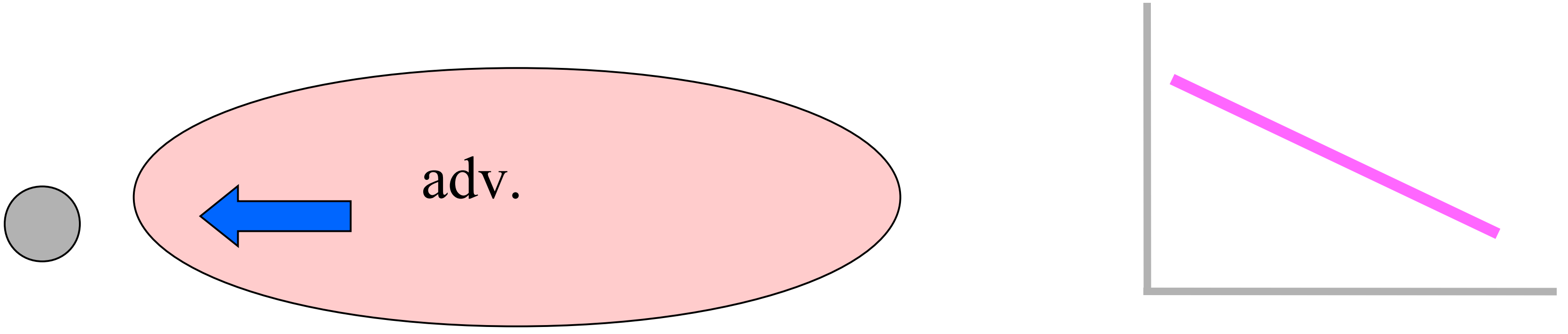
- Process producing this “viscosity” might also be dissipative… could turn gravitational potential energy into heat (and eventually radiation)

Standard Accretion Disk Model (Shakura and Sunyaev 1973) : α

MRI (Balbus and Hawley 1991) can generate magnetic turbulence and enhance the efficiency of angular momentum transport

State Transition in Accretion Disks





Eddington Limit

Radiation coming from the disk carries radiation pressure.

Radiation pressure is felt by accreting matter --→

eventually radiation pressure becomes higher than gravitational pull of compact object/star and accretion stops.

Radiation pressure force will be proportional to luminosity (more photons=more radiation pressure)

The limiting luminosity at which an object can accrete is:

$$L_{edd} = \frac{4\,\pi G M m_p}{\sigma_T}$$

σ_T = Thomson cross section

Derived for spherical accretion but approximately correct also for accretion disk

Obtain Ledd by setting Fgrav=Frad

Fgrav (gravitational force per electron) = $GM (m_p+m_e)/r^2 \sim GM\, m_p/r^2$

Frad = (Number photons x Thompson cross-section) x p

Energy of typical photon = $h\nu$
The number of photons crossing unit area in unit time at radius r is:
$L/ h\nu\, 4\pi r^2$
<u>Number of collisions</u> per electron per unit time= $L\, \sigma^T/ h\nu\, 4\pi r^2$
Each photon gives a momentum $p= h\nu /c$ to the electron in each collison

$$\mathrm{Frad} = L\sigma_T/ h\nu\, 4\pi r^2 \quad \mathrm{x} \quad p = L\sigma_T/4\pi r^2 c$$

(The radiation pressure acts upon the electrons, however protons and electrons coupled by Coulomb interaction)

Obtain Ledd by setting Fgrav=Frad

$$\text{Fgrav} = GM\, m_p/r^2$$
$$\text{Frad} = L\sigma_T/4\pi r^2 c$$

$$\text{Ledd}\ \ \sigma_T/4\pi r^2 c = GM\, m_p/r^2$$

$$\text{Ledd} = 4\pi c\, G\, M\, m_p\ /\sigma_T$$

$$L_{edd} = 1.3\ 10^{38}\ M/M_0\ \ \text{erg/sec}$$

X-ray binary luminosities

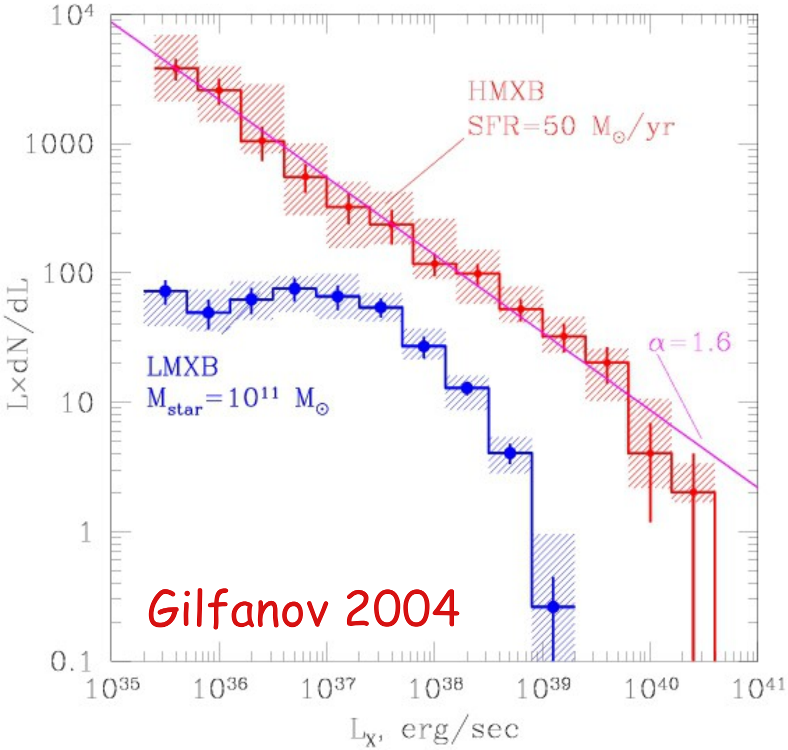
X-ray binaries typically have L_X<<10^{38}erg/s

LMXRBs:

- Flat distribution at faint-end
- max luminosities ~ 10^{38}-10^{39}erg/s.

HMXRBs:

- Power-law distribution
- Max L_X~ 10^{40}erg/s



Gilfanov 2004

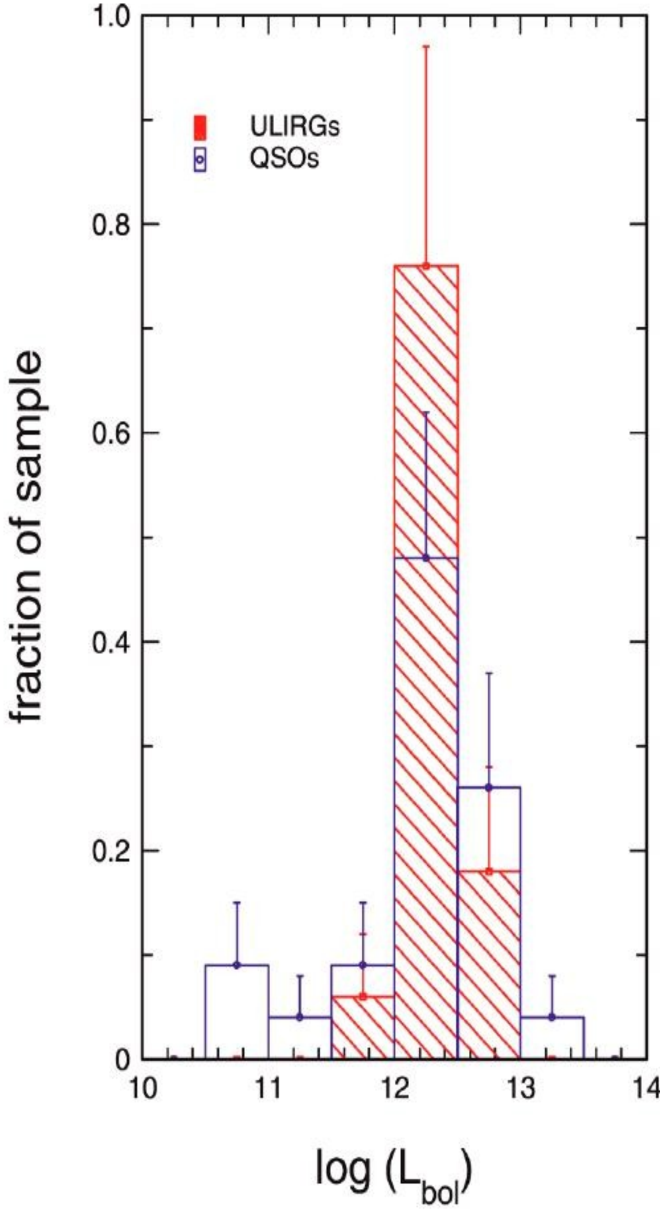
Supermassive BH

$L_{edd} = 1.3\ 10^{38}\ M/M_0$ erg/sec

$Ledd/L_0 = 10^5\ M/M_0$

for M/M_0 in the range of $10^{6-8} M/M_0$

$Ledd/L0 \quad 10^{11-13}$



Energy flows from one form to another...

GRAVITATIONAL POTENTIAL ENERGY

↓

KINETIC ENERGY

↓

HEAT

↓

RADIATION

If the disc radiates like a Blackbody

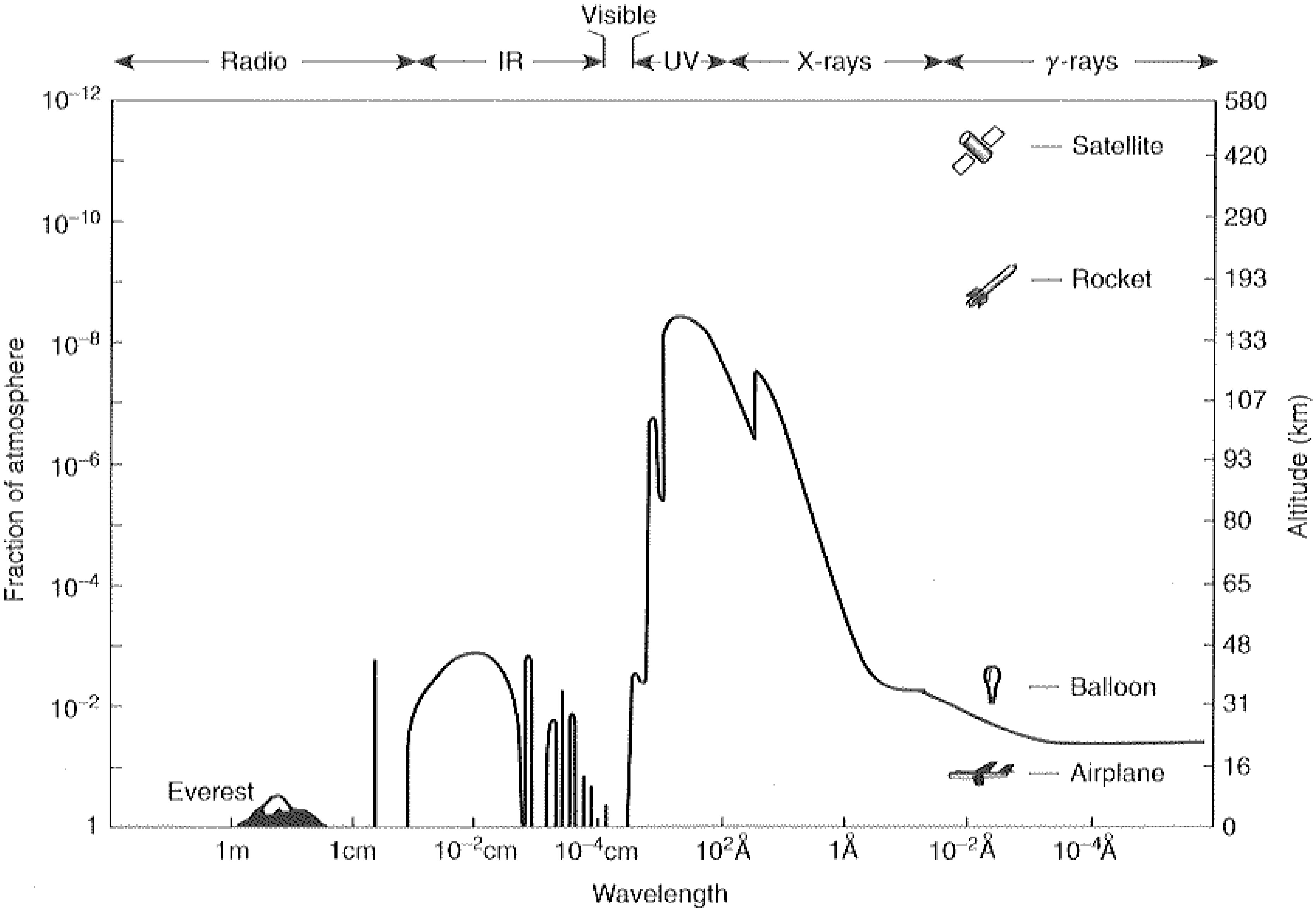
$$L_E = T^4 4\pi\ r^2\ \sigma_{\mathit{Stefan\text{-}Boltzmann}}$$

We assume as „r“ the last stable orbit around the black hole

$$T = 2 \times 10^7\ M^{-1/4}\ K$$

	M (solar masses)	T (K)	λ (Angstrom)	
Microquasar	3	1.5 10^7	2	X-ray
AGN	10^9	10^5	300	uv

The reason for the delay in discovering the much closer to us microquasars is the fact that their disc emits in X-rays and our atmosphere is opaque at these wavelengths.

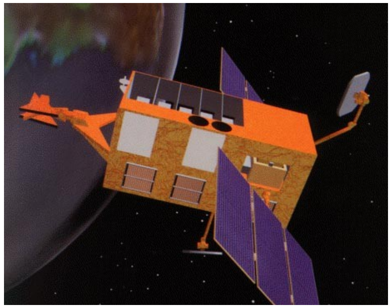


Absorption of electromagnetic radiation by the atmosphere

1962: Giacconi et al. discovery of Sco X-1
1967: Discovery of radio pulsars.

1970: First astronomy satellite, an X-ray mission called Uhuru, was launched.

- Uhuru, Einstein, ROSAT, ASCA, BeppoSAX, RXTE,XMM,Chandra



- -Rossi X-ray Timing Explorer (RXTE) - NASA, launched 1995
- - very large collecting area in energy range 2-100 keV
- - very high time resolution
- - reasonable spectroscopy
- - enormous field of view, but no images

- -X-ray Multi-Mirror Mission (XMM-Newton) - ESA, launched 1999
- - large collecting area in range 0.2-12 keV
- - reasonable time resolution
- - high-resolution spectroscopy up to few keV
- - 10 arcsec resolution over 30’ FOV

- - Chandra X-ray Observatory (AXAF, CXO) - NASA, launched 1999
- - modest collecting area in range 0.5-10 keV
- - high time resolution
- - very high-resolution spectroscopy up to few keV
- - 0.9 arcsec resolution over 16’ FOV

Swift is a multi-wavelength space-based observatory: gamma-ray,X-Ray,UltraViolet Optical telescope

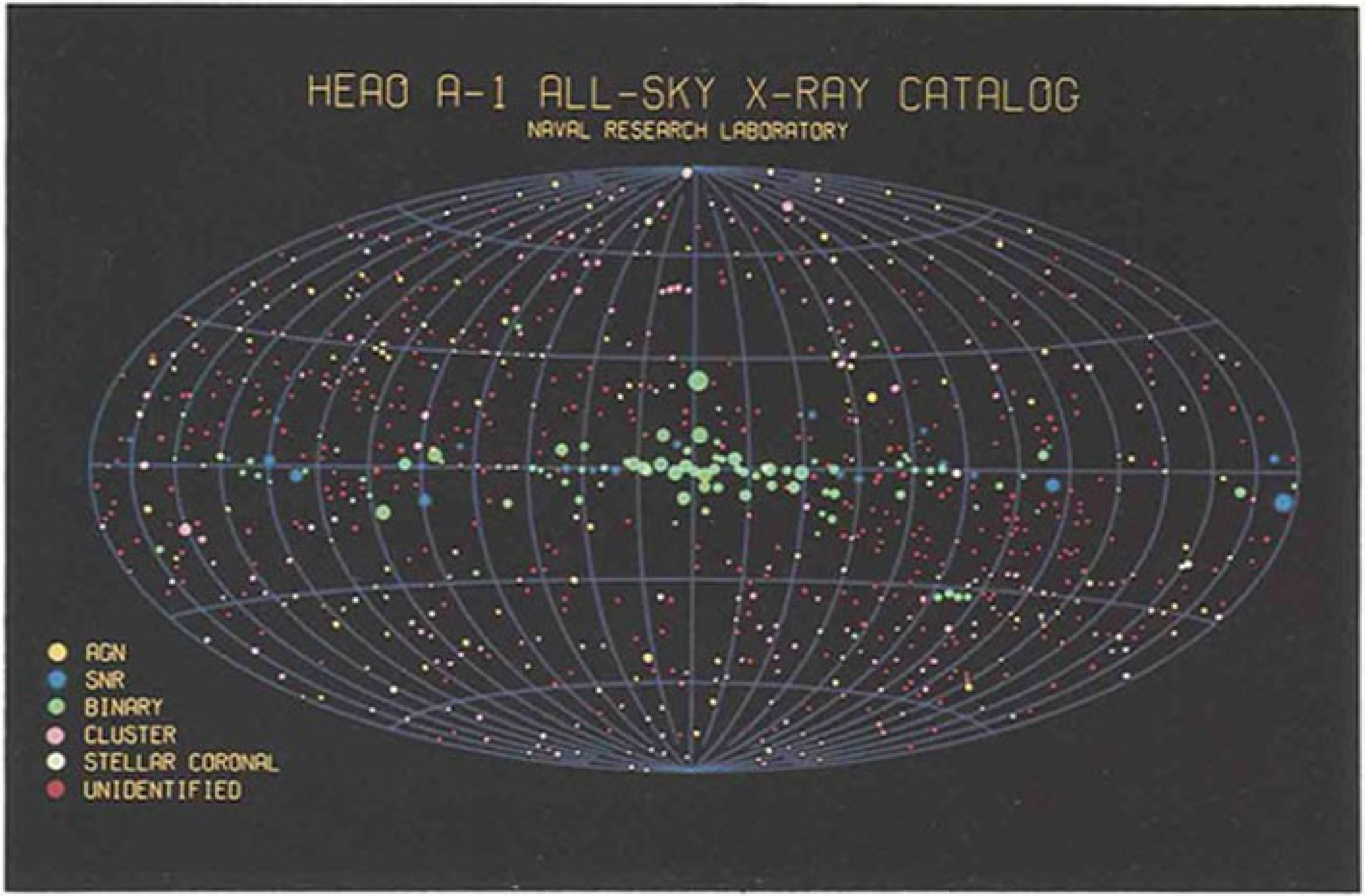
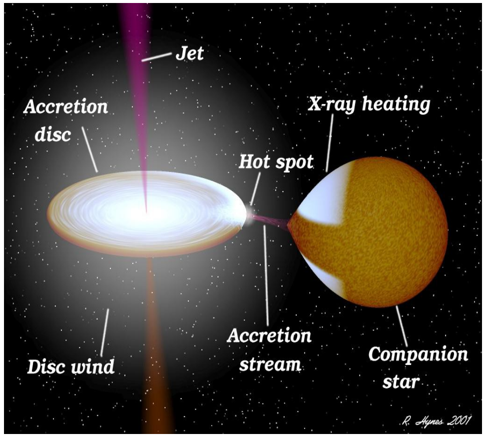


Fig. 1.7 Map showing X-ray sources from the HEAO-1 all-sky survey. Size of the dot shows the brightness of the source. Colours indicate type of source. (Courtesy of K. Wood, NRL.)

Where are the other objects like SS433 ?

Margon 1980,1984

Radio-loud X-ray Binaries:



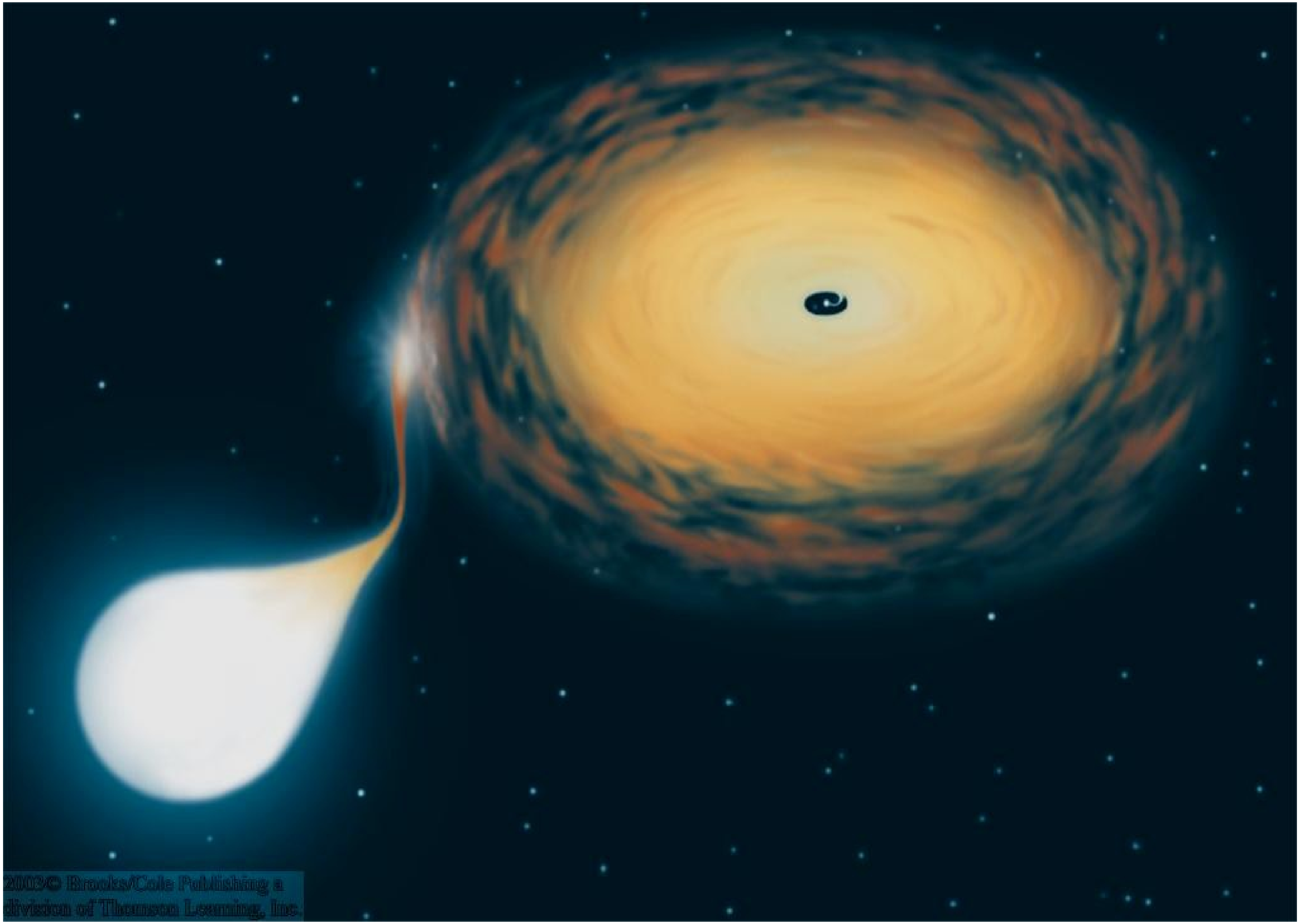
MICROQUASARS:

SS433	Margon 1979, Spencer 1979
1E1740-2942	Mirabel et al. 1992
GRS1758-258	Rodriguez et al. 1992
Cygnus X-3	elongation Geldzahler et al. 1983 Spencer et al 1986 Schalinski et al. 1990, 1995
Circinus X-1	Stewart et al. 1993
LS I 61303	**Massi et al. 1993**
GRS1915+105	Mirabel & Rodriguez 1994
GROJ1655-40	Tingay et al. 1995; Hjellming & Rupen 1995
XTEJ1748-288	Hjllming et al. 1998
CI Cam	Mioduszewski et al. 1998
LS 5039	**Paredes et al. 2000**
V461 Sgr	Hjllming et al. 2000
Cygnus X-1	Stirling et al. 2001
Sco X-1	Fomalont et al. 2001
XTEJ1550-564	Hannikainen et al. 2001
XTEJ1859+226	Brocksopp et al. 2002

INVERTED / FLAT SPECTRUM COMPACT SOURCES:

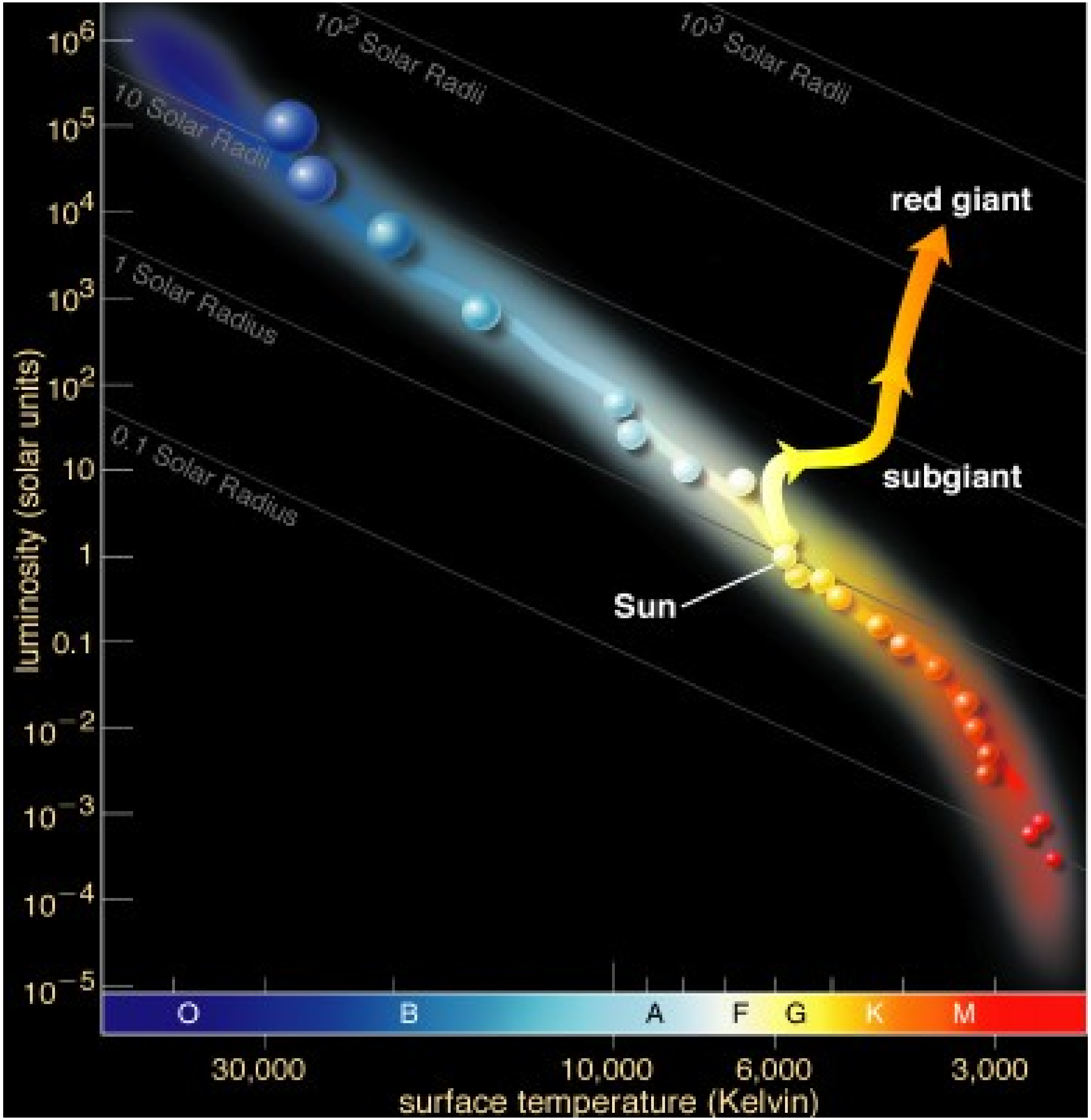
GX339-4	Fender et al. 1997, recently resolved by Gallo et al. 2004
XTEJ1118+480	Fender et al. 2001

Accreting neutron stars and black holes

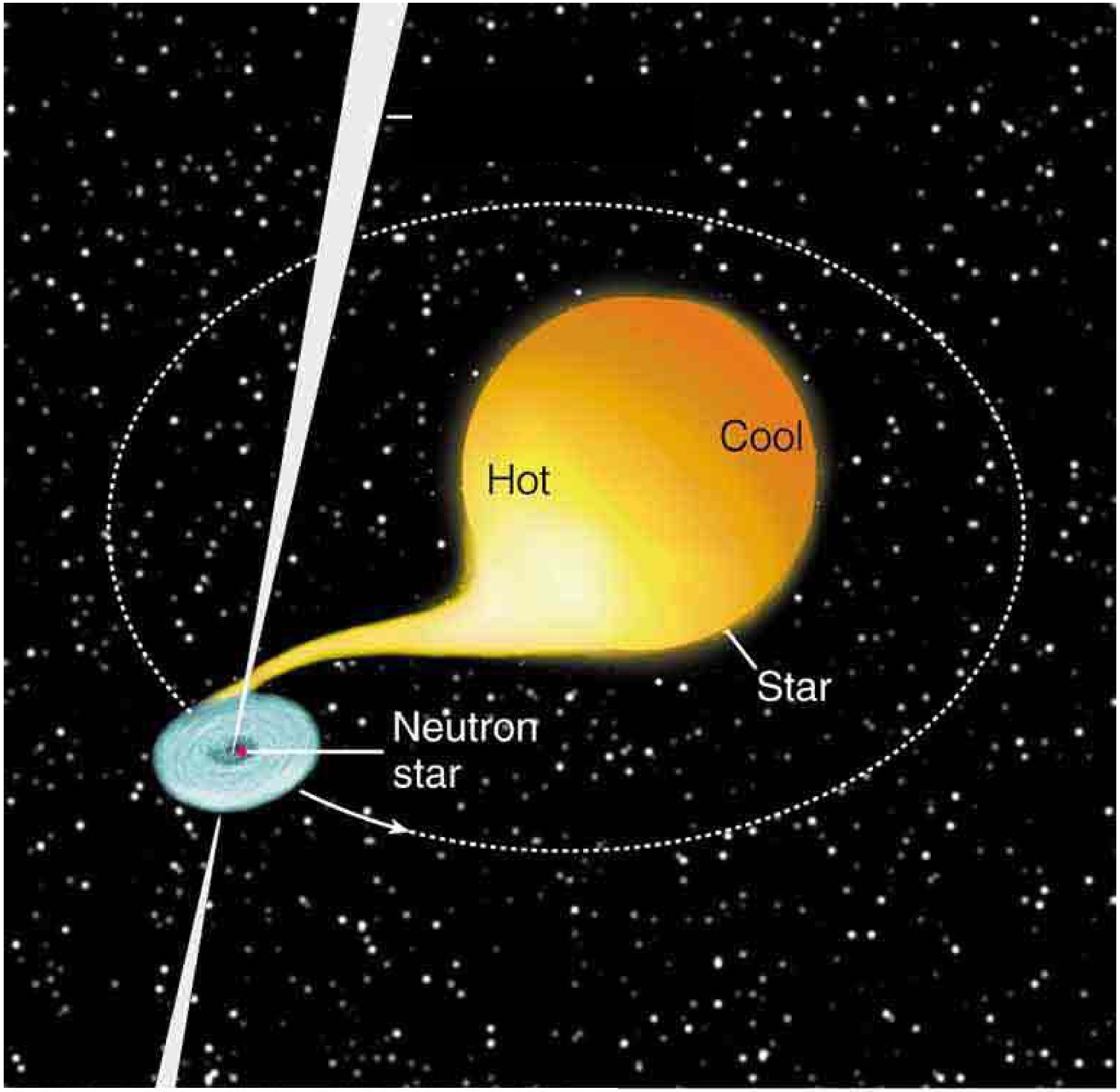


Properties	HMXBs	LMXBs
Donor star	O-B (M$>$ 5 M$_\odot$)	K-M (M$<$ 1 M$_\odot$
Population	I (10^7 yr)	II (5-15 x10^9 yr)
L_X/L_{opt}	0.001-10	100-1000
Optical spectrum	stellar like	reprocessing
Orbital Period	1-100 d	10 min-10 d
Accretion disc	yes, small	yes
X-ray Eclipses	common	rare

Hertzsprung-Russell-Diagramm

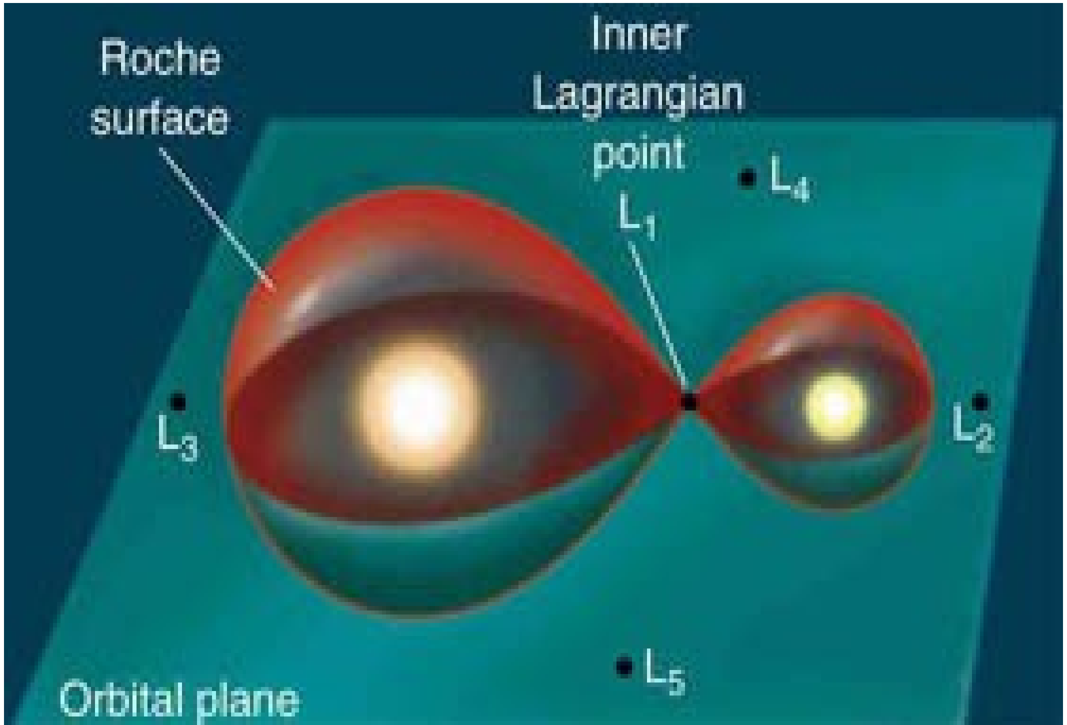


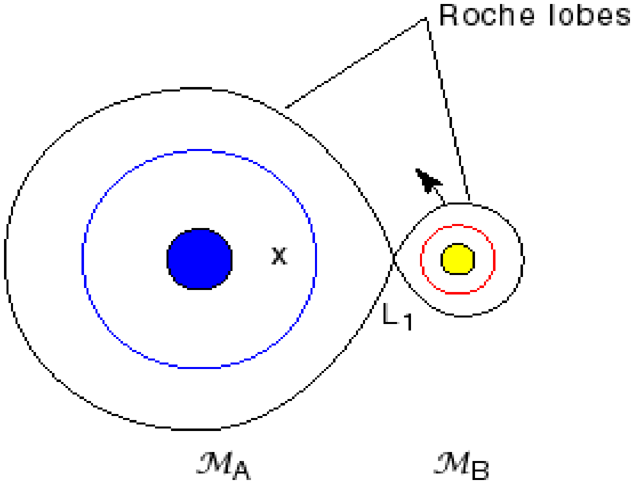
Accretion onto a neutron star



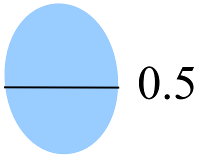
Close to each star, the potential is dominated by the gravity of that star, and the equipotential surface is a sphere around the center of that star. Further out, the equipotential surfaces are deformed. They assume a pear-like shape. For a critical value of the potential the equipotential surfaces of the two stars touch, in the inner Lagrangian point.

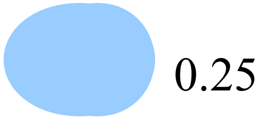
ROCHE LOBE
EQUIPOTENTIAL SURFACE THROUGH THE INNER LAGRANGIAN POINT L1





Lagrange point = point of stability, where matter can remain without being pulled towards one of the stars.


0.5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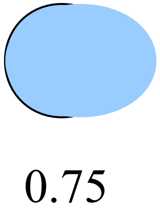
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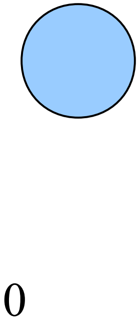
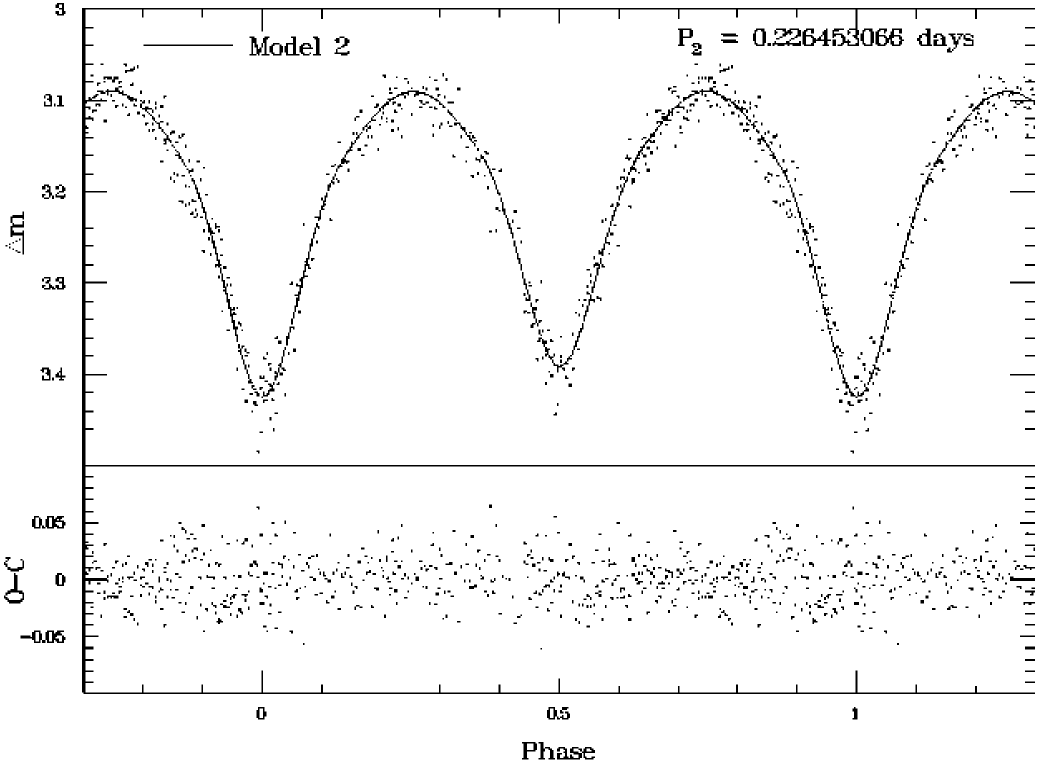
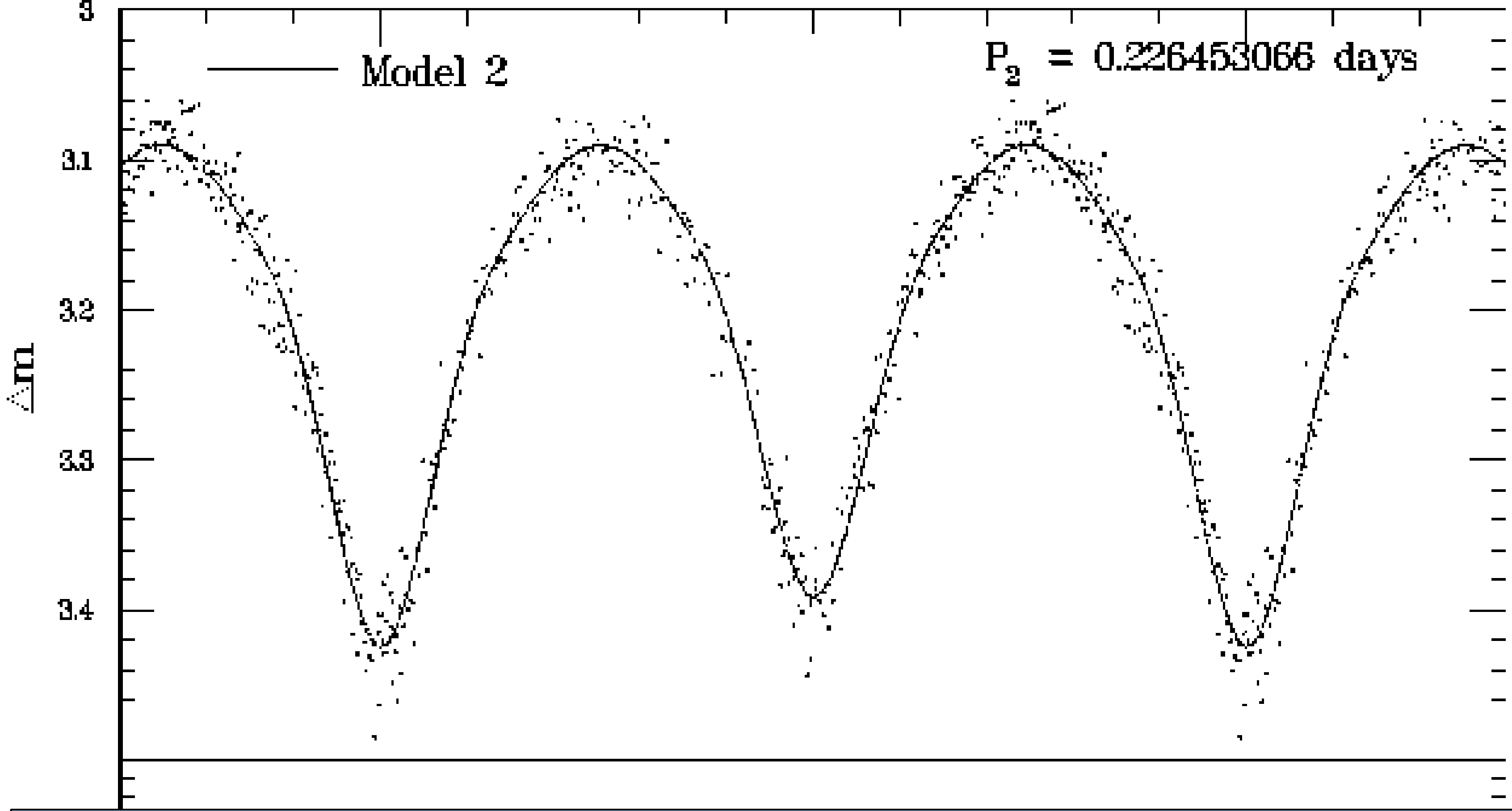

0


Model 2
P_2 = 0.226453066 days
Δm
3
3.1
3.2
3.3
3.4
O−C
0.05
0
−0.05
0
0.5
1
Phase



This shape of the light curve reflects the pear-like shape of one star that is filling its Roche-lobe

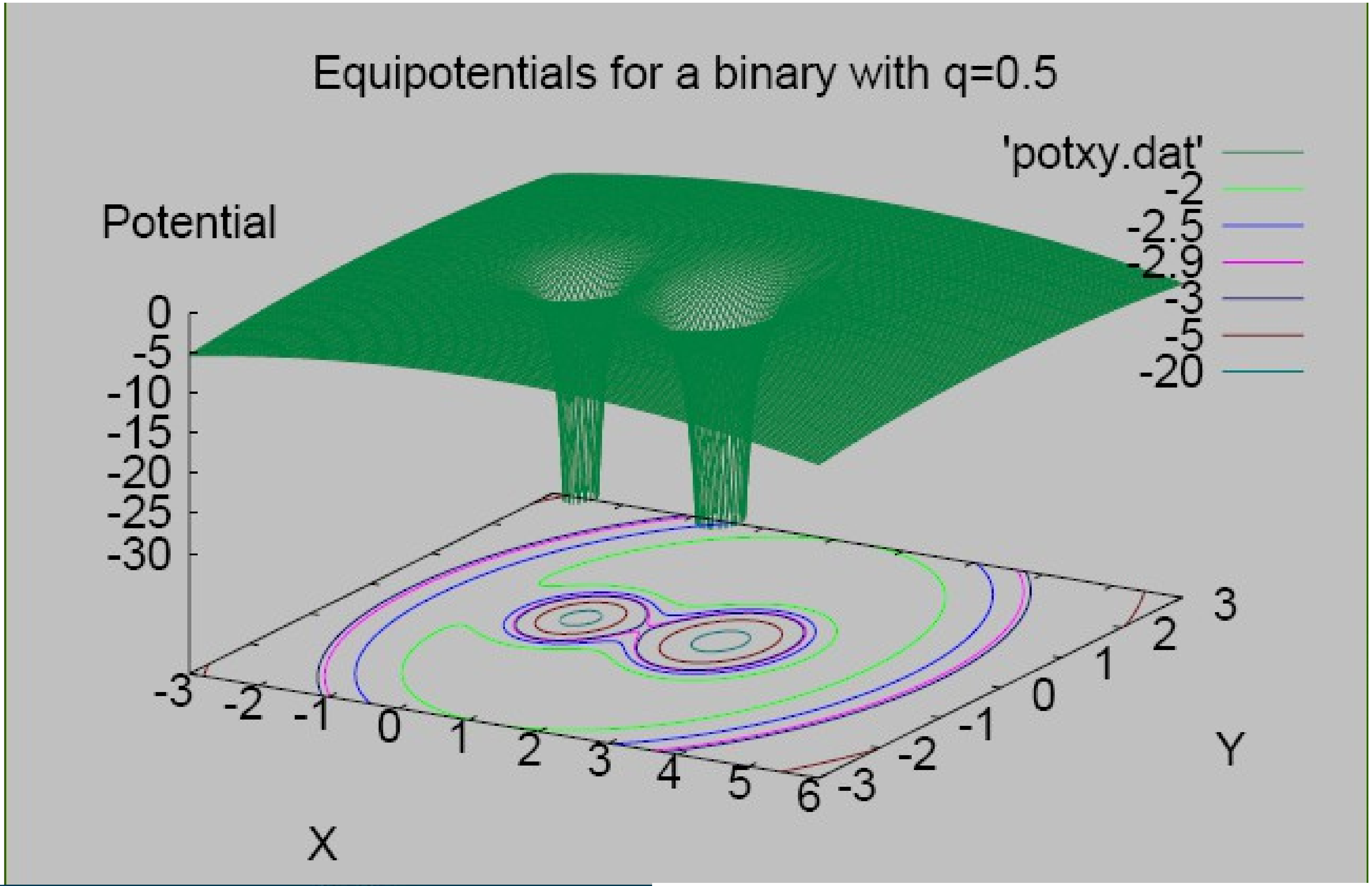
Observative evidence of roche lobe deformation:

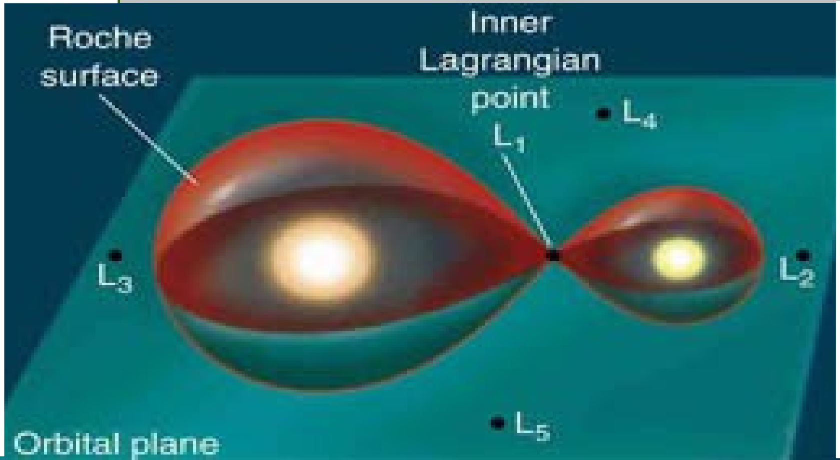
The primaries of some HMXBs are supergiants. Many fill their Roche lobes,as is apparent from the amplitude of their optical ligth curves with moderate ($\leq$ 10%) variations, with 2 maxima and two minima per orbit that occur at quadratures and conjuctions respectively (Fig. 2.3 , 2.4 e pag.63 LPH). These so-called ellipsoidal light curves are caused by the rotational and tidal distortions of the primary which fills (or nearly fills) its critical lobe, and the non-uniform distribution of its surface brightness.

The double-waved shape of the ellipsoidal light curve reflects the pear-like shape of the equipotential surfaces :near conjunctions the **projected stellar disc** is smallest. At superior conjuction ($\Phi = 0.5$) of the primary, L_1 is directed towards the observer; since near L_1 the surface gravity, and therefore the surface brightness, is a minimum, the corresponding minimum in the light curve is the deeper of the two.

(NOTE: Von Zeipel's theorem: the local radiation flux is proportional to the local surface gravity (LPH p. 64)).

In practice a fraction of the X-ray is absorbed by the primary (by its outer layers) and reradiate at lower energy (UV and optical). This effect is seen in the light curve by the filling in of the deeper minimum (near inferior conjuction of the X-ray source)

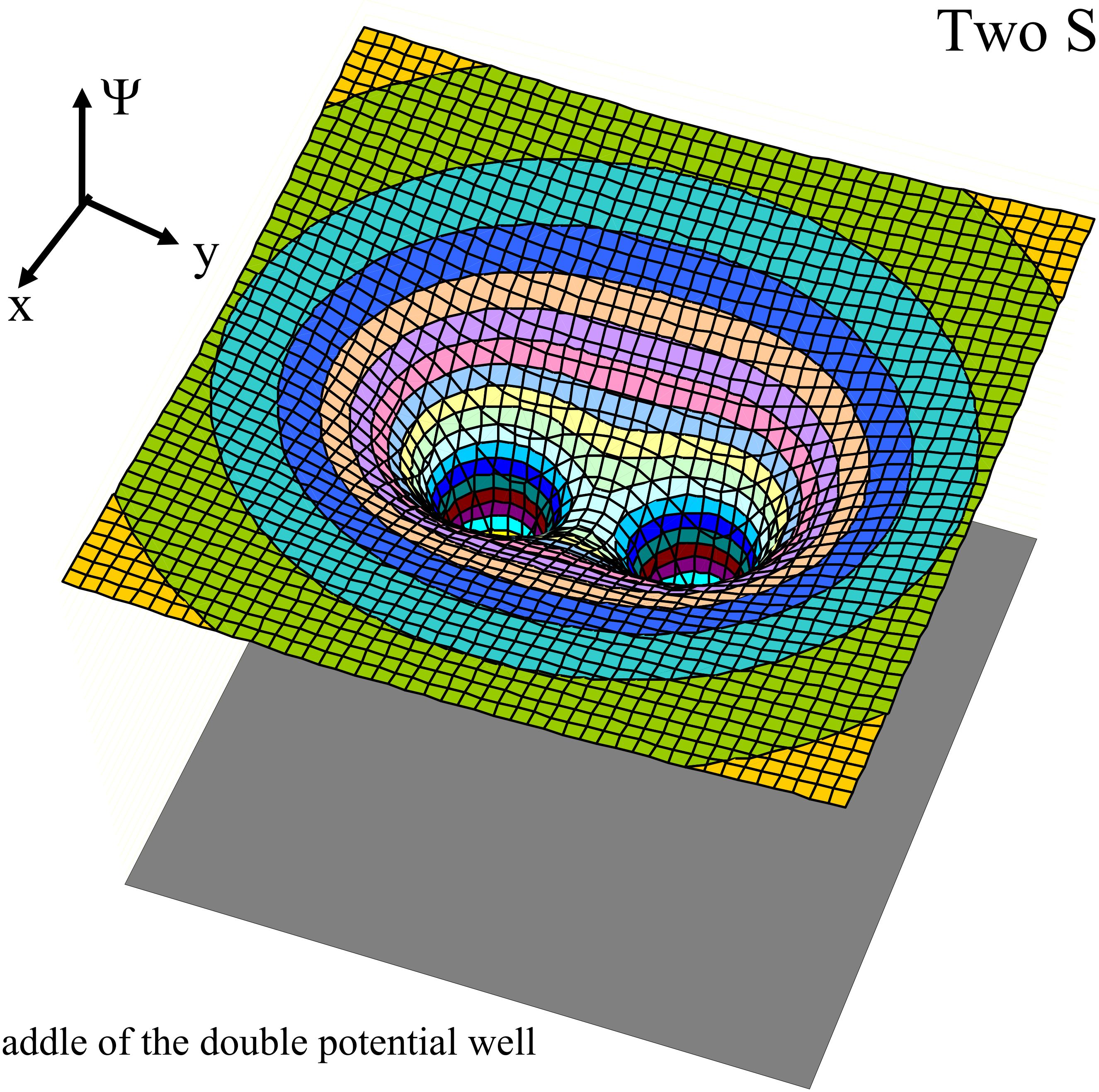




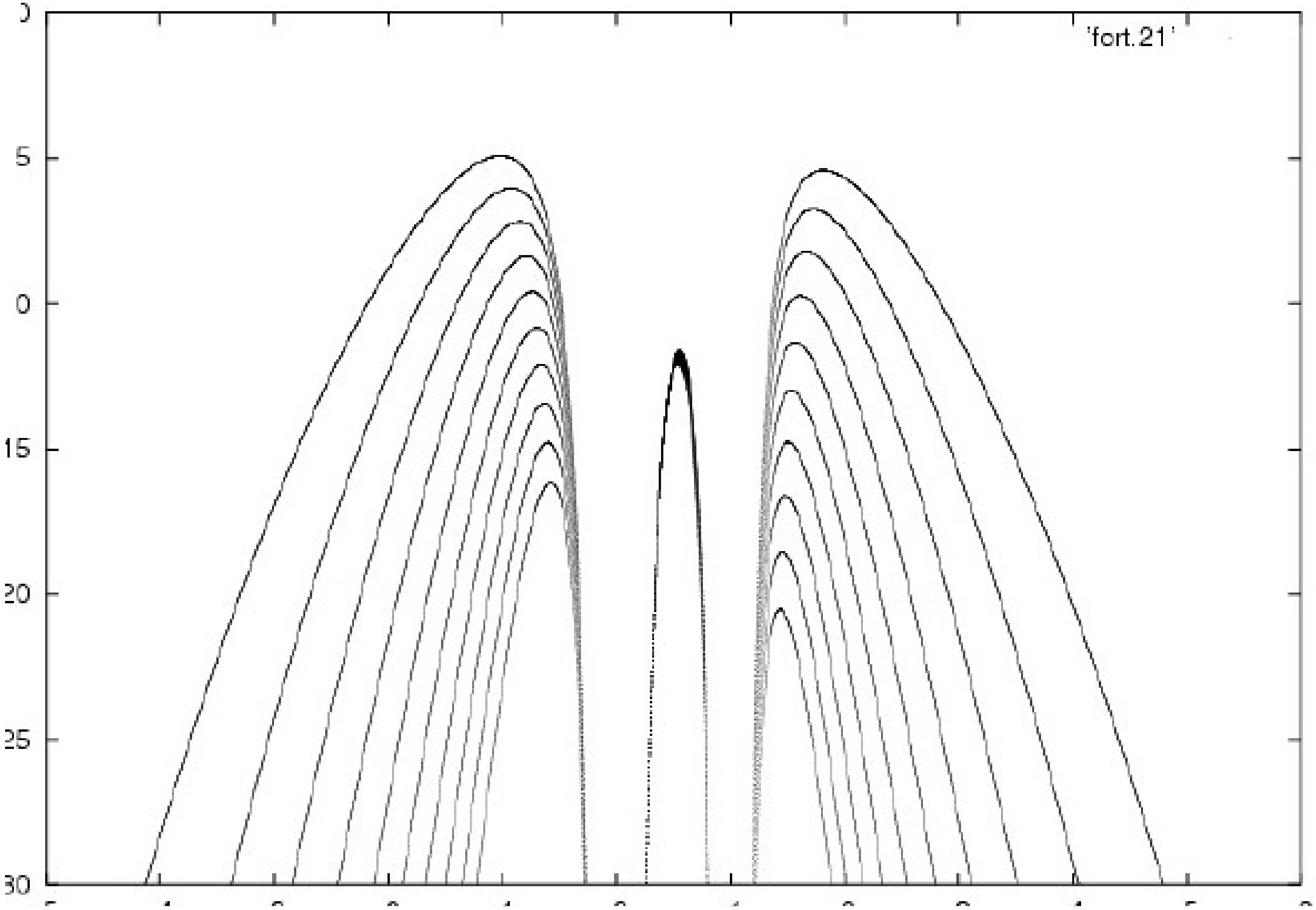
A- 2-dimensional cut in the equatorial plane (xy)

B- 3-dimensional structure

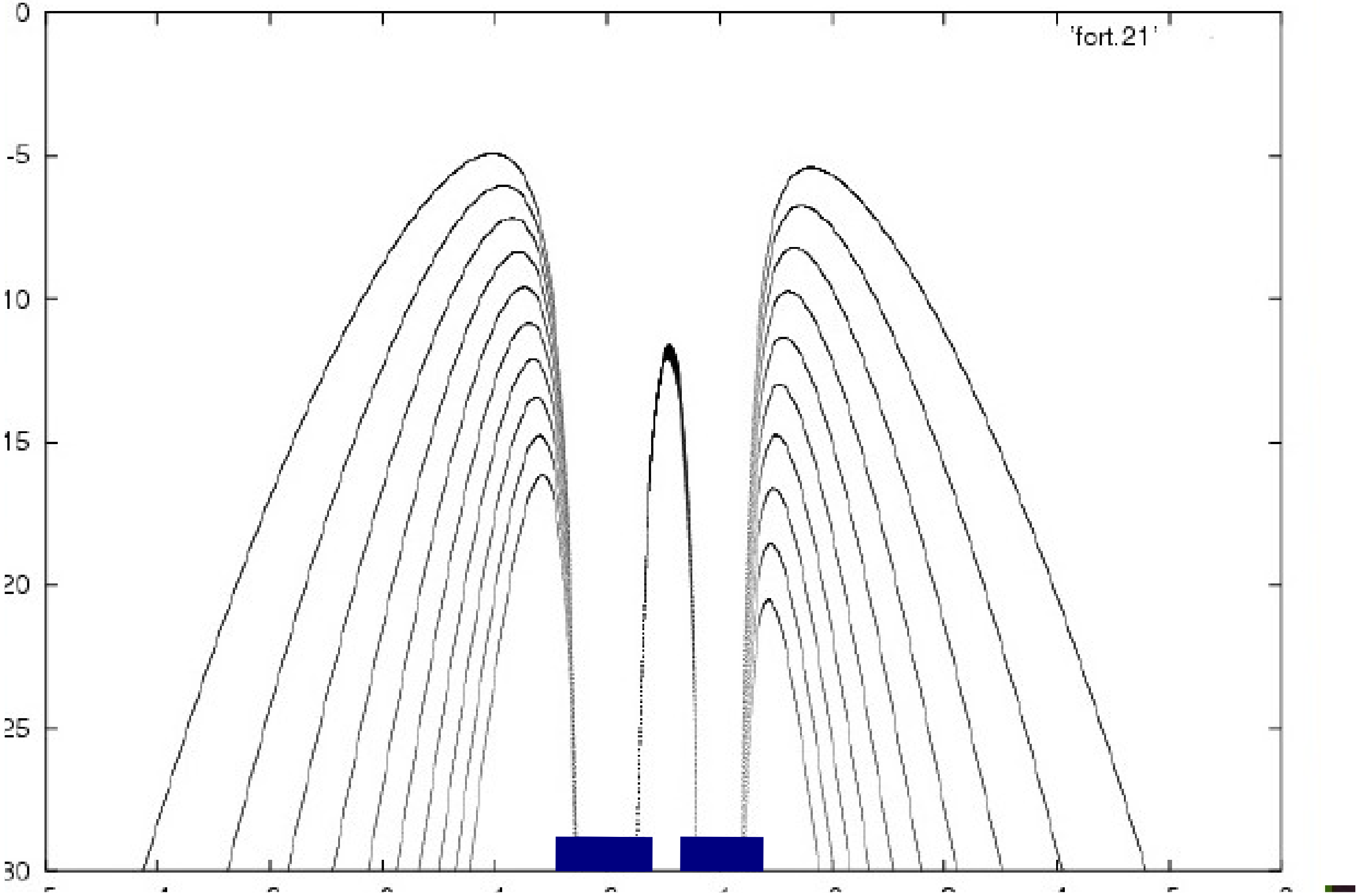
Two Stars



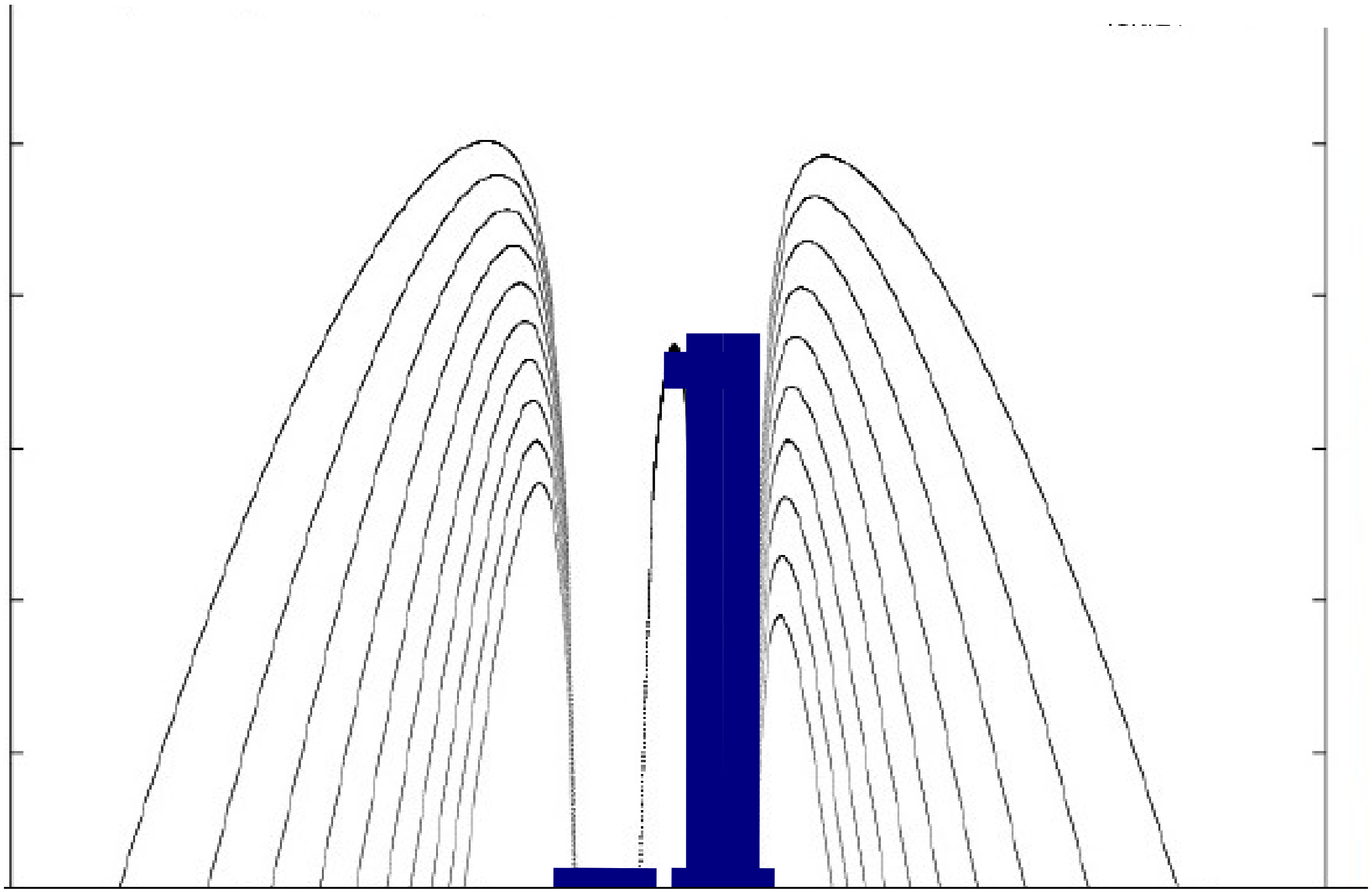
..the saddle of the double potential well



the top of the "hill" (Lagrancian point), can also be thought as a low mountain pass between two valleys.

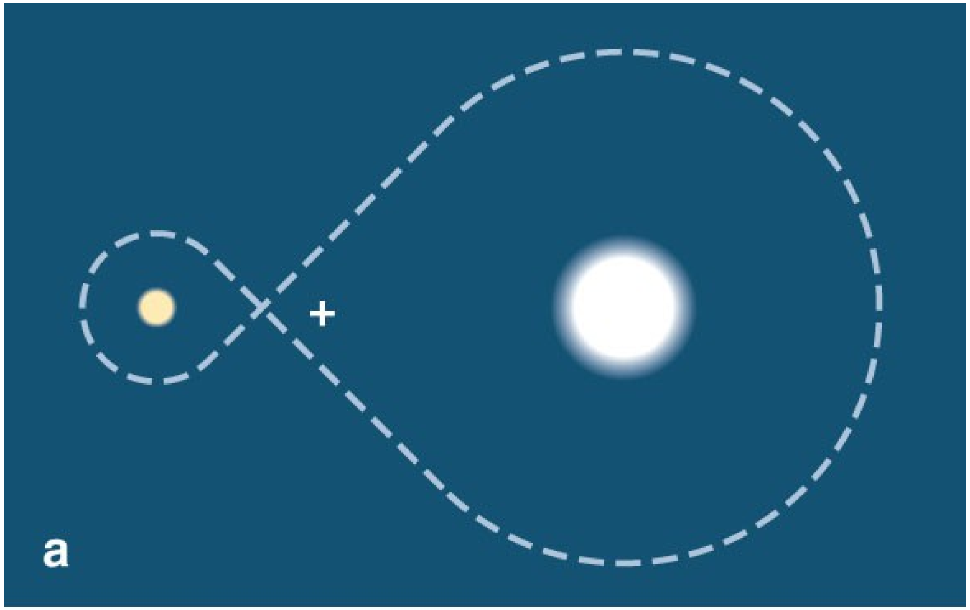


the top of the "hill" (Lagrancian point), can also be thought as a low mountain pass between two valleys.
Continuing this analogy the stars are lakes at the bottom of these valleys.



When one of the lakes fills up its valley, it produces a stream flowing down into the other lake.

This "water transfer" process is analogous to the gas tra process between two stars when **one star has evolved into a giant** and has overflowed its gravitational "basin".......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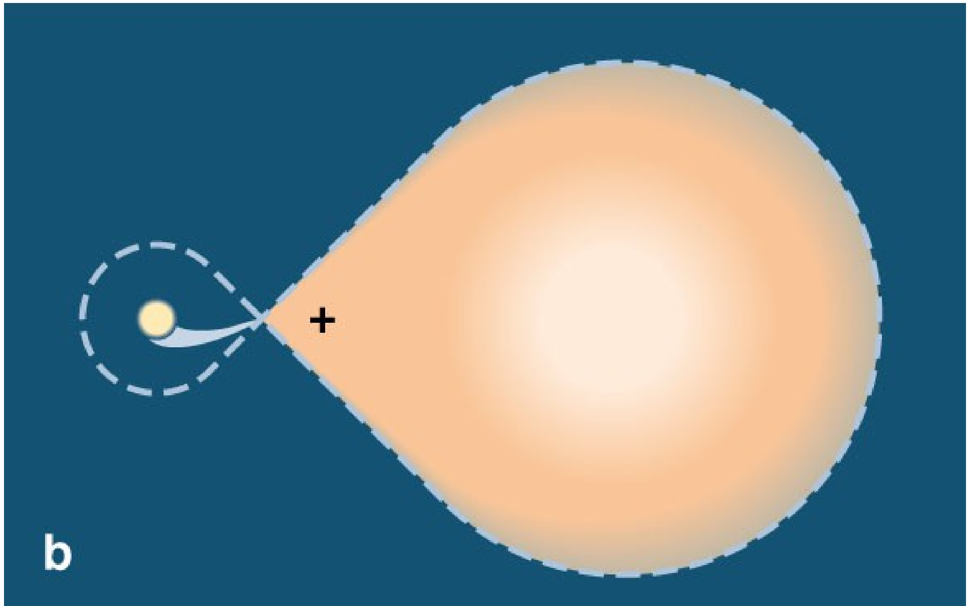
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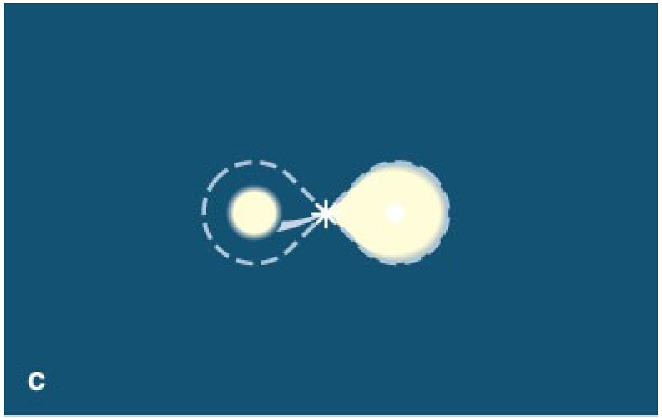
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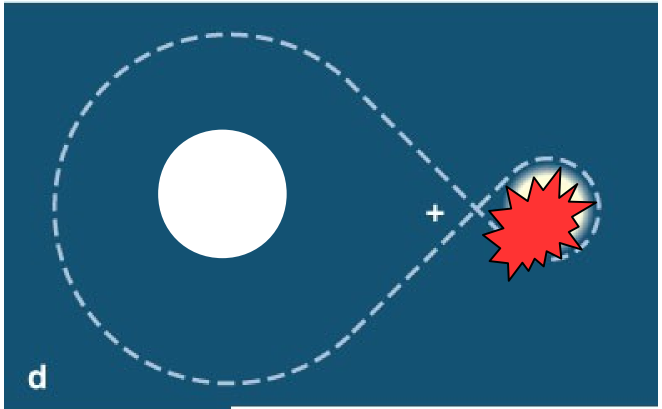
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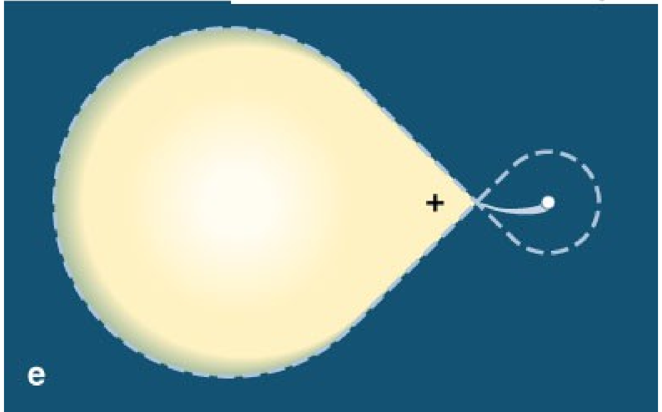
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Mechanisms proposed to explain the presence of a compact object in a binary system:

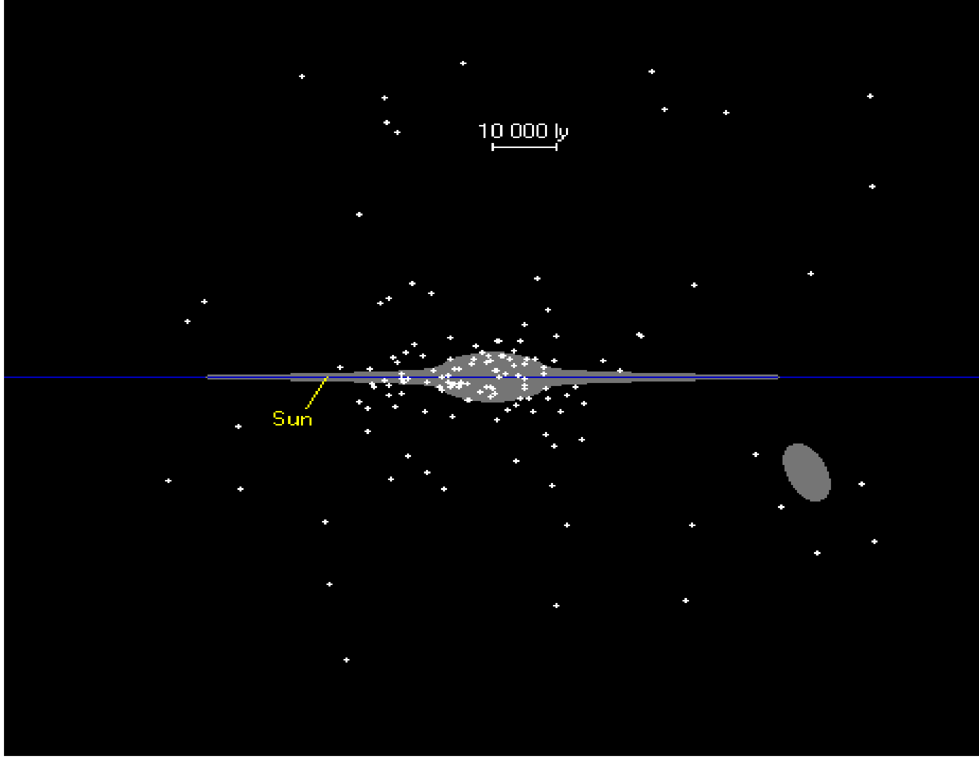
a) standard collapse mechanism for formation of neutron star/bh, provided that the binary system was able to survive the supernova explosion}.

In the case of the high-mass X-ray binaries, this survival is a clear consequence of the **large-scale mass transfer which precedes the supernova explosion** of the initially more massive component of the system, such that at the moment of the explosion this star became the less massive of the two. Explosive mass ejection from the less massive component will, in general, not lead to disruption unless the effects of impact are very large which for **high-mass systems** is not expected to be the case. In the case of low-mass X-ray binaries, it is much more difficult to see why the systems were not disrupted. (LPH, cap. 11, pag. 457)

b) previous formation of the neutron/bh which later coupled with its companion in a (tidal) capture process.

Several LMXBs are close to the core of globular clusters.
In the core , the stars may be so closely packed that encounters are quite likely
(pro and contra on LPH cap. 11, pag 486)

Globular Clusters



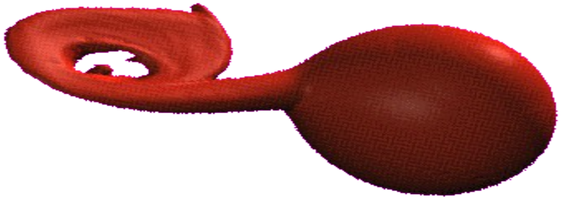
- Hundreds of thousands of stars,
- tightly gravitationally bound
- and spherically symmetric.

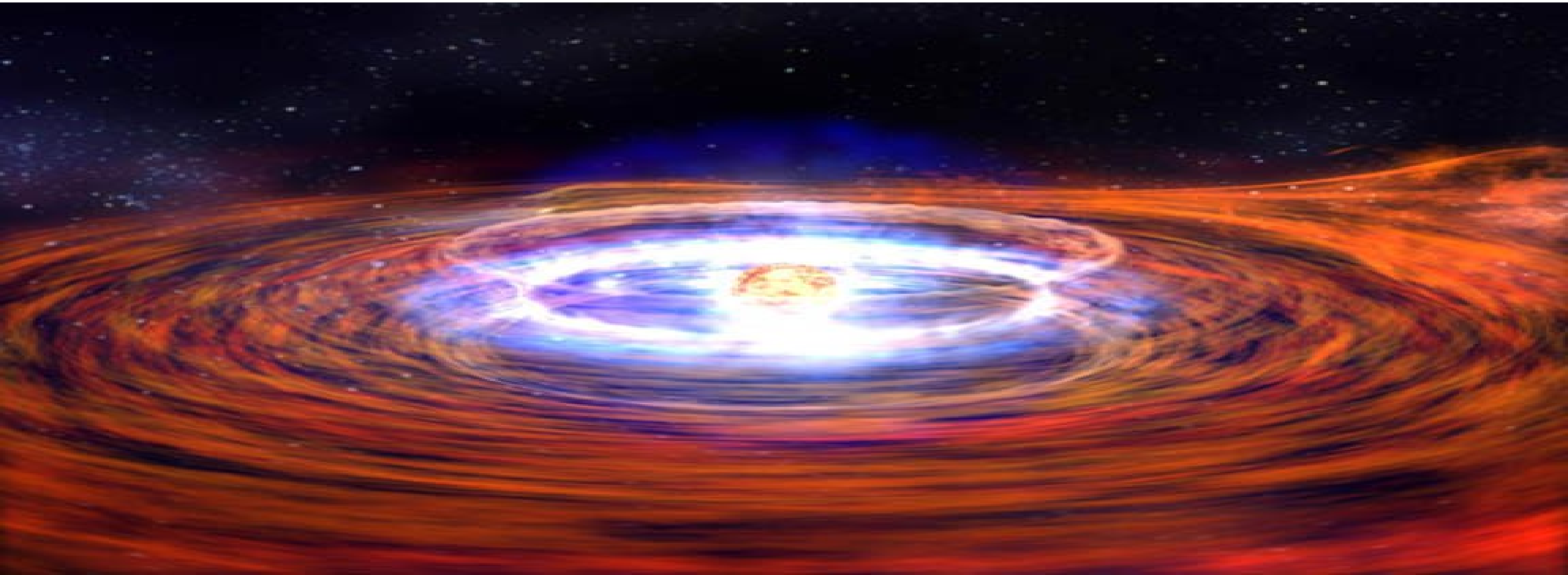
- Contain the oldest galactic stars

- Symmetrically distributed about our galaxy.

- No gas or nebulosities

The accretion disc





2. Accretion

There are four main reasons why mass transfer takes place at some stage in the evolution of close binaries:

i) One of the stars may eject as much as $10^{-5} M\odot$ of its mass in the form of a stellar wind; some material will be captured gravitationally by the companion (stellar wind accretion).

ii) In the course of its evolution, one of the two stars in a binary system may increase his radius, or the binary separation may shrink, to the point where the gravitational pull of the companion can gradually remove the outer layers of its envelope (Roche lobe overflow).

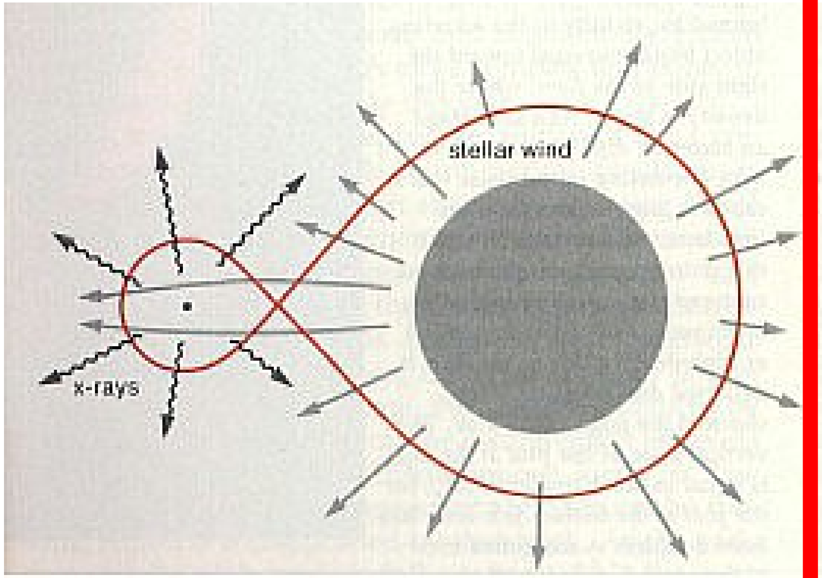
iii) Eruptive or equatorial mass loss from rapidly spinning (0.7 of the star break-up velocity) B-emission stars often in highly eccentric ($e \geq 0.3$) binary systems.

iv) X-ray emission from the compact object can irradiate the outer layers of the companion star causing or increasing the mass transfer rate.

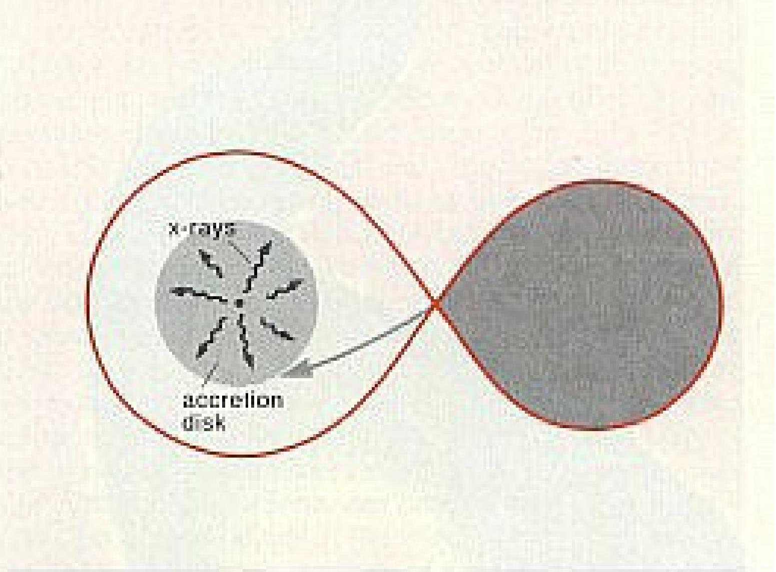
How the matter from a star can be brought to L1 point?

Two mechanisms of mass transfer in a binary system

Accretion from stellar wind



Accretion through Roche lobe outflow



Massive stars have very strong radiation-driven **stellar winds**

What is a stellar wind?

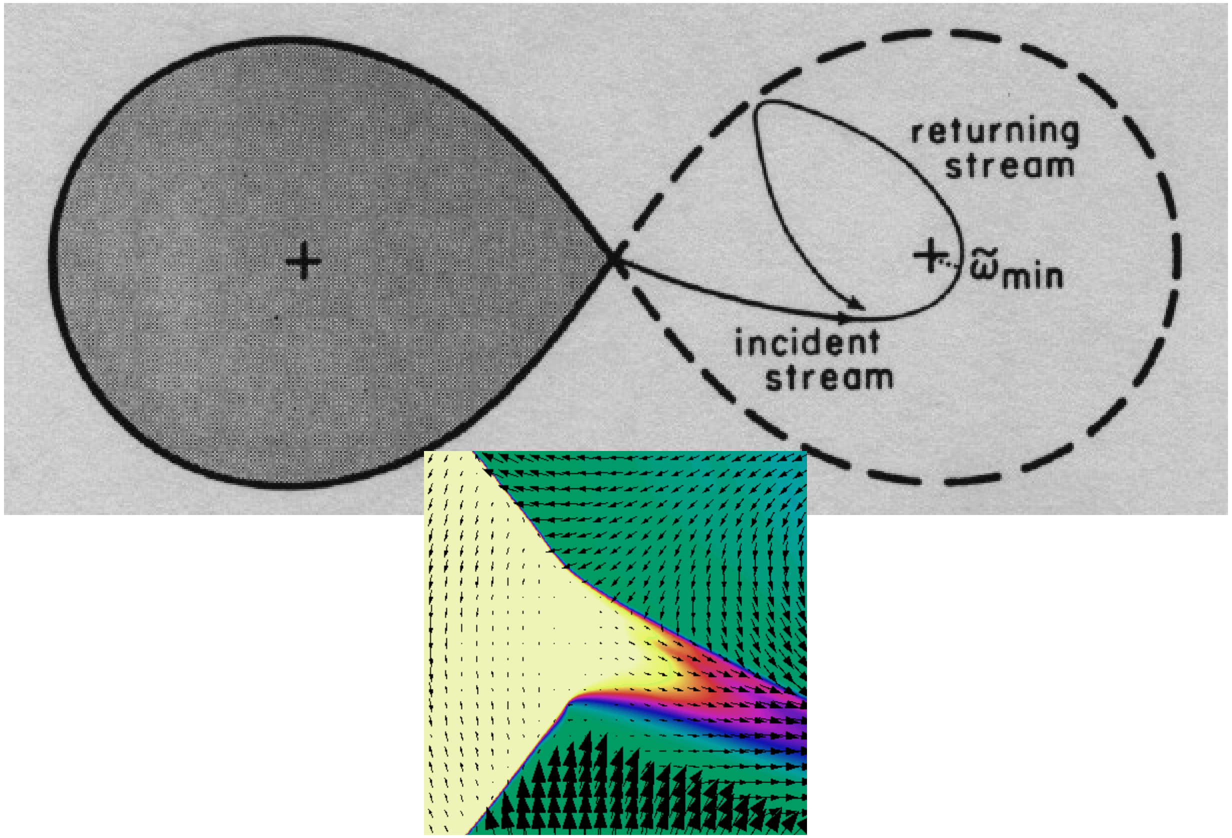
It is the *steady* loss of mass from the surface of a star into interstellar space

The Sun has a wind (the “solar wind”) but the winds of hot stars can be a *billion* times as strong as the Sun’s

Wolf-Rayet:
Intense stellar winds drive mass loss rates of several 10-5 up to 10-4 M¤ per year; the latter are at least three or four times that expected for other hot, O-type or B-type stars

Formation of an Accretion Disk

The rotation of the binary systems implies that gas flowing through the L1 point will have relatively high specific angular momentum - too much to directly accrete onto a compact companion star.



The OB stars have a substantial stellar wind removing between $10^{-10} - 10^{-5}\ M\odot/year$ (for the Sun this is as low as $10^{-14} M\odot/year$) with a terminal velocity of 2000 km/sec. A compact object in a relatively close orbit will capture a significant fraction of the wind, sufficient to power the X-ray source. LMXB tipically contains a late type (K,M) low mass donor star. A late type star does not have a natural wind strong enough to power the observed X-ray source. Significant mass transfer will occur only if the companion fills its critical gravitational potential lobe, the Roche lobe.

A disc can be formed only when the flow will carry sufficient angular momentum. Accreting matter forms a disc when its specific angular momentum J is too large to hit the accreting object (mass M_x) directly.

By setting:

$F_{grav} = F_{centr}$

$$\frac{GM_x m}{R^2} = m\omega^2 R$$

we determine the (circularization) radius:

$$R_{circ} = \frac{J'^2}{GM_X}$$

with $J' = J/m = \omega R^2$. A disc can be formed only if R_{cir} is larger than the effective size of the accretor. When the mass transfer takes place via Roche lobe the above condition is fulfilled (LPH p.2). The specific angular momentum captured from a stellar wind is determined by gradients in the wind. The magnitude of the captured specific angular momentum is much less in this case and any resulting accretion disc may be very tenuous.