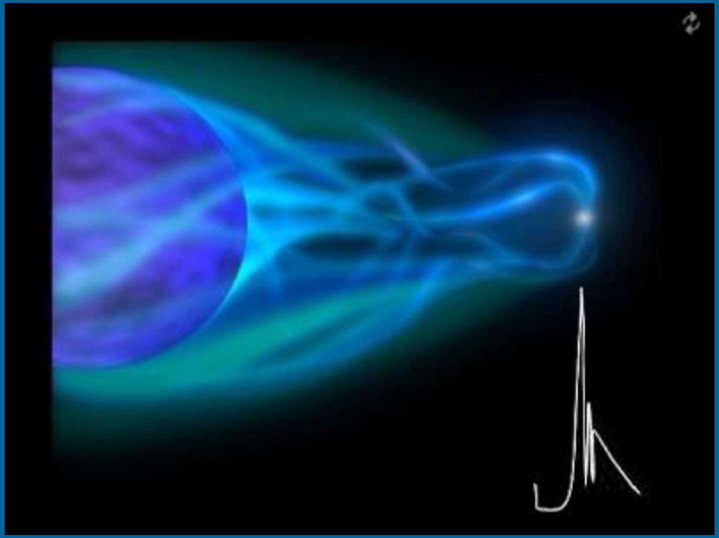
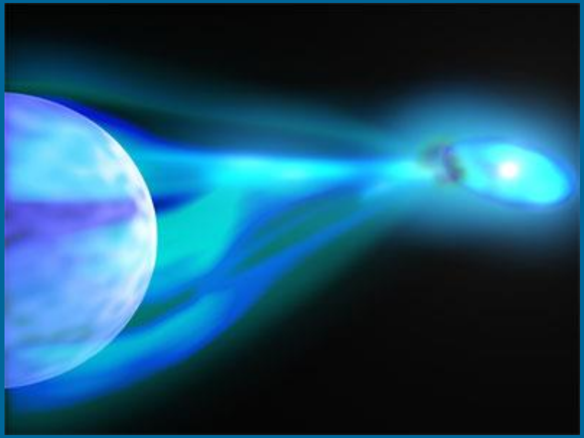
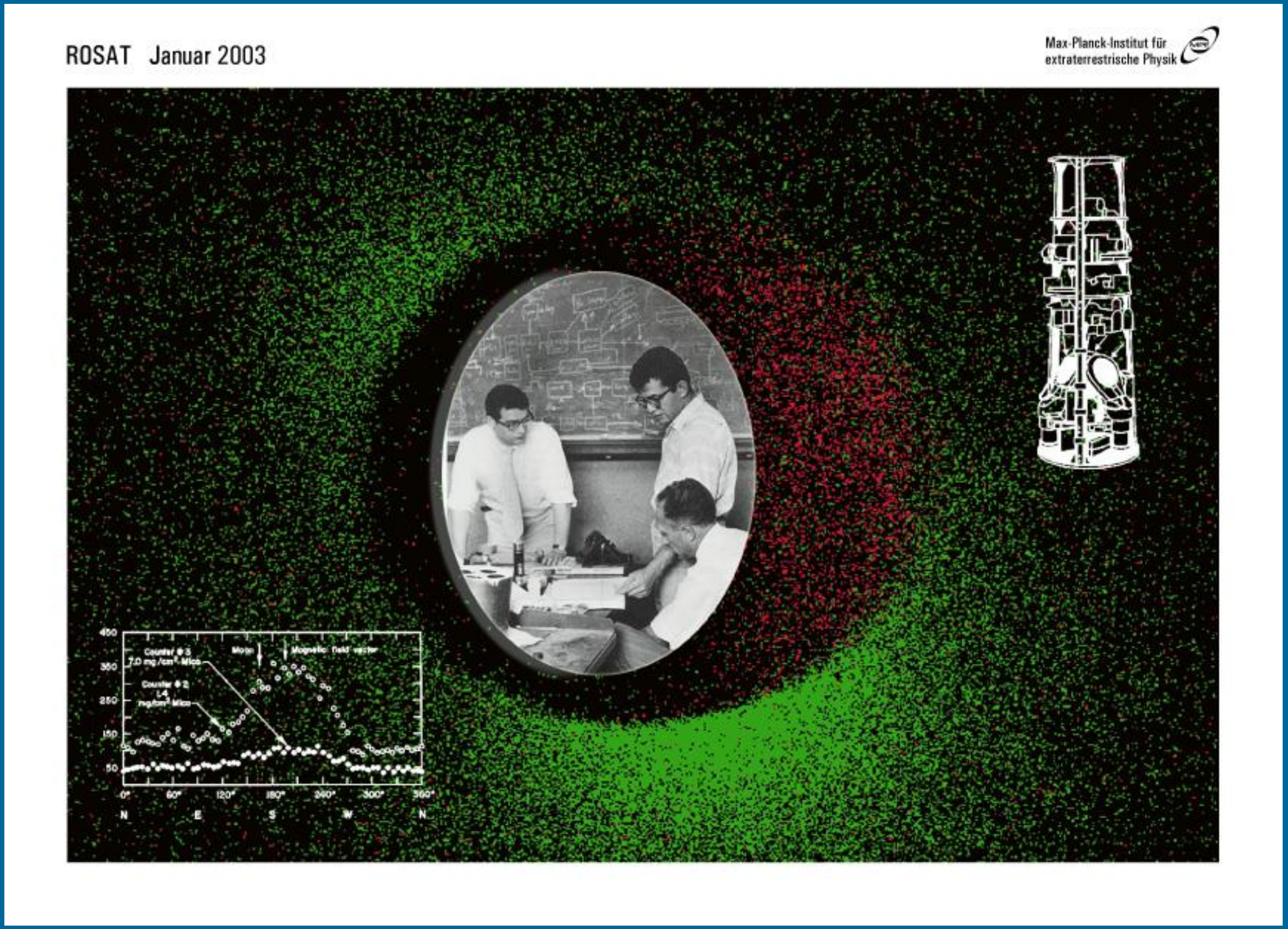
X-ray binaries



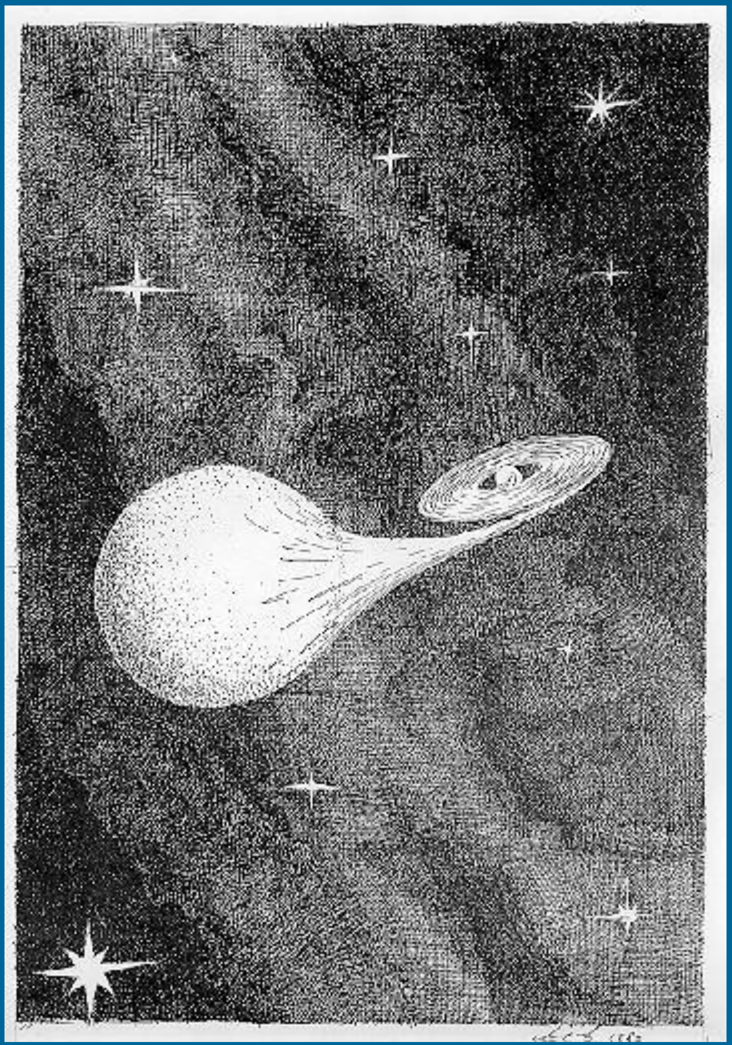


Rocket experiments. Sco X-1

Giacconi et al. 1962



Binaries are important and different!



Wealth of observational manifestations:

Visual binaries ➔ orbits, masses

Close binaries ➔ effects of mass transfer

Binaries with compact stars ➔

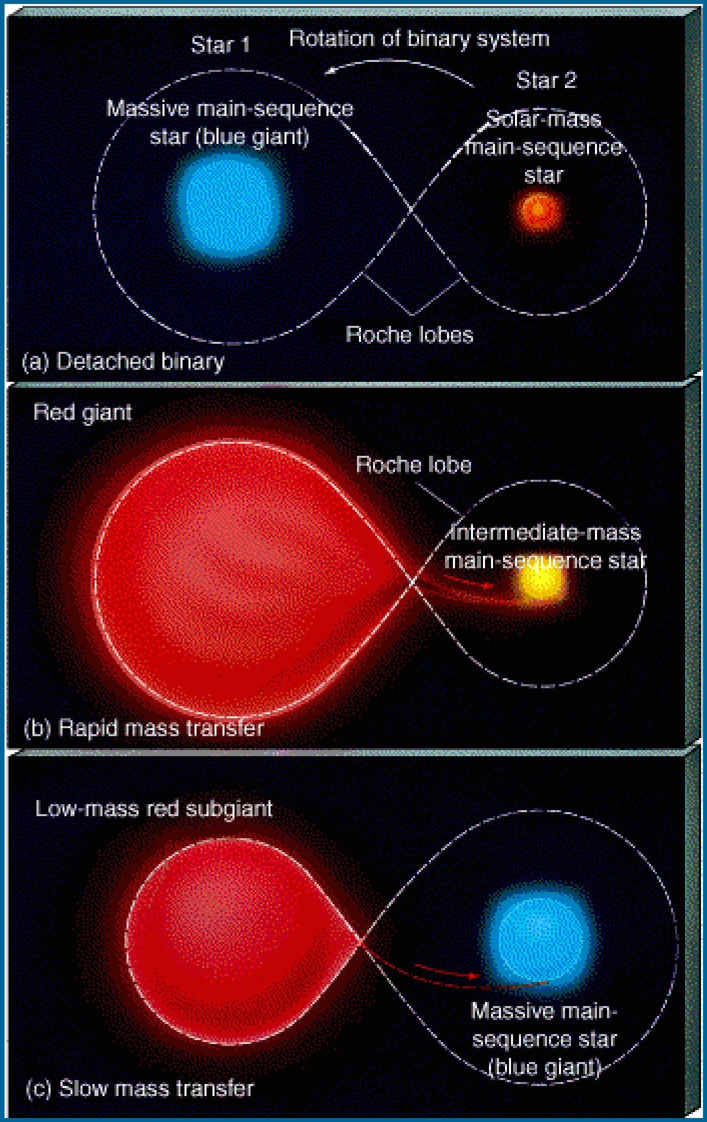
X-ray binaries, X-ray transients, cataclysmic variables, binary pulsars, black hole candidates, microquasars…

Picture: V.M.Lipunov

Algol paradox

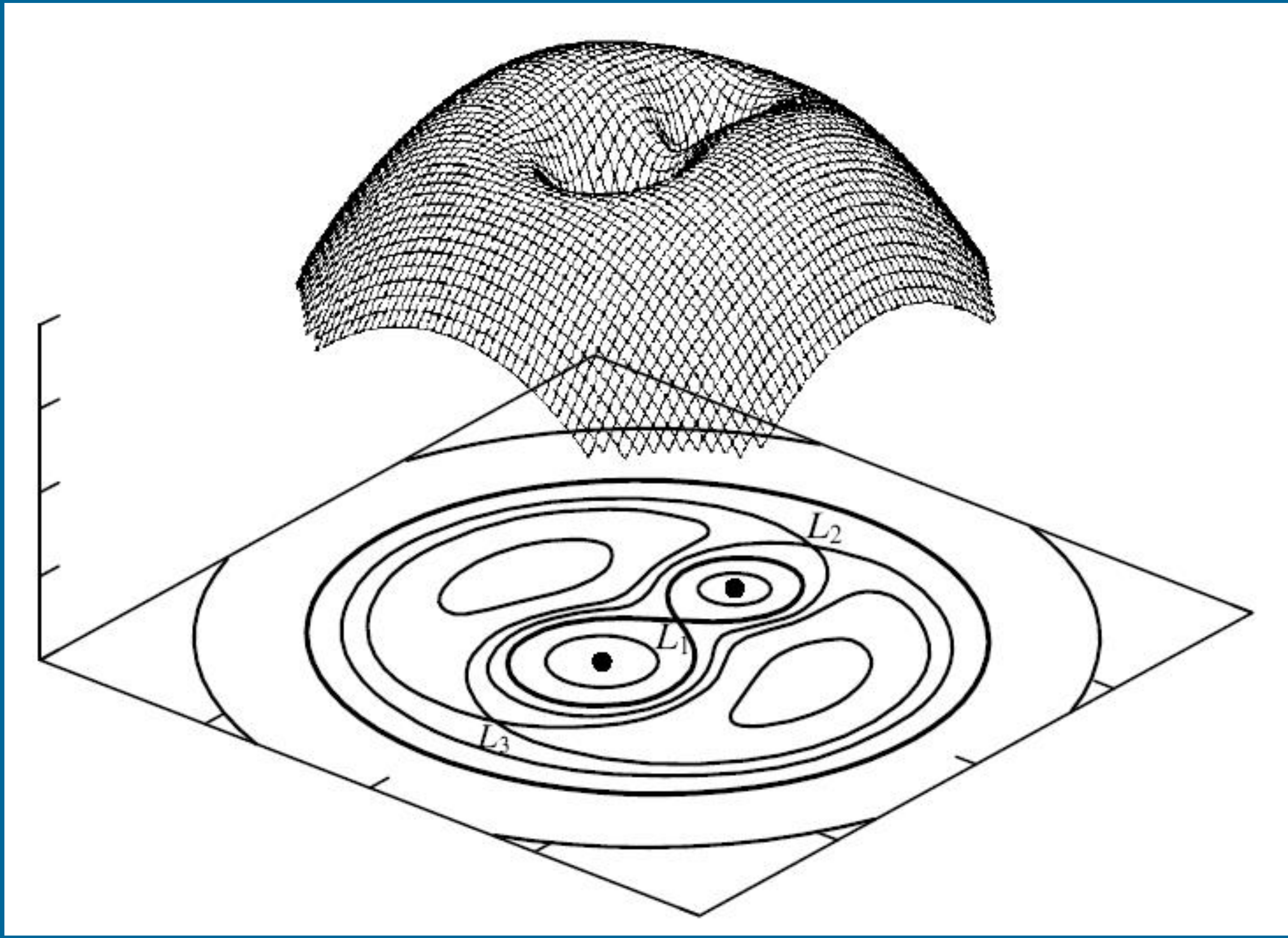
Algol (β Per) paradox:
late-type (lighter) component
is at more advanced
evolutionary stage
than the early-type (heavier) one!

Key to a solution:
component mass reversal due to
mass transfer at earlier stages!

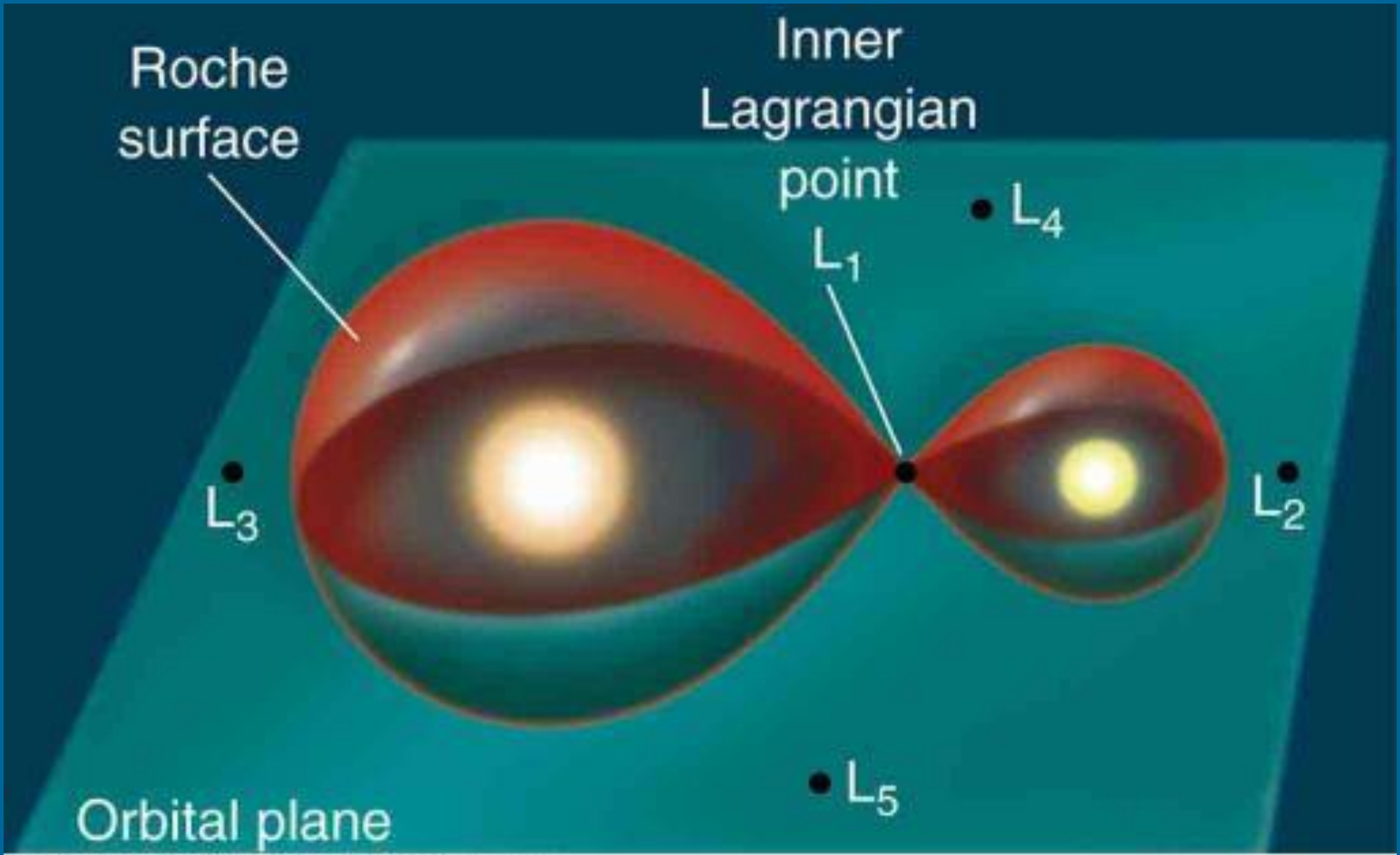


0.8 $M_\odot$ G5IV **3.7 B8 V**

Roche lobes and Lagrange points



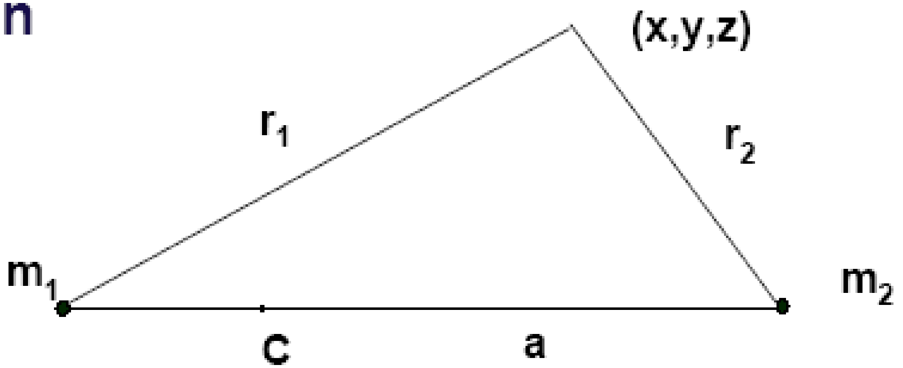
Three-dimensional representation of the gravitational potential of a binary star (in a corotating frame) and several cross sections of the equipotential surfaces by the orbital plane. The Roche lobe is shown by the thick line


Roche surface
Inner Lagrangian point
L_1
L_2
L_3
L_4
L_5
Orbital plane

Roche Potential

Assumes:

- synchronous rotation
- circular orbit
- 2 point masses
- rotating frame



$$\omega^2 = \left(\frac{2\pi}{P}\right)^2 = \frac{G\,M}{a^3}$$

$$r_1^{\,2} = x^2 + y^2 + z^2 \qquad r_2^{\,2} = (\,x - a\,)^2 + y^2 + z^2$$

$$\frac{x_c}{a} = \frac{m_2}{M} = \frac{q}{1+q} \qquad q \equiv \frac{m_2}{m_1} \le 1$$

$$\Phi = -\frac{G\,m_1}{r_1} - \frac{G\,m_2}{r_2} - \frac{\omega^2}{2}\left[(\,x - x_c\,)^2 + y^2\right]$$

Dimensionless Roche Potential

$$\text{factor out } -\frac{\omega^2}{2} = -\frac{G\,M}{2\,a^3} \quad \text{and} \quad x \to \frac{x}{a}, \quad \text{etc.}$$

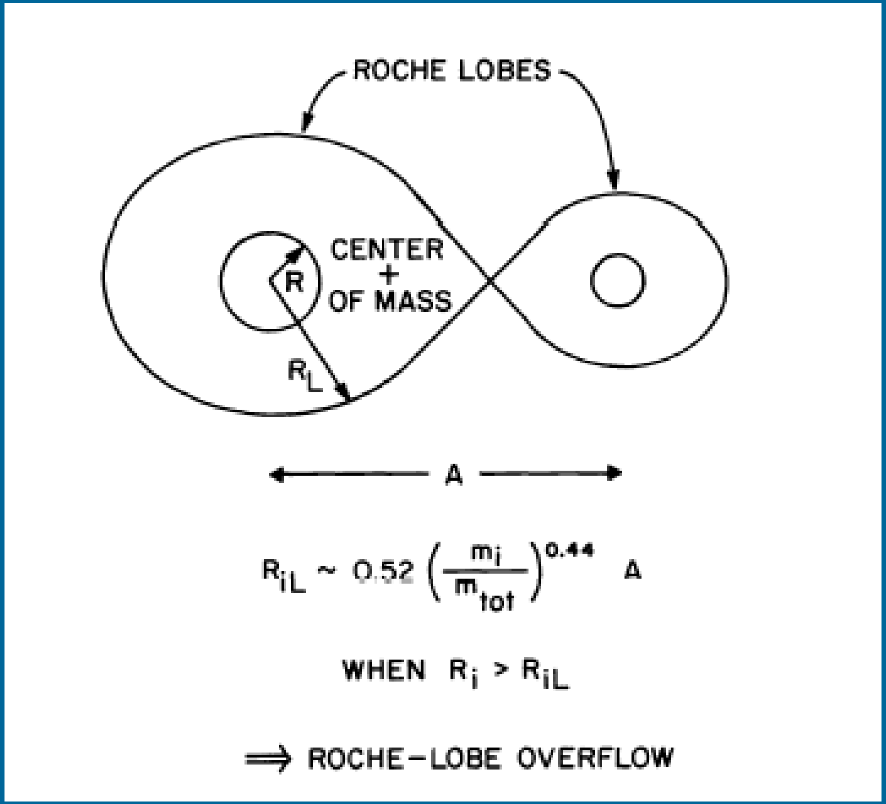
$$\Phi(x,y,z) = -\frac{\omega^2}{2}\,\Phi_N\left(\frac{x}{a},\frac{y}{a},\frac{z}{a},\right)$$

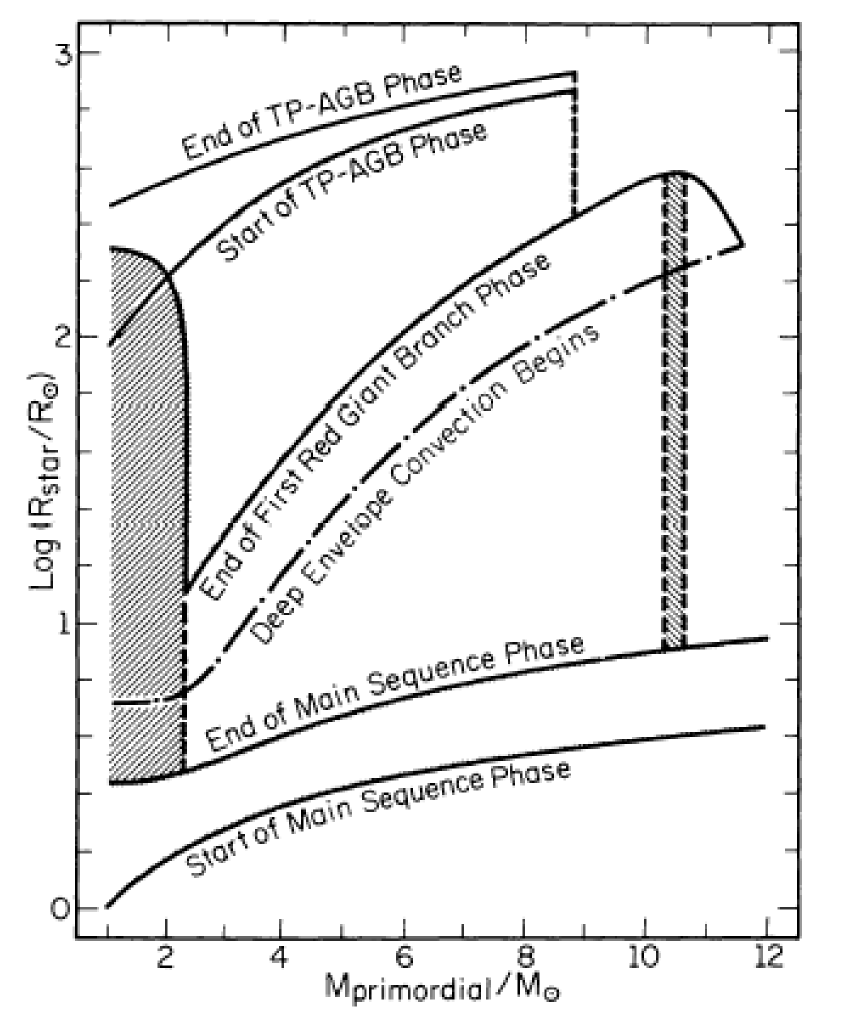
dimensionless Roche Potential:

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

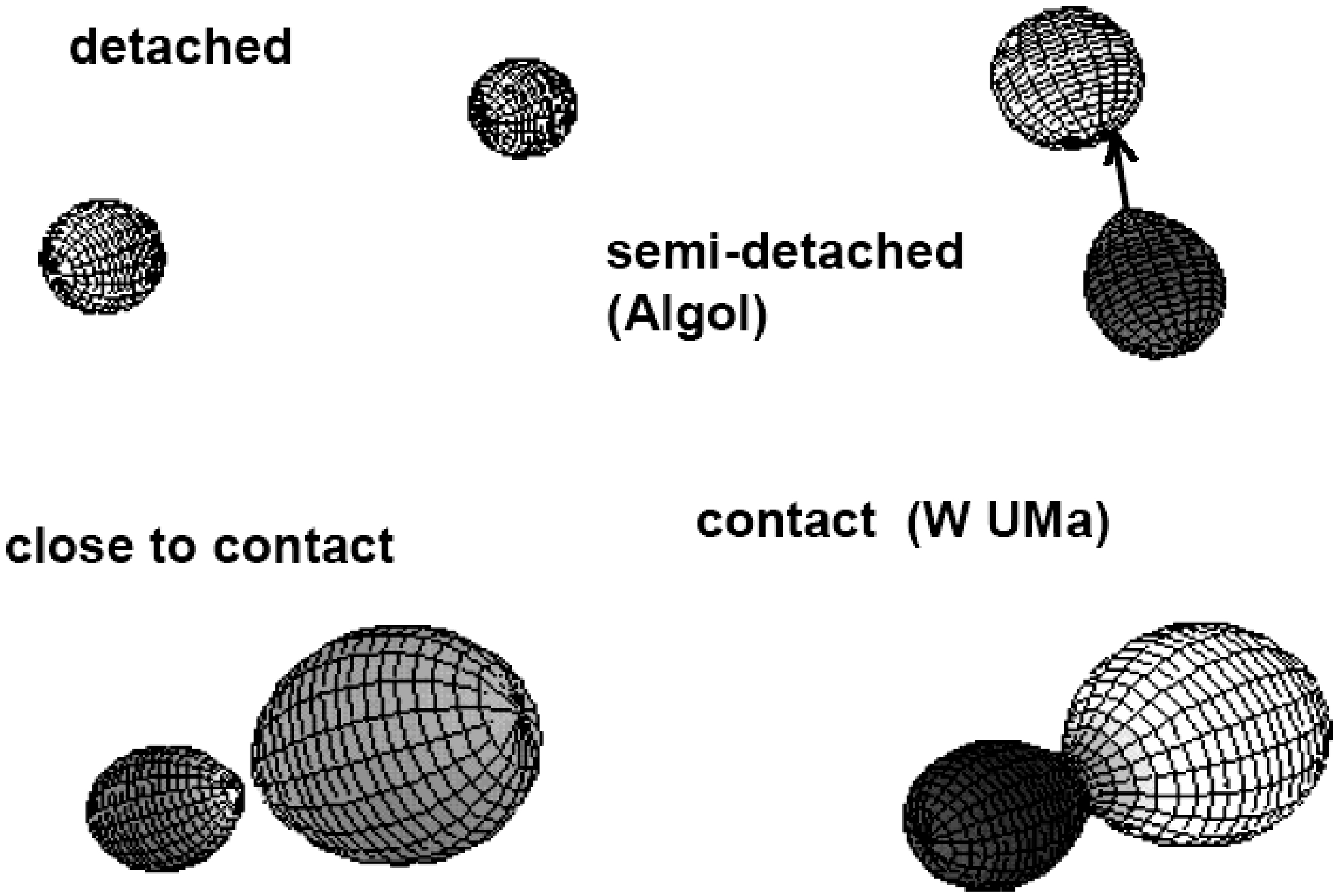
Describes shape of potential surfaces independently of the mass and size of the system.

single parameter : q

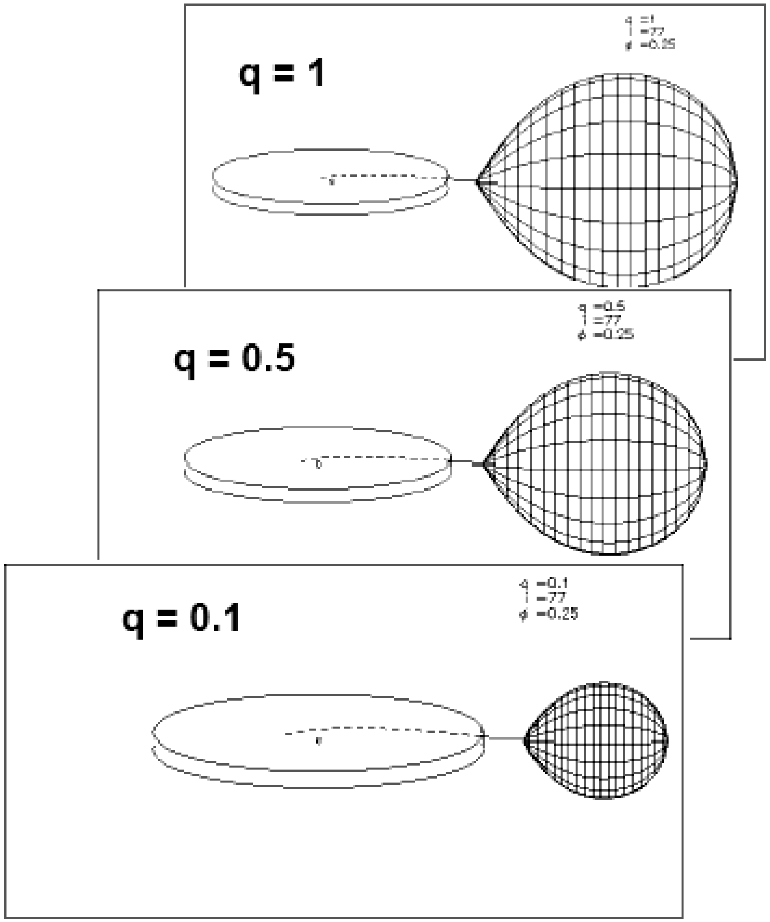

ROCHE LOBES
CENTER
+
OF MASS
R
R_L
A
$R_{iL} \sim 0.52 \left(\frac{m_i}{m_{tot}}\right)^{0.44} A$
WHEN $R_i > R_{iL}$
$\Longrightarrow$ ROCHE-LOBE OVERFLOW


End of TP-AGB Phase
Start of TP-AGB Phase
End of First Red Giant Branch Phase
Deep Envelope Convection Begins
End of Main Sequence Phase
Start of Main Sequence Phase
$\mathrm{Log}\,(R_{star}/R_\odot)$
$M_{primordial}/M_\odot$
0
1
2
3
2
4
6
8
10
12

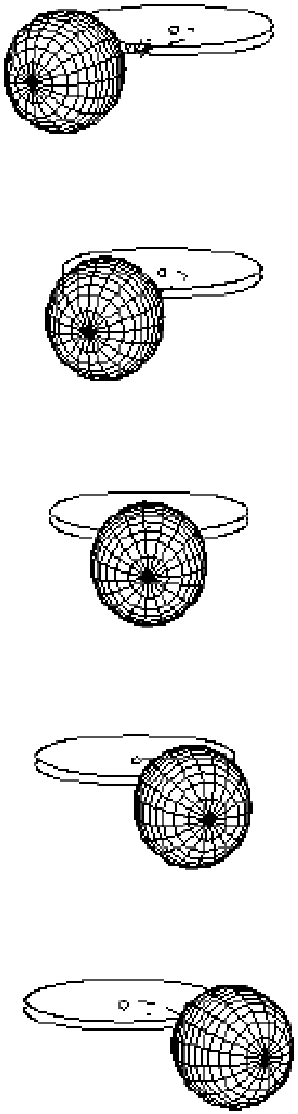
Binaries in Roche-Lobes



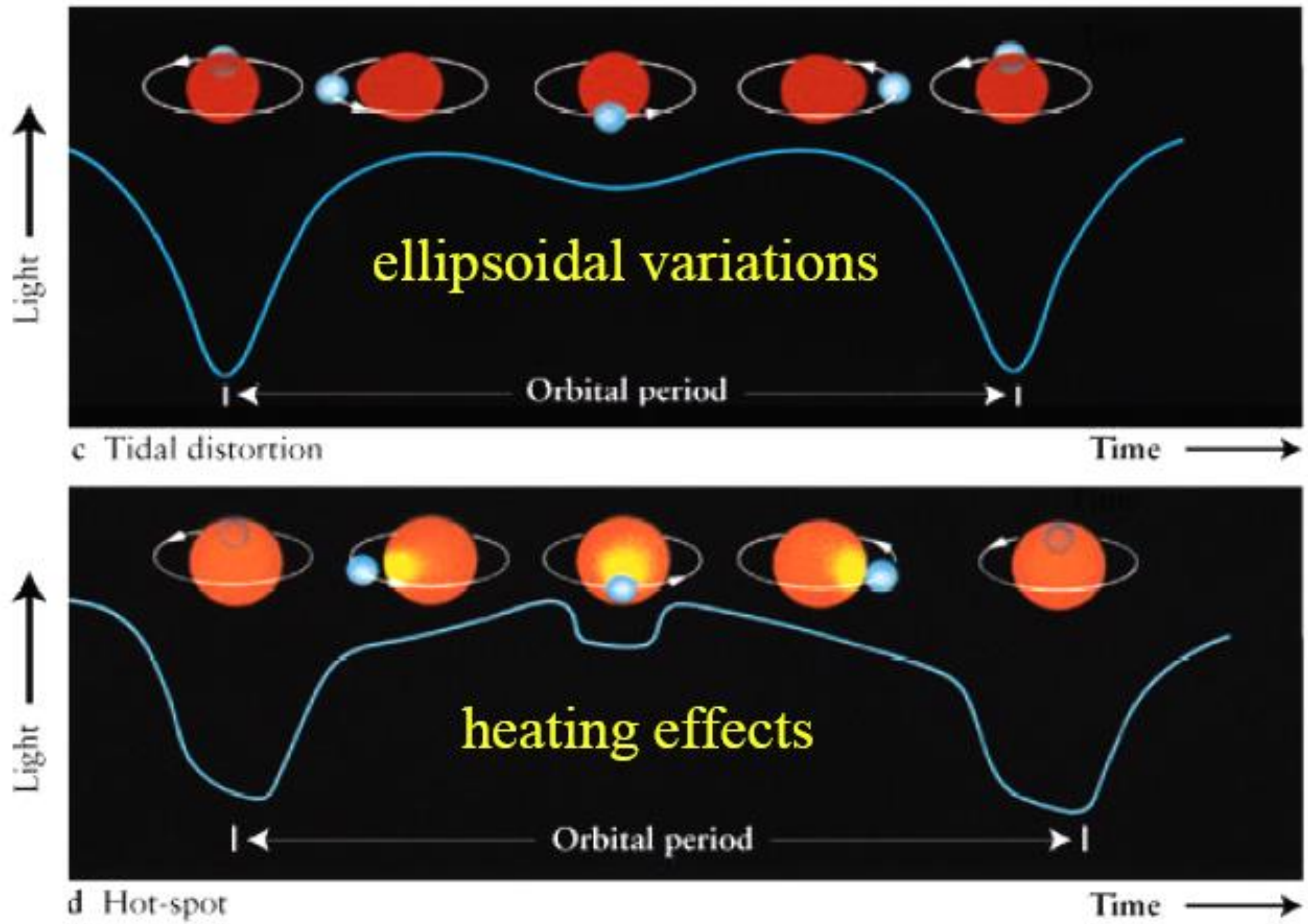
Roche Lobes



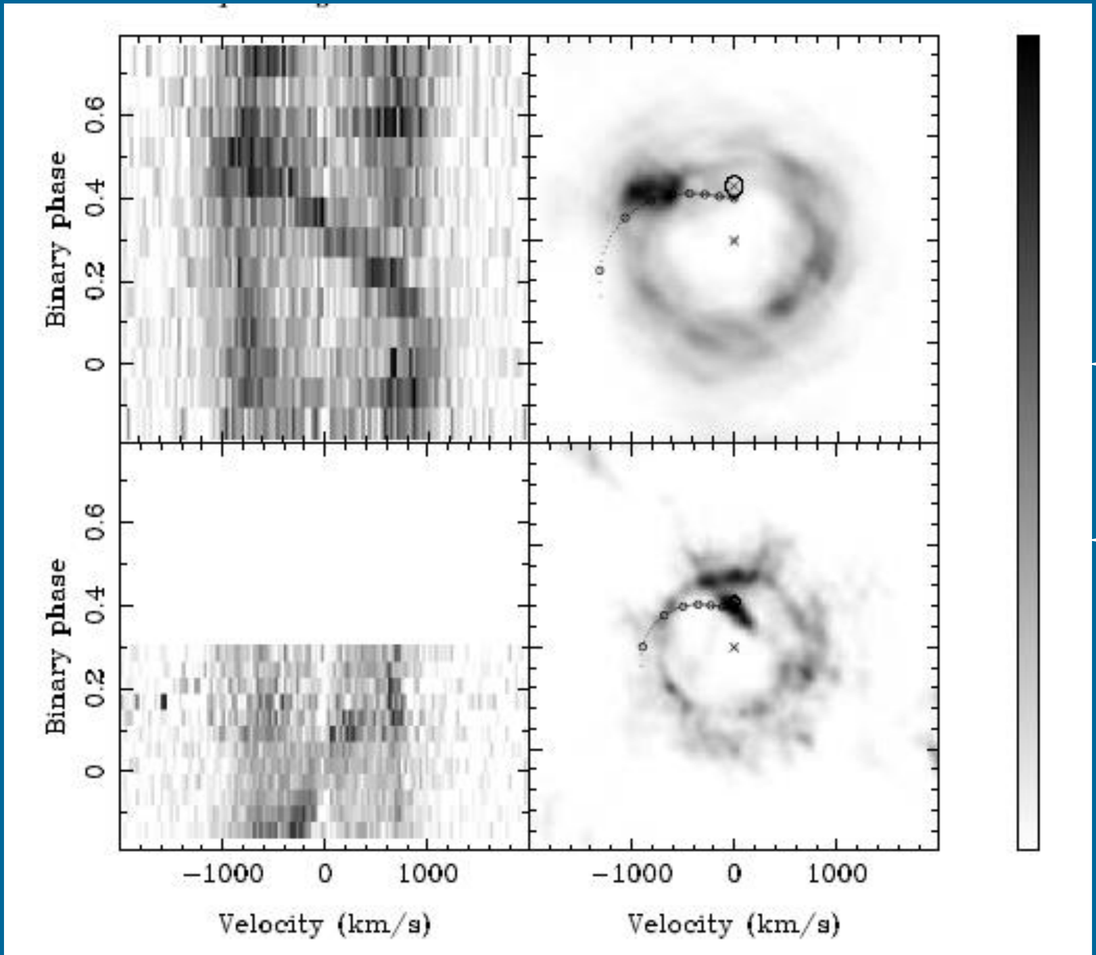
eclipses



Proximity Effects



GS 2000+25 and Nova Oph 1997



On the left – Hα spectrum,
On the right – the Doppler image

GS 2000+25

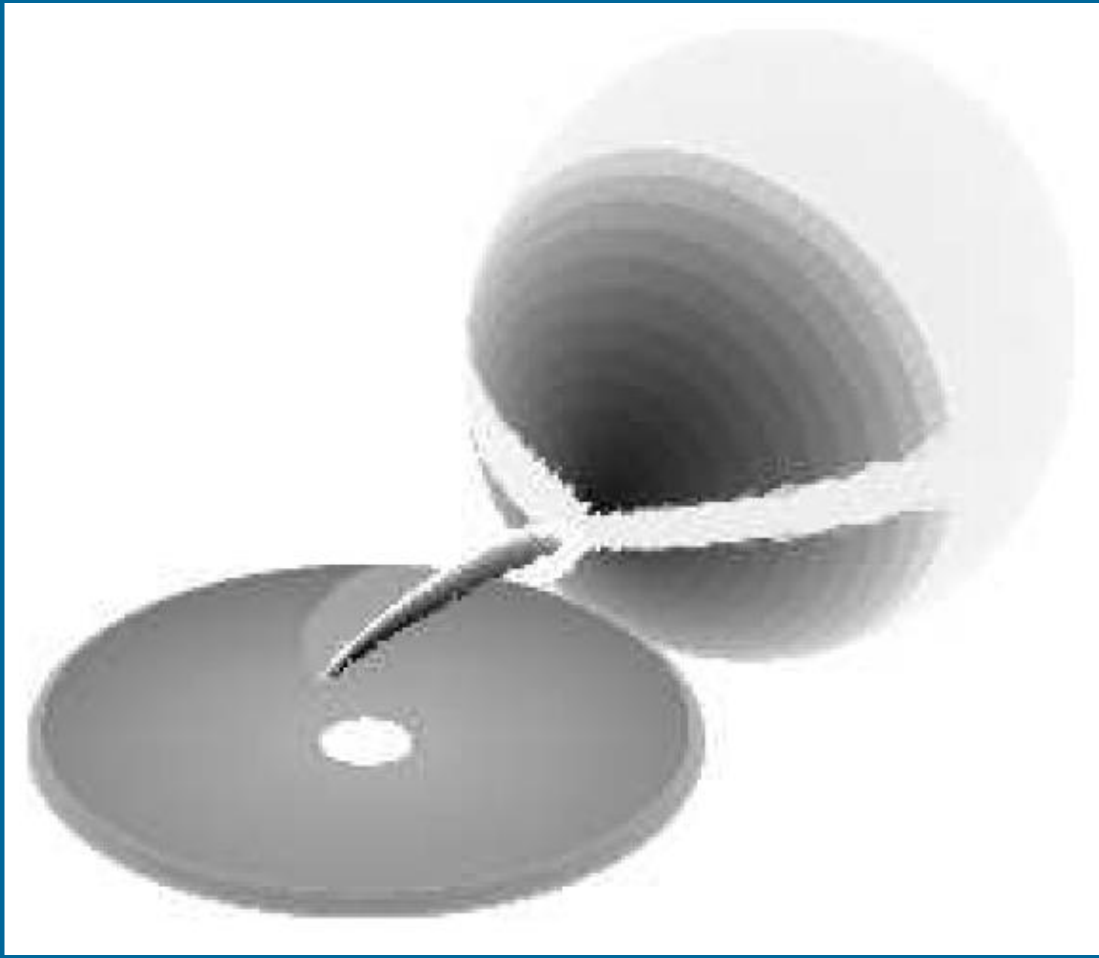
Nova Oph 1997

See a review in Harlaftis 2001 (astro-ph/0012513)

(Psaltis astro-ph/0410536)

There are eclipse mapping, doppler tomography (shown in the figure), and echo tomography (see 0709.3500).

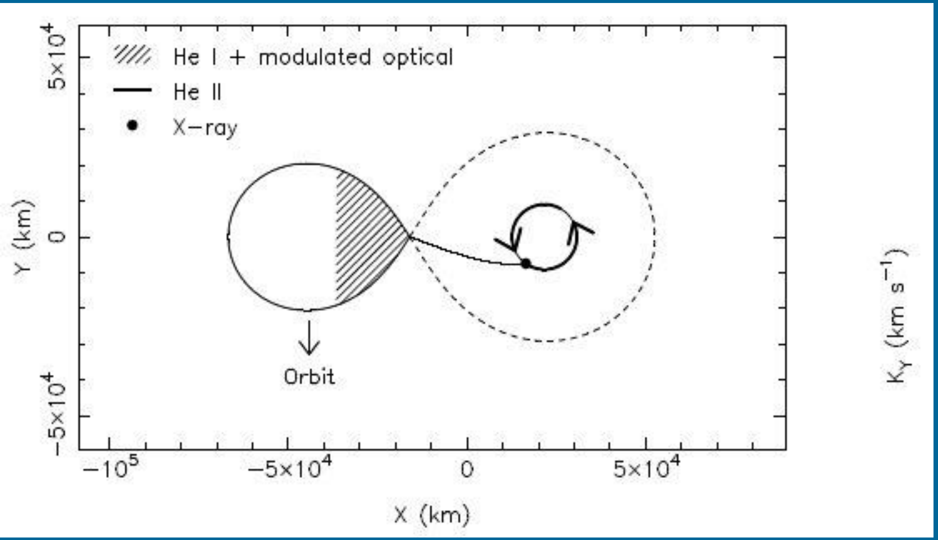
Models for the XRB structure



(astro-ph/0012513)

The tightest binary

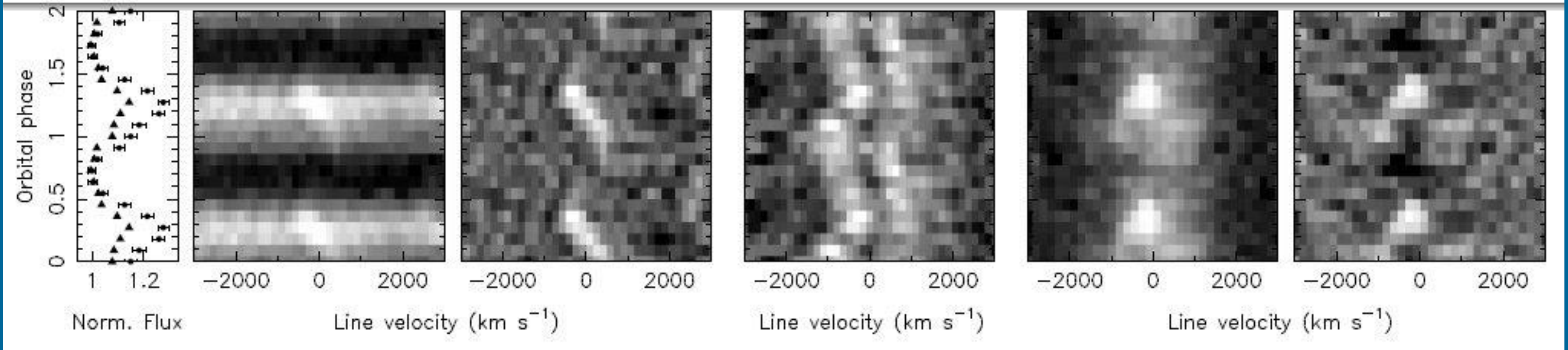
Two white dwarfs.
Orbital period 321 seconds!
Distance between stars: <100 000 km.
Orbital velocity > 1 000 000 km per hour!
Masses: 0.27 and 0.55 colar
Gravitational wave emission



HM Cancri

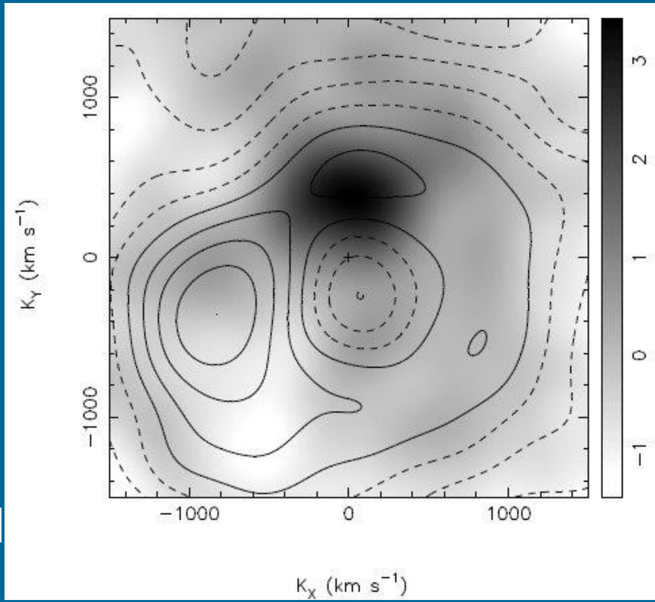
arXiv: 1003.0658

How is it measured?



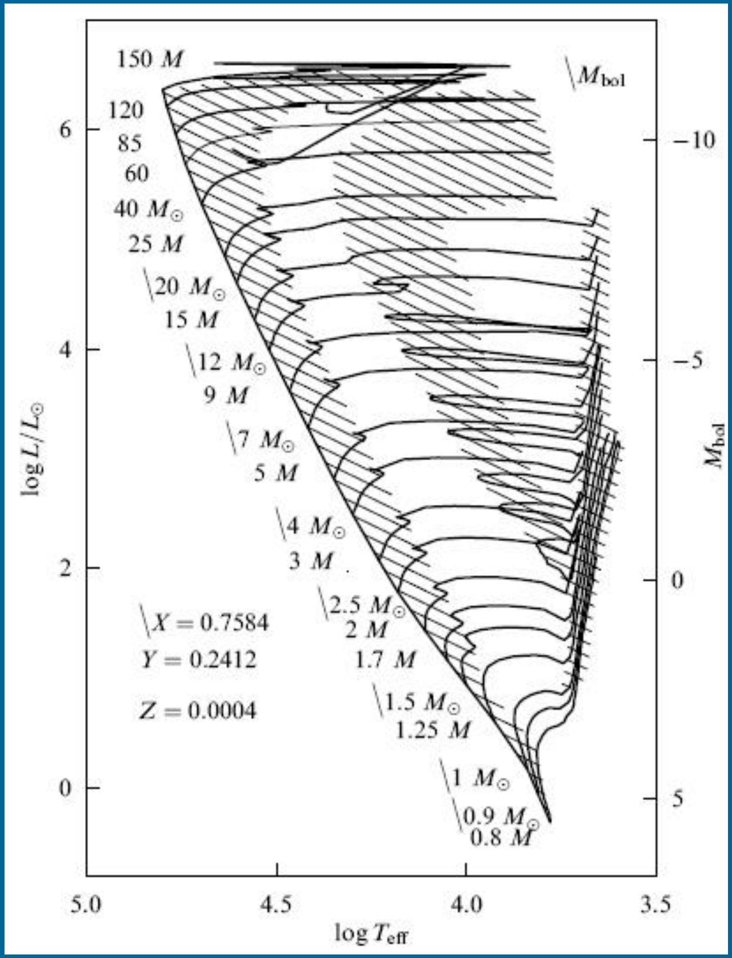
Specta obtained by the Keck telescope.
Due to orbital motion spectral lines are shifted:
one star – blueshifted, another – redshifted.
The effect is periodic with the orbital period.

Doppler tomograms of He I 4471 (gray-scale) and He II 4686 (contours).
The (assumed) irradiation-induced He i 4471 emission from the secondary star has been aligned with the positive K_Y -axis.



arXiv: 1003.0658

Evolution of normal stars



Evolutionary tracks of single stars with masses from 0.8 to 150M. The slowest evolution is in the hatched regions (Lejeune T, Schaerer D Astron. Astrophys. 366 538 (2001))

A track for a normal 5 solar mass star

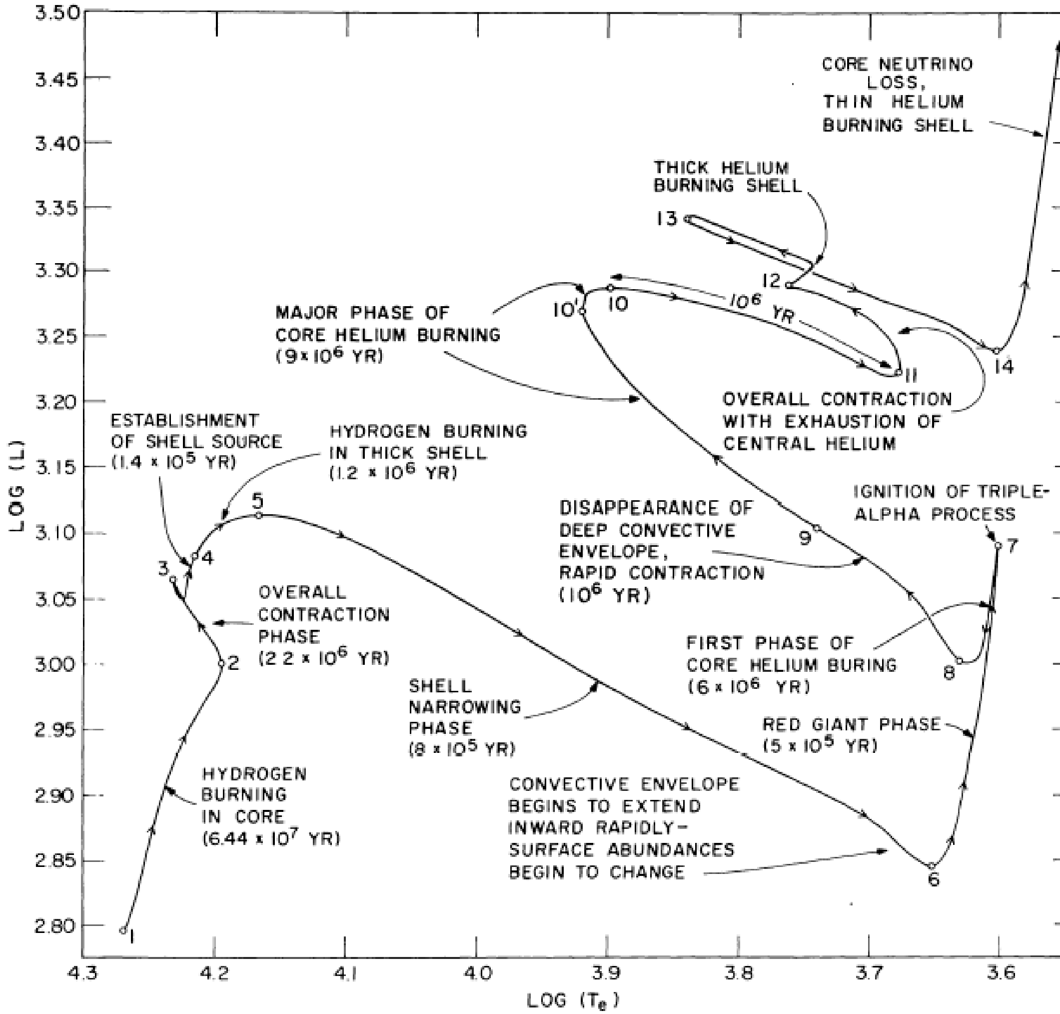
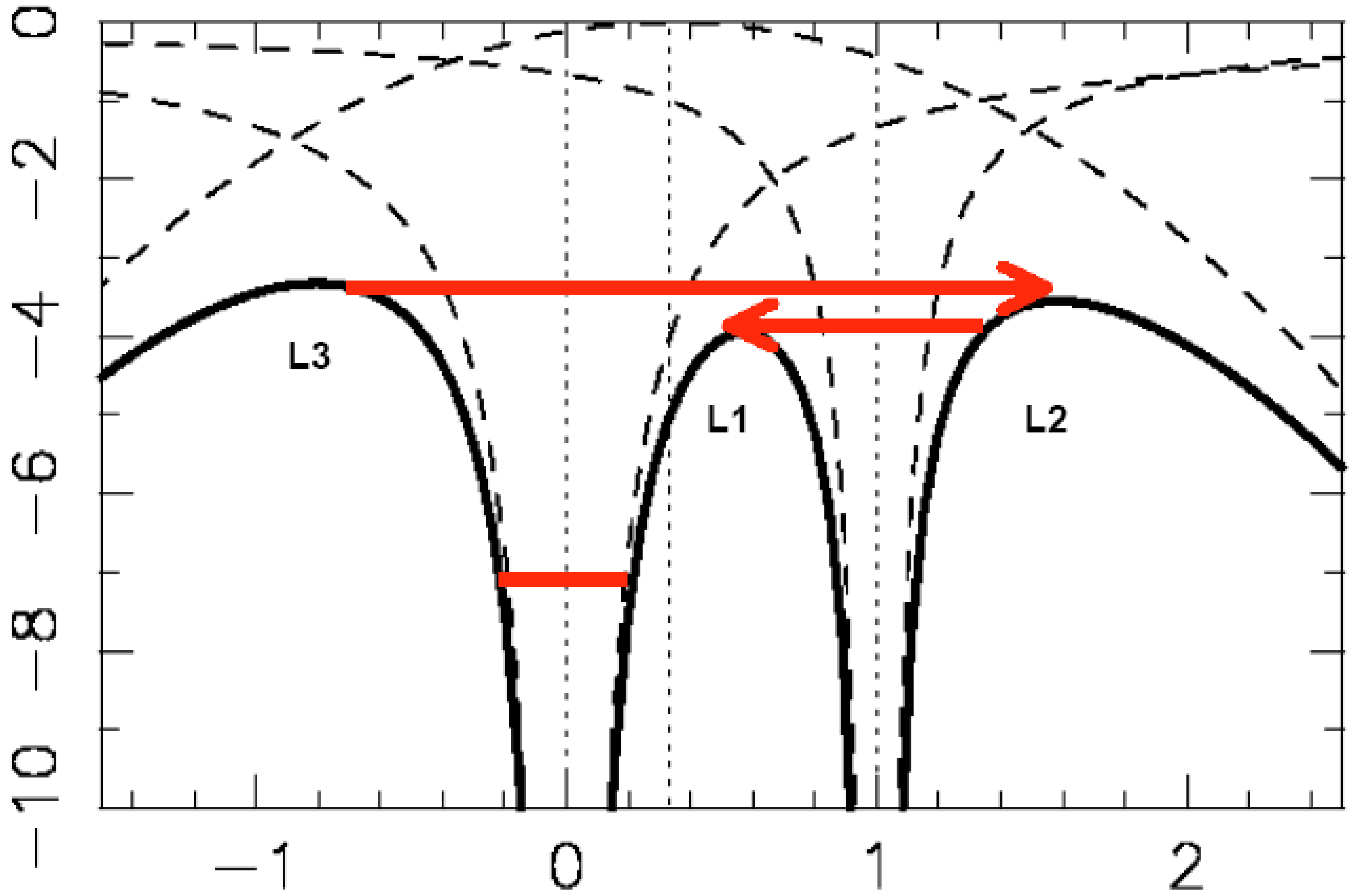
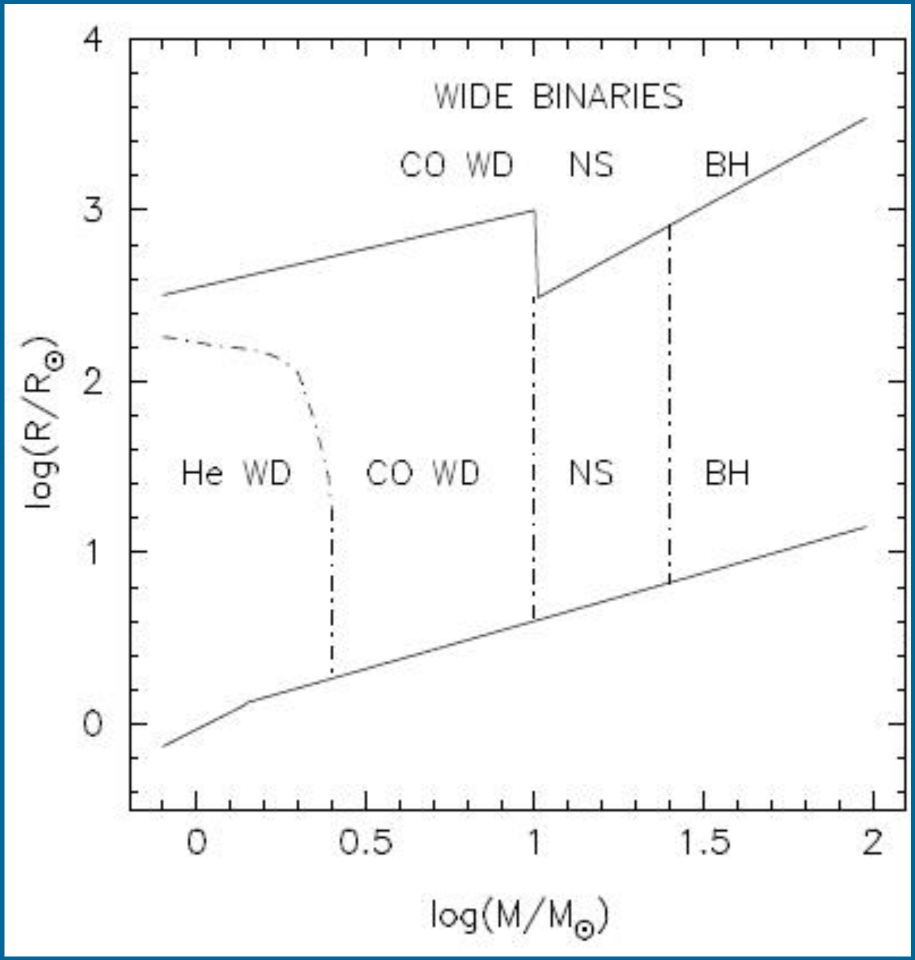


FIG. 2.—The track in the H-R diagram of a theoretical model star of mass 5 $M_{\odot}$ and of Population I composition. Text beside various portions of the track describe an important physical process occurring within the star at the indicated position. From Iben (1967*c*).

Mass transfer and loss



Progenitors and descendants



Descendants of components of close binaries depending on the radius of the star at RLOF.

The boundary between progenitors of He and CO-WDs is uncertain by several $0.1M_O$.
The boundary between WDs and NSs by ~ $1M_O$, while for the formation of BHs the lower mass limit may be even by ~ $10M_O$ higher than indicated.

[Postnov, Yungelson 2007]

Mass loss and evolution

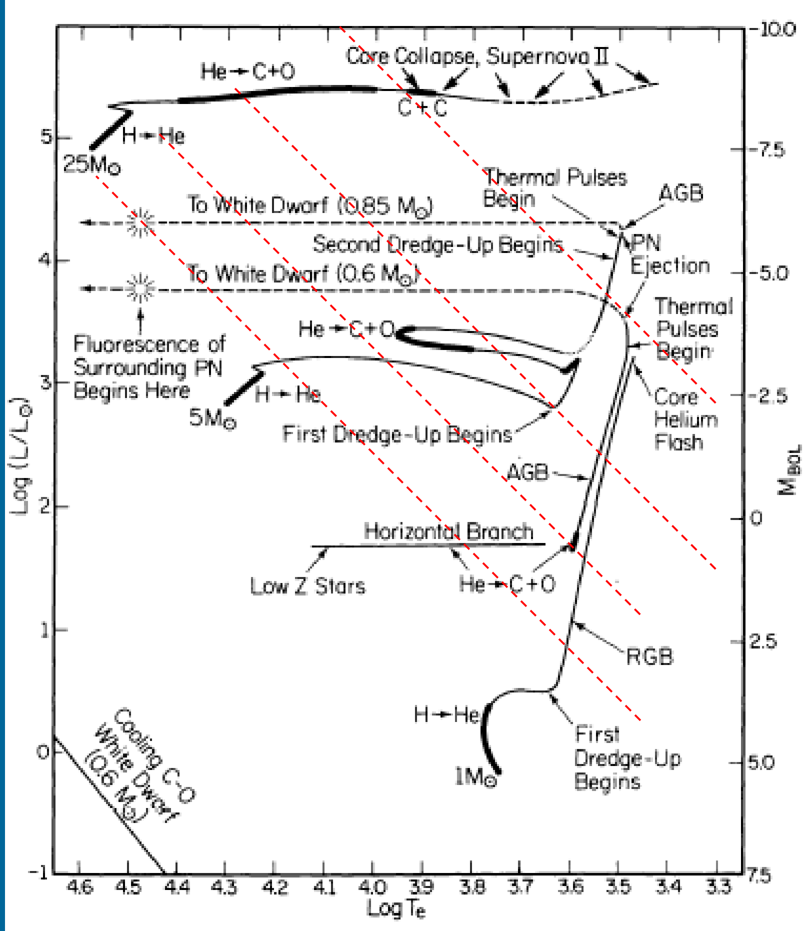


FIG. 5.—Tracks in the H-R diagram of theoretical model stars of low (1 $M_\odot$), intermediate (5 $M_\odot$), and high (25 $M_\odot$) mass. Nuclear burning on a long time scale occurs along the heavy portions of each track. The places

Mass loss depends on
which stage of evolution
the star fills its Roche lobe

If a star is isentropic
(e.g. deep convective envelope - RG stage),
mass loss tends to increase R with
decreasing M which generally leads to
unstable mass transfer.

Evolution of a 5M star in a close binary

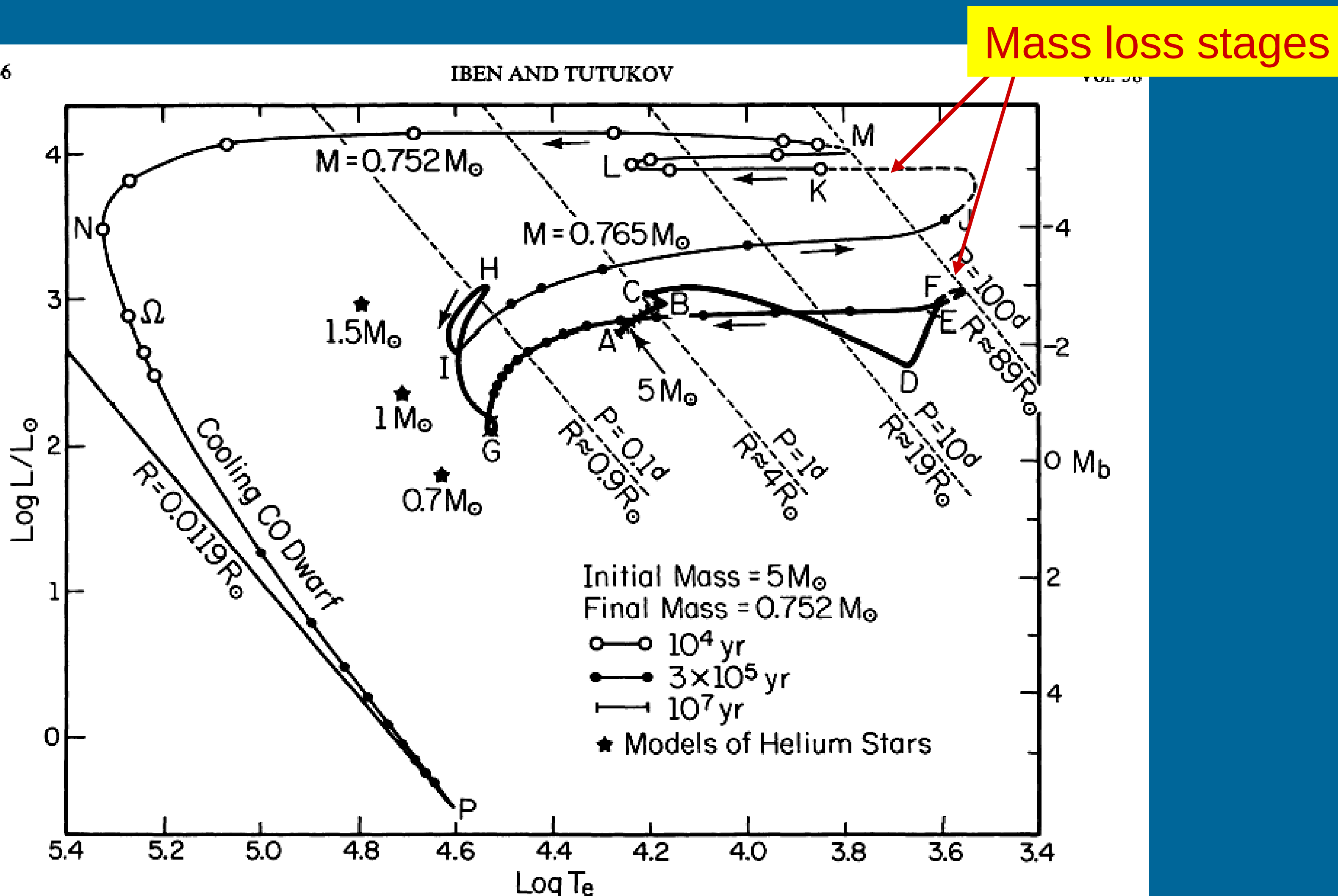
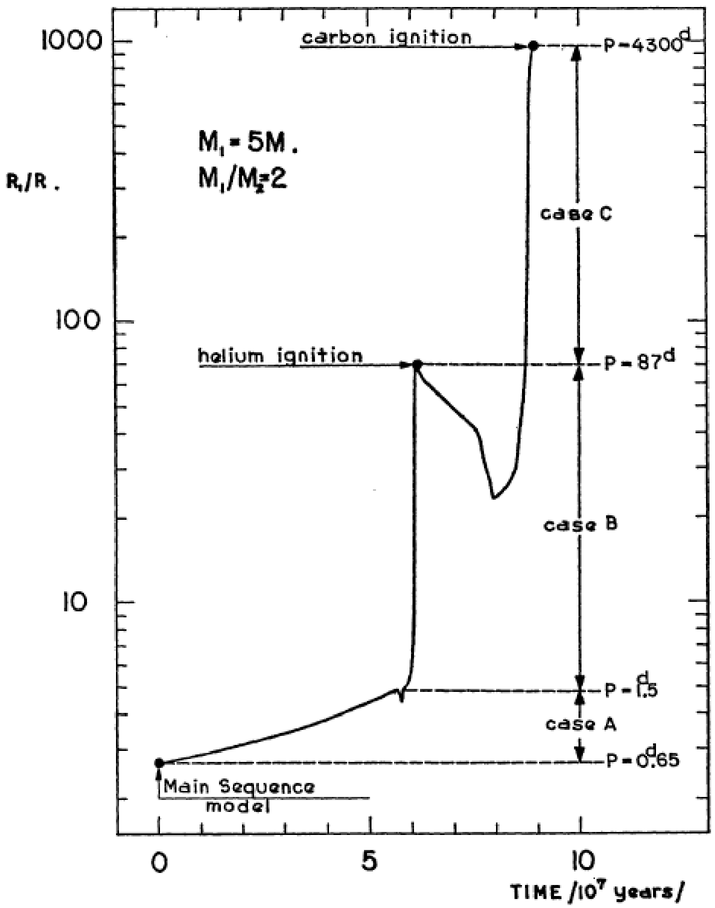


FIG. 1.—Evolution in the H-R diagram of a binary component of initial mass 5 $M_\odot$. Initial composition parameters are $X = 0.7$, $Z = 0.02$. The positions of helium model stars are given by the filled, five-pointed "stars" (Paczyński 1971). Lines of constant orbital period and Roche-lobe radius for a system consisting of two 5 $M_\odot$ unevolved stars are also shown. The temperature of the CO shell reaches a maximum at the point Ω along the track. The main parameters of the stellar model at other labeled points (A, B, ...) are presented in Table 1. Mass loss occurs along dashed portions of the track (E to F; J to K). Time evolution is measured by tick marks (10^7 yr), filled circles (3×10^5 yr), and open circles (10^4 yr).

Different cases for Roche lobe overflow

PACZYŃSKI



URE 1. The time variation of the radius of a 5 $M_\odot$ star. The ranges of orbital corresponding to the evolution with mass exchange in cases A, B, and C are d. A mass ratio of $M_1/M_2=2$ is adopted.

Three cases of
mass transfer loss
by the primary star
(after R.Kippenhahn)

In most important case B mass transfer occurs on thermal time scale:

$$dM/dt \sim M/\tau_{KH}\,,\ \tau_{KH}=GM^2/RL$$

In case A: on nuclear time scale:

$$dM/dt \sim M/t_{nuc}$$

$$t_{nuc} \sim 1/M^2$$

Close binaries with accreting compact objects

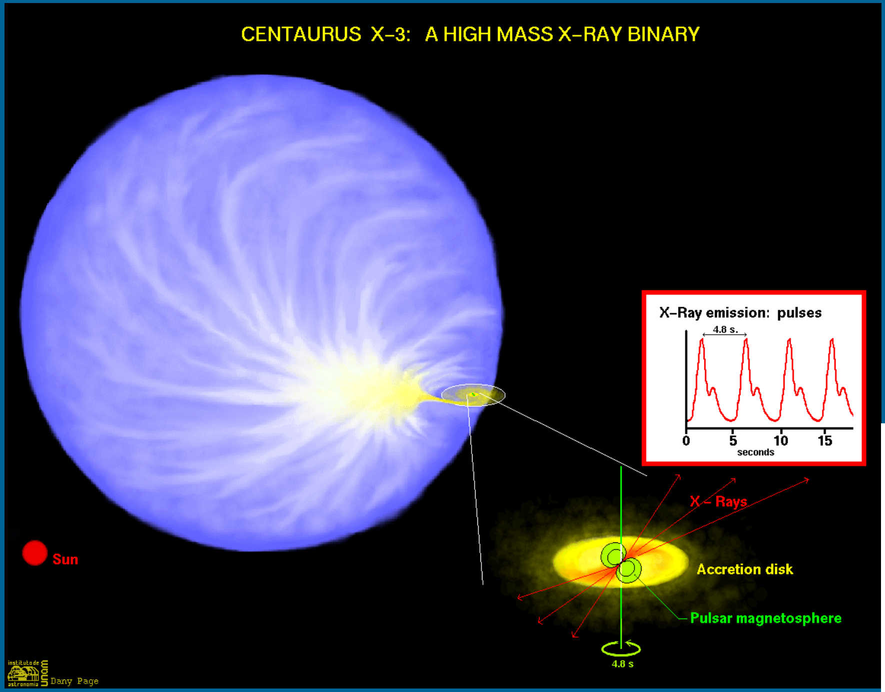
LMXBs
Roche lobe overflow.
Very compact systems.
Rapid NS rotation.
Produce mPSRs.

IMXBs
Very rare.
Roche lobe overflow.
Produce LMXBs(?)

HMXBs
Accretion from
the stellar wind.
Mainly Be/X-ray.
Wide systems.
Long NS spin periods.
Produce DNS.

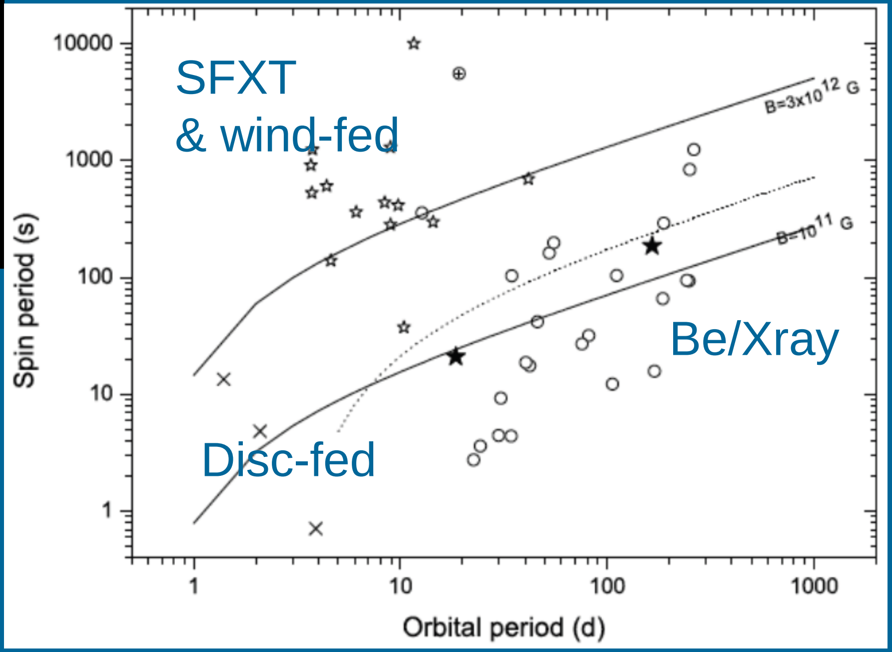
Among binaries ~ 40% are close and ~96% are low and intermediate mass ones.

HMXBs



Different types:

- Be/Xray binaries
- SFXT
- “Normal” supergiants
  - disc-fed
  - wind-fed

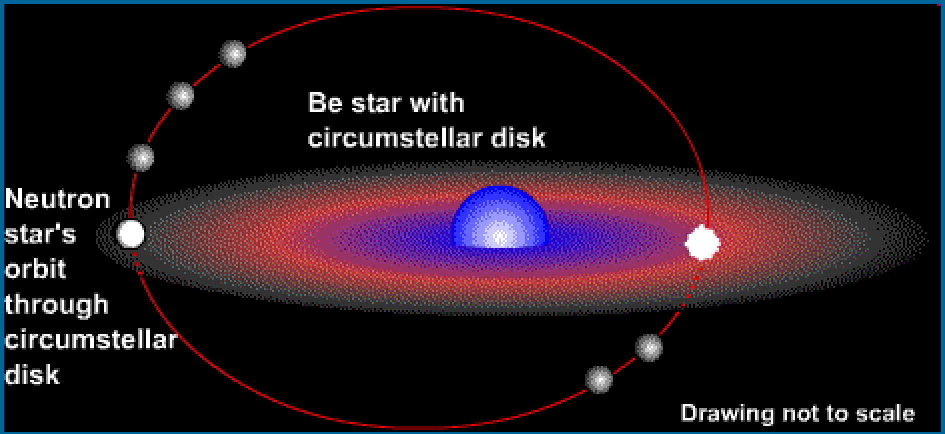


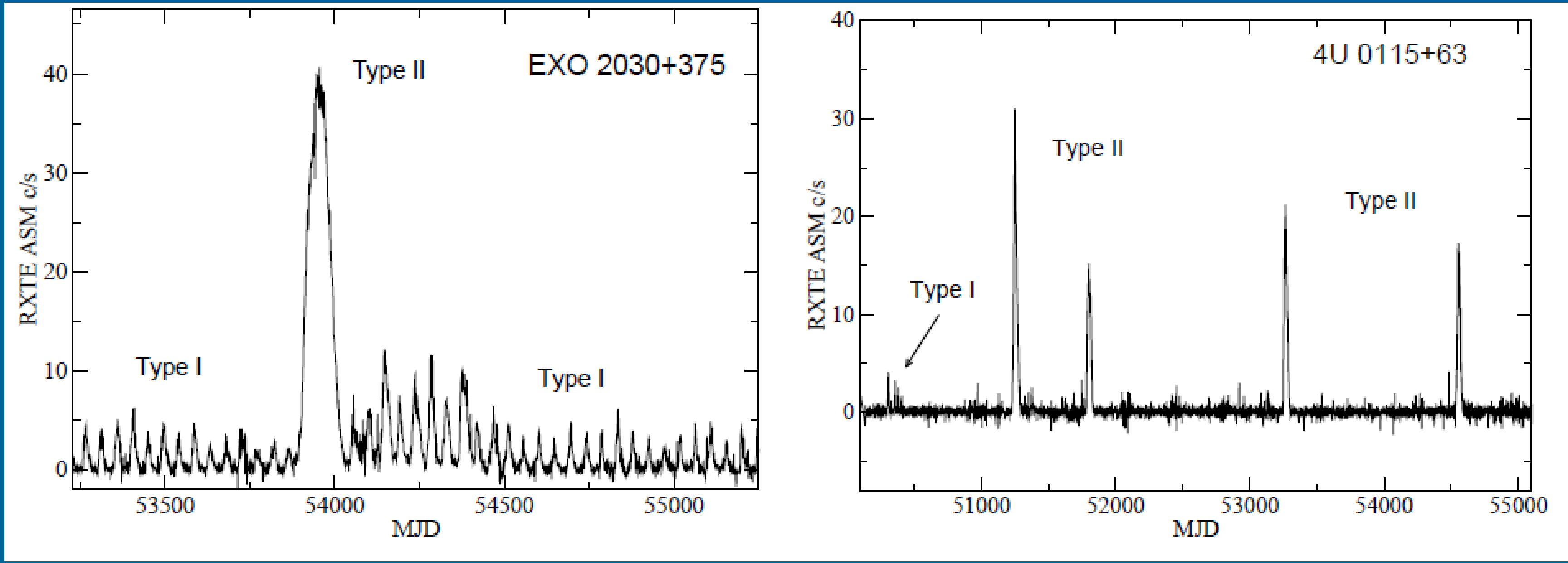
>100 in the Galaxy and >100 in MC

1012.2318

Be/X-ray binaries

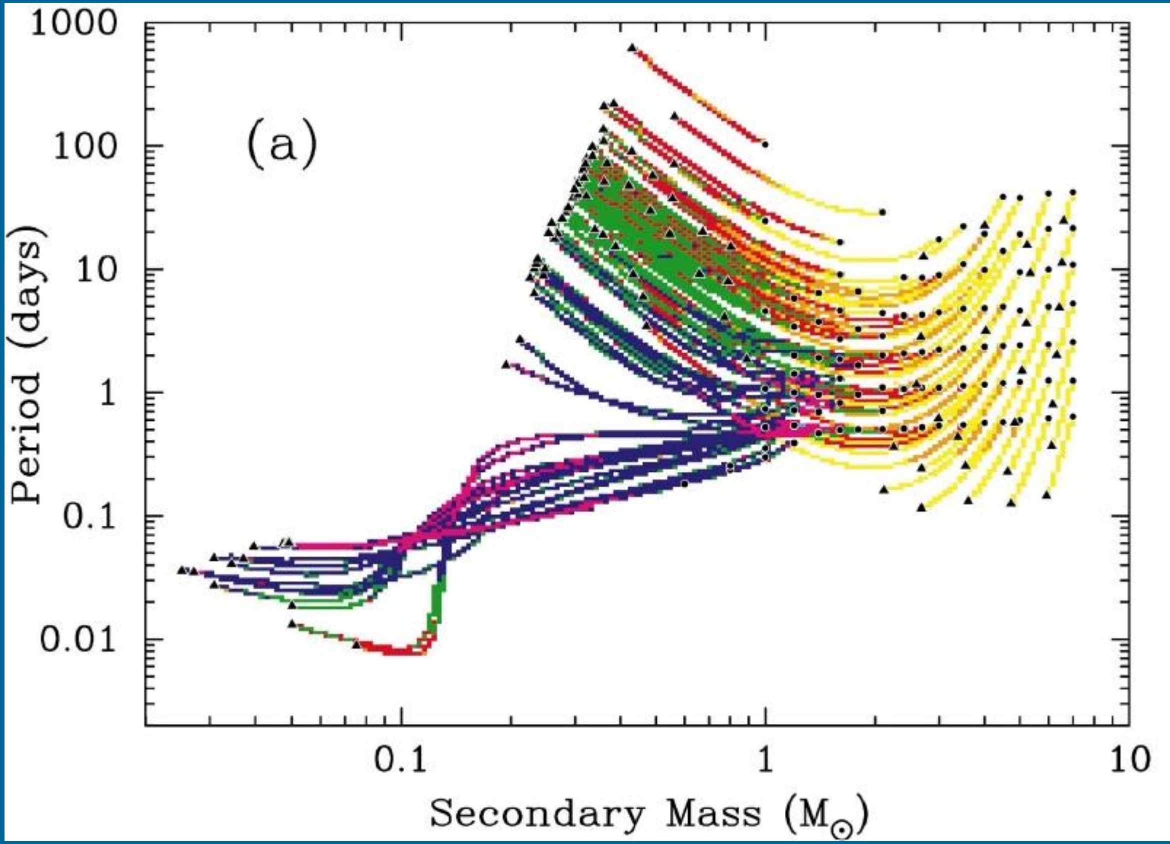
Very numerous.
Mostly transient.
Eccentric orbits.





1101.5036

Intermediate mass X-ray binaries



Most of the evolution time systems spend as an X-ray binary occurs after the mass of the donor star has been reduced to <$1M_\odot$

Otherwise, more massive systems experiencing dynamical mass transfer and spiral-in.

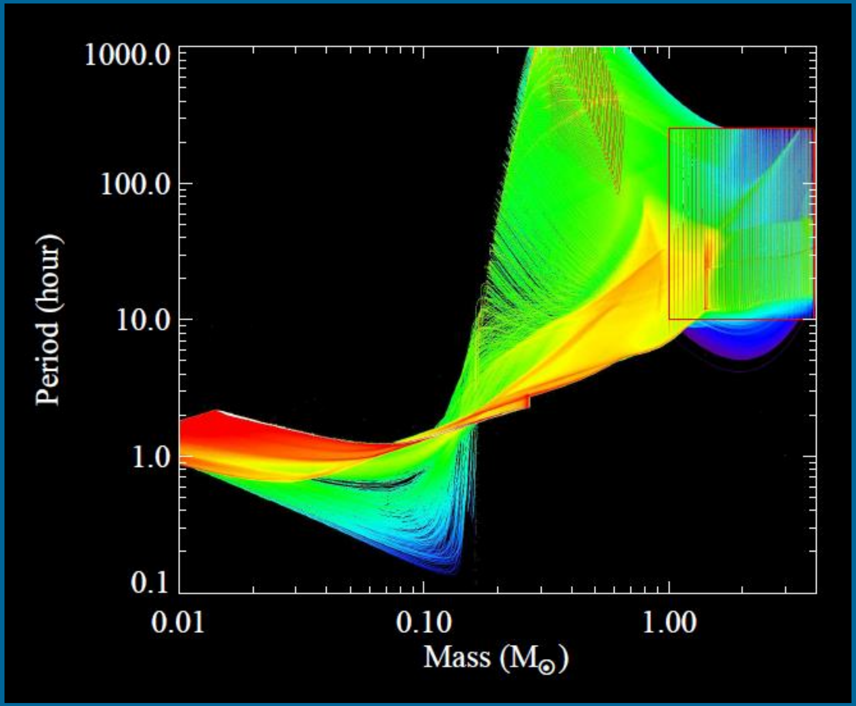
The color of the tracks indicates how much time systems spend in a particular rectangular pixel in the diagrams (from short to long: yellow, orange, red, green, blue, magenta, cyan).

(Podsiadlowski et al., ApJ 2002)

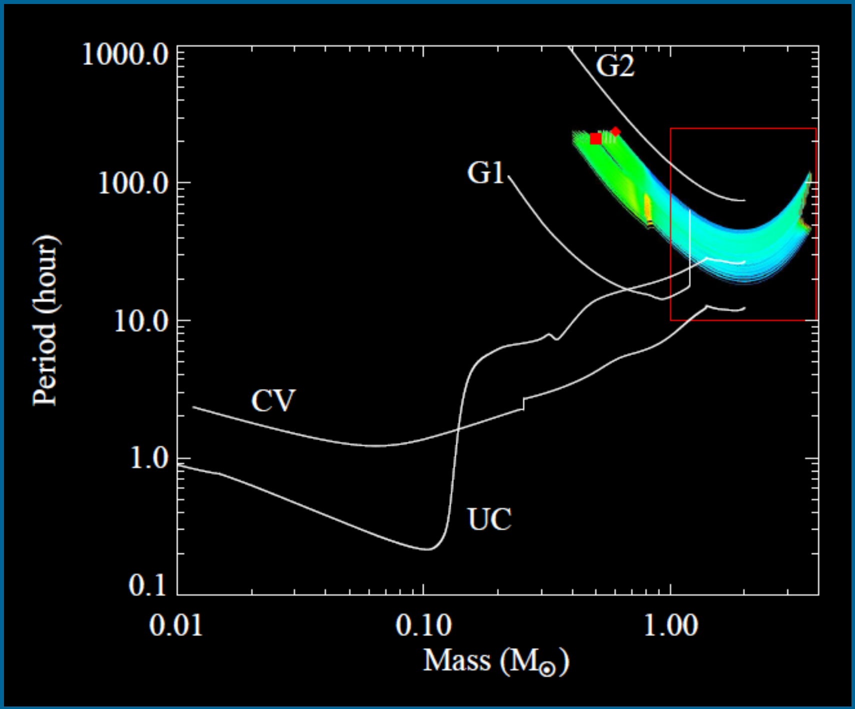
New calculations and specific systems

The task: to reproduce with a new code PSR J1614-2230

Red box shows the initial grid of models

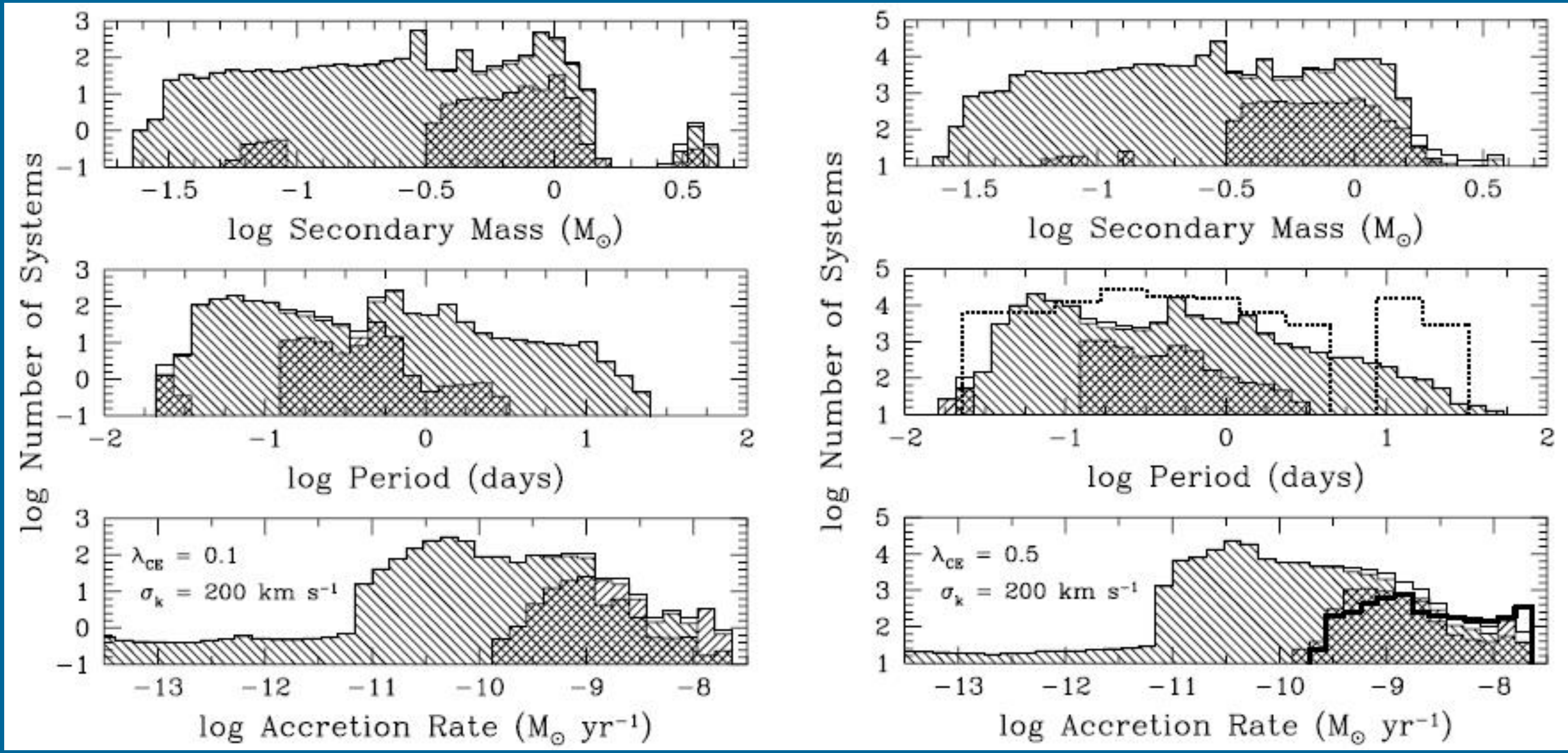


The PSR is a "relative" of Cyg X-2



1012.1877

IMXBs and LMXBs population synthesis



The hatched regions indicate persistent (+45) and transient (-45) X-ray sources, and the enclosing solid histogram gives the sum of these two populations. Overlaid (dotted histogram) on the theoretical period distribution in the figure on the right is the rescaled distribution of 37 measured periods (Liu et al. 2001) among 140 observed LMXBs in the Galactic plane.

(Pfahl et al. 2003 ApJ)

Low mass X-ray binaries

NSs as accretors
X-ray pulsars
Millisecond X-ray pulsars
Bursters
Atoll sources
Z-type sources

WDs as accretors
Cataclysmic variables
- Novae
- Dwarf novae
- Polars
- Intermediate polars

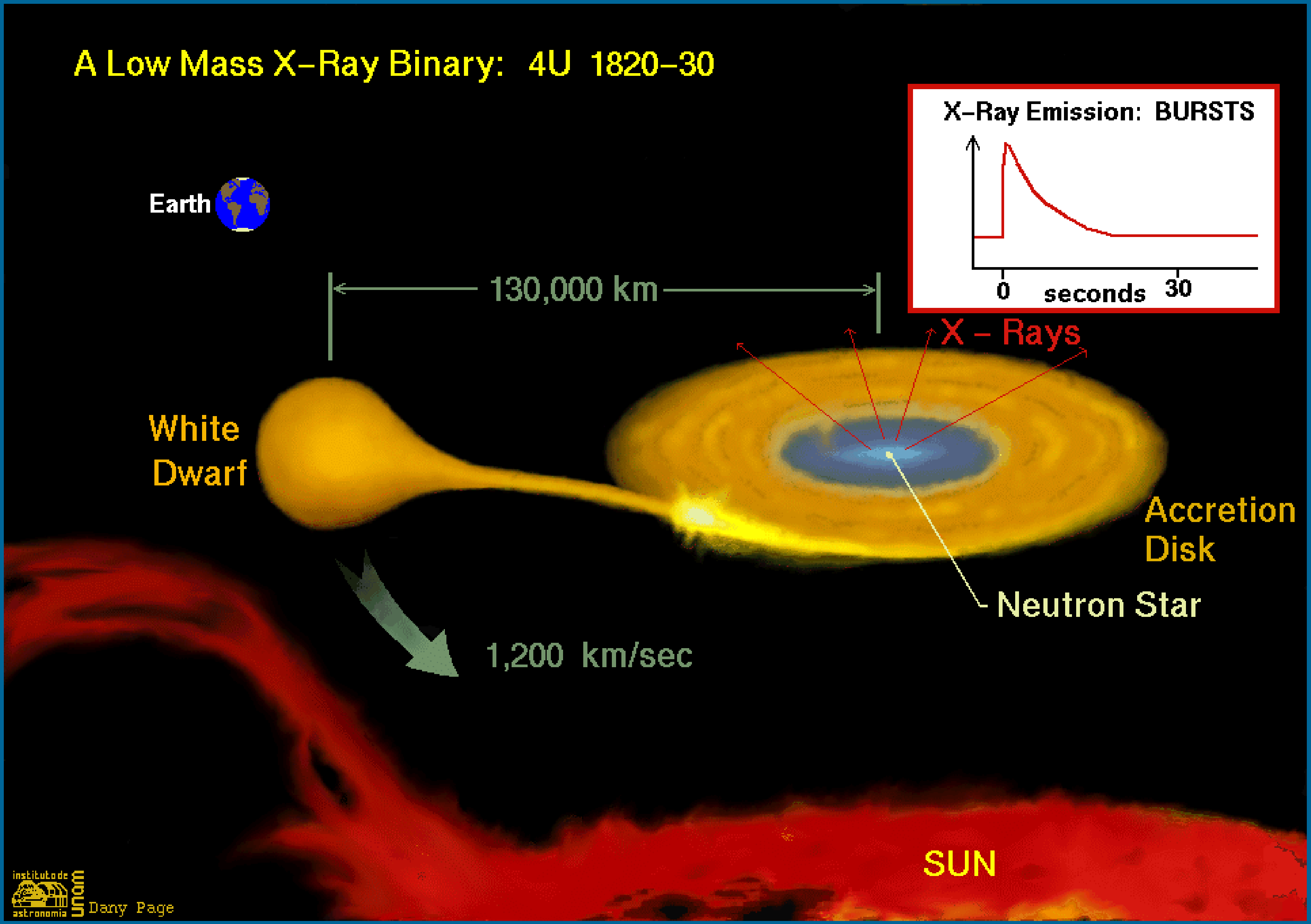
Supersoft sources (SSS)

BHs as accretors
X-ray novae
Microquasars
Massive X-ray binaries

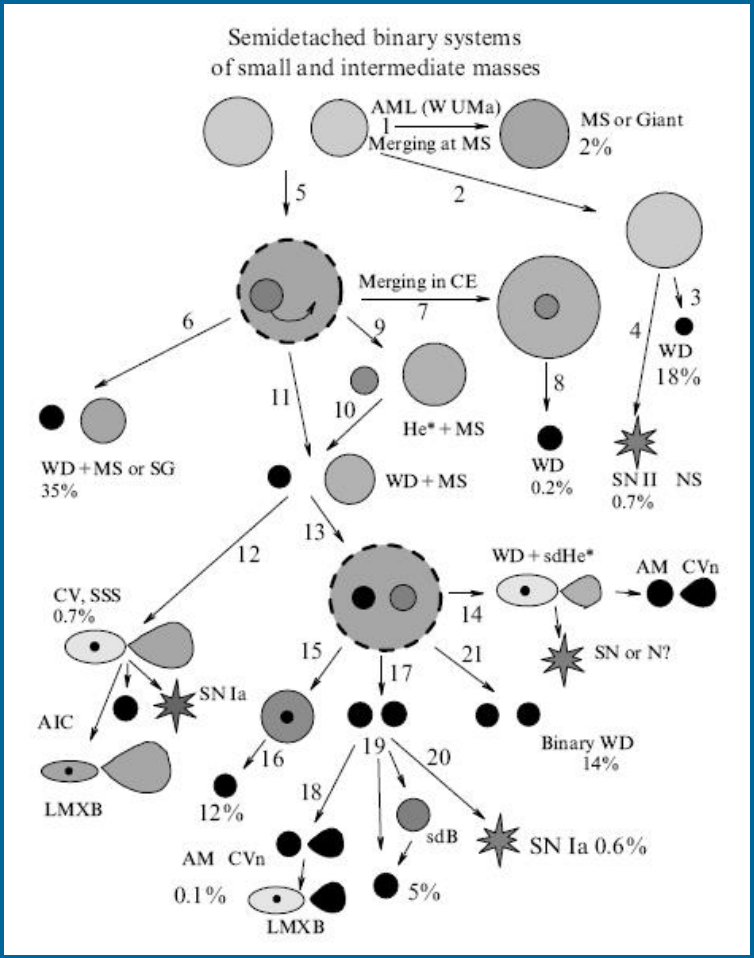
LMXBs with NSs or BHs

The latest large catalogue (Li et al. arXiv: 0707.0544) includes 187 galactic
and Magellanic Clouds LMXBs with NSs and BHs as accreting components.
Donors can be WDs, or normal low-mass stars (main sequence or sub-giants).
Many sources are found in globular clusters.
Also there are more and more LMXBs found in more distant galaxies.

In optics the emission is dominated by an accretion disc around a compact object.
Clear classification is based on optical data
or on mass function derived from X-ray observations.
If a source is unidentified in optics, but exhibits Type I X-ray bursts,
or just has a small (<0.5 days) orbital period, then it can be classified
as a LMXB with a NS.
In addition, spectral similarities with known LMXBs can result in classification.


A Low Mass X-Ray Binary: 4U 1820-30
X-Ray Emission: BURSTS
0
seconds
30
Earth
130,000 km
X - Rays
White Dwarf
Accretion Disk
Neutron Star
1,200 km/sec
SUN
instituto de astronomia unam
Dany Page

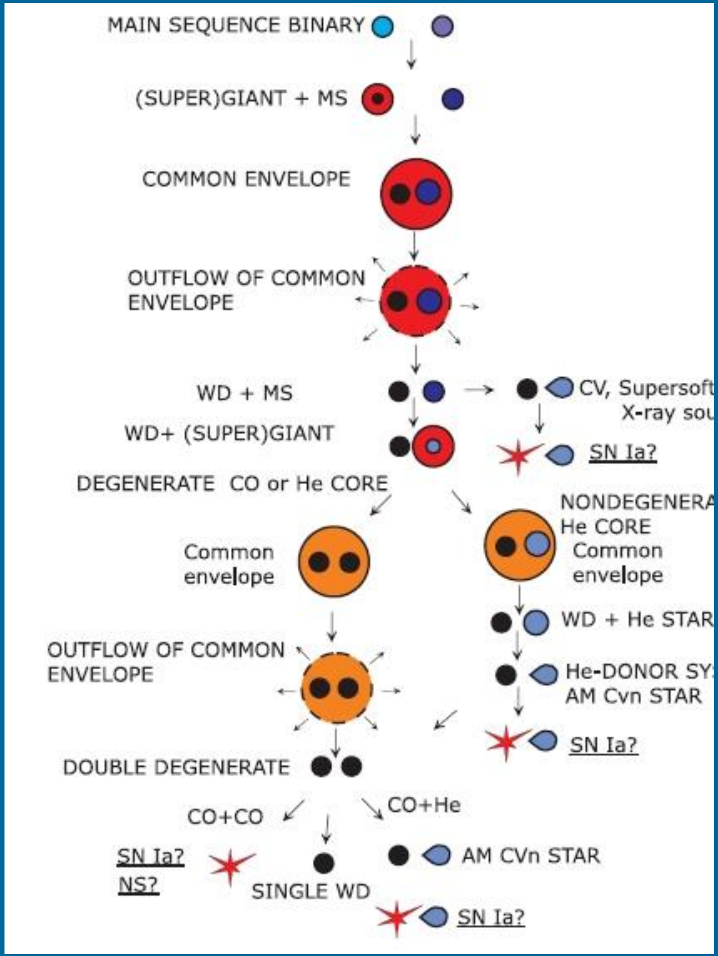
Evolution of low-mass systems

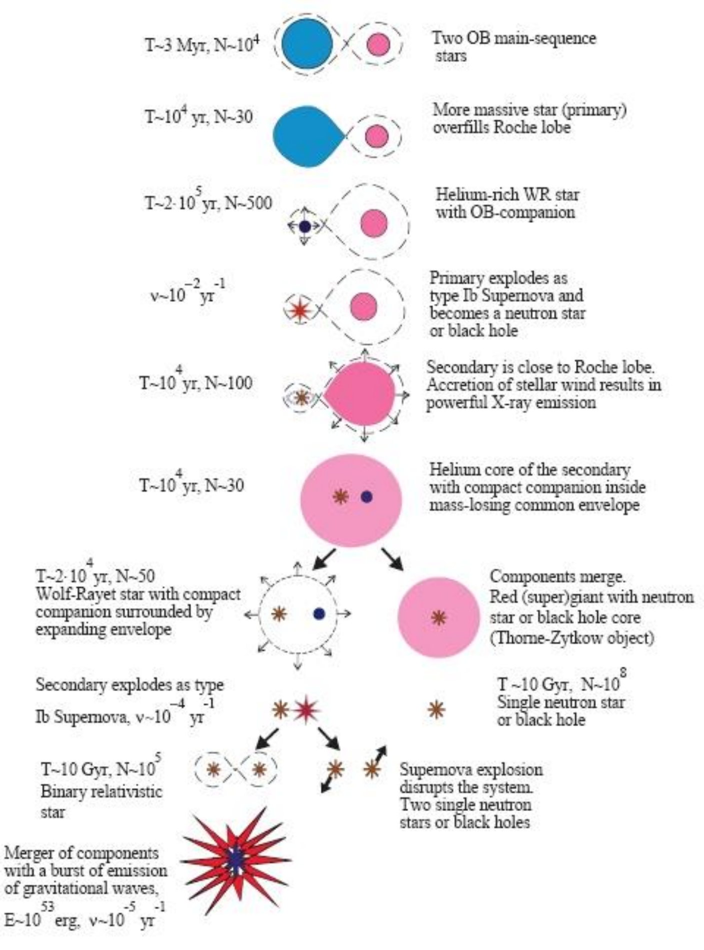


A small part of the evolutionary scenario of close binary systems

[Yungelson L R, in Interacting Binaries: Accretion, Evolution, Out-Comes 2005]

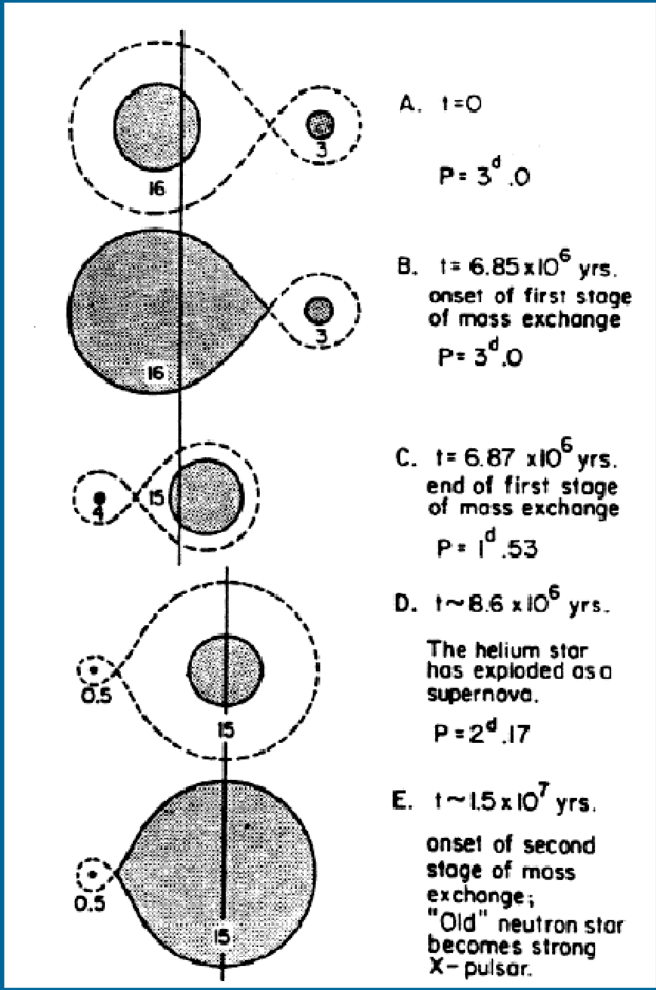
Evolution of close binaries





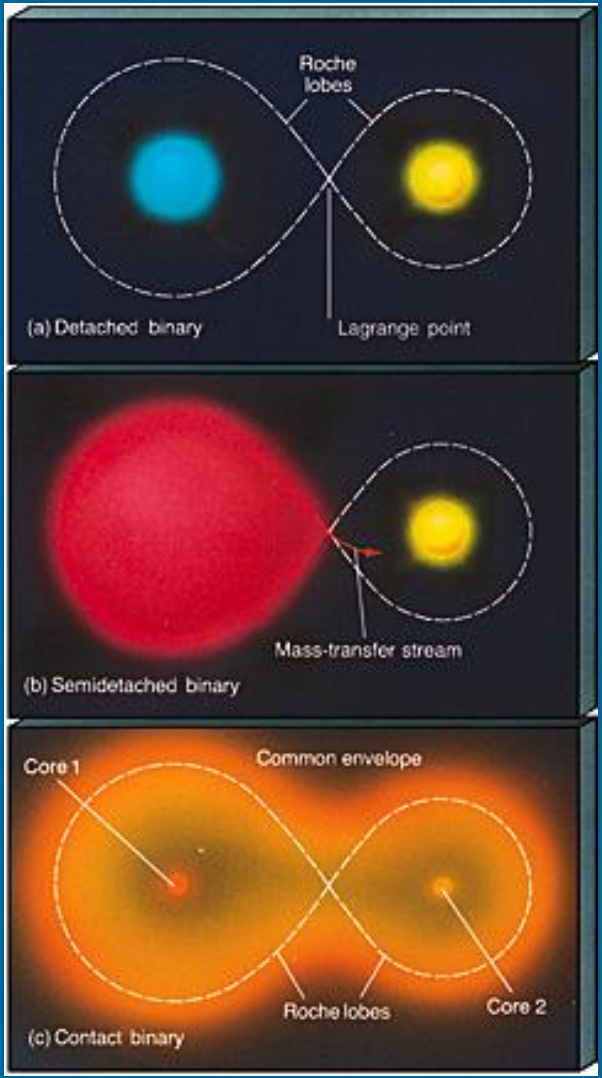
(Postnov, Yungelson 2007)

First evolutionary "scenario" for the formation of X-ray binary pulsar



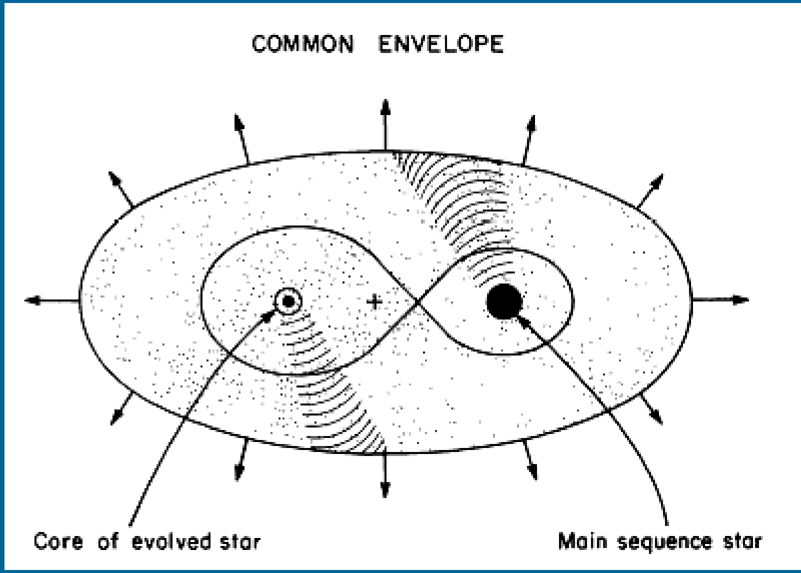
Van den Heuvel, Heise 1972

Common envelope



Problem: How to make close binaries with compact stars (CVs, XRBs)? Most angular momentum from the system should be lost.

Non-conservative evolution: Common envelope stage (B.Paczynski, 1976)



Dynamical friction is important

Tidal effects on the orbit **(Zahn, 1977)**

1. Circularization

$$t_{\rm circ} \sim (q(1+q)/2)^{-1}(a/R)^8$$
$$\sim 10^6 q^{-1}((1+q)/2)^{5/3} P^{16/3} \quad \text{years}$$

2. Synchronization of component's rotation

$$t_{\rm sync} \sim q^{-2}(a/R)^6 \sim 10^4((1+q)/2q)^2 P^4 \quad \text{years}$$

Both occur on a much shorter timescale than stellar evolution!

Conservative mass transfer

$\mathrm{M{=}M_1} + \mathrm{M_2} = const$

Assuming (B.Paczynski): $J_{orb} = \dfrac{M_1 M_2}{M}\sqrt{aM} = const$

$\Rightarrow$ Change of orbital parameters after mass transfer:

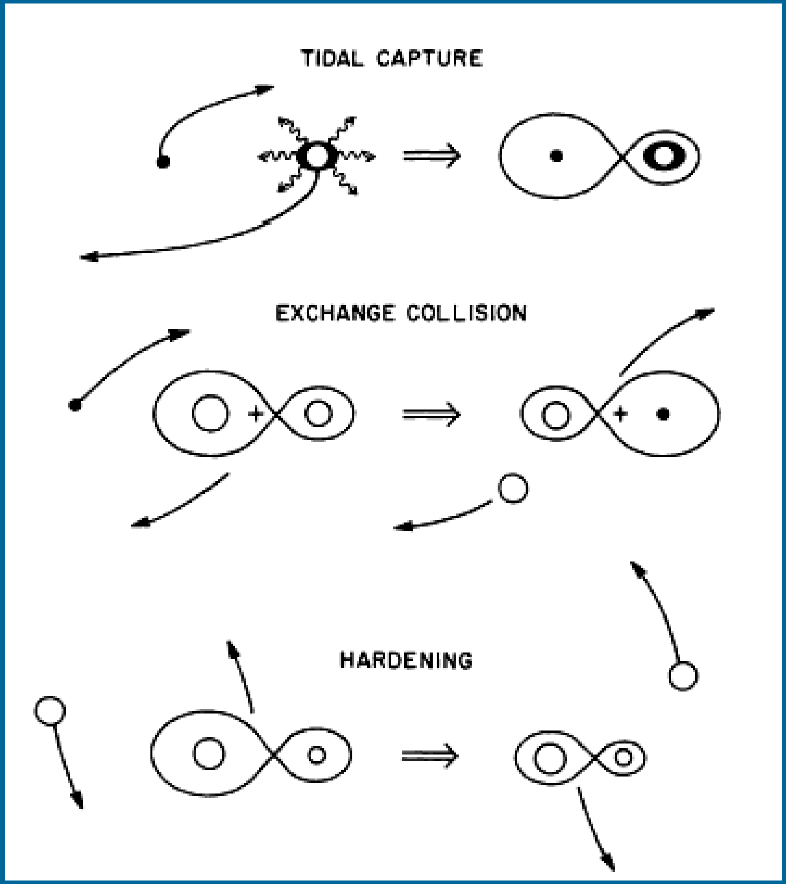
$M_1^{'} = M_1 - \Delta M,\ M_2^{'} = M_2 + \Delta M,$

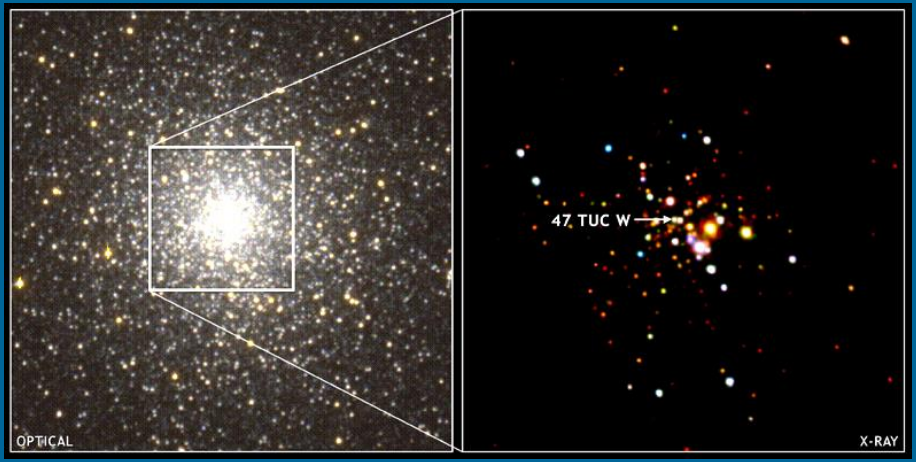
$$\frac{\Delta a}{a} = 2\Delta M\,\frac{M_2 - M_1}{M_1 M_2}\begin{cases} > 0, & \text{if}\quad M_2 > M_1 \\ < 0, & \text{if}\quad M_2 < M_1 \end{cases}$$

Non-conservative evolution

- *Massive binaries: stellar wind, supernova explosions, common envelops*
- *Low-massive binaries: common envelops, magnetic stellar winds, gravitational wave emission (CVs, LMXBs)*
- *Stellar captures in dense clusters (LMXBs, millisecond pulsars)*

Binaries in globular clusters





Hundreds close XRB and millisecond pulsars are found in globular clusters

Formation of close low-mass binaries is favored in dense stellar systems due to various dynamical processes

Isotropic wind mass loss

- Effective for massive early-type stars on main sequence or WR-stars
- Assuming the wind carrying out specific orbital angular momentum yields:

$a(M_1+M_2)=\mathrm{const}$ ➔

$\Delta a/a=-\Delta M/M > 0$

The orbit always gets wider!

Supernova explosion

- First SN in a close binary occurs in almost circular orbit ➔ $\Delta M = M_1 - M_c$, M_c is the mass of compact remnant
- Assume SN to be instantaneous and symmetric

Energy-momentum conservation $\Rightarrow$

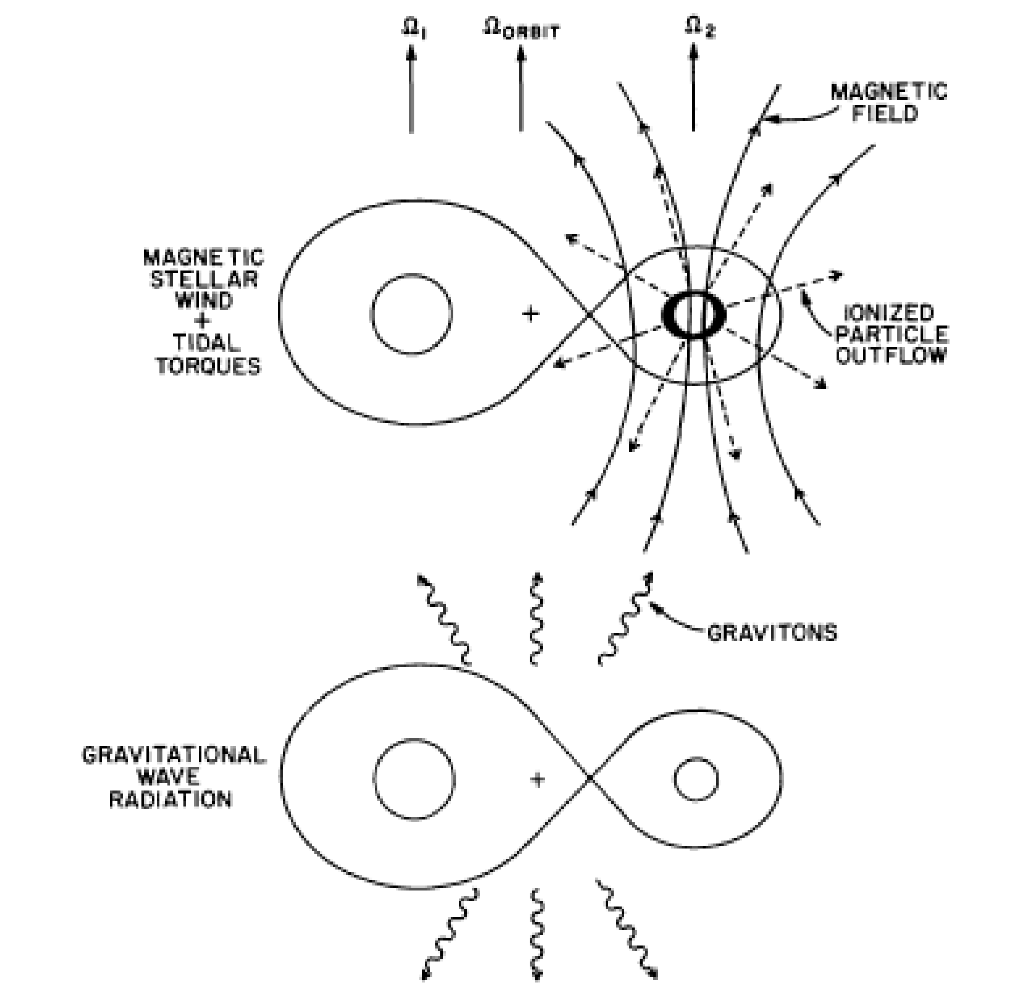
$$\frac{a_f}{a_i} = \left[2 - \frac{M_1 + M_2}{M_c + M_2} \right]^{-1}$$

$$e = \frac{\Delta M}{M_c + M_2}$$

➔ If more than half of the total mass is lost, the system becomes unbound

BUT: Strong complication and uncertainty: Kick velocities of NS!

Angular momentum loss



- **<u>Magnetic stellar wind</u>.** Effective for main sequence stars with convective envelopes $0.3<M<1.5\ M_\odot$
- **<u>Gravitational radiation.</u>** Drives evolution of binaries with P<15 hrs

Especially important for evolution of low-mass close binaries!

Mass loss due to MSW and GW

Axial rotation braking of single G-dwarfs (Skumanich, 1972)

$$V \sim t^{-1/2}, \quad \text{where } t \text{ is the age}$$

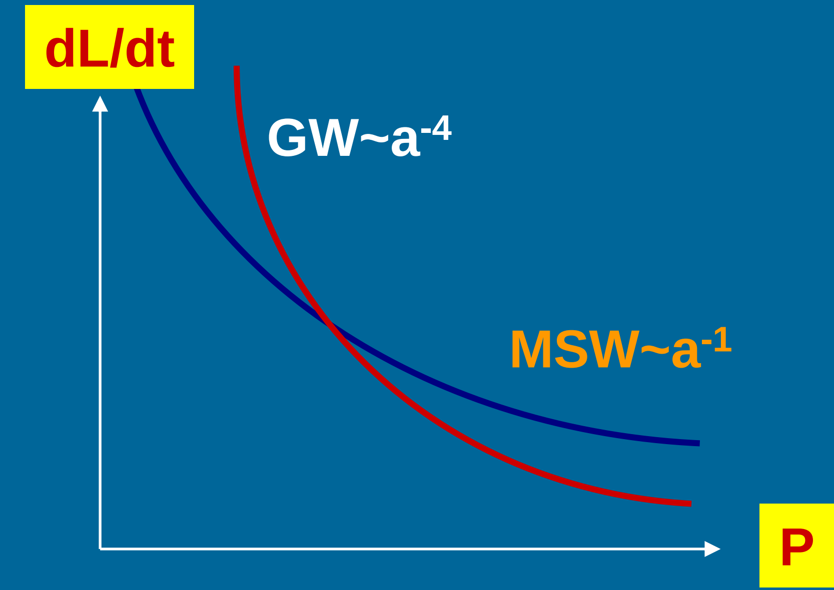
Physics: stellar wind plasma ``streams" along magnetic field lines until $\rho v^2 \sim B^2(r)/4\pi$, so carries away much larger specific angular momentum (Mestel).

Assume the secondary star in a low-mass binary $(0.4 \le M_2 \le 1.5 M_\odot)$ experiences m.s.w. Tidal forces tend to keep the star in corotation with orbital revolution: $\omega_2 = \omega$. Angular momentum conservation then leads to:

$$\frac{dL_{orb}}{dt} = \frac{dJ_2}{dt}$$

Recolling that: $L_{orb} = \mu\omega a^2$ and using Kepler's 3d law we get

$$\frac{d\ln L_{orb}}{dt} \sim -\frac{R_2^4}{M_1}\frac{GM^2}{a^5} \qquad \Rightarrow$$

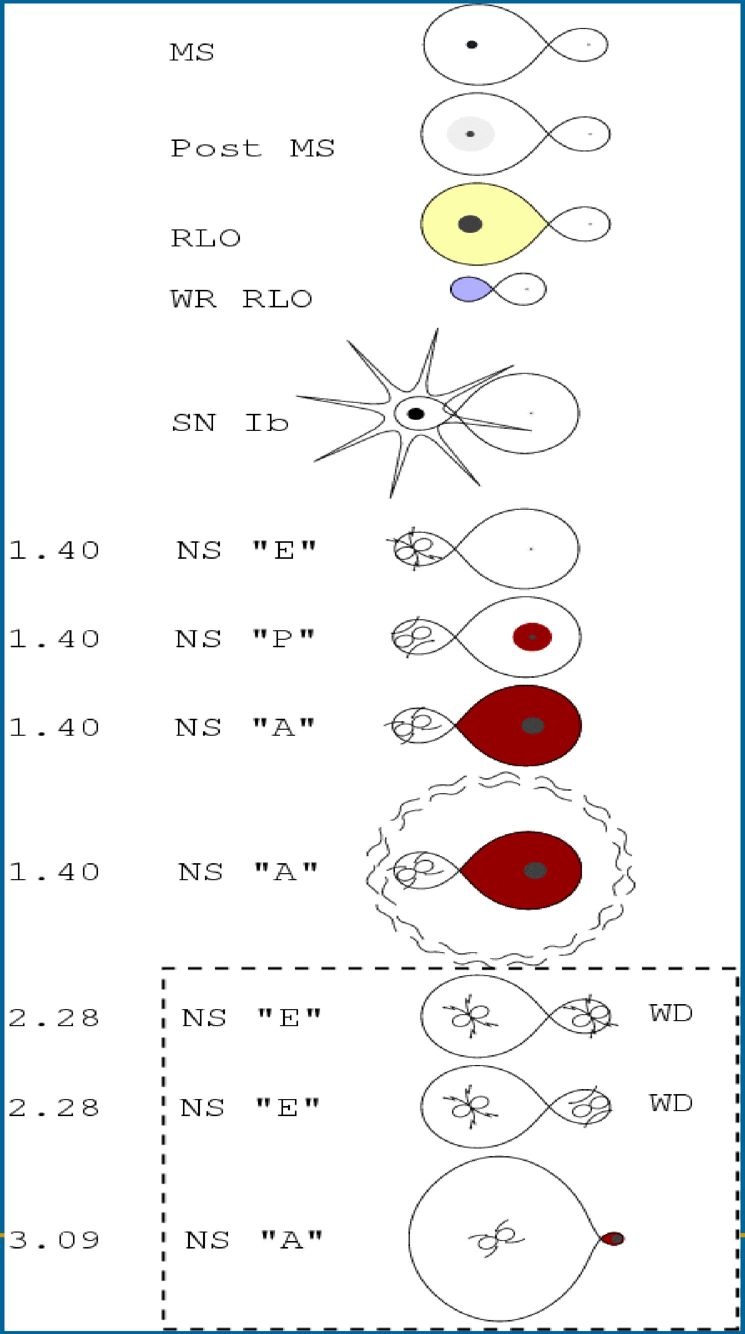


MSW is more effective at larger orbital periods, but GW always wins at shorter periods! Moreover, MSW stops when M_2 ~0.3-0.4 $M_\odot$ where star becomes fully convective and dynamo switches off.

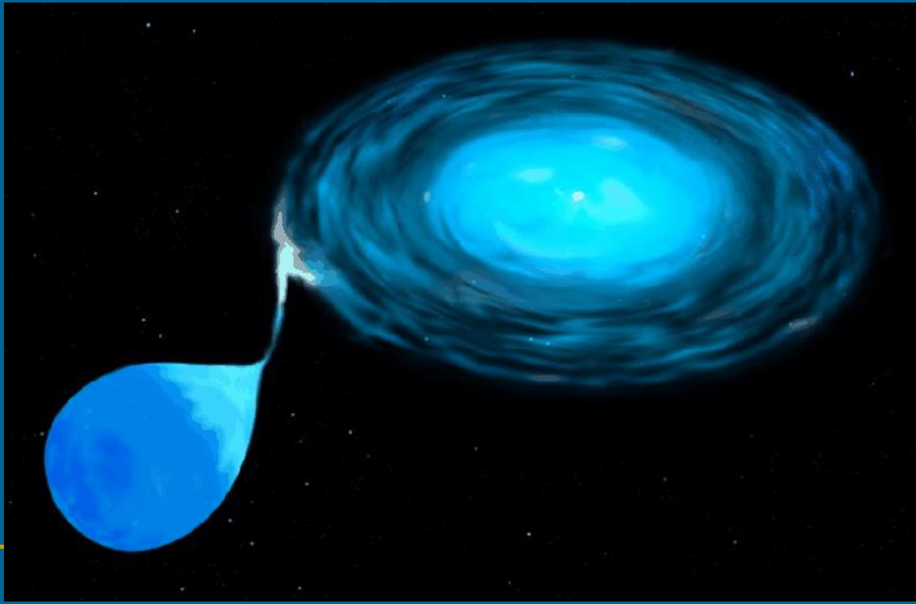
Binary evolution: Major uncertainties

- All uncertainties in stellar evolution (convection treatment, rotation, magnetic fields…)
- Limitations of the Roche approximation (synchronous rotation, central density concentration, orbital circularity)
- Non-conservative evolution (stellar winds, common envelope treatment, magnetic braking…)
- For binaries with NS (and probably BH): effects of supernova asymmetry (natal kicks of compact objects), rotational evolution of magnetized compact stars (WD, NS)

Evolution



NSs can become very massive during their evolution due to accretion.

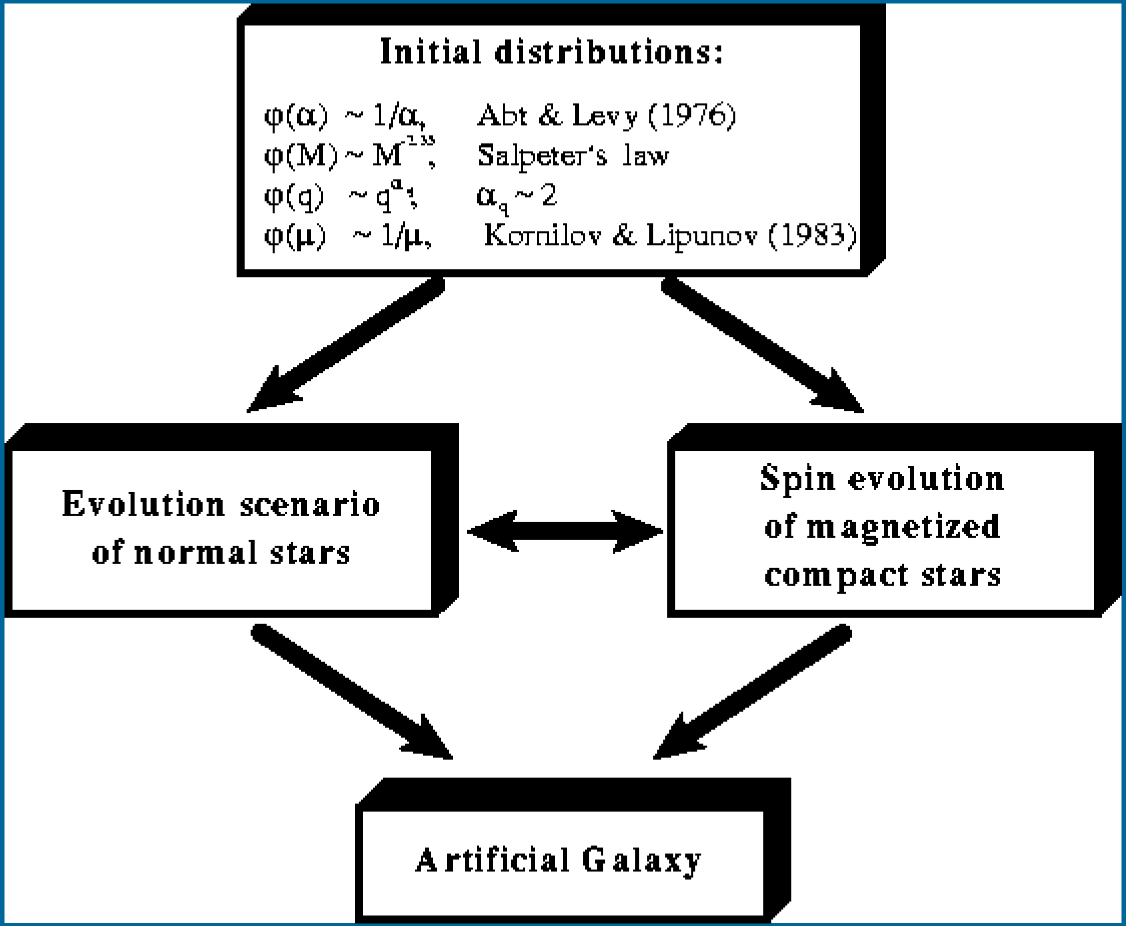


Population synthesis of binary systems

Interacting binaries are ideal subject for population synthesis studies:

- The are many of them observed
- Observed sources are very different
- However, they come from the same population of progenitors...
- ... who's evolution is non-trivial, but not too complicated.
- There are many uncertainties in evolution ...
- ... and in initial parameter
- We expect to discover more systems
- ... and more types of systems
- With new satellites it really happens!

Scenario machine



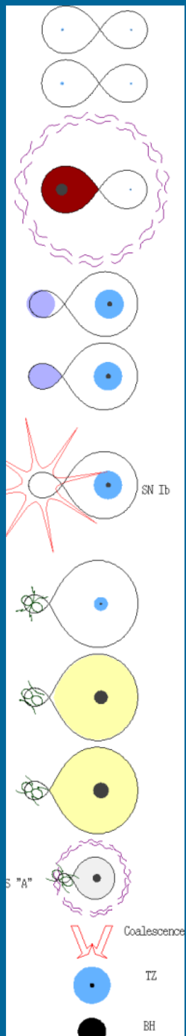
There are several groups in the world which study evolution of close binaries using population synthesis approach.

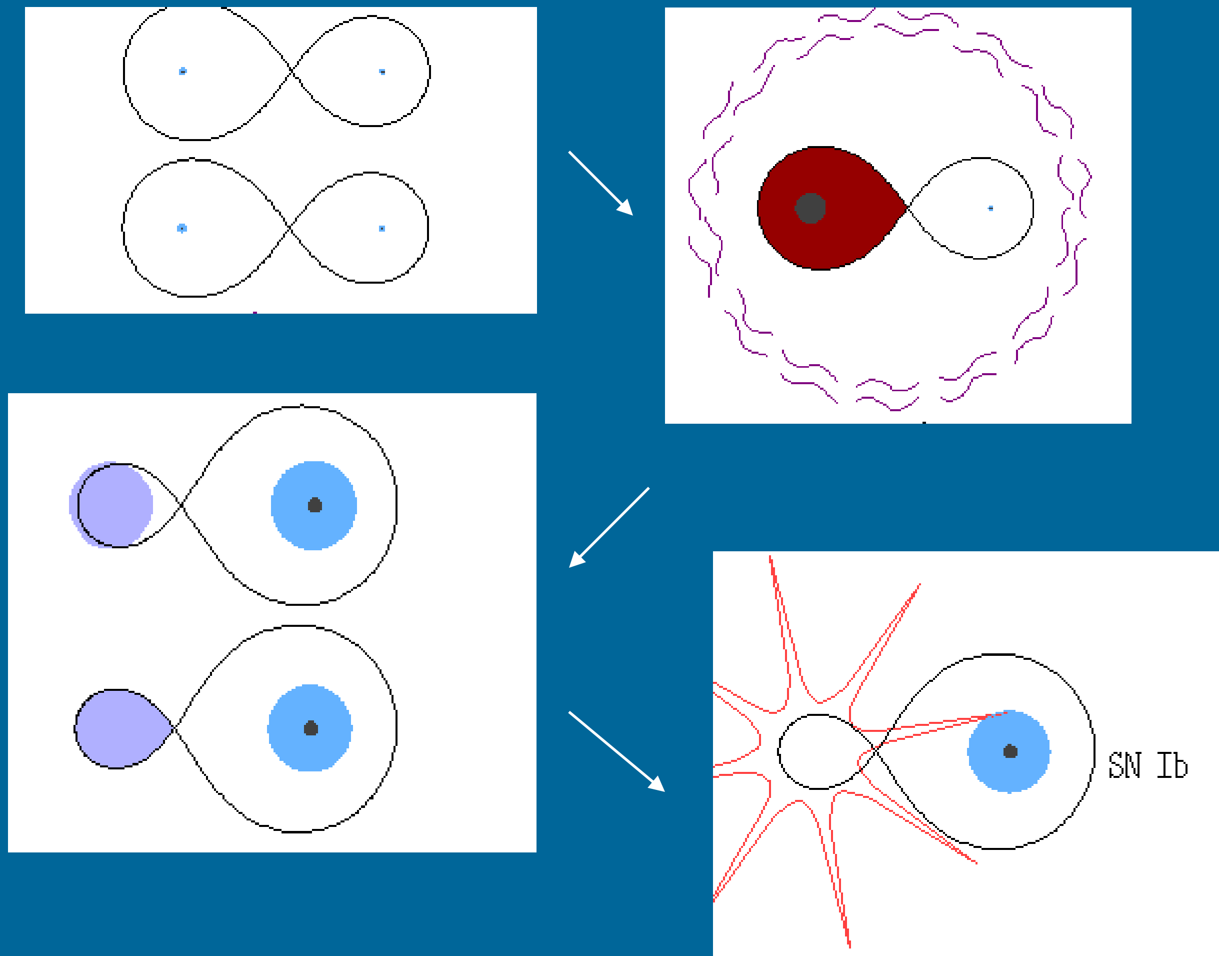
<u>Examples of topics</u>

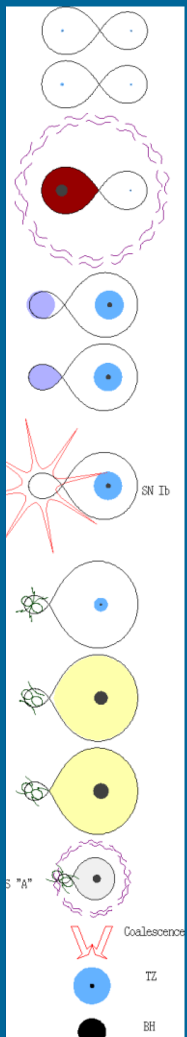
- Estimates of the rate of coalescence of NSs and BHs
- X-ray luminosities of galaxies
- Calculation of mass spectra of NSs in binaries
- Calculations of SN rates
- Calculations of the rate of short GRBs

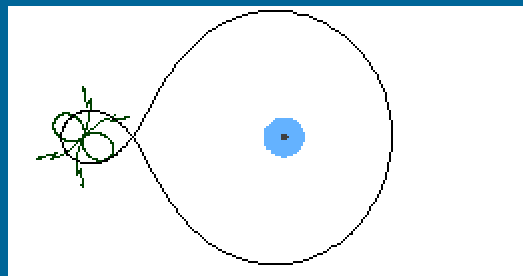
(Lipunov et al.)

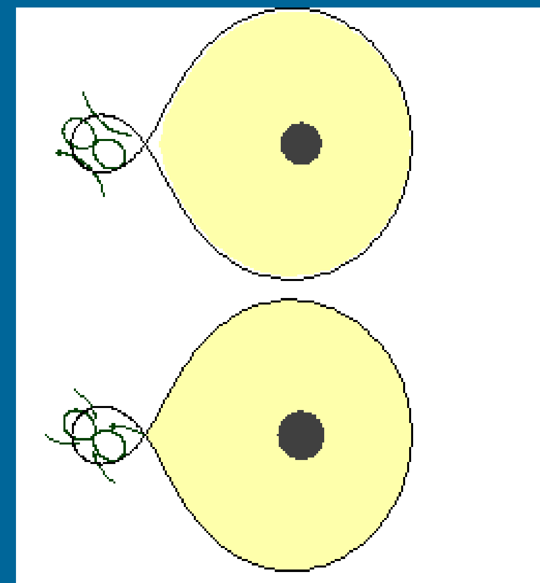
Evolution of close binaries

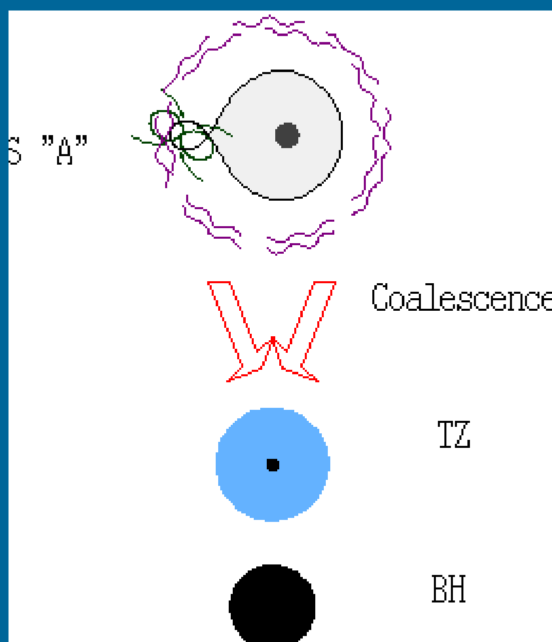












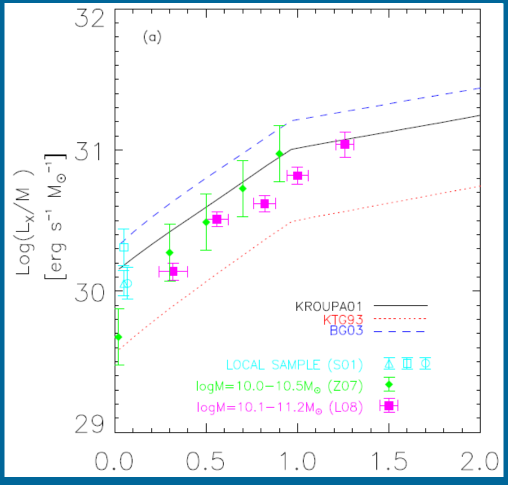
(“Scenario Machine” calculations)

http://xray.sai.msu.ru/sciwork/

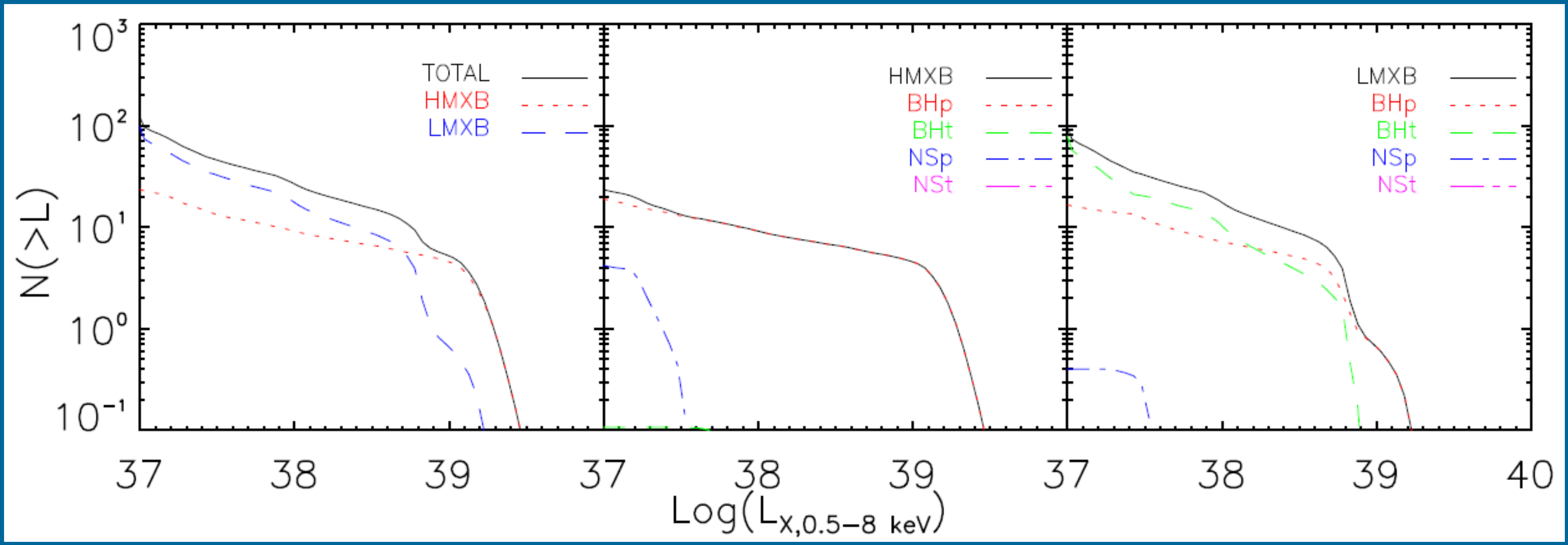
The role of binaries in the properties of galaxies

The authors use the code by Hurley et al.
to model X-ray luminosity of a late-type galaxy.

Evolution of L_X with z



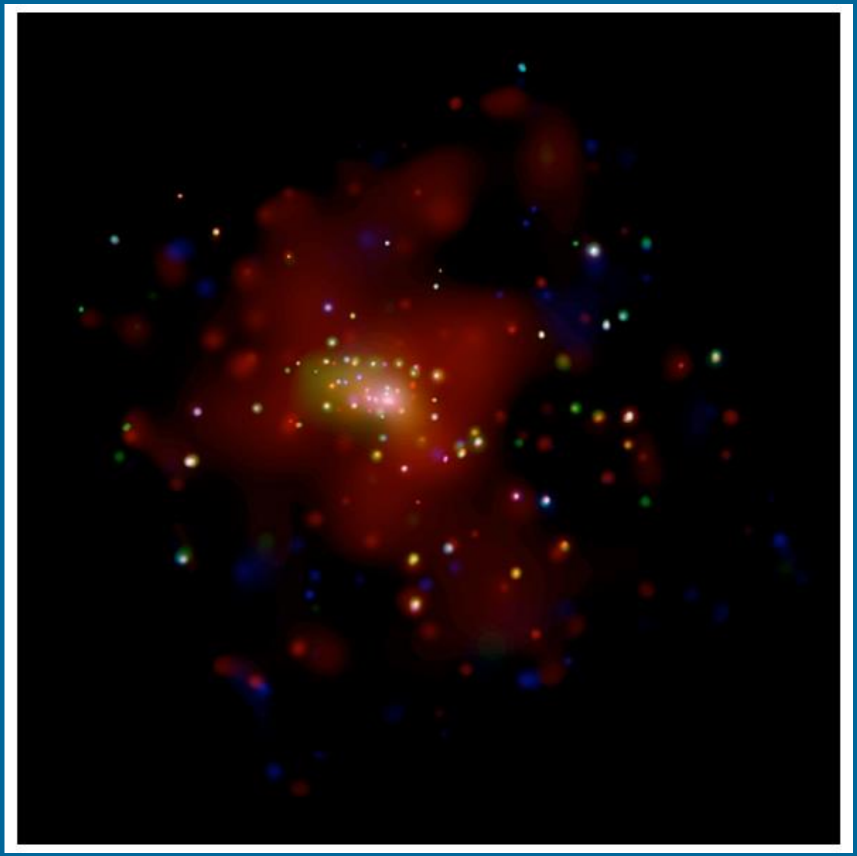
cumulative X-ray luminosity function



1103.2199

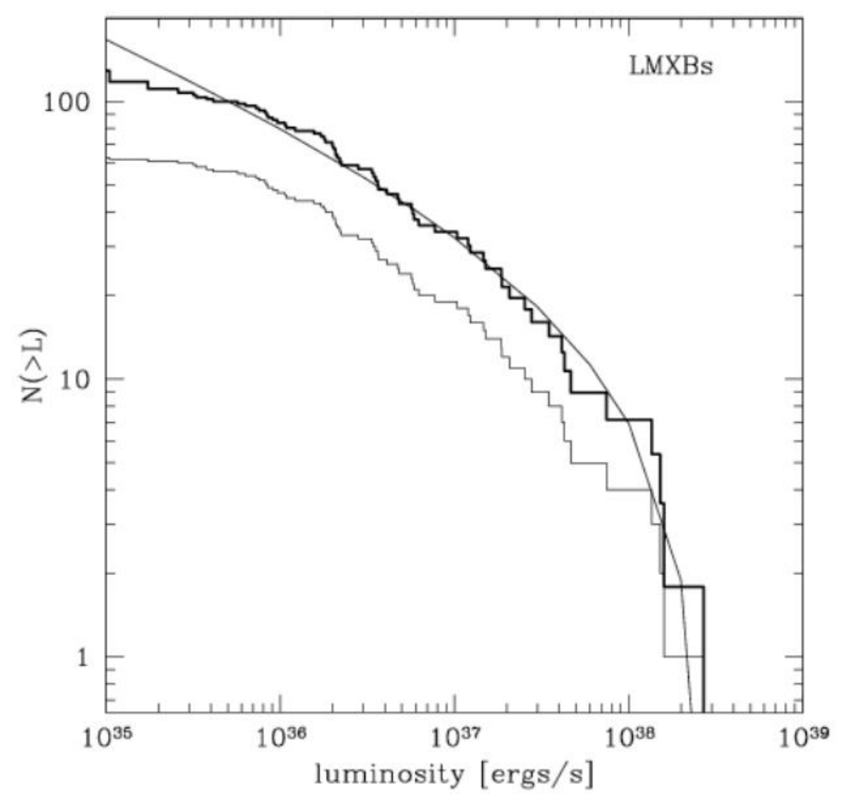
Extragalactic binaries

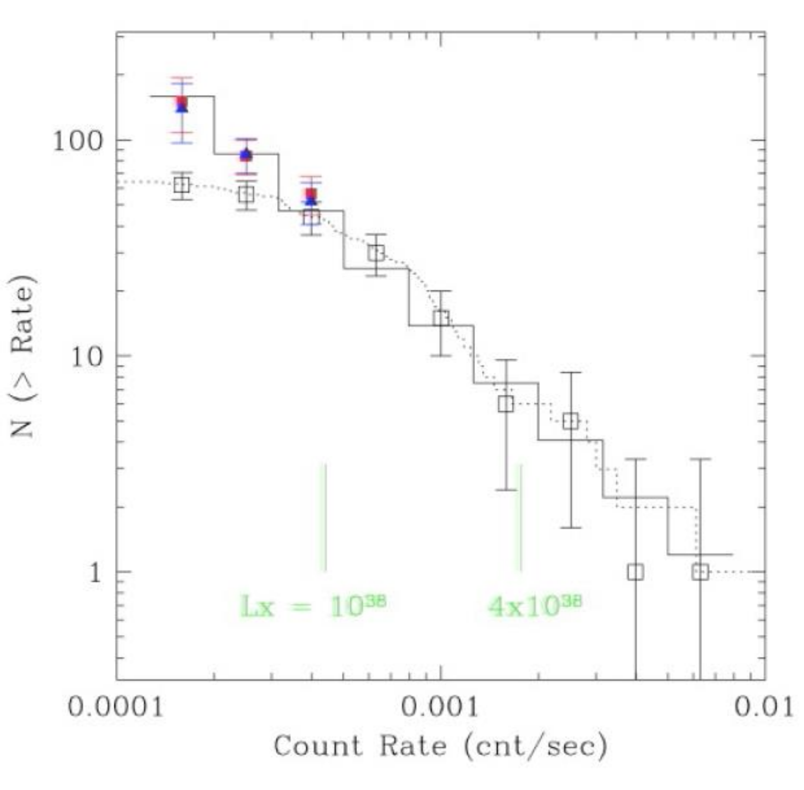
It is possible to study galactic-like binaries up to 20-30 Mpc.
For example, in NGC 4697 80 sources are known thanks to *Chandra*
(this is an early type galaxy, so most of the sources are LMXBs).



astro-ph/0511481

LMXBs luminosity function

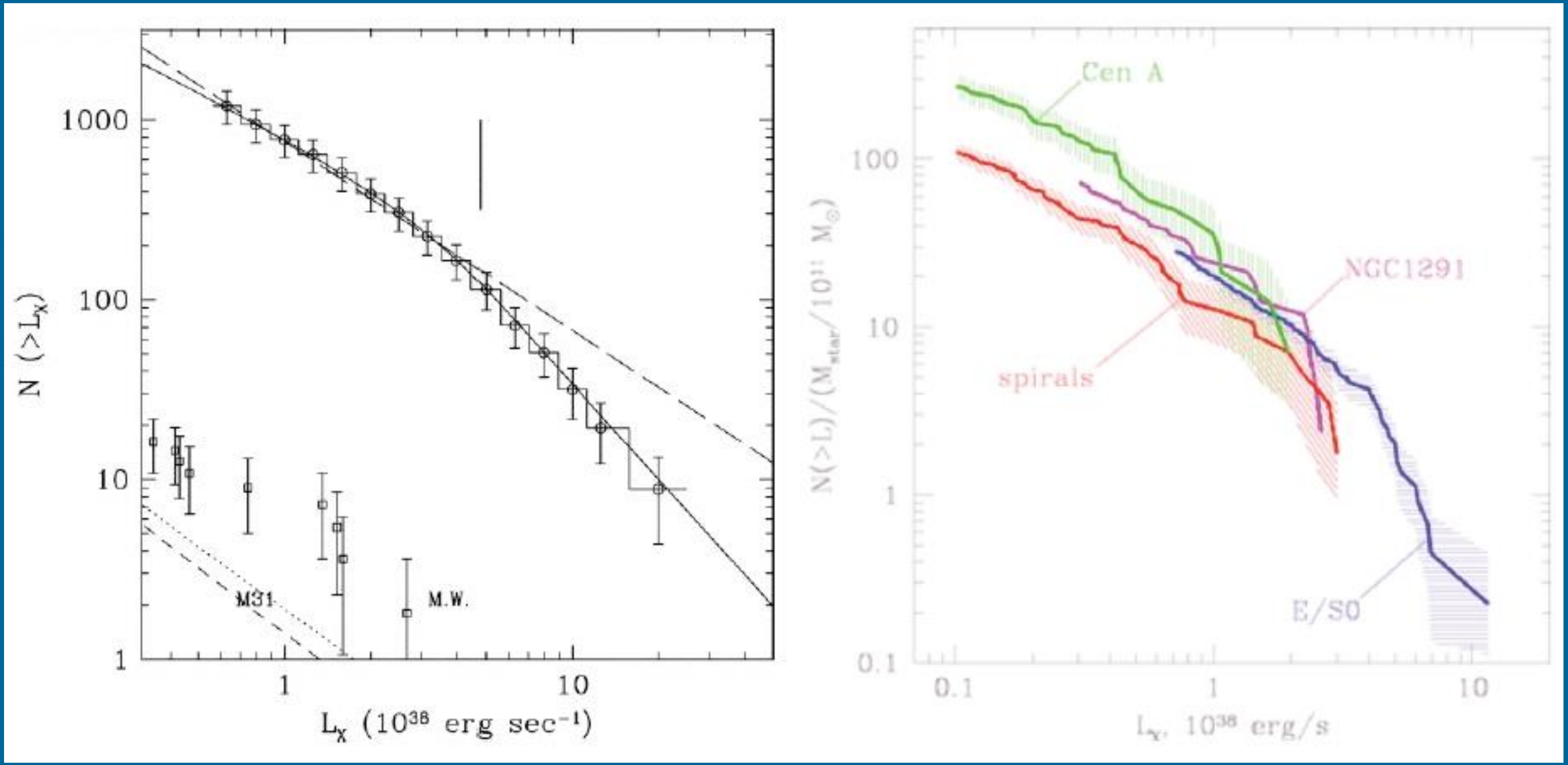




LMXB galactic luminosity function (Grimm et al. 2002)

LMXB luminosity function for NGC 1316 (Kim and Fabbiano 2003)

LMXBs luminosity function



Cumulated XLF for 14 early-type galaxies.

(see Fabbianno astro-ph/0511481)

List of reviews

- Catalogue of LMXBs. Li et al. arXiv:0707.0544
- Catalogue of HMXBs. Li et al. arXiv: 0707.0549
- Evolution of binaries. Postnov & Yungelson. astro-ph/0701059
- Extragalactic XRBs. Fabbiano. astro-ph/0511481
- General review on accreting NSs and BHs. Psaltis. astro-ph/0410536
- CVs
  - Evolution. Ritter. arXiv:0809.1800
  - General features. Smith. astro-ph/0701564
- Modeling accretion: Done et al. arXiv:0708.0148
- NS binaries: Sudip Bhattacharyya arXiv: 1002.4480
- Be/X-ray binaries: Pablo Reig arXiv: 1101.5036
- Population synthesis. Popov & Prokhorov. Physics Uspekhi (2007)