# X-Ray Binaries

Literature:

- An Introduction to Modern Astronomy, Carroll & Ostlie, Chapter 17 (good basic source)
- Black Holes, White Dwarfs and Neutron Stars, Shapiro & Teukolsky (more advanced, but good source)
- "The Formation and Evolution of Compact X-Ray Sources", Tauris & van den Heuvel, Online review (google astro-ph/0303456), almost up-to-date

*I. Types and Basic Properties*

*II. Formation Channels*

*III. Mass Transfer and Accretion*

*IV. Variability, X-Ray Bursts*

*V. Do Black Holes Exist?*

*VI. Ultraluminous X-Ray Sources*

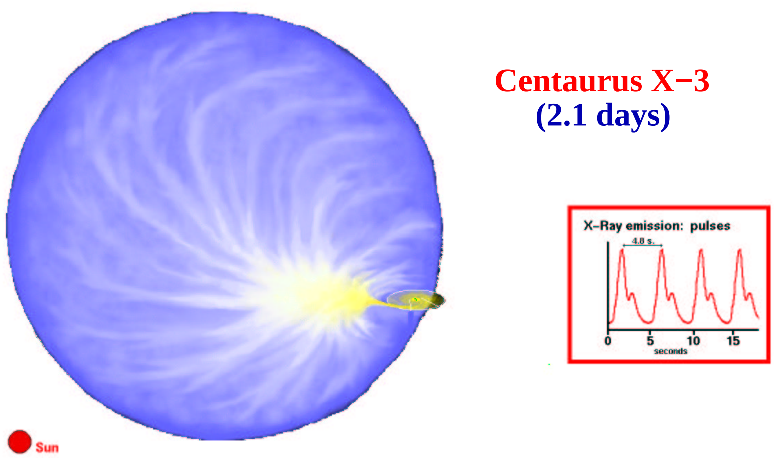
## Basic Properties

- generic system: a Roche-lobe filling star (low-mass, massive, white dwarf) transfers matter to a compact companion (neutron star, black hole, [white dwarf])
- *traditionally* two main classes: *high-mass X-ray binaries* (HMXBs; $M_2 \gtrsim 10\,M_\odot$) and *low-mass X-ray binaries* (LMXBs; $M_2 \lesssim 1.5\,M_\odot$)
  - ▷ missing intermediate-mass systems?
  - ▷ probably not: most systems classified as LMXBs almost certainly originate from *intermediate-mass X-ray binaries* (IMXBs, $1.5\,M_\odot \lesssim M_2 \lesssim 5\,M_\odot$), but have already lost most/transferred most of their mass

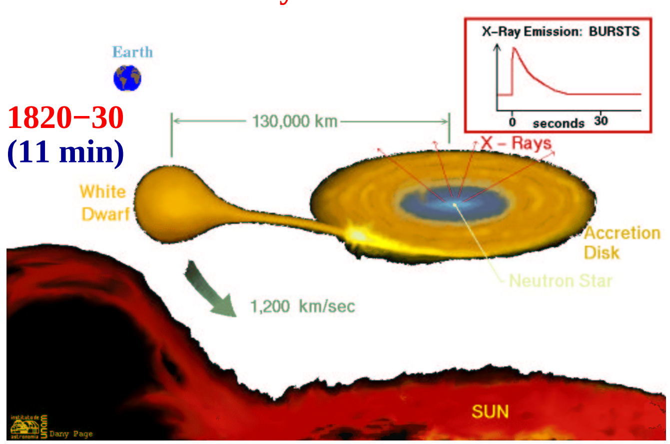
*High-Mass X-Ray Binaries*

- relatively *hard* X-ray spectra: $kT \gtrsim 15\,\text{keV}$
- type of variability: regular *X-ray pulsations;* no X-ray bursts
- concentrated towards the Galactic plane, *young age* $\lesssim 10^7\,\text{yr}$
- optical counterparts: *O, B stars* with $L_{\rm opt}/L_X > 1$

High−Mass X−Ray Binaries




Low−Mass X−Ray Binaries

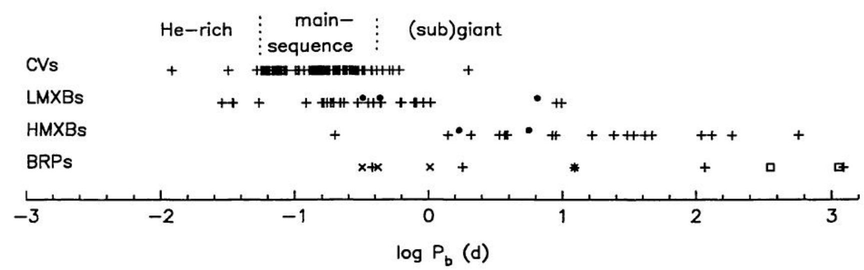



*Low-Mass X-Ray Binaries*

- *softer* X-ray spectra: (kT $\lesssim$ 15 keV)
- type of variability: often *X-ray bursts*, sometimes *pulsations* (recent: ms pulsations!)
- not so concentrated to the Galactic plane; *older?*
- faint optical counterparts: $L_{opt}/L_X < 0.1$ (usually undetectable!)

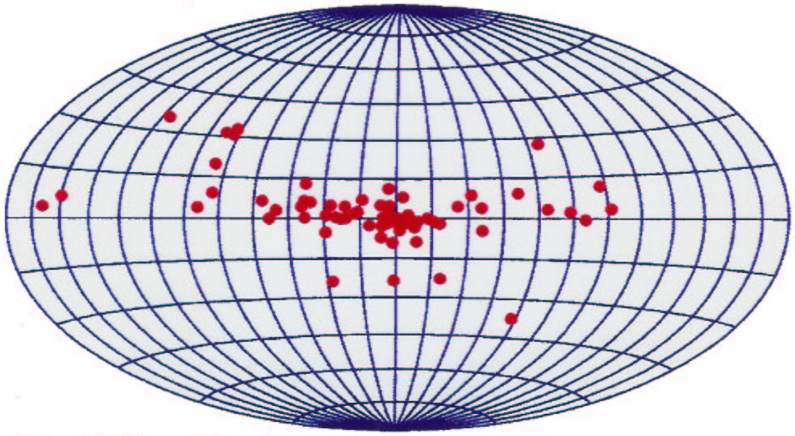
*Orbital Period Distributions*

- *known* periods only! Selection effects!



# Galactic Distribution of X-ray binaries

"Low-Mass" X-ray binaries



"High-Mass" X-ray binaries

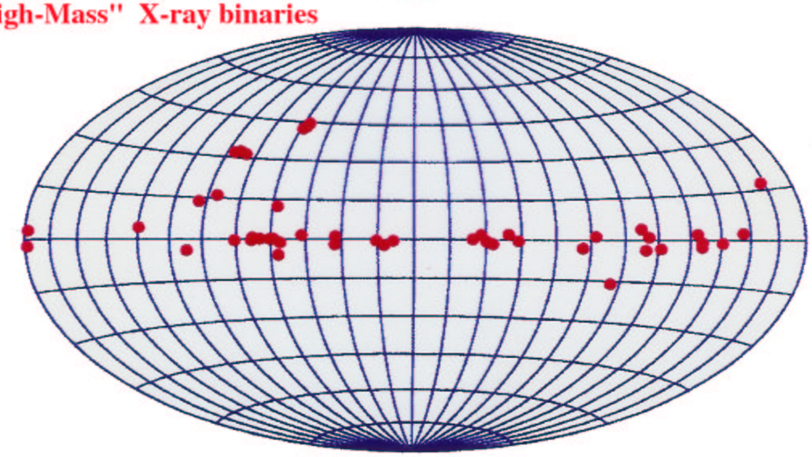
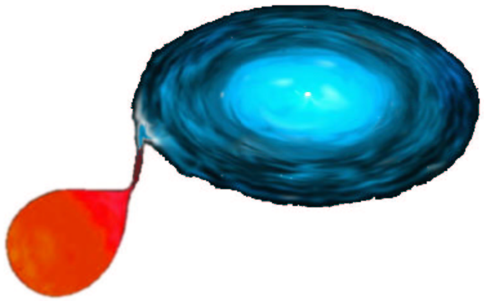




**Table 1** Properties of some X-ray binaries and all currently known radio binary pulsars†

| Name | Position | $P$ (s) | $\log L_x$ (erg/s) | $P_b$ (d) | $e$ | Spectral | Reference |
|---|---|---|---|---|---|---|---|
| | | | X-ray binaries | | | | |
| | | | high-mass X-ray binaries | | | | |
| LMC X-4 | 0532−66 | 13.5 | 38.6 | 1.4 | 0.011 | O7III | 1 |
| LMC X-3 | 0538−64 | — | 38.5 | 1.7 | ∼0 | BIII-IV | 2 |
| Cen X-3 | 1119−60 | 4.8 | 37.9 | 2.1 | 0.0007 | O6.5II | 3 |
| SMC X-1 | 0115−74 | 0.7 | 38.8 | 3.9 | <0.0008 | B0I | 4 |
| Cyg X-1 | 1956+35 | — | 37.3 | 5.6 | ∼0 | O9.7I | 5 |
| Vela X-1 | 0900−40 | 283 | 36.8 | 9.0 | 0.092 | B0.5I | 6 |
| LMC tran | 0535−67 | 0.069 | T39.0 | 16.7 | ∼0.7 | B2IV | 7 |
| — | 0115+63 | 3.6 | T36.9 | 24.3 | 0.34 | Be | 8 |
| V725 Tau | 0535+26 | 104 | T37.3 | 111.0 | 0.3–0.4 | Be | 9 |
| | | | low-mass X-ray binaries | | | | |
| KZ TrA | 1627−67 | 7.7 | 36.8 | 0.029 | | | 10 |
| V1405 Aql | 1916−05 | | 36.9 | 0.035 | | | 11 |
| UY Vol | 0748−68 | | T37.0 | 0.159 | | | 12 |
| V4134 Sgr | 1755−34 | | 36.8 | 0.186 | | | 13 |
| V616 Mon | 0620−00 | | T38.3 | 0.323 | | | 14 |
| Cen X-4 | 1455−31 | | T38.0 | 0.629 | | | 15 |
| Sco X-1 | 1617−16 | | 37.5 | 0.787 | | | 16 |
| Cyg X-2 | 2142+38 | | 38.0 | 9.843 | | | 17 |

# Low-Mass X-Ray Binaries



- *neutron-star* (black-hole) binaries with orbital periods of typically hours to less than a few days (for those $\sim 30\,\%$ with known periods)
- the companion stars are "believed" to be *low-mass objects:*

  $P < 1\,\mathrm{hr}$: degenerate stars ($M_2 \lesssim 0.1\,M_\odot$)

  $3\,\mathrm{hr} < P \lesssim 10\,\mathrm{hr}$: main-sequence stars

  $P \gtrsim 10\,\mathrm{hr}$: subgiants, giants (?)

- they are concentrated in the direction of the Galactic center ("Bulge Sources") and in globular clusters (old population?)

  *BUT:* neutron stars receive a kick at birth (median: $200-250\,\mathrm{km/s}$)

  → LMXBs receive a kick of $180 \pm 80\,km\,s^{-1}$ (Brandt and Podsiadlowski 1994/95)

  → the LMXB distribution is consistent with a *young* progenitor population

*Formation Scenarios*

- the present size of many XRB's ($\sim 0.1 - 10\,R_\odot$) is much smaller than the size of a blue/red supergiant, the progenitor of the compact object

  → *require drastic shrinkage of orbit*

- *common-envelope evolution*
  - ▷ mass transfer for supergiant is often *unstable* (star expands when losing mass rapidly; Roche lobe shrinks) → companion star cannot accrete all the transferred matter and is engulfed → formation of a common envelope (CE) → friction → *spiral-in*
  - ▷ *CE is ejected* when $\alpha_{CE}\,\Delta E_{orb} > E_{bind}$, where $\Delta E_{orb}$ is the orbital energy released, $E_{bind}$ the binding energy of the envelope and $\alpha_{CE}$ a generally poorly determined efficiency factor

    (Note: the modelling of CE evolution is one of the major uncertainties in binary stellar evolution)

- LMXBs are more frequent in globular clusters (GCs)
  - ▷ Galaxy: $\sim 100$; GCs: $\sim 10$ LMXBs

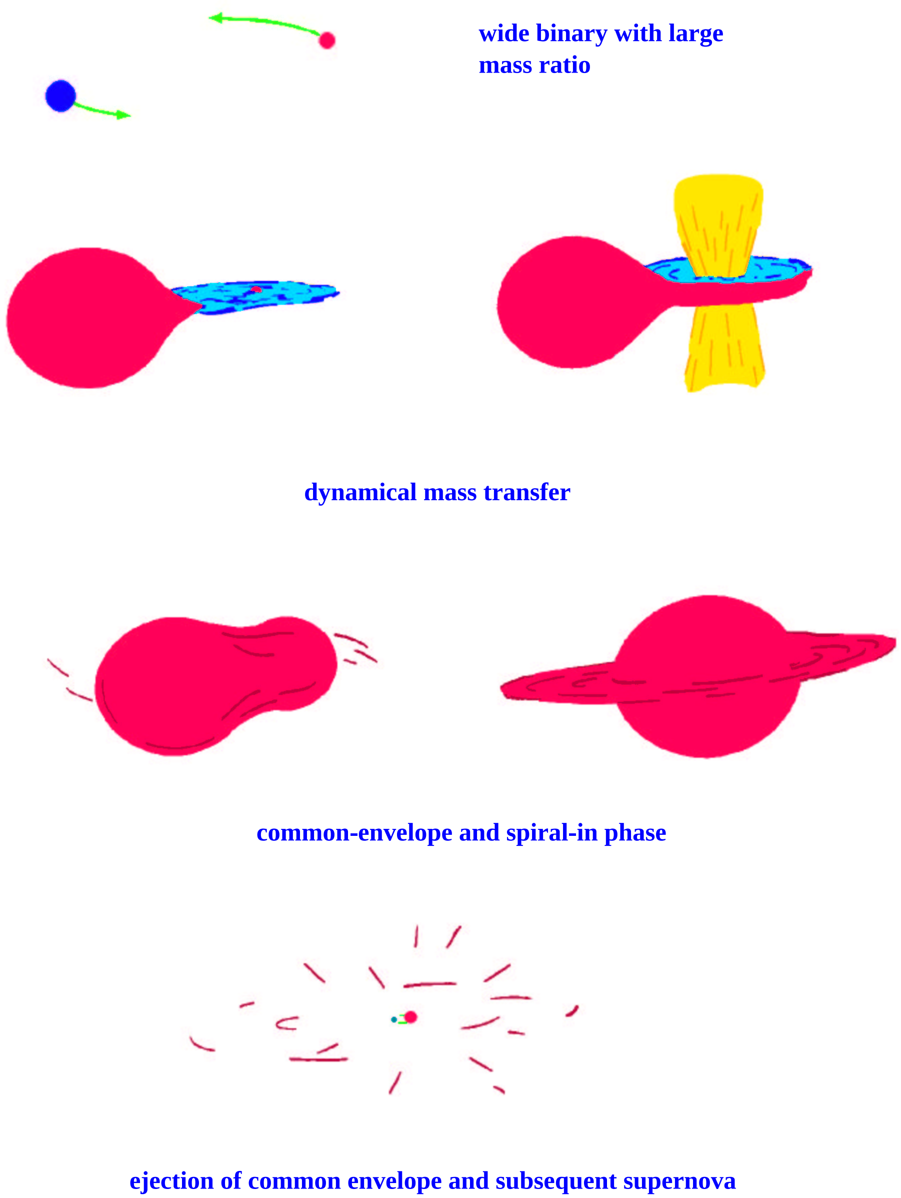
  *but:* globular clusters only contain $0.05\,\%$ of the mass of the Galaxy

  → *20 times more frequent*

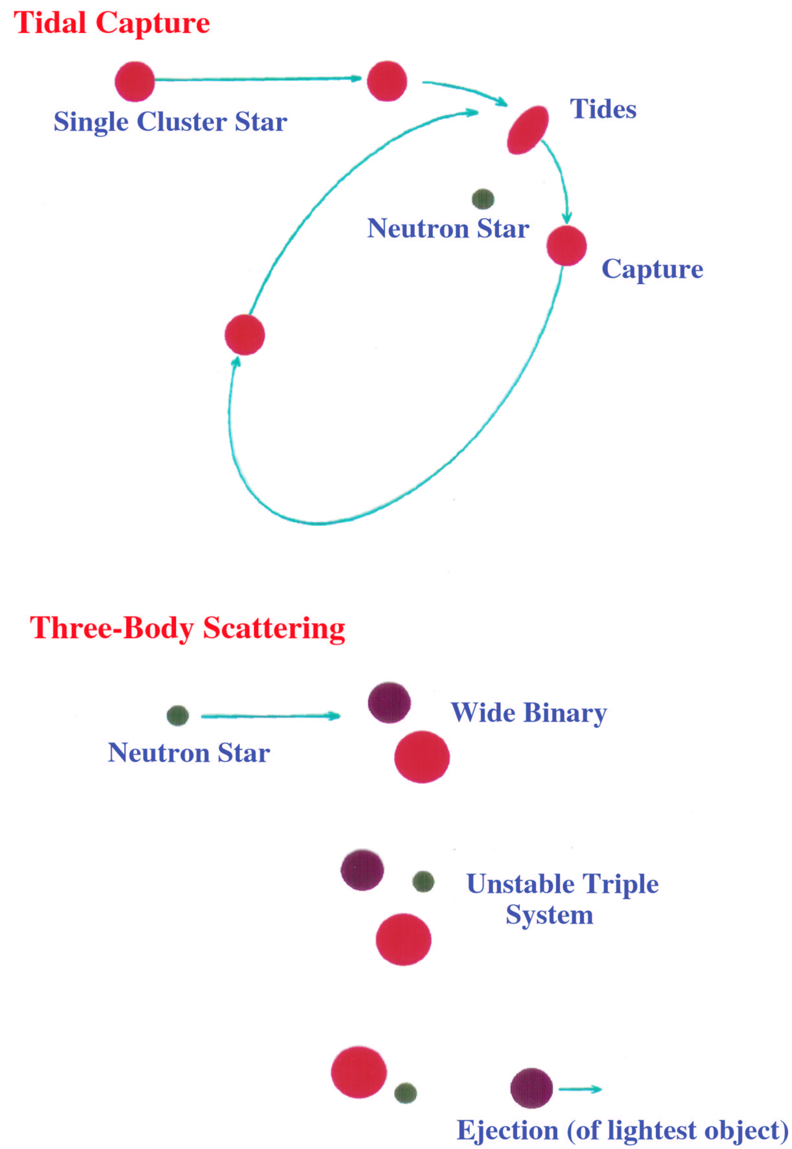
  → *different formation mechanisms*

  - ▷ *tidal capture, three-body interactions* in GCs

## Formation of Low-Mass X-Ray Binaries (I)




## Formation of Low-Mass X-ray Binaries
### (in globular clusters)



- LMXBs are the progenitors of the majority of *millisecond pulsars*
  - ▷ *recycling scenario:* spin-up of the neutron-star due to accretion (requires "magnetic field decay")

*Problems with the standard Model for LMXBs (supplementary)*

- the *formation of LMXBs* requires a very contrived evolution:
  - ▷ extreme initial mass ratio
  - ▷ *ejection* of a *massive* common envelope by a *low-mass* star
  - ▷ *survival* as a bound system after the *supernova* (eject $< 1/2$ of the total mass or supernova kick)
- LMXBs are very <u>rare objects</u> (1 in $10^6$ stars)
- standard theory cannot explain
  - ▷ *orbital period distribution:* different from CV distribution
  - ▷ *luminosity distribution:* too many luminous systems
- the problem of the missing intermediate-mass X-ray binaries (should be the most common)

- *LMXB/ms-pulsar statistics* (e.g. in globular clusters [Fruchter])

$$\frac{\#\text{ of LMXBs}}{\#\text{ of ms pulsars}} \simeq \frac{\text{lifetime of LMXBs}}{\text{lifetime of ms pulsars}}$$
$$\sim 5 \times 10^9\ \text{yr}$$

$$N_{\text{LMXB}} \approx 10$$

$$N_{\text{PSR}} \approx 1500\, \frac{\overbrace{(1+\beta)}^{\text{binary correction}}}{\underbrace{f}_{\text{beaming factor}}} \simeq 10^4$$

$$\rightarrow \boxed{t_{\text{LMXB}} \sim 10^7\ yr}$$

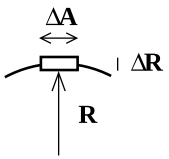
  - ▷ implied LMXB lifetime too short by a factor of 10 to 100 both in globular clusters and in the Galaxy

*Possible solutions*

- *X-ray irradiation*
  - ▷ irradiation-driven wind (Ruderman et al. 1988)
  - ▷ irradiation-driven expansion (Podsiadlowski 1991)
- different channel for the formation of ms pulsars
  - ▷ accretion-induced collapse
  - ▷ formation from intermediate-mass X-ray binary population in the past

## The Eddington Limit

- Definition: the maximum luminosity for which the gravitational force on a fluid element exceeds the radiation pressure force (i.e. the maximum luminosity at which matter can be accreted)




▷ fluid element with cross section $\Delta A$ and height $\Delta R$ at a distance R from the centre of gravity of mass M,

- the (inward) *gravitational force* on the element is

$$F_{grav} = \underbrace{-\frac{GM}{R^2}}_{\text{gravity}} \quad \underbrace{\rho\,\Delta A \Delta R}_{\text{mass}}$$

- the (outward) *radiative force* on the element (due to the deposition of momentum by photons absorbed or scattered): $F_{rad} = \underbrace{\frac{L}{4\pi R^2\,c}\Delta A}_{\text{momentum flow}} \quad \underbrace{\kappa\rho\,\Delta R}_{\text{momentum “deposited”}}$

- maximum luminosity: $F_{grav} + F_{rad} = 0$ and solving for L then yields $\boxed{L_{edd} = \frac{4\pi GMc}{\kappa}}$

- for Thomson scattering in a solar-type plasma ($\kappa = 0.034\,\mathrm{m^2\,kg^{-1}}$), $L_{edd} \simeq 3.8 \times 10^4\,L_\odot\,(M/M_\odot)$.

*Eddington accretion rate* (maximum accretion rate)

- if the luminosity is due to accretion luminosity (i.e. gravitational energy release) $L_{grav} = GM\dot{M}/R$, where R is the inner edge of the accretion flow, equating $L_{edd} = L_{grav}$: $\boxed{\dot{M}_{edd} = \frac{4\pi cR}{\kappa}}$

- For a *neutron star*, $\dot{M} \simeq 1.8 \times 10^{-8}\,M_\odot\,\mathrm{yr}^{-1}$

## Mass-Transfer Driving Mechanisms

- mass transfer is driven either by the expansion of the mass donor or because the binary orbit shrinks due to angular momentum loss from the system

- *expansion of the donor:*

  ▷ due to *nuclear evolution* (“evolutionary driven mass transfer”; then $\dot{M} \sim M/t_{nuclear}$) or

  ▷ *non-thermal-equilibrium evolution* (“thermal timescale mass transfer”; then $\dot{M} \sim M/t_{KH}$)

  *conservative mass transfer:*

  ▷ total angular momentum of binary:

$$J = \frac{M_1 M_2}{M_1 + M_2} \quad \underbrace{\sqrt{G(M_1 + M_2)\,A}}_{\text{specific angular momentum}}$$

  (A: orbital separation)

  ▷ if J, $M_1 + M_2$ conserved $\rightarrow$ $(M_1 M_2)^2\,A = $ constant (implies minimum separation if $M_1 = M_2$)

- *angular momentum loss from the system:*

  *gravitational radiation:*

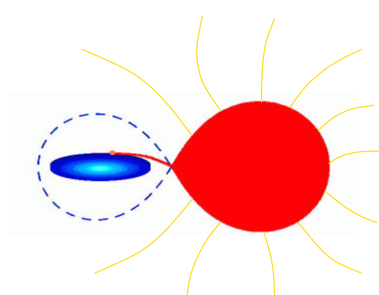
  ▷ effective for $P_{orb} \lesssim 12\,\mathrm{hr}$

*magnetic braking*

▷ red dwarf loses angular momentum in magnetic wind

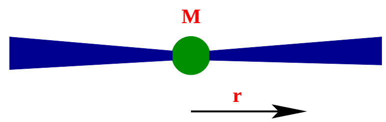
▷ tidal locking of secondary

▷ extracts angular momentum from orbit



# Accretion discs

- an accretion disc forms when the stream of material flowing from the secondary intersects with its own trajectory before hitting the surface of the accreting star (typically if $R_{acc} \lesssim 0.1\,A$)




- in a Keplerian accretion disc: inflow of matter requires a source of *viscosity* so that angular momentum can diffuse outwards and matter inwards (not well understood, magnetorotational instability?)

*the disc temperature structure:* $T(r)$

▷ energy per unit mass in disc at radius r
$E = \frac{1}{2}v^2 - \frac{GM}{r} = -\frac{GM}{2r}$ (virial theorem)

$\rightarrow$ $\frac{dE}{dt} = \frac{GM}{2r^2}u$, where u is the radial drift velocity;

▷ energy radiated by unit area ($\Sigma(r)$ : surface density [mass/area]), assumed to be *blackbody* (the disc has two sides!): $\frac{GM}{2r^2}\,u\,\Sigma(r) = 2\sigma T^4$

▷ and using mass conservation
$\dot{M} = 2\pi r u \Sigma(r) \rightarrow T^4 = GM\dot{M}/8\pi r^3\sigma$

▷ with proper viscous energy transport

$$\boxed{T^4 = \frac{3GM\dot{M}}{8\pi r^3\sigma}}$$

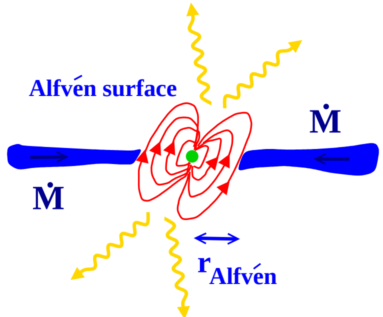
▷ examples: accretion onto a neutron star (no magnetic fields) with $\dot{M} \simeq 2\times10^{-8}\,M_\odot\,yr^{-1}$, $M = 1.4\,M_\odot$, $R = 10\,km$

$\rightarrow$ $R = 10km$: $T \simeq 1.5\times10^7\,K \simeq 1.4\,keV$ (X-rays)

▷ for a massive black hole ($\dot{M} \sim 1\,M_\odot\,yr^{-1}$, $M = 10^8\,M_\odot$, $R = 3R_s = 9\times10^8\,km$)

$\rightarrow$ $T \simeq 2.2\times10^5\,K \simeq 20\,eV$ (UV)

## Neutron Star Spin up by Accretion




- when magnetic fields are important, the accretion flow near the neutron star becomes dominant and channels the mass towards the poles, making the object a ***X-ray pulsar***
- ***Alfvén radius:*** where kinetic energy $\sim$ magnetic energy density,i.e. $\frac{1}{2}\rho\,\mathrm{v}^2 \simeq \frac{\mathrm{B(r)}^2}{2\mu_0}$
- approximating the flow velocity v by the free-fall velocity, i.e. $\mathrm{v} \simeq \mathrm{v_{ff}} = \left(\frac{2\mathrm{GM_{NS}}}{\mathrm{R_{Alf}}}\right)^{1/2}$,
- obtaining the density $\rho$ from mass conservation (quasi-spherical flow) $\rho \simeq \frac{\dot{\mathrm{M}}}{4\pi \mathrm{R_{Alf}^2 v_{ff}}}$
- and assuming a dipole magnetic field ($\mathrm{B} \propto \mathrm{r}^{-3}$) $\mathrm{B(r)} \sim \frac{\mathrm{B_0 R_{NS}^3}}{\mathrm{R_{Alf}^3}}$ (where $\mathrm{B_0}$ is the surface field strength)

$$\rightarrow\ \mathrm{R_{Alf}} \simeq 2.9 \times 10^4\,\mathrm{m}\left(\frac{\mathrm{B}}{10^5\,\mathrm{T}}\right)^{4/7}\left(\frac{\dot{\mathrm{M}}}{2\times 10^{-8}\,\mathrm{M_\odot}\,yr^{-1}}\right)^{-2/7}$$

- ***equilibrium spin period*** (spin-up line!): $\mathrm{P_{spin}} \sim$ orbital period at $\mathrm{R_{Alf}} = 2\pi\sqrt{\mathrm{R_{Alf}^3/GM_{NS}}}$

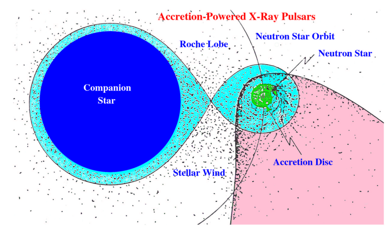
$$\rightarrow\ \mathrm{P_{eq}} \simeq 2.3\,\mathrm{ms}\left(\frac{\mathrm{B}}{10^5\,\mathrm{T}}\right)^{6/7}\left(\frac{\dot{\mathrm{M}}}{2\times 10^{-8}\,\mathrm{M_\odot}\,yr^{-1}}\right)^{-3/7}$$

## High-Mass X-Ray Binaries

- because of the large mass ratio, mass transfer generally becomes ***unstable***, leading to a common-envelope and spiral-in phase
- mass transfer is either due to ***atmospheric Roche-lobe overflow*** (short-lived) or ***wind accretion*** (relatively low luminosity)

***Bondi-Hoyle wind accretion***

▷ accretion from a stellar wind onto an object of mass $\mathrm{M_{acc}}$ with velocity $\mathrm{v_{wind}}$ occurs from a radius (Bondi-Hoyle accretion radius $\mathrm{R_{BH}}$) where $\frac{1}{2}\,\mathrm{mv_{wind}^2} \sim \mathrm{GM_{acc}/R_{BH}}$




$$\rightarrow\ \mathrm{R_{BH}} \simeq \frac{2\mathrm{GM_{acc}}}{\mathrm{v_{wind}^2}}$$

▷ accretion rate: $\dot{\mathrm{M}}_{\mathrm{acc}} = \pi \mathrm{R_{BH}^2}\,\mathrm{v_{wind}}\,\rho(\mathrm{A})$,

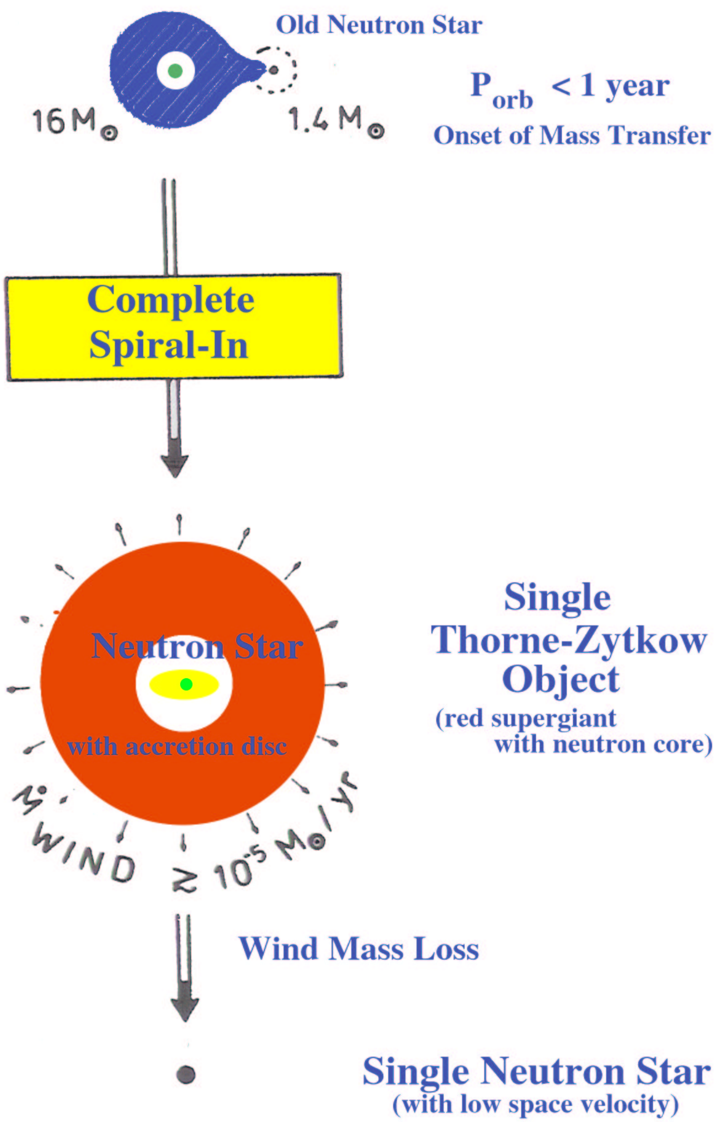
▷ where the wind mass density $\rho$ at orbital separation A follows from ***mass conservation***: $\rho(\mathrm{A}) \simeq \frac{\dot{\mathrm{M}}_{\mathrm{wind}}}{4\pi \mathrm{A}^2\,\mathrm{v_{wind}}}$,

▷ using $\mathrm{v_{orb}^2} = \mathrm{G(M_{acc} + M_{donor})/A}$, one obtains

$$\frac{\dot{\mathrm{M}}_{\mathrm{acc}}}{\dot{\mathrm{M}}_{\mathrm{wind}}} = \left(\frac{\mathrm{v_{orb}}}{\mathrm{v_{wind}}}\right)^4\left(\frac{\mathrm{M_{acc}}}{\mathrm{M_{acc}+M_{donor}}}\right)^2 << 1$$

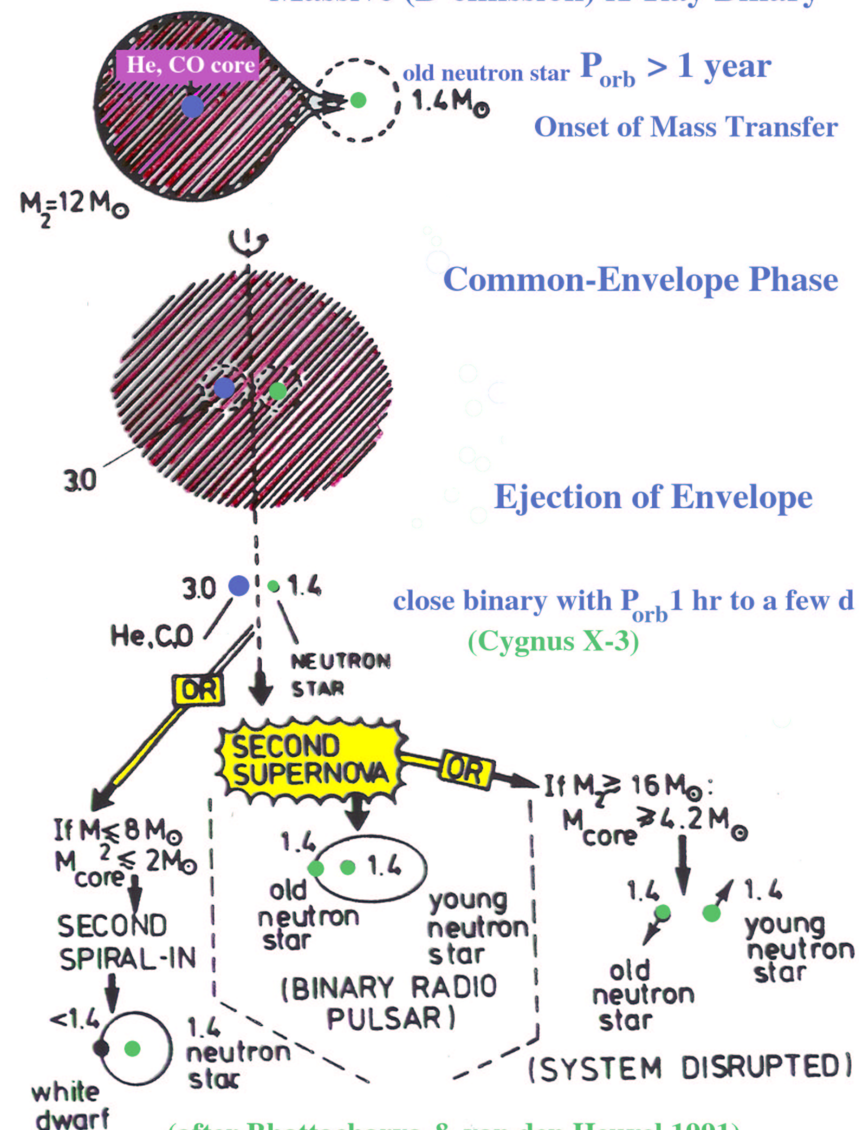
*(for $\mathrm{v_{orb}} << \mathrm{v_{wind}}$)*

## a) Final Evolution of a Close Massive X-Ray Binary




(after Bhattacharya & van den Heuvel 1991)

## Final Evolution of a Wide Massive (B-emission) X-Ray Binary



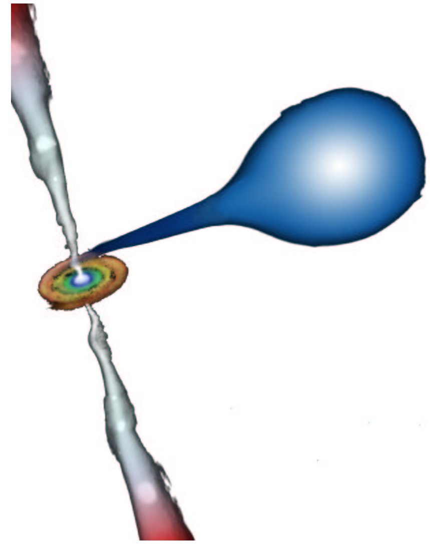

(after Bhattacharya & van den Heuvel 1991)

## Final Fate of HMXBs

- depends on orbital period
- short orbital period ($P_{orb} \lesssim 1\,yr$): $\rightarrow$ *complete spiral-in* $\rightarrow$ *singe red supergiant with a neutron core ("Thorne-Żytkow object")* $\rightarrow$ after envelope loss in stellar wind: *single neutron star*
- long orbital period ($P_{orb} \gtrsim 1\,yr$): common-envelope ejection $\rightarrow$ *second supernova* $\rightarrow$ *double neutron-star binary* (if binary is not disrupted in the supernova)

*Double neutron star (DNS) binaries*

- PSR 1913+16 (with $P_{orb} \simeq 8\,hr$, $P_{spin} = 59\,ms$) discovered by Taylor & Hulse (1975)
- about half a dozen are now known
- orbital evolution is driven by *gravitational radiation* $\rightarrow$ one of the best *tests of general relativity*
- DNSs with orbital periods $\lesssim 10\,hr$ will ultimately merge to
  - ▷ produce a short-duration *gamma-ray burst (?)*
  - ▷ major source of *gravitational waves* directly detectable by modern gravitational wave detectors (e.g. Advanced LIGO)
  - ▷ produce *neutron-rich elements* (r-process, e.g. gold)



*Mass Loss from XRBs*

- ▷ *relativistic jets* from the accreting object
- ▷ e.g. *SS 433*
- ▷ disc winds driven by X-ray irradiation

## X-Ray Variability

- X-ray binaries are variable on many timescale in different ways
  - ▷ *X-ray pulsations:* periodic with spin period, due to magnetically funnelled accretion onto the poles
  - ▷ *flickering, quasi-periodic oscillations:* caused by instabilities in the disc (noise)
  - ▷ *transient accretion events:* alternation between phases of high and low accretion dates due to thermal transitions in the accretion disc (in particular for black holes accreting at low rates; also cataclysmic variables)

# X-Ray Bursts

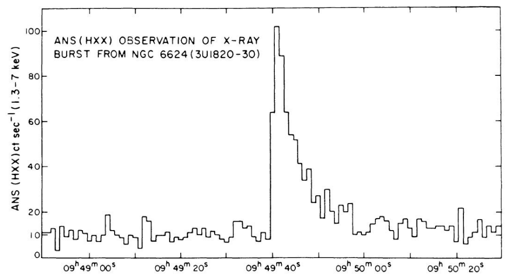


Fig. 3. The discovery of X-ray bursts. Detection of an X-ray burst from a source located in the globular

- *thermonuclear explosions*, once enough H/He fuel has been accreted
- Eddington-limited, thermal (blackbody) X-ray spectrum
- can potentially be used to determine the radius of neutron stars and potentially constrain the neutron-star equation of state

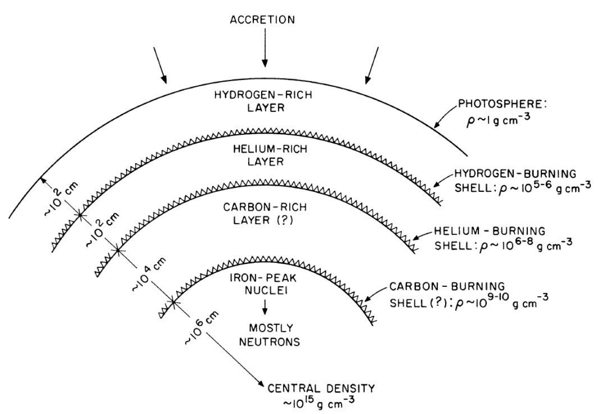


Fig. 37. Schematic sketch of the surface layers of an accreting neutron star. This figure is from Joss [143].

# Do Black Holes Exist?

- *present methods are indirect*
  - ▷ using the *binary mass function* of the secondary
    $$f_2(M_1) = \frac{M_1^3 \sin^3 i}{(M_1 + M_2)^2} = \frac{P\,(v_2 \sin i)^3}{2\pi G}$$
  - ▷ determined from observables P and $v_2 \sin i$
  - ▷ for $M_2 \ll M_1 \rightarrow f_2(M_1) \simeq M_1 \sin^3 i$
  - ▷ *largest mass* of a compact object to-date: $\gtrsim 10\,M_\odot$ (GRS 1915+105)
  - ▷ much larger than the maximum possible mass of a neutron star $(2 - 3\,M_\odot)$

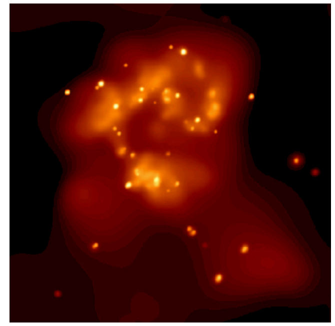
  but: NS structure is not well understood; postulates of strange matter star, Q-balls, etc. that do not have a maximum mass limit
- *spectral properties*
  - ▷ accreting black holes emit a softer *X-ray spectrum* since the inner edge of the accretion disc is larger for a more massive black hole
  - ▷ $R_{\rm inner}$ is determined by the last stable orbit for particles: $R_{\rm stable} = 3R_{\rm Schwarzschild} = 9\,{\rm km}\,(M_{\rm BH}/\,M_\odot)$
- need to prove *the existence of an event horizon*
  - ▷ e.g. by observing an inflow of *mass-energy* that *disappears* without observable trace
  - ▷ Note: for an object with a hard surface, material has to hit the surface, which produces photons
  - ▷ possible in principle, but has not been demonstrated convincingly to date

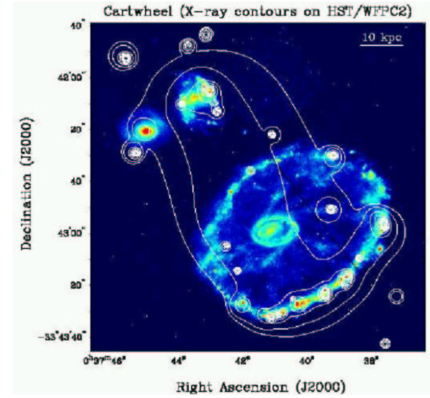
## Ultraluminous X-Ray Sources (ULXs)

- discovered by EINSTEIN (Fabbiano 1989), confirmed by ROSAT, ASCA, $L_X > 10^{32}$ W (i.e. above the Eddington limit for a $\sim 10\,M_\odot$ object)
- *stellar-mass black holes* ($10^2 - 10^5\,M_\odot$)*?* (Colbert & Mushotzky 1999) (i.e. the missing link between stellar-mass [$\sim 10\,M_\odot$] and super-massive black holes [$\gtrsim 10^6\,M_\odot$])
- possibly important
  - ▷ as *building blocks* of supermassive black holes
  - ▷ as seeds for *star formation* (triggering the collapse of gas clouds)
  - ▷ *dark matter* in galactic halos
  - ▷ forming the *cores of globular clusters*
- argument in support: *soft X-ray spectrum*
- association with *starburst galaxies, interacting galaxies (e.g. Antennae)*

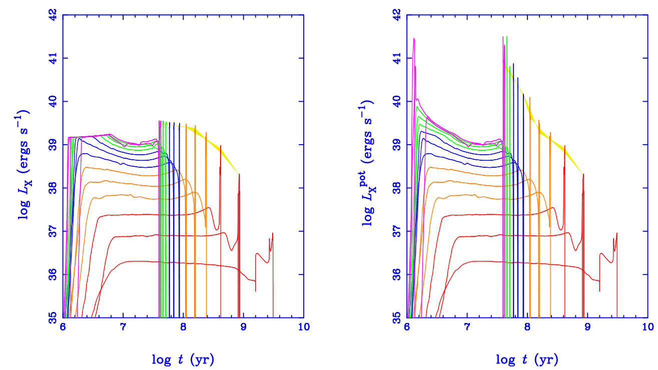
but: *GRS 1915+105* is a *Galactic counterpart* containing a $\sim 14\,M_\odot$ black hole

*Do ULX contain intermediate mass black holes or do they form the luminous tail of the known black-hole binary population?*






- association with star formation (e.g. the clustering in the star-formation wave seen in the Cartwheel galaxy) connects them with massive stars




- modelling of intermediate-mass BH binaries consistent with observed luminosities, luminosity function
- require moderate amount of *super-Eddington luminosities* for the most luminous ULXs (+ beaming?)
  - ▷ as observed in many neutron-star (NS) X-ray binaries (magnetic accretion?)
  - ▷ see e.g. Begelman (2002): photon-bubble instabilities in magnetic disc
- *probably most ULXs are BH binaries*