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

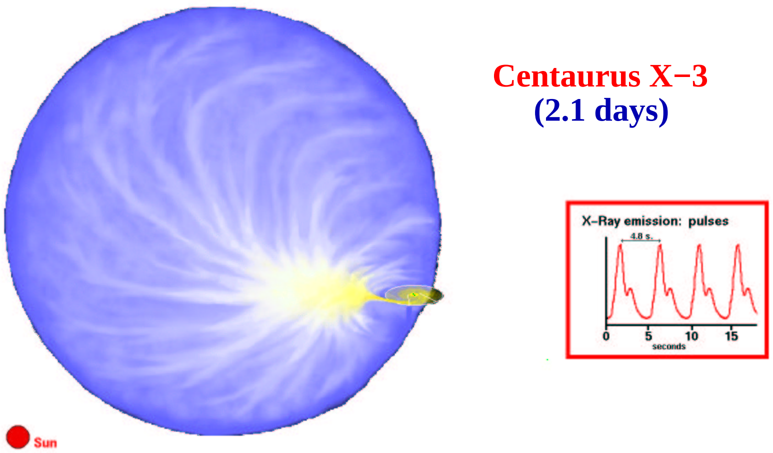
Basic Properties

- 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

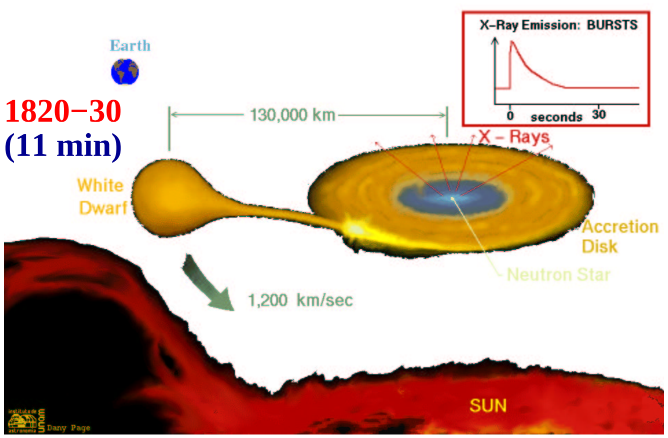
High-Mass X-Ray Binaries

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

High−Mass X−Ray Binaries



Low−Mass X−Ray Binaries

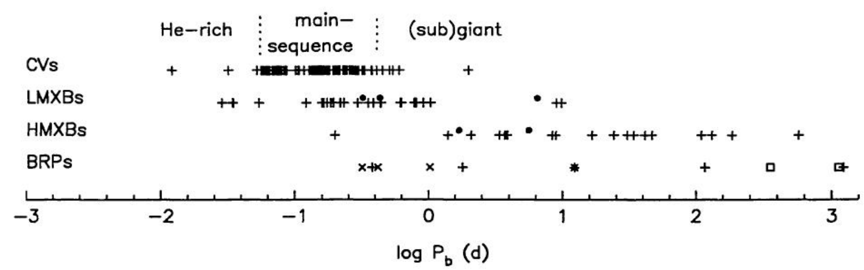


Low-Mass X-Ray Binaries

- 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!)

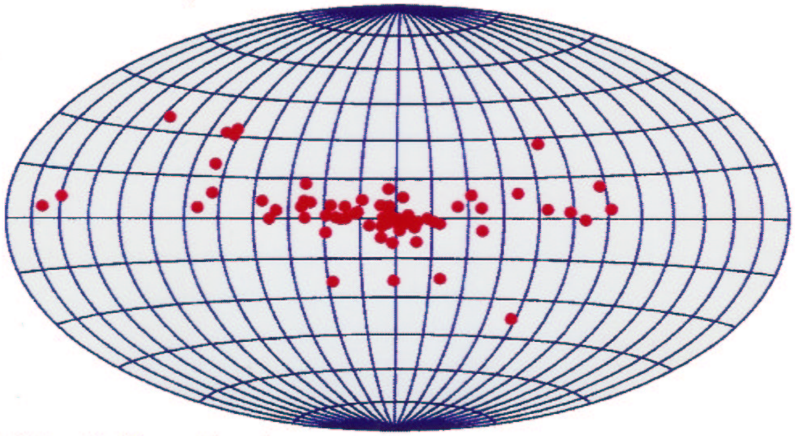
Orbital Period Distributions

- known periods only! Selection effects!



Galactic Distribution of X-ray binaries

"Low-Mass" X-ray binaries



"High-Mass" X-ray binaries

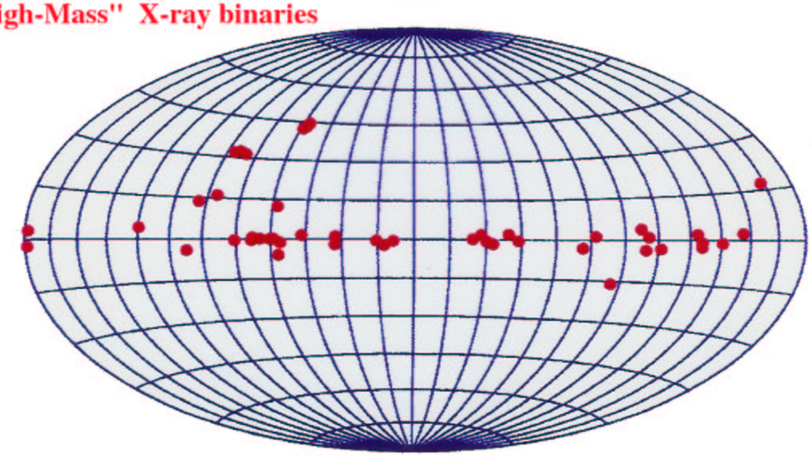
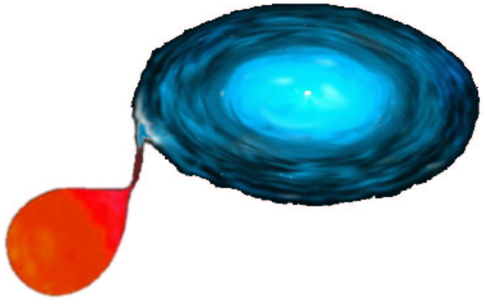


Table 1 Properties of some X-ray binaries and all currently known radio binary pulsars†

Name	Position	P (s)	$\log L_x$ (erg/s)	P_b (d)	e	Spectral	Reference
			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 $180 \pm 80\,\mathrm{km\,s^{-1}}$ (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 ΔE_{orb} is the orbital energy released, E_{bind} the binding energy of the envelope and α_{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: ~ 100; GCs: ~ 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)

wide binary with large mass ratio

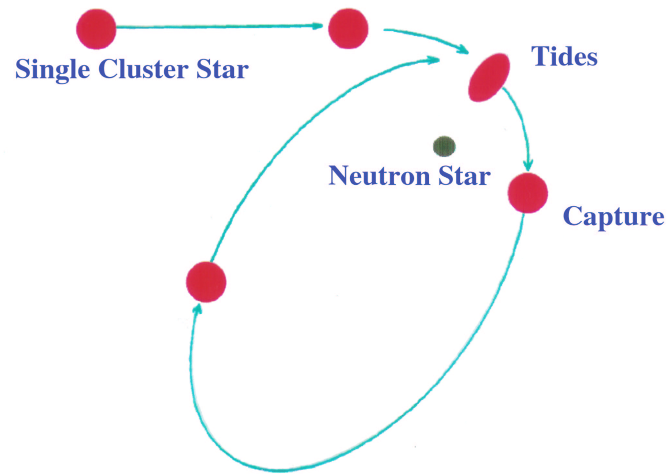
dynamical mass transfer

common-envelope and spiral-in phase

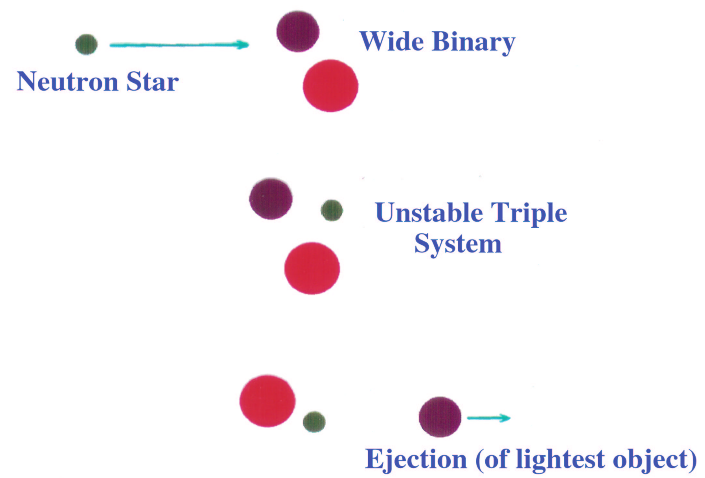
ejection of common envelope and subsequent supernova

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

Tidal Capture



Three-Body Scattering



- 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])

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

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

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

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

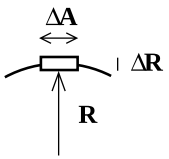
  - ▷ implied LMXB lifetime too short by a factor of 10 to 100 both in globular clusters and in the Galaxy

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 ΔA and height ΔR 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 $(\kappa = 0.034\,m^2\,kg^{-1})$, $L_{edd} \simeq 3.8 \times 10^4\,L_\odot\,(M/M_\odot)$.

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, $\dot{M} \simeq 1.8 \times 10^{-8}\,M_\odot\,yr^{-1}$

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 $\rightarrow$ $(M_1 M_2)^2\,A = \text{constant}$ (implies minimum separation if $M_1 = M_2$)

- angular momentum loss from the system:

  gravitational radiation:

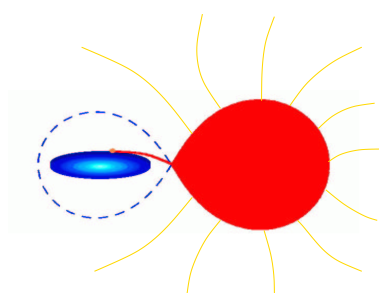
  ▹ effective for $P_{orb} \lesssim 12\,hr$

magnetic braking

▹ red dwarf loses angular momentum in magnetic wind

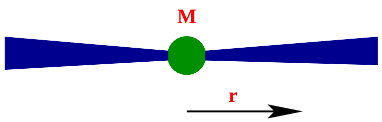
▹ tidal locking of secondary

▹ 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

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

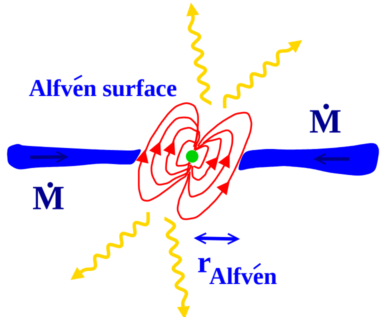
▷ examples: accretion onto a neutron star (no magnetic fields) with $\dot{M} \simeq 2\times10^{-8}\,M_\odot\,yr^{-1}$, $M = 1.4\,M_\odot$, $R = 10\,km$

$\rightarrow$ $R = 10km$: $T \simeq 1.5\times10^7\,K \simeq 1.4\,keV$ (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 ∼ magnetic energy density,i.e. $\frac{1}{2}\rho v^2 \simeq \frac{B(r)^2}{2\mu_0}$
- approximating the flow velocity v by the free-fall velocity, i.e. $v \simeq v_{ff} = \left(\frac{2GM_{NS}}{R_{Alf}}\right)^{1/2}$,
- obtaining the density ρ from mass conservation (quasi-spherical flow) $\rho \simeq \frac{\dot{M}}{4\pi R_{Alf}^2 v_{ff}}$
- and assuming a dipole magnetic field ($B \propto r^{-3}$) $B(r) \sim \frac{B_0 R_{NS}^3}{R_{Alf}^3}$ (where B_0 is the surface field strength)

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

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

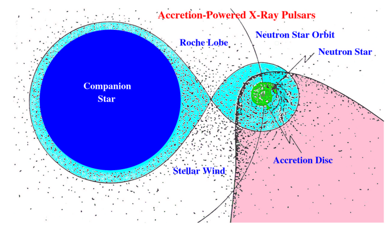
$$\rightarrow \quad P_{eq} \simeq 2.3\,\mathrm{ms} \left(\frac{B}{10^5\,\mathrm{T}}\right)^{6/7} \left(\frac{\dot{M}}{2 \times 10^{-8}\,M_\odot\,\mathrm{yr}^{-1}}\right)^{-3/7}$$

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 M_{acc} with velocity v_{wind} occurs from a radius (Bondi-Hoyle accretion radius R_{BH}) where $\frac{1}{2} m v_{wind}^2 \sim GM_{acc}/R_{BH}$



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

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

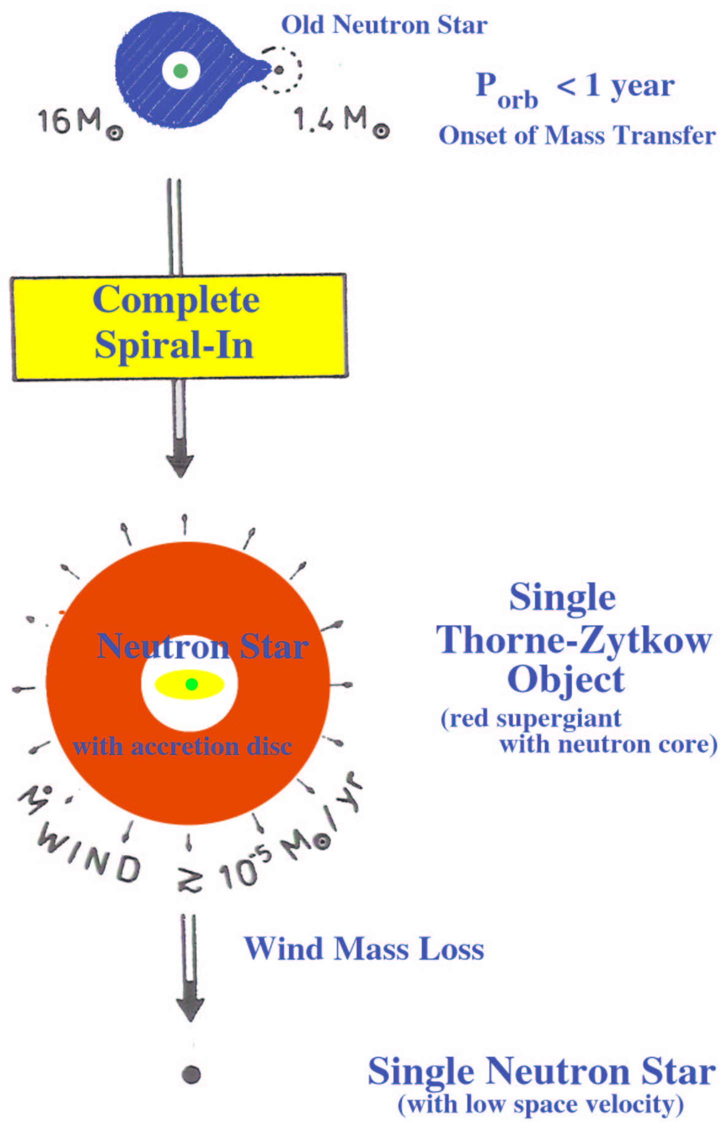
▷ where the wind mass density ρ at orbital separation A follows from mass conservation: $\rho(A) \simeq \frac{\dot{M}_{wind}}{4\pi A^2\, v_{wind}}$,

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

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

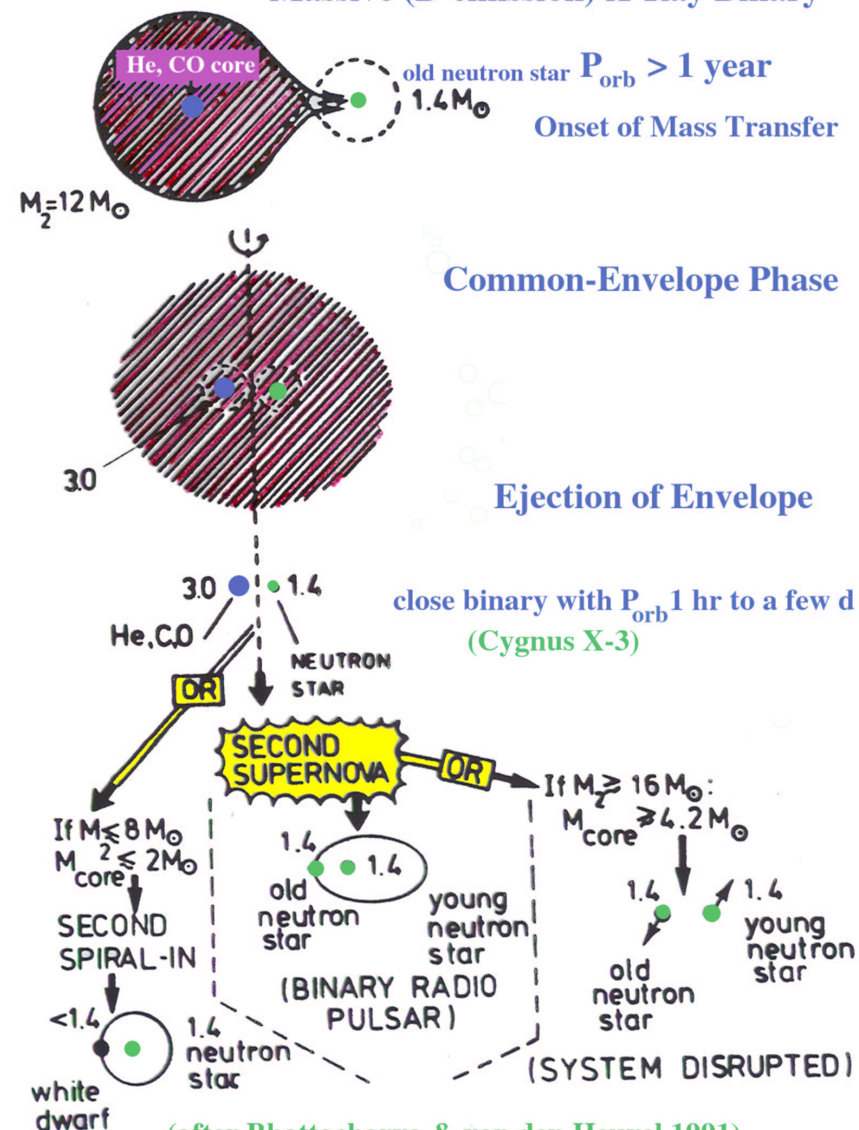
(for $v_{orb} << v_{wind}$)

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



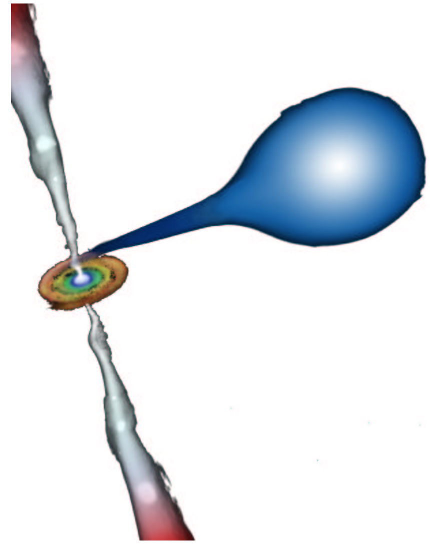
(after Bhattacharya & van den Heuvel 1991)

Final Fate of HMXBs

- depends on orbital period
- short orbital period ($P_{orb} \lesssim 1\,yr$): → complete spiral-in → singe red supergiant with a neutron core ("Thorne-Żytkow object") → after envelope loss in stellar wind: single neutron star
- long orbital period ($P_{orb} \gtrsim 1\,yr$): common-envelope ejection → second supernova → 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 → 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

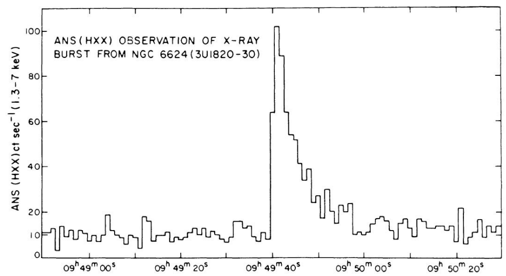


Fig. 3. The discovery of X-ray bursts. Detection of an X-ray burst from a source located in the globular

- 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

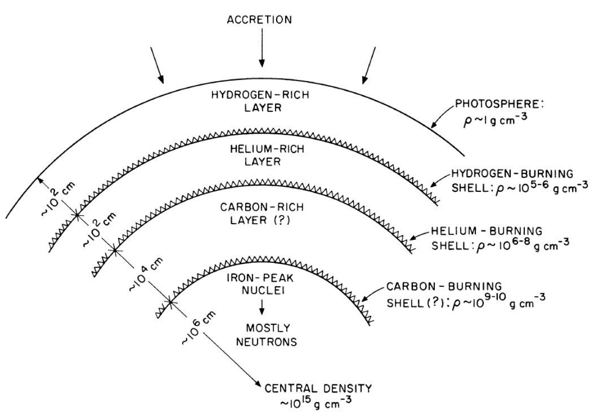


Fig. 37. Schematic sketch of the surface layers of an accreting neutron star. This figure is from Joss [143].

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 $(2 - 3\,M_\odot)$

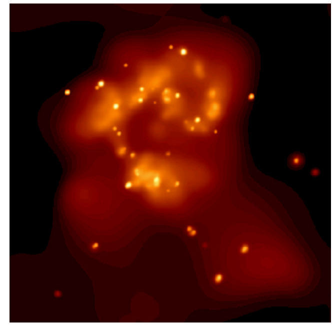
  but: NS structure is not well understood; postulates of strange matter star, Q-balls, etc. that do not have a maximum mass limit
- spectral properties
  - ▷ accreting black holes emit a softer X-ray spectrum since the inner edge of the accretion disc is larger for a more massive black hole
  - ▷ $R_{\rm inner}$ 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

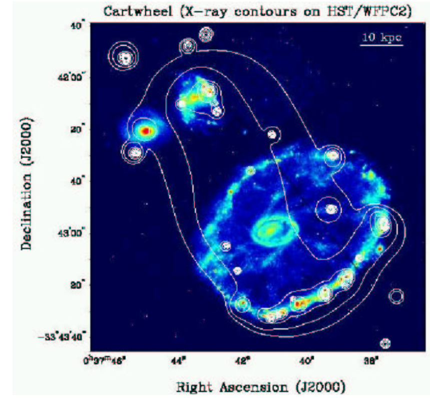
Ultraluminous X-Ray Sources (ULXs)

- discovered by EINSTEIN (Fabbiano 1989), confirmed by ROSAT, ASCA, $L_X > 10^{32}\,\mathrm{W}$ (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)

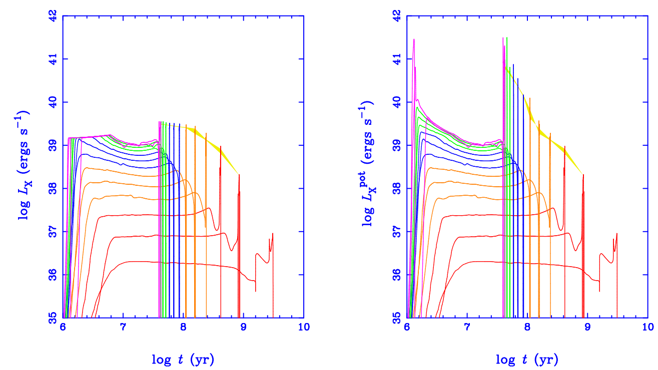
but: GRS 1915+105 is a Galactic counterpart containing a $\sim 14\,M_\odot$ black hole

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