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

Centaurus X-3 (2.1 days)

Low-Mass X-Ray Binaries

1820–30 (11 min)

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

Orbital Period Distributions

- known periods only! Selection effects!
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<td>X-ray binaries</td>
<td>&quot;High-Mass X-ray binaries&quot;</td>
<td>[Image]</td>
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<td>Table 1: Properties of some X-ray binaries and all currently known radio binary systems.</td>
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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:
  - \( P < 1\) hr: degenerate stars \( (M_2 \sim 0.1M_\odot) \)
  - \( 3\) hr \( < P \sim 10\) hr: main-sequence stars
  - \( P \approx 10\) 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: \( 200 – 250\) 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 \( (\sim 0.1 – 10R_\odot) \) 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) \( \rightarrow \) companion star cannot accrete all the transferred matter and is engulfed \( \rightarrow \) formation of a common envelope (CE) \( \rightarrow \) friction \( \rightarrow \) spiral-in
  - CE is ejected when \( \alpha_{\text{CE}} \Delta E_{\text{orb}} > E_{\text{bind}}, \) where \( \Delta E_{\text{orb}} \) is the orbital energy released, \( E_{\text{bind}} \) the binding energy of the envelope and \( \alpha_{\text{CE}} \) 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
    - \( \rightarrow \) 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
  - Single Cluster Star
  - Tides
  - Neutron Star
  - Capture

- Three-Body Scattering
  - Neutron Star
  - Wide Binary
  - Unstable Triple System
  - Ejection (of lightest object)
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 rare objects (1 in 10⁶ 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])

- \[
  \frac{\text{# of LMXBs}}{\text{# of ms pulsars}} \sim \frac{\text{lifetime of LMXBs}}{\text{lifetime of ms pulsars}} \sim 5 \times 10^9 \text{ yr}
  \]

- \[
  N_{\text{LMXB}} \approx 10
  \]

- \[
  N_{\text{PSR}} \approx 1500 \frac{(1 + \beta)}{t} \sim 10^4
  \]

  → \[
  t_{\text{LMXB}} \sim 10^7 \text{ yr}
  \]

- 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

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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)

\[ F_{\text{grav}} = \frac{GM}{R^2} \rho \frac{\Delta A \Delta R}{\text{mass}} \]

- the (inward) gravitational force on the element is

\[ F_{\text{grav}} = \frac{GM}{R^2} \rho \frac{\Delta A \Delta R}{\text{mass}} \]

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

- maximum luminosity: \( F_{\text{grav}} + F_{\text{rad}} = 0 \) and solving for \( L \) then yields

\[ L_{\text{edd}} = \frac{4\pi GMc}{\kappa} \]

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

Eddington accretion rate (maximum accretion rate)

- if the luminosity is due to accretion luminosity (i.e. gravitational energy release) \( L_{\text{grav}} = GMM/R \), where \( R \) is the inner edge of the accretion flow, equating

\[ L_{\text{edd}} = L_{\text{grav}} : \frac{M_{\text{edd}}}{\kappa} = \frac{4\pi c R}{\kappa} \]

- For a neutron star, \( \dot{M} \approx 1.8 \times 10^{-8} M_\odot \text{yr}^{-1} \)

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 \( \dot{M} \sim M/t_{\text{nuclear}} \)) or
  - non-thermal-equilibrium evolution ("thermal timescale mass transfer"; then \( \dot{M} \sim M/t_{\text{KH}} \))

- conservative mass transfer:
  - total angular momentum of binary:
    \[ J = \frac{M_1 M_2}{M_1 + M_2} \sqrt{G(M_1 + M_2)A} \]
    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 \( P_{\text{orb}} \approx 12 \text{ hr} \)
  - 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 $R_{\text{acc}} \lesssim 0.1 \ A$)

- 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?)

Accretion discs

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)

- 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
  \[ \dot{M} = 2\pi r u \Sigma(r) \rightarrow T^4 = \frac{GM\dot{M}}{8\pi r^3\sigma} \]

  - with proper viscous energy transport

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

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

  - $R = 10 \text{ km}$: $T \approx 1.5 \times 10^7 \text{ K} \approx 1.4 \text{ keV (X-rays)}$

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

  - $T \approx 2.2 \times 10^5 \text{ K} \approx 20 \text{ eV (UV)}$
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. $\frac{1}{2} \rho v^2 \sim \frac{B(r)^2}{2\mu_0}$
- approximating the flow velocity $v$ by the free-fall velocity, i.e. $v \simeq v_{\text{ff}} = \left(\frac{2GM_{\text{NS}}}{R_{\text{Alf}}}\right)^{1/2}$
- obtaining the density $\rho$ from mass conservation (quasi-spherical flow) $\rho \approx \frac{\dot{M}}{4\pi R_{\text{Alf}}^2 v_{\text{ff}}}$
- and assuming a dipole magnetic field ($B \propto r^{-3}$) $B(r) \sim \frac{B_0 R_{\text{NS}}^3}{R_{\text{Alf}}^3}$ (where $B_0$ is the surface field strength)
- equilibrium spin period (spin-up line!): $P_{\text{spin}} \sim$ orbital period at $R_{\text{Alf}} = 2\pi \sqrt{R_{\text{Alf}}^3 / GM_{\text{NS}}}$
  \[ P_{\text{eq}} \approx 2.3 \text{ ms} \left(\frac{B}{10^5 \text{T}}\right)^{6/7} \left(\frac{\dot{M}}{2 \times 10^{-8} \text{M}_\odot \text{yr}^{-1}}\right)^{-3/7} \]

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 $M_{\text{acc}}$ with velocity $v_{\text{wind}}$ occurs from a radius (Bondi-Hoyle accretion radius $R_{\text{BH}}$) where
  \[ \frac{1}{2} m v_{\text{wind}}^2 \sim GM_{\text{acc}} / R_{\text{BH}} \]
  \[ R_{\text{BH}} \approx \frac{2GM_{\text{acc}}}{v_{\text{wind}}^2} \]
- accretion rate: $\dot{M}_{\text{acc}} = \pi R_{\text{BH}}^2 v_{\text{wind}} \rho(A)$,
- where the wind mass density $\rho$ at orbital separation $A$ follows from mass conservation: $\rho(A) \approx \frac{\dot{M}_{\text{wind}}}{4\pi A^2 v_{\text{wind}}}$
- using $v_{\text{orb}}^2 = G(M_{\text{acc}} + M_{\text{donor}})/A$, one obtains
  \[ \frac{\dot{M}_{\text{acc}}}{\dot{M}_{\text{wind}}} = \left(\frac{v_{\text{orb}}}{v_{\text{wind}}}\right)^4 \left(\frac{M_{\text{acc}}}{M_{\text{acc}} + M_{\text{donor}}}\right)^2 \ll 1 \]
  (for $v_{\text{orb}} \ll v_{\text{wind}}$)
(After Phokhetsiri & van den Heuvel 1991)

(SYSTEM DISRUPTED)

1) white dwarf
2) neutron star
3) young neutron star
4) old neutron star
5) neutron pulsar
6) binary radio star
7) supernova
8) core collapse
9) core collapse supernova
10) neutron star
11) old neutron star
12) young neutron star
13) white dwarf
14) He, C, O
15) 3.07 M_☉, 1.4 M_☉, 1.4 M_☉
16) M = 2 M_☉, M = 8 M_☉, M = 3.72 M_☉
17) Cय_3

(1) Single Neutron Star

(With low space velocity)

Single Neutron Star

Wind Mass Loss

(With accretion disc)

Uneven Object

Thorne-Zykov

Single

Complete Spinal-In

Massive X-Ray Binary

Final Evolution of a Wide Binary

(Quiescent X-Ray Binary) Mass Loss (P-emission) X-Ray Binary

Final Evolution of a Close Binary

Quiescent Phase

Close Binary with P orb < 1 year

Mass Transfer

M2 = 1.2 M_☉
Final Fate of HMXBs

- depends on orbital period

- short orbital period ($P_{\text{orb}} \lesssim 1 \text{ yr}$): → 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 ($P_{\text{orb}} \gtrsim 1 \text{ yr}$): 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 $P_{\text{orb}} \approx 8 \text{ hr}$, $P_{\text{spin}} = 59 \text{ ms}$) 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 $\lesssim 10 \text{ hr}$ 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**

- 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

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**Do Black Holes Exist?**

- present methods are indirect
  - using the binary mass function of the secondary
    \[
    f_2(M_1) = \frac{M_1^3 \sin^3 \theta}{(M_1 + M_2)^2} = \frac{P (v_2 \sin \theta)^3}{2\pi G}
    \]
  - determined from observables P and \( v_2 \sin \theta \)
  - for \( M_2 \ll M_1 \rightarrow f_2(M_1) \approx M_1 \sin^3 \theta \)
  - 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
  - \( R_{\text{inner}} \) is determined by the last stable orbit for particles: \( R_{\text{stable}} = 3R_{\text{Schwarzschild}} = 9 \text{ km} (M_{\text{BH}}/M_\odot) \)

- 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