High Energy Astrophysics II

10 lectures to A3/A4, beginning January 2006

Course website:

http://www.astro.gla.ac.uk/users/martin/teaching/hea2/index.html

username: honours *password:* honours

See also: http://www.astro.gla.ac.uk/users/martin/teaching/hea1/index.html

XMM Newton, launched 1999

Aims

To develop further the ideas and tools introduced in HEA1, and apply them in some specific astrophysical situations.

High Energy Astrophysics II

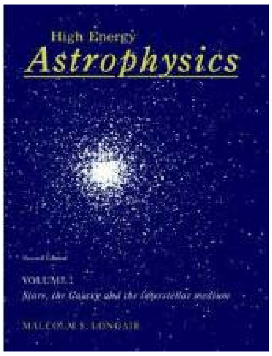
Course topics

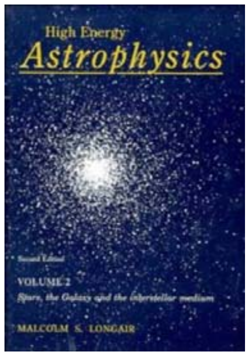
- **Black Body Sources:** X-ray binaries, ULXs, X-ray bursters
- **Bremsstrahlung and Atomic Line Sources:** Stellar winds; Coronal loops
- **Cyclotron and Synchrotron Sources:** SN remnants; Active galaxies
- **Inverse Compton Sources:** Diffuse backgrounds; Cosmic rays
- **Gamma Ray Sources:** Gamma ray bursters; Annihilation line; Solar and atmospheric gamma lines

Textbooks

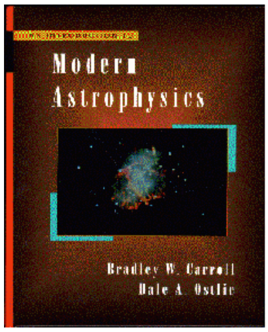
(Not required for purchase, but useful for consultation)

- High energy astrophysics,
  Malcolm S. Longair
  Vols 1 & 2, (CUP)





- Introduction to Modern Astrophysics,
  Carroll & Ostlie, (Addison-Wesley)



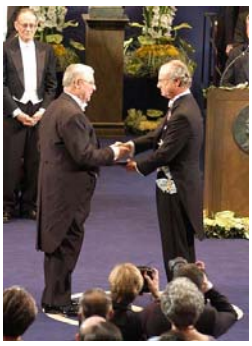
1. X-Ray Binaries

There exist large numbers of compact X-ray sources concentrated near the Galactic plane. **X-Ray Binaries**


Advanced information on the Nobel Prize in Physics 2002, 8 October 2002

KUNGL. VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Information Department, P.O. Box 50005, SE-104 05 Stockholm, Sweden
Phone: +46 8 673 95 00, Fax: +46 8 15 56 70, E-mail: info@kva.se, Website: www.kva.se



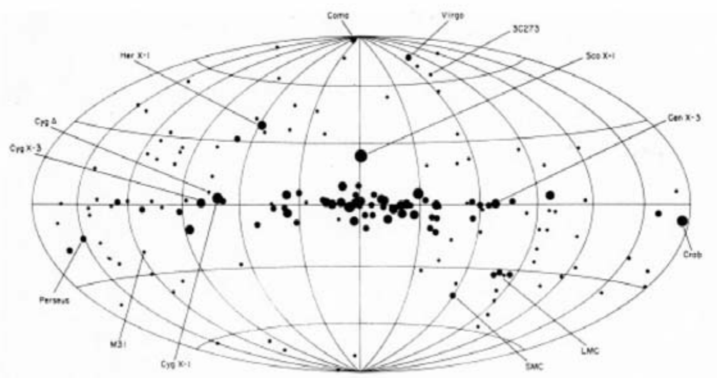


Fig. 9 A map of the X-ray sky in galactic coordinates derived from the 3U Catalog, based on UHURU data. The location of each X-ray source is approximately shown. The size of the dots is proportionate to the logarithm of the intensity. Several of the sources of outstanding astrophysical interest are shown.

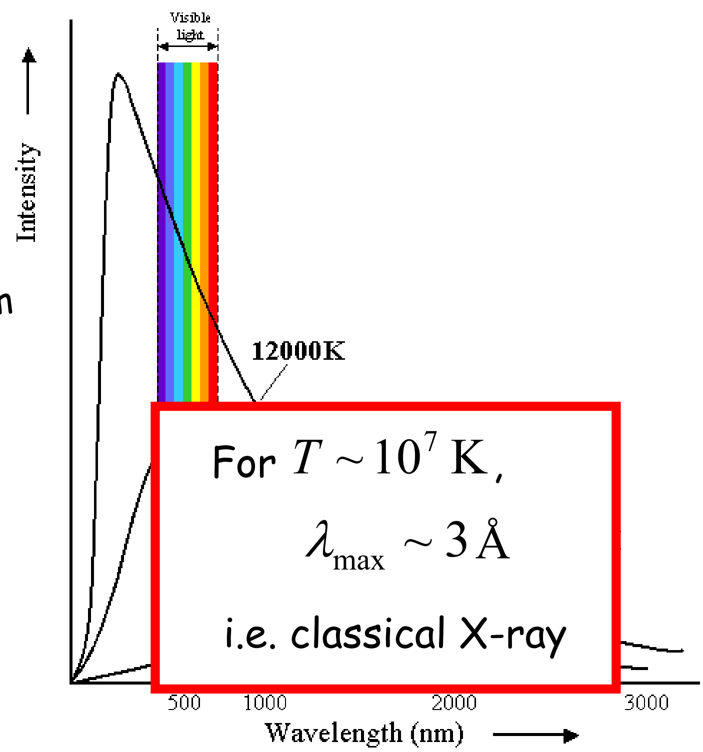
Source characteristics:

- very high X-ray luminosity, up to 10^{32} W ($\sim 10^5 L_{\rm bol}$ for sun)
- approx. black body spectrum with $T \geq 10^7$ K
  $\Rightarrow$ from Wien's law, peak lies in X-ray region of spectrum
- rapid flickering on timescales $\tau \leq 1$ sec $\Rightarrow$ size $\lesssim 3 \times 10^8$ m
- slow, periodic variation on timescales of hours to days
  $\Rightarrow$ sources are close binary systems (can constrain masses)

- Planck Spectrum characterised by the temperature of the source
- Isotropic
- Unpolarised

For Main Sequence stars, the peak of the black body curve lies in, or close to, the visible part of the E-M spectrum

For X-ray sources, peak lies at X-ray Wavelengths



For $T \sim 10^7$ K,

$\lambda_{\max} \sim 3$ Å

i.e. classical X-ray

Wien's Law

(1.1) $$\lambda_{\max} T = 2.9 \times 10^{-3}$$

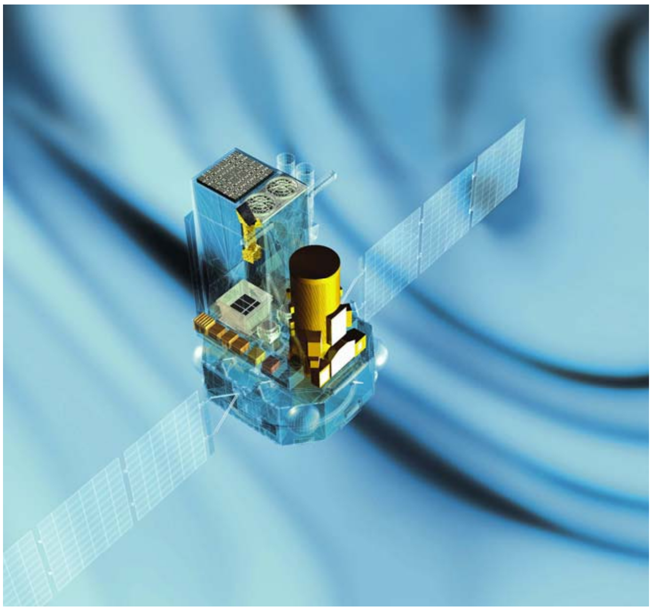
$\lambda_{\max}$: in m; T: in K

Source characteristics:

- very high X-ray luminosity, up to 10^{32} W ($\sim 10^5 L_{\text{bol}}$ for sun)
- approx. black body spectrum with $T \geq 10^7$ K
  $\Rightarrow$ from Wien's law, peak lies in X-ray region of spectrum
- rapid flickering on timescales $\tau \leq 1$ sec $\Rightarrow$ size $\lesssim 3 \times 10^8$ m
- slow, periodic variation on timescales of hours to days
  $\Rightarrow$ sources are close binary systems (can constrain masses)
- many sources have massive ($M_{\text{opt}} \sim 10 M_\odot$) optical companion

$\longrightarrow$ *High Mass X-ray Binaries* e.g. Cygnus X-1. $15 M_\odot$ BH, $M_{\text{opt}} \sim 33 M_\odot$

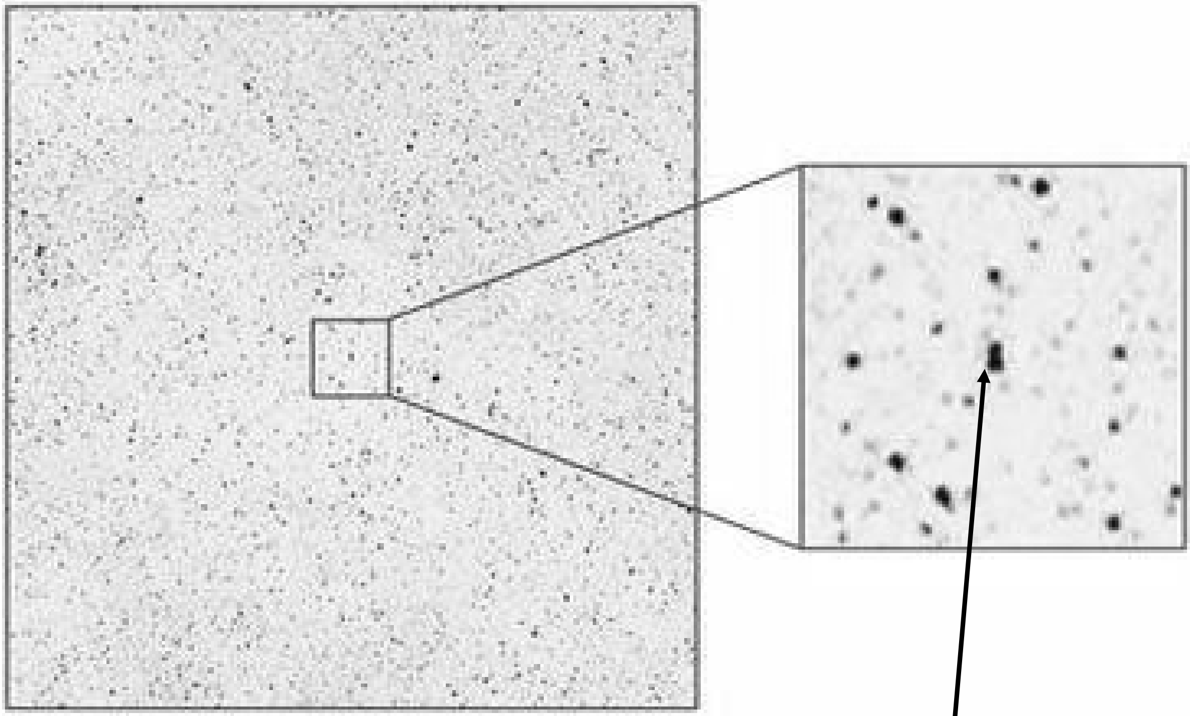
Lifetime of the system set by Main Sequence lifetime of massive companion $\tau \leq 10^{7-8}$ years



ESA INTEGRAL: launched 2002

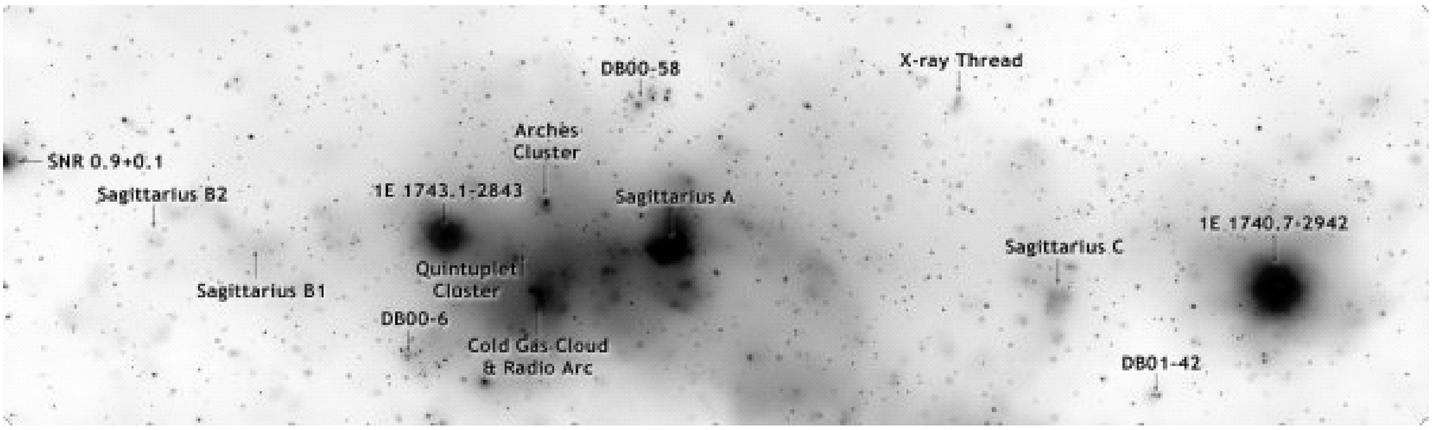
4 onboard instruments:

Simultaneous high-resolution imaging and spectroscopy in the optical and X-ray



Optical companion of Cygnus X-1

Chandra has revealed many more X-ray binary sources in the Milky Way, globular clusters and external galaxies.



Chandra (launched 1999): high-resolution X-ray map of the Galactic Centre

Chandra has revealed many more X-ray binary sources in the Milky Way, globular clusters and external galaxies – including **ellipticals**.

Indicates population of *Low Mass X-ray Binaries*

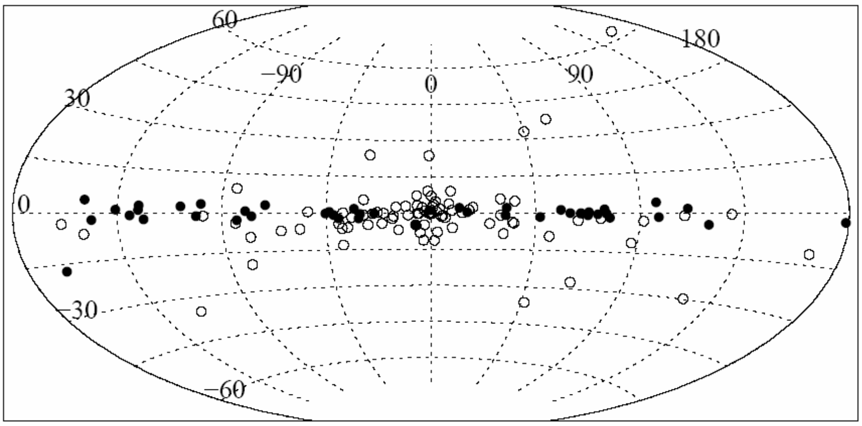
Mass of optical companion $M_{\rm opt} \sim 1 M_{\odot}$

$\Rightarrow$ Characteristic timescale $\tau \sim 10^{10}$ years

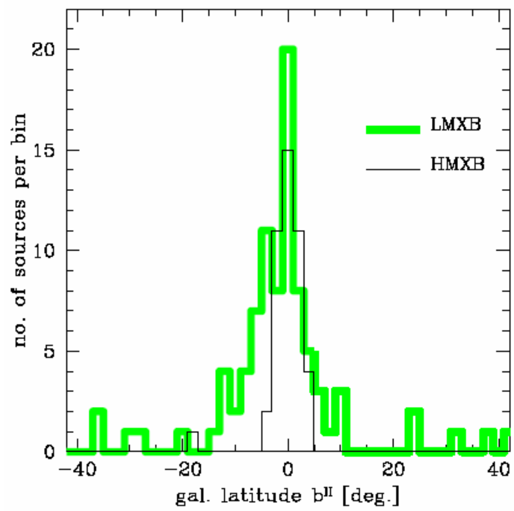
Distribution of LMXBs consistent with our understanding of star formation (see also Galaxies 2):

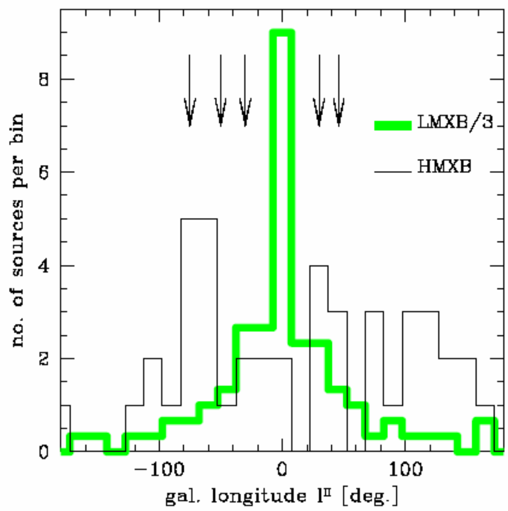
- no recent SF in GCs or ellipticals
- massive stars evolved off the Main Sequence long ago in these systems.

LMXBs could be significant sources of **gravitational waves**



Open circles = low mass XRBs
Filled circles = high mass XRBs





From Grimm et al. 2003

For how long might we expect such an X-ray binary source to shine?...

Suppose we could completely annihilate a source of, say, $2M_\odot$

$$\tau \sim \frac{E}{L} \sim \frac{2M_\odot c^2}{L_X} \sim \frac{4\times 10^{30}\times 10^{17}}{10^{31}} \sim 10^9 \text{ years} \qquad (1.2)$$

So if we want a source lifetime of, say, 10^8 years we would need to extract around 10% of the source's rest mass energy (same efficiency would give *longer* lifetime for a less luminous source)

Is this realistic?

Energy source believed to be gravitational infall (accretion) of matter onto a neutron star from a binary companion.

$$\text{Energy yield / unit mass} \simeq \frac{GM_{NS}}{R_{NS}} \sim 0.3c^2 \qquad (1.3)$$

So gravitational accretion appears to be a viable power source.

But in reality things are a little more complicated...

If the source is a black body, the Stefan Boltzmann law says that

$$L_X \sim A\sigma T^4 \qquad (1.4)$$

X-ray luminosity (L_X)

Source area (A)

Stefan Boltzmann constant $\sigma = 5.67\times 10^{-8}\ \mathrm{J\,m^{-2}\,s^{-1}\,K^{-4}}$

and $A \sim (\text{size})^2$ so that

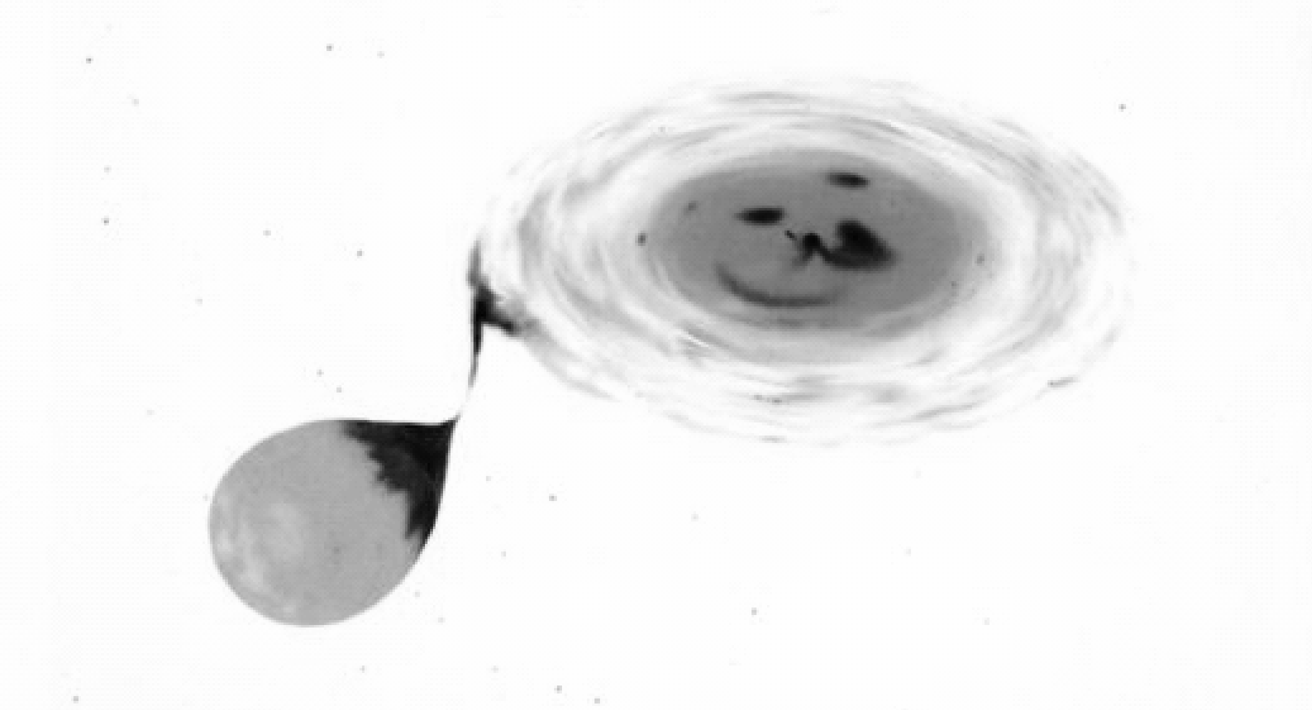
Much larger than a NS

$$\text{size} \sim \left(\frac{L_X}{\sigma T^4}\right)^{1/2} \leq 500\ \text{km} \qquad (1.5)$$

Matter falls in via an **accretion disk** (see also Galaxies 2).

Some orbital angular momentum is lost by viscous friction.

XRB luminosity comes from disk as well as the central source.



1.1 Accretion Luminosity and the Eddington Limit

If matter accretes at rate $\dot{M}$ then we expect, at radius r

$$L_{\rm acc} \sim \frac{GM\dot{M}}{r} \qquad (1.6)$$

But if $\dot{M}$ is large, the accretion process becomes self-limiting, because the emitted luminosity exerts a significant **radiation pressure** force on the infalling material.

Consider a proton of mass m_P at radius

Radiation force

$$F_{\rm rad} = \frac{L\sigma_T}{4\pi r^2 c} \qquad (1.7)$$

Thomson cross-section $= 6.65 \times 10^{-29}\ {\rm m}^2$

Radiation force reduces the effective gravitational force to

$$F_{\text{grav}} = \frac{GMm_P}{r^2} - \frac{L\sigma_T}{4\pi r^2 c} \quad (1.8)$$

We can write this as $$F_{\text{grav}} = \frac{GMm_P}{r^2}\left[1 - \frac{L}{L_{\text{crit}}}\right] \quad (1.9)$$

where the critical, or Eddington, luminosity is $$L_{\text{crit}} = \frac{4\pi GMm_P c}{\sigma_T} \quad (1.10)$$

Putting in some numbers we find that $$L_{\text{crit}} \sim \left(\frac{M}{M_\odot}\right) \times 3\times10^4\, L_\odot \quad (1.11)$$

which is close to the maximum observed L_X

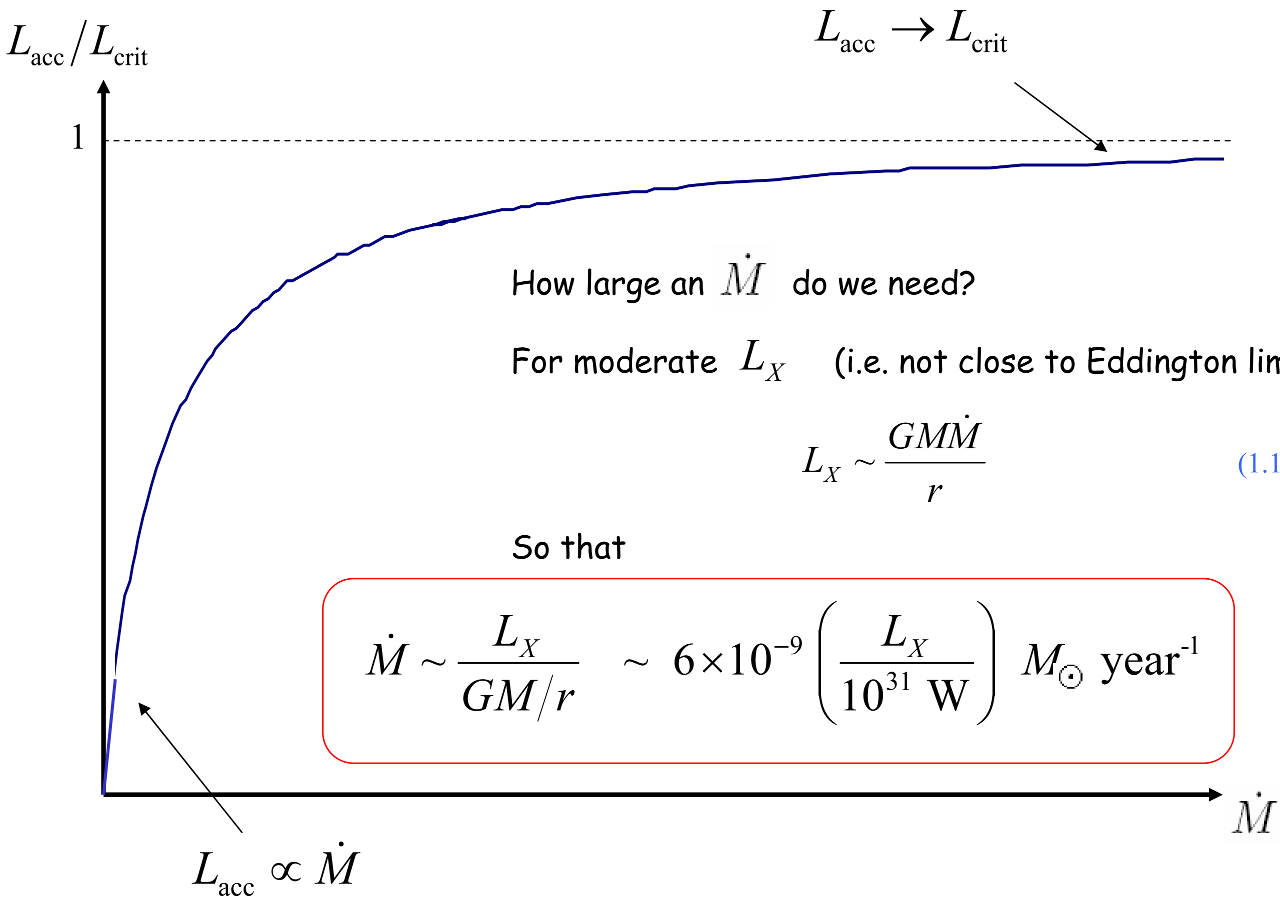
The effective gravitational potential is $$\frac{GM}{r}\left[1 - \frac{L}{L_{\text{crit}}}\right] \quad (1.12)$$

So, more correctly $$L_{\text{acc}} = \frac{GM}{r}\left[1 - \frac{L_{\text{acc}}}{L_{\text{crit}}}\right]\dot{M} \quad (1.13)$$

which we can rearrange as $$L_{\text{acc}} = \frac{L_{\text{crit}}}{1 + \dfrac{L_{\text{crit}}}{GM\dot{M}/r}} \quad (1.14)$$

$$L_{\text{acc}} \to L_{\text{crit}} \quad \text{as} \quad \dot{M} \to \infty$$

$$L_{\text{acc}} \to \frac{GM\dot{M}}{r} \quad \text{as} \quad \dot{M} \to 0$$



How large an $\dot{M}$ do we need?

For moderate L_X (i.e. not close to Eddington limit)

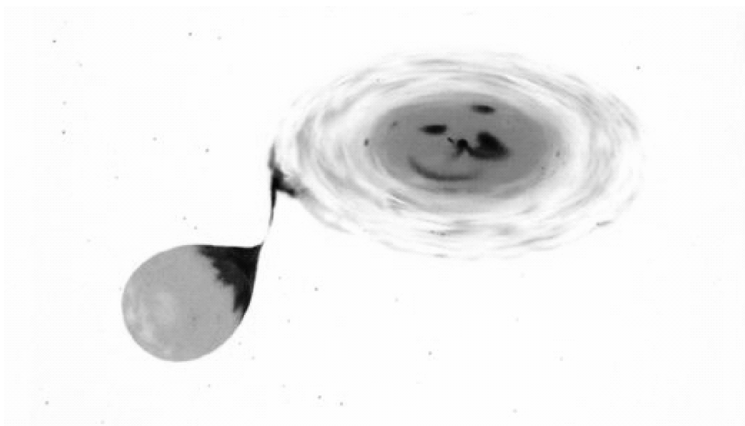
$$L_X \sim \frac{GM\dot{M}}{r} \tag{1.15}$$

So that

$$\dot{M} \sim \frac{L_X}{GM/r} \sim 6\times10^{-9}\left(\frac{L_X}{10^{31}\ \mathrm{W}}\right) M_\odot\ \mathrm{year}^{-1} \tag{1.16}$$

1.2 Accretion Mechanisms

What is origin of $\dot{M}$?



Accretion of mass from the companion star by one of two mechanisms:

a) Wind capture (c.f. SAW course)

b) Roche lobe overflow

We will make some rough estimates of $\dot{M}$ for the case of HMXBs.

Similar physics (but somewhat different numbers) for LMXBs.

1.2 Accretion Mechanisms

a) Wind capture

Companion is a hot giant star of luminosity $L_{\rm opt}$ with a wind driven by radiation pressure. Let the star have mass $M_{\rm opt}$ and radiation pressure. Let the star have mass $M_{\rm opt}$ and radius $R_{\rm opt}$

Rearranging eqs. 1.8 – 1.10, we can show that the force on a proton at distance s from the companion star is

$$F_{\rm grav} = \frac{K}{s^2} \quad (1.17) \qquad \text{where} \quad K = \frac{\Gamma \, L_{\rm opt} \, \sigma_T}{4\pi \, c} \quad (1.18)$$

and the factor $\Gamma = \left[\frac{L_{\rm crit}}{L_{\rm opt}} - 1\right]$ (1.19) where $L_{\rm crit} = \frac{4\pi \, G M_{\rm opt} \, m_P c}{\sigma_T}$ (1.20)

So the equation of motion of the proton is

$$m_P \frac{d\upsilon_{\rm w}}{dt} = m_P \, \upsilon_{\rm w} \frac{d\upsilon_{\rm w}}{ds} = \frac{K}{s^2} \quad (1.21)$$

where $\upsilon_{\rm w}(s)$ is the wind speed at distance s

We can show that this equation has solution

$$\upsilon_{\rm w}(s) = \upsilon_\infty \left(1 - \frac{R_{\rm opt}}{s}\right)^{1/2} \quad (1.22)$$

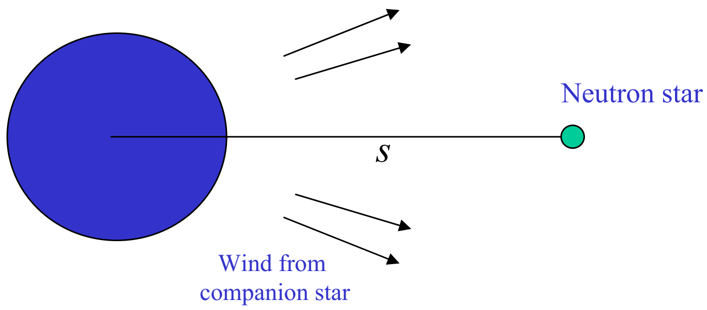
where $\upsilon_\infty \equiv \upsilon_{\rm w}(s \to \infty)$ (1.23)

known as the **wind terminal speed** (can be deduced from width of spectral lines)

Suppose the neutron star * is in a circular orbit at distance s from the companion star

Orbital speed of neutron star:

$$\upsilon_{\rm orbit} = \sqrt{\frac{GM_{\rm opt}}{s}} \qquad (1.24)$$



(assumes mass of companion much greater than mass of NS)

From the **continuity equation** (see e.g. A2 SATS, SAW)

$$\rho_{\rm w}(s) = \frac{\dot{M}_{\rm w}}{4\pi s^2 \upsilon_{\rm w}(s)} \qquad (1.25)$$

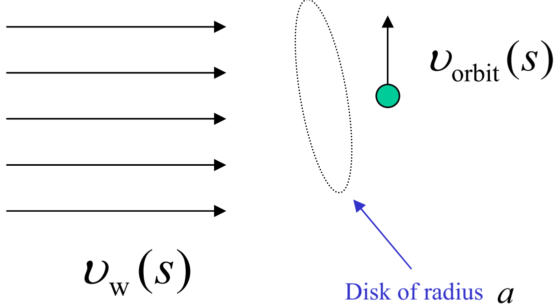
Mass loss rate from companion

* could also be WD or BH

The neutron star *captures* material from the companion star at a rate $\dot{M}$

This capture occurs over an **accretion radius** a

(c.f. cross section in HEA 1)



$$\dot{M} = \pi a^2 \rho_{\rm w}(s) \upsilon_{\rm rel}(s) \qquad (1.26)$$

where *relative* speed of the wind and neutron star is $\upsilon_{\rm rel}(s) = \sqrt{\upsilon_{\rm w}^2 + \upsilon_{\rm orbit}^2}$

We can write $\upsilon_{\rm rel}(s)$ in terms of dimensionless scaling parameters:

$$x = s / R_{\rm opt}$$

$$y = GM_{\rm opt} / R_{\rm opt}\, \upsilon_\infty^2$$

$$\Rightarrow \quad \upsilon_{\rm rel} = \upsilon_\infty \left[\frac{x + y - 1}{x} \right]^{1/2} \qquad (1.27)$$

What is the value of a ?

Take it to be the distance from the neutron star where K.E. = P.E. for material moving relative to the wind. i.e.

$$\tfrac{1}{2}\upsilon_{\rm rel}^2 = \frac{GM_{\rm NS}}{a}\left[1-\frac{L}{L_{\rm c}}\right] \qquad (1.28)$$

$$L_{\rm c} = \frac{4\pi\, GM_{\rm NS}\, m_P c}{\sigma_T}$$

After some rearranging this becomes

$$a = \frac{2GM_{\rm NS}}{\upsilon_{\rm rel}^2}\left[1-\frac{L}{L_{\rm c}}\right]$$

or

$$a = \frac{2GM_{\rm NS}}{\upsilon_\infty^2}\left[\frac{x}{x+y-1}\right]\left[1-\frac{L}{L_{\rm c}}\right] \qquad (1.29)$$

Also

$$\rho_{\rm w}(s) = \frac{\dot{M}_{\rm w}}{4\pi\, s^2\, \upsilon_{\rm w}(s)} = \frac{\dot{M}_{\rm w}}{4\pi\, R_{\rm opt}^2\, \upsilon_\infty x^{3/2}(x-1)^{1/2}} \qquad (1.30)$$

Combining eqs. (1.26) - (1.30)

$$\frac{\dot{M}}{\dot{M}_{\rm w}} = \left(\frac{M_{\rm NS}}{M_{\rm opt}}\right)^2\left[1-\frac{L}{L_{\rm c}}\right]^2\frac{y^2}{(x-1)^{1/2}}\left[\frac{1}{x+y-1}\right]^{3/2} \qquad (1.31)$$

Capture fraction

Example: Centaurus X-1

High mass XRB

$$M_{\rm NS} = 1.5 M_\odot$$

$$M_{\rm opt} = 17 M_\odot$$

$$R_{\rm opt} = 9 \times 10^9 \,\rm m$$

$$s = 1.3 \times 10^{10} \,\rm m \quad \Rightarrow \quad x = 1.444$$

$$\dot{M}_{\rm w} \sim 1.4 \times 10^{17} \,\rm kg\, s^{-1}$$

$$\upsilon_\infty \sim 10^6 \,\rm ms^{-1}$$

$$L = L_X \sim 10^{30} \,\rm W$$

Plugging in some numbers

$$y = \frac{6.673 \times 10^{-11} \times 17 \times 2 \times 10^{30}}{9 \times 10^9 \times \left(10^6\right)^2} = 0.252$$

$$L_{\rm c} = \frac{4\pi G M_{\rm NS}\, m_P\, c}{\sigma_T} = 1.9 \times 10^{31} \,\rm W \quad \Rightarrow \quad L/L_{\rm c} = \tfrac{1}{19}$$

$$\frac{\dot{M}}{\dot{M}_{\rm w}} = \left(\frac{1.5}{17}\right)^2 \left[1 - \frac{1}{19}\right]^2 \frac{0.252^2}{(0.444)^{1/2}} \left[\frac{1}{0.696}\right]^{3/2} \sim 0.001 \qquad (1.32)$$

Hence

$$\dot{M} \sim 1.4 \times 10^{14} \,\rm kg\, s^{-1} \quad \sim \quad 2.2 \times 10^{-9} \, M_\odot \,\rm year^{-1} \qquad (1.33)$$

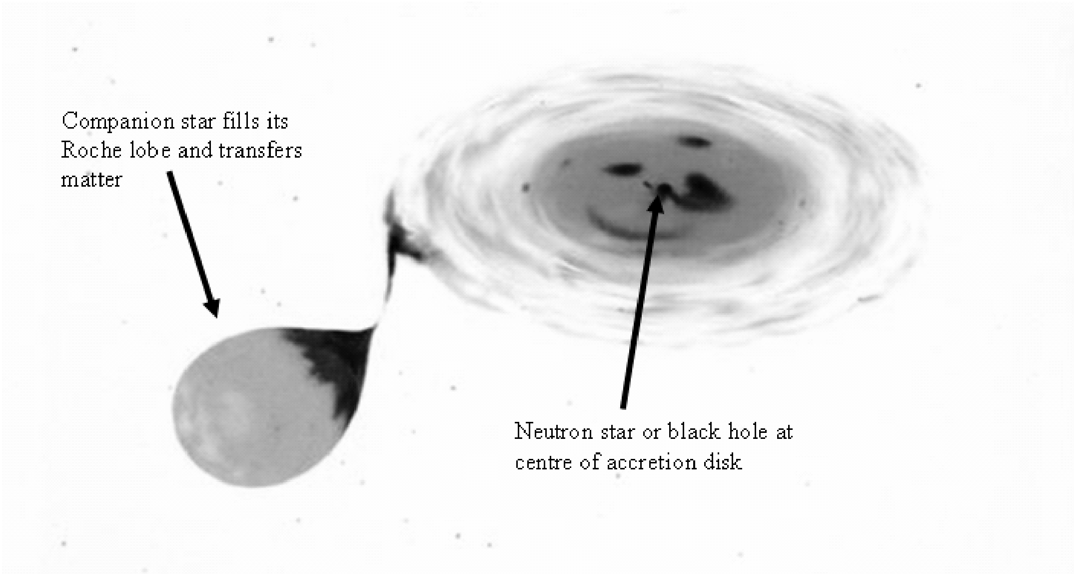
Consistent with eq. (1.16)

1.2 Accretion Mechanisms

b) Roche lobe overflow

Here mass of the companion can be lower and companion wind is small.

- Companion expands to post-MS giant phase, outer layers approach NS
- Thermal expansion / flow of layers above **Roche Lobe surface** transfers mass to NS

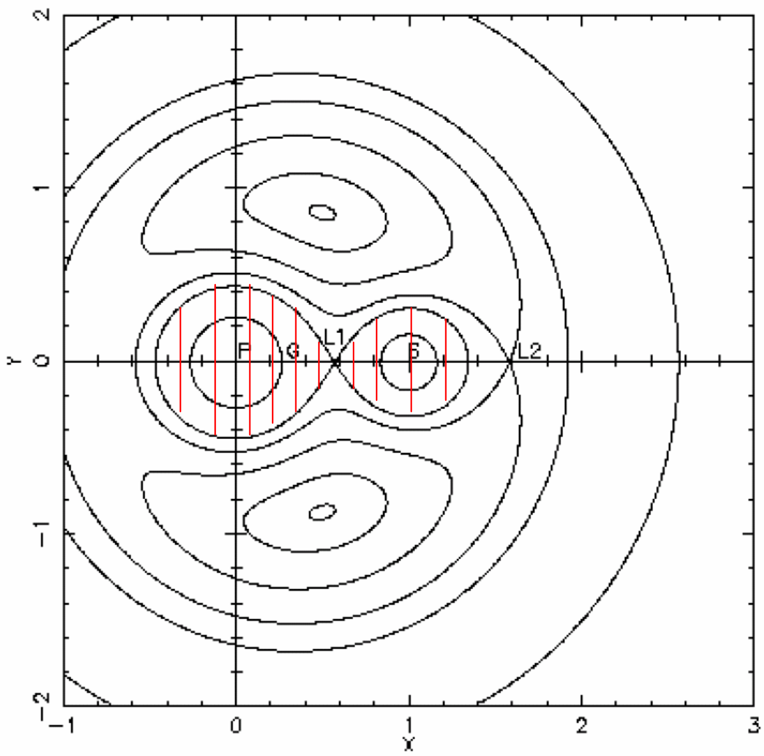


Roche Lobe Overflow

This figure shows surfaces of equal gravitational potential in the vicinity of two close binary stars.

Contours are roughly spherical close to each star, but are distorted further out, and merge at the **critical surface** which defines two cusped volumes that touch at point **L1**

These volumes are known as the **Roche Lobes**

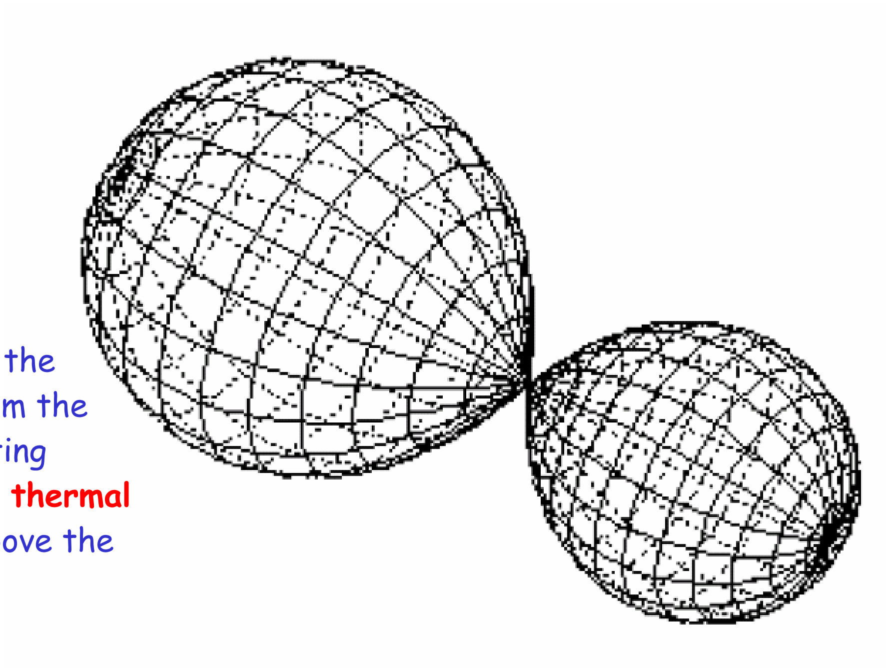


Credit: Vik Dhillon, Univ of Sheffield

Roche Lobe Overflow

Proper treatment requires solution of a complex 3-D hydrodynamics problem…

But we can crudely estimate the rate at which mass flows from the optical companion by calculating the mass flux from the **free thermal expansion** of the primary above the Roche Surface



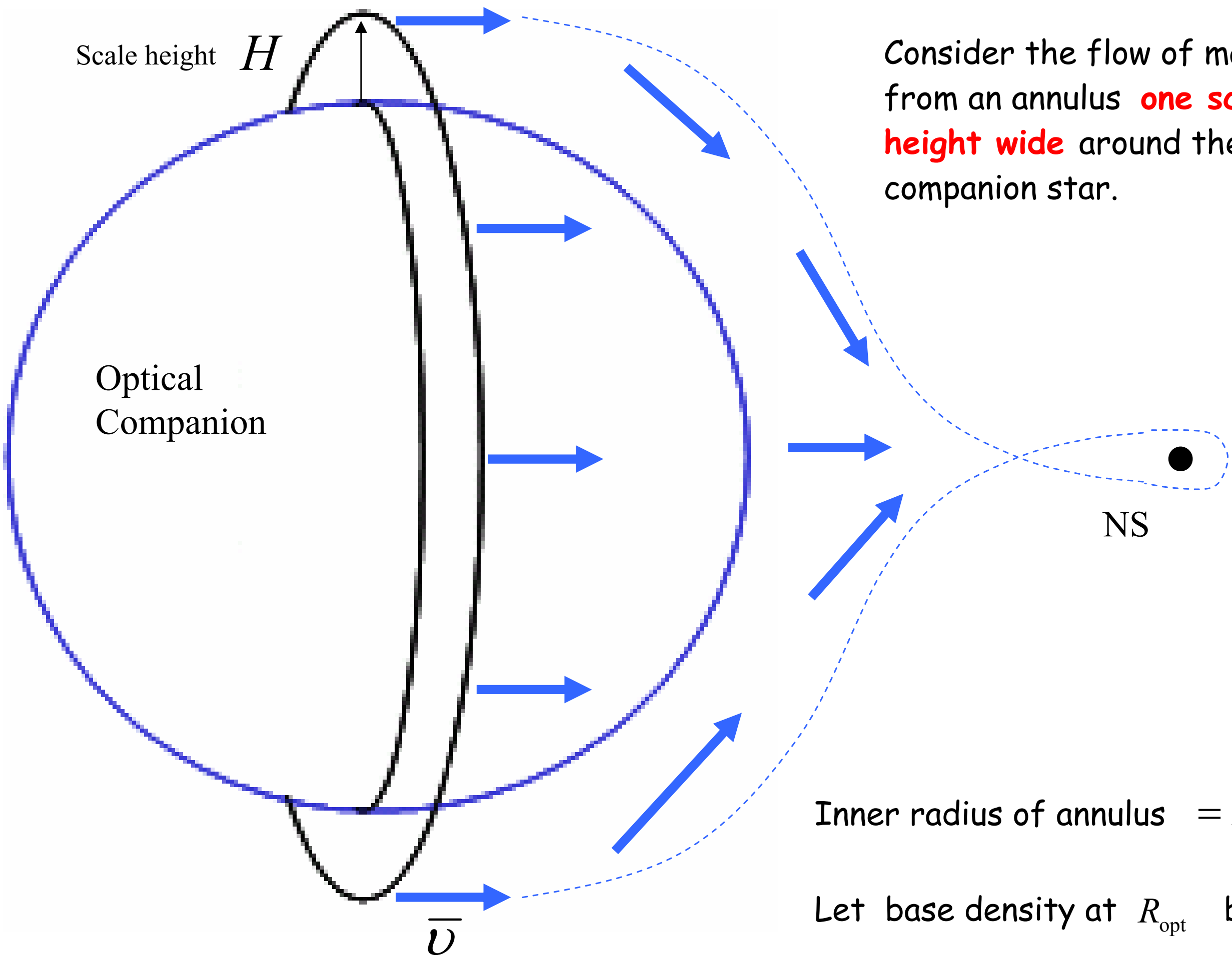
Credit: Vik Dhillon, Univ of Sheffield

Simplifying Assumptions

- Envelope near companion is **isothermal** with constant scale height

$$H \sim \frac{2kT}{m_P g} \quad \text{where} \quad g = \frac{G M_{\rm opt}}{R_{\rm opt}^2}$$

$\Rightarrow$ mean flow speed: $$\bar{\upsilon} = \left(\frac{kT}{2\pi\, m_P}\right)^{1/2} \qquad (1.34)$$ [from Maxwellian distribution]



Consider the flow of matter from an annulus **one scale height wide** around the primary companion star.

Inner radius of annulus $= R_{\rm opt}$

Let base density at $R_{\rm opt}$ be ρ_0

Assuming that $H << R_{\rm opt}$, mass flux from the companion is approximately

$$\dot{M} = 2\pi R_{\rm opt}\, H\, \rho_0\, \overline{\upsilon} \qquad (1.35)$$

Substituting from eq. (1.34) we can write this as

$$\dot{M} = \left(\frac{2\pi kT}{m_P}\right)^{1/2} R_{\rm opt}\, H\, \rho_0 \qquad (1.36)$$

What are typical values? $n_P \sim 10^{18}\ {\rm m^{-3}} \Rightarrow \rho_0 \sim 10^{-9}\ {\rm kg\,m^{-3}}$

$$T \sim 10^5\ {\rm K}, \quad M_{\rm opt} = 10 M_\odot, \quad R_{\rm opt} = 10 R_\odot \Rightarrow H \sim 3\times 10^6\ {\rm m}$$

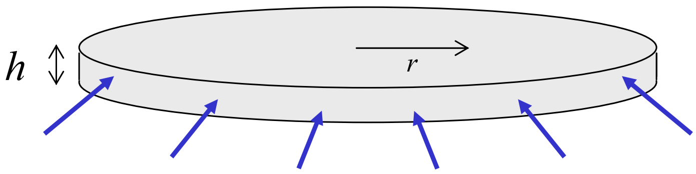
$$\Rightarrow \quad \dot{M} \sim 10^{-9}\ M_\odot\ {\rm year^{-1}}$$

which is consistent with eq. (1.16) for $L_X \sim 10^{30}\ {\rm W}$

1.3 Accretion Disk Structure (see also Galaxies 2)

Assume uniform thickness, h

(in reality h increases with r)



Suppose inflow speed is υ

Then

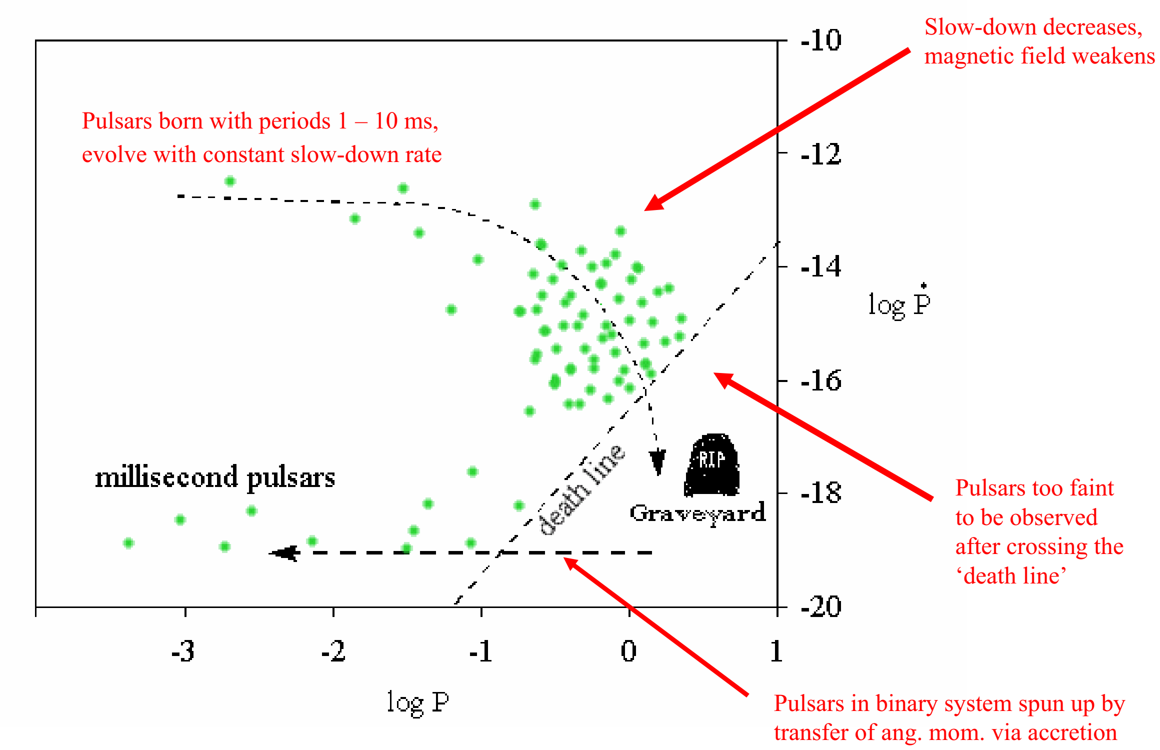
$$\dot{M}(r) \sim 2\pi r\, h \times n(r)\, m_P \times \upsilon \qquad (1.37)$$

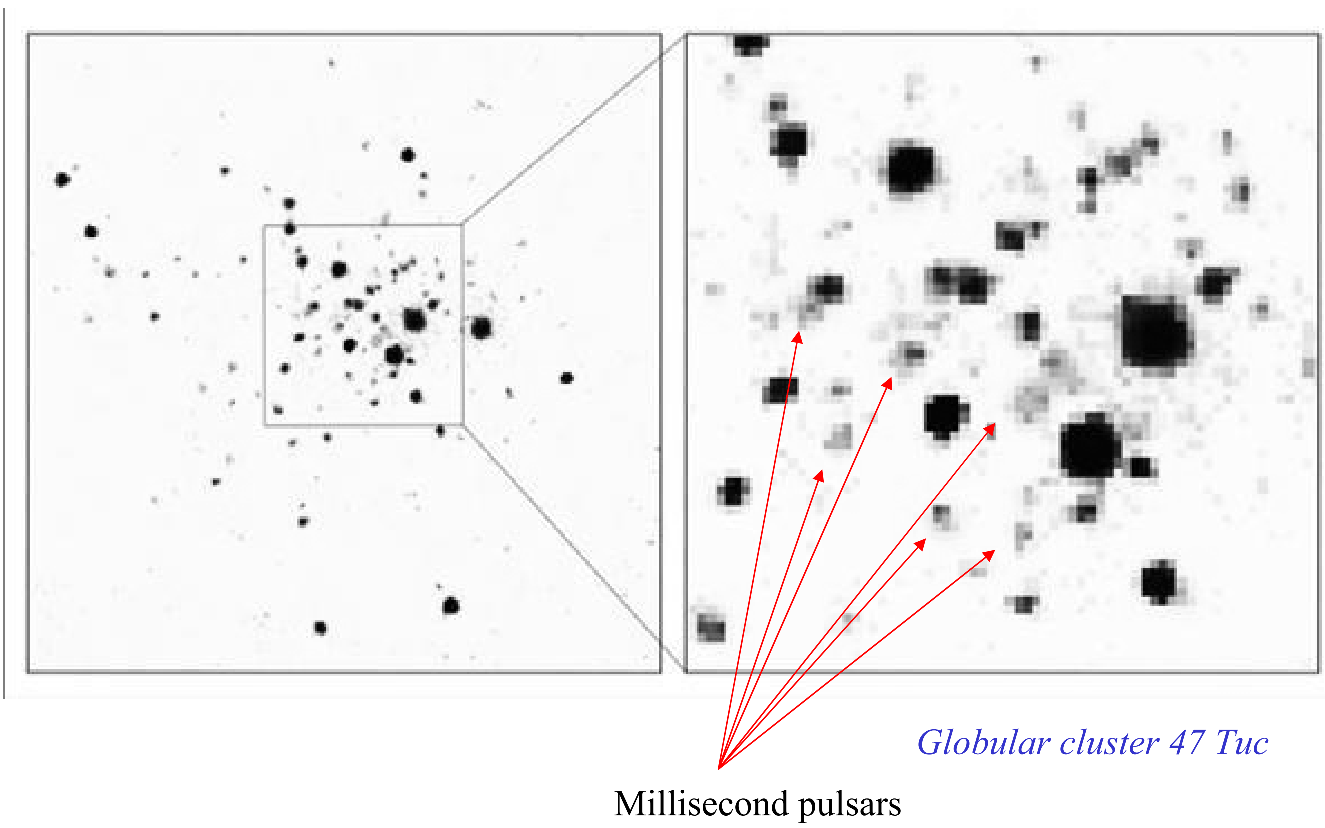
By considering the P.E. and K.E. of infalling matter, we can show (see Galaxies 2) that

$$T(r) = \left[\frac{GM\dot{M}}{8\pi r^3 \sigma}\right]^{1/4} \qquad (1.38)$$

Equation 1.38 ignores radiation pressure, and the fact that about ½ of the accretion energy goes into spinning the accretion disk.

Accretion disk can then, in turn, 'spin up' compact star.
Origin of millisecond pulsars in e.g. globular clusters.





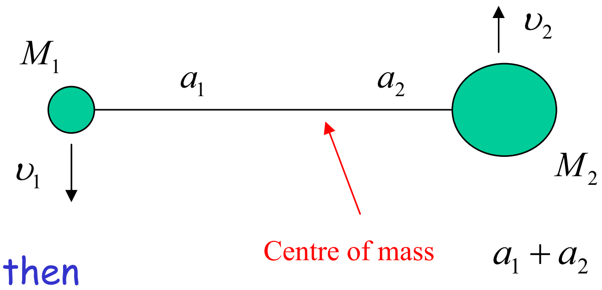
Globular cluster 47 Tuc

- Close proximity of stars in the core of a GC increases chance of binary capture
- Stars can 'change partners' – like on a crowded dance floor

1.4 Mass Transfer and Orbital Evolution

If there is no mass loss, then

$$M_1 + M_2 = \text{constant} \;\; M_{\text{tot}}$$



$$a_1 + a_2 = a$$

If there is no angular momentum loss then

$$M_1\upsilon_1 a_1 + M_2\upsilon_2 a_2 = \text{constant} \;\; \text{H}_{\text{tot}}$$

But M_1, M_2, a_1, a_2 change, as does the **period**

$$P = 2\pi\left(\frac{a^3}{GM_{\text{tot}}}\right)^{1/2} \qquad (1.39)$$

From the **centre of mass condition** we can show that

$$\frac{a_1}{a} = \frac{M_2}{M_{\text{tot}}} \quad \text{and} \quad \frac{a_2}{a} = \frac{M_1}{M_{\text{tot}}} \qquad (1.40)$$

Also, $\upsilon_1 = \dfrac{2\pi a_1}{P}$ and $\upsilon_2 = \dfrac{2\pi a_2}{P}$ (1.41)

which we can re-write, using eqs. (1.39) and (1.40) as

$$\upsilon_1 = \sqrt{\frac{G}{M_{\text{tot}}a}}M_2 \quad \text{and} \quad \upsilon_2 = \sqrt{\frac{G}{M_{\text{tot}}a}}M_1 \qquad (1.42)$$

Defining the **mass ratio** $\mu = \dfrac{M_1}{M_{\text{tot}}}$ (also $1-\mu = \dfrac{M_2}{M_{\text{tot}}}$)

it follows that

$$H_{\text{tot}} = (Ga)^{1/2} M_{\text{tot}}^{3/2}\,\mu(1-\mu) \qquad (1.43)$$

Since $\dfrac{dH_{\text{tot}}}{dt} = 0 \;\Rightarrow\; \dfrac{d}{dt}(\ln H_{\text{tot}}) = 0$

Hence, $$\frac{1}{2}\frac{d}{dt}\ln a+\frac{d}{dt}\ln\mu+\frac{d}{dt}\ln(1-\mu)=0 \qquad (1.44)$$

This reduces to $$\frac{1}{a}\frac{da}{dt}=2\left[\frac{1}{1-\mu}-\frac{1}{\mu}\right]\frac{d\mu}{dt} \qquad (1.45)$$

or $$\frac{1}{a}\frac{da}{dt}=\frac{4}{M_{\text{tot}}}\left[\frac{\mu-\frac{1}{2}}{\mu(1-\mu)}\right]\frac{dM_1}{dt} \qquad (1.46)$$

Suppose M_1 is the primary companion which loses mass $\Rightarrow \frac{dM_1}{dt}<0$

Then, if $\mu<\frac{1}{2}$ we see that $\frac{da}{dt}>0 \Rightarrow$ stars separate, mass accretion rate falls.

Conversely, if $\mu>\frac{1}{2}$ then $\frac{da}{dt}<0 \Rightarrow$ orbit shrinks, mass accretion rate increases.

The $\mu>\frac{1}{2}$ case is unstable, and leads to accelerated accretion, mass transfer

1.5 The Mass Transfer Paradox

In HMXB systems the optical companion, with $M_{\text{opt}}\geq 10M_\odot$, is losing mass to a low mass compact object, with e.g. $M_{\text{opt}}\sim 2M_\odot$ for a NS.

Q. How can a low mass star reach the post-Main Sequence stage of evolution *earlier* than a high mass star? Shouldn't the high mass star evolve faster?...

A. In the original system, the progenitor of the compact object *was* more massive than its companion. It *did* evolve faster, but its mass was reduced by:

- supernova explosion and/or
- earlier episode of mass transfer

so that now $M_{\text{NS}}<M_{\text{opt}}$

1.45 Intermediate mass black holes?

Chandra observations have presented some fresh mysteries:

(a) 'Quasisoft' X-ray sources:

$$T \sim 1-4\times10^6\ \mathrm{K}$$

but with luminosity comparable to NS or stellar mass black hole.

(c.f. 'Hard' X-ray sources for NS / BH: $T \geq 10^7\ \mathrm{K}$

'Supersoft' sources for WD $T \sim 10^5\ \mathrm{K}$)

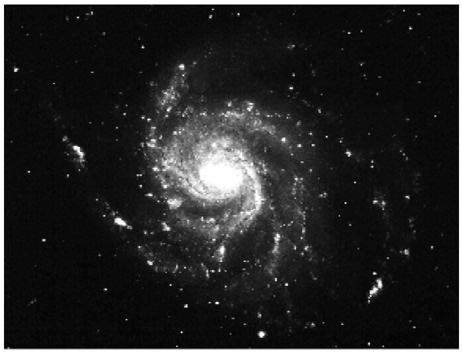
Stefan-Boltzmann law $\Rightarrow$

X-ray producing region is much larger than for NS or stellar mass black hole.

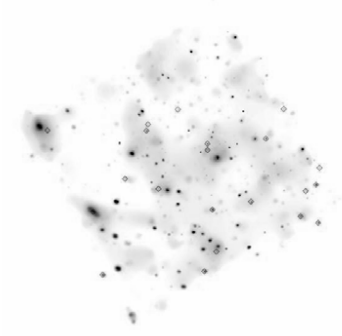
Could be intermediate mass black holes?

Masses of a few hundred times solar?...

Optical image of M101

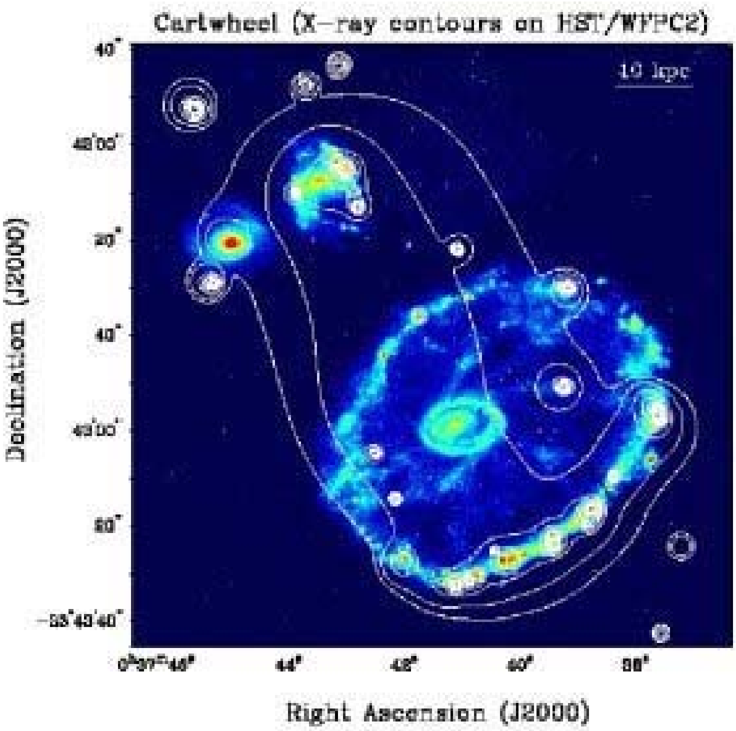


X-ray image of M101



Similar sources known as ULXs: Ultra-Luminous X-ray sources.

Their luminosity is too high for stellar mass compact objects, as it would exceed the **Eddington limit**. (See also Galaxies 2).



Explanation?...

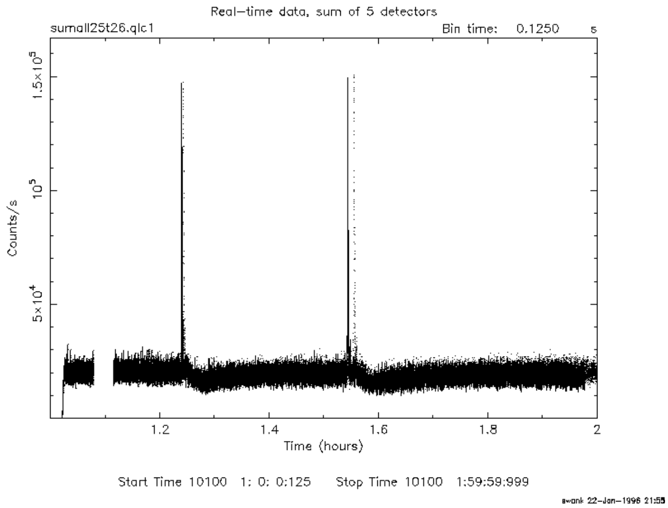
Collapse of extremely massive stars formed during recent merger event? (See Galaxies 2).

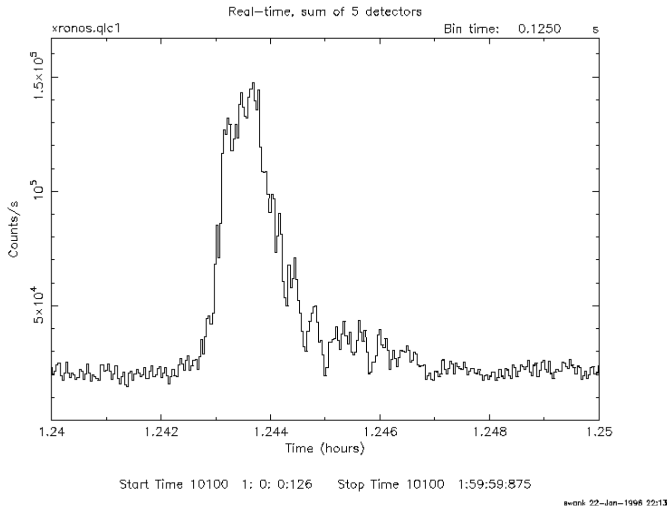
Beaming of X-ray emission from stellar mass BH or NS? (This reduces luminosity, and hence mass, since $L < 4\pi R^2 F$)

?????

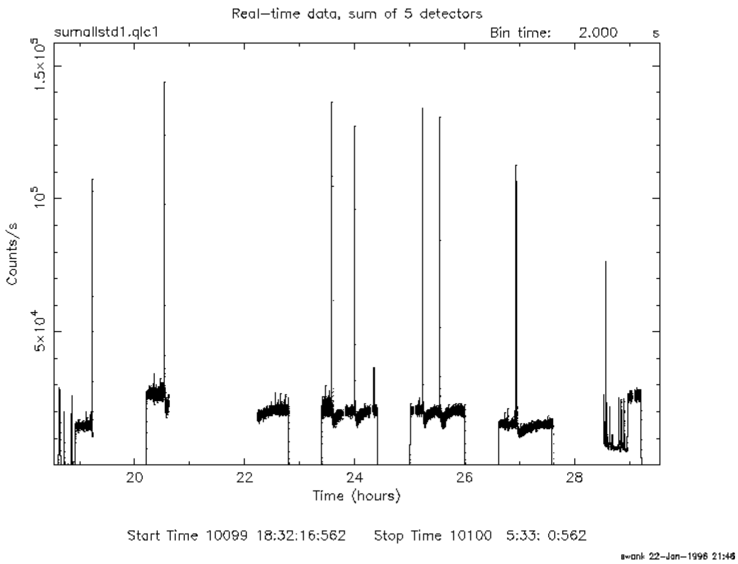
1.7 X-ray Bursters

Some XRB systems exhibit irregularly occurring bursts, superposed on quasi-steady continuous X-ray flux





(e.g.GRO J1744-28, observed by RXTE)



(a) Bursts last $\delta t \sim$ minutes, separated by mean intervals of $\Delta t \sim$ hours. Rapid rise, then slower decay.

(b) Averaged over long time intervals, mean excess power in bursts is

$$\bar{L}_{\text{Burst}} \sim L_{\text{cont}}/100 \qquad (1.47)$$

Typically $L_{\text{Burst}}^{\text{peak}} \sim 10^{31} - 10^{32}\,\text{W}$

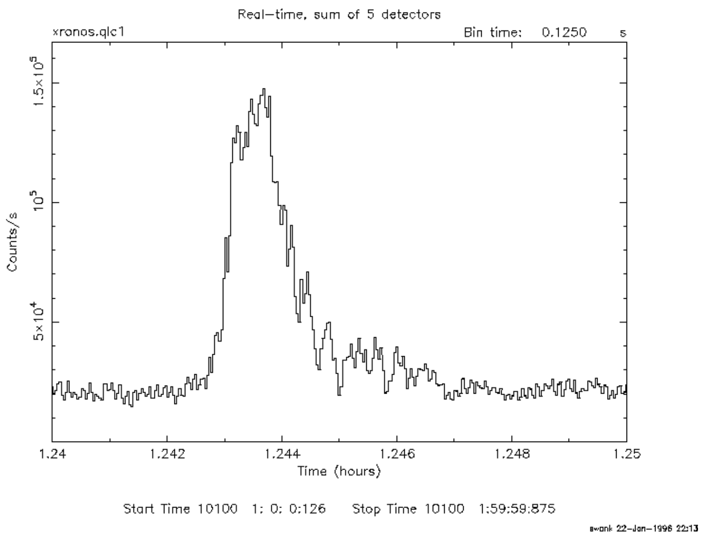
(c) And

$$\bar{L}_{\text{Burst}} \sim L_{\text{Burst}}^{\text{peak}}\left(\frac{\delta t}{\Delta t}\right) = L_{\text{Burst}}^{\text{peak}} \times \left(\frac{\text{mins}}{\text{hours}}\right) \sim 10^{29} - 10^{30}\,\text{W}$$

(d) Total energy in a burst $\propto$ elapsed time since previous burst

Intepretation

- Quasi-steady component of bursts due to mass accretion onto NS.
- Fact (d) suggests a 'reservoir' of energy which builds up before release.



Burst energy comes from nuclear fusion of accreted matter, when ρ, T Are high enough to 'ignite' it.

Calculations show that ρ, T is high enough for continuous H → He fusion on the surface of the neutron star.

From Eq. (3), accretion produces an (energy yield/ unit mass)* ~ $0.3c^2$

H → He fusion yields

$$\Delta E_{\mathrm{H}\rightarrow\mathrm{He}} = \eta_{\mathrm{H}\rightarrow\mathrm{He}} c^2 \sim 2\times10^{-3} c^2 \qquad (1.48)$$

So this adds less than 1% to the accretion luminosity continuously.

However, random and unstable variations in ρ, T may also allow He → C fusion.

So we expect

$$\frac{\bar{L}_{\mathrm{burst}}}{L_{\mathrm{cont}}} \sim \frac{\eta_{\mathrm{He}\rightarrow\mathrm{C}} c^2}{0.3c^2} \sim \frac{2\times10^{-3}}{0.3} = 6.7\times10^{-3} \qquad (1.49)$$

in rough agreement with eq. (1.47)

* For a NS of 2 solar masses