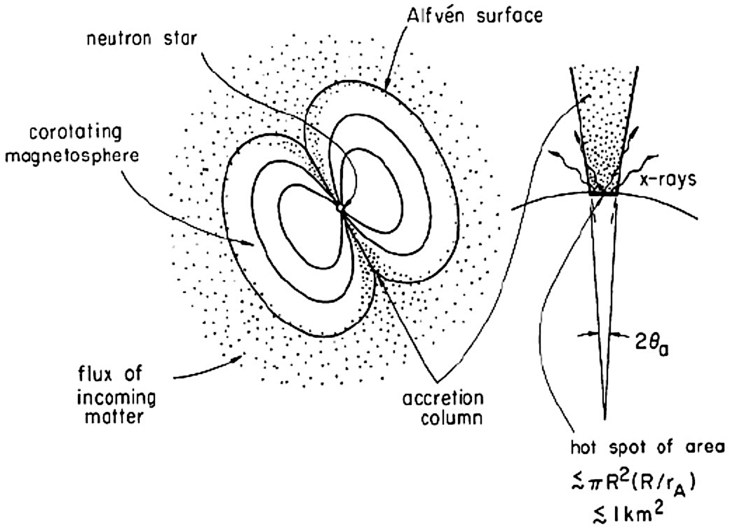
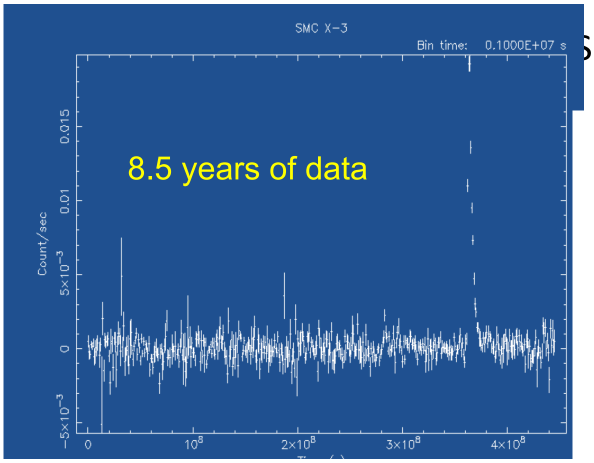
Accreting Neutron Stars: Longair 13.5.2- Also Ch 14

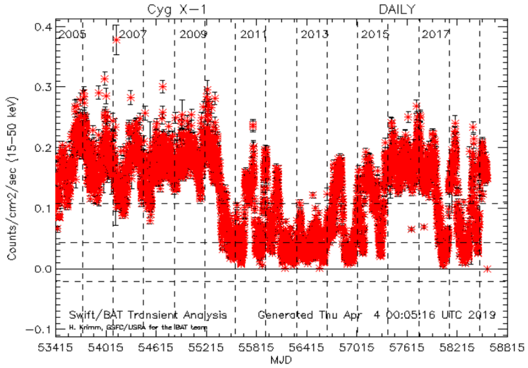
- These are the brightest x-ray sources in the sky and were the first x-ray sources discovered
- They have a wide range of properties (spectral and temporal) and show an almost bewildering array of behaviors
- Their luminosities range over 6 orders of magnitude and are highly variable



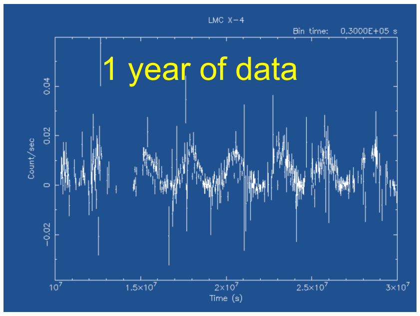
Some Representative Light Curves



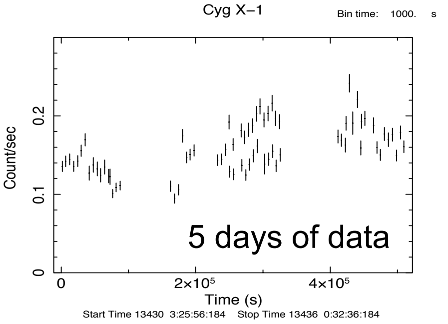
8.5 years of data



14.5 years of data



1 year of data



5 days of data

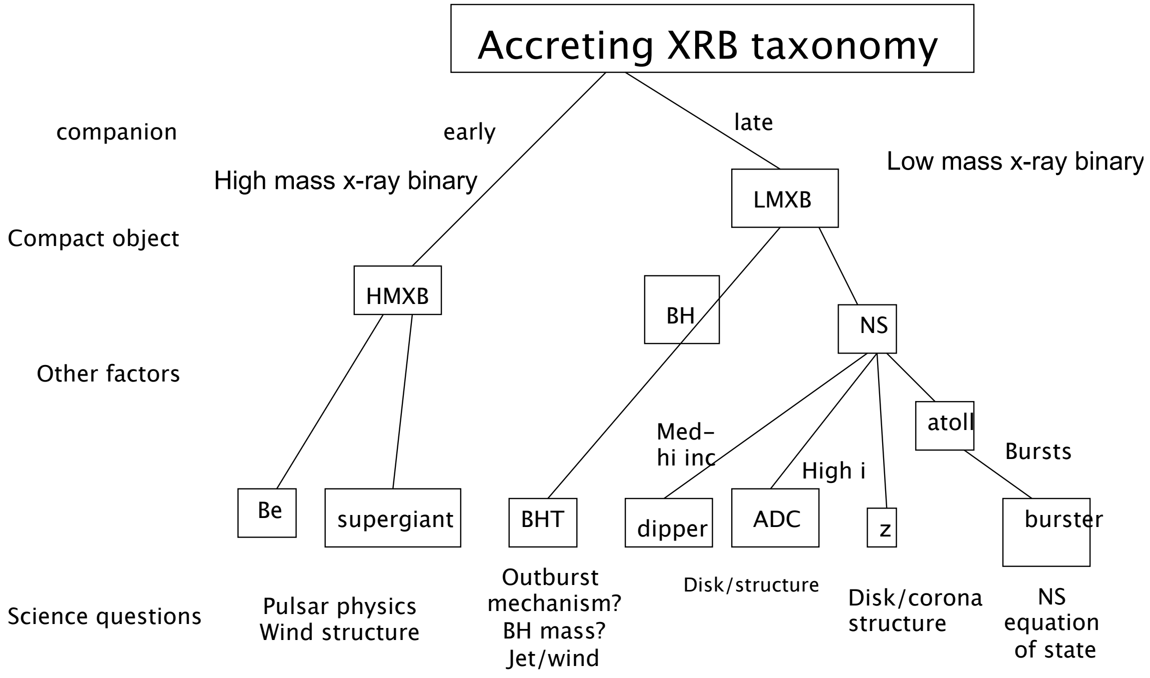
Accreting Neutron Stars

- NSs which accrete matter from their companion stars,
  - either from the stellar winds or
  - from an accretion disk that forms if the companion overflows its Roche Lobe.
- The gravitational energy from the infalling matter provides the energy for the observed radiation and the accretion torques that dominate the spin evolution.
- Despite these common properties, accreting NSs display a wide variety of behaviors, depending on the NS magnetic field strength, mass of the companion and properties of the accretion.

A. Harding

A Short Introduction to terminology

Kallman 2009



Accreting XRB taxonomy

companion

early

late

High mass x-ray binary

LMXB

Low mass x-ray binary

Compact object

HMXB

BH

NS

Other factors

Med-hi inc

atoll

High i

Bursts

Be

supergiant

BHT

dipper

ADC

z

burster

Science questions

Pulsar physics
Wind structure

Outburst mechanism?
BH mass?
Jet/wind

Disk/structure

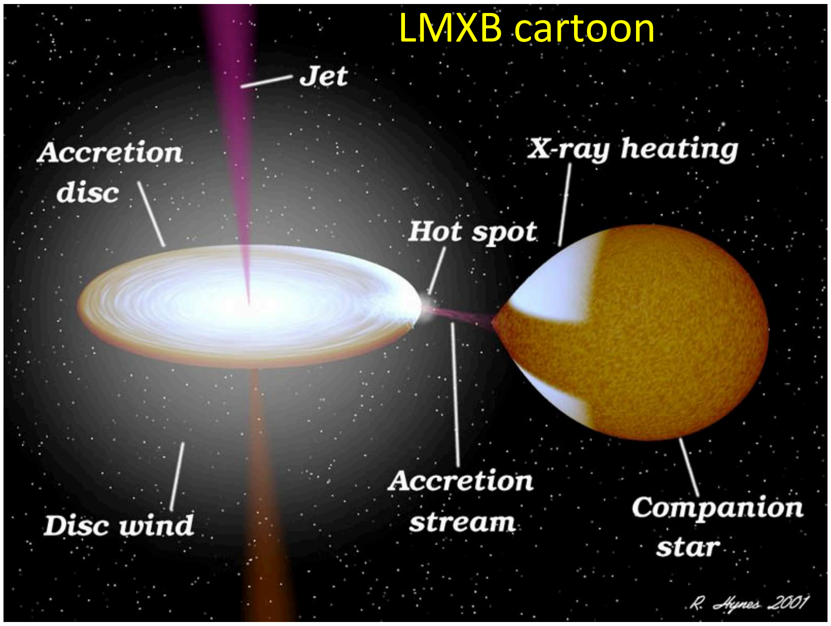
Disk/corona structure

NS equation of state

We will be discussing only a *tiny* fraction of this phenomenology

Accreting Neutron Stars

- Two types- based on mass of companions
  - Low mass x-ray binaries-NS star tends to have low magnetic field- low mass BHs are transient
  - High mass-NS tends to have high magnetic field- BHs on all the time

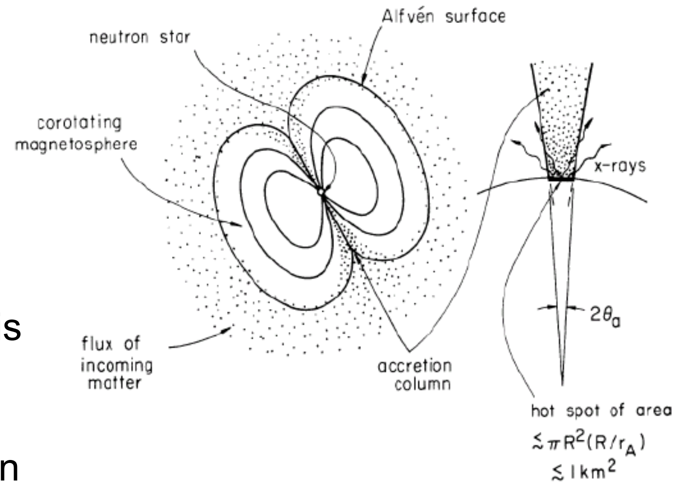


Accreting Neutron Stars

-

In the case of strong magnetic fields matter is channeled by the magnetic field and accretion occurs at/near the magnetic poles

When magnetic pressure is less than the thermal pressure the accreting material usually accretes in a disk down to the NS surface



Accreting Neutron Stars

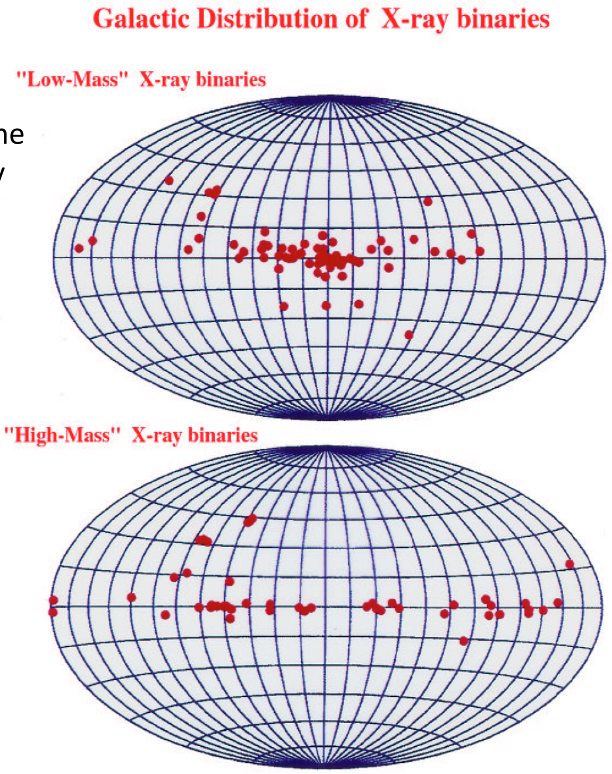
- Two types- based on mass of companions
  - **Low mass x-ray binaries-NS star tends to have low magnetic field- - are 'old' (~10^{9-10} yrs) - BHs are transient**
  - **High mass-NS tends to have high magnetic field- - are are 'young' (~10^{7-8} yrs)-BHs on all the time**

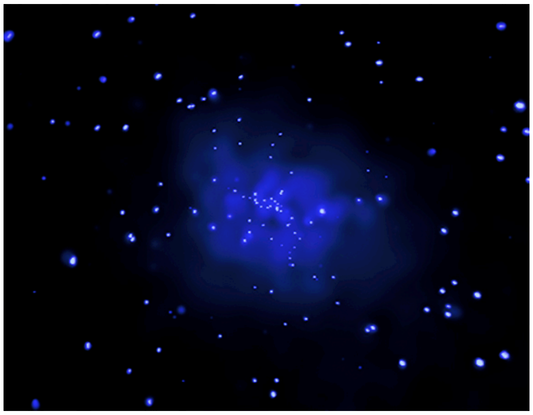
	HMXB	LMXB
Donor star	O-B ($M>5M_{sun}$)	K-M ($M<1M_{sun}$)
Age/Population	10^7 yrs I	5-15x10^9 II
L_x/L_{opt}	0.001-10	10-1000
X-ray Spectrum	flat power law	kT<10keV,bremms-like
Orbital period	1-100d	10min-10d
X-ray eclipses	common	rare
Magnetic field	strong (~10^{12}G)	weaker (10^7-10^8 G)
X-ray pulsations	common (0.1-1000s)	rare (and often transient)
X-ray bursts	never	often
X-ray luminosity	~10^{35-37}	10^{33-38} erg/sec
# in MW	~35	~100
Accretion mode	stellar wind	Roche Lobe overflow
In glob clusters	never	frequently

(from M. Porzio)

Space Distribution of X-ray Binaries

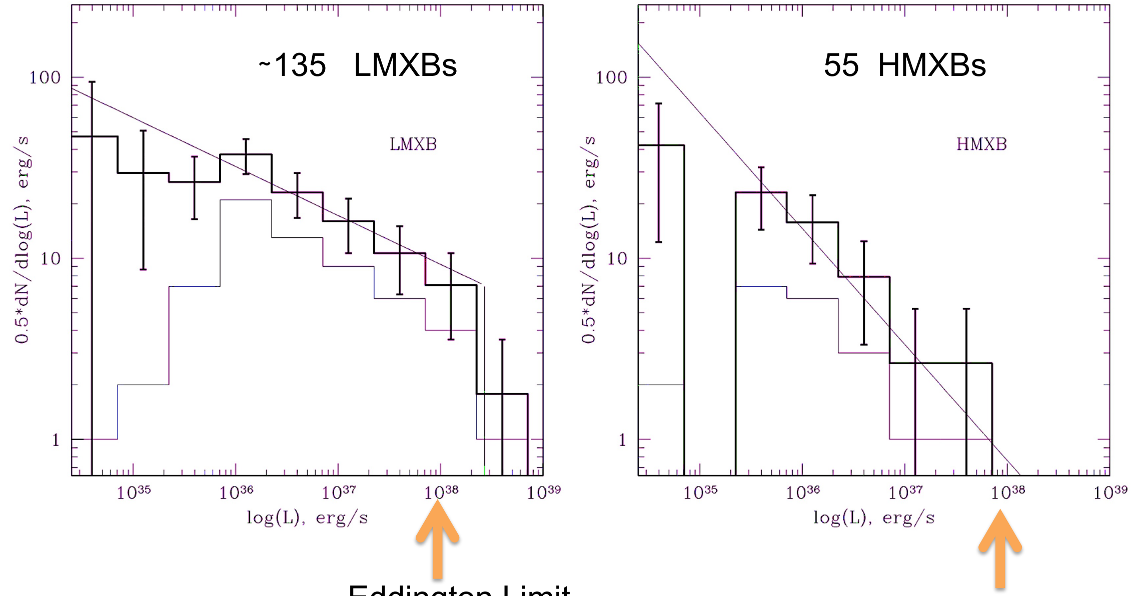
- X-ray binaries are concentrated in the galactic plane and in the two nearby satellite galaxies of the Milky Way (the Magellanic clouds)
- Chandra images of XRB in nearby galaxies (core of M31 below)





Luminosity of Neutron Stars

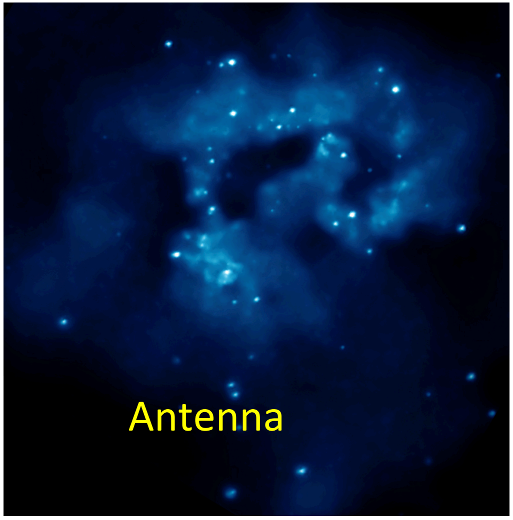
- The integrated X-ray emission of the **Milky Way** is dominated by the~5–10 most luminous sources at any time



Eddington Limit

M31 and the Antenna

- Chandra can detect x-ray binaries to d~100 Mpc
- allows population studies relation of x-ray binaries to galaxy properties



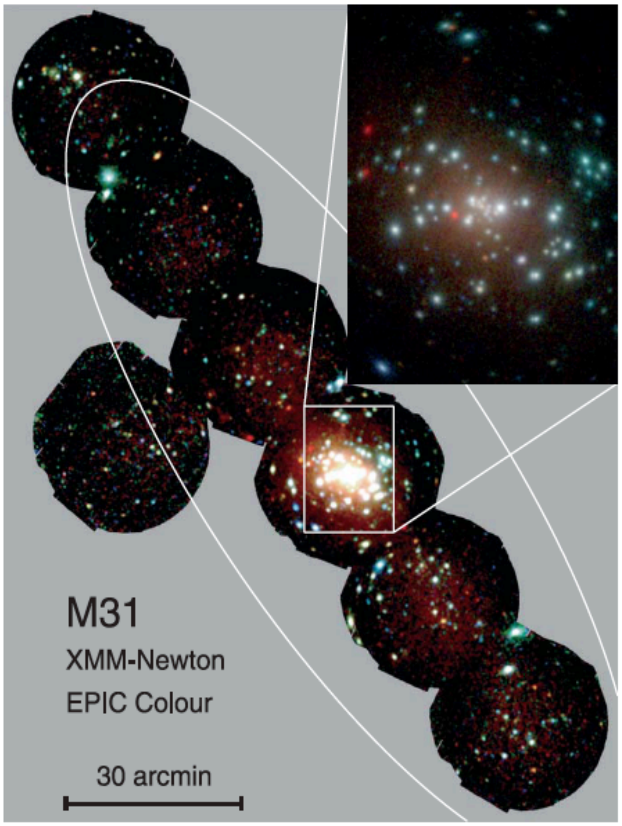
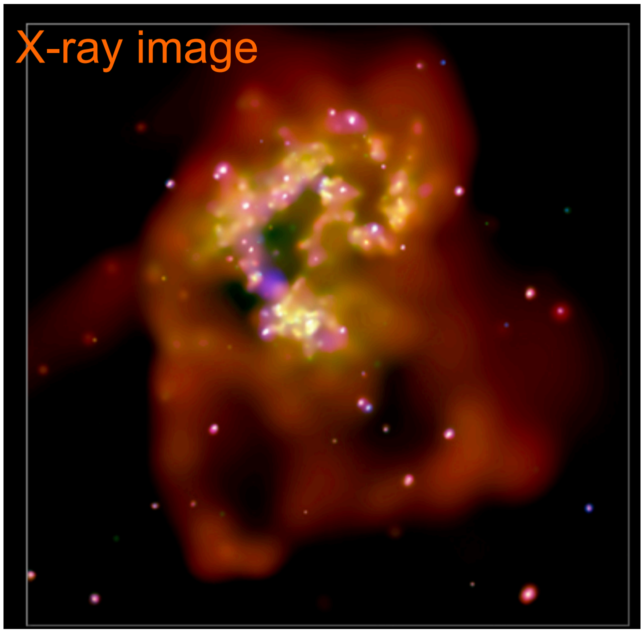
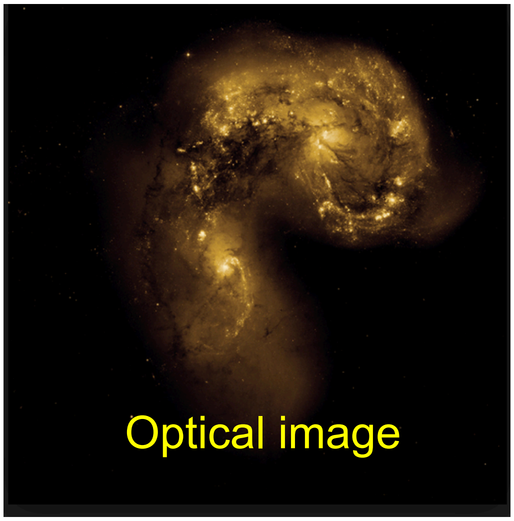


Fig. 1 (online colour at: www.an-journal.org) Logarithmically-scaled, three-color XMM-

Antenna Galaxy

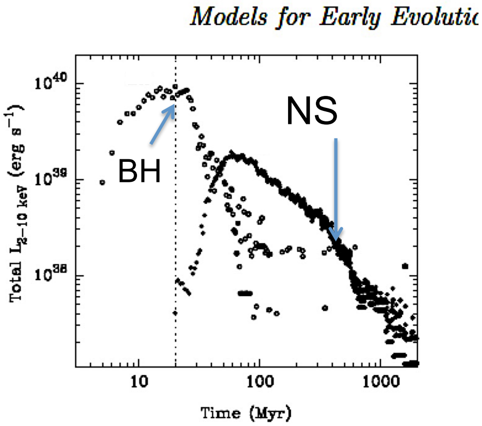
- A merging starburst galaxy



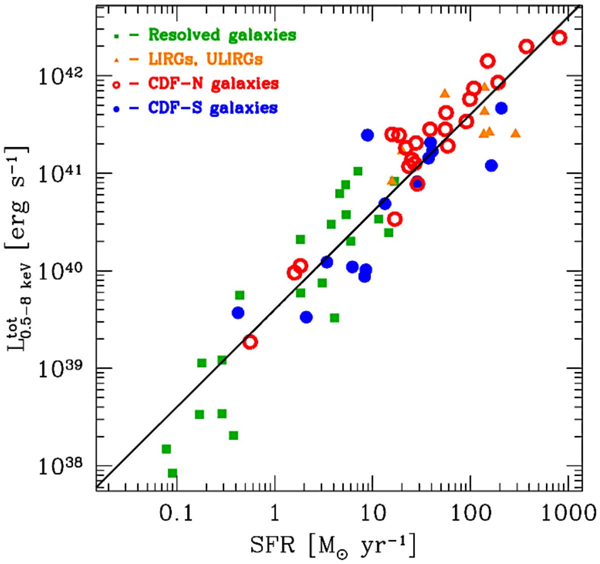


Relation to Star Formation

- Since HMXB are young stars the relative number of them should be related to amount of star formation in the galaxy!
- Another way of measuring star formation rate



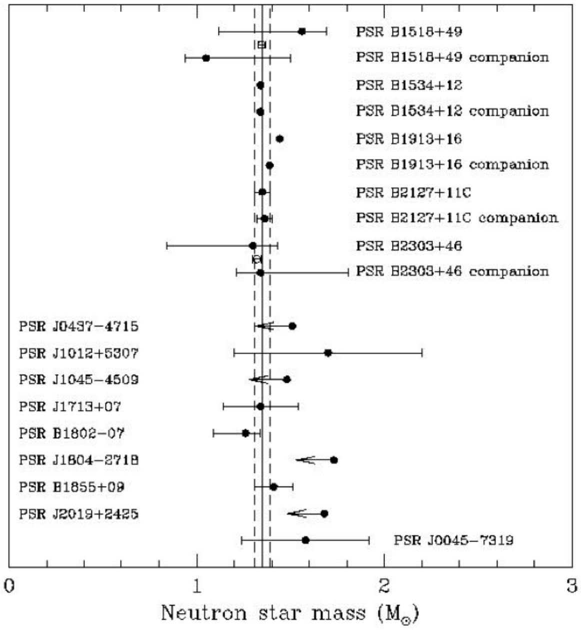
Correlation of XRB luminosity with Star formation

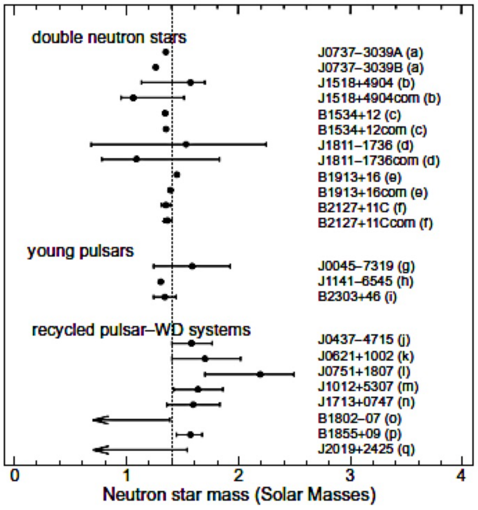


Example of a theoretical model of the luminosity in x-ray binaries in a star forming galaxy
Eracleous et al 2009

Masses of Neutron Stars – Longair pg 417

- Observed masses of non-accreting NS in binaries strongly clusters around 1.4 $M_\odot$ the Chandrasekar mass





Basics of Accretion – Longair 14.2

- If accretion takes place at a rate dM/dt=$\mathscr{M}$ then the potential energy gained by the material is

  E=G$\mathscr{M}M_x$/R (where M_x is the mass of the accreting object) - if this energy is released as radiation it also is the luminosity L_{acc}
- Alternatively (Longair 443-444) one can calculate the free-fall velocity, v_{ff} ,from infinity as $\frac{1}{2}m_p v_{ff}^2 = \frac{GMm_p}{r}$. L=1/2$m_p v_{ff}^2$ $L = \frac{1}{2}\dot{m}c^2\left(\frac{r_g}{R}\right)$.

r_G= Schwarzschild radius

We can write this as $L = \xi \dot{m}c^2$ and thus the efficiency of turning matter in energy **ε depends on r.**

Normalizing the observed luminosity to a <u>typical value</u> of 1.3x10^{37} erg/sec gives accretion rates of

- L_{acc}=1.3x$10^{37}\mathscr{M}_{17}$**m_x**R_6

Frank, King & Raine, "Accretion Power in Astrophysics

- $\mathscr{M}_{17}$ is $\mathscr{M}$ in units of 10^{17}gm/sec= **1.5x10^{-9} M_{sun}/yr**
- R_6 Is the radius in units of 10^6cm
- **m_x** is the mass in solar units of the accretor

Accretion -Basic idea

- $L = 1/2m^{\cdot}\ c^2\ (r_g/R)$ (Longair eq 14.3)

- This expression for the luminosity can be written $L = \xi m^{\cdot}\ c^2$, where ξ is the *efficiency of conversion* of the rest-mass energy of the accreted matter into heat.
- the efficiency is roughly $\xi = (r_g/2R)$ and so depends upon how compact the star is. For a white dwarf star with $M = M_\odot$ and $R \approx 5$ x10^6 m, $\xi \approx 3\text{x}\ 10^{-4}$.
- For a neutron star with mass $M = M_\odot$ and $R = 10$ km, $\xi \sim 0.15$.
- In the case of nuclear energy generation, the greatest release of nuclear binding energy occurs in the conversion of hydrogen into helium for which $\xi \approx 7\text{x}\ 10^{-3.}$
- **Thus, accretion onto neutron stars is an order of magnitude more efficient as an energy source than nuclear energy generation.**

Basics of Accretion – Longair 14.2

- For a white dwarf star with $M = M_\odot$ and $R \approx 5$ x 10^6 m, $\xi \approx 3\ 10^{-4}$.
- Neutron star with mass $M = M_\odot$ and $R = 10$ km, $\xi \sim 0.15$.
- For nuclear energy generation the conversion of hydrogen into helium has $\xi \approx 7$ x 10^{-3}.

Gravity wins over nuclear burning

Frank, King & Raine, "Accretion Power in Astrophysics",

Accretion -Basic idea Longair 14.2.1

- Viscosity/friction moves angular momentum outward
  - allowing matter to spiral inward
  - Accreting onto the compact object at center

gravitational potential energy is converted by *friction* to heat

Some fraction is radiated as light

Very efficient process Energy

$\sim GM/R=1.7\text{x}10^{16}$ $(R/10\text{km})^{-1}$ J/kg $\sim 1/2mc^2$

Nuclear burning releases $\sim 7\text{x}10^{14}$J/kg

(0.4% of mc^2)

How is the Potential Energy Released

- Suppose that there is some kind of “viscosity” in the disk
  - Different annuli of the disk rub against each other and exchange angular momentum
  - Results in most of the matter moving inwards and eventually accreting
  - Angular momentum carried outwards by a small amount of material

- Process producing this “viscosity” might also be dissipative… could turn gravitational potential energy into heat (and eventually radiation)
- Physics of the 'viscosity' is very complex (see discussion in 14.3.2- pg 454) - it turns out that it is due to magnetic fields and an instability magnetorotational instability (MRI) , by which weak magnetic fields are amplified by differential rotation, gives the required viscosity

Basics of Accretion Longair 14.2.2

Is there a limit on accretion?

If the accreting material is exposed to the
radiation it is producing it receives a force due to radiation pressure

The minimum radiation pressure is
(Flux/c)xk (k is the relevant cross section)- digression here....

assume that the infalling matter is fully ionized and that the radiation pressure force is provided by *Thomson scattering of the radiation by the electrons in the plasma- the smallest 'normal' cross-section*

Eddington Limit Longair 14.2.2

The force is : $L\sigma_T/4\pi r^2 c$; ,
$L/4\pi r^2$ is the flux at radius r
(σ_T is the Thompson cross section ($6.6\text{x}10^{-25}$ cm^2) - L is the photon luminosity, r is the distance from the source)

The gravitational force on the proton is Gm_pM_x/R^2
m_p is the mass of the proton,M_x is the mass of the accreting object

Equating the two gives the Eddington limit
$L_{Edd}=4\pi M_x G m_p c/\sigma_T = 1.3\text{x}10^{38} (M_x/M_{sun})$erg/sec

where is it assumed that the accreting material is all hydrogen-

Eddington Limit- More Detail Longair pg 446

- $f_{\mathrm{grav}} \approx GMm_p/r^2$ force due to *gravity acting on the protons*
  The radiation pressure acts -upon the electrons-
- Each photon gives up a momentum $p = h\nu/c$ to the electron in each collision
- force acting on the electron is the momentum communicated to it per second by the incident flux density of photons N_{ph}.
- Thus, $f_{rad} = \sigma N_{\mathrm{ph}}\, p$ *(p is momentum, σ* is the relevant cross section , the smallest is the Thompson cross section σ_T= 6.6x10^{-25} cm^2*)*
- *As we go away from the source of photons the flux of photons is*
  $N_{ph}/4\pi r^2$; $N_{ph}=L/h<\nu>$; *L* is the luminosity of the source.
- so the outward force on the electron is $f = \sigma_T L/4\pi c r^2$.
- Equate this to gravity (e.g. radiation pressure and gravity balance)
  Gives **$L_E = 4\pi GMm_pc/\sigma_T$**
- maximum luminosity *a spherically symmetric source* of mass *M* can emit in a steady state. The limiting luminosity is independent of the radius *r* and depends only upon the mass *M* of the emitting region and the cross section

---

General Considerations

- Time scales:

$\tau_{dyn} = (r^3/G\,M)^{1/2}$ This is about 0.1 ms for matter at r = 10 km, and 2 ms at r = 100 km.

The typical orbital period of circulating matter,

$P_{orb} = 2\pi\tau_{dyn}$ ~1 ms:

- Characteristic velocity is ~$(GM/R_G)^{1/2}$ ~ 0.5c.

- The two main accretion mechanisms are
  - Roche lobe over flow, which most often occurs in low-mass binaries (LMXB,low B field, accretion disk and boundary layer dominated)
  - and stellar wind capture, which is common for high-mass binaries with super-giant companions (high B fields, pulsars)

General Considerations

- The Compton optical depth in a spherical accretor is $\tau=(2/\varepsilon)^{1/2}$ L/L_{edd}

- Two natural temperatures
  - Free fall $kT=3/16\ \varepsilon m_h c^2=2 10^5 \varepsilon$ kev
  - Black body temperature: minimum temperature for the object to radiate the observed luminosity
    - T_{BB}~$(L/A\sigma)^{1/4}$;A is the area and σ is the Stefan-Boltzman constant

    - about 0.2 keV for a white dwarf and 2 keV for a neutron star

---

Summary Considerations

- The luminosity that results from accretion is roughly
  - L~ $\varepsilon c^2 \mathcal{M}$ ($dM/dt=\mathcal{M}$) Where $\varepsilon=GM/Rc^2$ (the depth of the potential)
    - ε~3×10^{-4} for a white dwarf and 0.1 for a neutron star

- If the gas flow is spherically symmetric and steady state the luminosity should not exceed the Eddington limit (outward force from Compton scattering balances gravity)

Basics of Accretion

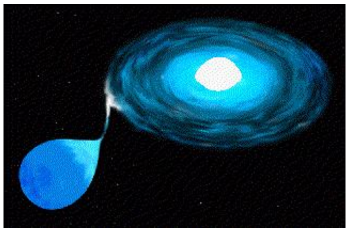
- Because of angular momentum considerations an accretion disk, **almost** always forms
- Matter is thought to form a physically thin (but optically thick* disk) which has Keplerian rotation
- Matter falls into by losing angular mometum via viscosity

the angular velocity is Ω_k=sqrt(GM/r^3)

The binding energy of a parcel of the disk is $E=GM_{disk}M_x/2R= 1/2\ L_{acc}$

The other half of L_{acc} is released very close to the star surface (the boundary layer) as matter in the disk tries to co-rotate with the NS

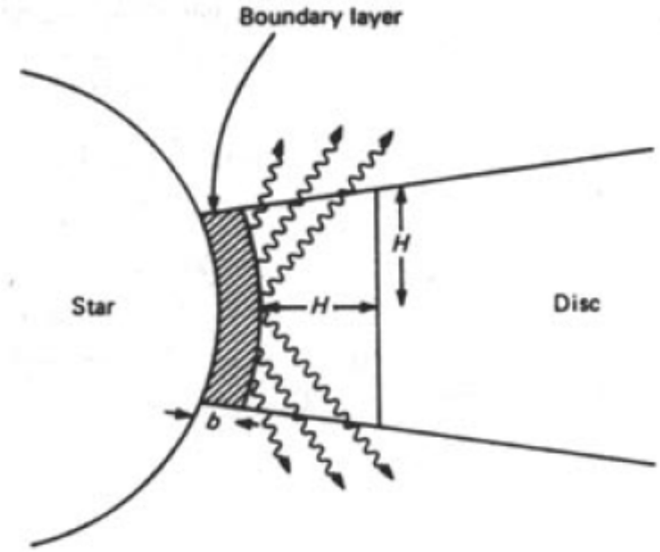
If the star spins more slowly than the innermost part of the accretion disk (angular speed ω_k) , the BL must release a large amount of energy as the accreting matter comes to rest at the stellar surface. Some of this is used to spin up the star, but there remains an amount $G\mathcal{M}M_x/2R(1- \omega_{k/}\Omega_k)^2$ which is radiated



* Optically thick means that a photon emitted inside the disk always interacts with matter at least once before 'escaping'

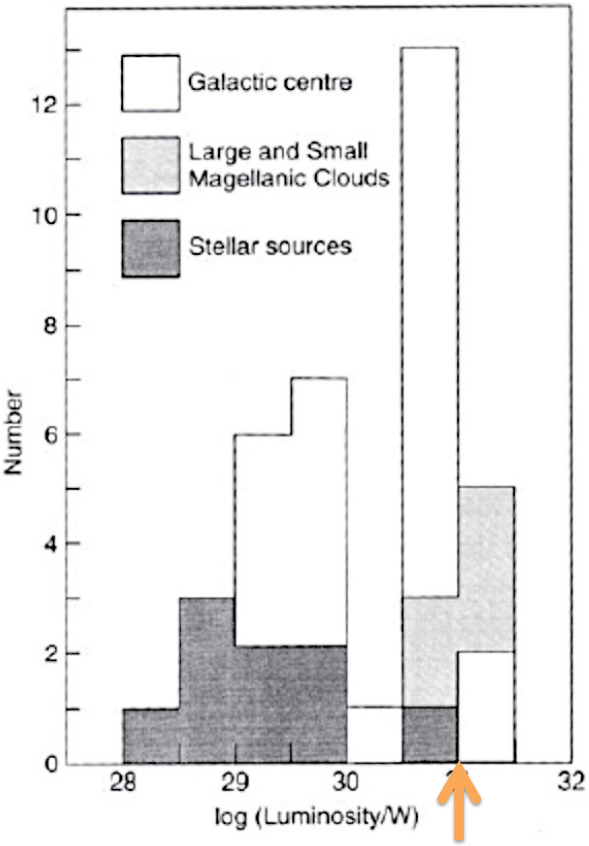
Where is the Accretion Occurring

- In a weak field neutron star (LMXB) has the accretion disk and the place where the material hits the star surface (boundary layer)



Simplistic Check

- If a NS is accreting at the Eddington limit and radiating via a black body what is its temperature?
- $4\pi r^2_{\mathrm{NS}} a T^4 = L_{\mathrm{edd}}$
- So put in 10km for r_{ns} and $1.3\mathrm{x}10^{31}$ W for L_{edd} for 1 solar mass and get
  - $(a=5.67\mathrm{x}1\ 0^{-8}\mathrm{Wm}^{-2}\mathrm{K}^{-4})$
- $T\tilde{}2\mathrm{x}10^7$K ; 'natural' for NS to radiate in the x-ray band.



Two Modes of Accretion- Longair 14.5.2

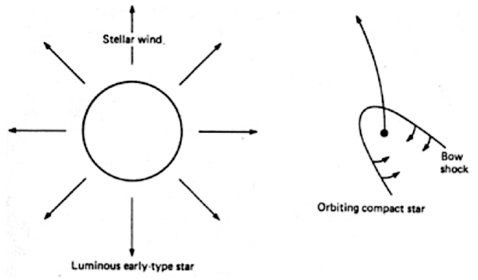


Figure 9: Accretion from a stellar wind.[23]

Accretion from a stellar wind

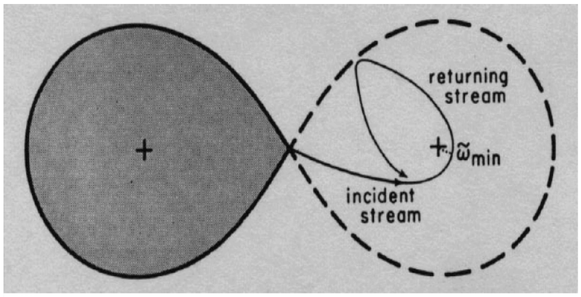


Figure 6: Roche lobe geometry, showing the incident mass stream through the inner Lagrangian point and the intersection of the returning stream with the newly arriving material. The low mass companion on the left hand side completely fills its Roche lobe, while the position of the compact object is denoted by a plus sign (+) inside the right hand lobe.[24]

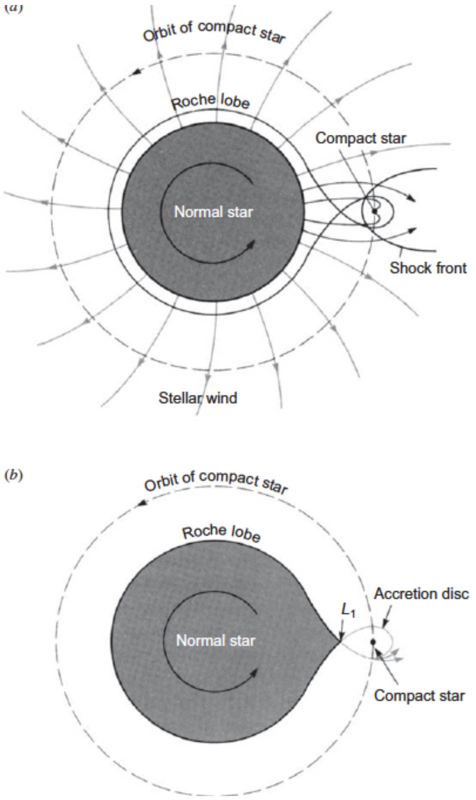
Accretion from Roche Lobe Overflow

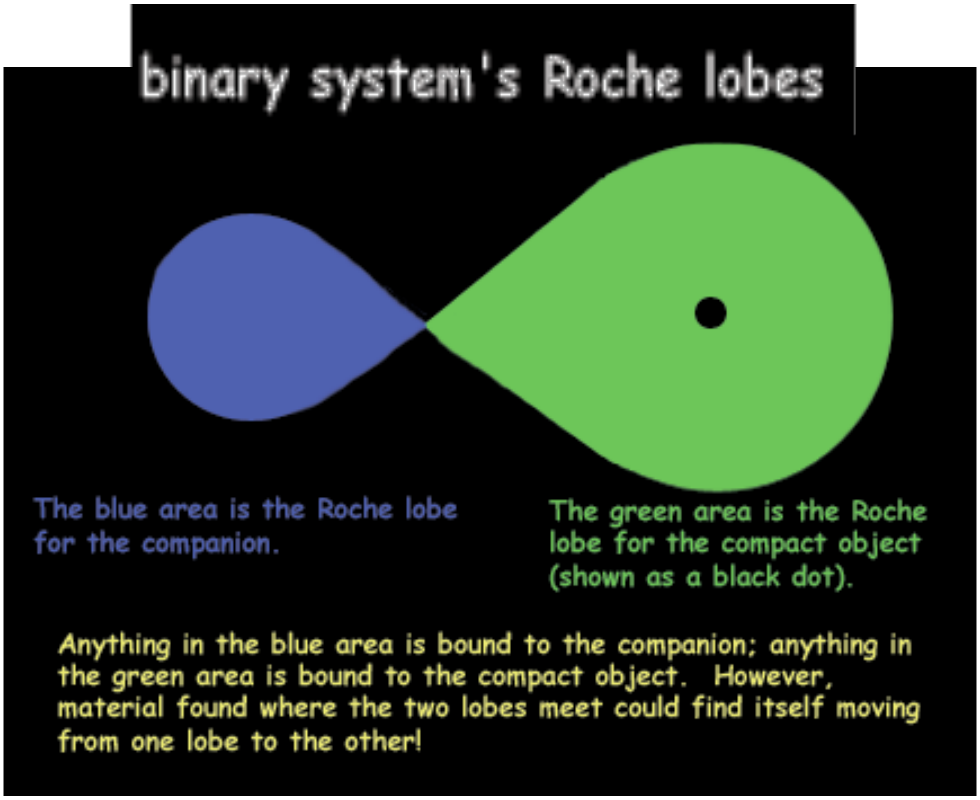
Cominsky (2002)

Two Modes of Accretion – Longair Fig 14.13

- Many stars emit stellar winds, which are very strong in the cases of luminous O and B stars in

  mass loss rates as high as $10^{-5}My_{-1}$ are observed -the compact companion is embedded in an outflowing stellar wind
- *Roche lobe overflow*. The equipotential surfaces of a close binary star system are distorted in the rotating frame of reference when the stars fill a substantial fraction of the Roche lobe





The blue area is the Roche lobe for the companion.

The green area is the Roche lobe for the compact object (shown as a black dot).

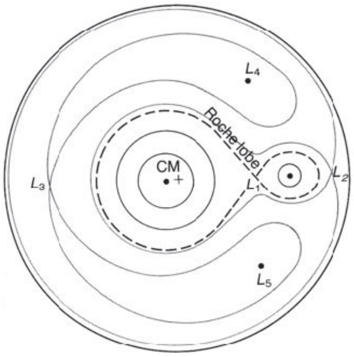
Anything in the blue area is bound to the companion; anything in the green area is bound to the compact object. However, material found where the two lobes meet could find itself moving from one lobe to the other!

Roche Lobe

- $\phi = GM_1/r_1 + GM_2/r_2 - \Omega^2 r^2$ = constant , (Longair 14.58)

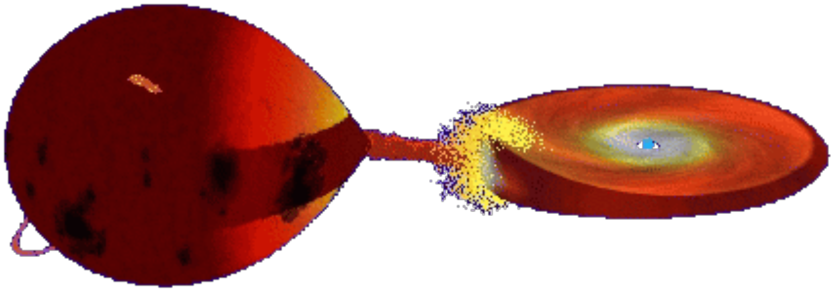
where r_1 and r_2 are the distances from the centres of the stars of masses M_1 and M_2 to the

- There is a critical equipotential surface encompassing both stars
- The equipotential surfaces within the Roche lobe show that the shapes of the stars are significantly distorted from spheres if they fill a significant fraction of the Roche lobe.
- separation $a=[GP^2(M_1+M_2)/4\pi^2]^{1/3}$



Roche lobe is ---
line (10:1 mass ratio

Accretion from a Dwarf Companion

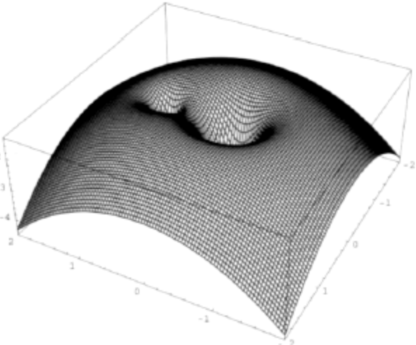


- http://physics.technion.ac.il/~astrogr/research/animation_cv_disc.gif

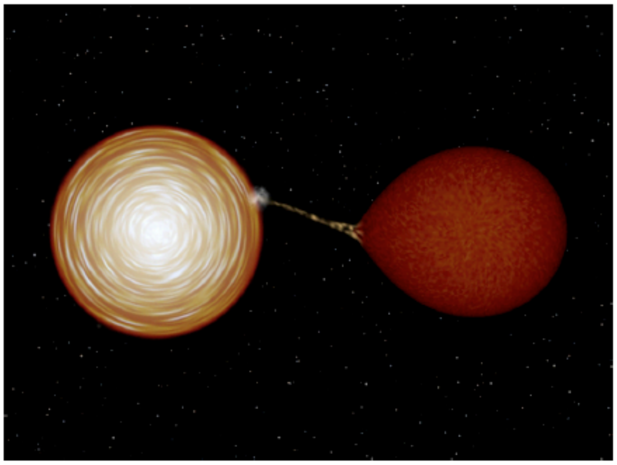
Roche Lobe Overflow Systems

Sample

- Almost all LMXBs and IMXBs
- Small fraction of HMXBs



From Frank et al., 2002, Accretion Power in Astrophysics



see http://cronodon.com/SpaceTech/CVAccretionDisc.html for more details

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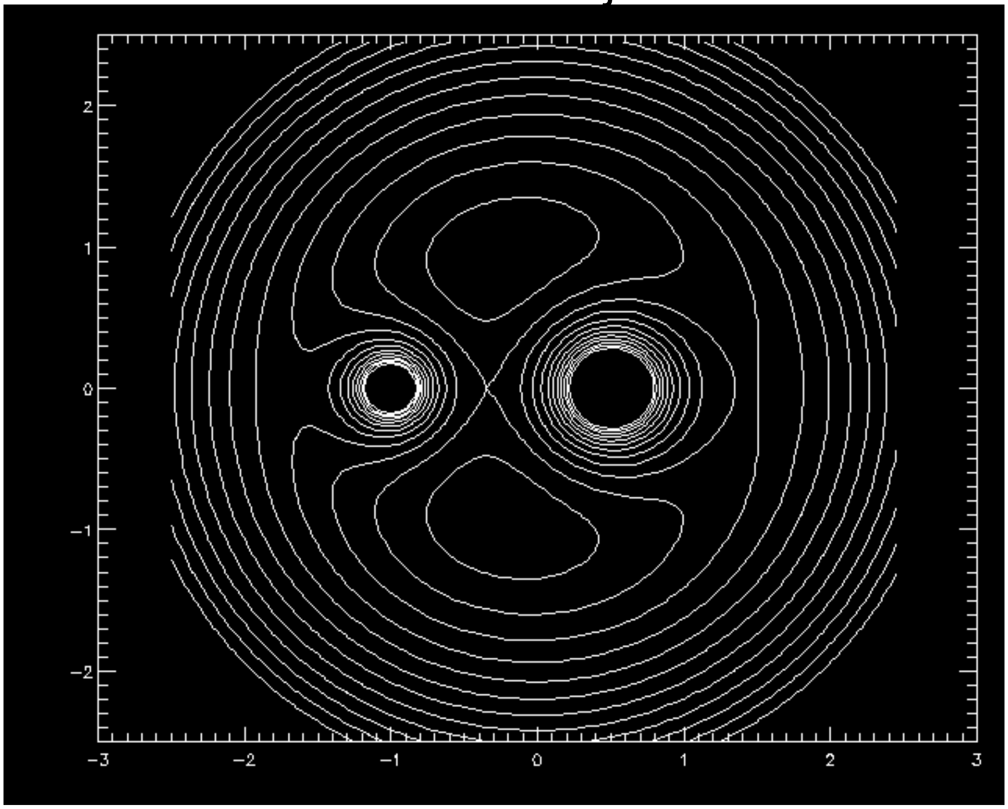
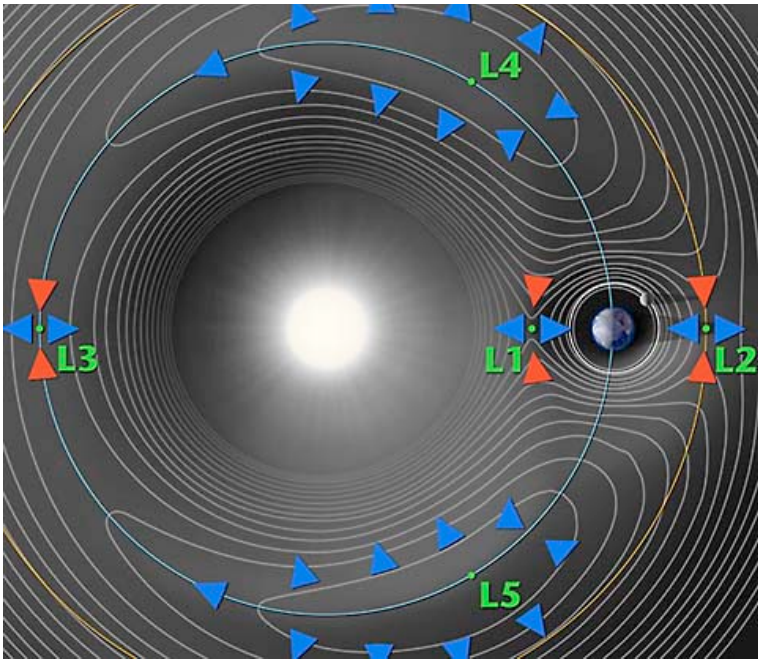
Potential For 2 Objects



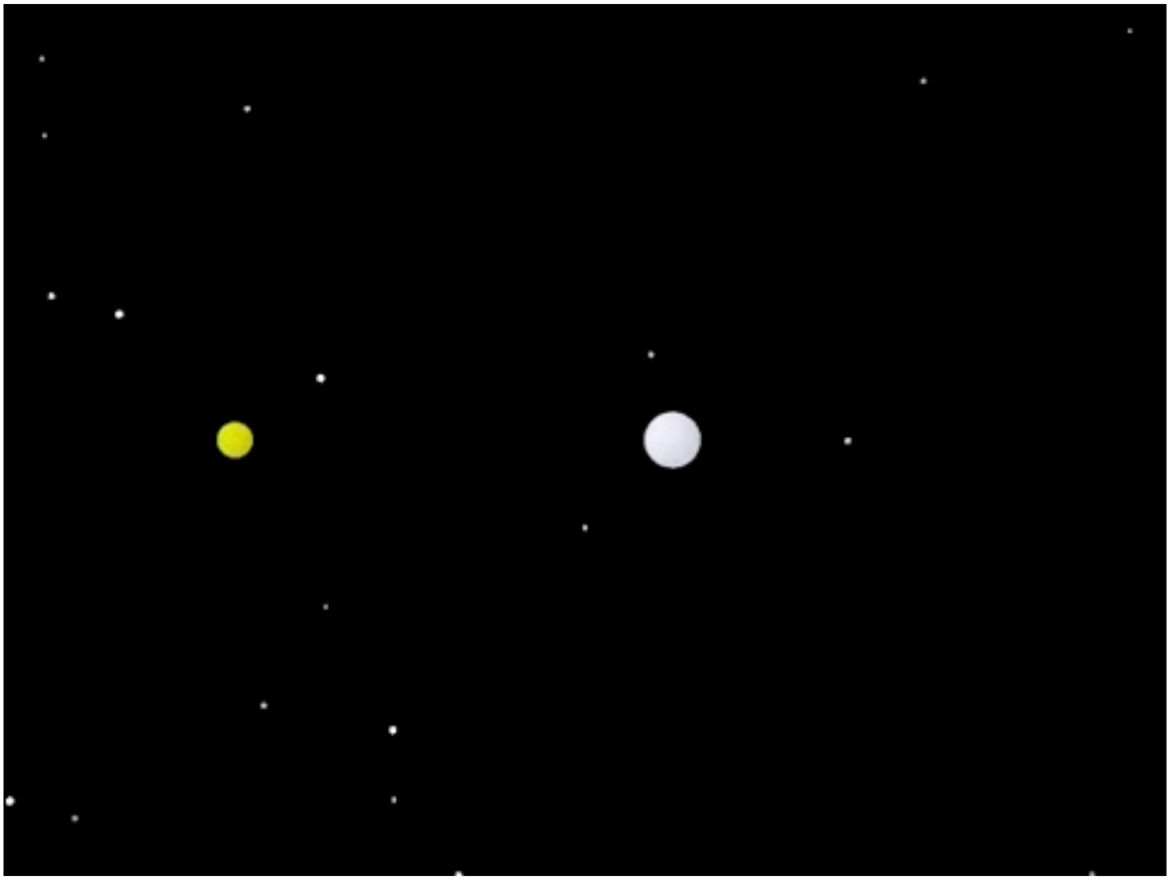
- Gravitational and centrifugal (angular momentum) terms
- ω is the angular momentum
- $\omega = [G\mathcal{M}/a^3]^{1/2}$

- where a is the separation and $\mathcal{M}$ = $[M_2/M_1+M_2]$

L1 is an unstable Lagarangian pt



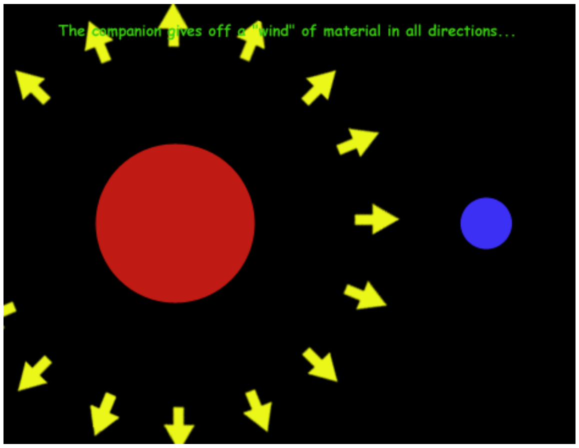
$$\Phi_R = -\frac{GM}{|\mathbf{r}-\mathbf{r_1}|} - \frac{GM}{|\mathbf{r}-\mathbf{r_2}|} - \frac{1}{2}(\omega \times \mathbf{r})^2$$



High Mass X-ray Binary

The high mass companion sheds mass through a wind.

- This wind flows isotropically from the companion, so a portion runs into the compact object.
- This material releases its potential energy as X-rays.



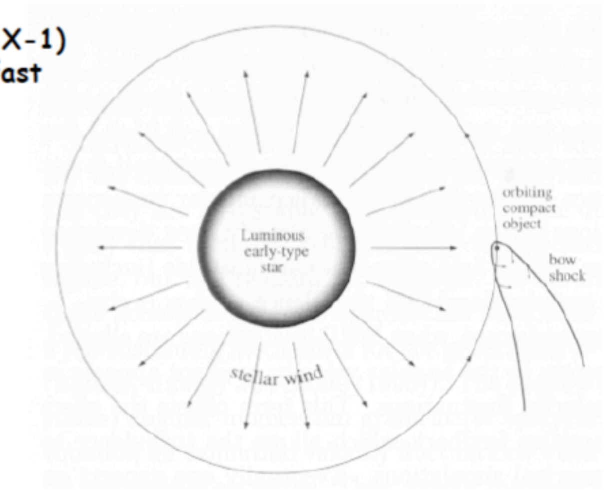
HMXBs T. Kallman

- Among the first discovered extra-solar sources (eg. Vela X-1, Cyg X-1, Cyg X-3, Her X-1)
- Often contain pulsar
- Often eclipsing
- Pulse timing + stellar radial velocity +eclipses = mass, orbital separation, inclination determination
- Accretion can occur from wind from primary, or from Roche-lobe overflow
- Two different subtypes:
  - Be binaries
  - Supergiant binaries
- Statistics: ~50 known in galaxy
- Young population, lifetime ~10^5 yrs: mass transfer is unstable- wide range in luminosities

Wind Fed Systems

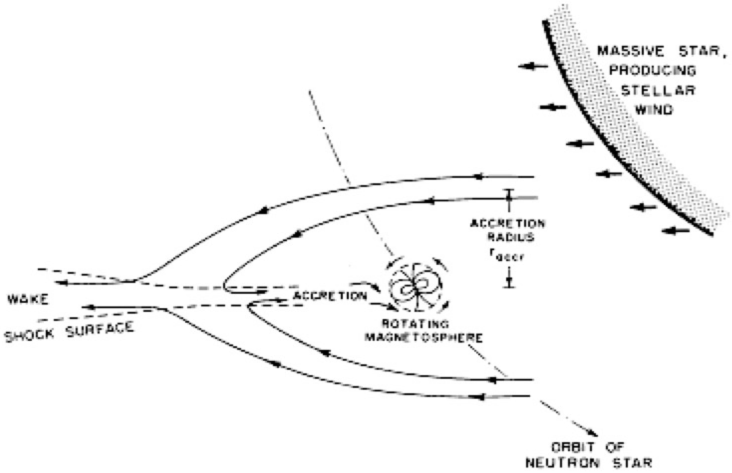
Sample

- Some HMXBs with supergiant companions (~1/3 of the systems
- Both persistent (e.g. Vela X-1) and transient (supergiant fast X-ray transients)
- Symbiotic X-ray binaries (e.g. GX 1+4)



From Frank et al., 2002, Accretion Power in Astrophysics

HMXB- wind accretion



From similar stars

Efficiency Guess: ~0.1

separation

Wind speed

Observed X-ray luminosity

$$L_x \sim \mathscr{M}_{wind}\, c^2G^2M^2\eta \,/(a^2\, v_w{}^4)$$

Theory of wind accretion:
(Davidson and Ostriker 1973):
$\rho v_w{}^2/2 = GM\rho/r$

Accretion From a Wind Longair 14.6.4

- The process is called Bondi accretion
- Consider a star of mass m, traveling through a gas of density ρ at relative velocity v_{rel}.
- Material inside a cylinder of radius

$r_{acc}=2GM/v_{rel}^2$ can lose enough energy to fall onto the star at an accretion rate of $S=\pi r^2_{acc} v_{rel} \rho f$ (where f is a fudge factor due to things not properly modeled due to radiation pressure effects and gas dynamics)

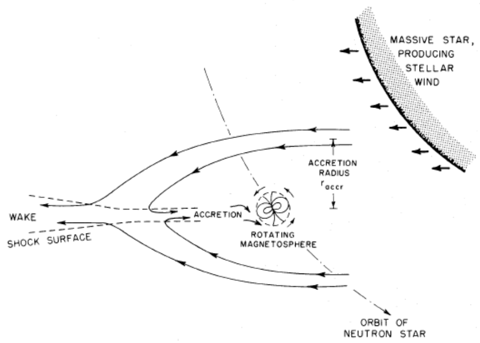


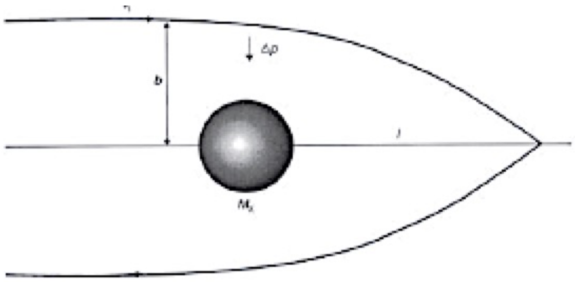
FIG. 3.—Streamlines of stellar-wind material, relative to an accreting neutron sta dimensions are not to scale.

giant stars stellar wind speeds are ~700km/sec giving

r_{acc}~ $5\text{x}10^{10}$cm

Accretion From a wind – Following Longair 14.6.4

- the impulse which a particle receives on passing a stationary mass is given by the inward force at the distance of closest approach *b* (see 5.2)
- The gravitational force of attraction per unit mass at distance *b* is GM_X/b^2 and the duration of this force is $2b/v_t$. The momentum impulse inwards is
- $\delta p = 2GM_X/bv_t$



process of accretion by a star of mass M_x in a stellar wind of velocity v_t.

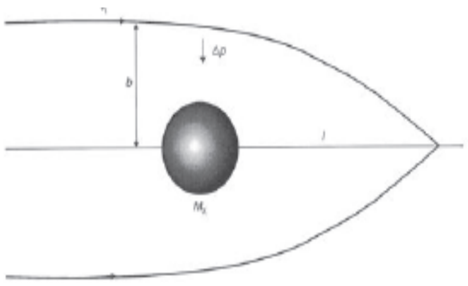
At distance *l* downstream,the particles with collision parameter *b* collide on the axis of the flow. The perpendicular component of the velocity goes to zero and the the matter is captured by the star

Giving a capture radius

$R_c=2GM_X/[v_x^2+v_w^2]$ Eq 14.69

Accretion From a wind – Following Longair

- $L_X \approx [\,\eta m^{\cdot}_{P} / 4]\,(2GM_X/R_P)^2 v_w^{-4}$
  - $m^{\cdot}_{P}$ the mass loss rate from the donor star
- accretion rate is ~$(m^{\cdot}_{P}/4)(R_c/R_p)^2$
- R_p is the distance of the compact object from the donor star ,R_c is the critical (capture radius)
- **Wind velocity v_w>> orbital velocity v_x**
- process is very inefficient compared to Roche lobe overflow in which almost all the material lost by the donor star is channelled through the Lagrangian point into the accretion disc.



s of accretion by a star of mass M_X in a stellar wind of velocity v_t.

So X-ray luminosity is directly proportional to the mass-loss rate of the donor star,$m^{\cdot}_{P}$, and is very sensitive to the wind velocity

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If the Magnetic Field is Strong (As In NS Pulsars)

- If magnetic pressure dominates over thermal pressure the magnetic field channels the accretion flow and matter flows along field lines that connect to the magnetic polar regions:
- As a result, almost all of the accretion energy is released in a "hot spot" near the two magnetic poles.
- If the magnetic axis is not aligned with the rotational axis, then as the star rotates we see more or less of the hot spot, and hence see pulsations in the X-rays.

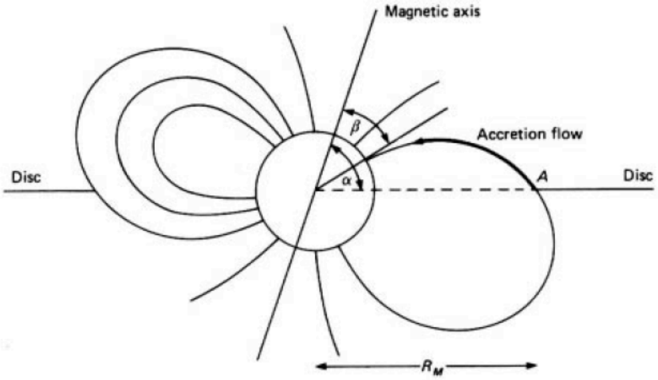

Figure 8: Accretion in a strong (~ 10^{12} Gauss) magnetic field. Note that the accretion disk is held off the neutron star surface by the centrifugal barrier formed by the rotating magnetosphere.[23]

Longair 14.5.3

Cominsky (2002)

Accreting Magnetic Neutron Stars

- Effect of magnetic field
  - flow of ionized gas is channeled by the field
  - Photon production in a strong field is different (cyclotron radiation)
- When/where does the magnetic field dominate the accretion flow?

The magnetic energy density is $B^2/8\pi$, and the kinetic energy density of the accreting matter is $1/2\rho v^2$, where ρ is the density and v is the typical velocity. So need $B^2/8\pi < 1/2\rho v^2$

Assume spherical symmetry so accretion rate $\mathcal{M}=4\pi R^2\rho v$; v is on the order of the free fall velocity sqrt(2GM/R); replace R by the Schwarzschild Radius $2GM/c^2$

One gets $B<6\times10^{17}(\mathcal{M}/10^{17}\text{gm/sec})(R/10\text{km})^{-5/4}\ (M/M_\odot)^{1/4}$ gauss

X-ray Pulsars

- Accrete matter through wind or via disk from a high mass companion. Because of a large magnetic field strength (typically 10^{12} G) the material is channeled onto small spots at the magnetic poles.
- the relativistically moving plasma is decelerated in a radiative shock near the surface and settles subsonically
  - **plasma radiates in the X-ray band**
- Pulsations are observed if the magnetic field is inclined relative to the rotation axis.
- Studies of the pulse profiles of individual pulsars allow one to constrain the emission pattern of the hotspots (or accretion columns) at the NS surface as well as the geometry of the magnetic field