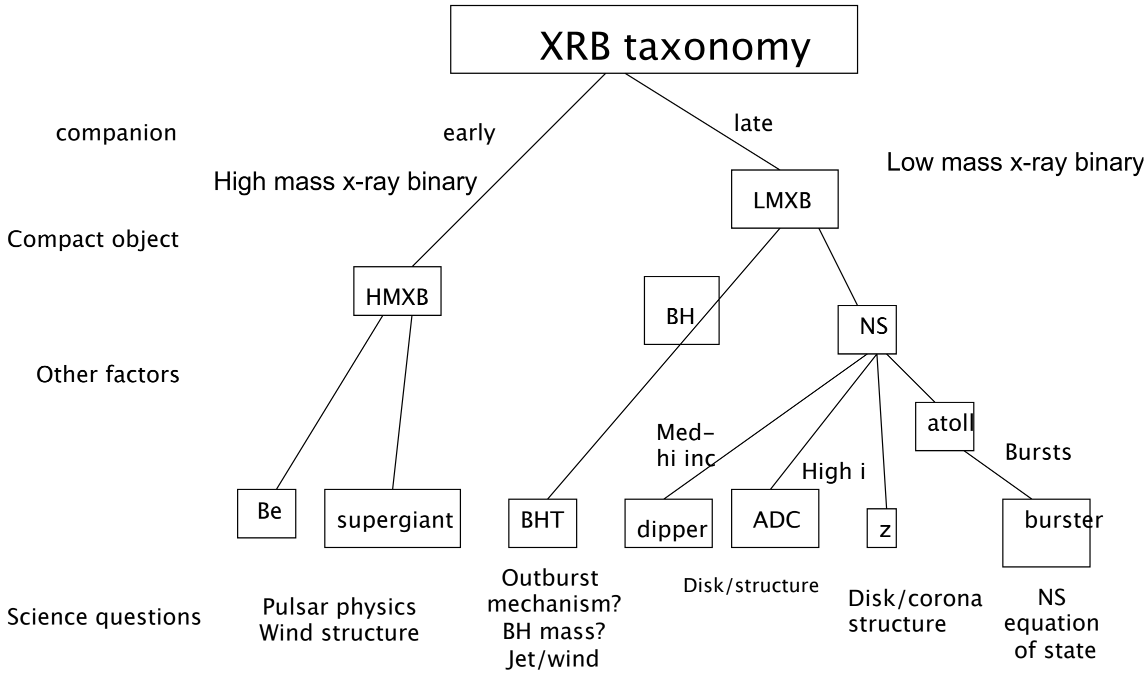
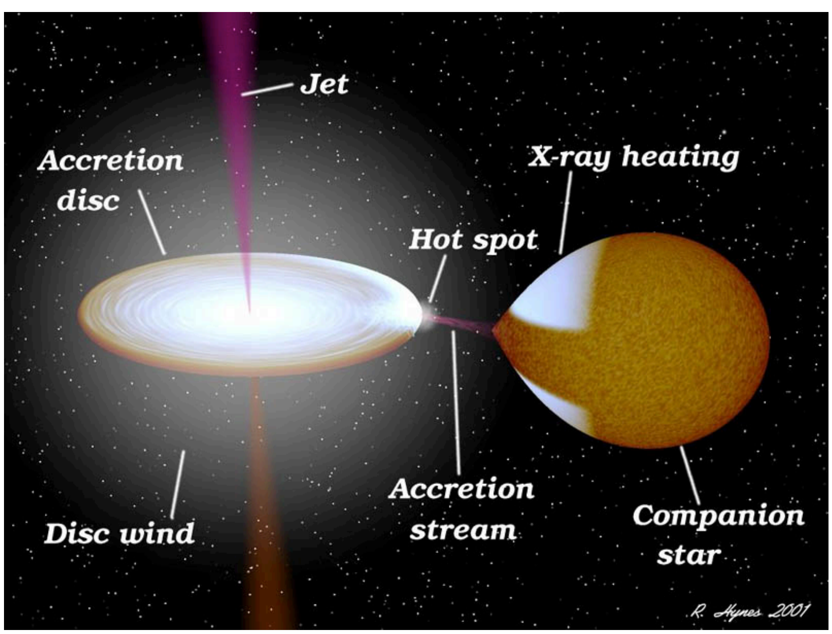
A Short Introduction to terminology



Kallman 2009

Accreting Neutron Stars

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



Accreting Neutron Stars

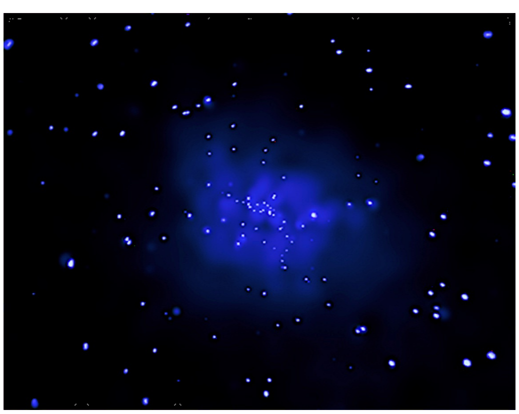
- Two types- based on mass of companions
  - Low mass x-ray binaries-NS star tends to have low magnetic field- - are 'old' (~10^{9-10} yrs) -BHs are transient
  - High mass-NS tends to have high magnetic field- - are are 'young' (~10^{7-8} yrs)- BHs on all the time

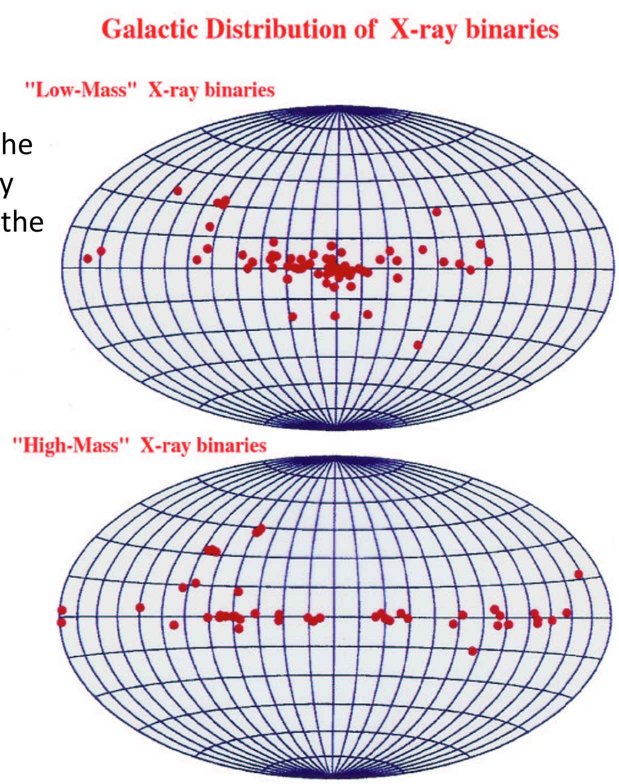
	HMXB	LMXB
Donor star	O-B ($M>5M_{sun}$)	K-M ($M<1M_{sun}$)
Age/Population	10^7 yrs I	5-15x10^9 II
L_x/L_{opt}	0.001-10	10-1000
X-ray Spectrum	flat power law	kT<10keV,b remms-like
Orbital period	1-100d	10min-10d
X-ray eclipses	common	rare
Magnetic field	strong (~10^{12}G)	weaker (10^7-10^8 G)
X-ray pulsations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





Distribution of Luminous X-ray Sources in Galactic Coordinates

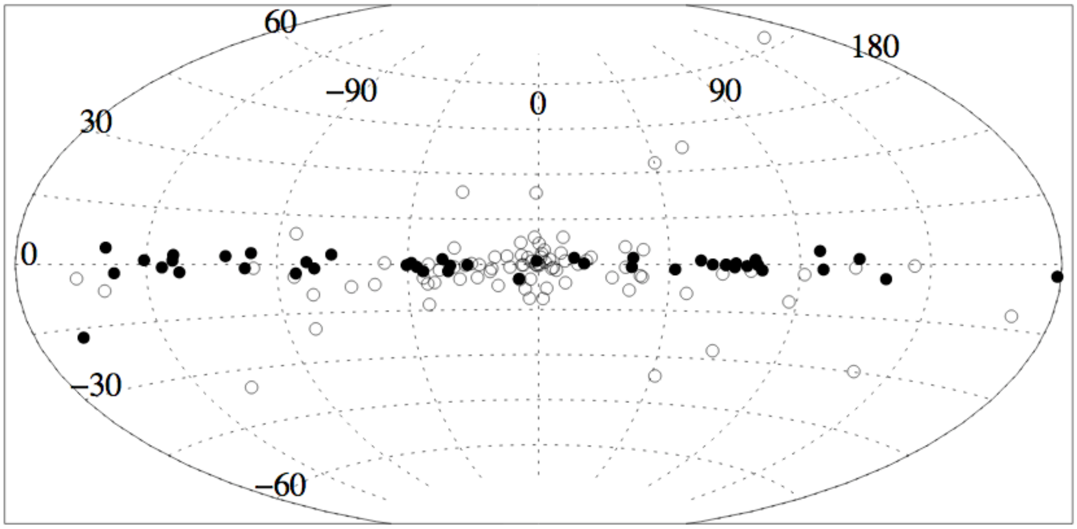


Fig. 1. Distribution of LMXBs (open circles) and HMXBs (filled circles) in the Galaxy. In total 86 LMXBs and 52

- Low mass x-ray binaries – open circle
- HMXBs filled circles

3D Distribution of Sources (Gatuzz et al 2018)

- Using GAIA the 3-D distribution of x-ray binaries can be determined

.

Gatuzz et al.

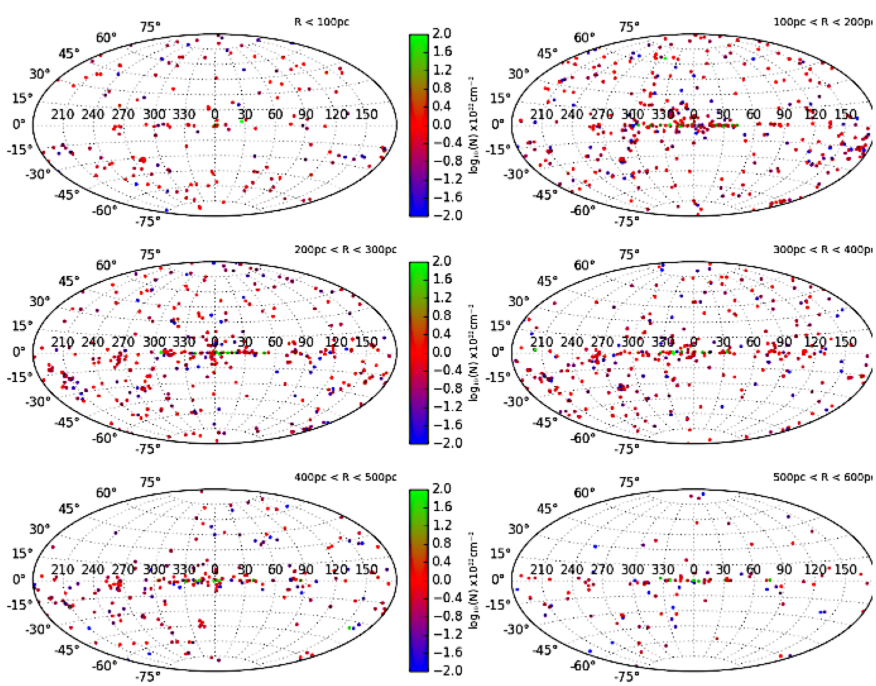
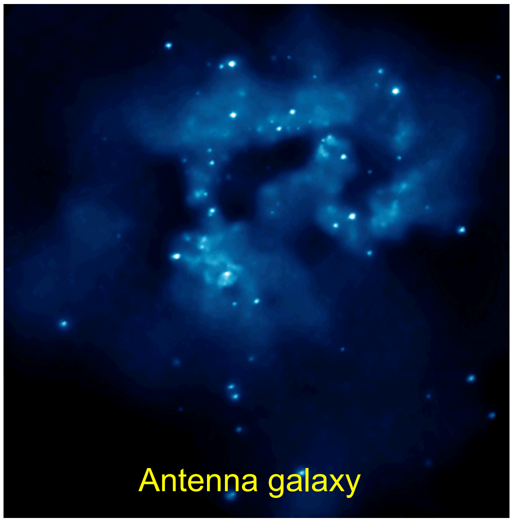


Figure 2. Galactic distribution of the sources in Galactic coordinates.

M31 and the Antenna

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



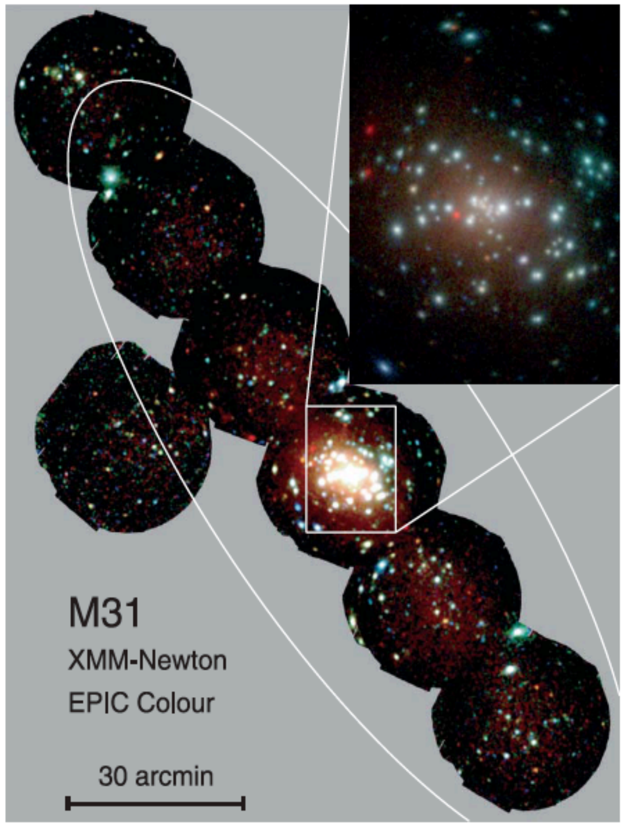
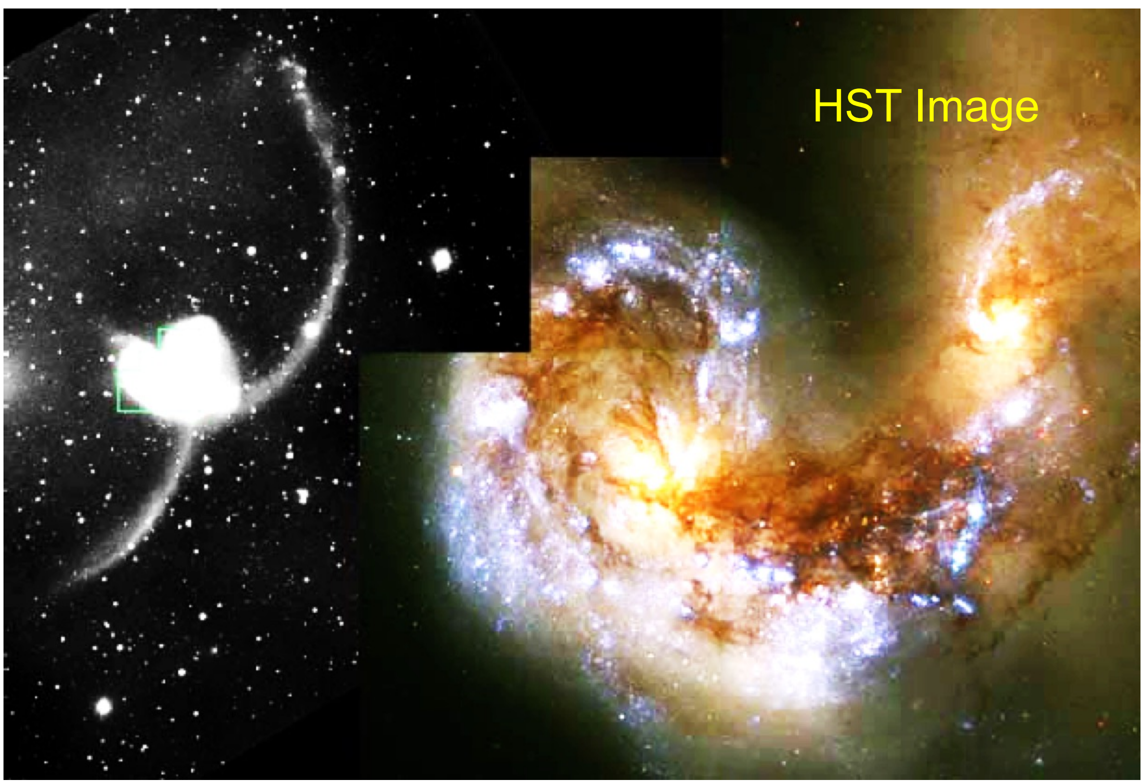


Fig. 1 (online colour at: www.an-journal.org) Logarithmically-scaled, three-color XMM-

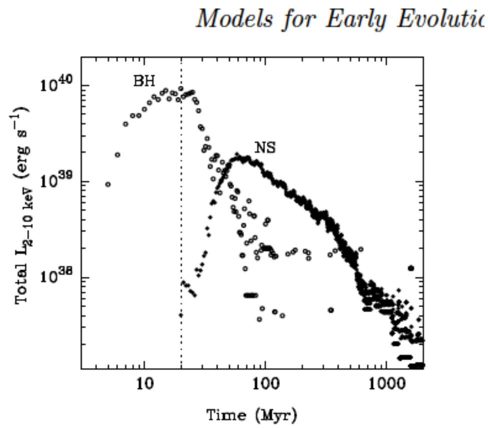
Optical Image of Antenna

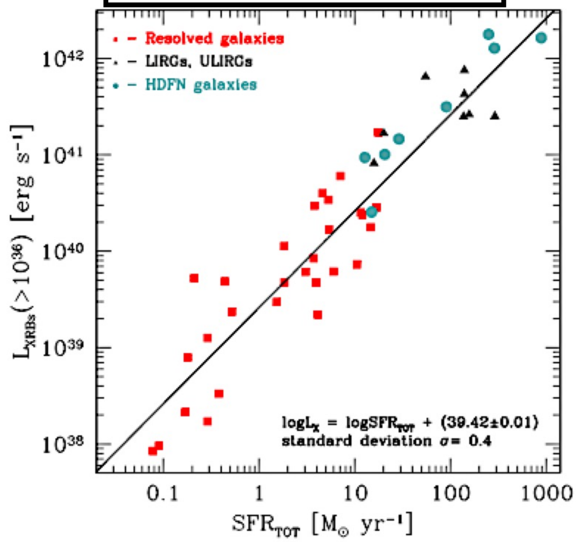


Relation to Star Formation

- 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

Star formation rate vs Luminosity in HMXB

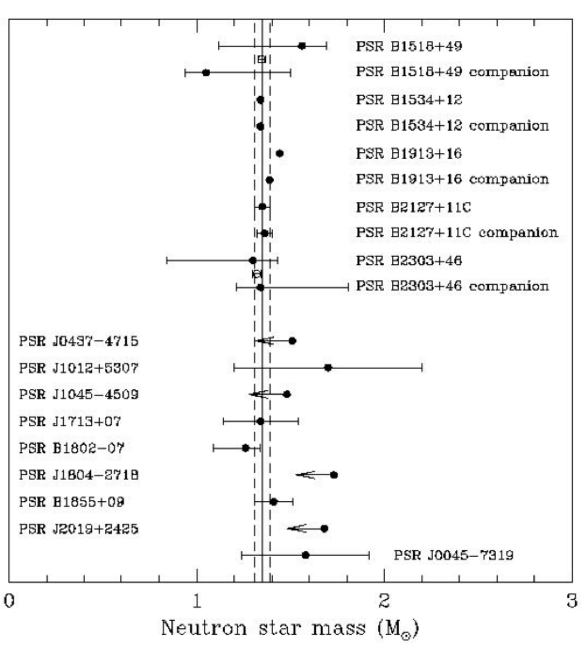


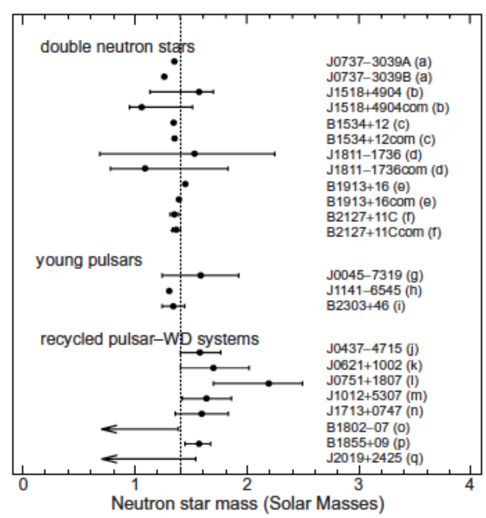


Example of a theoretical model of the luminosity in x-ray binaries in a star forming galaxy Eracleous et al 2009- right figure is star formation rate vs number of HMXB in a galaxy

Masses of Neutron Stars – Longair pg 417

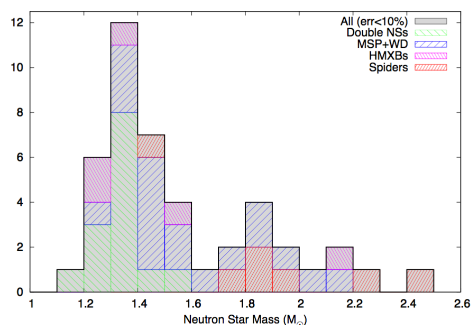
- Observed masses of <u>non-accreting NS in binaries</u> strongly clusters around 1.4 $M_\odot$ the Chandrasekar mass

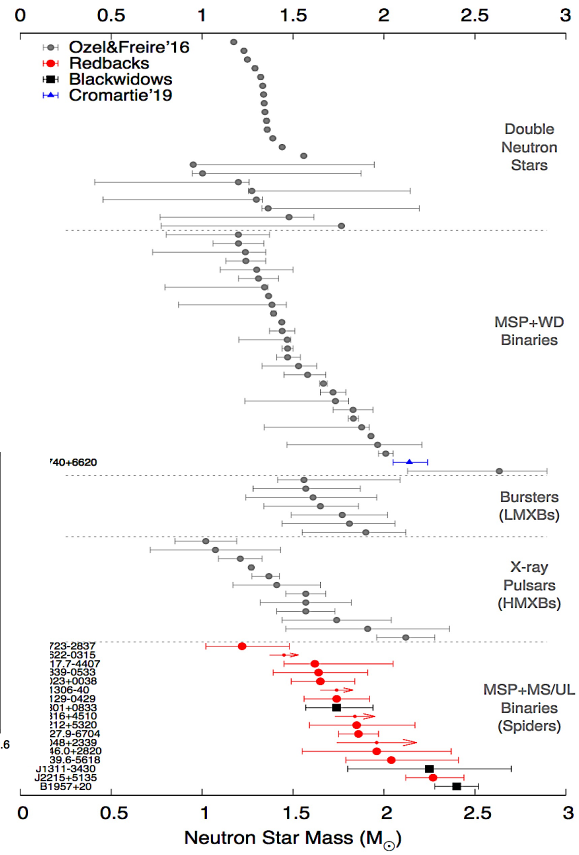




Masses of NS with small errors

- Linares /1910.09572.pdf





Accretion -Basic idea

- – physical origin of friction is complex .

  Given the typical densities and temperatures in accretion disks, viscosity is too low to drive the inward drift. It is thought that the friction comes from turbulence due to the rotation of the disk amplifying any magnetic fields that are already there.

If matter is to fall inwards it must lose not only gravitational energy but also lose angular momentum. Since the total angular momentum is conserved, the angular momentum loss of the mass falling into the center has to be compensated by an angular momentum gain of the mass far from the center.

In other words, angular momentum is *transported* outwards for matter to accrete

The magnetorotational instability (MRI), S. A. Balbus and J. F. Hawley) provides a direct mechanism for angular-momentum redistribution.[9]

Basics of Accretion – Longair 14.2

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

$E=G\mathcal{M}M_x/R$ (where M_x is the mass of the accreting object and R is the radius to which it 'falls') - **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 from infinity

$$\frac{1}{2} m_{\mathrm{p}} v_{\mathrm{ff}}^2 = \frac{G M m_{\mathrm{p}}}{r} .$$

- and convert the kinetic energy

$L=1/2mv_{ff}^2$ to heat and then radiation

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

Basics of Accretion – Longair 14.2

We can write this as $L = \xi \dot{m} c^2$ and ε depends on r (how much of potential energy is converted to luminosity under the assumption that all of the potential energy is converted to photons).

Normalizing the observed luminosity to a typical value of 1.3×10^{37} erg/sec for an x-ray binary gives accretion rates of

$$L_{acc}=1.3 \times 10^{37} \mathcal{M}_{17} m_x R_6$$

- $\mathcal{M}_{17}$ is $\mathcal{M}$ in units of 10^{17}gm/sec= 1.5×10^{-9} M_{sun}/yr
- R_6 Is the radius in units of 10^6cm (10km)
- m_x is the mass in solar units of the accretor (e.g. the NS)

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

Gravitational potential of spherically symmetric mass M of radius R

$$\Phi = -\frac{GM}{r} \qquad (r > R)$$

Acceleration of gravity

$$\mathrm{g} = -\nabla\Phi = -\frac{GM}{r^2}\hat{r}$$

Particles freely falling from $r \to \infty$ to r:

$$E_{\mathrm{K}} = \frac{1}{2}v^2 \qquad \text{(kinetic energy per unit mass)}$$

Energy conservation: $E_{\mathrm{K}} + \Phi = E = \mathrm{cst.}$

At r: $v^2 = \frac{2GM}{r}$ (free-fall or escape speed)

Viral temperature T_{viral}=GM/kr; for a NS M~1.4M_{sun}, R~10 km

T~10^{12}k

(H. Spruit)

Basics of Accretion – Longair 14.2

- For a white dwarf star with $M = M_\odot$ and $R \approx 5 \times 10^8$ cm, $\xi \approx 3\ 10^{-4}$.
- Neutron star with mass $M = M_\odot$ and R = 10 km, ξ ~ 0.15.
- For nuclear energy generation the conversion of hydrogen into helium has $\xi \approx 7 \times 10^{-3}$.

- For a NS accretion is much more efficient at converting mass into energy than nuclear fusion.

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

Accretion -Basic idea

- 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

– physical origin of friction is complex .

Accretion -Basic idea

Very efficient process Energy ~GM/R=1.7×10^{16} $(R/10\text{km})^{-1}$ J/kg ~$1/2mc^2$

Nuclear burning releases ~7×10^{14}J/kg (0.4% of mc^2)

- $L = 1/2\mathcal{M} c^2 (r_g/R)$ (14.3)
- This expression for the luminosity can be written $L = \xi\mathcal{M}c^2$, 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 $R \approx 5\times10^6$ m, $\xi \approx 3\times 10^{-4}$.
- For a neutron star with mass $M = M_\odot$ and $R = 10$ km, $\xi \sim 0.15$.

Accretion -Basic idea

Very efficient process.

- 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 14.2.2

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)xσ (σ is the ***relevant*** cross section)

assume that the infalling matter is fully ionised and that the radiation pressure
force is provided by the the smallest cross-section possible, Thomson scattering, of the radiation by the electrons in the plasma.

Basics of Accretion Longair 14.2.2

Expressed differently:

Radiation pressure is

$$L\sigma_T/4\pi r^2 m_p c$$

(σ_T is the Thompson cross section ($6.6\text{x}10^{-25}$ cm^2) m_p is the mass of the proton)

The gravitational force on the proton is

$$GM_x/R^2$$

Equating the two gives the Eddington limit

$$L_{Edd}=4\pi M_x G m_p c/\sigma_T = 1.3\text{x}10^{38} M_{sun} \text{erg/sec}$$

Eddington Limit- More Detail Longair pg 446

- ***$f_{grav} \approx GMm_p/r^2$***

  force due to gravity acting on the protons
- The radiation pressure acts -upon the electron-

  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, ***$f_{rad} = \sigma N_{ph}\, p$*** *(p is momentum, σ* is the relevant cross section , **the smallest is the Thompson cross section σ_T= $6.6\text{x}10^{-29}$ m^2**)

Eddington Limit- More Detail Longair pg 446

- *As we go away from the source of photons the flux of photons is*

  $N_{ph}/4\pi r^2$; $N_{ph}=L/h\langle\nu\rangle$; L is the luminosity of the source.
- so the outward force on the electron from radiation pressure is

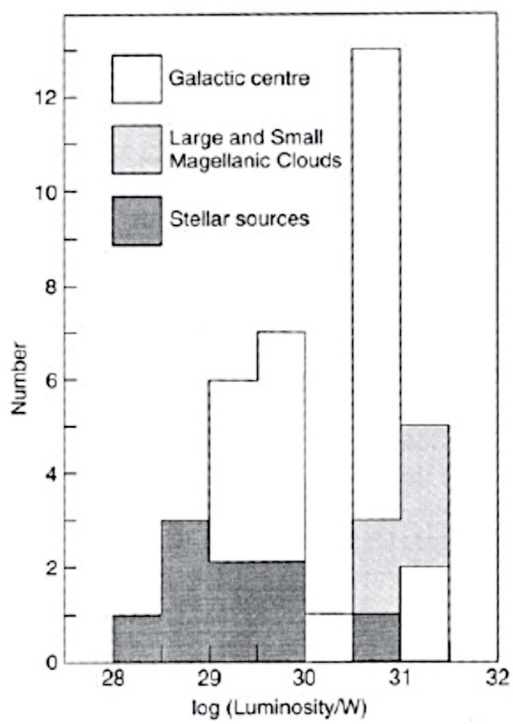
  $$f = \sigma_T L/4\pi c r^2.$$
- **Equate this to gravitational force** (e.g. radiation pressure and gravity balance)

  Gives $L_{Edd} = 4\pi G M m_p c/\sigma_T$
- **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

Simplistic Check

- If a NS is accreting at the Eddington limit and radiating via a black body what is its temperature?
- $4\pi r^2_{NS} a T^4 = L_{edd}$
- So put in 10km for r_{ns} and 1.3×10^{31} W for L_{edd} for 1 solar mass and get
  - ($a=5.67\times10^{-8}$ Wm^{-2}K^{-4})
- T~2×10^7K ; 'natural' for NS to radiate in the x-ray band.

Luminosity of XRB in MW



How much energy is released by accretion onto a compact object?

- Consider matter in an accretion disk assume that…
  - The matter orbits in circular paths (will always be approximately true)
  - Centripetal acceleration is mainly due to gravity of central object (i.e., radial pressure forces are negligible… will be true if the disk is thin)

$$\frac{v^2}{r} = \frac{GM}{r^2}$$

- Energy is..

$$E = \frac{1}{2}v^2 - \frac{GM}{r} = -\frac{GM}{2r}$$

total luminosity liberated by accreting a flow of matter is
- Longair 14.48

$$L = \left[0 - \left(-\frac{GM}{2r_{\text{in}}}\right)\right]\dot{M} = \frac{GM\dot{M}}{2r_{\text{in}}}$$

Initial energy (at infinity)

Final energy

Mass flow rate

•Total luminosity of disk depends on inner radius of dissipative

• part of accretion disk

Falling In

- The matter falling in from infinity passes through a series of bound Keplerian orbits for which the kinetic energy is equal to half the gravitational potential energy.

- The matter dissipates half its potential energy in falling from infinity to radius *r* and this is the source of the luminosity of the disc.

- When the matter reaches **the boundary layer**, it has only liberated half its gravitational potential energy. If the matter is then brought to rest on the surface of the star, the rest of the gravitational potential energy can be dissipated.

- Thus, the boundary layer can be just as important a source of luminosity as the disc itself.- of course black holes do not have a surface so the energy 'disappears'

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- 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

The First Physical Disk Model- Longair 14.3.3

- The first physical model of a disk was developed by Shakura and Sunyaev in 1973
- They made a set of reasonable assumptions which have proved to be reasonable.
- The disk is optically thick
- The local emission should consist of a sum of quasi–blackbody spectra

Shakura-Sunyaev Disk- Longair 14.3

- There are 3 pages of equations describing this simple disk and in a more complete version 20 pages in Melia's text book - we will take a dimensional analysis approach

Thin accretion disks

Accretion disks form due to angular-momentum of incoming gas

Once in circular orbit, specific angular momentum (i.e., per unit mass) is

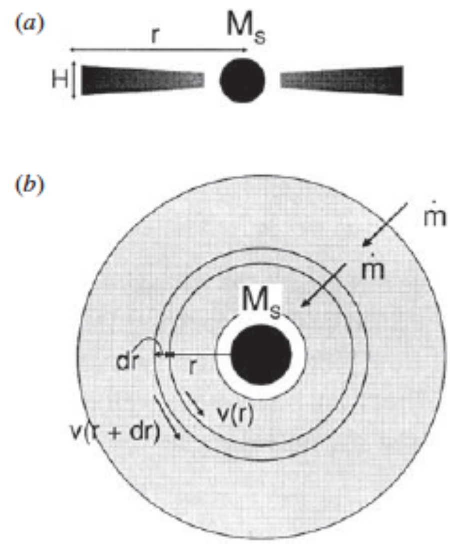
$$J = vr = \sqrt{GMr}$$

So, gas must shed its angular momentum for it to actually accrete…

Releases gravitational potential energy in the process!

Matter goes in, angular momentum goes out!

Angular velocity $\Omega \sim R^{-3/2}$



A Simple Disk- see Longair 14.48
C. Done IAC winter school

- The underlying physics of a Shakura-Sunyaev accretion disc (a very simple derivation just conserving energy -rather than the proper derivation which conserves energy and angular momentum).

- A mass accretion rate $\mathcal{M}$ spiraling inwards from R to R-dR liberates potential energy at a rate

$$dE/dt = L_{pot} = (GM\mathcal{M}/R^2)xdR.$$

A Simple Disk- see Longair 14.48
C. Done IAC winter school

- The virial theorem says that only half of this can be radiated, so

  $dL_{rad} = GM\mathcal{M}\,dR/(2R^2)$.

 If this energy is radiated as a BB

the temperature $T \sim (M\mathcal{M}/r^3)^{1/4}$

so as one goes closer to the NS/BH the disk gets hotter

A Simple Disk- see Longair 14.48
C. Done IAC winter school

- If this thermalises to a blackbody then $dL = (dA) x k T^4$ where k is the Stephan-Boltzman constant and area of the annulus $dA = 2 \times 2\pi R x dR$ (where the factor 2 comes from the fact that there is a top and bottom face of the ring).

- Then the luminosity from the annulus $dL_{rad} = GM\mathcal{M}\,dR/(2R^2) = 4\pi dRkdRT^4$ or
  - $kT^4(R) = (GM\mathcal{M}/8\pi R^3)$

- This is only out by a factor $3(1-(Rin/R)^{1/2})$ which comes from a full analysis including angular momentum
- Thus the spectrum from a disc is a sum of blackbody components, with increasing temperature and luminosity emitted from a decreasing area as the radius decreases.

Temperature Structure of Accretion disk Longair14.3.5

- Energy released by an element of mass in going from r+dr to r

Gravitational potential energy is

E_p =-GMm/2r so energy released is

E_g =-GMmdr/r^2.

the luminosity of this annulus, for an accretion rate $\mathscr{M}$, is

dL ~ GM$\mathscr{M}$ dr/r^2.

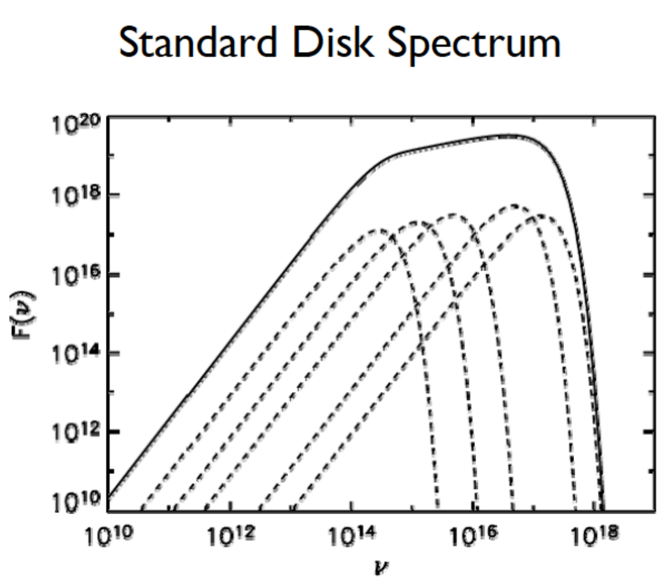
assuming the annulus radiates its energy as a blackbody

For a

- blackbody, L = σAT^4. The area of the annulus is $2\pi r dr$, and since
- L=M$\mathscr{M}$ dr/r^2 we have
- T^4 ~M$\mathscr{M}r^{-3}$, or
- **$T \sim (M\mathscr{M}/r^3)^{1/4;}$ e.g. $T \sim r^{-3/4}$; $T \sim \mathscr{M}^{1/4}$**
- .

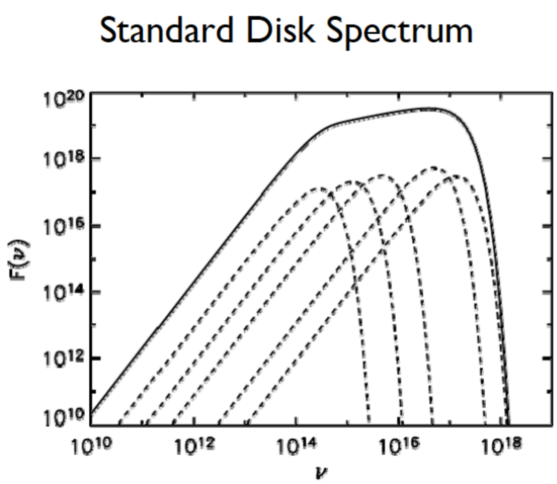
Total Spectrum- see Longair eqs 14.54-14.57

- If each annulus radiates like a black body and the temperature scales as $T \sim r^{-3/4}$
- The emissivity scales over a wide range of energies as $I(\nu) \sim \nu^{1/3}$



Total Spectrum- see Longair eqs 14.54-14.57

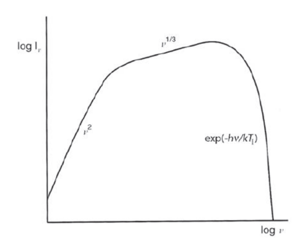
At lower frequencies the spectrum has a Raleigh-Jeans ν^2 shape and at higher energies has a exponential cutoff corresponding to the maximum temperature ($e^{-h\nu/kT_{inner}}$)



- Thus the spectrum from a disc is a sum of blackbody components, with increasing temperature and luminosity emitted from a decreasing area as the radius decreases.

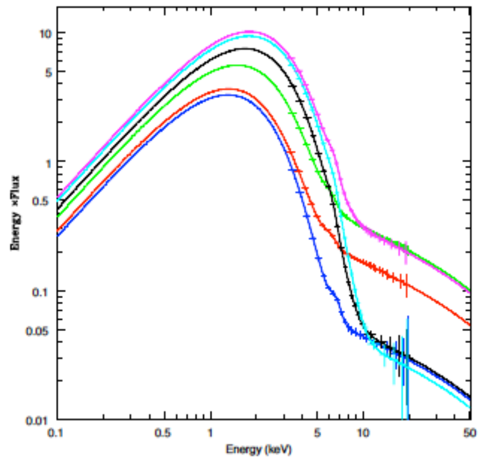
Total Spectrum

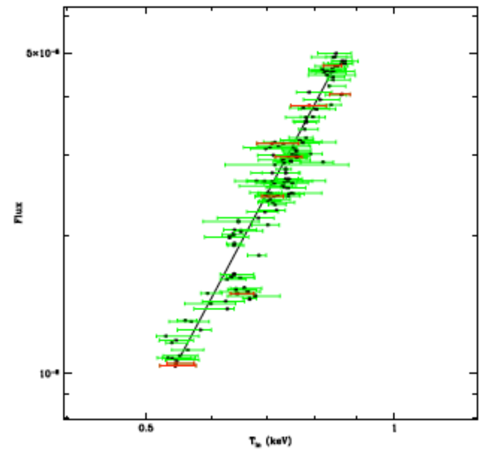
- . If the disk 'cuts off' at some radius r_{inner} then the temperature profile is
- $T(r) = 3GM\dot{M}/8\pi\sigma r^3[1 - (r_{inner}/r)^{1/2}]^{1/4}$ *eq 14.7.1*



- The exponential cut-off at high energies occurs at frequency $\nu = kT_l/h$,
- where T_l is the temperature of the innermost layers of the thin accretion disc.
- At lower frequencies the spectrum tends towards a Rayleigh–Jeans spectrum $I \propto \nu^2$

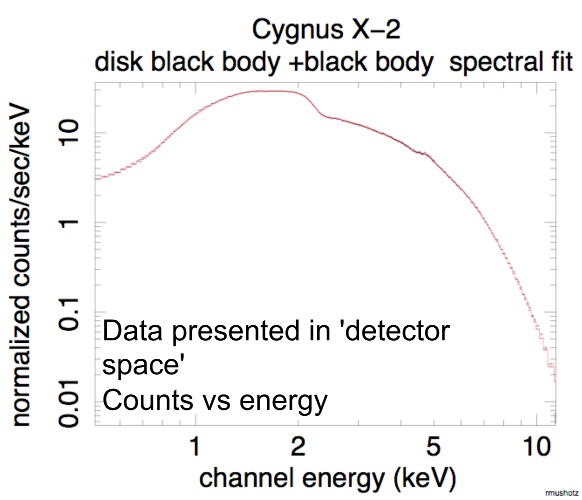
Do They Really Look Like That

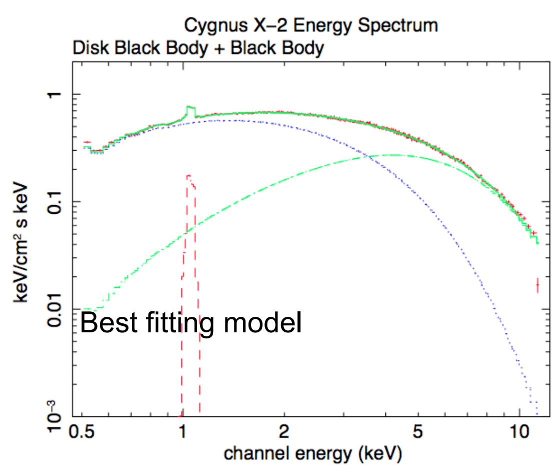




- X-ray spectrum of accreting Neutron star at various intensity levels
- Right panel is $T(r_{in})$ vs flux - follows the T^4 law

Fit to Real Data





The data is of very high signal to noise
Simple spectral form fits well over a factor of 20 in energy
Emitted energy peaks over broad range from 2-6 kev

Actual Neutron Star X-ray Spectra

- Low Mass x-ray binaries (NS with a 'weak' magnetic field) have a 2 component spectrum
  - The low energy component is well described by a multi-color disk black body spectrum
  - And the hotter temperuture black body is related to the boundary layer
    - However the observed temperatures disagree with simple theory due to three effects
      - General relativity
      - The 'non-black body' nature of the radiation
      - Reprocessing of the radiation of the central regions by the outer regions and then re-emission