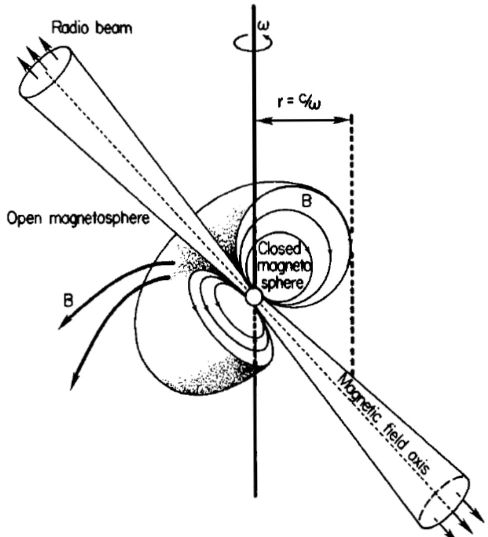
Isolated Neutron Stars Longair 13.5.1

- Most isolated neutron stars that are known are radio and γ-ray pulsars -
- These are rapidly spinning neutron stars that emit relativistic particles that radiate in a strong magnetic field
- The pulses originate from beams of radio emission emitted along the magnetic axis-the pulsar loses energy by electromagnetic radiation which is extracted from the rotational energy of the neutron star.
- In order to produce pulsed radiation from the magnetic poles, the magnetic dipole must be oriented at an angle with respect to the rotation axis and then the magnetic dipole displays a varying dipole moment
- Energy loss goes as Ω^4B^2
- As they radiate the star spins down- visible for ~10^7 yrs



Taylor 1991Proc. IEEE, 79, 1054

http://www.jb.man.ac.uk/~pulsar/Education/Tutorial/tut/tut.html

- The shortest period (or angular velocity Ω) which a star of mass M and radius R can have without being torn apart by centrifugal forces is (approximately)
- $\Omega^2 R \sim GM/R^2$
- Putting in the average density of the star ρ,
- $\Omega \sim (G\rho)^{1/2}$

- Putting in some numbers rotation periods of $P=2\pi/\Omega \sim 1$ sec requires density of $10^8 \mathrm{gm/cm}^3$

- To 'radiate' away the rotational energy $E_{rot} = 1/2\ I\Omega^2 \sim 2\mathrm{x}10^{46} I_{45} P^{-2}$ ergs
- Takes $\tau_{loss} \sim E_{rot}/L \sim 60 I_{45}\, P^{-2}\, L_{37}^{-1}$ yr ($I=2/5MR^2$)
  - Where the moment of inertia I is in units of 10^{45} gmcm^2

- If the star is spinning down at a rate $d\Omega/dt$ its rotational energy is changing at a rate $E_{rot} \sim I\Omega(d\Omega/dt) + 1/2(dI/dt)\Omega^2 \sim 4\mathrm{x}10^{32} I_{45} P^{-3} dP/dt$ ergs/sec

- However only a tiny fraction of the spindown energy goes into radio pulses- a major recent discovery is that most of it goes into particles and γ-rays.

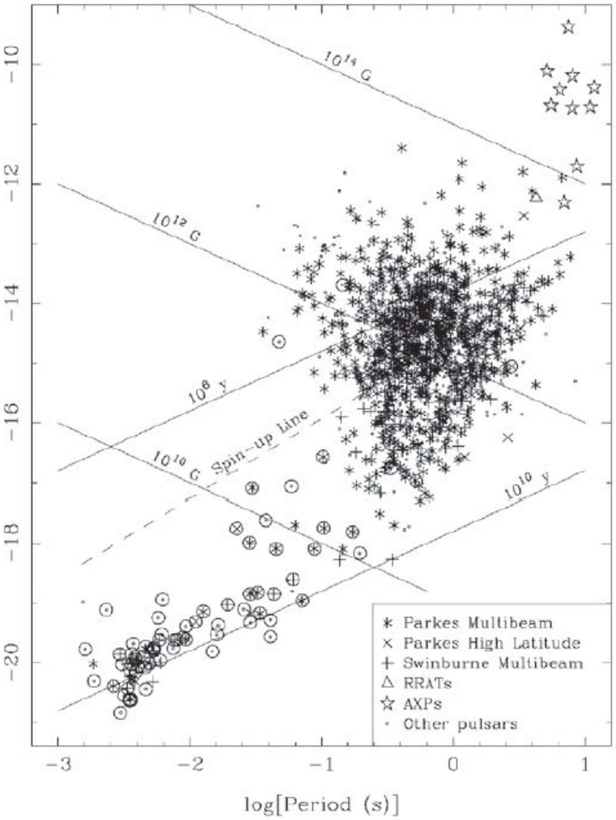
Radiation Mechanism

$-\mathrm{d}E/\mathrm{d}t \sim \Omega^4 p^2_{m0}/6\pi c^3$ .eq 13.33

Where p is the magnetic moment

- This magnetic dipole radiation extracts rotational energy from the neutron star.
- If I is the moment of inertia of the neutron star,
- $-\mathrm{d}/\mathrm{dt}[I\mathrm{X}^2]=I\Omega \mathrm{d}\Omega/\mathrm{dt}= \Omega^4 p^2_{m0}/6\pi c^3$ and so $\mathrm{d}\Omega/\mathrm{d}t \propto \Omega^3$
- The age of the pulsar can be estimated if it is assumed that its deceleration can be described by a a law $\mathrm{d}\Omega/\mathrm{d}t \propto \Omega^n$ if n throughout its lifetime
- It is conventional to set $n = 3$ to derive the age of pulsars
- and so $\tau = P/(2\,\mathrm{d}P/\mathrm{d}t)$.
- Using this relation the typical lifetime for normal pulsars is about 10^5–10^8 years.

- Where radio pulsars lie in the P,dP/dt plot.
  - the lines correspond to constant magnetic field and constant age.
- If magnetic braking mechanism slows-down of the neutron star then (see eqs 13.40-13.42)
- $B_s \approx 3\times 10^{15}(P\mathrm{d}P/\mathrm{d}t)^{1/2}$ T .



Magnetars

Their defining properties occasional huge outbursts of X-rays and soft-gamma rays, as well as luminosities in quiescence that are generally orders of magnitude greater than their spin-down luminosities.

- Their are two classes:two classes, the ‘anomalous X-ray pulsars’ (AXPs) and the ‘soft gamma repeaters’ (SGRs)

Magnetars are thought to be young, isolated neutron stars powered ultimately by the decay of a very large magnetic field.

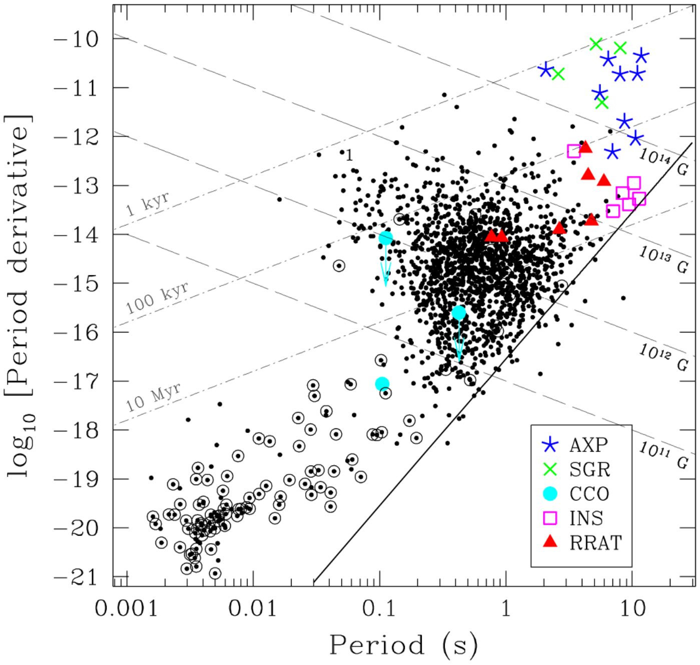
Their intense magnetic field [25, 26], inferred via spin-down to be in the range 10^{14}-10^{15}G ‘quantum critical field’ $B_{QED} \equiv m^2_e c^3/he=$ 4.4×10^{13}G.

In their most luminous outburst magnetars can briefly out-shine all other cosmic soft-gamma-ray sources combined

[Kaspi 2010]

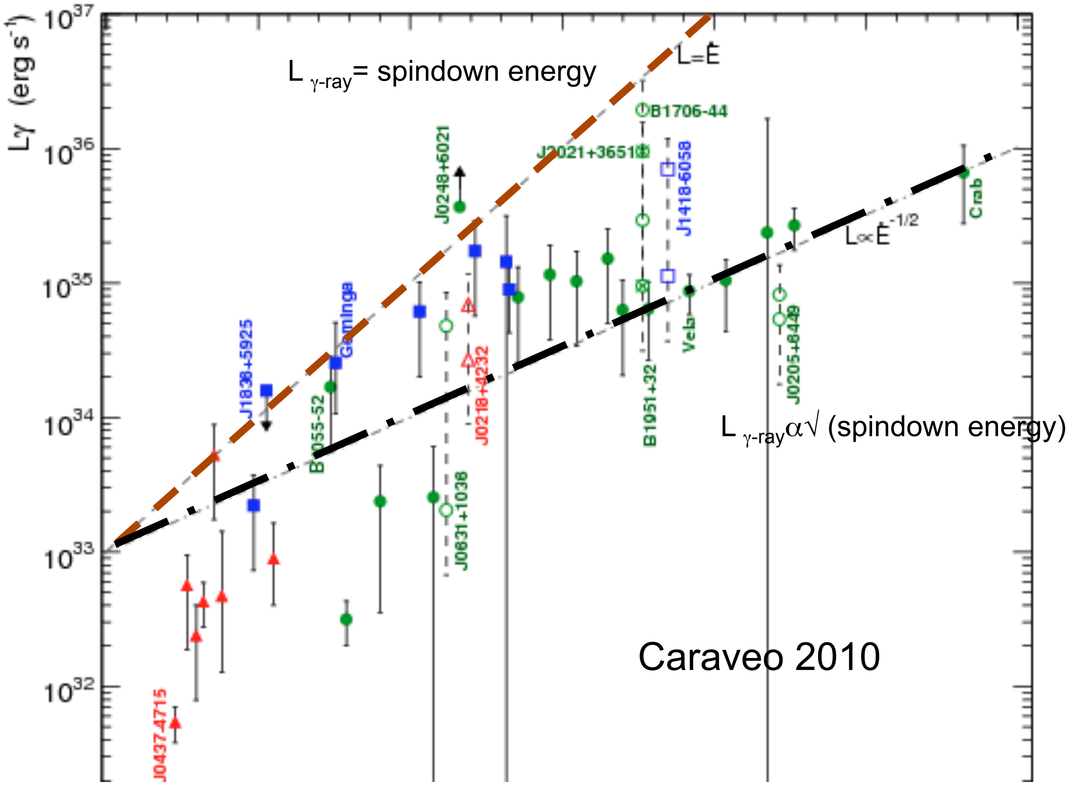
- The growing diversity of NSs includes the Xray-Dim Isolated NSs (XDINSs), Central Compact Object (CCOs) Rotating Radio Transients (RRATs),AXPS and Magnetars, milli-seconds pulsars
- ‘Millisecond pulsars’ are rotation- powered, but have different evolutionary histories, involving long-lived binary systems and a ‘recycling accretion episode which spun-up the neutron star and quenched its magnetic field

Longair 13.5.3-13.5.5



Open circles are in binaries

Comparison of Spin Down Energy and γ-ray Luminosity of Pulsars



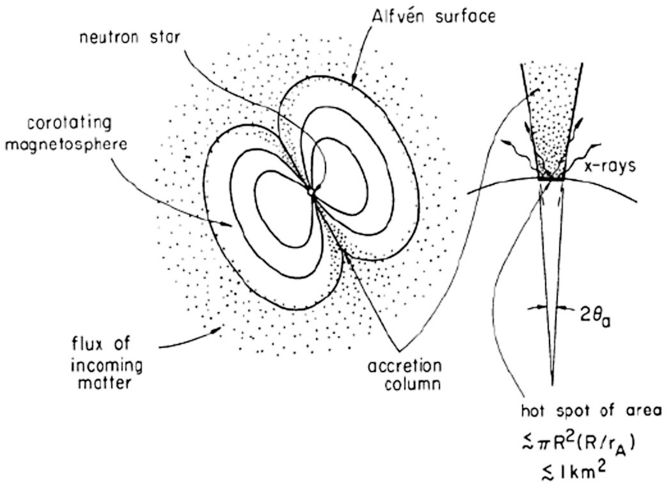
$L_{\gamma\text{-ray}}$ = spindown energy

$L_{\gamma\text{-ray}} \alpha \sqrt{}$ (spindown energy)

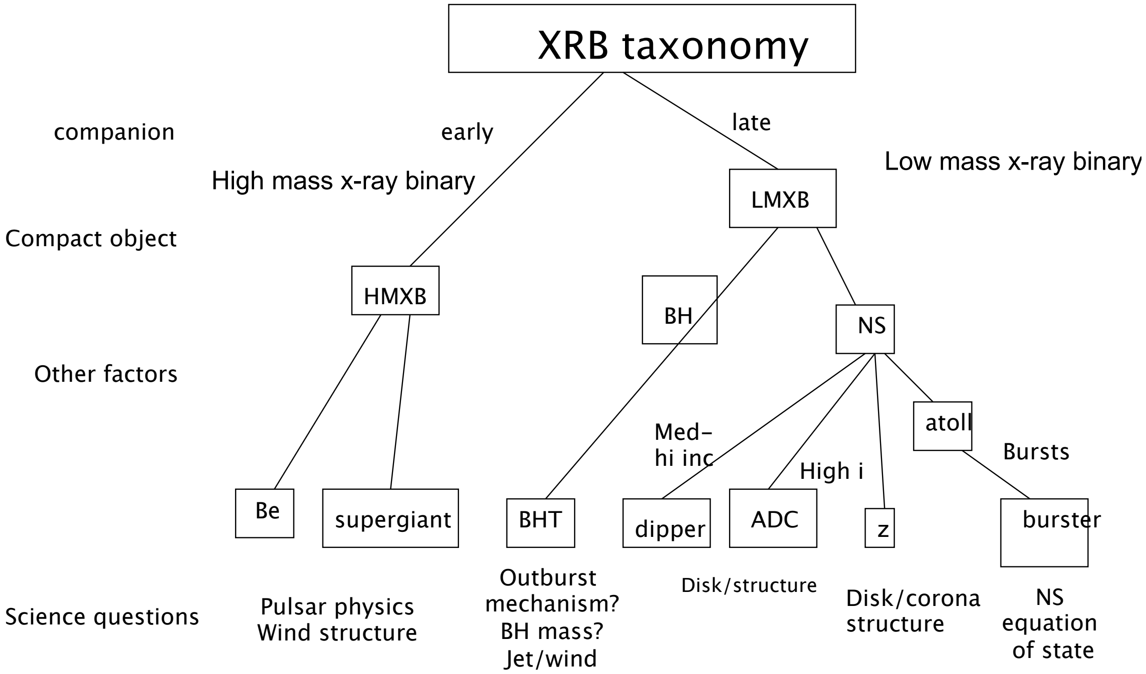
Caraveo 2010

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



A Short Introduction to terminology


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

Bursts

High i

Be

supergiant

BHT

dipper

ADC

z

burster

Science questions

Pulsar physics
Wind structure

Outburst
mechanism?
BH mass?
Jet/wind

Disk/structure

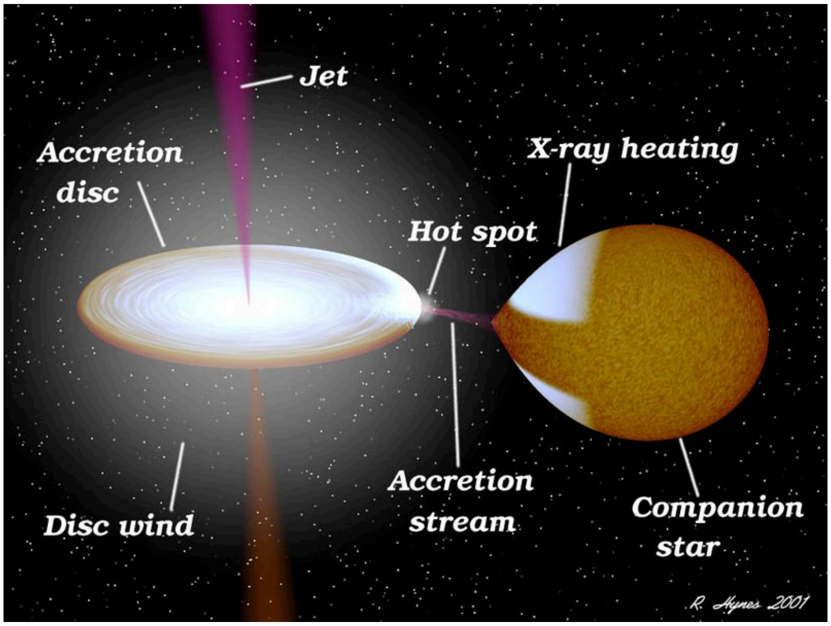
Disk/corona
structure

NS
equation
of state

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



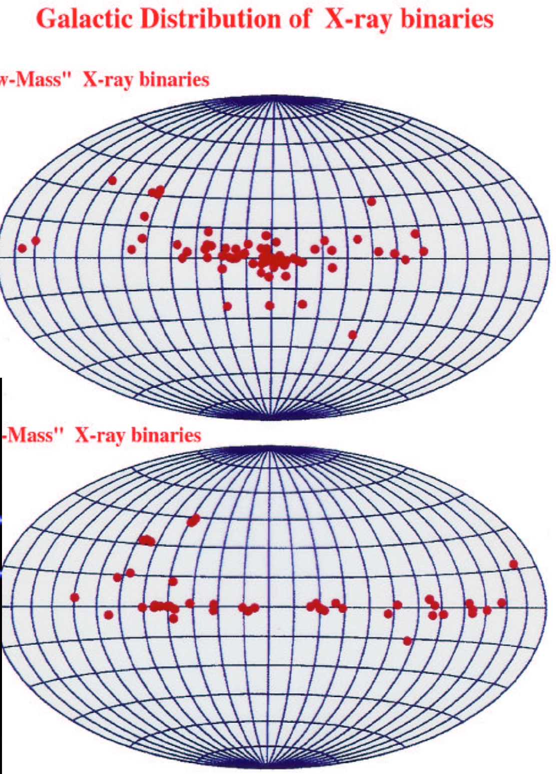
Accreting Neutron Stars

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

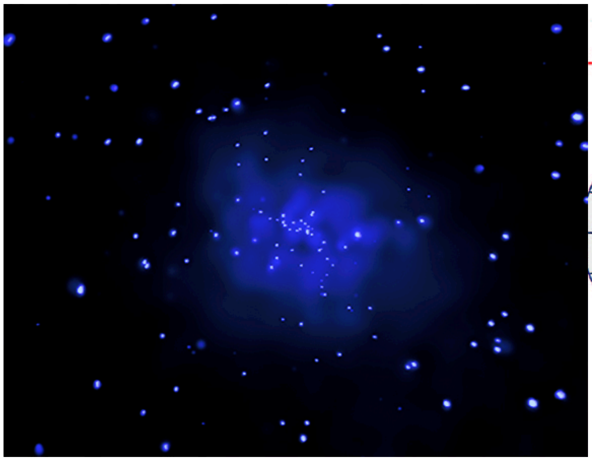
	HMXB	LMXB
Donor star	O-B ($M>5M_{sun}$)	K-M ($M<1M_{sun}$)
Age/Population	10^7 yrs I	5-15x10^9 II
L_x/L_{opt}	0.001-10	10-1000
X-ray Spectrum	flat power law	kT<10keV,b remms-like
Orbital period	1-100d	10min-10d
X-ray eclipses	common	rare
Magnetic field	strong (~10^{12}G)	weaker (10^7-10^8 G)
X-ray pulsations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

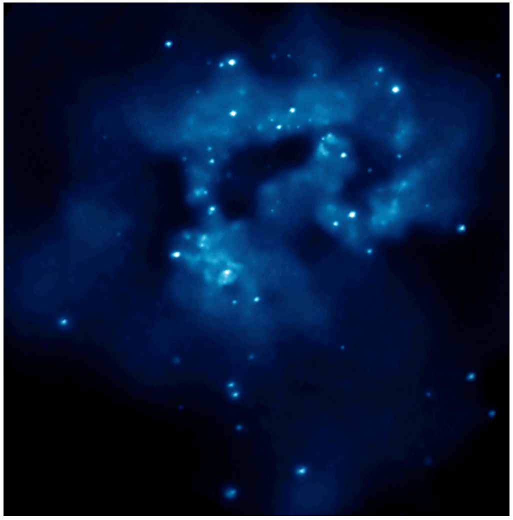


- X-ray binaries are concentrated in tl galactic plane and in the two nearby satellite galaxies of the Milky Way (the Magellanic clouds)
- Chandra images of XRB in nearby galaxies (core of M31 below)



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



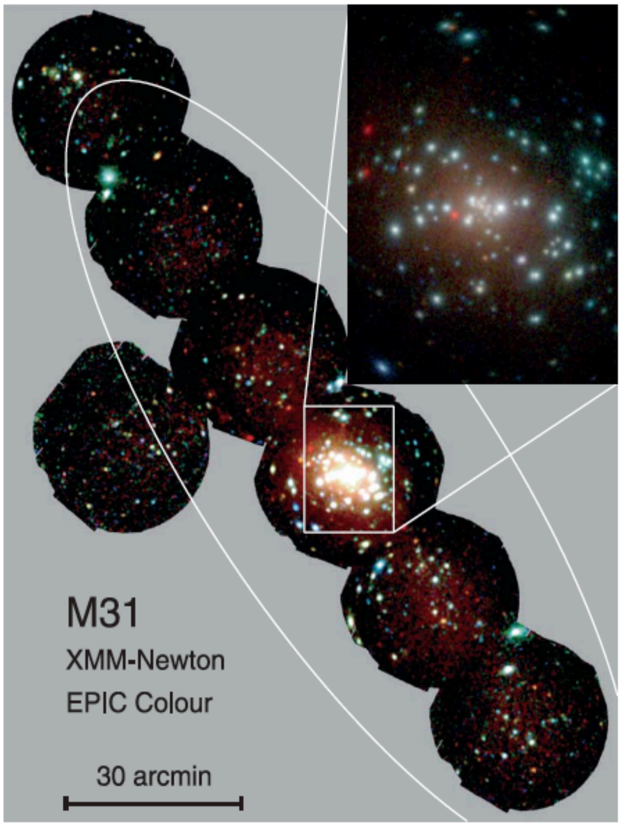
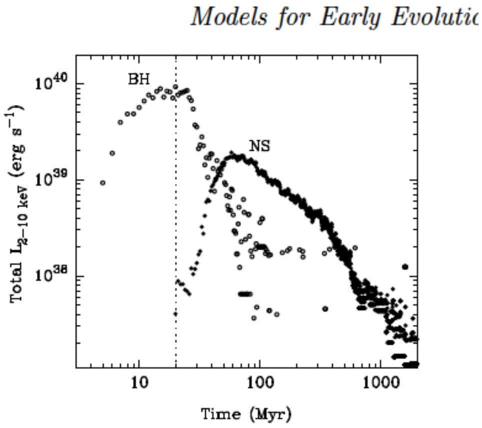
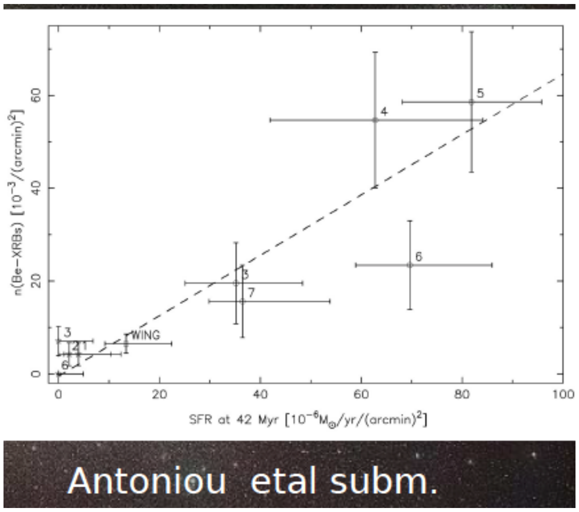


Fig. 1 (online colour at: www.an-journal.org) Logarithmically-scaled, three-color XMM-

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





Antoniou etal subm.

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

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) - if this energy is released as radiation it also is the luminosity L_{acc}

- Normalizing the observed luminosity to a typical value of $1.3\text{x}10^{37}$ erg/sec gives accretion rates of
- $L_{acc}=1.3\text{x}10^{37}\mathcal{M}_{17}m_xR_6$

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

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

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)
Or
$L\sigma_T/4\pi r^2 m_p c$ (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
$L_{Edd}=4\pi M_x G m_p c/\sigma_T = 1.3\text{x}10^{38} M_{sun}$erg/sec

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

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 theincident flux density of photons N_{ph}.
- Thus, $f_{rad} = \sigma_T N_{ph}\, p$ *(p is momentum,* σ_T is the relevant cross section , the smallest is the Thompson cross section 6.6×10^{-29} m^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 $f = \sigma_T L/4\pi c r^2$.
- Equation this to gravity (e.g. radiation pressure and gravity balance)

Gives **$L_E = 4\pi GMm_p c/\sigma_T$**

- 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})
- $T \sim 2\times10^7$K ; 'natural' for NS to radiate in the x-ray band.

Accretion -Basic idea

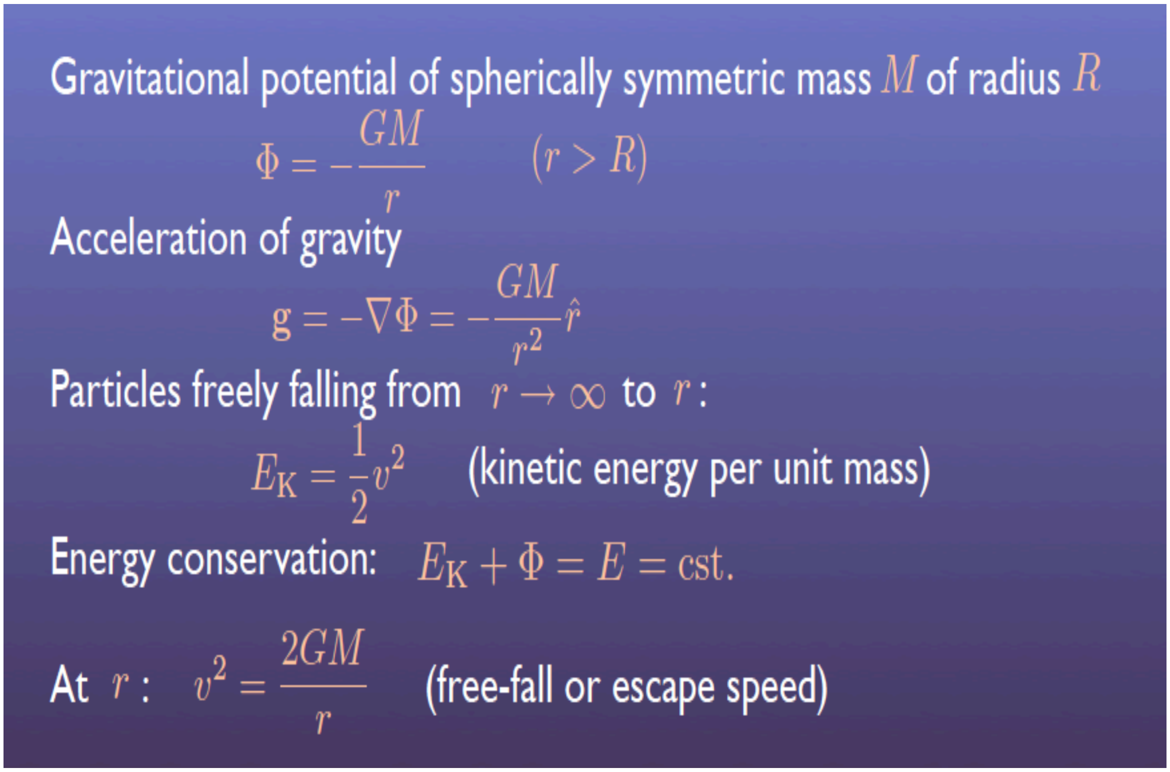
- Viscosity/friction moves angular momentum outward
  - allowing matter to spiral inward
  - Accreting onto the compact object at center

gravitational potential energy is converted by *friction* to heat Some fraction is radiated as light

Very efficient process Energy ~GM/R=1.7x10^{16} (R/10km) $^{-1}$ J/kg ~1/2mc^2

Nuclear burning releases ~7x10^{14}J/kg (0.4% of mc^2)

- $L = 1/2\dot{m}\, c^2\, (rg/R)$ (14.3)
- This expression for the luminosity can be written $L = \xi \dot{m}\, c^2$, 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 $R \approx 5 \times 10^6$ m, $\xi \approx 3 \times 10^{-4}$.
- For a neutron star with mass $M = M_\odot$ and R = 10 km, $\xi \sim 0.15$.
- In the case of nuclear energy generation, the greatest release of nuclear binding energy occurs in the conversion of hydrogen into helium for which $\xi \approx 7 \times 10^{-3}$.
- Thus, accretion onto neutron stars is an order of magnitude more efficient as an energy source than nuclear energy generation.



Gravitational potential of spherically symmetric mass M of radius R

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

Acceleration of gravity

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

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

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

Energy conservation: $E_K + \Phi = E = \text{cst.}$

At r: $v^2 = \dfrac{2GM}{r}$ (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)

The Known Galactic Black holes

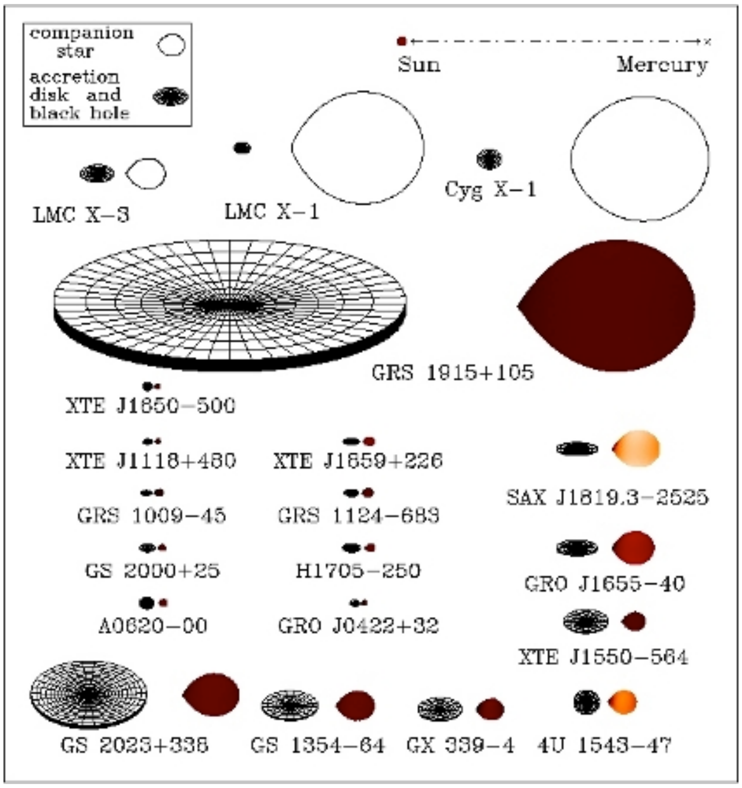
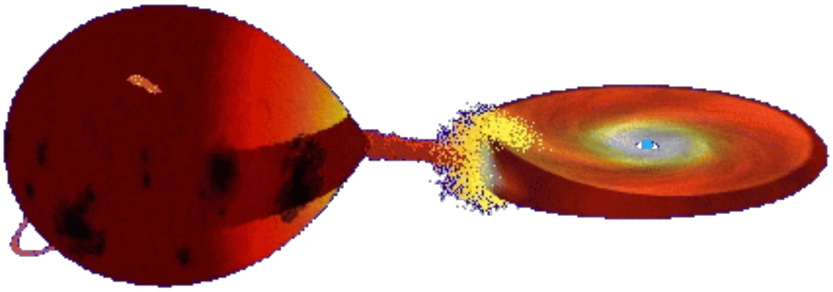


Figure by Jerome Arthur Orosz

Accretion from a Dwarf Companion



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