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 $\Omega^4 B^2$
- As they radiate the star spins down - visible for $\sim 10^7$ yrs


- The shortest period (or angular velocity $\Omega$) 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 $\rho$,
- $\Omega \sim (G\rho)^{1/2}$

- Putting in some numbers rotation periods of $P=2\pi/\Omega \sim 1$ sec requires density of $10^8$ gm/cm$^3$
- To 'radiate' away the rotational energy $E_{rot} = 1/2 I\Omega^2 \sim 2\times 10^{46} I_{45} P^{-2}$ ergs
- Takes $\tau_{loss} \sim E_{rot}/L \sim 60 I_{45} P^{-2} L_{-7} \sim 1$ yr ($I=2/5MR^2$)
  - Where the moment of inertia $I$ is in units of $10^{45}$ gm cm$^2$

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

\[ -\frac{dE}{dt} \sim \Omega^4 \frac{p^2_{\text{m0}}}{6\pi c^3}. \text{eq 13.33} \]

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,
- \( \frac{d}{dt}[I\dot{X}^2] = I\dot{\Omega}\dot{\Omega}/dt = \Omega^4 \frac{p^2_{\text{m0}}}{6\pi c^3} \) and so \( \frac{d\Omega}{dt} \propto \Omega^3 \)
- The age of the pulsar can be estimated if it is assumed that its deceleration can be described by a law \( \frac{d\Omega}{dt} \propto \Omega^n \) if \( n \) throughout its lifetime
- It is conventional to set \( n = 3 \) to derive the age of pulsars
- and so \( \tau = P/(2 \frac{dP}{dt}) \).
- Using this relation the typical lifetime for normal pulsars is about \( 10^5 - 10^8 \) years.

- Where radio pulsars lie in the \( P,\frac{dP}{dt} \) 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)
- \( B_s \approx 3 \times 10^{15}(P\frac{dP}{dt})^{1/2} \text{T} \).
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’ $B_{\text{QED}}=m^2_e c^3/\hbar e=4.4\times10^{13}$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 $\gamma$-ray Luminosity of Pulsars

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

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

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' (~10^9-10^10 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

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

(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)
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

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

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 \( \frac{dM}{dt} = \dot{M} \) then the potential energy gained by the material is

\[
E = G \frac{M_x}{R} \quad \text{where} \quad M_x \text{ is the mass of the accreting object) - if this energy is released as radiation it also is the luminosity } L_{\text{acc}}
\]

• Normalizing the observed luminosity to a typical value of \( 1.3 \times 10^{37} \text{ erg/sec} \) gives accretion rates of

\[
L_{\text{acc}} = 1.3 \times 10^{37} \dot{M}_{17} m_x R_6
\]

• \( \dot{M}_{17} \) is \( \dot{M} \) in units of \( 10^{17} \text{ gm/sec}= 1.5 \times 10^{-9} M_{\text{sun}}/\text{yr} \)
• \( R_6 \) is the radius in units of \( 10^6 \text{ cm} \)
• \( m_x \) is the mass in solar units

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

\[
(\text{Flux}/c)\sigma \quad (\sigma \text{ is the relevant cross section})
\]

Or

\[
L \sigma_T / 4 \pi r^2 m_p c \quad (\sigma_T \text{ is the Thompson cross section } (6.6 \times 10^{-25} \text{ cm}^2) \text{ } m_p \text{ is the mass of the proton})
\]

The gravitational force on the proton is

\[
GM_x / R^2
\]

Equating the two gives the Eddington limit

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

Frank, King & Raine, “Accretion Power in Astrophysics”,
Eddington Limit- More Detail Longair pg 446

- $f_{\text{grav}} \approx \frac{G M m_p}{r^2}$ 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 $N_{\text{ph}}$.
- Thus, $f_{\text{rad}} = \sigma_T N_{\text{ph}} p$ ($p$ is momentum, $\sigma_T$ is the relevant cross section, the smallest is the Thompson cross section $6.6 \times 10^{-29} \text{ m}^2$)
- As we go away from the source of photons the flux of photons is
  - $N_{\text{ph}}/4 \pi r^2$; $N_{\text{ph}} = L/h \nu$; $L$ 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 $L_E = 4 \pi G M m_p c / \sigma_T$

  - 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?
  - $4 \pi r^2_{\text{NS}} \sigma T^4 = L_{\text{edd}}$

  - So put in $10 \text{ km}$ for $r_{\text{ns}}$ and $1.3 \times 10^{31} \text{ W}$ for $L_{\text{edd}}$ for 1 solar mass and get
    - $(a=5.67 \times 10^{-8} \text{ Wm}^{-2} \text{ K}^{-4})$
  - $T \sim 2 \times 10^7 \text{ K}$; '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 \( \sim \frac{GM}{R} = 1.7 \times 10^{16} \text{ (R/10km)}^{-1} \text{ J/kg} \sim 1/2mc^2 \)

Nuclear burning releases \( \sim 7 \times 10^{14} \text{ J/kg} \) (0.4% of \( mc^2 \))

- \( L = 1/2m \cdot c^2 (rg/R) \) (14.3)
- This expression for the luminosity can be written \( L = \xi m \cdot c^2 \), where \( \xi \) is the efficiency of conversion of the rest-mass energy of the accreted matter into heat.
- the efficiency is roughly \( \xi = (rg/2R) \) and so depends upon how compact the star is. For a white dwarf star with \( M = M_\odot \) and \( R = 5 \times 10^6 \text{ m} \), \( \xi = 3 \times 10^{-4} \).
- For a neutron star with mass \( M = M_\odot \) and \( R = 10 \text{ km} \), \( \xi \approx 0.15 \).
- 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 \( R \)

\[ \Phi = -\frac{GM}{r} \quad (r > R) \]

Acceleration of gravity

\[ g = -\nabla \Phi = -\frac{GM}{r^2} \hat{r} \]

Particles freely falling from \( r \to \infty \) to \( r \):

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

Energy conservation:

\[ E_K + \Phi = E = \text{cst.} \]

At \( r \):

\[ v^2 = \frac{2GM}{r} = (\text{free-fall or escape speed}) \]

Viral temperature \( T_{\text{vir}} = \frac{GM}{kr} \); for a NS \( M \sim 1.4M_{\odot} \), \( R \sim 10 \text{ km} \)

\[ T \sim 10^{12} \text{k} \]

(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