Neutron Stars

- **Goals:**
  - What becomes of stars after they undergo a supernova
  - How do we detect neutron stars
  - How are they laboratories for General Relativity
- **After the Supernova**
  - The collapse of the core
    - The pressure generated by the collapse forces most of the e^- and p^+ to combine into neutrons.
    - This forms a degenerate gas (as with white dwarfs) that can support the neutron star.
    - Like the Chandrasekhar limit their is a mass limit on the neutron star (~$3M_\odot$).
    - End with a rapidly rotating core of neutrons with a density $4x10^{17}$ kg m^{-3} (the Earth would be 250 m across).
    - Size of the collapsed core is about 20 km.

• Conservation of angular momentum

– Angular momentum

- Angular momentum is defined as,

$$L = \sum m_i \ v_i \ r_i$$

- L:angular momentum
  m_i: mass of part i of an object
  r_i: radius of mass i
  v_i:velocity of mass i

– Conservation

- Angular momentum is conserved in the same way that momentum is conserved (Newtons first law).
- As the radius of an object (star) decreases the velocity must increase to conserve L.
- Assume the Sun (R=7x10^5 km) collapsed to the size of a neutron star (R=20 km). Velocity increases by 35000x.
- Velocity at surface of sun ($v_{surface}$)

$$V_{surface} = \frac{2\pi \, r}{P}$$

- P: period of rotation (3x10^6 s)
  R: radius of Sun (7x10^5 km)
- $V_{surface}$(Neutron star) = 51x10^6 m s^{-1}.
- P(Neutron star) = 2.4x10^{-3}s

• Density of Neutron Stars

– Rotational velocity

- For a star to remain intact the centripedal acceleration < gravitational acceleration.

$$\frac{V^2}{R} = \frac{GM}{R^2}$$

V:velocity of the star at the equator
R:radius of the star
M: mass of the star

- Maximal velocity is then

$$V = \sqrt{\frac{GM}{R}}$$

– Period of a neutron star

- For a period (P) of 2ms what is the density of the star

$$P = \frac{2\pi R}{V}$$

- Period is related to mass by

$$P = \frac{2\pi R^{3/2}}{(GM)^{1/2}}$$

- Substituting for density

$$P = \frac{3.8x10^5}{\rho^{1/2}}$$

- For P=0.002s: $\rho=4x10^{16}$ kg m^{-3}

- **Observing Neutron Stars**
  - **Discovery 1967 (Hewish and Bell)**

    Figure 23-1

    - **First radio surveys discovered variable radio stars (period of 1.337s)**
    - **Period too rapid for normal variable stars or eclipsing binaries (requires orbits of < 1000 km).**
    - **Named pulsars due to regular pulsations.**
    - **Predicted in 1930s by Zwicky and Baade.**
  - **Rotating Neutron Stars**

    Figure 23-3

    - **Pulsars are rapidly rotating (milliseconds to seconds) and extremely compact and dense.**
    - **The magnetic fields present in the Sun are conserved (increasing in strength by a factor of 10^{10}).**
    - **Field ~10^{12} Gauss (bar magnet 100 Gauss).**
    - **Model that describes the neutron star is the rotating lighthouse.**
    - **Magnetic pole and pole of rotation are not coincident. Magnetic pole rotates.**
    - **Neutron star acts like a giant generator creating strong electric fields.**

– Rotating Neutron star

Figure 23-4

- **Electric field pulls charged particles off the Fe crust of the neutron star.**
- **These are accelerated by the magnetic field and emitted in a tight beam.**
- **Accelerated electrons emit synchrotron radiation.**
- **If the beam intercepts with our line of sight we see a pulse of radiation (hence pulsars).**
- **Time between pulses is the rotation period (like a lighthouse).**
- **The emission of the electrons removes energy and angular momentum (the pulsar slowly slows down).**
- **Synchrotron radiation is emitted in the radio - we also see pulses in the X-ray and optical.**
- **The most well known pulsar is in the Crab nebula (period of 0.033s).**
- **Believed to form from Type II supernovae.**
- **Total energy output of the Crab Nebula is 3×10^{31} W.**

– Spin down of Pulsars

- **Crab pulsar outputs 3×10^{31} W of energy into the surrounding nebula.**
- **This energy loss slows the pulsar (period of typical pulsar increases 3×10^{-8} s yr^{-1}).**
- **Slow down can be used to <u>estimate</u> the age of a pulsar.**

$$t \approx \frac{P}{dP/dt}$$

- **t:age of pulsar**
  P:period of pulsar
  dP/dt: rate of change of period
- **For the crab nebula its spin down rate is about 1.2×10^{-13} s per s**

$$t \approx \frac{0.033}{1.2\times10^{-13}}$$
$$\approx 10^{11}\,\mathrm{s} \quad (10^{4}\ \mathrm{yrs})$$

- **Old pulsars spin slower than young pulsars.**
- **Neutron stars slow down faster when they are young.**

- **Interior of a Neutron Star**
  - **Superfluidity and superconductivity**

Figure 23-10

- **Core of the neutron star contains neutrons, protons and electrons.**
- **Surrounded by a crust of metals (e.g. iron).**
- **Protons and electrons anchor the magnetic field of the pulsar.**
- **Neutrons, protons move without friction (superfluidity) of electrical resistance (superconductivity).**
- **Core rotates freely as the crust slows down. The faster rotating core can deliver sharp jolts (glitches) to the crust speeding up the neutron star.**

- **Fastest Pulsars and Mass Transfer**
  - **Millisecond pulsars**
    - **In 1982 pulsars with 1ms periods were discovered (PSR 1937+21).**
    - **Pulsar should be extremely young and slowing rapidly but its period increases 10^{-6}x slower than the Crab pulsar.**
    - **Fastest pulsars are usually in close in binary systems.**
    - **If a pulsar is formed in a binary system and the second star becomes a red giant its atmosphere expands and fills its Roche lobe. Mass can then be transferred to the neutron star.**
    - **Adding mass adds angular momentum and the neutron star gets spun up.**
    - **Adding H and He to a neutron can lead to further rounds of nuclear burning and releases of >10^{37} J of energy.**

- **Mass Transfer**
  - **Equipotential Surfaces**

    Figure 21-16

    - **Gravitational potential energy declines as 1/r from the center of a star.**
    - **We can draw lines of constant potential energy (equipotential) around a star (circles orbits around an isolated star).**
    - **If we consider 2 stars in a binary system we can draw the combined equipotentials. One of these potentials forms the shape of an hour glass shapes (∞).**
    - **For this potential (<u>Roche lobe</u>) the effective gravity of the two stars is zero (they cancel out).**
    - **The interior of the Roche lobe describes the region in which gas is gravitationally bound to a particular star.**
    - **The <u>Lagrangian point</u> is the point where the lines of equipotential touch (equal pull from either star). Mass can be easily transferred from one star to the next across this boundary point.**

– Pulsating X-ray sources and Novae

- The transfer of mass from a companion gets funneled to the magnetic poles.
- When it impacts the neutron star it is travelling at 0.5 speed of light and the energy released heats the polar regions to 10^8 K (X-rays released).
- Mass accretion onto the pulsar is about 10^{-9} $M_{\odot}$ yr^{-1}.
- Mass can also be slowly accreted onto the surface of the neutron star (or white dwarf) if its magnetic field is weak
- When it releases a critical density the H (and later He) can star burning. T
- Star can increases in luminosity by 10^4 - 10^8 over the period of a few days (declines over period of days-months).
- For a white dwarf the <u>H burning</u> produces a <u>nova</u>. For neutron stars the <u>He burning</u> causes an <u>X-ray burster</u> (repeating X-ray emission).

- **Special Relativity Paradoxes**
  - **Narcissistic Runner**
    - Imagine a runner (who runs close to the speed of light). He holds a mirror in front of him (at arms length). Will he be able to see himself in the mirror?
    - This problem was one of the things Einstein puzzled about as a child.
  - **Moving Train**
    - Three people (A,B,C) are on a train that is moving near the speed of light. A is at the front, B at the back and C in the middle. A fourth person (C’) is standing beside the rail track. At the instant C passes C’ they both receive two signals from flash lights that A and B are holding.
    - Who sent the signal first ?