Neutron Stars

- $M_{\text{core}} > 1.4 M_{\odot}$ - collapse past WD
  - nuclei packed tightly together
  - protons absorb electrons; only neutrons left
  - collapse halted by neutron degeneracy pressure

- How do you find something so small?

Neutron Stars

- Mass $\sim 2.0 M_{\odot}$
- Radius $\sim 0.00002 R_{\odot}$
- Temperature $\sim 5\times10^5$ K

$$\frac{L}{L_{\odot}} = \left( \frac{R}{R_{\odot}} \right)^2 \left( \frac{T}{T_{\odot}} \right)^4$$

so, $L/L_{\odot} \sim 0.001$ - nearly all in X-ray

SMALL, DIM, and RARE: (end product of O, B star evolution) means:
- closest is still pretty far away
- very unlikely to see in optical (or even X-ray)
- concentrated and extreme stars
why does the Crab Nebula shine?

The Crab Nebula (optical, Fick) remnant of SN in 1054 AD

Discovery of Neutron Stars - Pulsars (1967)

- 1966-67: Tommy Gold (and Franco Pacini)
  - why does the Crab nebula shine???
  - supernova leaves a rapidly rotating neutron star
  - neutron star has an intense magnetic field
  - light produced by motion of e⁻ in magnetic field
  - energy for light derived from NS rotation
  - spin rate should decrease with time

The Gold-Pacini “model”

- Concentrated ROTATION
  - Radius shrinks from ~ $R_{\text{sun}}$ to ~ $10^{-5} R_{\text{sun}}$
  - Spin rate increases as $1/R^2$, or by a factor of $10^{10}$
  - scaling from the Sun's rotation (1 month = $3\times10^6$ sec) gives a rotation rate for a neutron star of 0.3 milliseconds
  - lots of energy available from neutron star rotation

- Concentrated MAGNETISM
  - Magnetic field of Sun ~ 10 Gauss
  - Field strength increases as $1/R^2$, or by a factor of $10^{10}$
  - scaling from the Sun's magnetic field gives a field strength for a neutron star of $10^{11}$ Gauss
  - for comparison:
    - Earth magnetic field = 1/2 Gauss (compass needle)
    - Strongest permanent magnet ~ 14,000 Gauss
    - Strongest magnetic field produced ~ $4\times10^7$ Gauss

The Gold-Pacini “model”

- Rapid Rotation + Strong magnetic field = COSMIC GENERATOR / ACCELERATOR
  - central engine surrounded by ionized particles (electrons, protons, ions)
  - particles constrained to move along magnetic field lines
  - crash down onto NS poles, heating up the material
  - additional radiation via synchrotron radiation
**The Gold-Pacini “model”**

- New Neutron Stars MUST
  - rotate rapidly
  - have strong magnetic fields
  - pump out energy via synchrotron radiation
  - energy lost must come at expense of rotation, so
  - rotation must slow down with time
- Rotating neutron stars could (must?) be the energy source for glowing supernova remnants

**Discovery of Neutron Stars - Pulsars (1967)**

- **1967: S. Jocelyn Bell** discovers a radio signal:
  - regularly pulsing
  - rapid
    (once every 1.33 seconds)
  - extraterrestrial
  - aliens? LGM1, LGM2, ...
    - no. why not?
  - Neutron stars!

**1974 Nobel Prize to... Tony Hewish**
(Bell’s advisor ?!#@)

**Neutron Star spin-down**

- Rotational Energy E:
  - \[ E \sim \Omega^2 R^2 \]
  - \[ \frac{\Delta E}{\Delta t} \propto 2\Omega \frac{\Delta \Omega}{\Delta t} R^2 \]
  - lose energy (< 0)
  - spin down ( < 0)

  - energy loss rate from nebular (and pulsar) emission allows an estimate of the spin-down rate expected for pulsars
- Over time, spin rate drops, so energy available drops
- Pulsars should SLOW DOWN and FADE with time
- Magnetic field drops also (leaks out):
Pulsar Evolution
- magnetic field decay, spin down, dropping luminosity
- young pulsars are
  - fast
  - bright
  - fast spin-down rate
  - strong magnetic field
- old pulsars are
  - slow
  - dim
  - slow spin-down
  - weak(er) magnetic field
- the pulsar “death line”
  - no more e+e- production

Measuring Spin-Down
- time is the thing that we can measure most accurately
- measuring period change directly is very difficult
- but period change <=> accumulating delay in pulse arrival time
- i.e. slow clock by 1/10,000
  - beat-by-beat is the same to 0.1 millisecond BUT
  - in 1 day, clock is 8.6 seconds slow
  - in 1 week clock is 1 minute slow
  - growing effect when compared to reference signal
- ticks lengthen - will get out of sync with lousy clocks eventually!
- reference clock needed - pulsar is its own reference
- Pulsars are the BEST CLOCKS in the UNIVERSE

Pulsars - a new tool for astronomy and physics

- **Binary Pulsars:**
  precise tests of general relativity (1993 Nobel, Hulse & Taylor)
- **Pulsars with Planets**
  timing “jitter” -> planet-sized companions (Alex Wolsczan)
- **Millisecond Pulsars**
  - fast pulsar, small dP/dt
  - recycled pulsars spun-up by companion (Don Backer)
  - should have companion - most do, many do not!
- **“Black Widow” Pulsars**
  pulsar blasts away its companion (Dan Stinebring)

Gamma Ray Bursts
- short-duration, high energy flashes
  - 0.1 to 100 seconds
Gamma Ray Bursts
- short-duration, high energy flashes
- evenly distributed across the entire sky
- cosmological distances - intensely bright supernovae

2704 BATSE bursts

Gamma Ray Bursts
- short-duration, high energy flashes
- evenly distributed across the entire sky
- cosmological distances - hypernovae
  - rapid rotation -> accretion disk
  - relativistic jet collimated by accretion disk
  - beam points towards us, we see gamma ray burst