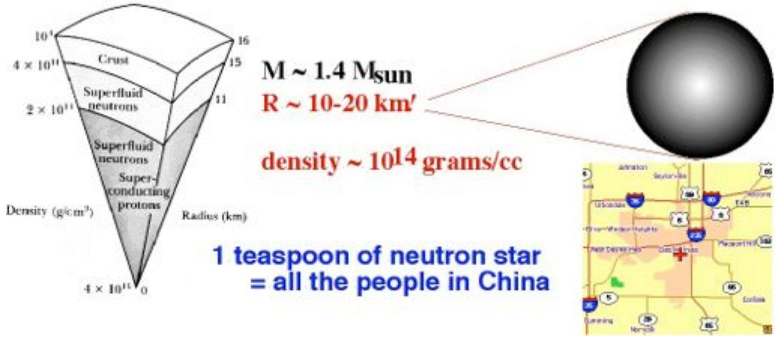
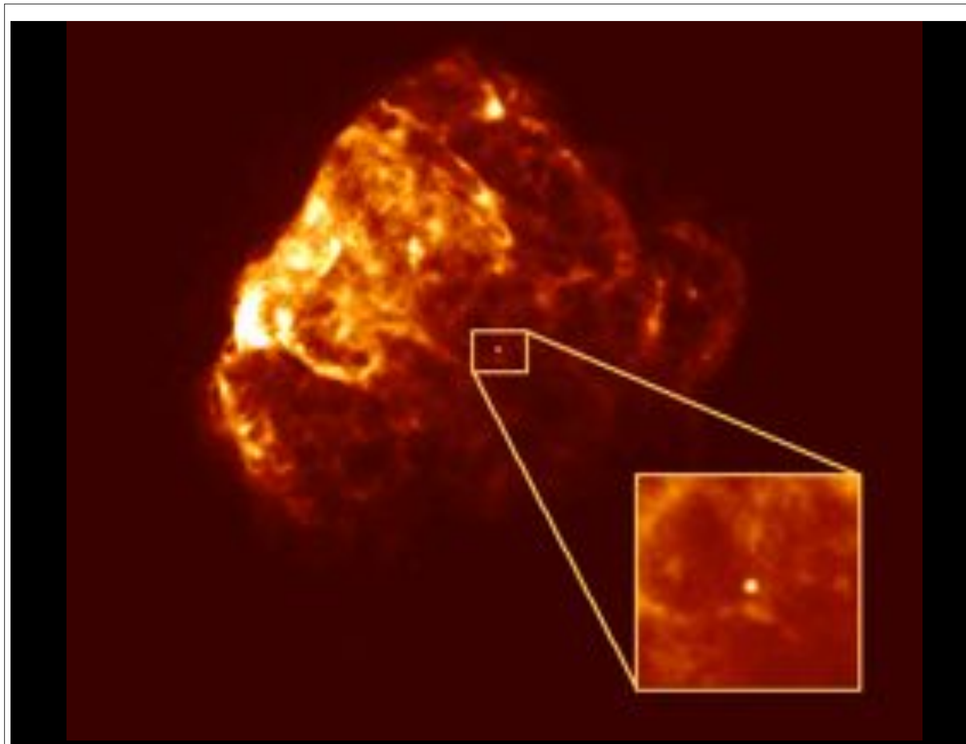
1

Neutron Stars

- $M_{core} > 1.4\ M_{sun}$ - 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?**



3

Neutron Stars

- Mass ~ 2.0 M_{sun}
- Radius ~ 0.00002 R_{sun}
- Temperature ~ 5×10^5 K

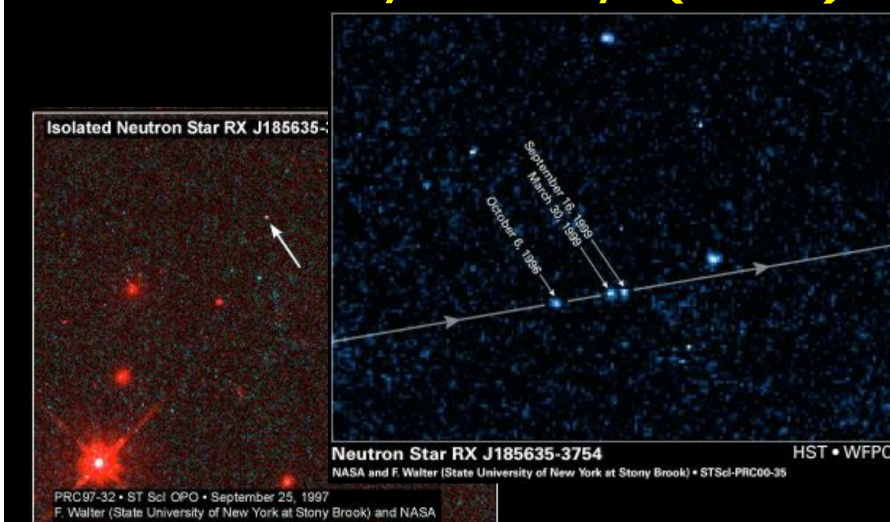
$$\frac{L}{L_{sun}} = \left(\frac{R}{R_{sun}}\right)^2 \left(\frac{T}{T_{sun}}\right)^4$$

so, L/L_{sun} ~ 0.001 - nearly all in X-ray

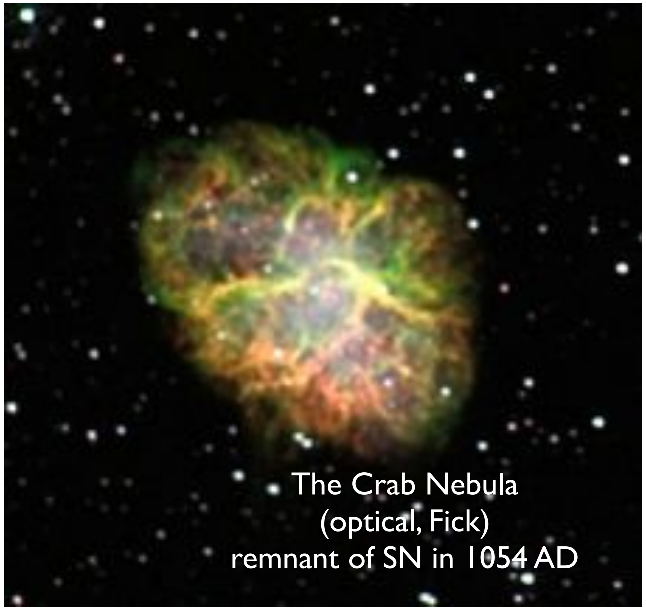
SMALL, DIM, and RARE: (end product of O, B star evolution) means:

- **closest is still pretty far away**
- **very unlikely to see in optical (or even X-ray)**
- **concentrated and extreme stars**

isolated neutron stars first "seen" only recently **(1997)**



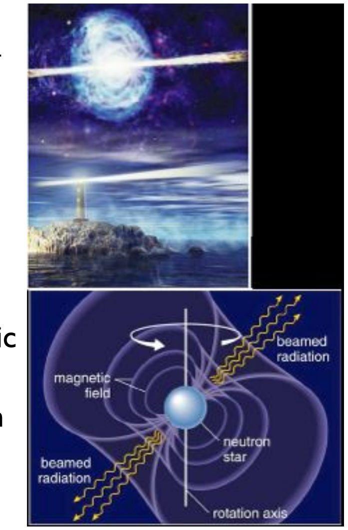
why does the Crab Nebula shine?



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

Discovery of Neutron Stars - Pulsars (1967)

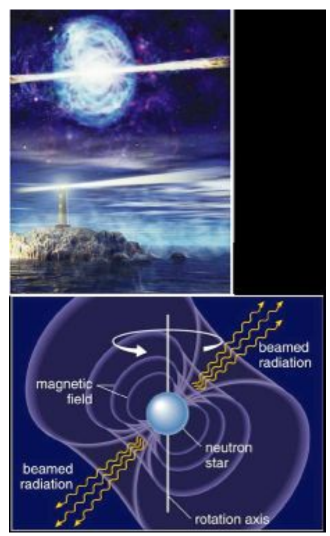
- **1966-67:** Tommy Gold (and Franco Pacini)
  - **why does the Crab nebula shine???**
  - supernova leaves a rapidly rotating **neutron star**
  - neutron star has an intense magnetic field
  - light produced by motion of e^- in magnetic field
  - energy for light derived from NS rotation
  - spin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



The Gold-Pacini "model"

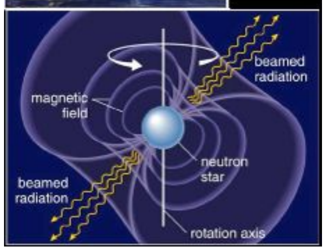
- **Concentrated ROTATION**
  - Radius shrinks from ~ R_{sun} to ~ 10^{-5} R_{sun}
  - Spin rate increases as $1/R^2$, or by a factor of 10^{10}
  - scaling from the Sun's rotation (1 month = $3x10^6$ sec) gives a rotation rate for a neutron star of 0.3 milliseconds
  - lots of energy available from 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 ~ $4x10^5$ 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"



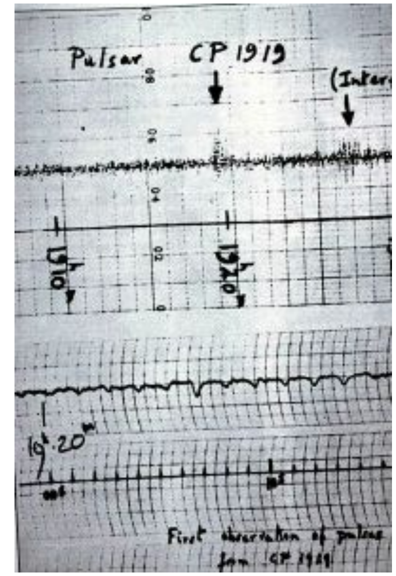
- New Neutron Stars MUST
  - rotate rapidly
  - have strong magnetic fields
  - pump out energy via synchrotron radiaton
  - energy lost must come at expense of rotation, so
  - rotation must slow down with time
- Rotating neutron stars could (must?) be the energy source for glowing supernova remnants

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 !

PSR 0329:
0.72 s

Vela:
0.089 s



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

Neutron Star spin-down

- Rotational Energy E:
  - E ~ Ω^2 R^2
  - $$\frac{\Delta E}{\Delta t} \propto 2\Omega \frac{\Delta \Omega}{\Delta t} R^2 \qquad\qquad L \propto B\Omega \frac{\Delta\Omega}{\Delta t}$$

lose energy (< 0)

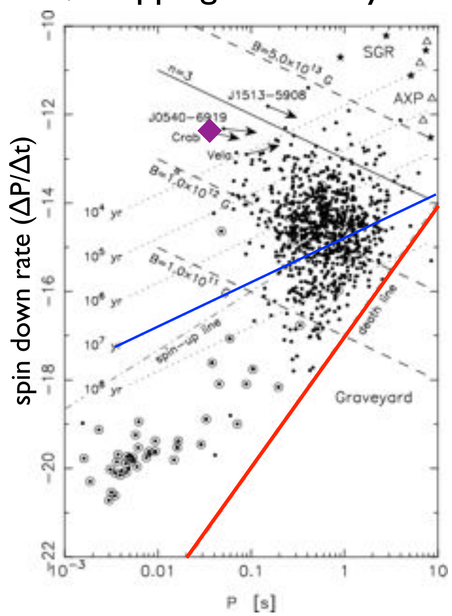
spin down (< 0)

  - 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

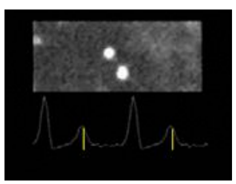


Measuring Spin-Down

- 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



Crab Pulsar (0.033 s)

- **Binary Pulsars**:

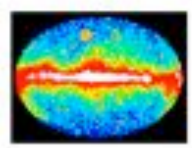
  precise tests of general relativity (1993 Nobel, Hulse & Taylor)
- **Pulsars with Planets**

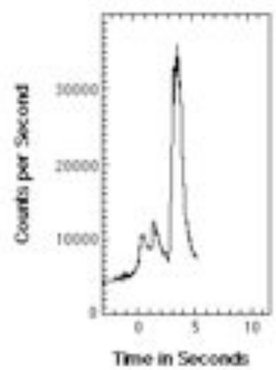
  timing "jitter" -> planet-sized companions (Alex Wolsczan)
- ***Millisecond* Pulsars**
  - fast pulsar, small dP/dt PSR 1937 (0.00167s)
  - recycled pulsars spun-up by companion (Don Backer)
  - should have companion - most do, many do not!
- **"Black Widow" Pulsars**

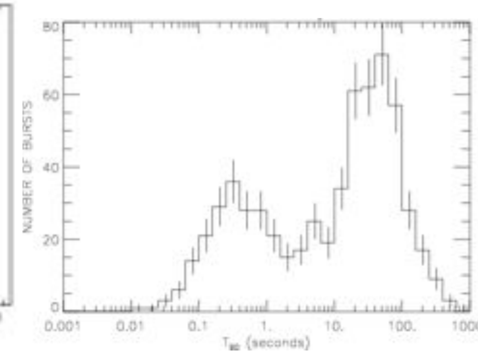
  pulsar blasts away its companion (Dan Stinebring)

Gamma Ray Bursts

- short-duration, high energy flashes
  - 0.1 to 100 seconds



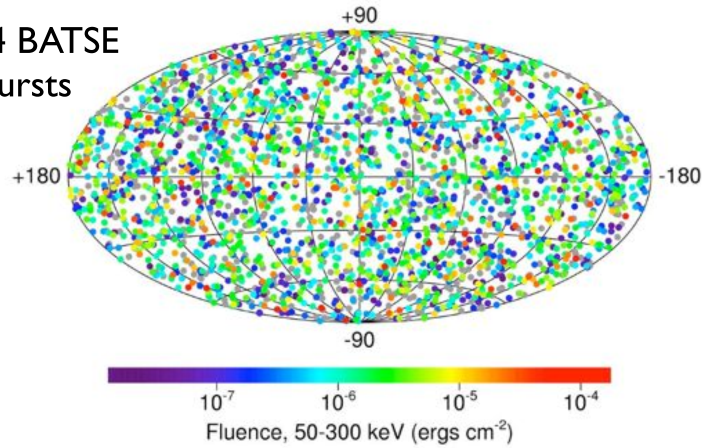




Gamma Ray Bursts

- 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