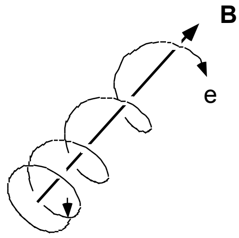
Supernova remnants

- eg Crab nebula (SN 1054); Veil nebula
- low density, heavy-element enriched nebulae show continuous spectra - not black-body (Kirchoff's laws)

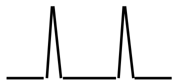
•synchrotron radiation seen in X-ray and radio; strongly polarised. Caused by relativistic electrons spiralling around weak magnetic field lines (magnetic field slightly stronger than ISM value).



•Accelerated electrons come from SN centre - the neutron star, observed for some time as a pulsar

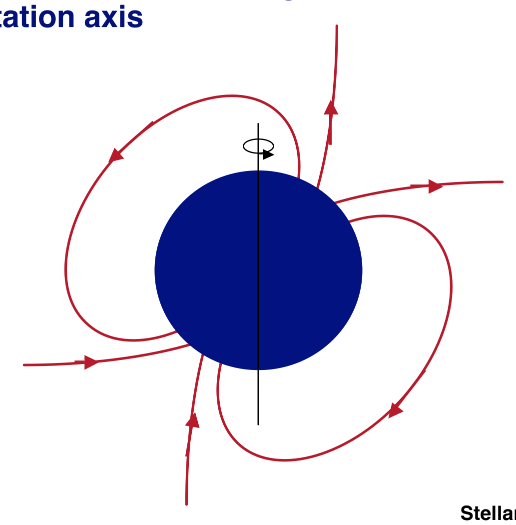
Pulsars

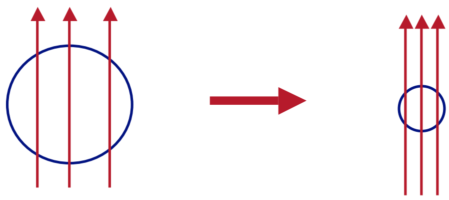
- pulsing radio sources PSR (S)
- radiation in sequence of pulses
- pulse duration ~ 3% pulse period
- > 450 known with pulse periods in range 1.56 ms → ~ 4 s



- Periods constant to ~ 1 part in 10^8 - but
  - increasing at steady rates ~ 10^{-15} s s^{-1} (30 ns yr^{-1})
  - glitches - sudden changes in pulse arrival times
- Some (younger?) pulsars seen in γ - ray, X - ray, UV, optical wavelengths (eg Crab) but mostly only in radio.

- Understood to be rapidly rotating magnetised neutron stars with magnetic axis inclined to rotation axis





Flux = area . B

- Conservation of magnetic flux as core of SN collapses ensures high field strength
- eg if collapsed Sun to NS dimensions:

$$B_{NS} = B_{SUN}\left(\frac{R_{SUN}}{R_{NS}}\right)^2 \approx 10^6 \ \mathrm{T}$$

- **Link between increasing pulse periods and observed luminosities (synchrotron radiation) of SN remnants in recent SNe.**
- **Rotational kinetic energy of pulsar**

$$E_{\mathrm{rot}} = \frac{1}{2} I \omega^2$$

with $\omega = \frac{2\pi}{P_{\mathrm{rot}}}$ **and** $I = \frac{2}{5} M R^2$

for a sphere of uniform density. Hence

$$\mathrm{E}_{\mathrm{rot}} = \frac{4\pi^2 M R^2}{5 P_{\mathrm{rot}}^2}$$

- **If all rotational energy converted to radiative energy, then conservation of energy demands total energy is constant, ie**

$$\frac{dE_{\mathrm{rad}}}{dt} + \frac{dE_{\mathrm{rot}}}{dt} = 0$$

↑ **the luminosity L**

Hence $$L = \frac{8}{5}\pi^2 MR^2 P_{\mathrm{rot}}^{-3}\left(\frac{dP_{\mathrm{rot}}}{dt}\right)$$

and rearranging gives

$$\frac{dP_{\mathrm{rot}}}{dt} = \frac{5}{8\pi^2}\left(\frac{LP_{\mathrm{rot}}^3}{MR^2}\right)$$

•For M = 1 M_{Sun}, R = 10km and, for the Crab nebula and pulsar, the observed values of L = 10^{31} W, P_{rot} = 0.03 s we obtain the observed slow-down rate.

$$\frac{dP_{\mathrm{rot}}}{dt} = 10^{-13} ss^{-1}$$

So rotational kinetic energy is removed from the neutron star by the free electrons ejected from its magnetic polar regions at high speeds.

Electrons emit synchrotron radiation, but remain “tied” to the open field lines out to large distances- hence magnetic braking.