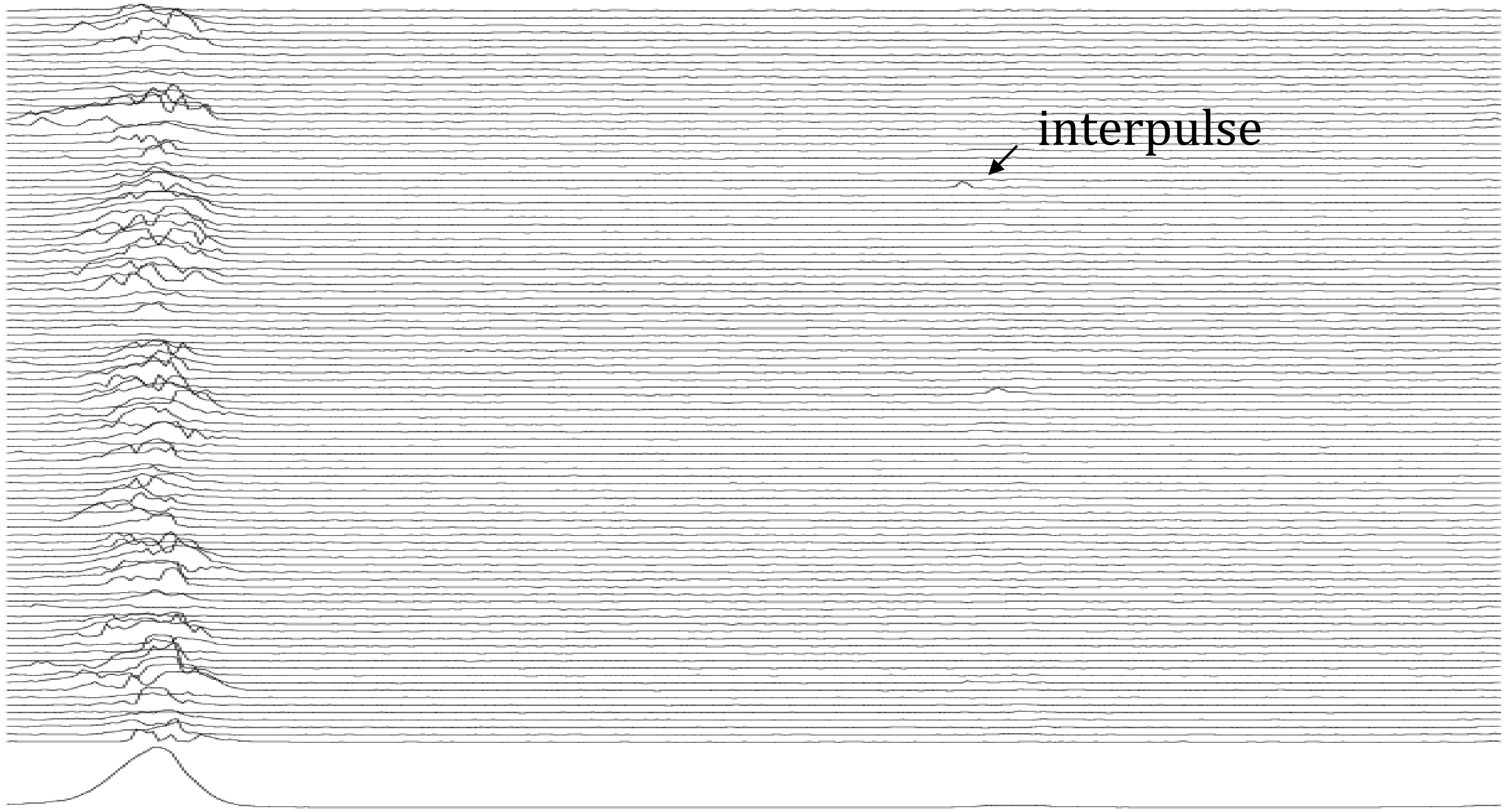
Pulsars and Supernovae II

6. MAGNETOSPHERES AND PULSE RADIATION MECHANISMS

individual pulses
polarisation of pulses
polar cap model
light cylinder and outer gap radiation
relativistic beaming
brightness temperature of coherent emission

Individual pulses

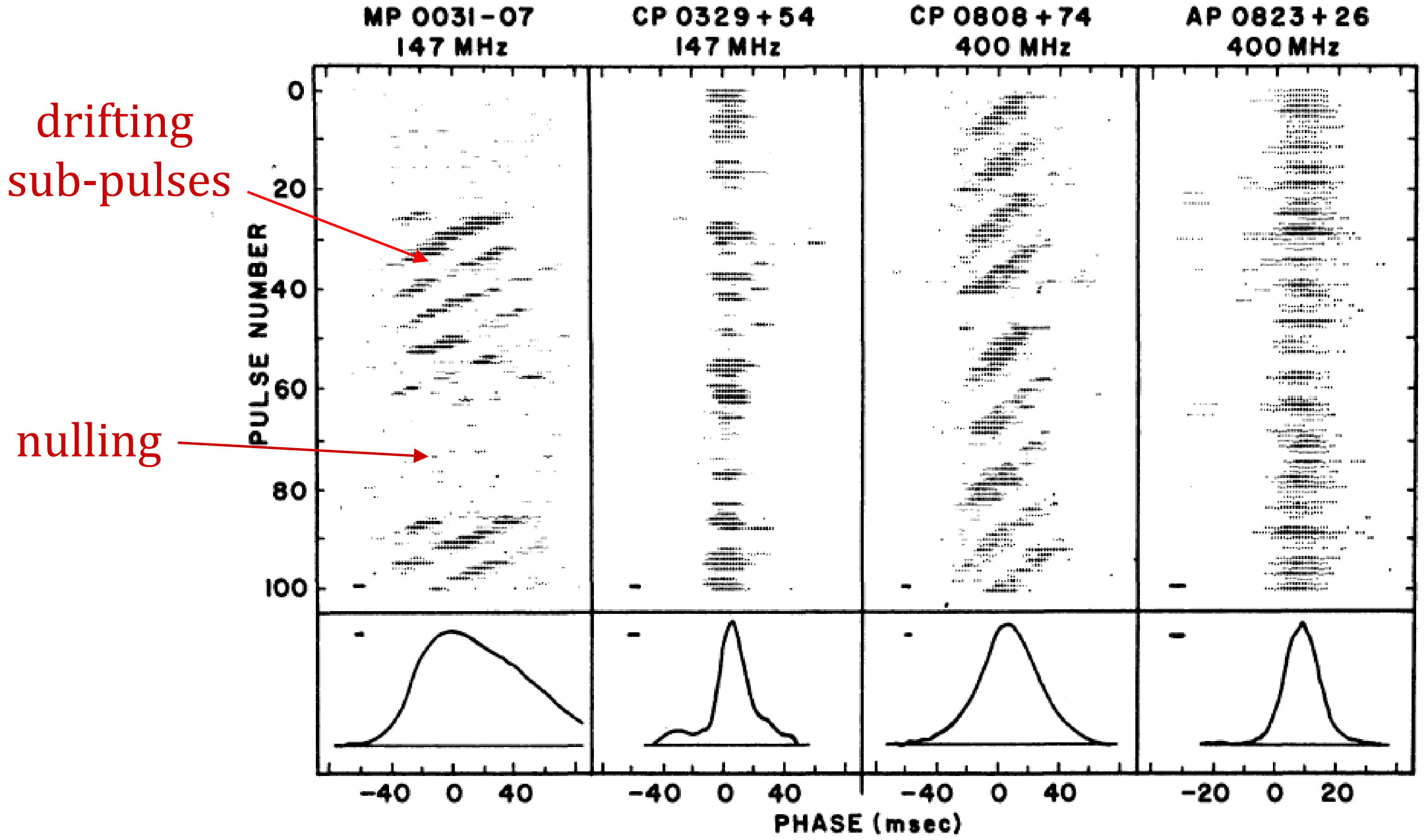
- A mean pulse profile is made up of the superposition of many ~gaussian sub-pulses, of random position and strength. The integrated profile reflects the statistics of these sub-pulses:



Stairs 2003

Drifting sub-pulses and nulling

- The sub-pulses can show complex and organised structure



drifting sub-pulses

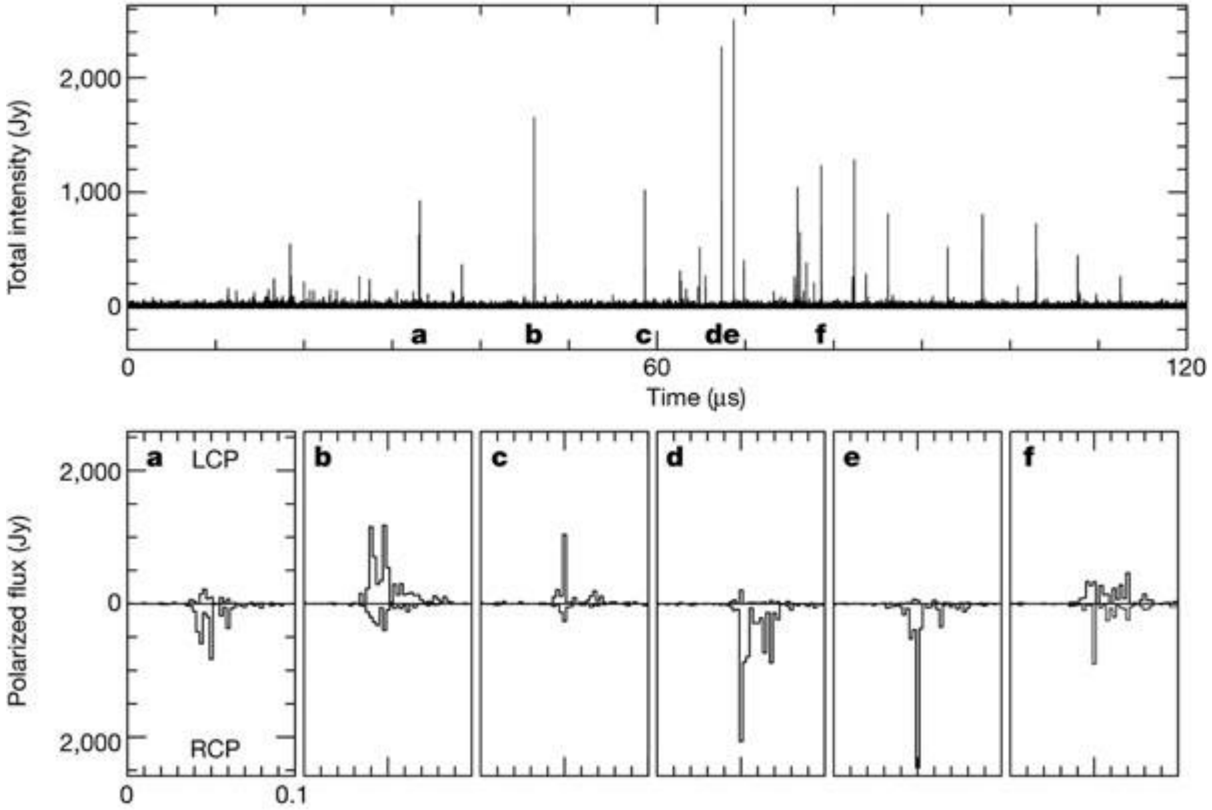
nulling

FIG. 4.—Phase-time diagrams for MP 0031−07, CP 0329+54, CP 0808+74, and AP 0823+26. Each horizontal row of characters represents a window centered on the expected time of arrival of a pulse. Successive rows are separated by one pulse period. Each vertical column represents 1 phase interval within the window. Average pulse shapes are shown at the bottom of each diagram. Short horizontal bars near the bottom of the phase-time diagrams, and near the top of the average pulse shapes, represent the effective time resolution of the data.

Taylor and Huguenin 1971

Micro-pulses

- Each pulse can itself be made from very fine micro-pulses.
  The Crab pulsar (again!) shows remarkably short micro-pulse structure in its ‘giant’ pulses:



2 ns resolution (Hankins et al 2003)

Polarisation of pulses

- In addition, the sub-pulses (and therefore the mean pulse profile) show strong polarisation structure:

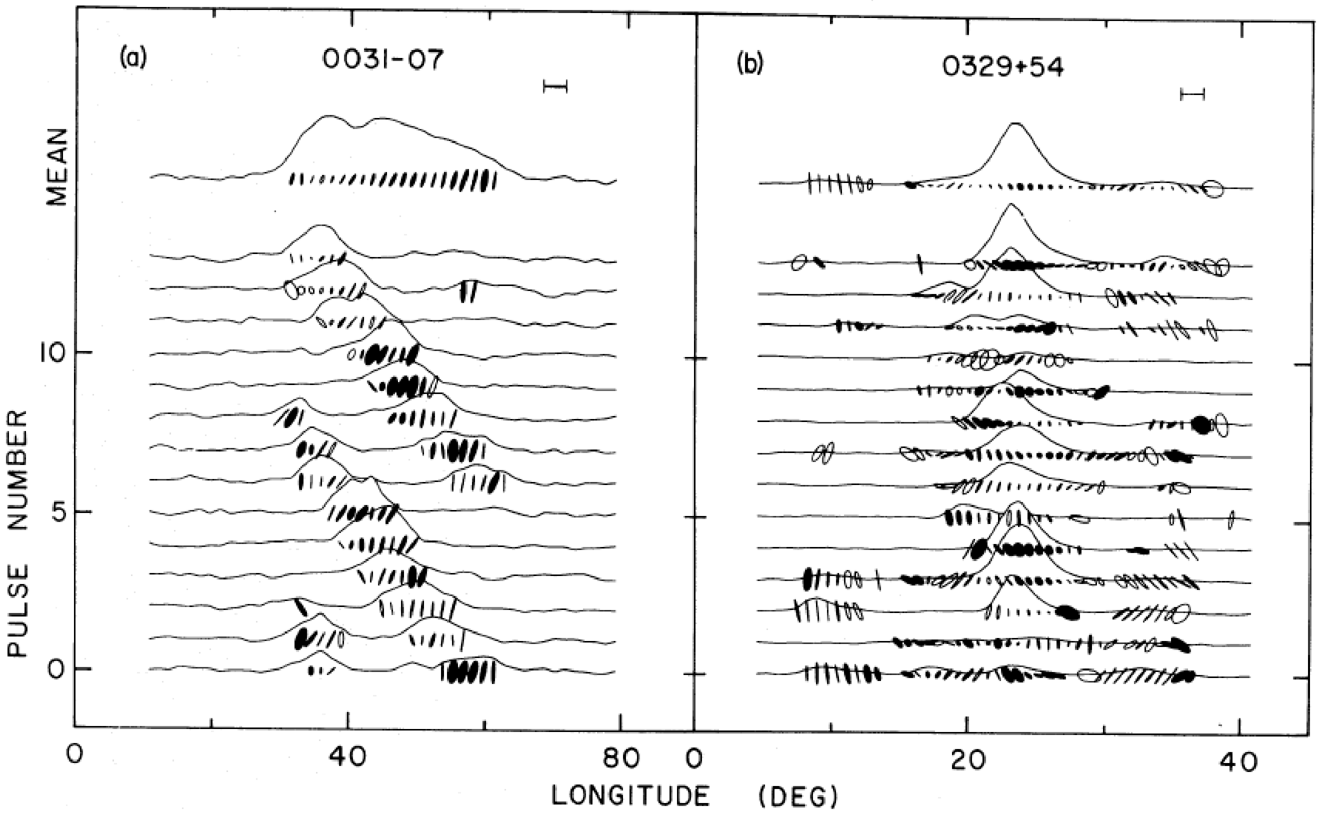
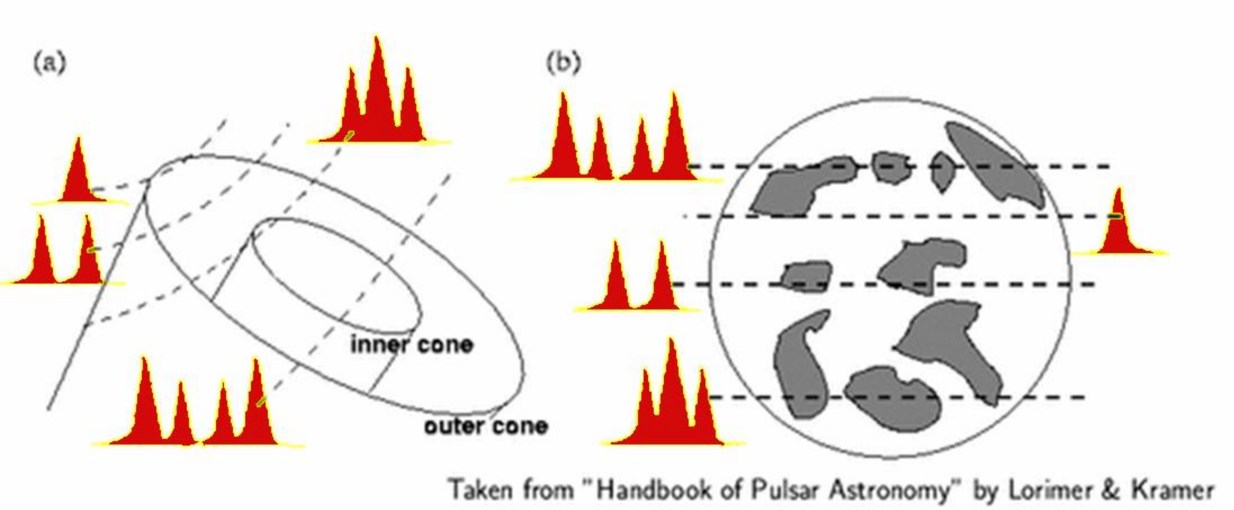


FIG. 1.—Polarization ellipses and total intensity profiles for 14 consecutive individual pulses and the integrated profile obtained by summing these pulses, for each of PSR 0031 − 07 and PSR 0329 + 54. The ellipses are filled for LH-circular polarization and open for RH-circular polarization, have a major axis length proportional to the degree of polarization, and are oriented according to the position angle of the radiation. The bar at the top of each diagram represents the length of the major axis corresponding to complete polarization, and both position angle and pulse longitude have an arbitrary zero.

Manchester, Taylor and Huguenin 1975

Proposed beam structures

- The pulse/sub-pulse profiles can be explained in terms of structure and evolution of the pulsar beam, perhaps imagined as nested cones or patches of radiating material:

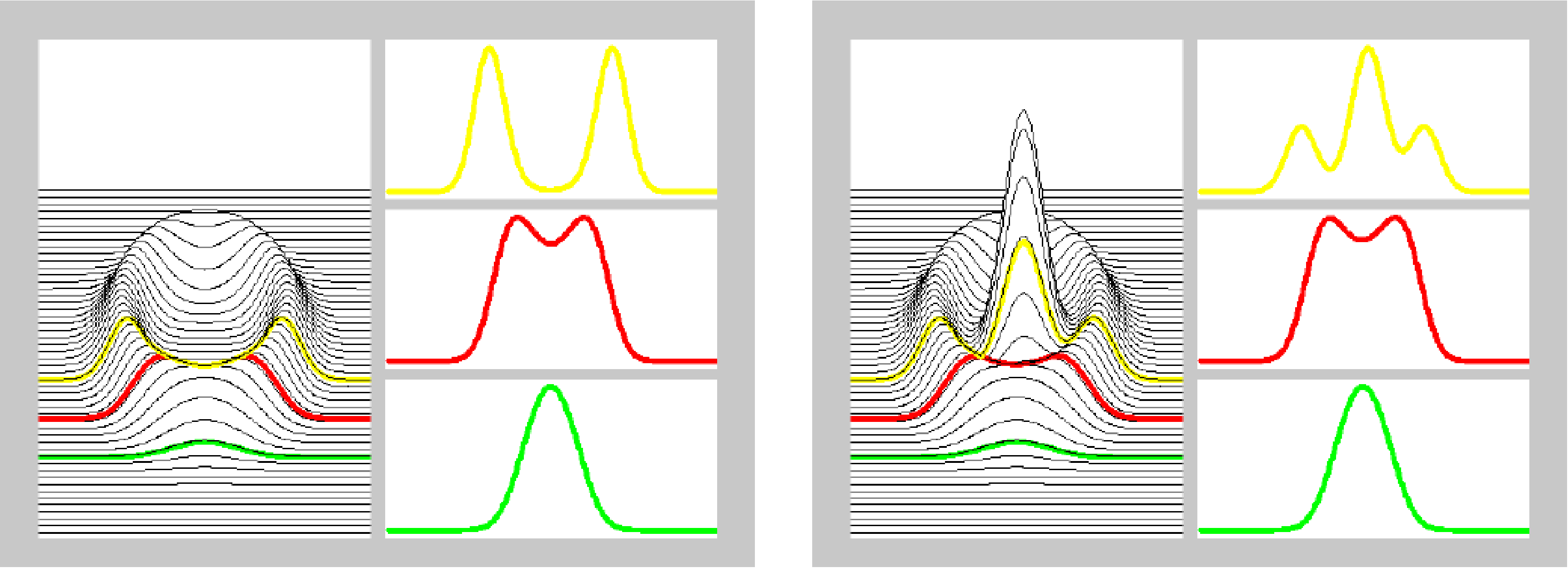


Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

- In each instance, the pulse profile depends on the exact portion of the beam that shines at us.

Beam precession

- Different slices through the structured beam will give different pulse profiles, and the evolution of the shape can predict when the pulsar will precess out of our line-of-sight, e.g. PSR B1913+16:



Kramer 2008

- Should vanish in about 2025 due to geodetic precession!

Magnetosphere

- Despite the intense strength of the gravitational field close to a neutron star, the Lorentz force on a charge vastly exceeds the gravitational force

$$\boldsymbol{F}_{\mathrm{em}} = e(\boldsymbol{v} \times \boldsymbol{B}) \\ \simeq eR\Omega B$$

$$F_{\mathrm{g}} = \frac{GMm_{\mathrm{e}}}{R^2}$$

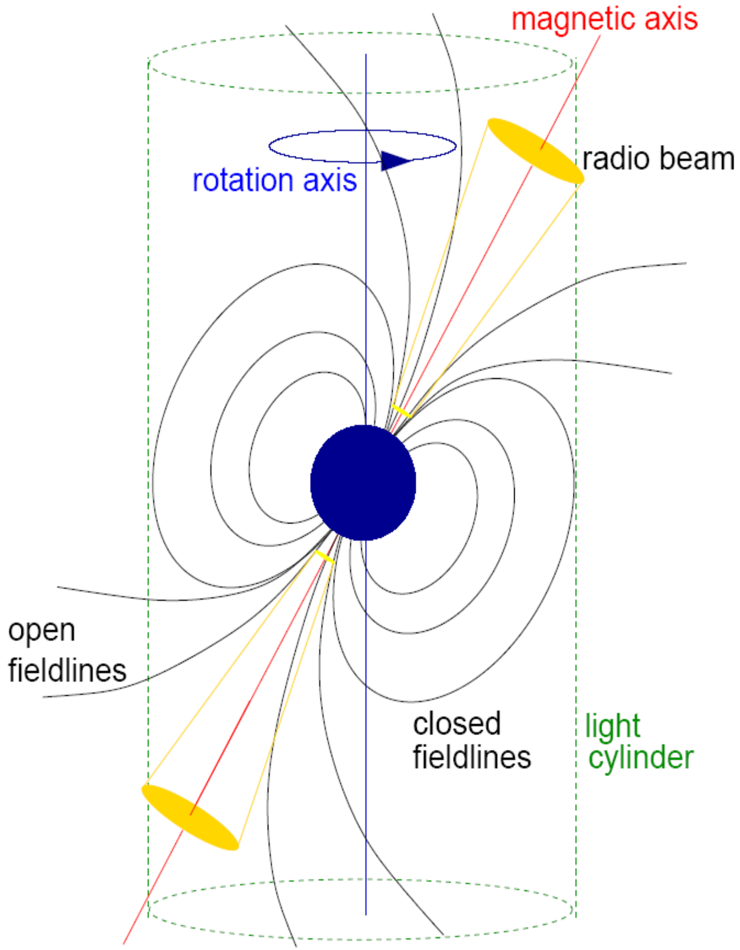
$$\frac{F_{\mathrm{em}}}{F_{\mathrm{g}}} = \frac{e\Omega BR^3}{GMm_{\mathrm{e}}}$$

- Put in $B = 10^9$ T, $\Omega = 2\pi/1$ s, $M = 1.4M_{\odot}$ we get

$$\frac{F_{\mathrm{em}}}{F_{\mathrm{g}}} \sim 10^{12}$$

Magnetosphere

- As a result, charges move as if there was no gravity at all, flowing freely along magnetic field lines but not across them (see plasma course!).
- Residual charges are stripped from the surface of the neutron star and a charged magnetosphere develops, co-rotating with the neutron star as if it were all a solid body.
- Charges also move freely in the neutron star, so that it behaves as a superconductor.



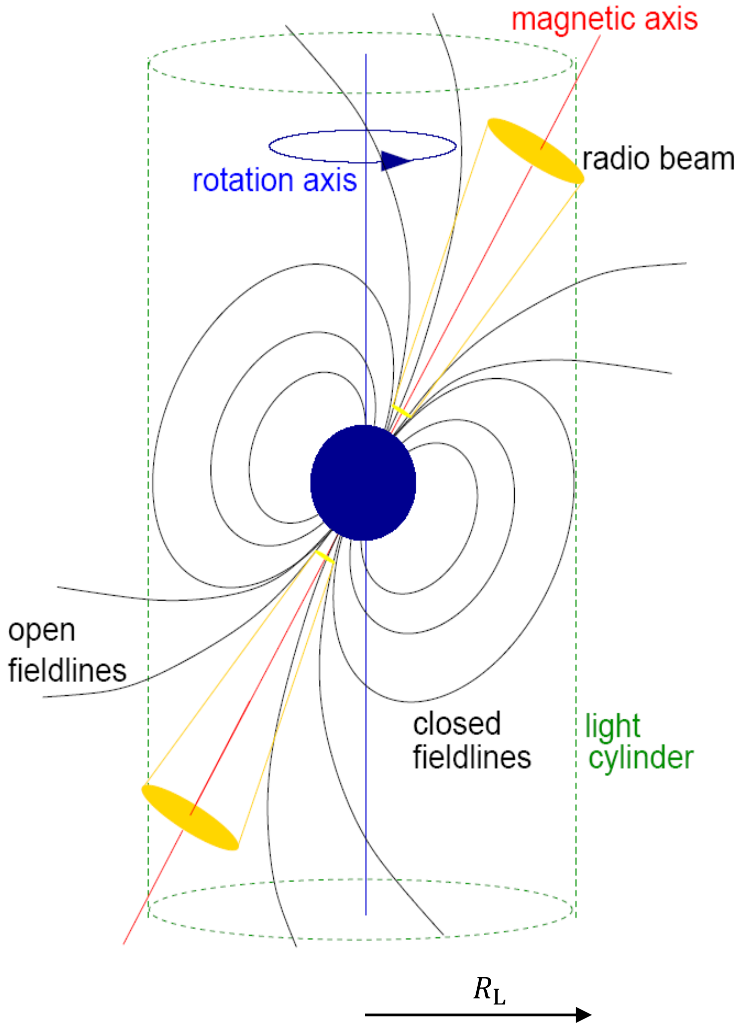
Magnetosphere

- Co-rotation is limited by relativity to the light cylinder, of radius

$$R_\mathrm{L} = \frac{c}{\Omega}$$

- Field lines within the light cylinder are closed. Outside they are open.
- Modelling of the magnetosphere is difficult, but charges should flow until the Lorentz force is balanced by an electric force, i.e. until

$$\boldsymbol{E} + (\boldsymbol{\Omega} \times \boldsymbol{r}) \times \boldsymbol{B} = 0$$

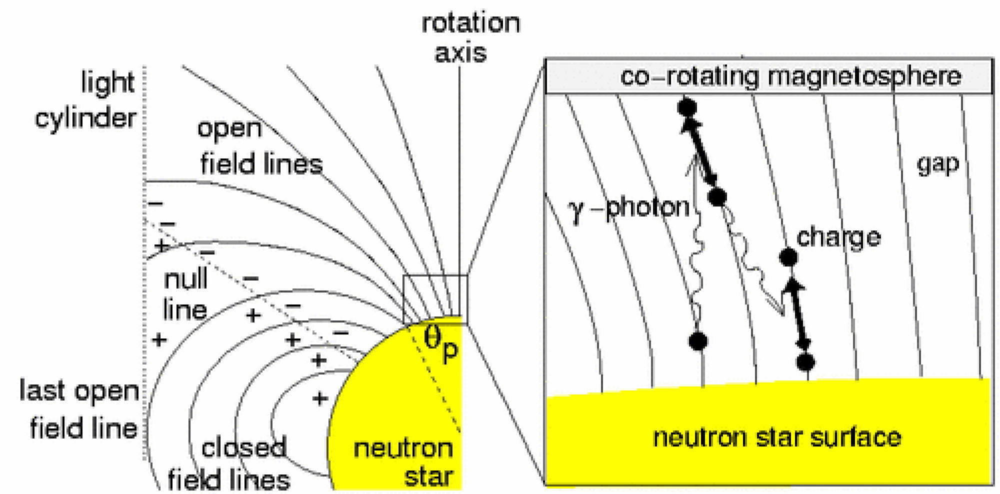


Polar cap model

- Regions in the magnetosphere where this force-free state cannot be maintained are called ‘gaps’. One of these is above the (magnetic) polar cap, where a depleted concentration of charges results in a (big!) net force on a charge.

- Gamma ray photons from these accelerating charges interact with the *B*-field to generate electron/positron pairs and a cascade of radiation and particles close to the surface of the neutron star.

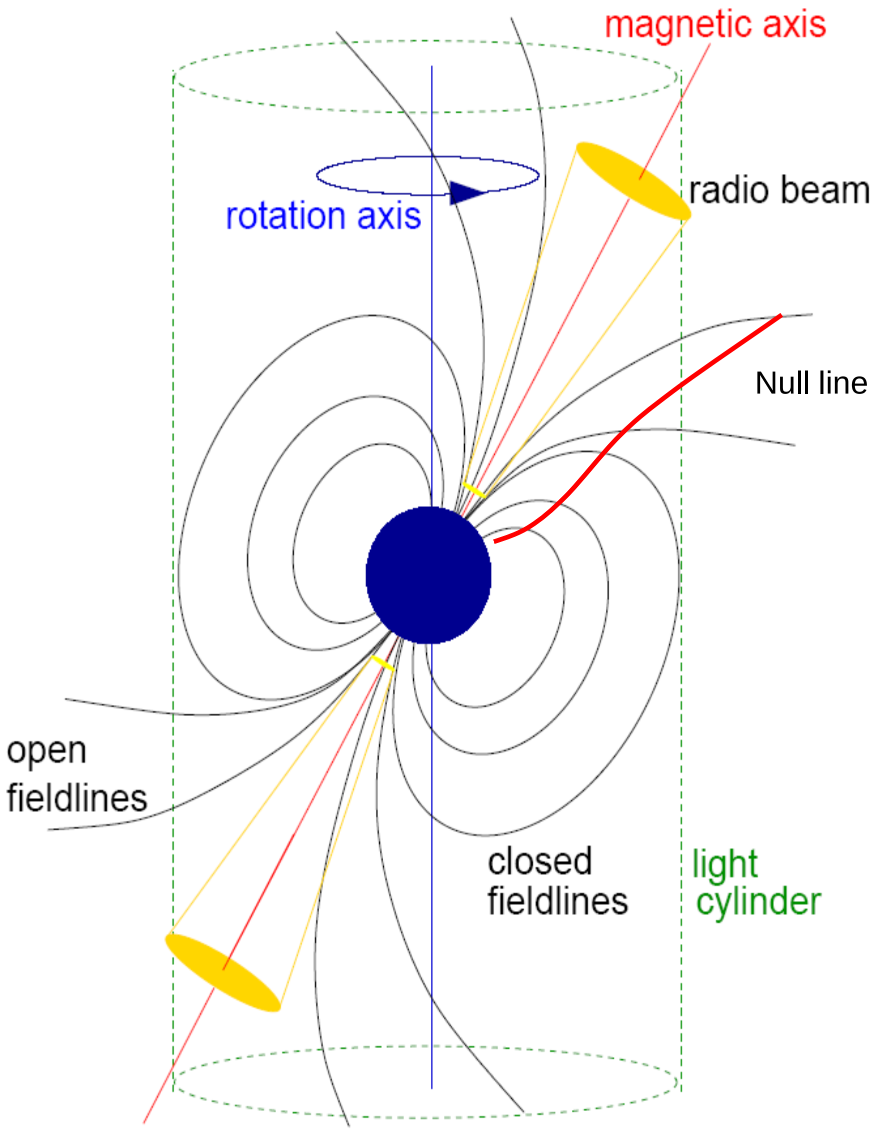
- The pair cascade is thought to generate the coherent emission we see as a radio pulse.



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

Outer gap radiation

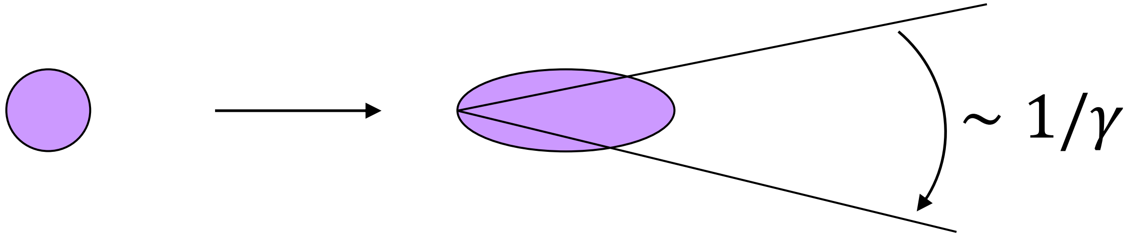
- Close to the light cylinder there is another gap – the outer gap ($\sim 10^{14}$ volts of drop).
- This gap is close to the null line at $\boldsymbol{\Omega} \cdot \boldsymbol{B} = 0$ separating regions of opposite charge.
- Here, the magnetic field is weaker and pair production harder. Radiation from this gap appears as synchrotron emission and curvature radiation (the electrons travel parallel to the magnetic field).
- Usually generates optical, X-ray and gamma ray emission.



Relativistic beaming

- Material close to the light cylinder is moving at nearly the speed of light.

- Relativistic beaming concentrates an otherwise isotropic radiation field into a beam of angular width $\sim \frac{1}{\gamma}$



- As the source chases its radiation, any apparent pulse is shortened by a further factor of $\sim 1/\gamma^2$

- The beam therefore sweeps over an observer in a time

$$\tau \simeq \frac{1}{\Omega \gamma^3}$$

Brightness temperature of coherent emission

- As we saw in lecture 1, the radio emission from pulsars shows a much greater apparent brightness temperature that can be achieved with *random* processes:

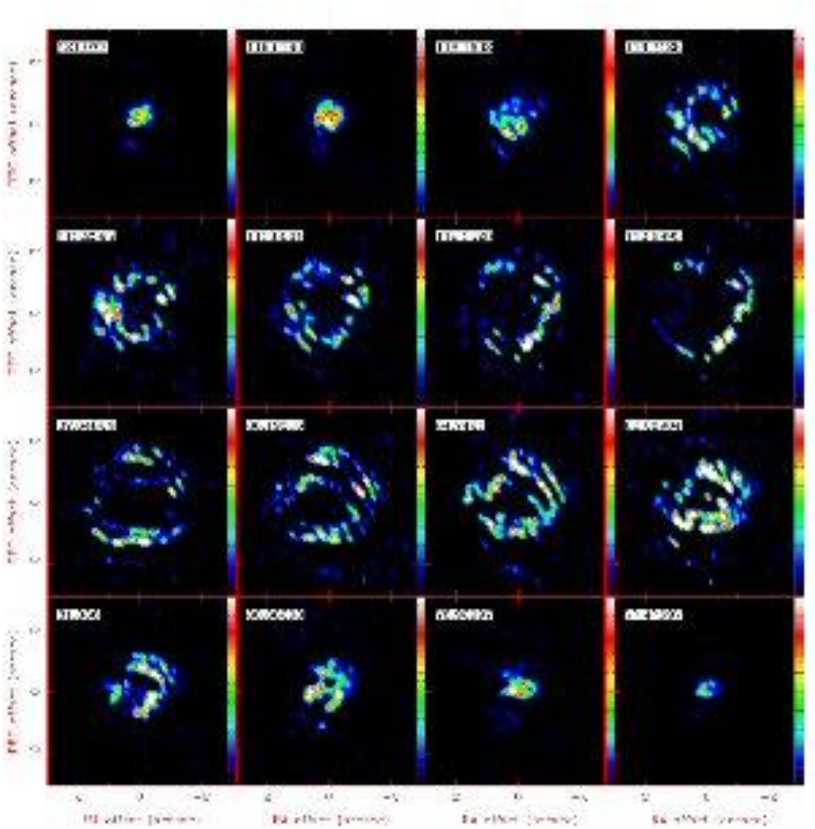
$$T_{\mathrm{b}} = \frac{Bc^2}{2\nu^2 k_{\mathrm{B}}} \sim 10^{30}\ \mathrm{K}$$

- Only coherent processes can achieve that (if phases of emission from different particles are fixed, then power increases as the number of particles squared).

Coherent emission -- Masers

- OH maser emission, e.g. from expanding shells around evolved stars.

- These are narrow band, whereas pulsar emission is (very) broadband, so this is not it…



Brightness temperature of coherent emission

- The process probably relies on electron bunching as they are accelerated.
- Radio pulse profiles widen with lower radio frequency. This may be because we are seeing emission from higher up the emission cone at lower frequencies (perhaps this is a plasma frequency effect?)
- An open problem in numerical relativistic plasma magnetoelectro-hydrodynamics!