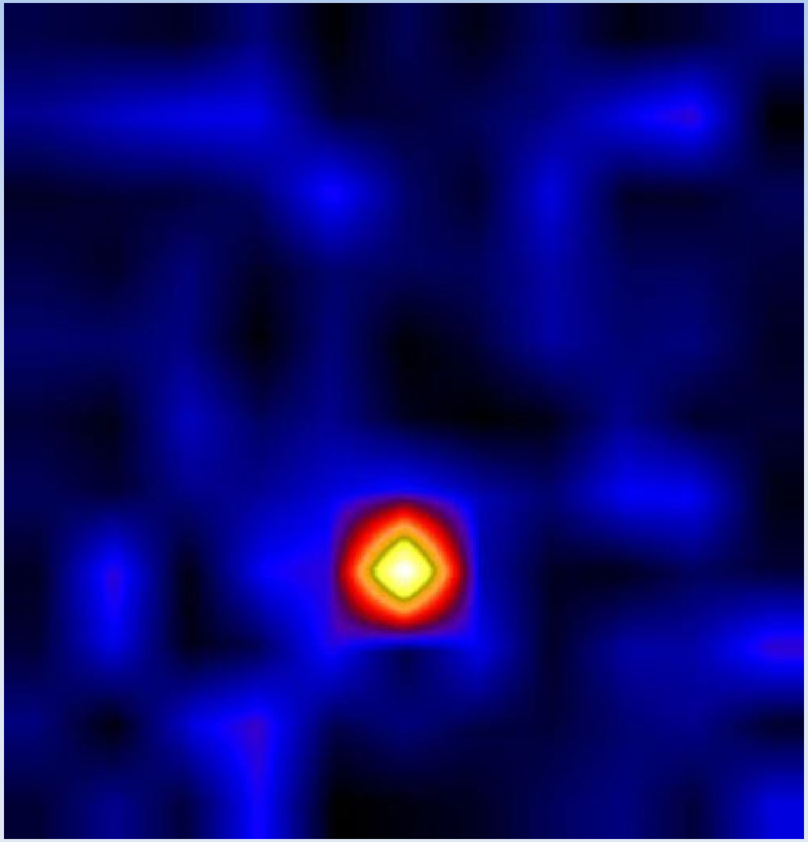
Compact Stars



Lecture 11

Summary of the previous lecture

- I talked about neutron stars, their internal structure, the types of equation of state, mass-radius relation and resulting maximum mass (Tolman-Openheimer-Volkoff limit)
- The neutron star EoS can be constrained if we know mass and/or radius of a star from observations
- The neutron star subsequent layers, outside-in, are: its surface ($\rho<10^6$ g/cm^3), outer crust ($\rho<4\text{x}10^{11}$, below neutron drip density), inner crust ($\rho<2\text{x}10^{14}$, below muons formation density), outer core (neutron liquid, $\rho<4\text{x}10^{15}$), inner core (even higher densities, possible formation of hyperons, kaon condensates, or solid quark matter).

Summary of the previous lecture

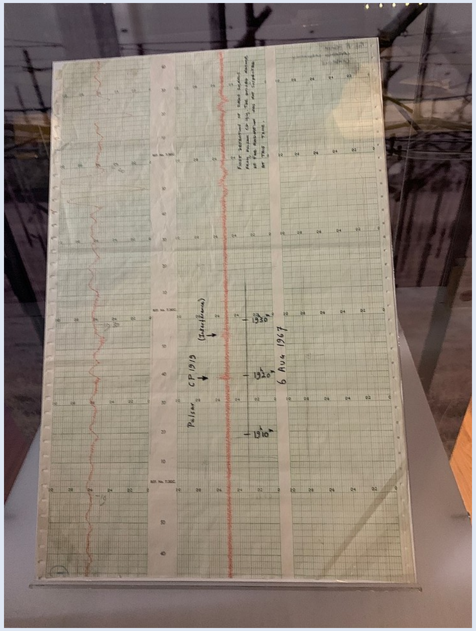
- Neutron stars exist in isolation, or are in binaries with MS stars, compact stars, including other NS. These binaries are final product of common evolution of the binary system, or may be a result of capture.
- Binary NS-NS merger leads to emission of gravitational waves, and also to the short gamma ray burst. The delay between these two signals was attributed to formation of hypermassive NS (HMNS). It is supported by differential rotation, but collapses to BH as soon as rotation slows down.

Today: pulsars

- Pulsars are also neutron stars. Their observational appearance is related to pulses of light, observed at radio frequencies.
- Pulsars were discovered in 1967, and brought interest to the neutron star physics, after some break due to lack of relevant observations

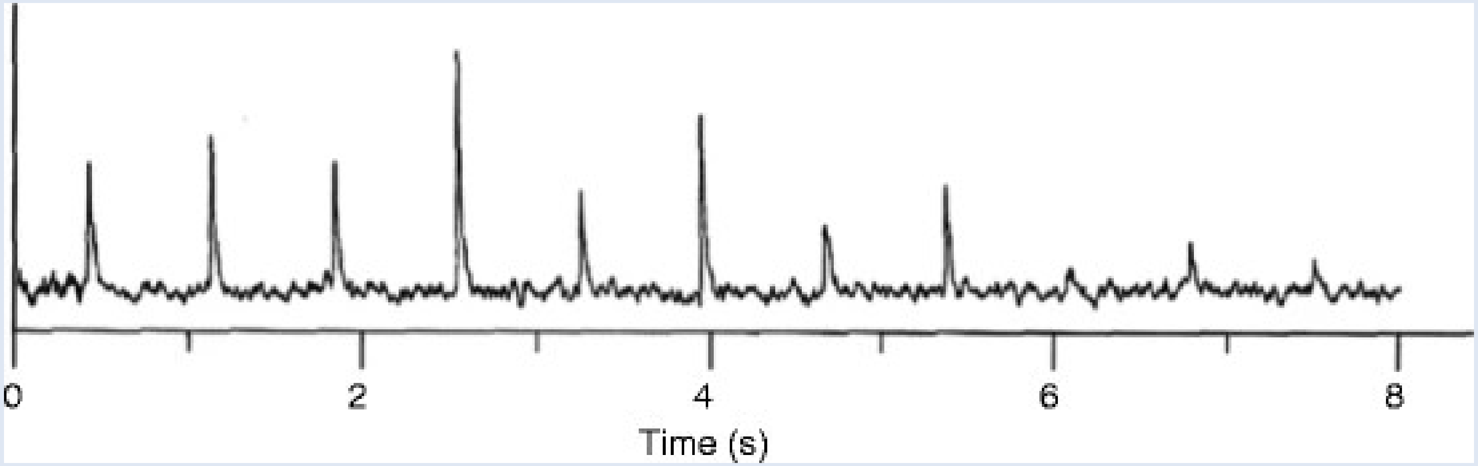
Discovery of pulsars

- Neutron stars were predicted in 1930’s, but not seen for 30 years after.
- Jocelyn Bell had a PhD project to study radio scintillation from quasars. She noticed that source CP 1919 emits regular pulses with periodicity of 1.337 s.
- She found next two pulsars in 1968.
- In 1974, Hewish and Ryle received the Nobel prize for discovery of pulsars



Pulse periodicities

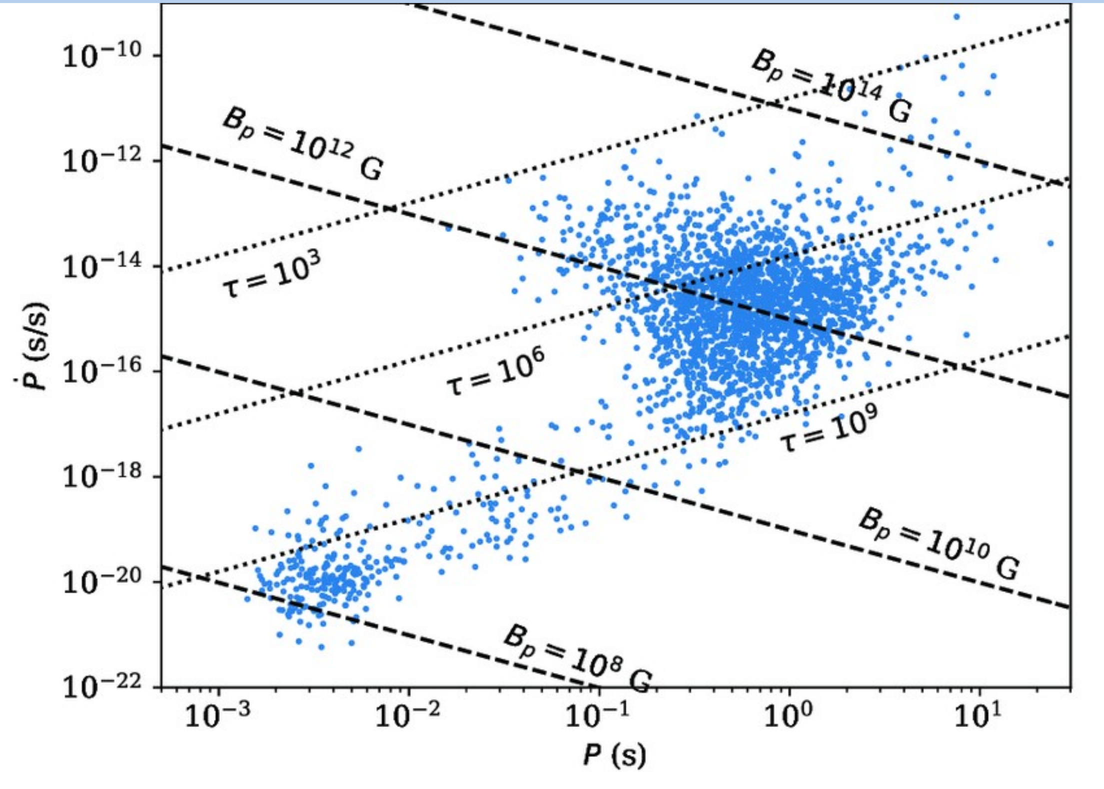
- Periods of ~1 s are common. The observed pulse periods range between 1 ms and 15 s, with most lying, between 0.3 s and 3 s, for the so-called “normal pulsars”.
- Periods are very stable, dP/dt ~ 10^{-15} s/s



The 0.714 s pulsar PSR 0329 + 54 at 410 MHz (Manchester & Taylor 1977)

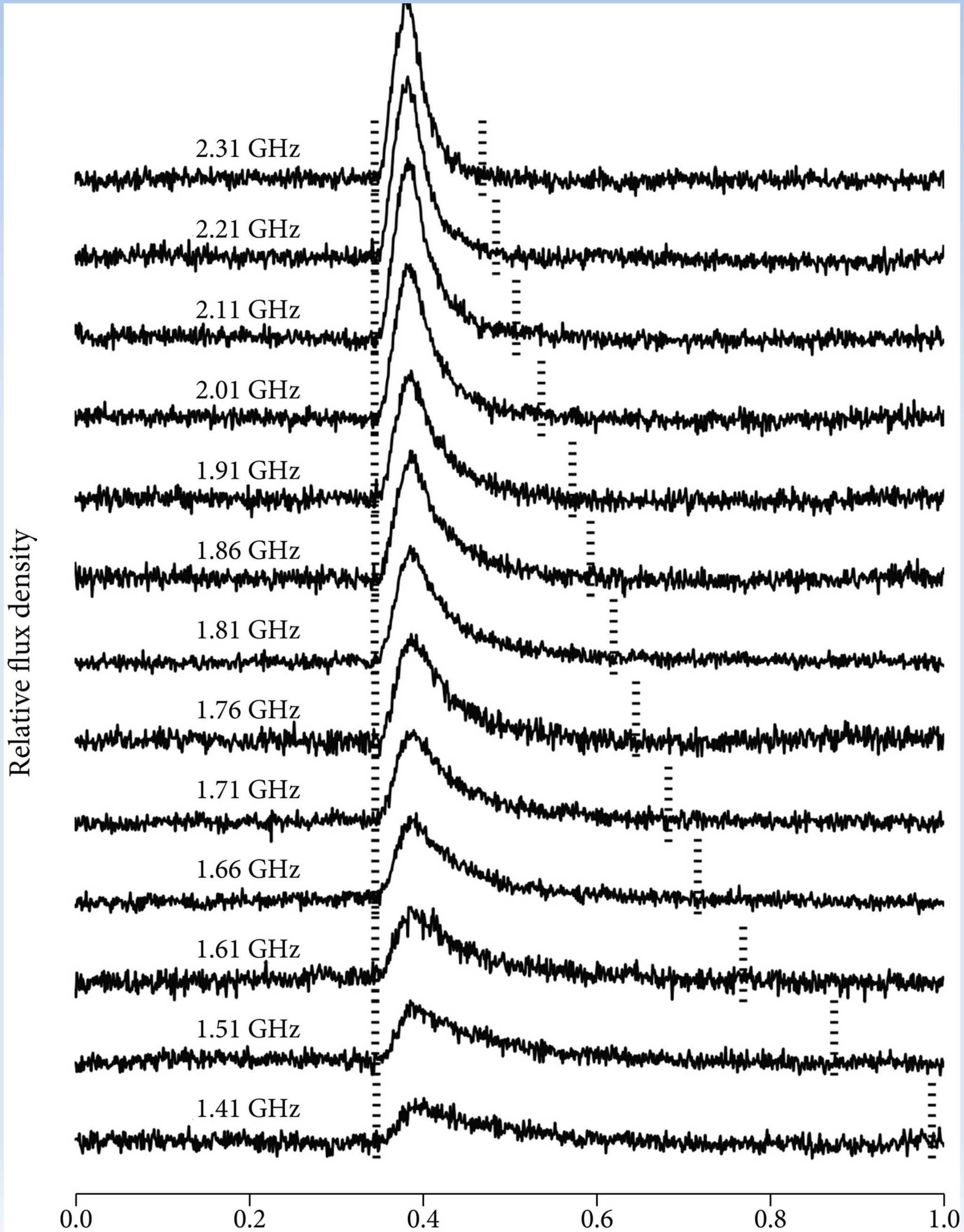
Period changes

- For PSR 1913+16, dP/dt = 8.6×10^{-18}
- For PSR 1952+29, dP/dt = 1.9×10^{-18}
- Empirical relation of period derivative with period
- Revised when millisecond pulsars discovered



Dispersion of impulse

- Pulse smearing for low frequencies
- Pulse shape change with frequency



Distance determination

- Radio signals undergo dispersion while travelling through interstellar medium
- Dispersion measure allows to determine distance to source
- Dispersion relation for radio waves propagating in the plasma is

$$\boxed{\omega^2=\omega_p^2+k^2c^2}$$

where $\omega_p = (4\pi n_e c^{2)}/m_e$ is plasma frequency

- Radio waves with $\omega > \omega_p$ propagate with group velocity $v_g = d\omega/dk = c\left(1-\omega_p^2/2\omega^2\right)$

Distance determination

- Time of arrival of a pulse with frequency ω is

$$t_a(\omega)=\int_0^D \frac{dl}{v_g}\approx\frac{D}{c}+\frac{2\pi e^2}{mc\,\omega^2}\int_0^D n_e\,dl$$

- We can get $dt_a/d\omega$ from pulses observed at different frequencies.
- Dispersion measure, $DM=\int n_e dl$ allows to determine distance to source, if we know the electron density integrated over line of sight
- In our Galaxy, average $\langle n_e \rangle = 0.03$ cm^{-3}

Crab pulsar

- Crab pulsar is located at the center of Supernova remnant, from 1054 *AD*.
- P=33 ms, dP/dt = 4.2x10^{-13} s/s.
- Rotational energy E_{rot} = ½ I Ω^2, where moment of inertia of a uniform sphere, I=2/3 MR^2 is about 10^{45} g cm^2 for a neutron star.
- The rate of change of E_{rot} is

$$\boxed{\frac{dE_{rot}}{dt} = I\Omega\frac{d\Omega}{dt} = -4\pi^2 I\frac{\dot{P}}{P^3}}$$

Crab pulsar

- Amount of energy radiated away by Crab nebula is

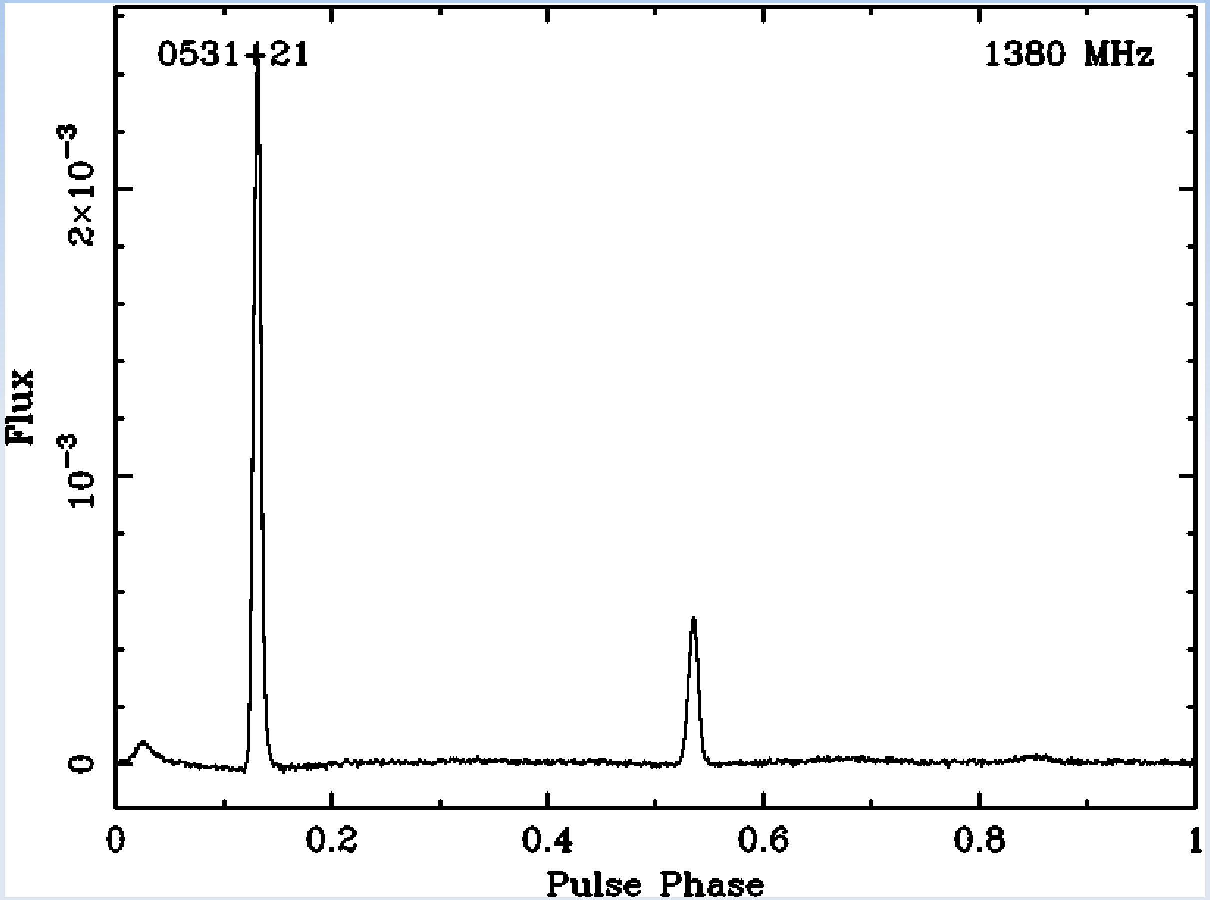
  $L = 5 \times 10^{38}$ erg/s.

- This is in agreement with

  $L = dE_{rot}/dt$, with $\Omega = 2\pi/P$ computed from pulse period.

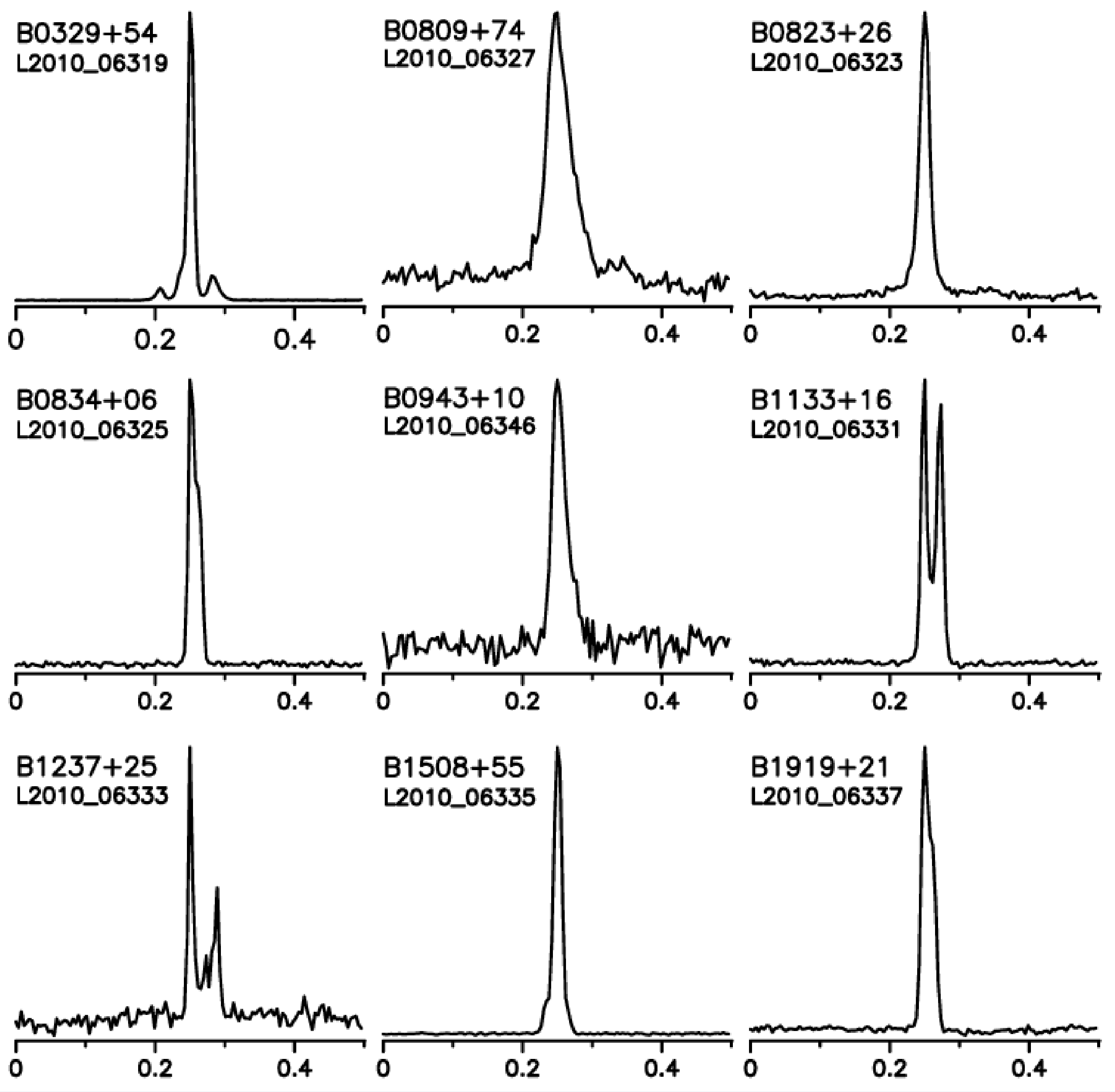
- Crab emits energy on the cost of slowing down the neutron star rotation.

Crab pulsar radio data



Average profile of the Crab pulsar consisting of the Precursor around 0.5 in phase, the main pulse at about 0.15 in phase and the interpulse at 0.52 in phase. The data was taken with the Westerbork Synthesis Radio Telescope (WSRT). (Lewandowska 2015)

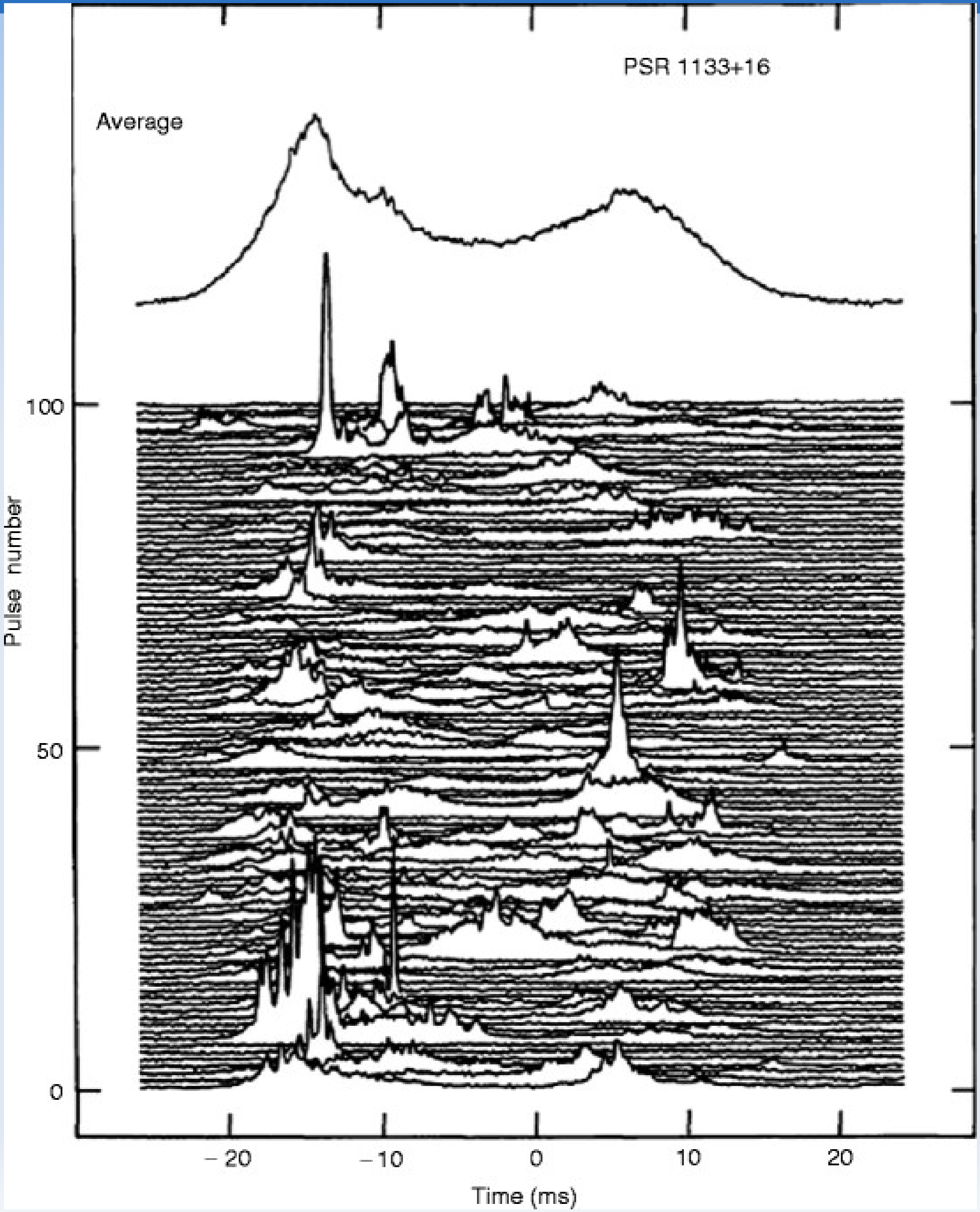
Pulse shapes



Average pulse profiles of nine pulsars, observed over the course of a weekend using an automatic scheduler. Only half the rotational phase is plotted in each case in order to show finer features of the pulse morphology.

LOFAR data (Hessler et al. 2010)

Average shape

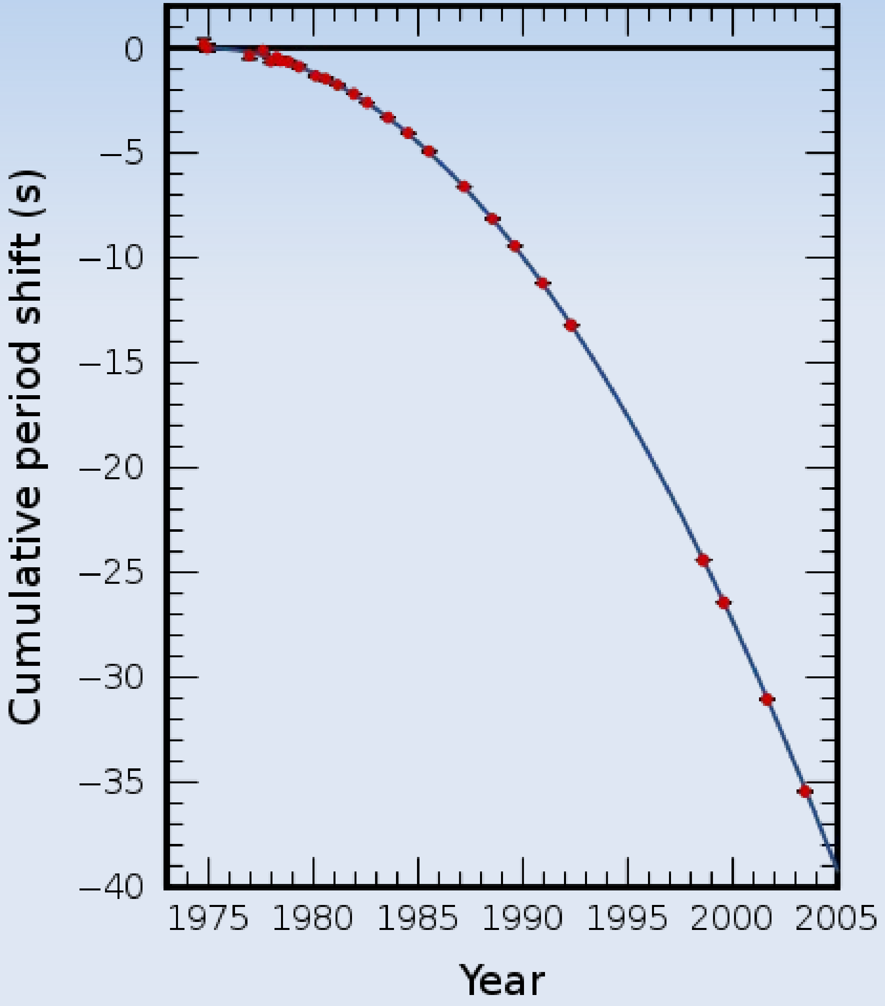


A sequence of 100 pulses from PSR 1133 + 16 at 600 MHz.

An average of 500 pulses is shown at the top (Cordes1979).

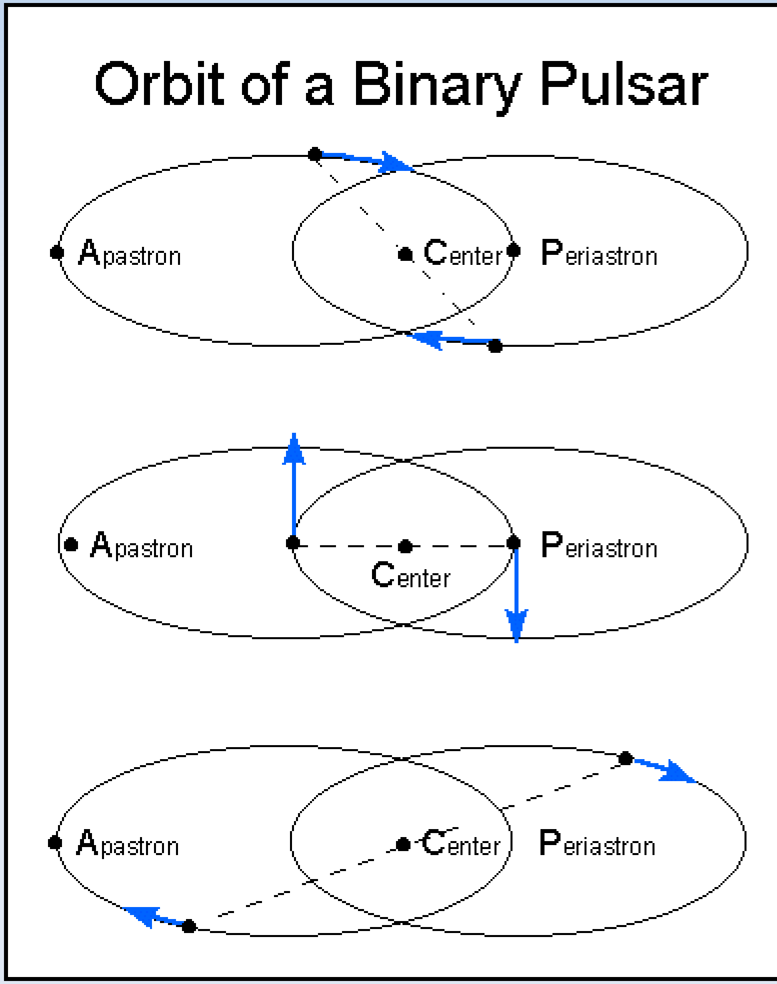
PSR B1913+16

- Pulsar is in binary system with another neutron star
- Discovered by R. Hulse and J.Taylor in 1974
- Mass M=1.441 M_{sun}
- Spin P=59.02 ms
- Orbital period t=7.75 hrs, decays 76.5 μs/yr
- Time to final inspiral is 300 mln yrs



PSR 1913+16

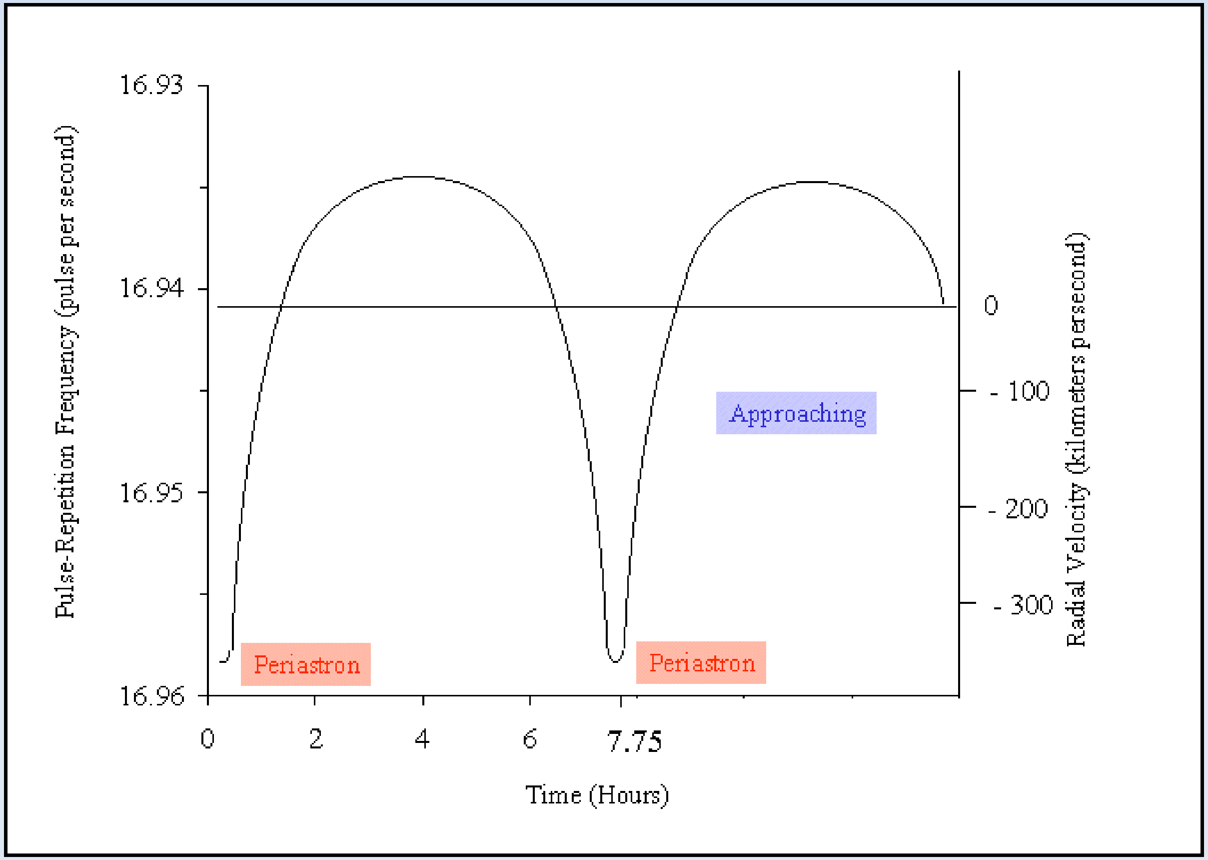
- The pulsar and its companion both follow elliptical orbits around their common center of mass.
- P= 7.75 hr, and the stars are nearly equal in mass, about 1.4 Msun.
- Orbits are eccentric. Minimum separation at periastron is 1.1 R_{sun}, the maximum separation at apastron is 4.8 R_{sun}



PSR 1913+16

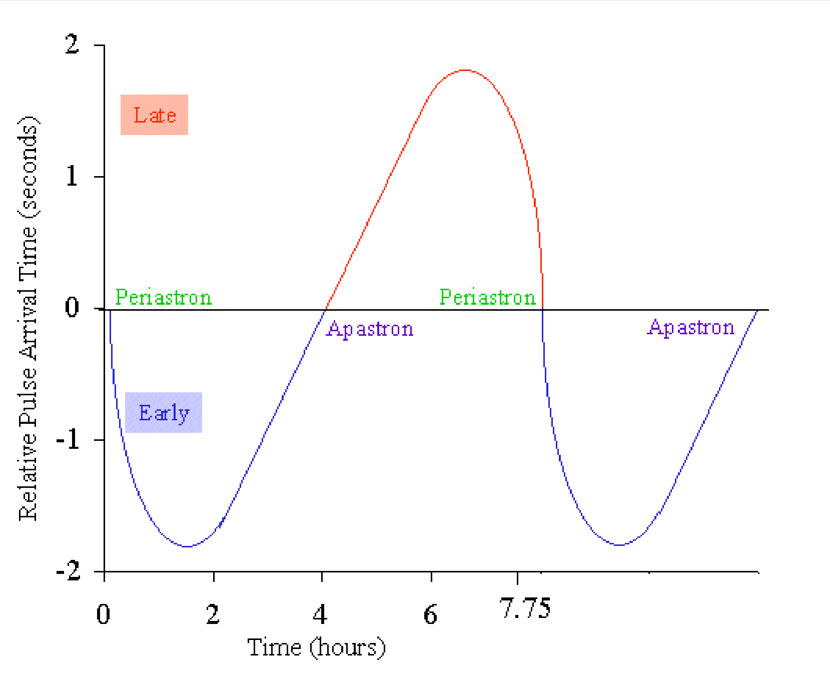
Radial velocity curve, inferred from pulse repetition frequency

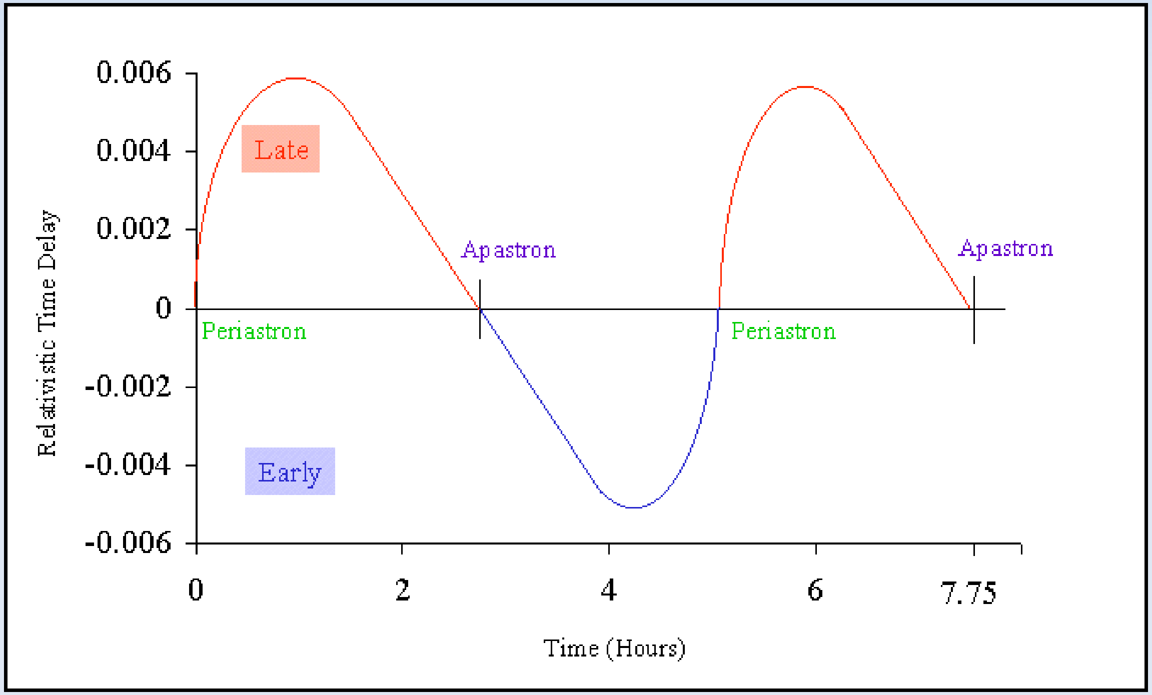
When the pulsar is moving towards us and is close to its periastron, the pulses should come closer together; and the pulse repetition rate will be highest. When it is moving away from us near its apastron, fewer pulses should be detected per second.



Relativistic time delay

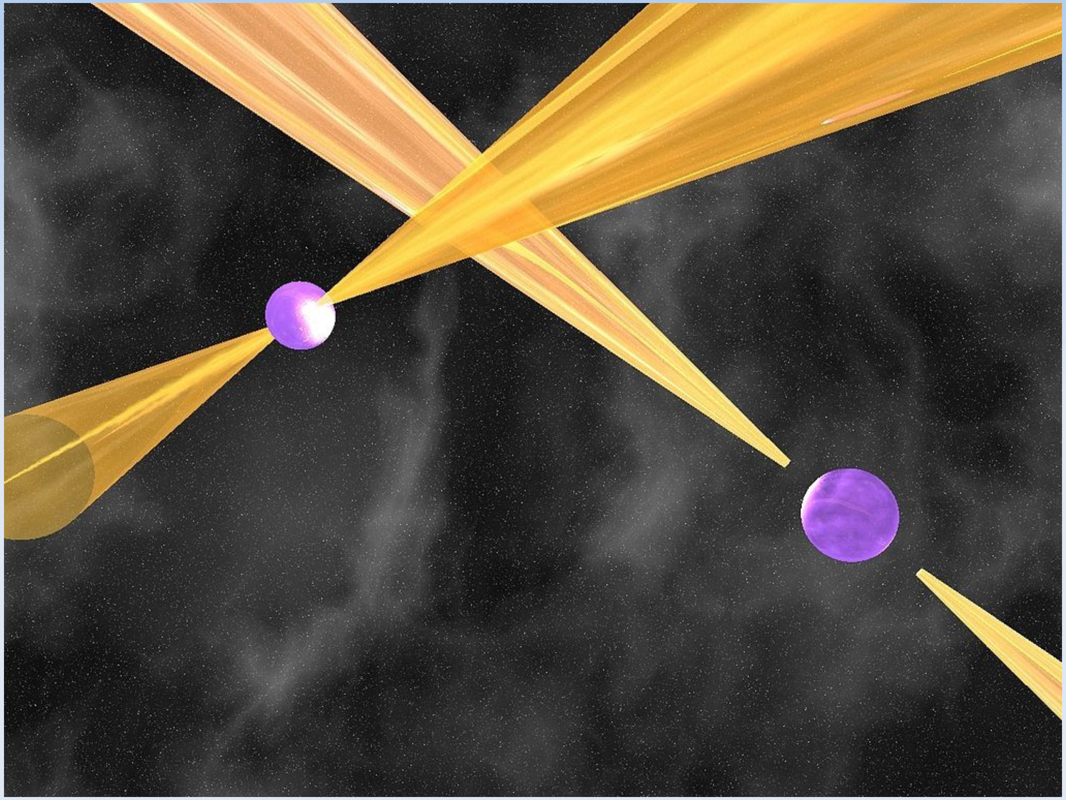
Since the orbit of the pulsar around its companion is elliptical, the gravitational field alternately strengthens at periastron and weakens at apastron. Thus the binary pulsar PSR1913+16 provides a powerful test of the predictions of the behavior of time perceived by a distant observer according to General Relativity.





The pulsar arrival times also vary as the pulsar moves through its orbit. When the pulsar is on the side of its orbit closest to the Earth, the pulses arrive more than 3 seconds earlier that they do when it is on the side furthest from the Earth. (Weinberg et al. 1981)

PSR J0737



- Double pulsar
- Discovered in 2003
- Masses:

  M_A=1.337 M_B=1.250
- Spin periods

  P_A=22.699 ms

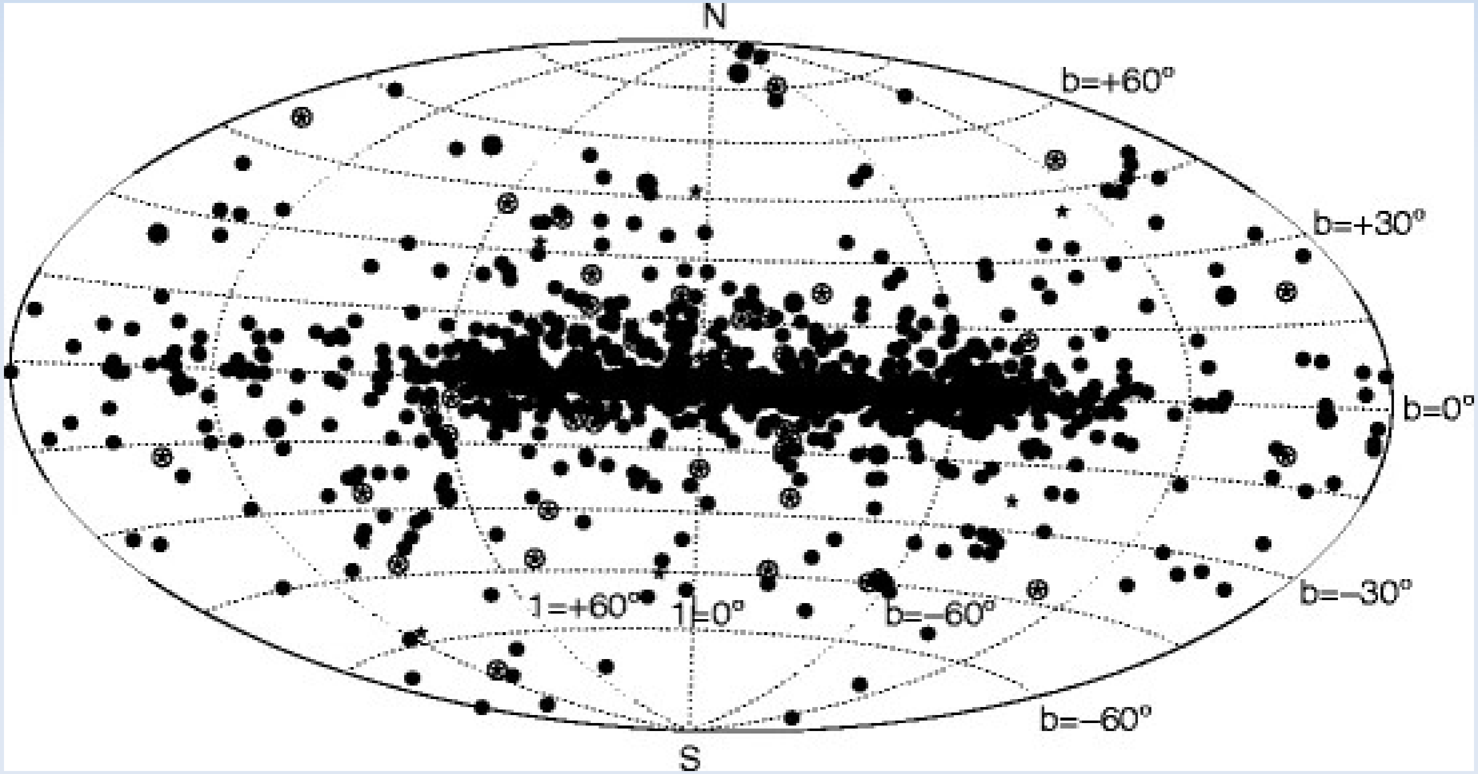
  P_B=2.773 s
- Orbital period t=2.454 hr

Binary pulsars

- Over 135 binary pulsars were known by the end of 2010, with orbital periods from an hour and a half to several years, and pulsation periods from 1.6 ms (millisecond pulsars) to over 1 s.
- An intermediate-mass binary pulsar (IMBP) is a pulsar-white dwarf binary system with a relatively long spin period of around 10 - 200 ms consisting of a white dwarf with a relatively high mass.

Distribution of pulsars

Pulsars concentrate around Galactic plane. Observed distribution is broader than that for massive stars, due to high proper motions of pulsars (natal kicks)



Distribution of 1395 pulsars in Galactic coordinates. Binary pulsars are encircled and msec pulsars are shown with a star (Seiradakis & Wielebinski, 2004)

Nature of pulsars

- Causality: variable object is smaller than the velocity of light times its characteristic variability timescale.
- Pulsars cannot exceed a size corresponding to a fraction of a light second. Objects larger than white dwarfs are excluded.
- Break up rotation is given by the gravitational binding energy

$$\boxed{\Omega_{max}^2 R^2 \approx \frac{GM}{R}}$$

Nature of pulsars

- Minimum observed period limits the star's density:

$$P_{min} = \frac{2\pi}{\Omega_{max}} \approx \frac{2\pi}{\sqrt{G\rho}}$$

- For ρ=10^8 g/cm^3, the period would be 10 s. Periods smaller than that imply the pulsar is neutron star.
- Periods increase with time. If the signal was due to orbiting NSs, the period would decrease.
- This points out to rotating NS as viable model.

Pulsar clock

- Periodicity related to rotation of a star
- Star is compact, as the signal is short
- Light travel time → size of source
- Critical rotation: breakup
- Neutron star matches the data
- White dwarf excluded due to lower density

Energy balance

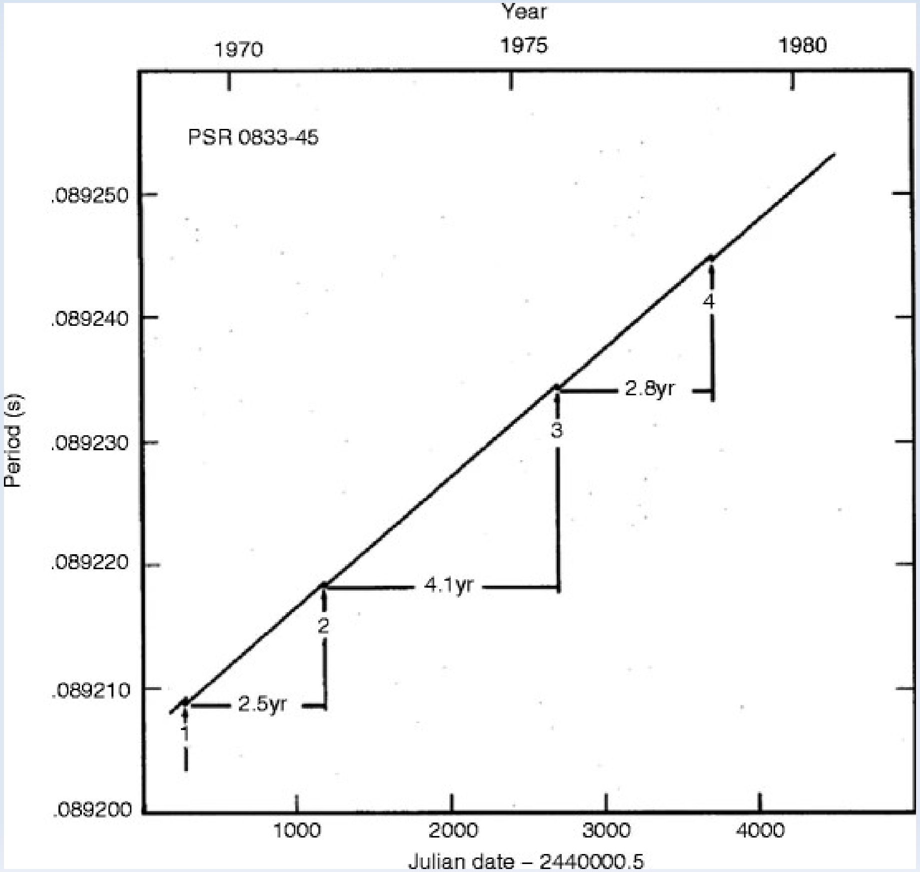
- Moment of inertia is related to rotational energy
- Change of rotational energy relates to change of period
- Abrupt changes of period may be related with star crust quakes and star reshaping (PSR 0532 and PSR 0833)

PSR 0833-45

- Abrupt period changes: The pulsation period of PSR 0833–45 is known to be gradually increasing, but between February 24 and March 3 the periodicity abruptly decreased by two parts per million (Radhakrishnan & Manchester, 1969, Nature).
- The source is called the Vela pulsar associated with the Vela supernova remnant, with a period of 89.2 msec.
- Like the Crab pulsar, it has high-frequency emissions.
- It exhibits extremely large “glitches,” wherein its period abruptly decreases by a small but readily detectable amount of about one part in a million.
- These events repeat at an irregular interval of ∼3 years and do not have exactly the same behavior each time.

Glitches

In some pulsars the period suddenly decreases at irregular intervals typically separated by a few years. These events are called glitches.



Pulse period of PSR 0833-45, the Vela pulsar, from 1968 to 1980.

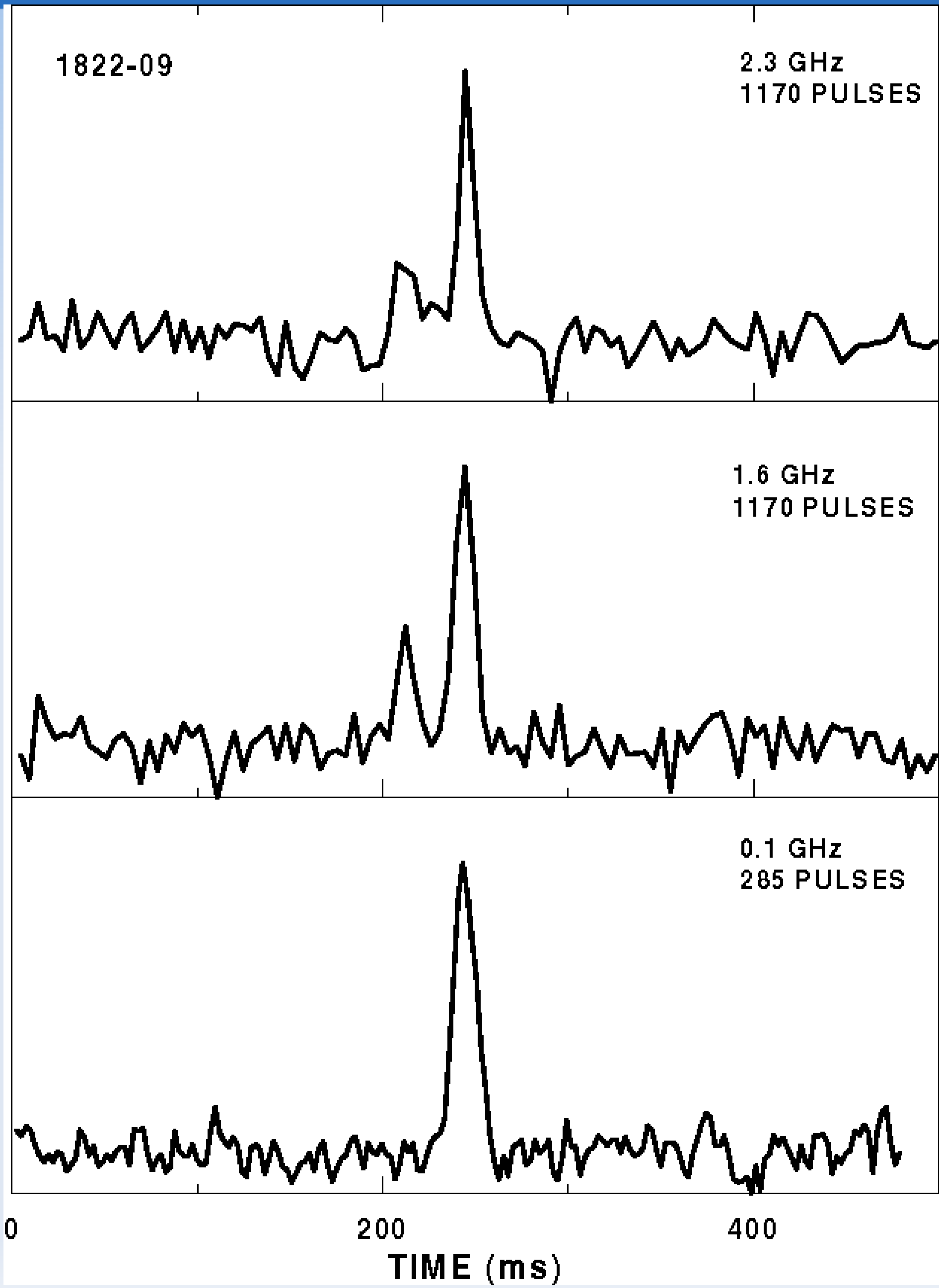
The period increases over time except for short glitches at intervals of a few years (Downs, 1981)

Pulsar glitches interpretation

- The angular momentum of an isolated neutron star is given by IΩ, where I is the moment of inertia and Ω the angular velocity,
- It remains constant in the absence of external perturbations.
- Ω will therefore react to changes in I and will increase, when the moment of inertia decreases.
- This happens episodically in the superfluid core of the neutron stars as the star adapts to its slowing rotation.
- Glitches are therefore interpreted as the consequence of “star quakes” in isolated neutron stars.

Superfuids

- For temperatures below 0.1 MeV, neutron fluid forms superfluid.
- This will affect specific heat and neutrino emissivities
- The superfluid may form a reservoir of angular momentum, which leads to pulsar glitch phenomenon. This is an occassional disruption of the otherwise regular profiles of pulsars, and change of the rotational frequency



Magnetic Dipole Model

- Magnetosphere is dipole, $B(r) \sim B_0 (r/R)^{-3}$
- Magnet releases electromagnetic power per unit area, $S \sim c/B^2$ (Poynting flux)
- Rotational energy change, $I\Omega(d\Omega/dt)$ is related with dipole moment, $|m| = (BR^3)/2$
- Estimated intensity of magnetic field at the star surface:

$$\boxed{B_0^2 \approx c^3 \frac{I}{R^6} P \dot{P}}$$

Magnetic field intensity

- In the case of the Crab pulsar P = 33 ms and dP/dt = 4.22×10^{-13}.
- Assuming a radius of 10 km and a mass 10^{33} g for the neutron star, the moment of inertia of the pulsar is $I \simeq 1.4 \cdot 10^{45}$ g cm^2.
- This gives $B \sim 5.2 \times 10^{12}$ G. This value is remarkably close to the one found when observing cyclotron emission lines in X-ray sources.

Does pulsar have atmosphere?

- The surfaces $\mathbf{E}\cdot\mathbf{B}=0$ are of particular interest because the velocity changes sign when the particle crosses this region. It is called a force-free surface and represents trapping regions for those particles
- There must be sufficient amount of plasma to shield the E field component in direction of B (Jackson 1976)
- Estimated thickness of an atmosphere: 50 cm

Pulsar radiation

- Goldreich & Julian model (1969)
- Electric field is generated, E= v x B. Charges orient on stars surface to cancel induced E.
- Electric field potential:

$$\boxed{\phi = -\frac{B_0 \Omega R^5}{6 r^3}\left(3\cos^2\theta - 1\right)}$$

- Magnetic field is continuous on the surface: no surface electric current
- Transverse electric field discontinuity → surface charge density

Pulsar magnetosphere

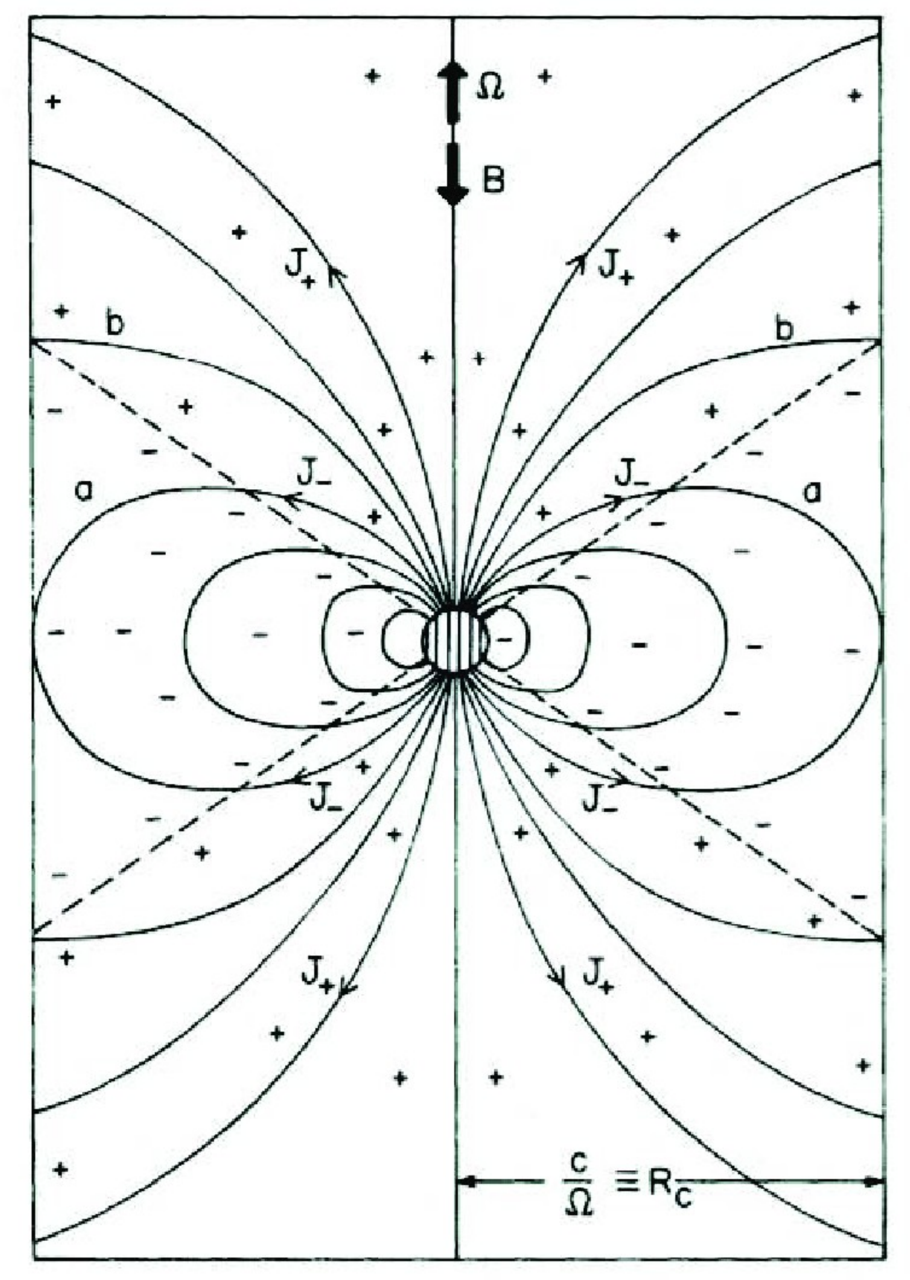
- Surface charge is not in equilibrium
- Electric force component along the magnetic field lines exceeds the gravity force:

$$\frac{e\,E_r}{GM\,m_e}R^2=\frac{e\,\Omega\,R^3\,B}{G\,M\,m_e}\approx 10^{12}$$

- Charges are removed and leave the surface

Pulsar magnetosphere

- Charge separation
- Magnetosphere divided into 3 parts
- Polar regions occupied by posotive charges and equatorial region by negative charges
- Aligned dipole model: Ruderman & Sutherland (1975)



Light cylinder

- Charged particles moving along the magnetic field lines can only follow them for

  $r < R_{LC} = c/\Omega$

- At larger distances the rotating magnetic field lines that are each attached to a point on the surface of the star would move faster than the speed of light.

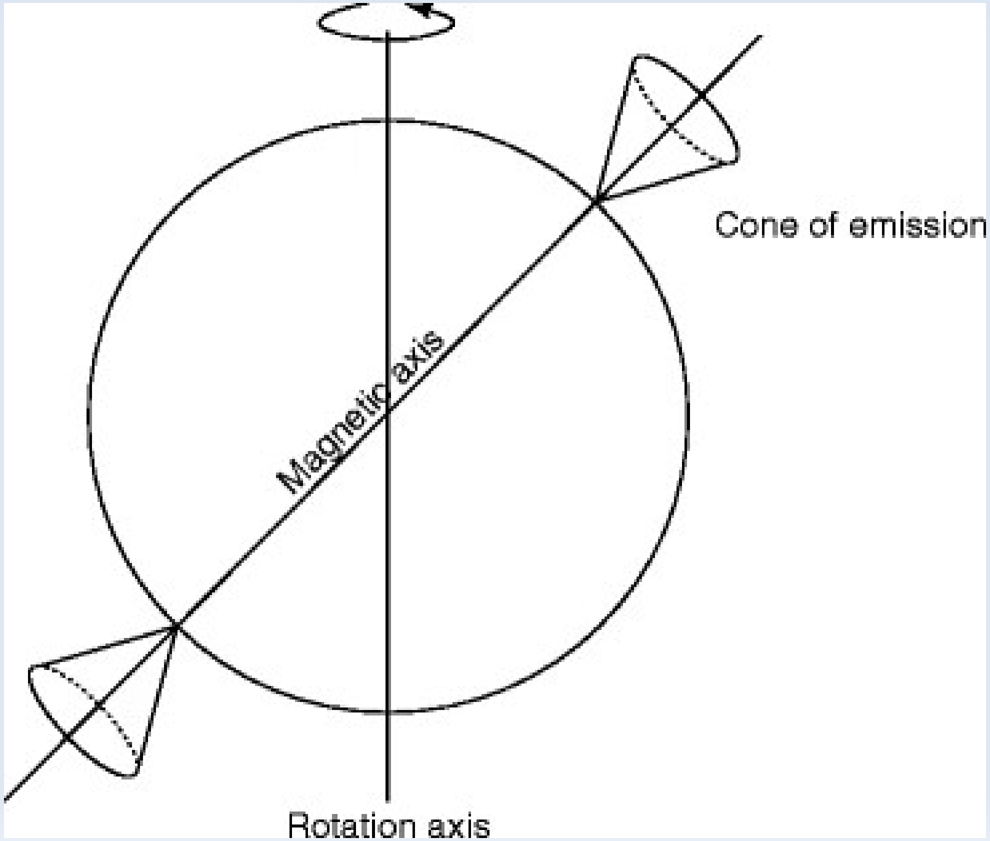
Lighthouse model

Geometrical arrangement of the line-of-sight, magnetic axis and rotation axis leads to a modulation of the emitted radiation with the period of the pulsar. The latter appears in the same way as a rotating light house.

A rotating neutron star with a misaligned magnetic dipole.

The radiation is modulated along the axis of the time variable magnetic moment.

The energy loss contains term related to misalignement angle, $\sin^2\alpha$



Polar caps

- Pulsar models studied particle (electron/positron) acceleration due to charge deficits at different locations in the neutron star magnetosphere
- PC model invokes formation of parallel electric field near magnetic poles

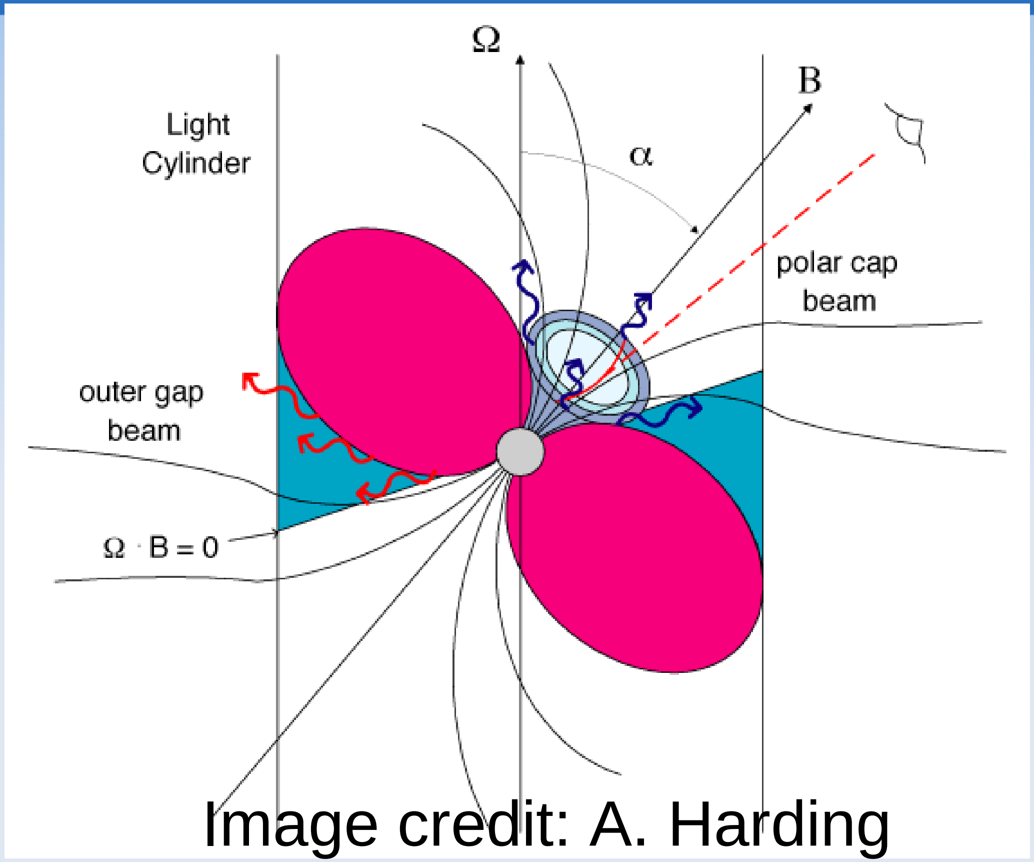
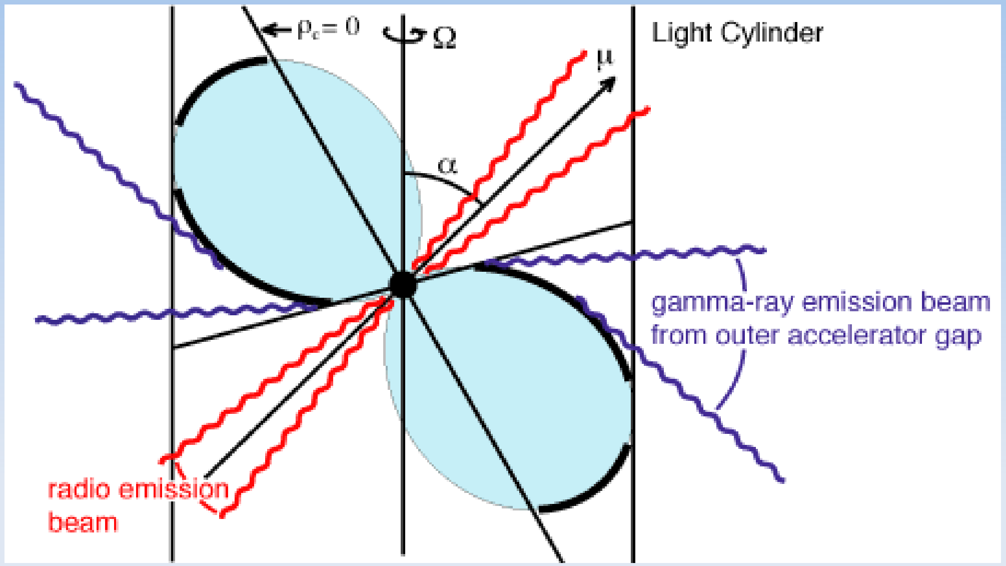


Image credit: A. Harding

Curvature radiation provides pair-producing photons. Inverse-Compton scattering of soft photons from NS surface by primary electrons can also be important.

Gap radiation



- Electrons can leave the suface, but ions (Iron atoms) are too heavy
- Potential gradient is created and gap forms
- In gap, E*B is nonzero

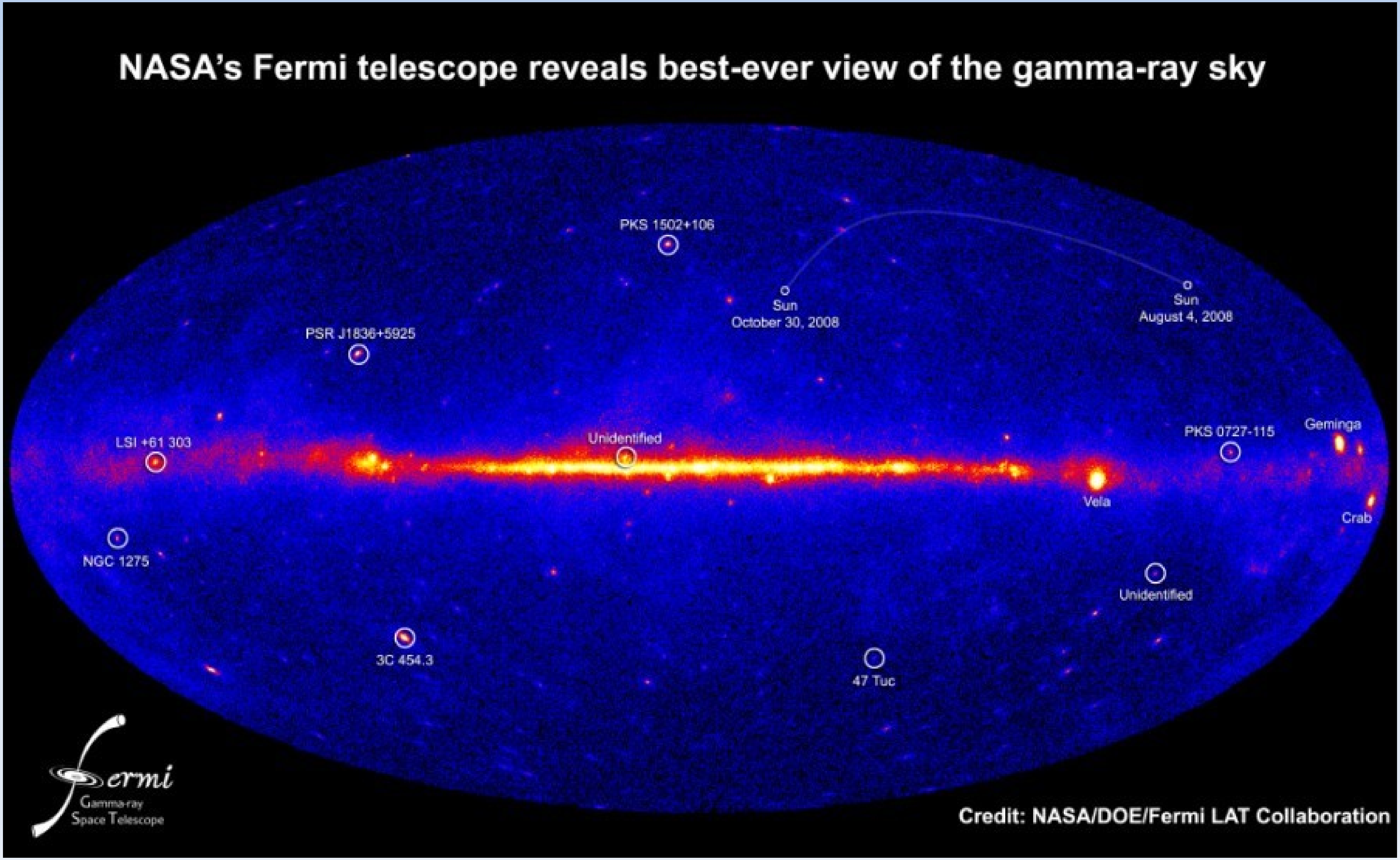
Gap thickness regulated by the potential gradient

Runaway process: electron positron pairs form photon cascades

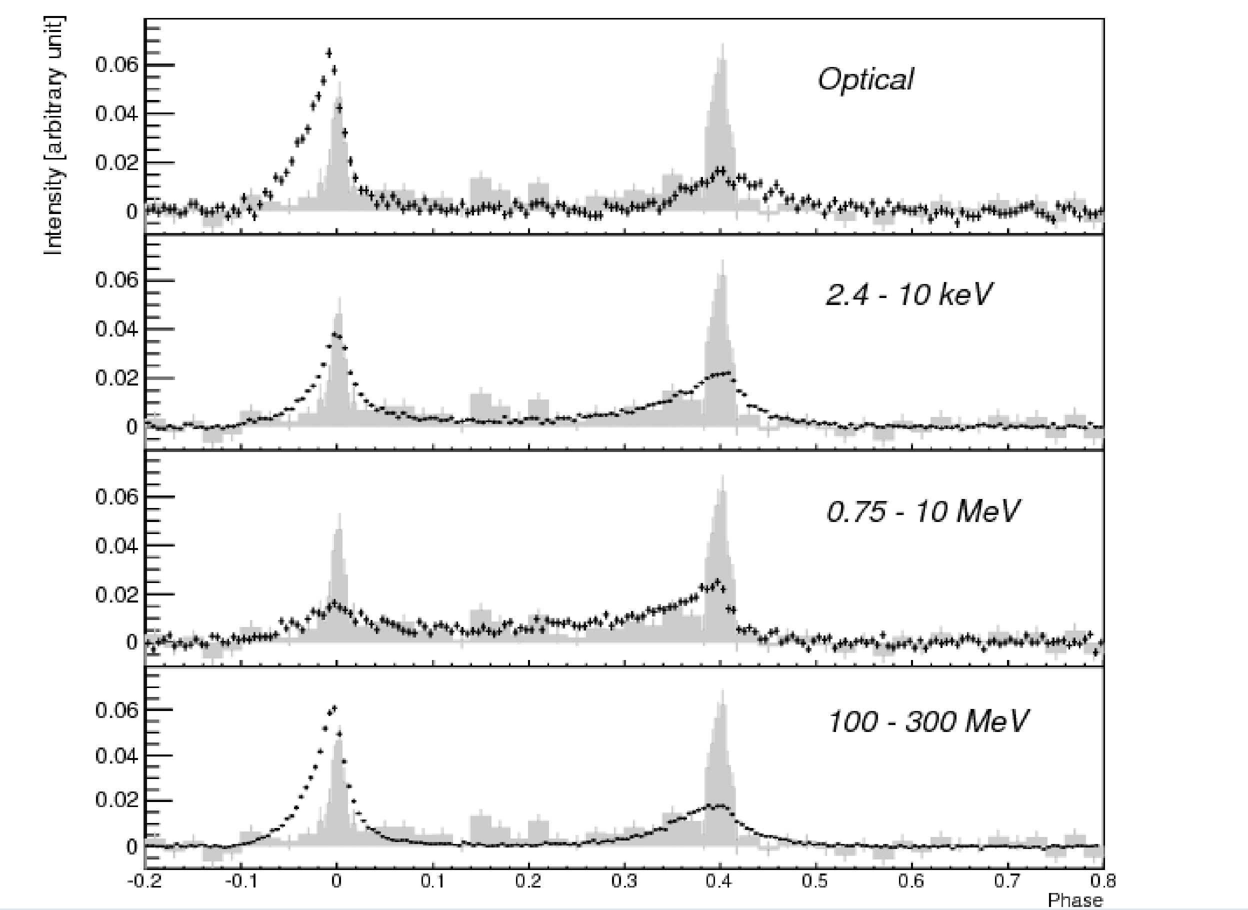
Gamma ray pulsars

- A few pulsars, can be observed not only in the radio domain, but also throughout the electromagnetic spectrum all the way to the hardest gamma rays.
- Shape of the pulse profile changes with photon energy → geometry of the emission region in the pulsar magnetosphere depends on the energy of the emitting electrons.
- Geminga was first of “unidentified” sources observed by EGRET in the 1990s, and in Cerenkov radiation on the ground at TeV energies in the 2000s.

Gamma ray pulsars

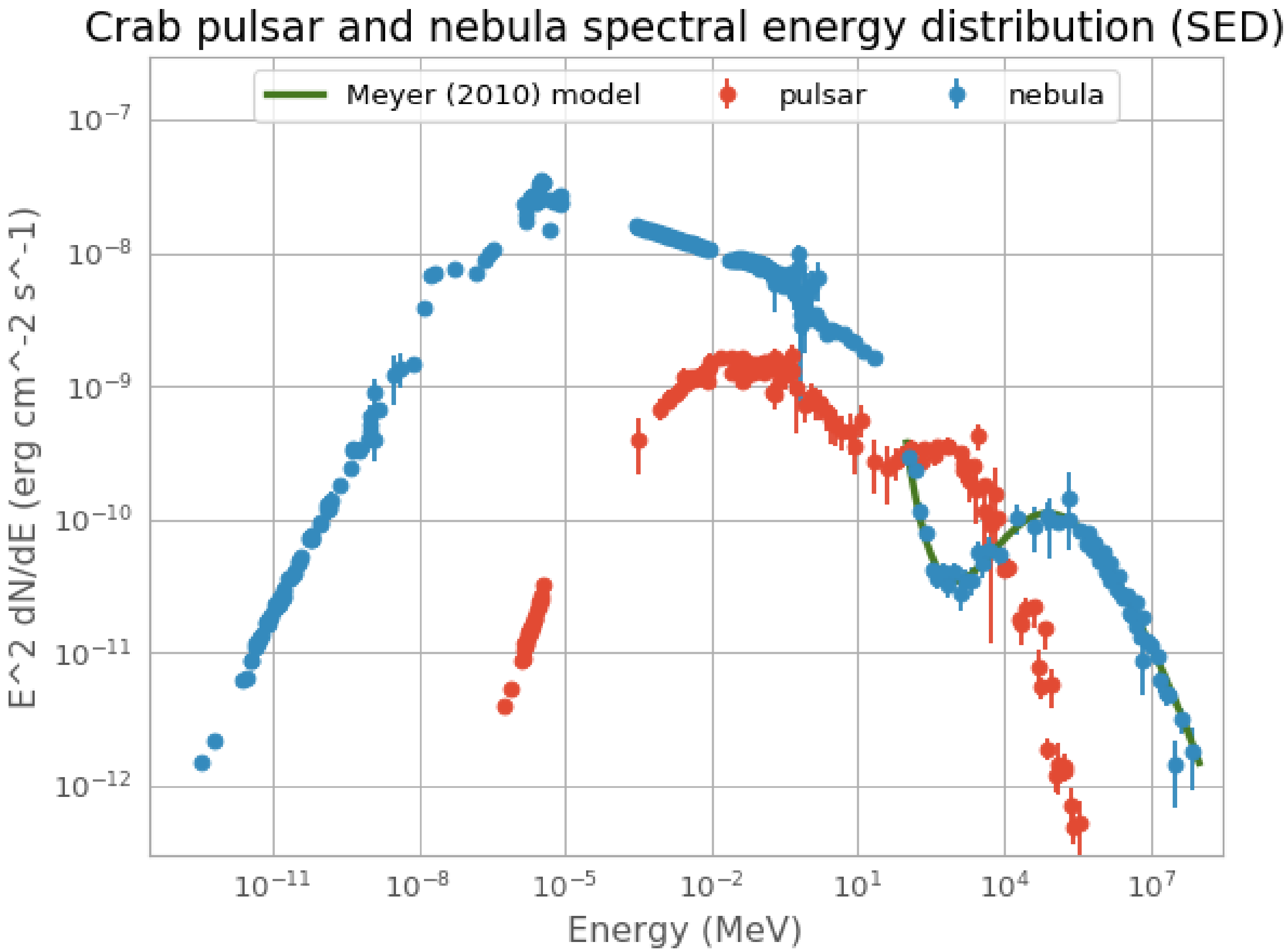


Crab at high energies



Light curve of the Crab pulsar at optical wavelength, 2.4 – 10 keV X-rays, 0.75 – 10 MeV, and 100 – 300 MeV gamma rays (from top to bottom). The light curve at 50 – 400 GeV is overlaid on each plot for comparison. The optical light curve was obtained with the MAGIC telescope using the central pixel of the camera [Lucarelli et al. 2008]. The keV and MeV light curves are from Kuiper et al. [2001]. The 100 – 300 MeV light curve was produced using the Fermi-LAT data. (Saito et al. 2015)

Crab spectrum



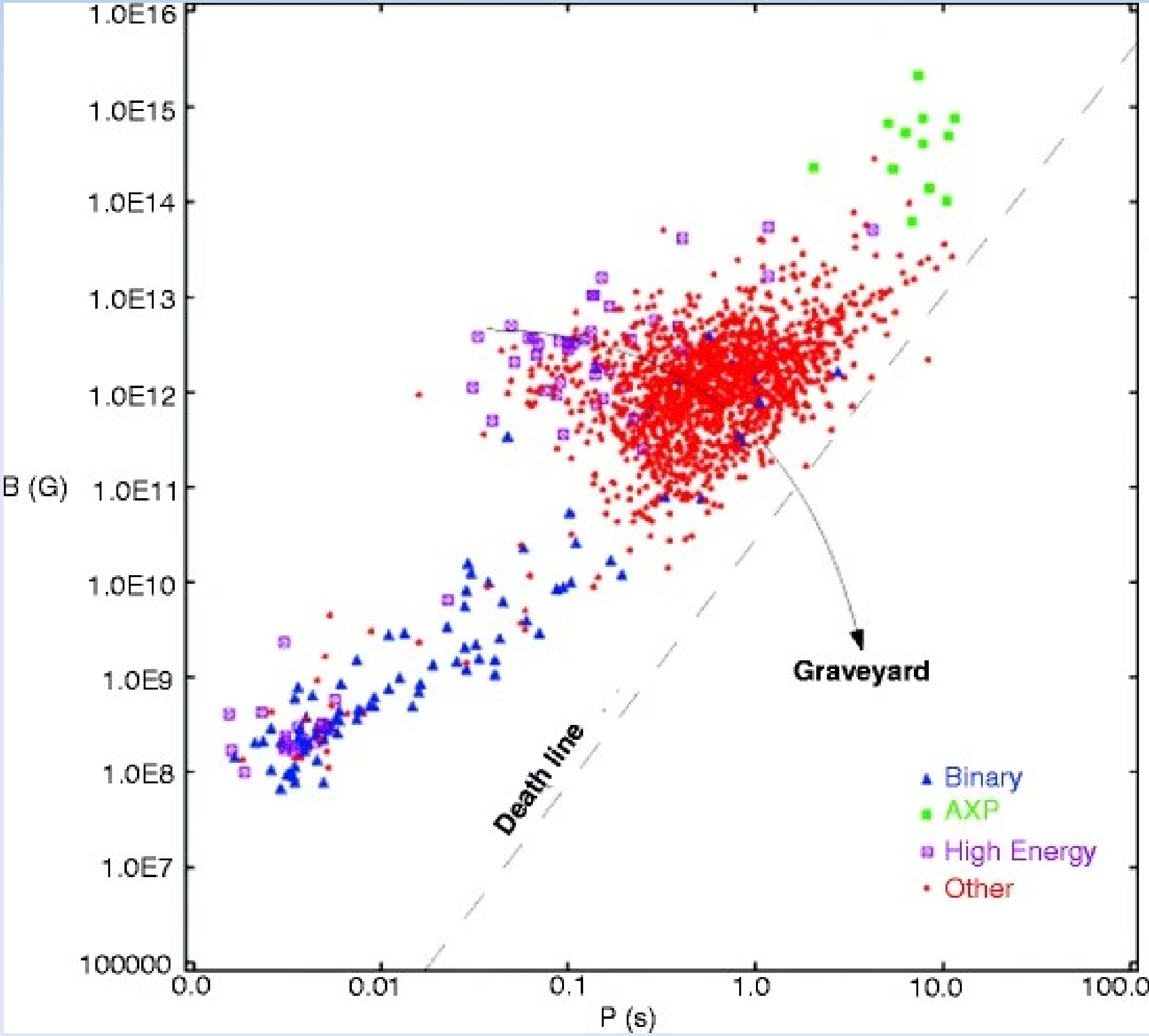
https://docs.gammapy.org/0.6/tutorials/crab_mwl_sed/index.html

Pulsar evolution

The magnetic field of the pulsars is advected from the original star and is locked in the star material.

In the absence of convection in the star no dynamo mechanism is possible, and the magnetic field can only slowly decrease with time.

As the pulsar slows down, its period increases. The resulting evolutionary path in a B versus P diagram will therefore be from the upper left corner towards the lower right.



Milisecond pulsars

- For a long time the Crab pulsar with a period P = 33 ms was the fastest known.
- In the 1980s, pulsars with P ~ few ms were discovered. They were called millisecond pulsars to distinguish them from the “normal” pulsars.
- They have very small period derivatives, which indicates weak magnetic fields, of the order of 10^8 G.

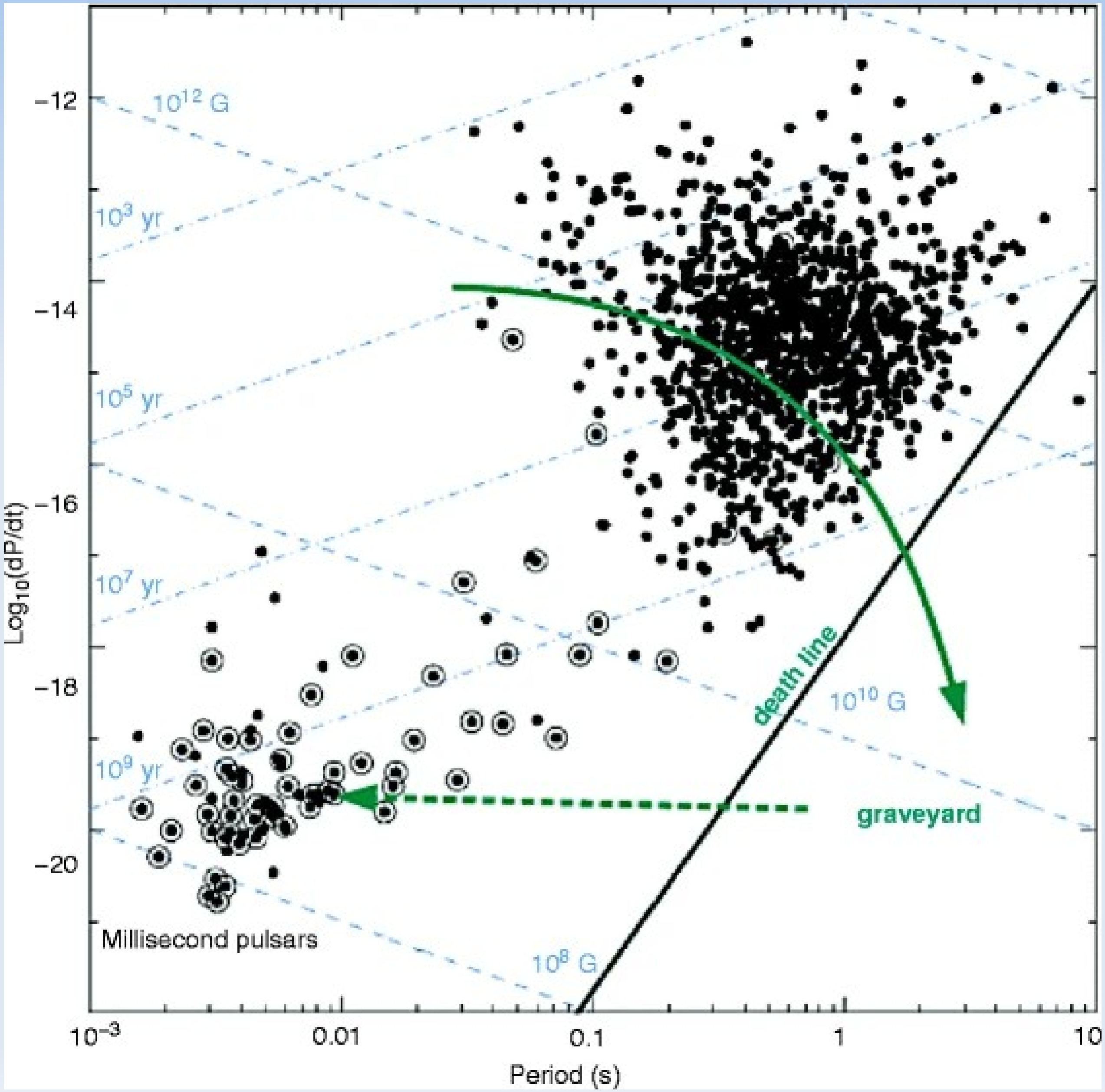
Origin of millisecond pulsars

- If the pulsar is in a binary system with a low mass normal star companion, the companion will eventually evolve to the red giant stage and fill its Roche lobe.
- The binary system then becomes a LMXB with a neutron star that radiates through accretion (and nuclear reactions).
- As the neutron star accretes material it will also accrete angular momentum. Since the magnetic field is weak, matter is locked to the magnetic field close to the neutron star, and the neutron star rotation will spin up.

X-ray pulsars

- Radio pulsars, pulsars in short, must be distinguished from X-ray pulsars, which also show regular pulses, however in the X-ray part of the electromagnetic spectrum.
- The physics of these latter objects is very different from that of the radio pulsars

Pulsar graveyard



P versus Pdot diagram for pulsars.

Lines of constant age and constant magnetic field are shown.

Pulsars in binary systems are encircled.

Pulsars evolve following the arrows

(Seiradakis & Wielebinski, 2004).

Next lecture

- Gravitational waves

Further reading:

"Measurements of General Relativistic Effects in the Binary Pulsar PSR1913+16" Taylor, J.H., Fowler, L.A. and Weisberg, J.M. 1979, Nature 277, 437.

”Polar Cap Model for Pulsar High-Energy Emission”, A. Harding, A. Muslimov, 1998, arXiv:astro-ph/9802044