# PULSARS

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## Abstract

We give a brief account of various observational data about pulsars, of some of the conclusions one can derive from these data, about the nature of the pulsars, and in particular, of the properties of the binary pulsar PSR 1913 + 16.

In August 1967, Miss Jocelyn Bell, a young research student of Dr. Anthony Hewish (Hewish, Bell, Pilkington, Scott, Rollins 1978) at the Mullard Radio Astronomy Laboratory, Cambridge (U. K.) was studying interplanetary scintillations in the radio emission of radio sources of small angular size. These scintillations are caused by the solar wind clouds traversed by the Earth on its orbit around the sun. With the new telescope especially designed for this study, she observed sources, which emitted weak pulses which had an extremely well defined and constant period of the order of 1s. Due to the low and strongly fluctuating intensity of the sources it took until November/December 1967 before Miss Bell and the other radio-astronomers in Cambridge were convinced that they had discovered a new type of astronomical source. By that time they had also found that—apart from the Doppler effect caused by the Earth's motion around the Sun—there was no other Doppler effect so that an earlier suspicion that the pulses might be signals from an extraterrestrial civilization, orbiting a distant star, could be laid to rest.

Miss Bell's discovery sparked off a large amount of observations and by now several hundred pulsars are known. The name pulsar was coined by Drake in April 1968. The observational properties of pulsars are now well charted and as a result theorists are strongly restricted in their attempts to explain the pulsar emission. The pulsars are nowadays indicated by the three capitals PSR followed by six numbers indicating their position in the sky. For instance, PSR 1133 + 16 has a right ascension $\alpha = 11^{h}33^{m}$ and a declination $\delta = +16^{\circ}$.

In a list of the observational properties we must first of all mention the pulse period P which is typically of the order of 1s and ranges from 33ns to about 4s with by far the most pulsars having periods between $\frac{1}{4}$s and 2s. As we mentioned earlier, P is extremely constant and in many cases is known with a very large accuracy with, for instance, the period of PSR 0301 + 19 being given as 1.387 583 579 43 with an error of 0.02 ns !

The three pulsars with the shortest periods are possibly also the most interesting ones and are the ones to which we shall return a number of times. They are PSR 0531 + 21 with a period of 33ms, PSR 1913 + 16 with a period of 59 ms, and PSR 0833 — 45 with a period of of 89 ms.

When we state that the period is constant, we must make one (and in a few cases, two) proviso(s) : all periods show a steady increase $\dot{P}$ which is typically of the order of $10^{-14}$ to $10^{-15}$ and PSR 0531 + 21 and PSR 0833—45 have shown sudden decreases in period (glitches), after which the steady increase started again. The steady increase $\dot{P}$ can be related to a characteristic time-scale, $P/\dot{P}$, which is often referred to as the "age" of the pulsar. For typical values of P ($\sim$ 1s) and $\dot{P}$ ($10^{-15}$) the "age" becomes of the order of $10^{7}$ to $10^{8}$ years. PSR 0531 + 21 and PSR 0833 — 45 have, however, much lower ages; they have the lowest values of all $P/\dot{P}$ ratios, which in their case are, respectively, 2000 and 20000 years. Apart from these two pulsars (which have the shortest periods and the smallest ages (PSR 1913 + 16 is a special case as we shall see at the end of this paper) there does not seem to be any correlation between P and $\dot{P}$.

The pulse width is typically 3 to 4% of the period, independent of P. Each individual pulse shows a great deal of structure which varies from pulse to pulse, as does the total intensity of the pulse. The structure shows details down to time-scales of the order of micro-seconds. These details seem to be intrinsic and not due to instrumental noise. An interesting feature emerges when one integrates a few hundred pulses. For each pulsar a distinctive, characteristic pulse window emerges which might be called the signature of the pulsar. This pulse window stays unchanged over the years. There are a few pulsars such as PSR 0329+54 which have two characteristic windows, a normal mode which occurs for most of the time and an abnormal mode which occurs for a much smaller fraction of the time. Huguenin, Taylor and Manchester have shown that pulsars can be divided into three classes. Type S pulsars have a pulse window which has a simple shape with one sharp maximum, type C pulsars have a pulse-window shape which is complex with several maxima, while inside the pulse window of type D pulsars the subpulses drift systematically across

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the window, usually from a later to an earlier moment. Type S pulsars usually have a relatively short period.

Many pulsars show a high degree of (usually linear) polarization, especially type C pulsars. This is true not only of individual pulses, where polarizations of up to 100% are observed, but also of the integrated pulses, where again high degrees of polarization (well over 25%) are observed. It must be noted that some of the integrated pulsars show circular polarization. An interesting feature of the polarization data is that the position in the case of linear polarization often shows a monotonic, uniform change through the pulse. These polarization characteristics seem to be independent of the pulse—or subpulse intensity, being independent of whether one is dealing with the normal and the abnormal modes of those pulsars which have two modes, of the position of the subpulses in type D pulsars, or of the frequency at which the pulsar is observed.

Very early in the pulsar-observation programme the Molonglo-group in Australia found the pulsar PSR-0833—45 with the very short period of 89 ms which was situated in a region of complex radio-emission within the boundaries of the supernova remnant Vela X. This connexion between a supernova remnant and a pulsar—which we shall return to presently—led to the search for a pulsar in the Crab Nebula, the remnant of the supernova observed in 1054 AD by the Japanese and shortly afterwards by the Chinese. This led to the discovery of PSR 0531+21, the pulsar with the shortest known period. The Crab pulsar is also known to pulse in the optical, X-ray and $\gamma$-ray band and the Vela pulsar emits $\gamma$-ray pulses and optical pulses. Most pulsars are observed only in the radio-band—the so-called X-ray pulsars fall outside the discussion of the present survey. They have been observed in the whole band from around 40 MHz to 8 GHz and there are several frequency effects. The pulse window at different frequencies is practically the same with a slight widening at lower frequencies—not to be confused with the broadening to be discussed in a moment.

The first frequency effect we want to mention is the difference in arrival time of pulses at different frequencies. This effect, like the next two to be discussed, is due to the fact that the dielectric permittivity of the interstellar medium is different from unity. The difference is small, as the medium is a very dilute plasma, but it is sufficient to produce over the distances of a few hundred parsec, which the signal from the pulsar must travel before reaching the Earth, a measurable retardation. The retardation is inversely proportional to the square of the frequency of the signal and proportional to the column density of the electrons. If we assume the electron density to be constant to first approximation, the time lag is directly proportional to the distance of the pulsar to the Earth and can thus be used to determine this distance. In many cases, one has more detailed knowledge about the electron density distribution and hence one can arrive at a more accurate distance determination. In passing we may mention another method for determining pulsar distances by using 21cm measurements. We saw earlier that the pulsar emission characteristically takes up about 4% of each period. During the 96% when the pulsar is switched off, we can observe the 21cm line in emission which gives us information about the neutral hydrogen distribution in the direction of the pulsar, both up to the pulsar and beyond it. During the 4% of the period when the pulsar is emitting, one observes the 21cm line in absorption. By comparing the two sets of data one can then determine the position of the pulsar relative to the neutral hydrogen concentrations.

The next frequency effect due to the interstellar plasma is the broadening of the pulses. This is due to the fact that the plasma density is not constant. This means that the dielectric permittivity in the interstellar medium has fluctuating values leading to a scattering of the radio wave. As the deviation of the dielectric permittivity from unity is inversely proportional to the square of the frequency, the scattering and thus the broadening will be the more pronounced the lower the frequency and, of course, also the longer the distance of the pulsar from the Earth. The observed effect is, in fact, in excellent agreement with theoretical results. This broadening also leads to an apparent decrease in the intensity of the pulsed component at low frequencies. The frequency spectrum, in general, decreases with increasing frequency.

Let us now discuss what we can conclude about the nature of the pulsars from the observational facts. The extreme constancy of the period P means that we must look for a very strict time-keeping mechanism for which we can take orbiting, pulsating or rotating bodies. As the period is of the order of 1s, we must look for the first mechanism to very tight orbits. If we take this to an extreme, we consider two masses M with radius R which are orbiting at a distance apart of their two centres of 2R, so that they are, in fact, touching. In that case we get for the period the relation

$$P = (8\pi^2 R^3/GM)^{1/2} = (6\pi/G\rho)^{1/2} \approx 2\times10^4 \rho^{-1/2}\mathrm{s}, \quad (1)$$

where G is the gravitational constant and $\rho$ the average density of the mass M in g/cm$^3$. If P is of the order of 1s, we need $\rho$ at least of the order of $10^8$ g/cm$^3$ which indicates strongly condensed bodies such as white dwarfs or neutron stars. We must note that the period of the pulsations of a mass of average density $\rho$ is given by a formula very similar to equation (1).

Before discussing orbiting, pulsating, and rotating white dwarfs or neutron stars let us briefly discuss stellar evolution. When a star has burnt up its nuclear fuel it will contract. This will be all right up to an average density of the order of $10^9$ g/cm$^3$ the pressure of the electrons in the Fermi sea can balance the gravitational pressure. This will be the end result for stars of masses of up to about 1 solar mass : a white dwarf, and these have been observed. If further collapse occurs, the electron pressure is insufficient to counteract the gravitational pressure and the collapse will continue until a density of $10^{13}$ g/cm$^3$ is reached when the pressure in the nucleon Fermi sea will provide the balancing; the result is a neutron star. This is the end product of a star with a mass between about 1 and about 10 solar masses. The collapse is quite violent, corresponding to a supernova outburst. The neutron star which is left behind has a mass of the order of one solar mass and a radius of the order of 10km. For heavier stars, the kinetic energy of collapse will be so large and the gravitational forces so strong that the internal pressure is not able to overcome the weight of the overlying layers and the star, with its internal density approaching a value of about $10^{16}$ g/cm$^3$, will possibly end up as a black hole.

Let us now consider the various possibilities for time-keeping mechanisms. The orbiting mechanism can be dismissed very easily : if two condensed bodies orbited with such a short period, they would lose energy through the emission of gravitational waves at such a rate that $\dot{P}$ would be much larger than is observed. The pulsating mechanism is also unsuitable. The sign of $\dot{P}$ is wrong, as pulsations would get faster, if there were damping present. Secondly, the pulsational period of white dwarfs is at least 2s, if one takes relativistic effects into account and that of neutron stars of the order of a few ms. Finally, we can rule out rotating white dwarfs : a white dwarf rotating with a period of less than 5s would be rotationally unstable. By elimination we have thus arrived at a rotating neutron star. It is interesting to note that before the discovery of pulsars neutron stars had not been observed, although Landau had suggested their existence already in 1932. The fact that pulsars are neutron stars also explains, of course, the connexion between pulsars and supernova remnants. It is interesting to investigate whether the number density of pulsars and their probable age agrees with the supernova outbursts in our galaxy. Pulsars are relatively weak emitters so that we can only be certain of having observed all, or practically all, pulsars up to, say, 500 pc from the Sun. Guseinov and Kasumov (1978) estimate the total number of pulsars in our Galaxy to be about $2\text{x}10^5$ and their life time to be about $10^7$ years. This would mean a birth rate of about one or two per century, in good agreement with the rate of supernova explosions in a galaxy such as ours. Another consequence of the supernova origin of pulsars would be that one would expect quite large velocities which would be reflected in measurable proper motions. It is therefore interesting that Gullahorn and Rankin (1978) from proper motion measurements have found pulsar velocities of the order of several hundreds km/s.

A rotating neutron star is an axially symmetric object and we therefore need something to break the symmetry. The obvious thing is a magnetic moment with the magnetic axis at an angle to the rotation axis. In fact, it is well known that the magnetic axis of many magnetic stars makes an angle of the order of $\pi/2$ with the rotational axis. The high degree of polarization also indicates the presence of a magnetic field. There are several indications that the maximum magnetic field strength may well be extremely large. The first argument is a theoretical one, any by itself not a very convincing one. If one assumes that the star before collapsing had a radius of the order of the solar radius ( $\sim 10^{11}$cm) and a maximum field of the order of 100 to 1000 gauss, and if one assumes that during the collapse (that is, during the supernova outburst !) magnetic flux is conserved, which means that $HR^2$ is a constant, the final magnetic field will come out to be of the order of $10^{12}$ to $10^{13}$ gauss. The second argument is based on energy arguments. As the period increases, the pulsar loses rotational energy at a rate given by the equation

$$dE_{rot} / dt = - 4\pi^2 \, I\dot{P} / P^3 , \qquad (2)$$

where I is the moment of inertia of the pulsar. We can equate this to the loss of energy due to the emission of electromagnetic radiation by the rotating magnetic moment, given by the equation

$$dE/dt = - 32\pi^4 \, M_{\perp}{}^2 / 3c^3 P^4 , \qquad (3)$$

where c is the velocity of light and $M_{\perp}$ the component of the magnetic moment at right angles to the rotational axis. If we put $dE_{rot}/dt$ equal to $dE/dt$ and take $M_{\perp} \sim H_{max} R^3$, $I \sim MR^2$, $P \sim 1$ s, $M \sim 1$ solar mass, $R \sim 10^6$ cm, we find

$$H_{max} \sim 10^{19} (\dot{P}/P)^{1/2} \text{ gauss} \backsim 10^{12} \text{ gauss}. \qquad (4)$$

We note that, if $P/\dot{P}$ truly reflects the age of the pulsar, the maximum magnetic field strength will decrease with increasing age and hence their luminosity will probably also decrease with time—if we assume that a more or less constant fraction of the energy loss is converted into the pulsar radio luminosity. The final argument in favour of $H_{max}$ of the order of $10^{12}$ gauss is the observation of spectral structure of the $\gamma$-ray emission of the X-ray source Her X-1 corresponding to an energy of the order of $10^4$ to $10^5$ eV, which in turn corresponds to a magnetic field of the order of $10^{12}$ to $10^{13}$ gauss.

The next question is how to explain the observed radio emission. This question is still far from satisfactorily answered. We first of all note that rotating magnetic neutron stars are likely to have extensive atmospheres. It was originally thought that neutron stars would only have a very thin atmosphere because of the huge gravitational field. However, a magnetic field of about $10^{12}$ gauss rotating with a period of the order of 1s will produce an electric force on an electron which is about $10^8$ times the gravitational force acting on it. This electric field is large enough to sustain a magnetosphere with a density of the order of $10^{10}$ particles/cm$^3$. The situation is, however, more complicated and the present consensus is that in the neighbourhood of the magnetic pole a gap will occur and that in that gap charged particles moving along the curved magnetic filed lines will emit high-energy photons which in turn when crossing the field lines will produce electron-positron pairs. This is essentially the theory first proposed by Ruderman and Sutherland (1975) which was based on earlier ideas of Sturrock's (1971). Many of the details of the situation in the pulsar magnetosphere are very uncertain but what is certain is that the plasma in the magnetosphere will be highly turbulent so that it is likely that all kinds of plasma processes may be involved. The question which is also undecided is the place where the radio emission takes place. Some people feel that the emission takes place well away from the pulsar surface near the so-called light cylinder where particles which are corotating with the pulsar would reach velocities equal to the velocity of light. Others feel that the emission takes place near the pulsar surface. We want to make two remarks here. Firstly, it does not seem unlikely that there may well be at least two main mechanisms for the radio emission, perhaps leading to the type S and the type C pulsars. Secondly, if one accepted the light-cylinder emission it would be hard to understand why not all pulsars have the same pulse window shape. Hence, it looks to us as if, even if type S pulsars produce their radio emission near the light cylinder the emission by type C and type D pulsars must taken place near the pulsar surface. Of course, if the emission is produced near the pulsar surface one must also carefully study the propagation of the radiation through the magnetosphere—a far from simple problem. We should also point out that the radio luminosity of the pulsars corresponds to brightness temperatures of the order of at least $10^{21}$ K so that one has to look for coherent emission mechanisms—either an antenna mechanism where the coherence is produced by particle bunching or a maser mechanism where negative absorption plays an important role, Both kinds of theories have been considered, but so far nobody has produed a theory which is accepted by the majority of people.

To conclude this paper we shall consider the properties of the second fastest pulsar, PSR 1913+16. This pulsar was discovered by Hulse and Taylor in July 1974 and found to show an orbital Doppler shift. This meant that they had discovered a pulsar which was part of a binary system. The observations corresponded to those of an ordinary binary where one observes the spectrum of one of the stars. This means that one can determine only some of the parameters of the binary system, or a combination of them. However, as we shall see presently, this is a very special binary and as a result pulse arrival-time data spanning just over 4 years enabled Taylor, Fowler, and McCullough (1979) to determine some extra parameters of the system.

Let us first of all summarize the position as it was soon after the pulsar had been discovered. The pulsar period P was, of course, known, and its derivative $\dot{P}$ was found to be small. From the Doppler shift the velocity curve was determined and hence several parameters of the orbit. The orbital period $P_{orb}$ was found to be about 8 hours, the eccenticity, e, about 0.6 and the projected semi-major axis, a sin i, about one solar radius, where a is the semi-major axis and i the inclination of the orbit to the plane of the sky. The longitude of the periastron $\omega$, was about 180° and its rate of change, $\dot{\omega}$, a few degrees per year. The total range of radial velocities was about 400 km/s, that is, more than 0.001 times the velocity of light. From Kepler's third law and these data one finds the mass function $f=(m_c \sin i)^3 / (m_c+m_p)^2$, where $m_p$ and $m_c$ are, respectively, the masses of the pulsar and of its binary companion. It turns out that f equals about 0.1 $M_\odot$, where $M_\odot$ is the solar mass.

From these data one can already reach many conclusions. The large radial velocities indicate that i cannot be very small, while the absence of eclipses shows that i cannot be too near $\pi / 2$. It then follows from the value of f that $m_c / m_p$ must be of the order of unity. We can go further. from the value of a sin i it follows that the radius of the companion must be less than a solar radius and that in itself excludes the possibility of the companion being a main-sequence star. This conclusion is further strengthened by the magnitude of $\dot{\omega}$ If the companion were a main-sequence star, $\dot{\omega}$ would be due to tidal effects and be at least three or four orders of magnitude larger than its observed value. The companion must thus also be a neutron star.

Once it was known that one was probably dealing with two neutron stars orbiting around one another at a distance of about one solar radius, one realized that we had here a nearly ideal relativity laboratory : an accurate clock moving at high speed in an eccentric orbit and in a strong gravitational field. The first results of an analysis of gravitational effects have just been announced by Taylor, Fowler, and McCullough (1979) and we shall now describe their work in some detail. Taylor and his collaborators used arrival-time data for the 4 years from 1974 to 1978. Apart from corrections due to the Earth's motion around the Sun and the dispersion effect of the interstellar medium, the proper time in the pulsar's frame of reference had to be corrected for the projection onto the line of sight—an effect of first order in v/c, where v is the pulsar velocity—, for the integrated effects of gravitational redshift and the transverse Doppler shift in the highly eccentric orbit—of second order in v/c—, and for the gravitational propagation delay—of third order in v/c. The arrival time is a function of various parameters, among which are P, $\dot{P}$, a sin i, e, $P_{orb}$, $\omega$, $\dot{\omega}$, $\dot{P}_{orb}$, sin i, and the transverse Doppler and gravitational redshift, $\Upsilon$. These parameters have now been determined with a great accuracy. For instance, P=0.059 029 995 269 with an uncertainty of 2 in the last decimal, $\dot{P} = 8.6 \times 10^{-18}$, e = 0.617, $P_{orb}$ = 27907s, $\omega = 179°$, $\dot{\omega} = 4.23$ deg/yr, sin i = 0.81 ± 0.16, and $\dot{P}_{orb} = -3 \times 10^{-12}$ ( we have not given all decimal places or errors, except in the two cases of P and sin i). The quantity sin i can be measured separately because it affects the gravitational propagation delay and the changes in the elliptical orbit due to general relativistic effects. The quantities $\Upsilon$, $\dot{\omega}$, sin i, and $\dot{P}_{orb}$ can be expressed as functions of $m_c$ and $m_p$— assuming general relativity to hold and we can thus use them to determine $m_c$ and $m_p$ separately. It turns out that the values of these four quantities are consistent with one another and with $m_c$ and $m_p$ both being equal to 1.4 $M_\odot$ .

Perhaps the most important result is that the orbital period decreases at a rate which is exactly that which would follow from general relativity, if the decrease were due to the emission of gravitational waves : an indirect proof of the existence of gravitational waves. Moreover, the magnitude of $\dot{P}_{orb}$ is such that practically all other theories of gravity are excluded.

There is one last general relativity effect which seems to be observed. The theory predicts that due to the spin-orbit coupling the pulsar rotational axis should precess at the rate of about 1 deg/yr. This would entail that we will be looking at different parts of the pulsar beam, which would lead to slow changes in the pulse-window shape. This has, indeed, been observed.

It should be realized that we have confined our attention, in this review, to the pulsating *radio* sources, In the last few years the X-ray pulsars like Her X-1 and Cen X-3 are revealing a good deal of information about the physical characteristics of neutron stars in a binary system.

To conclude let us sketch a scenario, due to de Loore, de Greve, and de Cuyper (1975) which may lead to a binary system such as PSR 1913+16 seems to be. They suggest that one starts with a binary consisting of one star of 20 $M_\odot$ and one of 8 $M_\odot$. Their separation d is 35 $R_\odot$ where $R_\odot$ is the solar radius, and $P_{orb} = 4.5$ days. Mass transfer from the heavy to the light star will occur for about 6 million years leading to a helium star of 5.4 $M_\odot$ and the second star having a mass of 22.6 $M_\odot$. At the end of this stage $P_{orb} = 11$ days and $d = 62\ R_\odot$. After just under a million years the helium star becomes a supernova, a neutron star of 2 $M_\odot$ with $P_{orb} = 12$ days and $d = 69\ R_\odot$. After 4½ million years the second star finishes its hydrogen burning, becomes an OB supergiant, producing a strong stellar wind which leads to the neutron star emitting strong X radiation like Cir X-1. After a period of about 20000 years matter start leaving the system. During the next 30000 years the system, finally consisting of a helium star of 6.3 $M_\odot$ and the neutron star surrounded by an envelope, looks like a WR star. At the end of the period $P_{orb} = 1$ hour and $d = 1.35\ R_\odot$. The envelope is blown off and for a short period the system looks like a short-period X-ray binary like Cyg X-3. Finally the helium star explodes leaving two neutron stars of 2 $M_\odot$ with $P_{orb} = 8$ hr, $d = 3\ R_\odot$ and an eccentricity $e = 0.58$, provided the second neutron star gets a velocity of 150 km/s in the right direction.

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