Chapter XII - Pulsating Radio Sources (Pulsars)

Unlike the quasi-stellar objects whose baffling nature was only revealed step-by-step as their story unfolded gradually over a period of several years pulsating radio sources (pulsars for short) appeared on the scene as a strange and completely new class of object right from the outset. Their discovery was announced by radioastronomers of the Mullard Radio Astronomy Observatory at Cambridge England in a single letter to the editor of the English scientific weekly "Nature" on 24th February 1968, and so great has been the interest aroused by these unusual objects that they have been featured in practically every subsequent issue of "Nature" for at least the ensuing twelve months.

The remarkable characteristic of pulsars which led to their discovery is their emission of pulses of radio frequency energy of duration only a few hundredths of a second with clock-like precision at intervals of around one second, and their detection was a triumph for the giant radio telescope (consisting of an array of 2048 dipoles arranged in sixteen rows each of 128 elements) which began operation at Cambridge in July 1967. As we saw in Chapter 3 radio astronomers radio receivers in which it is customary to integrate the signals for lengthy periods as a means of improving the ratio of signal to noise: provided the "wanted" signal is relatively steady this practice results in a much-needed increase in sensitivity. The new Cambridge aerial however was designed to study the structure of radio sources by observing the rapid variations in signal strength, or scintillations which are due to moving plasma clouds in the interplanetary medium. Its receiver and recording equipment were accordingly designed to have a very short time-constant so that they would respond to rapidly varying signals and it was this factor in particular which made possible the detection of pulsating signals which could have been blurred together - and their novel characteristic lost - in most conventional radio astronomy receivers. As soon as the discovery was announced these "radio clocks" in the skies, continuously beaming "pips" at us with such remarkable regularity, were inevitably seized upon by the popular press as evidence of civilizations on other planets endeavouring to attract our attention. We shall see below, however, that this interesting possibility can easily be ruled out on a number of grounds.

The initial detection was made during a new survey of the sky between declinations 8° south and 44° north, this area ~~has~~ being scanned regularly once a week. Not long after observations began it was noticed that signals which had the appearance of weak sporadic interference sometimes appeared, and always at the same declination and right ascensions i.e. they could not be of terrestrial origin. Systematic study of these signals soon showed that they consisted of short pulses of about one third of a second's duration and that they came in groups spaced from each other very accurately at a repetition period of about 1.33 seconds. Observations over a longer period showed that the repetition rate was remarkably constant, to better than 1 part in 10^7, although there was a systematic variation which appeared to be due to the Earth's motion in its orbit. The possibility that the signals might indeed be manmade transmissions from space probes, from radars used for planetary studies, or from reflection of terrestrial signals from the Moon (sometimes a source of interference in radioastronomy observations) were ruled out because the absence of any parallax i.e. apparent movement of the source due to the Earth's motion indicates that the source lies far outside the solar system. And so Hewish and his colleagues, convinced that this object was extraterrestrial announced to the world the discovery of yet another totally unexpected kind of celestial body - with a hint that there were at least three other such objects. For some time these four pulsating sources, designated CP 0834, CP 0950, CP 1133, and CP 1919* (the last named being

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*The prefixed letters CP stand for Cambridge Pulsar and the figures the hours and minutes of right ascension. Later discoveries were similarly designated by letters signifying the observatory which discovered them e.g. AP Arecibo, HP , JP Jodrell Bank, MP Molonglo, NP , PP . The later and

FOOTNOTE (contd)

preferred designation is PSR (Pulsar) followed by the hours and minutes of right ascension then sign and ~~dxx~~ degrees of declination, (as used for all sources).

the first to be located) stood alone but as many of the world's largest telescopes took up the chase more were discovered. In Australia the mile-long arms of the Molonglo Cross proved to be well suited to the detection of pulsars and this instrument has a total of fourteen pulsars to its credit, more than one third of the total located by April, 1969. The 210-foot reflector at Parkes, with its ability to track objects across the sky for long periods, has also been active in precise determinations of the frequency at which some of them pulsate: the first detailed measurements of the polarization of individual pulses were also made at Parkes. Characteristics of the 37 pulsars known so far (April 1969) are listed in Table 1.

The Radio Frequency Emissions

The signals received from all the pulsating sources consist of series of pulses separated by a period which, except for several pulsars, is constant to 1 part in 10^7, or better. The pulses vary in duration for different pulsars from 2 to 200 milliseconds, and have a characteristic shape for each source. In many cases this is a combination of two or more subpulses of unequal amplitude, and for several there is evidence of a small pulse in the interval between the main pulses. Fig. 1 is a section of a chart record taken at Parkes of the first pulsar to be discovered CP 1919. The gradual increase in amplitude of the pulses over a period of about one minute followed by a gradual decline is typical of the behaviour of this source: the signal is also present but at greatly reduced strength in the interval between the trains of stronger pulses. For other pulsars the pattern may be quite different and the intensity can remain almost constant for from 50 to 100 pulses, as for PSR 1833-45, or vary by a factor of 10 to 1 from one pulse to the next, as for example, for CP 0950+08 or CP 1133+16. No regularity has been detected in the periodicity of the fading, which cannot be ascribed to absorption or scattering by clouds of electrons in interstellar space. As the Earth follows its

Table 1

Characteristics of Known Pulsars

(as at April 1969)

Designation	R.A.			Dec.		Period (sec)	Pulse Width msec	Distance (pc)
	h	m	s	°	'			
MP 0031-07	00	31	37	-07		0.940	25	60
CP 0329+54	03	29	07	54	23	0.714518603	6	134
MP 0450-18	04	50	22	-18		0.548	20	125
NP 0526+21	05	26	10	21	58	3.745491	200	255
NP 0531+21	05	31	31	21	59	0.033094515	3	285
PSR 0628-28	06	28	53	-28	33	1.244	50	50
MP 0736-40	07	36	51	-40		0.375	40	500
CP 0808+74	08	08	58	74	38	1.292241325	45	30
AP 0823+26	08	23	52	26	48	0.53062	20	96
PSR 0833-45	08	33	39	-45	00	0.089208370	2	315
CP 0834+06	08	34	27	06	19	1.273763151	35	64
MP 0835-40	08	35	34	-40		0.765	20	600
PSR 0904+77	09	04		77	40	1.57905	<80	
MP 0940-56	09	40	40	-56		0.662	30	725
PP 0943+08	09	43		08		1.09		85
CP 0950+08	09	50	31	08	10	0.253065037	13	15
MP 0959-56	09	59	51	-56		1.438	50	450
CP 1133+16	11	33	27	16	08	1.187910980	38	24
AP 1237+25	12	37	17	25	10	1.3824	60	42
MP 1240-64	12	40	20	-64		0.388	60	1100
MP 1426-66	14	26	35	-66		0.788	10	300
MP 1449-65	14	49	22	-65		0.180	5	450
PSR 1451-68	14	51	29	-68	32	0.264	25	60
HP 1507+55	15	07	50	55	41	0.739677616	13	98
MP 1530-53	15	30	23	-53		1.372	25	100
AP 1541+09	15	41	10	09	38	0.74839	50	175
PSR 1642-03	16	42	25	-03	00	0.38765	5	200
MP 1727-50	17	27	50	-50		0.835	30	700
MP 1747-48	17	47	56	-48		0.742	20	200
PSR 1749-28	17	49	49	-28	06	0.5625533	6	254
MP 1818-05	18	18	14	-05		0.597	20	350
CP 1919+21	19	19	37	21	47	1.337301109	32	63
PSR 1929+10	19	29	52	10	53	0.226576	10	40
JP 1933+16	19	33	10	16	06	0.358764	6	715
AP 2015+28	20	15	58	28	31	0.557954	10	71
PSR 2045-16	20	45	48	-16	28	1.9615639	40	57
PSR 2218+47	22	18	18	47	30	0.538461	<30	219

NOTE: Where the period is given by more than 6 significant figures it has been corrected to the barycentre of the solar system, otherwise to the Sun only: where 5 or few significant figures are given no Doppler corrections have been made. Distances quoted are derived from dispersion measurements, assuming an electron density of 0.2 per cm^3. Pulse widths are full widths m at half intensity, and are indicative only because the profiles may vary from pulse to pulse and source to source.

path around the Sun it will pass in and out of "shadows" due to these electron clouds but simultaneous measurements made in Australia at Parkes and Culgoora 200 miles apart showed that the fading occurred simultaneously at both sites. Some at least of the variations in pulse amplitude which occur must thus be associated with the pulsar itself, and not with the intervening medium.

The fact that the radio emission from pulsars is polarized was ǂ first shown by using techniques which involved averaging a number of individual pulses. Radhakrishnan and his colleagues at Parkes were the first to report a high degree of linear polarization in the individual pulses, using the 210-foot radio telescope to study the pulsar PSR 0833-45. They found that this source (which is associated with the Vela supernova) is remarkable not only for its very short pulses and high and almost constant intensity, but that the pulses are almost one hundred per cent linearly polarized. They found, too, that the direction of polarization sweeps smoothly through almost a right angle during each pulse: as we shall see below these observations provide strong support for the idea that the source is a rotating neutron star.

One pulsar at least is known to emit light flashes which closely match the radio pulses, and the same pulsar is also a source of X-ray pulses. These are described more fully below.

Pulse Shape and Duration

Pulse profiles are obtained by superposing and averaging a large number of pulses. The average shapes for the original four pulsars CP 0834, 0950, 1133 and 1919 as recorded by the 250-foot radio telescope at Jodrell Bank are given in Fig. 2. These were recorded at a wavelength of 75 cms. The overall pulse durations vary, for 2 different pulsars, over thexxaxx range from 2 to 200 milliseconds but are remarkably constant for each source: for some the observed profile is clearly the result of two or more individual components of much shorter duration. The characteristic double pulse of PSR recorded at frequencies of 630 and 2650 MHz is shown in Fig. 3. In this illustration, to facilitate comparison of the profiles, the zeros of the time scales have been displaced by 113 milliseconds, the pulses at 630 MHz being delayed by this amount due to retardation in the intervening medium, as explained below. In general the average profile appears to be effectively independent of frequency, but there are several pulsars (fmx see for example Fig. 4) for which this is not the case.

The short duration of the pulses indicates that the size of the regions responsible for the radio frequency emissions must be very small by stellar standards, if we assume that the speed of travel of the disturbance which causes the emissions cannot exceed that of light. For an average pulsar emitting a 30 millisecond pulse the most distant edge of the source cannot be more than .030 times the velocity of light (i.e. 10,000 km) further away than the nearer edge. This is a good deal smaller than the Xxx Earth, and for the sources where the observed profile is a blend of several shorter pulses then the region producing the radio emissions must be comparable in size to the Moon.

Frequency of Pulsations

The period of the pulsations can be determined with very high precision by counting the total time elapsed for a large number of pulses. By tracking a source for several hours the period can easily be determined with a precision of 1 part in a million. This is sufficient to allow the counting of pulses to be resumed on successive days, and if this is continued for a week the accuracy is increased to 1 part in 2×10^8 while with a year's counting a precision of almost 1 part in 10^{10} is attainable. To arrive at the period of the pulsations at the source the apparent period derived by counting pulses must be corrected for the Doppler shifts introduced by the Earth's motion:

more pulses are received per second when the Earth is travelling generally towards the pulsar and fewer when, six months later, we are moving in the opposite direction. The Doppler effect can cause the apparent period to be in error by as much as 1 part in 10^4, an amount which is easily detectable after only an hour or two of observing. The fact that the period of the pulsations is constant when referred to the barycentre of the solar system (see Fig. 5) provides conclusive evidence that the pulsars cannot be space pulses or the like and must lie well outside the solar system.

The period of the pulsations varies over a wide range, the most rapid being an interesting source within the Crab Nebula, NP 0531+21, which pulses approximately 30 times a second, while the slowest NP 0526+21 takes 3.7 seconds to complete its cycle. The first four Cambridge pulsars appeared to be remarkably stable in frequency but observations over longer periods show that they are, in fact, slowing down. The source with easily the greatest variation is again NP 0531+21 in the Crab Nebula, whose xperiod is lengthening by as much as 1 part in 2400 per year. The rate of slowing down appears to be related to the pulse length and to the period which as we shall see below is consistent with Gold's hypothesis that pulsars are rotating neutron stars. On this theory those with the shortest pulse length are the youngest and subject to the greatest braking forces so they have the largest rate of change.

Distance

We saw above that the absence of any apparent movement of the pulsars due to parallax places them at a distance of at least one thousand times that of the Sun. Another estimate of the distance, in this case an upper limit, can be obtained from the observed delay in the time of arrival of a pulse with wavelength - pulses at a wavelength of 3 1/2 metres arrive more than 7 seconds later than the corresponding pulse at 10 cms. (See Figure 6.) This delay is due to the fact that impulsive radiation is dispersed or retarded during its passage through the ionized hydrogen which is present in the interstellar medium, the retardation being a function of the wavelength and the total ~~x~~ number of electrons in the path. The observed pulse delays are consistent with a virtually simultaneous origin of all wavelengths at the source and subsequent retardation in intervening space, so they can provide an estimate of the total number of electrons in a column of section 1 cm^2 between us and the pulsar.. A typical figure comes out to be around 2×10^{19} electrons per cm^2 column. The electron density in the neighbourhood of the solar system is known to be in the range 0.1 to 0.2 electrons per cm^3 so if all the delay occurs in the interstellar medium the length of the column, i.e. the distance to the source, can be determined. For CP 1919, assuming an electron density of 0.2 electron/cm^3, this distance curves out to be about light years. Our nearest stellar neighbour, α Centauri, the brighter of the two pointers to the Southern Cross, is 4.2 light years away and the centre of the Galaxy is 30,000 light years distant so the pulsars though not immediate neighbours are relatively local on a galactic scale. They are confined largely to the plane of the Milky Way, ~~xa~~ as can be seen from Fig. 7 which shows their distribution in galactic coordinates.

The distances derived in this way may well be in error by a factor of two or three, but there is little doubt that the stronger pulsars are relatively near to us. H-line absorption has been detected in the spectra of several pulsars and leads to distance estimates which appear to be somewhat greater than but in broad agreement with those derived from dispersion measures. Despite the fact that the positions of a number of pulsars are known to better than 1 second of arc attempts to identify their optical counterparts have not met with success, partly perhaps because most of them lie in crowded starfields of the Milky Way. In the case of the first Cambridge pulsar to be detected, CP 1919, two faint stars are located close to the radio position; neither appears to have any unusual properties and the juxtaposition may be purely one of chance.

The First Light Pulsar

In the search for identifications many attempts were made - accompanied by several false alarms - to detect optical flashes from the positions of the stronger pulsars. Success finally came to astronomers at the Steward Observatory of the University of Arizona and the pulsar concerned none other than NP 0531+21 which had already been found to be outstanding for its short pulse length and short period. Optical flashes from it were first picked up on January 15 and 16 1969. See Fig. 8. Their period was 33.095 milliseconds and they closely matched the radio pulses, even to the extent of having an occasional secondary pulse 4 milliseconds wide between the main pulses. The light flashes at maximum brightness were about 15th magnitude, and the averaged brightness about 18th magnitude, suggesting that all the light came during the flashes and nothing in between. (This appears to be the case also for the radio emissions). Because of the known association of NP 0531+21 with the Crab supernova several attempts have been made, but without success, to detect light pulses from the pulsar PSR 0833-45 which is also associated with a supernova (in Vela).

Even more recently the Crab pulsar has added further to its uniqueness by its identification as a source of X-ray pulses. Rocket and balloon flights of the past few years have established the existence of several X-ray sources in the skies which include the Crab Nebula. Friedmann of the U.S. Naval Research Laboratory reported the discovery of X-ray pulses from the Crab from records taken on an Aerobee rocket flight on 13th March 1969, and the pulse shape and period were confirmed as identical with the radio and optical flashes of NP 0531+21 from records taken on a high altitude balloon flight in 1967 by a group from Rice University. There can be no doubt that this pulsar thus gives rise to pulses of essentially identical form over a very wide range of wavelengths. Fig. 9 shows the X-ray pulse shape [illegible]ots) superimposed on the optical pulse.

Energy in the Pulses

The radio emission from the pulsating sources, as for most other sources, decreases rapidly with wavelength but the exact spectrum is difficult to determine because the amplitude of a pulse over a wide range of wavelengths is highly variable, presumably due to propagation through an irregular medium. On a long term average the energy is a maximum in the range 100-200 MHz with a slow cut-off at lower frequencies and a sharp cut-off above about 1 GHz. The pulse amplitude decreases by a factor of about one thousand in the range from 100 to 5000 MHz.

A representative value for the maximum amplitude of the pulses is 100 flux units, which represents a power flux of 10^{-24} watts per square metre per unit bandwidth, or 10^{-16} watts per square metre in a band 100 MHz wide. If the pulsar is situated at a distance of 200 light years and is radiating uniformly in all directions the peak power radiated is about 10^{21} watts. The total electrical power output of all the generating stations on Earth is of the order 10^{12} watts, an insignificant fraction of that put out by the average pulsar. This provides strong evidence that the pulses do not represent the efforts of other civilizations endeavouring to communicate with us, since it is scarcely conceivable that even the most advanced forms of life could be expected to produce, link up and control a thousand million times the power output of our entire planet.

The Nature of Pulsars

It is clear from the clock-like regularity of the pulsed emissions, and the fact that they are slowing down at an extremely slow rate, that the originating body must be very massive. On the other hand the extreme sharpness of the pulses indicates that the source must be of small dimensions - for many pulsars a good deal smaller than the Earth. This combination of large mass in a small volume implies that they must be very ~~xxxxx~~ dense.

Before the discovery of pulsars the densest objects known were stars in their senile "white dwarf" stage. At this stage in their evolution they are likely to be smaller than the Earth but enormously more dense: with their fuel supplies almost exhausted, and thus no radiation pressure to support their outer shells, their interiors are compressed by gravity forces to such a degree that a matchbox full would weigh some 50 tons. The first white dwarf was discovered in 1962: it is a companion to the bright star Sirius and its presence was revealed by the irregularities it caused to the observed position of Sirius. Hewish and his colleagues, who discovered the first pulsars, suggested that the extreme regularity of the pulses called for an origin in terms of the pulsation of an entire star, but realised that radial pulsations of white dwarfs (with a minimum fundamental period of about 8 seconds) could not reproduce the observed performance of the pulsars. They noted an earlier suggestion that the radial pulsation of neutron stars may play an important part in supernovae phenomena, and pointed out that in stars at this more advanced stage of collapse densities might reach the fantastic figure of 10^{13} gm/cm^3 (50 million tons for a matchbox full) and oscillatory periods down to a fraction of a second. Neutron stars represent the ultimate in packaging, when the electrons are stripped from the nuclei and the whole star consists of neutrons squeezed together into one huge atomic nucleus.

What is now generally accepted as the most satisfactory model for the pulsars was put ~~fxxxxxxd~~ forward by T. Gold of Cornell University, namely of a neutron star spinning at high speed in which the mechanism and precise timing of the pulses is due to the rotation. He was able to predict that pulsars of shorter period than those known at that time (period about 1 second) would be observed (because rotation periods down to a few milliseconds might be expected for such stars) and also that a gradual lengthening of the period should occur as the rotation slowed down.

There should thus be a correlation between pulse length and period, shorter periods going with younger neutron stars. Further Gold predicted that pulsars ought to be found in supernova sites because neutron stars are believed to be created only in the turmoil of supernova explosions. Progressive confirmation of these predictions as more data on the characteristics of pulsars became available has provided strong support for Gold's theory.

According to Gold's original hypothesis the core remaining after the supernova explosion gradually collapses as its fuel is burnt up and becomes a neutron star. In the process it loses little of its original gravitational energy, which is converted to energy of rotation and the rate of spin may be 1000 revolutions per second at the time of its formation. Collapse of the magnetic field associated with the original star is likely to lead to enormous field strengths on the surface of the neutron star, more than a billion (10^{12}) times that of the Earth's magnetic field. Gold considers that a large fraction of the rotational energy is likely to be dissipated in the early days of its life in oscillations and ejection of plasma, when its radio emissions were more nearly continuous. The pulsars which have been detected represent later stages in the life of neutron stars. Their cores continue to eject plasma-ionized gas - which is caught up in the magnetic field and whirled at high speeds as the field rotates with the star. As it travels outwards its speed increases until it approaches that of light when the plasma escapes into space at high speed and at the same time generates radio waves and also presumably, light.

The observed properties of pulsars fit well into this framework but particularly strong support comes from detailed studies of the polarization of individual pulses from pulsar 0833-45 made by Radhakrishnan et al. in Australia. Their measurements confirm that the source, the next fastest pulsar after that in the Crab, is associated with the supernova in Vela, and is slowing down by 1 part in 10^7 per day. (Figure 10). They also found that successive pulses have the same polarization, and that the position angle of the plane of polarization moves through more than 45° during each pulse. (Fig. 11). The conclusion that can be drawn from these observations is that each pulse comes from the same locality in the pulsar's magnetosphere, and this region must be close to its magnetic pole, its magnetic axis being inclined at a considerable angle to the rotational axis, as indicated in Fig. 12. The cone of emission is fairly narrow and we only see a pulsar if the cone sweeps across our line of sight as it rotates, so there may well be many that are undetectable because their axes are such that the emission does not take place in our direction. If the magnetic axis is almost at right angles to the rotation there is a possibility that emission may reach us from the other magnetic pole, as the interpulse which is present in some pulsars.

That this complex rhythm can be upset by eccentric behaviour was discovered independently by teams at Parkes and the N.A.S.A. tracking station at Goldstone U.S.A. when PSR 0833-45 suddenly and unaccountably increased its rate of pulsation by about 2 parts in a million at some time between 24th February and 3 March 1969. No conceivable changes in the medium between us and the pulsar could produce such a change and the conclusion is that it represents a real change in the rotational period of the source, presumably involving the same mechanism of collapse with conservation of angular momentum which was responsible for the rapid rotation at the outset. In this case if the pulsar had a diameter of 20 km before 24th February the observed change of period by 2 parts per million in the ensuing few days is equivalent to its sudden shrinking by 1 cm.

The pulsars thus continue to provide their puzzles. It is fairly generally accepted that there is no need now to seek an alternative to the concept of a rotating neutron star, but details of the mechanisms by which the emission takes place are still far from complete. Theoreticians are satisfied that pulses of radiation could originate from plasma accelerated and ejected from a rotating magnetosphere, but this would appear to involve injection of some energy into the system well after the initial explosion which created the neutron star if the lifetimes implied by some of the older pulsars are to be achieved. No other theory which fits the observed properties nearly so well has yet been proposed, although there are still a few advocates for a model involving a neutron star which pulsates.