

INVITED PAPERS

FIFTEEN MONTHS OF PULSAR ASTRONOMY

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DISCOVERY

Towards the end of February 1968 the astronomical world was staggered by a paper¹ from the Mullard Radio Observatory at Cambridge announcing the discovery of an astonishing periodic phenomenon. The characteristics of the pulsating radio source—or pulsar as it came to be called—involved a fantastic multiplicity of time-scales. The duration of the individual events was measured in tens of milliseconds, the repetition rate was of the order of a second, the pulse amplitude showed drastic variations over times of seconds, minutes, hours and even months and, lastly, the stability of the basic periodicity indicated a time-scale of millions of years. A series of pulses from CP 1919, the first pulsar, is shown in Figure 1, and one

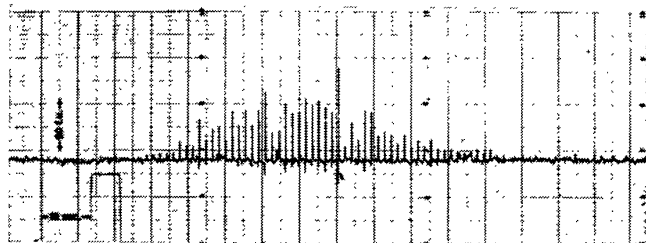


Figure 1. A train of pulses from CP 1919, the first pulsar. The receiving frequency was 150 MHz and the bandwidth 1.5 MHz.⁴

notices here both the regularity of the pulses and the variation in their amplitude with time. When the individual pulses were observed on an expanded time-scale it was found^{2, 3, 4} that the pulses were made up of sub-pulses (Figure 2) and that there was considerable structure even down to a millisecond time-scale.

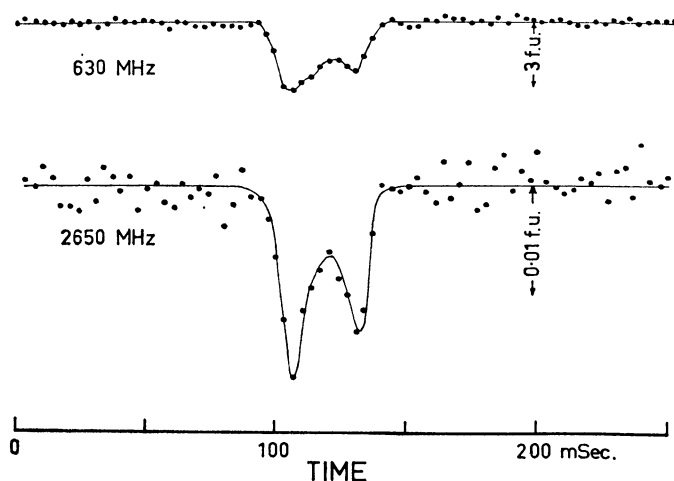


Figure 2. The double structure of the pulses from CP 1919 at two frequencies, obtained by averaging a large number of pulses.⁴

As reported in the discovery paper itself, Hewish, Bell *et al.*¹ went a great deal further than detecting the first pulsating radio source and noting the time-scales associated with it. They found that the pulses swept from high to low frequencies and the cause of this behaviour was correctly attributed to dispersion in the interstellar medium. By assuming a plausible value for the electron density they derived an approximate distance, showing that the object was local on a galactic distance scale. Three more such sources were discovered, establishing that the first object was not unique but one of a new class of astronomical bodies.

Considerations of the energy output as estimated from the flux and distance, of the physical size implied by the short time-scales of the pulses, and of the stability of the periodicity led them to the conclusion that the source must be small but massive. Only two possible classes of stable astronomical objects satisfied the requirements, namely white dwarfs and neutron stars. The former class had been studied both theoretically and observationally in considerable detail, but the latter was as yet only a prediction of theory.^{5, 6} The Cambridge group identified pulsars as belonging to one of these two categories, favouring neutron stars. They attributed the periodic nature of the signal to radial pulsations of the stellar object, noting that the observed periodicity lay awkwardly in the region between the theoretical periods of oscillation for white dwarfs and those for neutron stars.

MORE PULSARS

In the fifteen months since then, the number of known pulsars has grown to a total of 36 with contributions from six observatories around the world. They are listed in Table I together with some other details. The leader in the field has been the Molonglo Radio Observatory^{7, 8, 9} in Australia with 19 pulsars to its credit already, and surely more to come. The distribution in galactic co-ordinates of the pulsars known to date are shown in Figure 3.

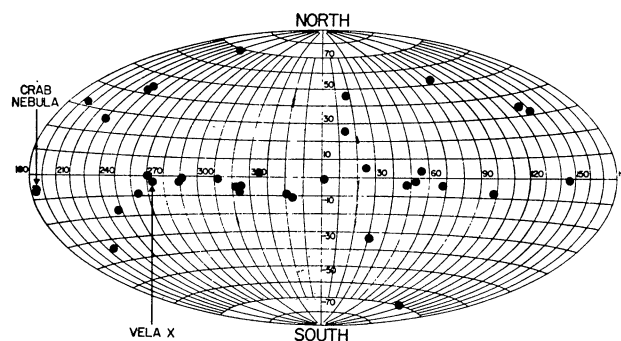


Figure 3. The distribution of known pulsars in galactic co-ordinates. A concentration towards the plane of the Galaxy is clearly seen.

TABLE I
Approximate Pulsar Characteristics*

(1)	(3)		(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Name	Galactic Co-ordinates		Period P	Pulse Width Δt	Dispersion Measure dm	Galactic Magnetic Field	$\frac{dP}{dr}$	$K = P \frac{dP}{dr}$	Field Strength H_0	Max. Age τ
	μ	δ	(s)	(ms)	(pc cm ⁻³)	(μ G)		(s)	(G)	(yr)
MP 0031	111	-69	0.940	25	12 $\pm$ 5					
CP 0328	145.0	-1.2	0.715	7	26.75	3.5, 2.8	(19 $\pm$ 2) $\times 10^{-16}$	1.4 $\times 10^{-16}$	9.4 $\times 10^{11}$	5 $\times 10^6$
MP 0450	217	-34	0.548	20	25 $\pm$ 10					
NP 0527	183.8	-6.9	3.745	190	49.3	0.9				
NP 0532	184.5	-5.8	0.0331	3	56.88	0.55	(4300 $\pm$ 185) $\times 10^{-16}$	1.42 $\times 10^{-14}$	3.0 $\times 10^{12}$	1.2 $\times 10^3$
PSR 0628-28	237	-16.7	1.24	100	5					
MP 0736	254	-9	0.375	40	100					
CP 0808	140.0	+31.6	1.2922	90	5.77		<3.18 $\times 10^{-16}$	<4.10 $\times 10^{-16}$	<5.0 $\times 10^{11}$	>6.5 $\times 10^7$
AP 0823+26	196.9	+31.8	0.531	13	19.4					
PSR 0833-45	263.5	-2.8	0.0892	2	69	0.8	(1242 $\pm$ 13) $\times 10^{-16}$	1.11 $\times 10^{-14}$	2.5 $\times 10^{12}$	1.1 $\times 10^4$
CP 0834	219.7	+26.3	1.2738	38	12.80		(51 $\pm$ 10) $\times 10^{-16}$	0.65 $\times 10^{-14}$	2.0 $\times 10^{12}$	4.0 $\times 10^6$
MP 0835	260	0	0.765	20	120					
PSR 0904+77	135	+34	1.579	<80	—					
MP 0940	279	-3	0.662	30	145					
PP 0943	228	+42	1.09	—	17					
CP 0950	228.9	+43.7	0.2531	21	2.98	<0.2	(2.9 $\pm$ 1) $\times 10^{-16}$	0.72 $\times 10^{-16}$	2.2 $\times 10^{11}$	1.4 $\times 10^7$
MP 0959	281	-1	1.438	50	90					
CP 1133	241.9	+69.2	1.1879	43	4.87		(41 $\pm$ 6) $\times 10^{-16}$	0.49 $\times 10^{-14}$	1.7 $\times 10^{12}$	4.6 $\times 10^6$
MP 1240	302	-1	0.388	60	220 $\pm$ 20					
MP 1426	313	-5	0.788	10	60					
MP 1449	315.3	-5	0.180	5	90 $\pm$ 10					
PSR 1451-68	313.9	-8.6	0.248	25	12 $\pm$ 5					
HP 1506	91.3	+52.3	0.740	20	19.6		(53 $\pm$ 4) $\times 10^{-16}$	3.9 $\times 10^{-16}$	1.6 $\times 10^{12}$	2 $\times 10^6$
MP 1530	326	+2	1.372	25	20 $\pm$ 5					
AP 1541+09	18	+46	0.748	50	35					
PSR 1642-03	14	+26	0.388	5	33 $\pm$ 5					
MP 1727	341	-9	0.835	30	140					
MP 1747	344	-11	0.742	20	40					
PSR 1749-28	1.5	-1.0	0.563	4.7	50.88					
MP 1818	25	+5	0.597	20	70 $\pm$ 10					
CP 1919	55.8	+3.5	1.3373	40	12.55		(11 $\pm$ 6) $\times 10^{-16}$	14.9 $\times 10^{-16}$	1.0 $\times 10^{12}$	1.9 $\times 10^7$
PSR 1929+10	47.4	-3.9	0.227	10	8					
JP 1933+16	52.3	-2.0	0.359	6	143					
AP 2015+28	68.1	-4.0	0.558	28	14.2	2.0				
PSR 2045-16	30.5	-33.1	1.962	100	11.40					
PSR 2218+47	98	-8	0.538	<30	43.8					

*Most of the information tabulated in the first 8 columns has been taken from Maran and Cameron.⁵⁹ See also Note added in proof at the end of this paper.

It is clearly seen from the concentration close to the plane that pulsars are galactic objects. The vast majority of those in the neighbourhood of the galactic plane in Figure 3 are Molonglo pulsars. The relatively high operating frequency (408 MHz) and large collecting area of the Mills Cross has paid handsome dividends in making detectable the more distant pulsars whose higher dispersion would obliterate the pulses in lower frequency surveys. The concentration on the southern side of the galactic equator seems to indicate an asymmetry in the dispersing layer.⁷ Independent evidence suggesting such an asymmetry is provided by the low frequency measurements of Hamilton.¹⁰

On the basis of their experience in pulsar search, Vaughan *et al.*⁸ expect that several more strong but sporadic pulsars will be discovered in the continuation of the Molonglo search programme. Consideration of the effort put in at various observatories, and the results produced, lead one to believe that the number of known pulsars is unlikely to be increased by more than a factor of two or so, except through resort to one of the following:

- de-dispersing techniques,^{9, 11}
- fast period detection techniques,¹²
- surveys at much higher or lower frequencies than used so far, in case there are pulsars with very different spectral characteristics.

New pulsars discovered by these means are very likely to show a strong concentration towards the galactic plane.

PULSARS AND SUPERNOVAE

It is natural to expect that a greatly increased sample of known pulsars will lead to a better understanding of them. However, so far, the contribution to our knowledge from the two pulsars marked by name on Figure 3 is out of all proportion to their number. We mentioned earlier that neutron stars were still only predictions of theory at the time that pulsars were discovered. It was generally believed that only supernova explosions could provide the extreme conditions necessary for the formation of such superdense objects, and the suggestion was made by Woltjer¹³ that the Crab nebula and other supernova sites be searched for pulsars. The first such pulsar to be found¹⁴ was PSR 0833-45 in the middle of the Vela supernova remnant, with the fastest pulsation period of 0.089 s.

The vibrating white dwarf hypothesis had, at this stage, already suffered setbacks. The difficulty of reconciling the observed periods with possible fundamental modes or plausible overtone modes under various conditions was becoming formidable.^{15, 16, 17} Even more significant was the fact that no optical objects could be located at the accurately determined positions of some low dispersion, and therefore nearby, pulsars.^{18, 19} The optical properties of white dwarfs were well known, and at the estimated distances of the pulsars in question they should have been clearly visible. The detection of a pulsar with a period ~ 0.1 s presumably associated with a supernova remnant provided two more reasons for abandoning the white dwarf hypothesis altogether. The short period of the

Vela pulsar was clearly outside the range of possible vibrational modes and even excluded, because of rupture, the *rotating* white dwarf model advanced by Ostriker.²⁰ Further, Chiu⁶ had shown that a white dwarf cannot result from the collapse of a massive star such as would cause a supernova explosion. Simple arguments indicated that the remnant of the collapse must be compressed to a minimum density of $10^{13} \text{ gm cm}^{-3}$ to liberate the gravitational energy required to eject the rest of the initial mass.

The detection of PSR 0833-45 by Large *et al.*¹⁴ tentatively established the identification of pulsars with neutron stars, and was the first significant advance in pulsar astronomy since the Cambridge papers. The detection not long after of a pulsar in the Crab nebula by Staelin and Riefenstein²¹ with an even faster period of 33 ms, as determined by Lovelace *et al.*,²² put the matter on what appears to be unshakeable ground. We shall return later to the part these two pulsars have since played in our present understanding, after first considering some aspects of the interstellar medium.

INTERSTELLAR ELECTRONS

The variation of dispersion measure ($\int n_e ds$ in units of pc cm^{-3}) with galactic latitude is plotted in Figure 4.

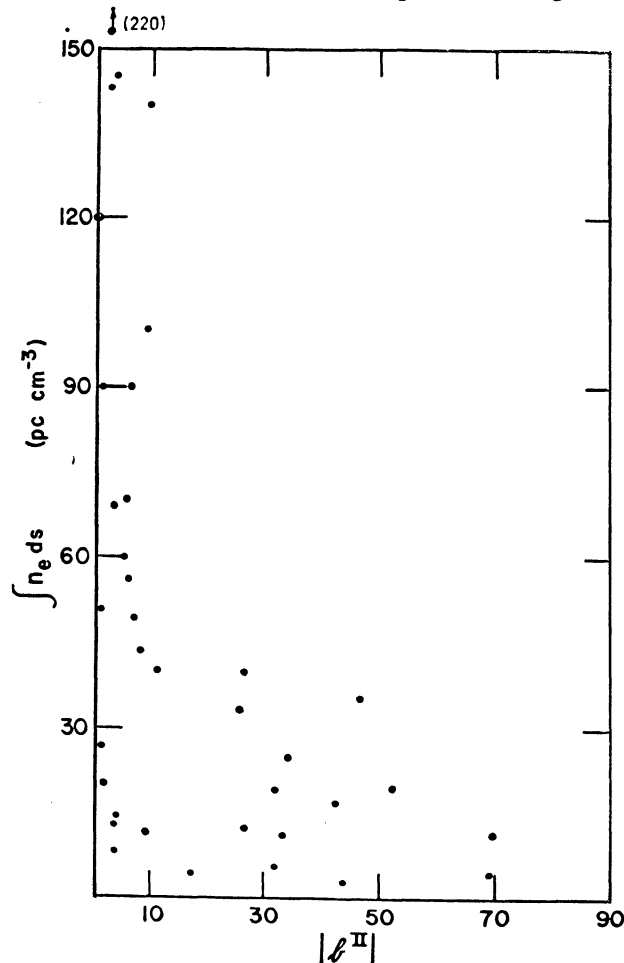


Figure 4. The variation of dispersion measure with galactic latitude. The pulsar MP 1240⁹ with the highest known dispersion measure is indicated by the arrow at the top of the figure.

All known pulsars with the exception of 0904+77 are represented here. The galactic distribution is quite obvious in this diagram. The arrow at the top refers to the pulsar with the highest known dispersion so far (220 pc cm^{-3}), discovered at Molonglo through the use of a dispersion-removing arrangement.⁹ From a similar diagram containing pulsars known at the time, Mills⁷ constructed a model for the dispersing layer which indicated an electron density of 0.1 cm^{-3} near the plane. He was led to the conclusion that the dispersion must arise in a tenuous intercloud medium, whereas the high-frequency radio emission and low-frequency absorption must arise in HII clouds, where the mean-electron density is higher. In deriving the above-mentioned electron density of 0.1 cm^{-3} , Mills⁷ assumed that the dispersing layer has a half-thickness of 100 pc similar to the neutral hydrogen distribution. We would like to emphasize that the neutral hydrogen thickness referred to here dates from a time when there was no appreciation of the 'cold dense cloud—hot tenuous intercloud medium' picture that we have today of the interstellar hydrogen.^{23, 24, 25, 26} There are indications that the intercloud medium may have a half-thickness well in excess of 100 pc, and Mills' estimate of 0.1 electrons per cm^3 should, in our view, be considered an upper limit.

Some attempts^{27, 28} have been made to determine pulsar distances from the dispersion measures, by studying the H-line emission profiles in the directions of the various pulsars. Using a two-component model for the interstellar hydrogen and the theories of its heating and ionization by sub-cosmic rays, Rohlfs *et al.*²⁷ studied 21 pulsars and arrived at the opposite conclusion, namely that the dispersion of pulsar signals is produced by the same electrons that are responsible for the thermal component of the galactic background. As we shall see in the following section, the truth must lie in between.

H-LINE OBSERVATIONS AND DISTANCE MEASUREMENTS

An independent determination of the distance of pulsars would provide a reliable method of establishing the interstellar electron density from the dispersion measure. 21 cm line absorption measurements offer one such possibility for obtaining minimum distances, but the method is fraught with difficulties both in the measurement and in the interpretation. The first such attempt on a pulsar by de Jager *et al.*²⁹ placed CP 0328 at $\geq 4.2 \text{ kpc}$, implying a mean-electron density $\leq 0.006 \text{ cm}^{-3}$. A subsequent observation by Guelin *et al.*,³⁰ although performed with bandwidths quite unsuited for absorption measurements, nevertheless indicated a clear discrepancy with the Jodrell Bank result.²⁹ The best observations to date have been made at Green Bank by Gordon *et al.*³¹ who observed 5 pulsars for H-line absorption. Two pulsars were found to show measurable absorption namely CP 0328 and PSR 1749-28, and the high quality of the profiles seems to leave little doubt that the Jodrell Bank observation of the former is in error. According to Gordon *et al.*³¹ the minimum distance for CP 0328 is just under 1 kpc, which leads to a value of ≤ 0.03 for the mean-electron density. In a further paper from the same observatory, Hjellming *et al.*³² have used the pulsar observations to determine the properties of interstellar hydrogen clouds and the intercloud medium. Their findings, although limited by the small number of observations available, are in excellent

agreement with other absorption studies^{23, 25, 26} of the interstellar hydrogen.

21 cm line absorption has also been detected³³ in the spectrum of PSR 0736-40 showing a high optical depth at velocities near zero. Its galactic latitude of 9° makes it difficult to place an upper limit on the distance, but it would appear that a figure of 1 kpc is not inconsistent with the available observations.

Optical identification is yet another method of distance determination. For the two pulsars associated with optically observable supernova remnants, a reliable distance based on the measured expansion rate is available for one remnant, and an estimate based on the radio-surface brightness for the other. Trimble³⁴ has obtained a distance of 2 kpc for the Crab nebula which, combined with the dispersion measure of 56 for NP 0532, gives us $n_e \approx 0.03 \text{ cm}^{-3}$, a value similar to that obtained for CP 0328 above. On the other hand, if we adopt Milne's estimate of 500 pc for the distance to the Vela supernova³⁵ and combine this with the best available dispersion measure³⁶ of 69 pc cm^{-3} for PSR 0833-45, we obtain $n_e \approx 0.14 \text{ cm}^{-3}$. Clearly if this distance estimate is valid then, as Mills⁷ has noted, there are considerable variations in the electron-density distribution, and the dispersion measure is not a reliable distance indicator. Some of these variations must surely involve HII regions of one form or another along the line of sight to the pulsar.³⁷ Manchester *et al.*³³ have investigated the cases of PSR 0833-45 and PSR 0736-40 and concluded that the Gum nebula must be contributing substantially to their dispersion measures.

It seems to us that the most reasonable picture of the origin of the dispersion is one in which the intercloud medium is the main contributor for very nearby pulsars. At intermediate distances, chance encounters of the line of sight with an HII region confuse the picture; for large distances in the galactic disk the main contributors should be HII regions and the pulsars would have dispersion measures far greater than any detected hitherto, and corresponding to mean-electron densities well above 0.1 cm^{-3} .

AMPLITUDE VARIATIONS

Whatever the location of the electrons causing the dispersion, it is only to be expected that there are irregularities in their distribution in interstellar space. A movement of either the source or the observer with respect to this intervening 'screen' would then lead to scintillation effects of the kind produced by the ionosphere or by the interplanetary medium. The special circumstance in the case of pulsars is the angular size of the source, many orders of magnitude smaller than the smallest quasi-stellar radio sources whose scintillation was being studied by Hewish and his colleagues when they stumbled on pulsars.¹

Scheuer³⁸ investigated the possibility that the observed amplitude variations of the pulses could be ascribed to interstellar scintillation and found that the pulse-to-pulse variations could not be explained this way, but that the slower variations could be caused by a two-screen model. In addition to the general interstellar medium, Scheuer required refractive irregularities of somewhat greater strength within 0.1 pc of the source. Fine spectral structure in the fluctuations at long wavelengths was predicted on the basis of this model and subsequently found by Komesaroff *et al.*³⁹ Spaced receiver observations^{40, 41} with baselines of 300 and 5000 km have so far failed to reveal a time displacement in the observed amplitude

pattern that could be interpreted in terms of a drift velocity for the interstellar medium.

Salpeter⁴² re-analysed the problem and concluded that a single screen model could suffice to explain all the slow variations, given irregularities on a scale of 10^6 - 10^9 km such as might characterize shock fronts in the interstellar gas. He attributed the failure of the spaced receiver observations to detect a time displacement to the dominance of the intrinsic pulse-to-pulse variations, and has suggested alternative methods of correlation to detect the drift. The existence of scale sizes such as required by Salpeter was shown by Rickett⁴³ who demonstrated the correlation of dispersion measure with the characteristic bandwidth over which amplitude variations are correlated for a given pulsar. He was thus able to establish that the same electrons were involved in both the dispersion of the signal and its slow variations in amplitude, and to derive some of the parameters of their distribution.

GALACTIC MAGNETIC FIELDS

The electron density distribution is not the only interstellar property which pulsars can be used to probe. Very shortly after their discovery, it was shown by Lyne and Smith⁴⁴ that the radiation from pulsars exhibited linear polarization and they pointed out that the mean-longitudinal magnetic field could be determined by combining a Faraday rotation measure with the dispersion measure. This method has been used successfully by Smith^{45, 46} on three pulsars, CP 0950, CP 0328 and AP 2015+28, at frequencies of 151 and 408 MHz. The respective values obtained for the magnetic field are <0.2 , 3.5 and $2 \mu\text{G}$. Staelin and Reifenstein⁴⁷ have very recently obtained a lower value of $2.8 \mu\text{G}$ for CP 0328 and also one of $0.9 \mu\text{G}$ for NP 0527 both from measurements at 112 MHz. The first two measurements of Smith have been questioned^{48, 49} on the respective bases that the large ionospheric correction used could be in error, and that the polarization characteristics of pulsars at these frequencies is unpredictable due to a variable Faraday rotation in or near the source.

Whether these criticisms are valid or not, it is certainly desirable to make these measurements, if possible, at frequencies where they are not confounded by the effect of the ionosphere. It is also necessary to show that the variation of the plane of polarization with frequency follows a λ^2 law, thus making it plausible that all frequencies are generated at the source with the same plane of polarization. PSR 0833-45 is one of the few pulsars with high-frequency characteristics that enable these requirements to be easily met. Faraday rotation of the polarization from this pulsar has been measured at wavelengths from 18 cm to 11 cm and the line-of-sight component of the field derived as $0.8 \mu\text{G}$.^{50, 51, 52} Large *et al.*¹⁴ had already arrived at a similar value on the assumption, now vindicated, that the rotation measure for the pulsar would be similar to that for the polarized emission from the associated supernova remnant.³⁵ In like manner, Verschuur⁵³ has combined the rotation measure for the polarized nebular radiation from the Crab nebula with the dispersion measure for NP 0532 and derived a value of $0.55 \mu\text{G}$ for the mean magnetic field in that direction. All of these measurements have been listed in Table I.

Taking these 6 measurements at their face value, we notice a spread of over an order of magnitude. This variation can be ascribed to the inclination of the line of sight with the direction of the local magnetic field, to

reversals in field direction along the path, and to field amplification in dense cool HI clouds as suggested by Verschuur.⁵⁴ He has further suggested that the prime contribution to the interstellar Faraday rotation comes from dense HI clouds rather than from the intercloud medium which produces most of the dispersion. A proper evaluation of these suggestions must await polarization and HI absorption measurements on a significant number of pulsars or their associated remnants.

The difficulties one encounters can be illustrated by citing two examples. In the case of the Crab nebula one has a rotation measure of -25 rad m^{-2} over a 2 kpc path intersecting several dense HI clouds.^{26, 55} For PSR 0833-45 the rotation measure⁵¹ is $+42 \text{ rad m}^{-2}$ and measurements at Parkes³³ have shown that there is no dense HI cloud in the line of sight although one is looking essentially along the spiral arm. Both the column density of electrons and the derived magnetic field for the latter pulsar are greater than those for the Crab nebula, whereas the distance must be considerably less. The relative importance of HII regions, and of the other three factors mentioned earlier, in contributing to the rotation measure has yet to be determined.

PULSAR PERIODS

In Table I we have listed the pulse periods and widths for the various pulsars. Although in general, there is only one pulse per basic repetition period, some pulsars have precursors or interpulses located between the main pulses at some fixed point of time in the pattern. The existence of periodicities in the amplitude fluctuations is suggested by the measurements of Conklin *et al.*⁴¹ who found an additional peak in the auto-correlation function for the pulses from CP 1919. This was interpreted by Drake and Craft⁵⁶ as supporting their detection of a second class of periodicity from the drift of sub-pulses within the main pulse. Slee⁵⁷ has also found additional peaks in the power spectrum of the amplitude variations from CP 1919. However he has concluded that, if the interpretation of Drake and Craft were correct, the Class 2 period had changed by $\sim 8\%$ in the three months separating the measurements. Slee⁵⁸ has recently detected such an additional peak in the spectrum of CP 0834.

In Table I, we list only the basic period P and an approximate value for the width Δt of the main pulse.⁵⁹ These two quantities are also plotted on logarithmic scales in Figure 5. The range of known pulsar periods is seen to cover more than two orders of magnitude, whereas the spread of the duty cycle, or pulse width to period ratio, is an order of magnitude less. This relative independence of the duty cycle on period is one of the key clues we have to the emission mechanism of pulsars, but let us consider for the moment only the pulse periodicities.

In order to account for the extraordinary regularity in pulse arrival time shown by the first pulsars, a great variety of theories were advanced. Besides vibrations, which had been the original Cambridge choice for the basic clock mechanism, rotation and orbital motion of highly condensed objects were the two other most discussed possibilities. Among those advocating the rotation of a neutron star as the likely explanation were Gold,⁶⁰ Woltjer,¹³ Eastlund⁶¹ and Pacini.⁶² Since neutron stars would be capable of very high rotational speeds without rupture, Gold⁶⁰ predicted that even shorter period pulsars would be found, and that accurate measurements would show a

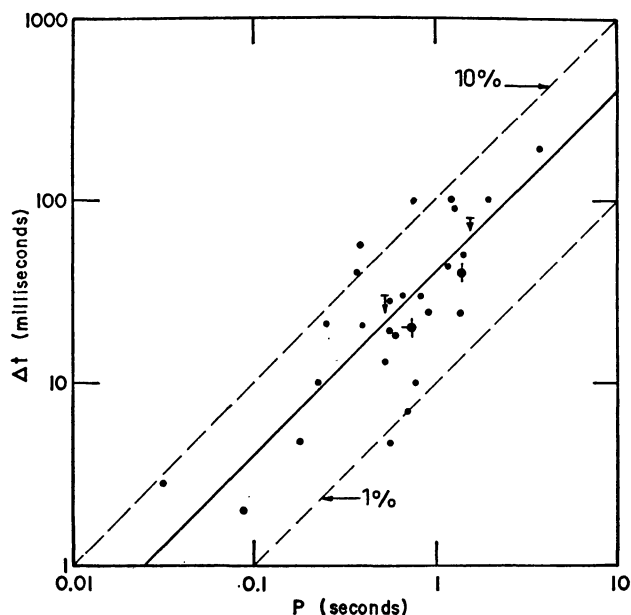


Figure 5. The distribution of pulse widths and periods for the known pulsars. The widths are very approximate. A concentration around 3% (solid line) for the duty cycle is apparent from the diagram.

small but steady slowing down of the observed periods. The first of these predictions came true with the discovery of the Vela¹⁴ and Crab²¹ pulsars, and the second was borne out when it was found by Richards⁶³ that the Crab pulsar with the fastest known period of $\sim 33 \text{ ms}$ was slowing down at the rate of $1/2400$ per yr. The periods of several more pulsars have since been found to be increasing, as discussed in a later section.

NP 0532

In addition to supporting the rotational hypothesis, the deceleration of the Crab pulsar was of great significance to a problem older than pulsars. As was immediately recognized and discussed by Gold⁶⁴ and also Finzi and Wolf,⁶⁵ the magnitude of the observed loss rate of rotational energy of NP 0532 could account for the sustenance of the Crab nebula whose energy source had long been one of the most intriguing of astrophysical puzzles. Woltjer¹³ in the course of advocating an inclined-dipole rotating neutron star model for pulsars, had already envisaged the likelihood of this, and Wheeler⁶⁶ and Pacini⁶⁷ had suggested the possibility of such a source of energy even earlier.

The Crab nebula, which even before the discovery of pulsars was remarkable in so many ways,^{68, 69} had more surprises coming. Cocke, Disney and Taylor⁷⁰ succeeded in detecting optical pulsations from it very similar to the radio pulses. A host of optical observations rapidly followed⁷¹ and have contributed to establishing that the optical pulses come from the south preceding star originally identified by Baade as the probable remnant,⁷² that they are linearly polarized,^{73, 74} that the pulse spectrum is continuous,^{75, 76} and that the periodicity is precisely that of the radio periodicity at a given time.⁷³

More recently Neugebauer *et al.*⁷⁷ have detected pulses at a wavelength of 2μ , and two groups^{78, 79} have detected X-ray pulsations of similar characteristics to the radio and

optical from rocket observations. Even more recently Fishman *et al.*⁸⁰ have re-analysed data obtained during a 1967 balloon-borne measurement of the Crab nebula and found pulsed hard X-radiation at the expected period. Bewildering as is the impact of each of these discoveries, it appears that at least as far as the energetics are concerned the rotational energy of a neutron star can indeed account for all of the activity of the nebula, subject to two assumptions. One is that the efficiency of conversion into particle energy is high, and the other is that the observed rotation applies to the whole of the neutron star and not just to an outer shell. We shall be discussing later an observation which may have some bearing on this matter.

PULSAR DECELERATION MECHANISMS

Gold⁶⁴ had envisaged a rotating neutron star with an intense co-rotating magnetosphere which would encounter shearing forces at the radius corresponding to circular motion at the velocity of light. The consequent drag presumably due to radiation would cause a slowing down of the rotation rate. Goldreich⁸¹ attacked the problem quantitatively, using a simple axisymmetric model, and concluded that both energy and angular momentum would be carried away by ultra-relativistic particles escaping along those polar field lines extending beyond the velocity of light cylinder. From the observed period and rate of change of period for NP 0532 he deduced a value for the magnetic field of 3×10^{12} G, and an age for the pulsar in reasonable agreement with the known age of the Crab nebula.

Gunn and Ostriker⁸² adopted a different approach to the problem and calculated the effects of magnetic dipole radiation from an inclined dipole. A similar discussion had already been published by Pacini⁶² based on an earlier treatment by Deutsch.⁸³ Gunn and Ostriker concluded that low-frequency electromagnetic radiation must carry away energy and angular momentum and arrived at the same values for the magnetic field and age of NP 0532 as Goldreich had obtained. According to them, their model would also lead to the copious production of ultra-relativistic particles.⁸⁴ The low-frequency radiation, would push along charged particles riding the wave at essentially constant phase, accelerating them to energies similar to those derived by Goldreich.⁸¹ Thus both treatments lead to the possibility of accounting for the origin of galactic cosmic rays, yet another long-standing astrophysical mystery.

We find the remarkable agreement between the two theories peculiar. For the dipole radiation model the energy loss rate is due to electromagnetic radiation in vacuo which is then converted into particle energy if the radiation encounters a circumstellar plasma. In the absence of the circumstellar plasma the loss rate of energy and angular momentum would be unchanged, and the neutron star would slow down exactly as before. For a given dipole moment and angular velocity the energy loss rate is dependent, however, on the inclination of the magnetic dipole to the rotation axis, and would vanish for an alignment of the two axes. It is precisely this perfectly aligned case that Goldreich has treated and which, according to him, loses energy at the same rate but in the form of relativistic particles. The density of particles which are accelerated is not a function of the region of space in which the neutron star finds itself, but only of the magnetic-field strength and the period of rotation. In other words, the neutron star provides its own space charge in the zone of co-rotation

and accelerates it, thus losing energy and angular momentum at the *same rate* as it would have through electromagnetic radiation in a vacuum, if the dipole were rotated through an angle $\theta = 90^\circ$. We have compared the equations governing the loss rate in the two above-mentioned theories, and find them to be *identical* but for one important difference. The component of the magnetic moment involved is parallel to the axis of rotation in the one case and perpendicular in the other.

If both treatments are valid, we can only conclude that there are two complementary processes, respectively proportional to $(\sin^2 \theta)$ and $(\cos^2 \theta)$, both acting to extract energy from the rotation and directly or ultimately accelerating particles to relativistic energies. The total loss rate must then be independent of the obliquity of the two axes, and dependent only on the strength of the magnetic field of the neutron star and its period. If our conclusion is right, the total energy loss rate is given by (cf. Goldreich,⁸¹ equation (4); Pacini,⁶² equation (8); Deutsch,⁸³ equation (15)).

$$\frac{dE}{dt} = \frac{10^{-28} H_0^2 R^6}{P^4} \text{ erg/s,} \quad (1)$$

where H_0 is the surface magnetic-field strength (G), R is the radius of the neutron star (cm), P the period of rotation (s) and the inclination of the magnetic axis is arbitrary. If solid body rotation is assumed, the change in periodicity can be related to the rotational energy and it follows that

$$K = 2.5 \times 10^{-30} \frac{H_0^2 R^6}{I}, \quad (2)$$

where $K = P dP/dt$, the measured difference in seconds between successive periods, and I is the moment of inertia (g cm^2).

PULSAR MAGNETIC FIELDS AND AGES

From a measurement of the period and rate of change of period of a pulsar, the magnetic field can be derived from equation (2) and is given by

$$H_0 \approx 2.5 \times 10^{19} K^{\frac{1}{2}}. \quad (3)$$

We have taken the moment of inertia I to be $1.6 \times 10^{45} \text{ g cm}^2$ and the radius 10^6 cm . For NP 0532 the value of K is $1.5 \times 10^{-14} \text{ s}$ and the corresponding field strength is $\approx 3 \times 10^{12} \text{ G}$.

The discovery of the deceleration of the Crab pulsar led to a renewed interest in the stability of pulsar periods, and to date 5 more pulsars have been found to be slowing down.^{85, 86, 50} The rates of slowing down are listed in Table I as also the magnetic-field strengths calculated according to equation (3). In Figure 6 we have plotted the stability against period on logarithmic scales for 7 pulsars with good measurements. The two pulsars associated with visible supernova remnants have the most rapid periods and the highest rates of decay. The remaining 5 are all Cambridge pulsars and hence are those that have been studied for the longest time. The fact that 4 out of these 5 show a measurable decay in period suggests strongly that most of the known pulsars would reveal similar decays if observed as carefully and for as long. It is also to be expected that higher order terms in the equation

relating period and time will eventually be detected, and will provide a further test of the theory.

In terms of the retarding processes discussed in the previous section, ages can be derived for pulsars using the simple formula:^{81, 82, 87}

$$\tau = \frac{1}{2}P \left/ \left(\frac{dP}{dt} \right) \right. = \frac{P^2}{2K} \quad (4)$$

on the assumption that the initial periods were very small, ($P_0^2 \ll P^2$). We have just seen that K is a measure of the magnetic energy of the neutron star in question at the present time. If the magnetic energy has decayed with time, as might be expected to happen, then the age determined according to (4) would be an upper limit. Maximum ages obtained in this manner are listed in Table I and are in accord with the hypothesis that for the 5 Cambridge pulsars the debris from the supernova explosions have long since been dispersed into the interstellar medium. The observed values of P and dP/dt depend on the age, the initial magnetic energy and its characteristic decay time. Grewing and Priester⁸⁷ find that for 6 of the 7 pulsars in Figure 6, the observations are compatible with

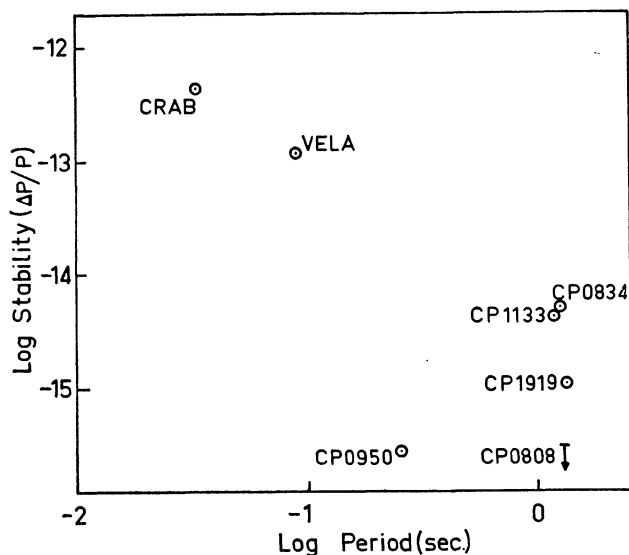


Figure 6. The stability of the period as a function of period for 7 pulsars with good measurements. The 2 pulsars at the top left hand of the diagram are associated with visible supernova remnants. The other 5 are Cambridge pulsars which have been observed for the longest span of time.

the hypothesis that they all started with the same initial $K_0 = (1.2 \pm 0.2) \times 10^{-14}$ and decayed exponentially with a characteristic time t_d , where $(2.5 \leq t_d \leq 5) \times 10^6$ yr. According to them, the magnetic field of the odd pulsar CP 0950 must have had a decay time of $< 10^5$ yr if it had also started at the same K_0 -level. On the other hand, if the field had decayed at the same rate as for the other pulsars, it must have been much weaker at formation of the neutron star.

It seems to us that a far greater spread should be expected for the K_0 values of pulsars than for their decay times. Since the masses, radii and compositions of neutron stars are severely restricted by theory, it is only reasonable to suppose that their conductivities and hence their field

decay times will be very similar. The strength of the field at formation, however, will depend on the initial conditions, particularly the field in the collapsing parent star, and the measured values for stellar magnetic fields spread over orders of magnitude. For simple compressions of the initial field, it is remarkable that 4 out of 7 pulsars lead to almost the same value for K . One is led to suspect strongly that there is a maximum value for the magnetic field that neutron stars can be formed with, of approximately $B_0 \leq 3 \times 10^{12}$ G. As more and more measurements for period changes become available, one should find more pulsars like CP 0950, CP 0808 and CP 1919, suggesting smaller K_0 values but none with $K_0 \gg 10^{-14}$. In other words, one should not find long period pulsars slowing down at rates comparable to those of the short period pulsars.

VELA'S JUMP

All the evidence so far presented in favour of a rotational model for pulsars has been indirect, to say the least. Vibration and orbital motion⁸⁸ were discarded because the range of observed periods were not compatible with models so far conceived. No other clock mechanism had been theoretically developed to seriously compete with rotation. The prediction⁶⁰ of period decay based on a rotational model, and its subsequent observation had swayed the scales heavily in favour of this hypothesis. Lastly, the energetic arguments and retardation mechanisms proposed so far had all strongly supported the spinning star model. It had been argued that a rotational model would show an *increase* in period with time, as opposed to vibrational and orbital models for example. Earlier this year it was discovered by Reichley and Downs⁸⁹ that the Vela pulsar had actually decreased its period between 1969 February 24 and March 3. Their extremely accurate observations are shown in Figure 7 where the nature and magnitude of the discontinuity is clearly illustrated.

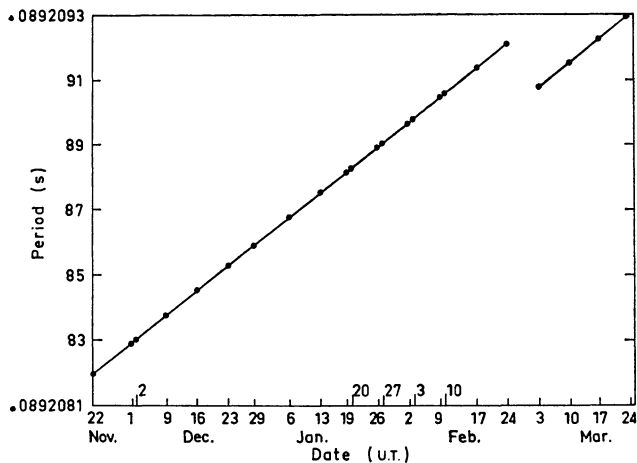


Figure 7. The observations of Reichley and Downs⁸⁹ showing the 134 ns decrease in period of PSR 0833-45 between 1969 February 24 and March 3. So far, this is the only discontinuity observed in the periodicity of pulsars.

This extraordinary event, astonishing even by pulsar standards, was also observed at Parkes⁹⁰ and it was suggested that a sudden readjustment was made necessary by the rapidly changing periodicity of this pulsar.⁵⁰ We cannot refrain from contemplating with amusement the

consternation that would have reigned in the camp of the rotational advocates if such an effect had been discovered last year in an otherwise stable pulsar. Direct and graphic evidence showing that the radio pulses from this pulsar must be synchronized with its rotation had, however, already been published.⁵⁰ It was shown there that such synchronization is a logical consequence of a polarization pattern which varies systematically across the pulse, but nevertheless, repeats itself over long periods of time, even in spite of the changing periodicity of the pulsar. This polarization pattern has preserved itself through the discontinuity in period mentioned above, and is shown in Figure 8. In the face of such independent evidence for

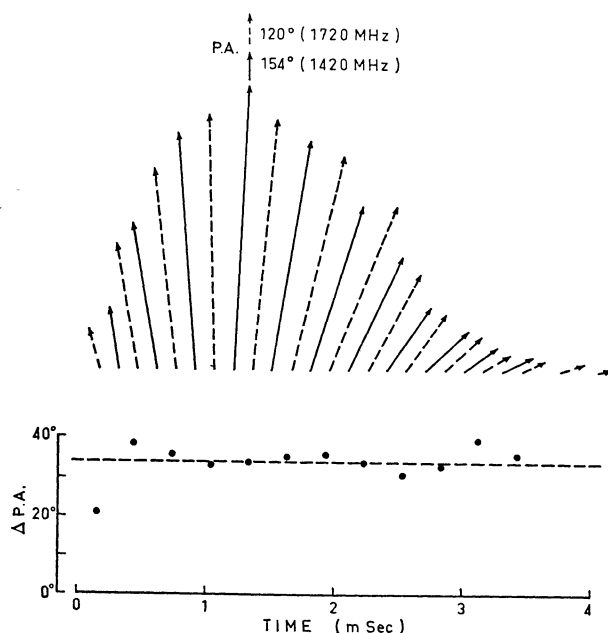


Figure 8. The sweep of the polarization angle of PSR 0833-45 during the pulse.⁵¹ Measurements at 1420 and 1720 MHz have been interleaved in the upper figure by removing the mean difference of 34° (lower figure) in the position angle at the two frequencies. The similarity of the 'spread' at the two frequencies establishes that it is intrinsic and not an effect of Faraday rotation en route. The polarization pattern was unaffected by the sudden discontinuity observed in the periodicity of the pulsar.^{89, 90}

rotation, one is forced to interpret the jump in periodicity as a sudden increase in the angular velocity of the pulsar.

One possibility for increasing the angular velocity is through a sudden decrease in effective radius,^{89, 90} in this case by an amount of the order of 1 cm. A suggestion of a similar nature credited to Rudermann has been discussed by Cocconi.⁹¹ The drop in period is attributed to the sudden re-adjustment of the neutron star to a new figure of revolution with a slightly lower moment of inertia. From the magnitude of the observed change in the Vela pulsar it is predicted that such changes can be expected every 700 yr, and for the Crab pulsar every 10 yr. Feldman *et al.*⁹² have theorized on the possibility of a shrinkage in radius of the necessary amount resulting from the ejection of mass in an explosive event or flare.

Cameron and Greenstein⁹³ have proposed that drag forces on the envelope might cause differential rotation between interior and exterior layers leading to the setting up of fluid instabilities. The sudden mixing of material

between inner and outer regions to relieve an instability will then tend to equalize their rotation rates manifesting itself as a decrease in rotation rate of the envelope. The concept of differential rotation also leads to the possibility of re-adjustments of the internal magnetic field with consequent equalization of rotation rates.⁹⁴

We have only one such observation of sudden period decrease available to date. An appreciation of its likelihood of occurrence, and probably also its understanding, will have to await other such observations. Some general remarks, however, can be made on the basis of what we already know. Firstly, the neutron stars observed as pulsars are not all in an ultimate configuration, but are still subject to internal changes. Secondly, the degree of differential rotation contemplated affects the validity of the arguments based on solid body rotation relating to the energetic output of NP 0532 for driving the Crab nebula. If a change of angular velocity of the envelope of 2 parts in 10^6 could take place due to equalization of rates, then the interior, by definition, must have a rotational rate of $>(1+2 \times 10^{-6})$ that of the envelope. As there are 10^6 periods per day the field lines, if they extend to the interior as one suspects they must, would get wound around at least twice per day. If reconnection of the lines of force takes place on the average after n turns, one may expect an internal re-adjustment once every $\frac{1}{n}$ days. The observations of Reichley and Downs⁸⁹ suggest that a small change in the strength of the external magnetic field was involved in the sudden change. They found that dP/dt and consequently K was increased by 1% after the event. A decrease in radius of 1 part in 10^6 could not possibly increase the magnetic energy by the necessary amount due to simple volumetric compression. Lastly, the gross structure of the external magnetic field was unaffected by the jump as seen in Figure 8 where the polarization pattern is unchanged.⁵¹

RADIATION MECHANISMS

Of all aspects of pulsar astronomy, perhaps the one in which no tangible progress has been made is the theory of the actual emission mechanism. The relative independence of duty cycle on period is one of the more significant clues we have to work on. The detailed polarization structure of the pulses^{50, 95, 96, 52} is another very important clue. A study of PSR 0833-45 has established that the variation of the plane of polarization during the pulse (Figure 8) is intrinsic and not due to Faraday rotation en route. Consequently, this sweep of the position angle can only be interpreted in terms of the near alignment of the magnetic axis with the line of sight during the pulse as shown by Radhakrishnan and Cooke.⁵¹ Measurements of the optical polarization of the Crab pulsar have shown a similar variation across the pulse⁷³ and have led Wampler *et al.*⁷⁴ to the same model. A similar conclusion has been independently reached by Bohm-Vitense⁹⁶ from considerations of the shape of the optical pulse from the Crab pulsar.

Komesaroff, Morris and Cooke³⁶ have found that two pulsars with a double pulse structure show a rapid change in polarization angle in the interval between the sub-pulses. This phenomenon had already been noted by Clark and Smith⁹⁵ for the case of CP 0328. Geometric considerations indicate that such a rapid variation might result from an almost perfect alignment of the line of sight with the sweep of the magnetic pole.

We are assuming in this discussion that the polarization reflects the magnetic-field structure of the pulsar. Since the ordered field of the pulsar cannot co-rotate beyond the velocity of light cylinder, we can conclude that the radiation must be generated within the region of co-rotation of the magnetosphere. The enormous field strengths in this region would preclude any synchrotron radiation in the radio-frequency spectrum. One possible mechanism is emission from ultra-relativistic electrons moving along the field lines radiating by virtue of the acceleration associated with the curvature of these lines. For the generation of this type of radiation, the relevant radii of curvature will depend on the geometry of the magnetic-field lines and not the radii of gyration associated with synchrotron radiation. To a first approximation, the linear polarization produced will have the electric vector parallel to the projected magnetic-field lines and not perpendicular as in the case of synchrotron radiation.

Deutsch's⁸³ treatment of an idealized rotating star in vacuo leads to one possible solution in which the field close to the surface is a magnetic dipole, associated with a more complex electric field, both in rigid rotation. The far field effects of this model, as we have seen, were discussed by Pacini⁸² and also by Gunn and Ostriker.⁸² We are led to believe that in the near field domain, for values of rotational frequency and magnetic field associated with pulsars, surface electric fields can be as high as 10^{12} Vm⁻¹. Charged particles can therefore easily acquire the energies needed to radiate by the mechanism proposed in the previous paragraph. A detailed investigation along these lines might be well worthwhile.

Any really satisfactory theory of the operative emission mechanisms must, of course, explain the whole spectrum of radiation observed from the Crab pulsar, ranging from metre waves to hard X-rays, and the odd shape⁷⁷ of the spectrum. The indications are that the spectrum steepens rapidly with age, as witness the fact that no optical pulses have been seen for Vela in spite of its relative proximity and lack of obscuration. If the conclusions about magnetic decay times drawn earlier are true, then the steepening of the spectrum has resulted only from the decay of angular velocity, and must surely be of significance. The likelihood of finding pulsars at the sites of the other known supernova remnants is affected by the number of neutron stars—if more than one—formed per explosion, the favourable inclination of the beaming, and the interstellar dispersion along the path. Since the last factor affects only radio signals, we suggest that an optical search for pulsations or continuous spectra also be made on likely objects at these sites. Further clues to the radio mechanism are the rapid intra-pulse fluctuations in intensity,^{97, 98} the cut-off in the radio spectra of most pulsars,^{98, 99} and the varying circular polarization reported for some pulsars.^{97, 95} Let us hope that our understanding of these aspects will improve substantially in the next fifteen months.

I acknowledge with gratitude the vast amount of unpublished information that was made available to me, both by my colleagues in the Radiophysics Laboratory and by investigators abroad through preprints and letters. Due to the subjective bias that is bound to affect any review of this kind, and to the limitation of space, many significant contributions have probably been overlooked. To the authors of these, I extend my apologies.

Note added in proof (August 18, 1969)

Due to an oversight Pulsar AP 1237+25 was unfortunately omitted from Table I. The characteristics of this pulsar¹⁰⁰ are given below with those of four others recently announced from Molonglo,¹⁰¹ one of which has the highest known dispersion measure of 300 cm⁻³ pc. Two of the pulsars listed in Table I have recently been found to be slowing down. The slowing-down parameters determined at Cambridge¹⁰² together with the calculated magnetic fields and ages have now been included in Table I.

	$\dot{P}$	$b\dot{P}$	P	Δt	dm
AP 1237+25	253	+87	1.3824	60	8.5
MP 0254	271	-55	0.448	10	10
MP 1154	297	-0.1	0.400	—	270
MP 1706	7	+15	0.654	20	10
MP 1911	31	-7	0.825	20	75

Units are as in Table I

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