PULSARS

The more we learn about the newly discovered pulsating radio sources, the more difficulty we have in producing a theory that will explain their remarkably regular pulse repetition periods and otherwise highly irregular behavior.

STEPHEN P. MARAN and A. G. W. CAMERON

THE DISCOVERY OF PULSARS, or rapidly pulsating radio sources, was, like certain other historic events in astronomy, an accident. It is reminiscent of the unexpected detection of radio bursts from Jupiter by Bernard F. Burke and Kenneth L. Franklin,[1] who were studying the Crab Nebula, and of the discovery of the cosmic fireball radiation by Arno A. Penzias and R. W. Wilson,[2] who had intended to survey the galactic continuum at high latitudes.

Six months after the pulsar discovery we know many properties but have no satisfactory theory. The four known pulsars have remarkably regular radio pulse-repetition periods ranging from 0.25 to 1.34 sec. Their other properties are highly irregular. Intensity fluctuations are different at different frequencies, pulse shape varies even at a single frequency and the polarization of a given source can be linear or circular. The objects may be as close as 30 to 128 parsecs, and at least one may emit light that varies sinusoidally with a period different from the radio period.

The flurry of activity stimulated by the discovery prompted a gathering at Goddard Institute for Space Studies in New York on 20–21 May. It was sponsored by Goddard and the Belfer Graduate School of Science of Yeshiva University. (Material reported in the talks at Goddard is identified in this article as reference 3.) On page 46 is a box of the recent developments.

Serendipity at Cambridge

The pulsar discovery at Cambridge came while Anthony Hewish, S. J. Bell, John Pilkington, Paul Scott and R. A. Collins[4] were using a scintillation technique to measure angular structure in celestial radio sources. The measurement of angular structure has considerable importance in astrophysics. Angular sizes are combined with optical distance estimates to yield physical dimensions; these dimensions are used to infer lower limits to ages of radio sources such as the strong radio galaxies. Two methods of measuring angular size have received considerable attention recently: long-baseline interferometry and the lunar occultations of radio sources.

A less known technique is more suited to measuring sizes of many sources in a relatively short time. One studies the scintillations induced in the radio signals by the small-scale structure of the interplanetary gas or "solar wind." This scintillation phenomenon was first noted at the Mullard Radio

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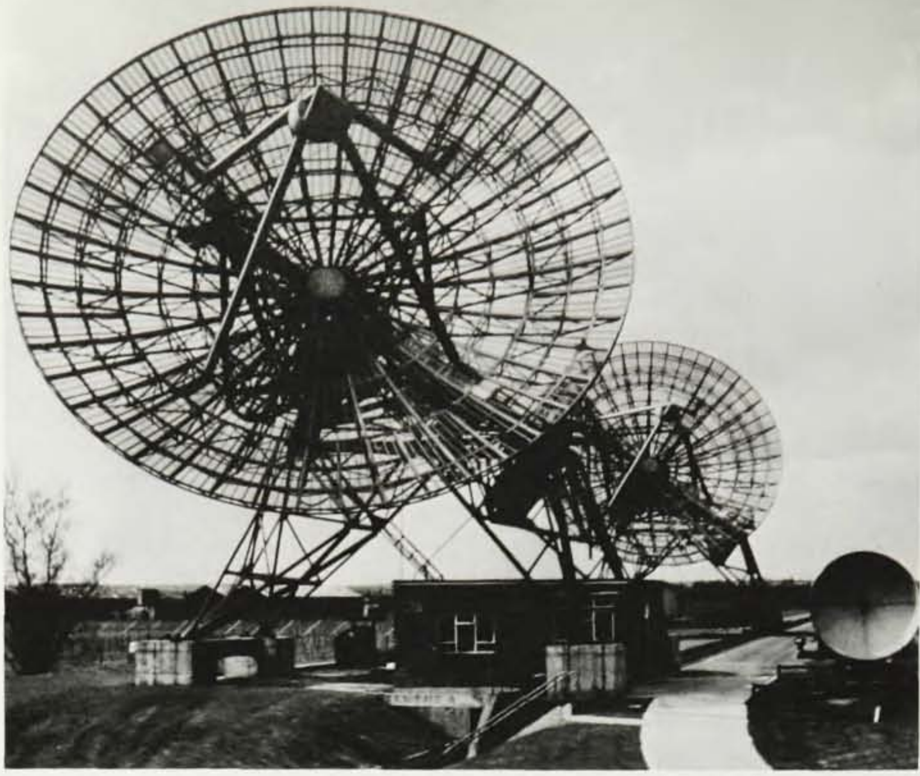
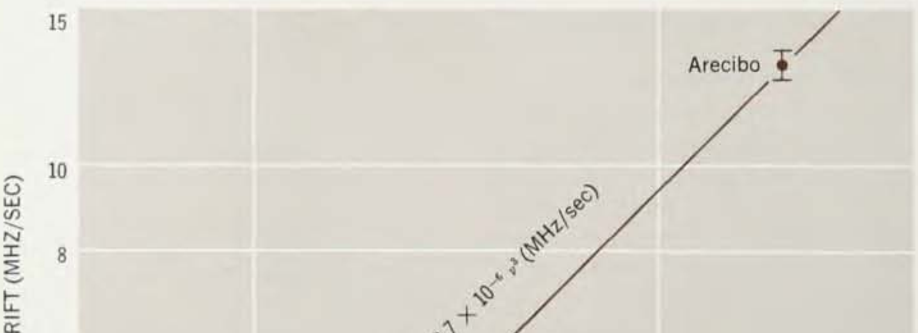
A. G. W. Cameron received his PhD in nuclear physics from the University of Saskatchewan, taught at Iowa State College for two years and then went to Chalk River for seven. In 1961 he went to Goddard Institute for Space Studies, where he worked on stellar evolution, quasars, x-ray sources, planetary atmospheres and lunar evolution. Since 1966 he has been professor of space physics at Belfer Graduate School.



PORTION OF CAMBRIDGE 1-MILE INTERFEROMETER used to determine accurate location of CP 1919. Two of the three dishes are shown. The more distant of the two moves on railroad tracks. Solid dish is German World War 2 relic. —FIG. 1



FREQUENCY DRIFT in the radio pulse arrival times for CP 1919, observed at Arecibo[11] and Cambridge,[5] is attributed to dispersion in the interstellar medium (based on Drake and his collaborators[11]). Equation of curve appears on drawing. —FIG. 2

Astronomy Observatory, Cambridge, by Hewish, Scott and D. Wills.[5] They recognized the potential value of source-size determinations by this technique, and accordingly proceeded to design a radio telescope optimized for such work.

The antenna designed at Cambridge is a 470 × 45-meter array of copper-wire dipoles. Working at 81.5 MHz, it can survey the celestial sphere between declinations 44° N and 8° S once per week. It went into operation in July 1967. Shortly thereafter, the observers began to notice occasional sporadic interference. After a few months, they decided to track down the source of the worst (strongest) of the interfering signals. The "interference" came from a fixed location in the constellation Vulpecula; thus a terrestrial cause for it was ruled out. The signals proved to be periodic in nature, consisting of brief pulses separated by about 1.3 seconds. After observing the source for several months, the Cambridge astronomers reported their discovery and subsequent findings in the 24 Feb. issue of *Nature*.[4] The object is called "pulsar 1" or CP 1919. (The digits represent the position in Right Ascension; thus CP 1919 means Cambridge pulsar at $19^h\ 19^m$.)

The possibility of using the interplanetary scintillations to identify small angular structure in radio sources had grown increasingly attractive in the three years since Hewish, Scott and Wills first attempted it. Thus it happened that astronomers at the University of Manchester and at the California Institute of Technology were preparing to make scintillation measurements when the Cambridge discovery was announced. Since both groups were suitably instrumented to record weak, rapidly varying signals, they immediately turned their attention to CP 1919. The Manchester astronomers[6,7] used the 250-foot (76-m) steerable paraboloid at Jodrell Bank; the Cal Tech team[8] observed with the 210-foot (64-m) antenna maintained by the Jet Propulsion Laboratory at the Goldstone Tracking Station. Among the other groups that promptly began radio measurements of CP 1919 were those at the Commonwealth Scientific and Industrial Research Organization, Sydney[9] and at the Arecibo Ionospheric Observatory.[10,11]

Meanwhile, at Cambridge, Martin Ryle and Judy A. Bailey[12] used the one-mile (1.6-km) interferometer (figure 1) to determine a more accurate position for CP 1919. Examining the Palomar Sky Survey photos of the region, they found a faint object about 5 arc sec from their new position. They—and subsequent observers—have referred to it as the "blue star," although measurements of its light now show that it is more nearly red in color. The confusing terminology persists because Ryle and Bailey also found a fainter, redder object, somewhat further from the radio position, that is known as

Table 1. CP 1919 Optical Pulse Studies

Observatory	*Telescope aperture (cm)*	*Detection technique*	*Reference number*
Asiago	122	rotating disk/image-tube camera	37
Harvard	155	photomultiplier/mag. tape recorder	38
Kapteyn	61	rocking camera	39
Kitt Peak	127	photomultiplier/multichannel scaler	14
Lick	305	photomultiplier/mag. tape recorder	40
Lowell	183	photomultiplier/multichannel scaler	41
McDonald	208	photomultiplier/multichannel scaler	H. J. Smith[3]
Mees	61	photomultiplier/multichannel scaler	42
Palomar	508	photomultiplier/mag. tape recorder	J. Kristian[3]
Royal Greenwich	91	rotating disk/image-tube camera	43
Cambridge	92	photomultiplier/multichannel scaler	44

the "red star." Also at Cambridge, John Pilkington and his collaborators[13] were using the scintillation telescope to investigate some 50 possible sky locations where "interference" had been observed in the original survey. Pulsars were found at three of the possible sites; they are called CP 0834, 0950 and 1133.

The announcement by Ryle and Bailey of a possible optical counterpart for CP 1919 inspired many astronomers to search for optical pulses. The early efforts to detect periodic radiation from the blue star, the red star or even adjacent blank sky are summarized in table 1. Most of these first attempts failed, but Roger Lynds, Steve Maran and Donald Trumbo at Kitt Peak[14] obtained a weak positive result on 2 May. This observation did not appear to represent optical pulses at the radio pulse rate. Displayed on the cathode-ray tube of a multichannel scaler, it had the form of a sine curve with a period twice that of the 1.3-sec radio period. Thus it had neither the expected time scale nor the expected form. A similar phenomenon was observed on 3 May and on 4 May, and it was possible to combine the data for the three nights and obtain a good level of statistical significance for the resultant sine wave.

THE OBSERVATIONS

So far only four pulsars are known. However, the limitations of the Cambridge survey suggest that the discovery of additional objects is likely:

Sky coverage. Almost the entire southern hemisphere, and much of the northern sky, has yet to be checked.

Frequency response. A time constant of 0.1 sec was used in the scintillation survey; thus "fast pulsars," if any, would have been missed.

Selection for low dispersion. The Cambridge 81.5-MHz receiver had a 1-MHz bandwidth. The pulse arrival time varies with frequency depending on interstellar dispersion; hence, if the pulsar is at a large distance, successive pulses may overlap within the finite bandwidth, thus simulating a steady source.

Energy and distance

Table 2 is a summary of the principal observed properties of the pulsars.

The "spectral index" α is defined by

$$S_\nu \propto \nu^\alpha$$

where S_ν is the flux density in the pulse and ν is the frequency. Individual pulse amplitudes are highly variable, and hence the spectral index is a rough average property. There are indications that the spectral index itself is variable when averaged over intervals of a few minutes. The flux density of CP 1919 decreases much more rapidly at higher frequencies. This high-frequency cutoff is not found in CP 0950 and 1133, at least to 2300 MHz.[15] The data on CP 0834 are incomplete. A low-frequency cutoff has not been established for any pulsar.

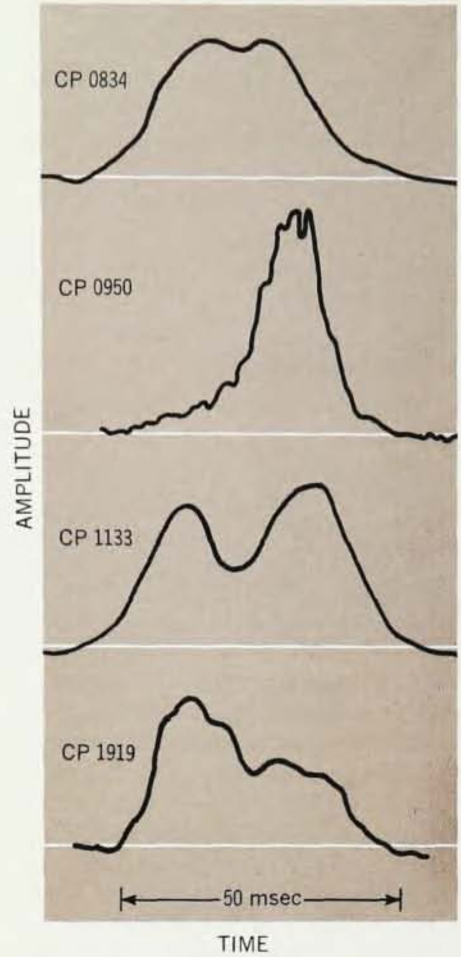
Observed arrival time of a pulse depends on frequency of observation, arrival time being later for lower frequencies. This phenomenon is attributed to dispersion of the radio waves in the ionized component of the interstellar medium between the pulsar and the earth. Variation of arrival

Table 2. Observed Properties of Pulsars*

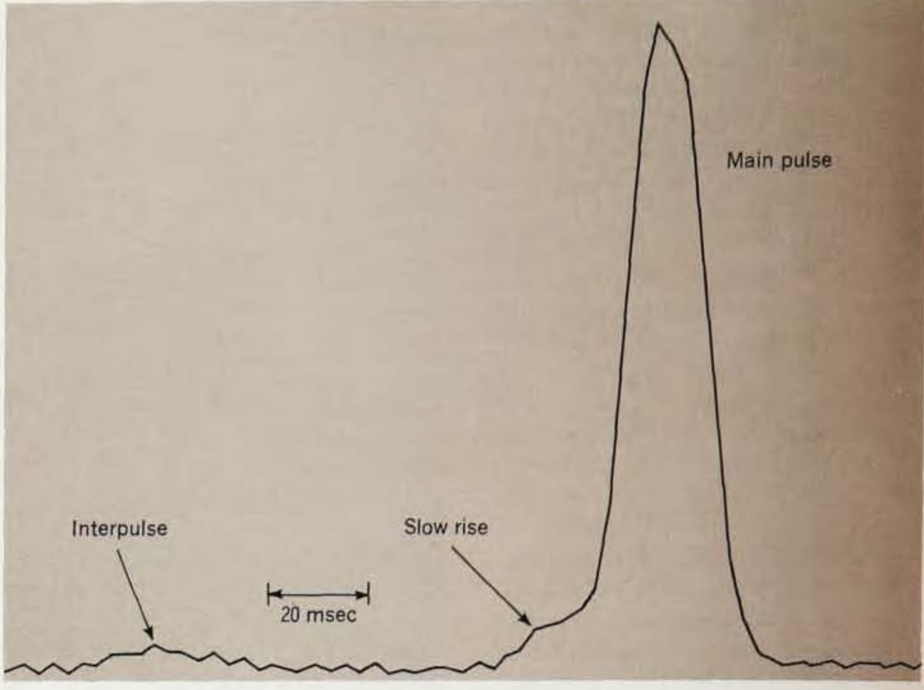
Name	*Right ascension and declination (epoch 1950)*	*Radio pulse-repetition period (sec)*	*Spectral index*	*Pulse envelope shape*	$\int n_e dl$ *(parsecs cm^{-3})*	*Distance estimate (parsecs)*
CP 0834	$08^h34^m22^s \pm 10^s$ $+06°07'00'' \pm 180''$	1.2737642 ± 3	-1.2	Double	12.80	128
CP 0950	$09^h50^m28^s.95 \pm 0^s.7$ $+08°11'06'' \pm 42''$	¶ 0.25306515 ± 6 ¶ 0.25306504 ± 5	-1.1 -1.1	Single; precursor at -100 msec	$2.98 \pm .04$	30
CP 1133	$11^h33^m36^s \pm 3^s$ $+16°07'36'' \pm 18''$	1.18791106 ± 15	-1.1	Double	4.87	49
CP 1919	† $19^h19^m37^s.0 \pm 0^s.2$ † $+21°47'02'' \pm 10''$ ‡ $19^h19^m36^s.88 \pm 0^s.1$ ‡ $+21°46'57''.4 \pm 1''.5$	1.33730109 ± 1	-1.5 (40–400 MHz) -3.2 (400–2300 MHz)	Double	12.55	126

† = Radio position; ‡ = position of "blue star;" ¶ = independent determinations.

* Compiled from references 9, 12, 15, 17, 18, 36, 45, 46 and the following papers at the Conference on Pulsars, New York, NY, 20–21 May 1968: M. M. Davis, Ekers and Moffet, D. Richards (as quoted by Drake), Graham Smith.



MEAN PULSE PROFILES observed at Manchester are averaged over 8 min at 408 MHz for the four sources (Lyne and Rickett[17]). Receiver bandwidths and time resolutions are shown. —FIG. 3



AN "INTERPULSE" precedes the main pulse emitted from CP 0950 by 100 msec out of a total repetition period of 253 msec (based on Rickett and Lyne[21]). —FIG. 4

time with frequency is given by

$$\frac{d\nu}{dt} = -\frac{c\nu^3}{\int \nu_p^2 dl} \qquad (1)$$

where ν_p is the plasma frequency and l is the distance along the ray path. Since

$$n_e = 1.24 \times 10^4 \nu_p^2 \qquad (2)$$

(n_e is the electron number density) one can see that variation in arrival time gives a measure of integrated electron density along the line of sight to the pulsar.

Figure 2 shows measurements of the drift rate of the pulse radio frequency for CP 1919 measured at Arecibo[11] and Cambridge.[4] Equation 1 is well fitted by the measurements. The fit corresponds to an integrated electron density of 3.84×10^{19} cm^{-2} for this pulsar, or 12.55 parsecs cm^{-3} as given in table 2. This figure stayed constant in March to one part in 10^3.[11] Equation 1 is valid only when $\nu \gg \nu_p$, and the absence of any need for additional terms demonstrates that the average value of n_e must be less than 10^4 electrons/cm^3; so the minimum distance in which the bulk of the dispersion occurs is 5×10^{15} cm, or 300 astronomical units.[16] Since it will be argued later that source size is many orders of magnitude smaller than this, it is not possible to attribute the dispersion to some kind of stellar corona; hence the interstellar medium must be responsible.

Distance estimates for the pulsars thus depend on an estimate of the mean value of n_e between earth and pulsars. Interstellar space is divided into clouds of neutral hydrogen gas with $n_e \gtrsim 10^{-3}$ cm^{-3} embedded in an ionized hydrogen gas with $n_e \approx 0.1$ cm^{-3}. In addition the observations of thermal radio radiation from the galactic disk suggest a mean value $n_e \approx 0.1$ cm^{-3}, but it is evident that n_e must be quite variable with position. The distance estimates given in the last column of table 2 are nominal values corresponding to $n_e = 0.1$ cm^{-3}; perhaps these very crude estimates should be regarded as lower limits.

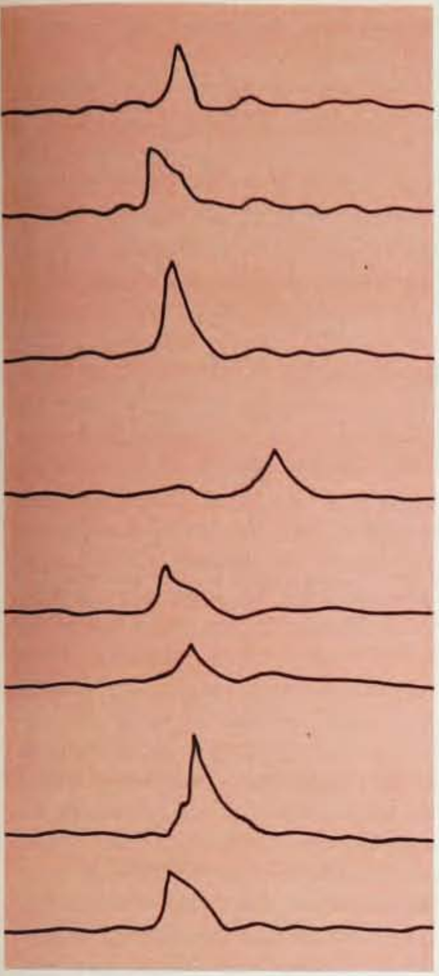
CP 1919 has a mean power at 81.5 MHz of 10^{-26} watt/meters^2 Hz, but some individual pulses correspond to peak power levels more than ten times as great.[4] Taking the nominal distance of 126 parsecs, the quoted power corresponds to a mean radio output above 40 MHz of 10^{28} ergs/pulse, with some pulses radiating more than 10^{29} ergs. This estimate assumes that the emission is isotropic.

The energy is radiated within a total pulse width of 50 milliseconds. The period between pulses is remarkably constant, not varying by more than a few parts in 10^6 per year, or more than a few parts in 10^{13} per pulse (Kip S. Thorne, Cal Tech[3]). The other three pulsars appear to be as close or closer than CP 1919 (table 2), but their mean power levels are smaller.

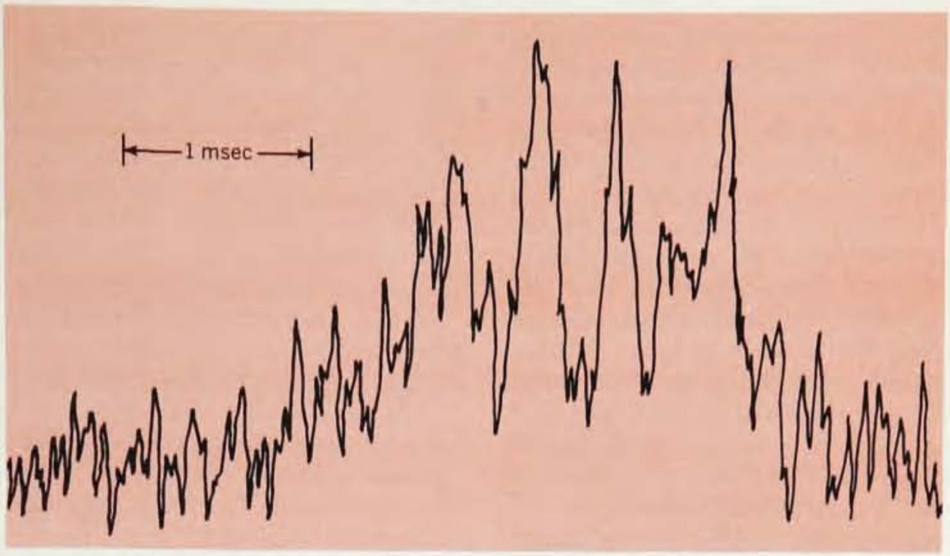
Pulse amplitude variations

Variations in the amplitudes of pulses observed at different frequencies have been extensively studied. The results are interesting, complex and slightly contradictory.

Manchester observations. Andrew Lyne and Barney Rickett[17] and F. Graham Smith[3] discussed two types of pulse amplitude variation in CP 0950. One variation is strongly frequency dependent; the other is not. Variation in strength of successive individual pulses does *not* depend on fre-



PULSE SHAPES OF CP 1133 observed by Moffet and Ekers, selected to show typical variations. There are also occasions on which practically no pulse amplitude is observed. —FIG. 5



FINE STRUCTURE within a pulse from CP 1133 (Moffet and Ekers). —FIG. 6

quency. Thus, if a pulse is stronger than the preceding one on 151 MHz, the same is true at 408 MHz and 922 MHz. But changes in average power of a 2-min train of pulses vary greatly with frequency. For example, the average pulse power at 151 MHz may be declining while that at 408 MHz is rising, and the variations may differ significantly at frequencies separated by only 2–3 MHz near 151 MHz. Similar effects are observed in the other pulsars. The time scale of the variation in average pulse power is strongly dependent on frequency. Thus, in CP 1919 and 1133, variations at 408 MHz are much slower than those at 151 MHz.

Arecibo observations. Frank Drake and his colleagues[11] find that in CP 1919 pulse-to-pulse amplitude variation *is* strongly dependent on frequency. In this source, a frequency change of 3 MHz is sufficient to produce a decorrelation of the amplitude ratio for successive pulses; however, most of the Arecibo observations were taken at frequencies lower than those used in the Manchester studies of CP 0950. In any case the variation of average pulse amplitude in CP 1919 is similar to that found in the other sources by the Manchester workers.

Do the radio pulses show any periodicity at half the basic observed frequency? G. Grueff, G. Roffi and M. Vigotti find that the amplitude of 408-MHz pulses in CP 1133 varies with a period equal to twice the pulse repetition interval. However, such an effect is not evident in the Cambridge and Manchester observations of CP 1133 (Pilkington[3]; Graham Smith[3]) and is also absent in the data for the other three pulsars.[18,19]

Pulse shapes and polarization

There is a great variety in pulse structure, even for a given frequency and a given source. However, the average of a great many observations reveals a typical "envelope" for each pulsar that does not appear to depend on frequency. There was some indication in the early Arecibo work[10,20] for a basic triplet structure in some of the pulsars, but an extensive series of observations[17] shows that the three 1-sec pulsars (CP 0834, 1133, 1919) are characterized by double pulse structures, while the 0.25-sec object (CP 0950) has a single pulse (figure 3). The leading edge of a CP 0950 pulse does have a much slower rise time than is typical of the other objects, which may imply that this object is also double pulsed, with a weak first subpulse. The envelope width is about 50 msec for all four pulsars, although individual pulses are sometimes as short as one tenth of this duration. Rickett and Lyne[21] found an "interpulse" that occurs about 100 msec before the peak of the main pulse (figure 4). At 408 MHz the energy in the interpulse is 1.8% of that in the main pulse.

Lyne and Smith[7] found that the emission of all four pulsars is polarized. They obtained proof for strong (essentially 100%) linear polarization in discrete components of the pulse structure, with different position angles of the electric vector for the different components. Arecibo observations at 430 MHz (H. D. Craft[3]) revealed that all the pulsars have elliptical polarization. Sometimes observed polarization of a source is strongly linear; at other times it may be mostly circular. The interpulse in CP 0950 is 85–100% linearly polarized at 408 MHz.

Much structure variation occurs within individual pulses. Figure 5 shows a selection of pulses from CP 1133 observed by Alan T. Moffet and R. D. Ekers[3] that demonstrates this variability.

The Arecibo work and also that done at Goldstone (Ekers and Moffet[3]), shows that the subpulse structure is highly variable, and consists of polarized subpulses as short as 0.3–0.4 msec (figure 6). This fine structure suggests many short-lived emitting regions with linear scale $\lesssim$ 50 km. Drake's[3] alternative explanation involves scintillation due to matter moving across the line of sight at velocities of about 10^4 km/sec, at distances of about 10^3 km from the pulsar.

Graham Smith[3] has discussed the possibility that the slow variations in average pulse amplitude may be caused by a scintillation or focusing effect due to the interstellar medium. In this connection, he pointed out that the angular size of a pulsar may be about 10^{-11} radian, which can be compared to a quasar size of about 10^{-8} radian. Thus the Cambridge survey, intended to observe scintillation in the interplanetary gas, may have led to the discovery of scintillation at much greater distances from the earth. P. A. G. Scheuer[22] finds that the data on the slow variations require a two-screen model if they are to be explained on the scintillation hypothesis. Scintillations of the high-frequency radiation would be caused by the general interstellar medium; those at low radio frequencies would be due to matter at $\lesssim$ 0.1 parsec from the pulsar.

Optical observations

An apparent sinusoidal variation in light of CP 1919 (figure 7) with a period of twice the radio-pulse repetition period was found at Kitt Peak.[14] This result was the end product of 8.7 hours of integration time with a 50-inch (127-cm) telescope, an unfiltered 1P21 photomultiplier tube and a 400-channel R.I.D.L. multiscaler. The photometer diaphragms were 14 and 17 arc sec in size and were centered on blank sky near the radio position. Although they did include the blue star, it was not centered in the field, and thus the source of the periodic optical emission was uncertain. Figure 8 is a sketch of the field of view near CP 1919 and the blue star.

At the New York meeting David Cudaback reported work done at Lick Observatory with colleagues from Stanford and Berkeley[18] that appeared to confirm the optical double period. The analysis suggested that harmonics of this period were present and that the period itself was somewhat variable. Cudaback has subsequently found, however, that these conclusions are questionable because of instrumental difficulties.

Subsequent work at Kitt Peak shows that if the sinusoidal variation is real, its amplitude is variable. In any case, confirmation with other equipment is needed.

Various observations of the blue star have been made at the Mount Wilson and Palomar observatories and at Kitt Peak. Photometry by Allan Sandage (Mount Wilson and Palomar) and J. Kristian (Cal Tech)[3] yields a visual magnitude of 17.46 and color differences (in magnitudes) of blue–visual = 1.41 and ultraviolet–blue = 0.70. Spectra by H. C. Arp, W. L. W. Sargent and Maarten Schmidt show a red continuum with the H and K lines of singly ionized calcium present in absorption. The observations are thus consistent with the hypothesis that the blue star is an ordinary G or K type star, reddened by interstellar absorption. However, the early Kitt Peak spectra[14] showed a relatively strong and broad absorption line at the position of Hβ, the second line of the hydrogen Balmer series, in addition to the H and K lines. Additional hydrogen lines are present in better spectra recently obtained by Lynds. These have widths of about 15Å (1.5 nm); such widths are probably too small to allow a rotating white-dwarf model.

Considerable photometry has been performed in the regions of the other pulsars; the accuracy of the available radio positions is not satisfactory for optical studies, however, and it is not surprising that the efforts so far have been to no avail.

In CP 1919, the sinusoidal optical variation at twice the radio period corresponds to a peak-to-valley amplitude of about 0.04 magnitudes in the blue star. In energy terms, if we assume isotropic radiation at a distance of 126 parsecs, this means that once every 2.6 seconds, the optical emission of CP 1919 fluctuates by about 3×10^{29} ergs/sec in the 1000-Å bandwidth of the photometer. Thus the optical variations, when present, correspond to a fluctuating energy emission somewhat greater than that in the radio pulses.

LATEST PULSAR NEWS (as of mid-July)

A fifth pulsar has been discovered; the Parkes radio telescope has found line structure in CP 1919, and the 200-in. telescope has failed to find optical variation in CP 1919.

The fifth pulsar, located at $15^h06^m \pm 2^m$ and $55.5° \pm 1.0°$ and called HP 1506, was reported (Int. Astron. Union circ. no. 2084) by Richard Huguenin and Joseph Taylor Jr, working with the 90-meter Green Bank radio telescope. The period is 0.7397 sec, which suggests a continuous distribution of pulsar periods.

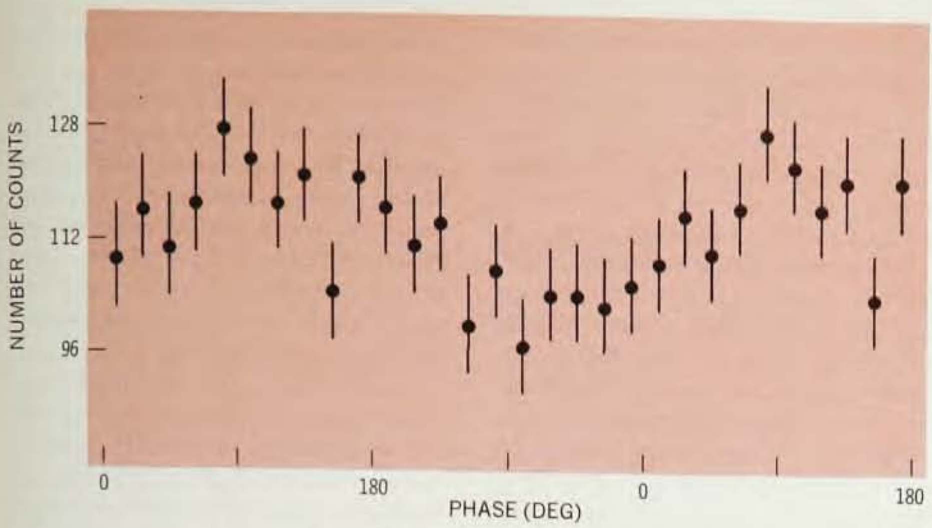
At a pulsar session of the International Symposium on Contemporary Physics, Trieste, which occurred on 24 June, John G. Bolton of Commonwealth Scientific and Industrial Research Organization, Australia, reported that a University of Tasmania group, using the Parkes radio telescope, had found a line structure in CP 1919. Using ten adjacent channels of bandwidth 100 kHz centered at 80 and later at 150 MHz, they observed that the pulsar signal appeared in only one channel at a time. Typically, it might appear in a given channel for about five pulses and then jump to another (not necessarily adjacent) channel. Hence within a 1-MHz bandwidth the pulsar signal is a line which is narrow compared to 0.1 MHz. There must be many such lines in the entire spectrum, and some of the "quiescent" phases of pulsars reported by observers may simply mean that the lines have shifted out of the observed bandwidth.

It now appears that a pulsar radio pulse exhibits tremendous complexity. In addition to the line structure, the temporal variation of the signal exhibits components as short as ten microsec in duration (reported by Frank Drake at the Los Alamos meeting of the American Physical Society).

Also at Trieste, Maarten Schmidt, Cal Tech, reported on optical observations of CP 1919 carried out by Jerome Kristian, Allan Sandage, Grant Snellen, James Westphal, and himself with the 200-in. telescope and a magnetic tape recorder. In 110 minutes of observation on the night of 28–29 May, they failed to observe any optical variations at 1, 2, 3, 4, 6 or 12 times the radio period. At twice the radio period, the upper limit on optical variation was 0.2 per cent of the amplitude of the signal from the "blue star."

THEORETICAL CONSIDERATIONS

It must be recognized at the outset that theorists are baffled by the pulsars. No one as yet has proposed a comprehensive scheme that attempts to account for all of the peculiarities we have discussed. The best that can be done at present is to place some limitations on the types of model



POSSIBLE OPTICAL VARIATION of CP 1919 found by Lynds, Maran and Trumbo.[14] To obtain the number of counts, add 4300 to the plotted value and multiply by 100. The period of the approximate sine wave is double the radio pulse period. —FIG. 7

that may offer some hope for success.

The most striking pulsar features are the exceptional regularity of the radio period and the great irregularity of other properties. From observations last spring, it can be concluded that CP 1919 has a period stable to a few parts in 10^6 per year. Thus the radio pulses constitute a good clock.

Jeremiah Ostriker[23] has given a useful classification scheme for the kinds of objects in nature that have good time-keeping properties. We can consider objects that are vibrating, orbiting or rotating.

The fundamental vibrational period of an object is essentially the dimension divided by the velocity of sound, which in turn in a gravitating gas is proportional to the square root of mass divided by radius. Hence the period is roughly proportional to the inverse square root of the mean density. If the fundamental period is to be in the neighborhood of 1 sec, only very compact objects can be considered. For objects of stellar mass, these must be white dwarf stars or neutron stars. White dwarf stars are objects with degenerate electron-gas interiors that are observed as end products of stellar evolution. Neutron stars are objects with degenerate nucleon-gas interiors that are hypothetical products of supernova explosions.

Vibrations of neutron stars can be rejected immediately. Most calculated models of these have fundamental periods in the vicinity of 1 msec. Only a very low-mass neutron star can vibrate with a period near 1 sec, and Thorne and J. R. Ipser[24] have shown that these contain more energy than the same mass of iron nuclei dispersed to infinity.

A variation of this idea has been proposed by Fred Hoyle and J. Narlikar,[25] who suggested that the collapse phase of a supernova may be reversible, so that the object oscillates between the neutron-star configuration and the original collapse radius. The tremendous dissipation accompanying such a collapse[26] is a severe difficulty, however.

In their original paper, the pulsar discoverers[4] noted recent work by D. W. Meltzer and Thorne[27] in which the minimum value for the fundamental vibrational period of a white dwarf star was found to be 8 sec, clearly at variance with pulsar observations. Meltzer and Thorne used an equation of state corresponding to matter cold-catalyzed to the end point of thermonuclear energy release, and they also made some approximations that overestimated the minimal attainable period (as pointed out by John Faulkner and J. R. Gribbin[28] and also shown by J. Skilling[29]). White dwarfs with central densities in the range 10^{10}–10^{11} gm/cm^3 are candidates for these minimal periods. At these densities electron Fermi levels are 10–20 MeV and ordinary nuclei will have undergone electron capture (for example, at Fermi energies above 5.52 MeV Mg^{24} undergoes two electron captures to become Ne^{24}). For these very relativistic electrons, the equation of state has become much less stiff against compression, and this fact, together with a relative reduction of electron pressure due to the electron captures, tends to render the white dwarf unstable against collapse. The actual collapse will occur at slightly higher density due to a general relativistic instability, but before this is reached the fundamental vibrational period becomes longer (approaching infinity at the actual point of collapse).

Faulkner and Gribbin[28] and Jeffrey Cohen, Institute for Space Studies,[3] have found minimal white-dwarf periods of about 1.6 sec. Cohen has found that a slight additional reduction of period can be obtained by including ion zero-point energies in the equation of state, but it does not appear possible to obtain periods as small as the pulsar radio periods. New computations by Skilling[30] yield theoretical oscillation periods $\gtrsim 2$ seconds. In any case, it is possible to obtain the optical "double period" of CP 1919.

The first-overtone periods of the denser white dwarfs become less than the quarter-second period of CP 0950. However, relatively low density white dwarfs will have first-overtone periods near 1.3 sec.

A. G. W. Cameron, Belfer Graduate School of Science,[3] has drawn attention to the problem that a vibrating white dwarf will require a suitable energy source. Density-sensitive (pycnonuclear) reactions involving helium or carbon in the interior may suffice for this purpose. But such reactions would also heat the star, and we do not see highly luminous blue white dwarfs in the positions of the pulsars. He suggested that internal so-called "URCA" shells would limit vibrational amplitudes and provide strong cooling in the interior. The URCA process occurs when the Fermi energy of the electrons is in the vicinity of a beta-decay end-point energy, so that if the Fermi surface either oscillates or is thermally rounded, phase space exists for the same nucleus to undergo alternate electron captures and beta decays, with accompanying energy loss by emission of neutrinos and antineutrinos. Such a condition can only persist for nuclei with odd mass numbers, but such nuclei will be plentiful as products of carbon and oxygen reactions in the deep interior of the star.

Ostriker[23] has given strong arguments against any orbiting clock mechanism. For a pair of very compact white dwarf stars orbiting in contact, the orbital period is too long. The period can be made short enough with a pair of orbiting neutron stars, but then the fractional change of period due to emission of gravitational radiation will exceed 7×10^{-5} per day, which is excluded by the radio observations. A gravitational lens model of orbiting neutron stars suggested by William C. Saslaw, John Faulkner and Peter A. Strittmatter[31] encounters difficulty on this score, and hence these authors are forced to postulate that the gravitational radiation will not occur. Their model encounters difficulties in accounting for the fine structure of the radio pulses. Geoffrey Burbidge and Strittmatter[32] attempted to circumvent this restriction by postulating the orbiting of a small object around a neutron star. However, Franco Pacini and Edwin Salpeter[33] have examined in some detail the limitations on models of such a satellite that are imposed by tidal disruption and gravitational radiation. If the satellite is held together by self-gravitation, its density must exceed 10^8 gm/cm^3 and its mass must be much less than 10^{-2} solar masses. So small a mass cannot evolve to so dense a state. On the other hand if the satellite consisted of matter at ordinary densities, and was held together by solid-state cohesion, its size could not exceed 10 meters, and it is hard to see how so small an object could be responsible for the pulsar radiation.

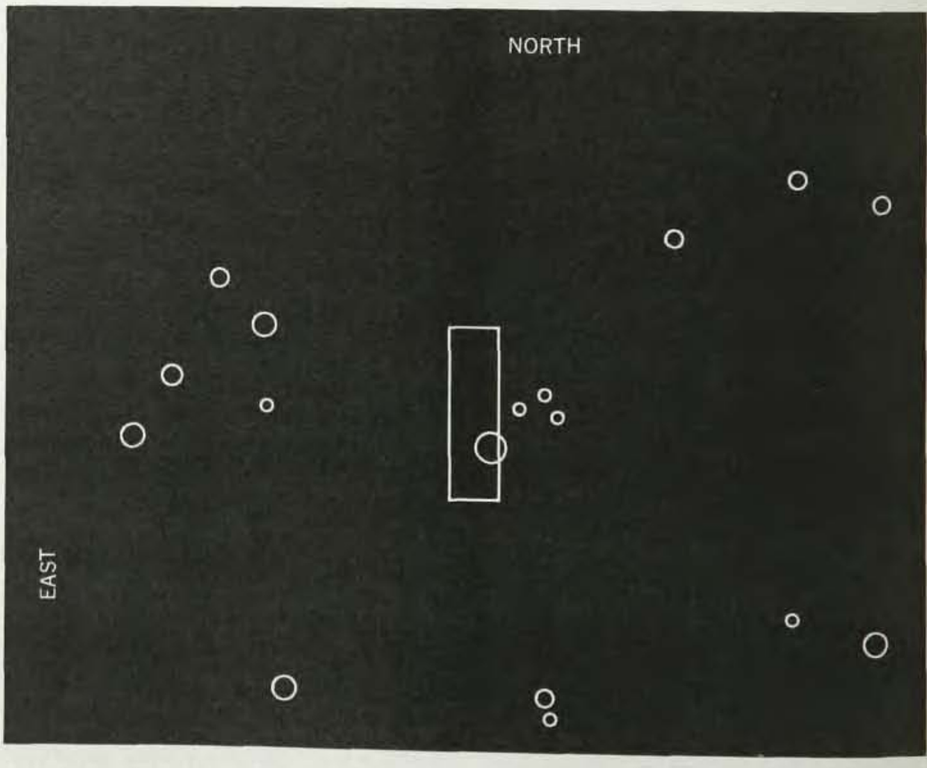
Rotating bodies will generally make good clocks, especially if they have no quadrupole mass moment, and hence do not radiate gravitational waves. However, the equatorial region of a star cannot spin faster than the rate corresponding to Keplerian orbital velocity. A neutron star can spin once per millisecond without encountering difficulty on this score. Hence a rotating neutron star can certainly provide good timekeeping properties for periods in the vicinity of 1 sec.

A white dwarf star encounters difficulties in spinning fast enough to synchronize with the radio pulse periods of the pulsars. Ostriker[23] showed that he could construct models of fast spinning white dwarfs that are very flattened and have variable periods at different latitudes. The various pulsar periods could be found at various latitudes on such a model. In his original models Ostriker had found that the pulsar radiation would have to emerge from a patch not more than a few centimeters wide in latitude for the model to have good timekeeping qualities. At the New York conference, however, he argued that crystalline viscosity in the interior of such white dwarfs would cause rigid rotation of the polar cap regions so that the apparently strong dimensional restrictions on the emitting patches would be greatly relaxed.

About the only features of the radio pulse-emission mechanism on which theorists are agreed are that the radiation is nonthermal and highly coherent with a brightness temperature of 10^{21} K or greater. There are many plasma radiation mechanisms available that meet these criteria, and a successful pulsar model must show how energy can be pumped into the appropriate plasma mode and then radiated in a way that allows variation of pulse and subpulse amplitudes, not only from event to event but also from one frequency to another. The polarization of the radiation must be capable of changing from nearly completely linear to circular with random variations from one subpulse to another. Finally the observations now appear to require that there are two very regular radio pulses associated with one optical period.

If the basic pulsar mechanism involves vibration, it is natural to look for the excitation mechanism in shock waves that develop in a stellar atmosphere during each vibrational period. Peter A. Sturrock, Stanford,[3] suggests that shock waves in a fairly weak transverse magnetic field will be able to excite ion plasma waves rather than the usual electron plasma waves and that the radiation then arises from the ion plasma waves. Graham Smith and Franz Kahn[3] suggest that shocks impinging on a sharp boundary between a plasma and a magnetic field can produce the required radiation. Neither of these models is consistent with the two-to-one ratio of the optical and radio periodicities.

If the basic pulsar mechanism in-



PULSAR CANDIDATE. Map based on a 200-inch Palomar plate taken by H. C. Arp is centered on CP 1919. The sizes of the circles roughly represent the relative apparent luminosities of the stars in the field. The box shows the uncertainty in the radio position. The star in the box is the pulsar candidate. The faintest stars recorded on the plate are not shown. One lies near the center of the box. —FIG. 8

volves rotation the radiation must be beamed and more or less continuous. Thomas Gold[34] suggests a rotating magnetosphere into which plasma is fed by a "sore spot" at a white-dwarf or neutron-star surface. The magnetosphere is considered to rotate rigidly with the star out to a surface upon which the tangential velocity is the speed of light, at which point the plasma becomes relativistic and shears off the lines of force. Gold suggests that the plasma must radiate during this acceleration and shearing process. The radiation then proceeds into a narrow cone about the direction of motion and would be seen only by an observer close to the equatorial plane of the rotating star. There is no place for the observed optical output in this model.

Wallace H. Tucker and F. Curtis Michel, Rice,[3] suggest a model of a rotating star with a magnetosphere having a large neutral sheet lying in one of the planes of longitude. Magnetic-field annihilation across the neutral sheet accelerates particles that radiate by a coherent synchrotron mechanism with the radiation directed outwards in a fan beam in the plane of the neutral sheet. The model is somewhat artificial, and it is not clear that it can account for the polarization and subpulse structure.

Bernard Eastlund, Atomic Energy Commission,[3] suggests a more conventional magnetosphere with magnetic poles near the equator of a rotating star. Such a magnetosphere, he says, may be subject to many of the instabilities that are observed in thermonuclear machines, and particle acceleration along the lines of force can produce Cerenkov radiation, perhaps accompanied by other radiation directed along the force lines. A model of this type might be expected to give two radio pulses per rotation period. There is some question about whether the radiation can be sufficiently directional and can account for the polarization and subpulse structure.

A more exotic suggestion concerning pulsars is that they represent signals from an intelligent civilization. The Cambridge observers at first informally designated these objects as LGM's (for "Little Green Men"). Drake and his associates[11] point out that the spectrum shape of the pulsars is not uncharacteristic of natural sources and that it is unsuited for efficient communication. They also note that the energy emission is too high for a plausible extraterrestrial technology.

Applications

Pulsars may have some useful applications in astronomy and physics. The Drake group[11] points out that accurate measurements of period may enable orbital motion of the source to be detected. It seems somewhat doubtful, however, that these measurements can be made accurately enough to provide a test of general relativity, as Banesh Hoffman[35] has suggested. Drake and his coworkers also suggest that the pulsars can provide an accurate time service and that they will be useful for measurements of projected electron density.

Graham Smith[36] has analyzed Faraday rotation of the highly polarized pulses from CP 0950, and thereby found that the component of the interstellar magnetic field parallel to the line of sight is surprisingly small.

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