Reports

Pulse Structure of Four Pulsars

Abstract. *The pulse structure of the four known pulsars is given. The pulse is about 38 milliseconds for the two pulsars of longest period, and within the pulsewidth three subpulses typically appear. The pulsar of next longest period typically radiates two pulses separated about 23 milliseconds in time. The one short-period pulsar emits single pulses of constant shape. The first subpulses of all pulsars have nearly the same shape. The shape of the first subpulse agrees well with the pulse shape expected from a radio-emitting sphere which is excited by a spherically expanding disturbance, and in which the radio emission, once excited, decays exponentially.*

The structure of the radio pulses emitted by pulsars is of great importance in determining the physical nature of pulsars and the mechanism of their radio emission. Knowledge of the pulse shape is also necessary if the best possible results are to be achieved in the timing of pulse periods, in the measurement of the delay in pulse arrival as a function of frequency, and in the search for new pulsars. The "typical" pulse shape of the first known pulsar, Pulsar 1 in Vulpecula, shows a complex but well-defined pattern, despite the great variation in pulse shape that occurs from pulse to pulse (*1*). Here we present the results of measurements of the pulse structure of Pulsars 1 through 4 (*2*).

The observations were made with the 1000-foot (30.48-m) telescope at radio frequencies of 111.5 or 195 Mhz, at which frequencies maximum signal-to-noise ratio is achieved on these objects. Pulsars 1 and 4 give maximum flux densities of about 150 flux units, and Pulsars 2 and 3 about 60 flux units, all at 111.5 Mhz. In all observations, the shortest possible time constant permitting satisfactory signal-to-noise ratio was used. Bandwidths were selected such that the variation in pulse arrival time with frequency would not distort the observed pulse shapes (*1*). The sweep of a storage oscilloscope was synchronized with the known period of pulse repetition, and the sequence of pulse presentations was observed to insure that the pulses observed on the oscilloscope were indeed from the pulsar. The validity of pulses could be established without doubt through the accurate synchronization of the pulses with the known period and the appearance of the pulses, which is quite dissimilar from any other sources of pulsed radio emission observed at Arecibo. When it was clear that a pulsar was being observed, the pulses of greatest signal-to-noise ratio were stored and photographed.

With Pulsar 3, the pulsar whose period is about 0.25 second and therefore greatly different from the periods of the other known pulsars, the pulse shape is simple and invariant from one pulse to another. Thus a single photograph provides full information on the pulse shape. With Pulsars 1, 2, and 4, however, the pulse shape varies greatly from pulse to pulse. However, as observed in Pulsar 1, there is a basic format to the pulse shape which is soon recognized. To show that basic morphology, we have taken a number of intense pulses and added together their amplitudes as a function of time (Fig. 1). The correctness of the time synchronization of the several pulses which are combined is established by the time coincidence of the first subpulses. The first subpulse is usually the best defined and most intense.

Although there is a clear-cut difference in the pulse shapes, certain quite striking similarities exist in them:

1) Pulsars 1 and 2, with the longest interpulse period, have the same overall pulse width of about 38 msec to within the observational errors. Pulsar 4 has a slightly longer overall pulse width of about 43 msec.

2) The pulsars with a period of more than 1 second contain subpulses which seem to retain the same format from one pulsar to another, but with the different subpulses being given different degrees of prominence from one pulsar to another. It appears that in all three there are three subpulses which follow one another at about 12-msec intervals. This is clear in Pulsar 1. Although the composite pulse for Pulsar 2 shown in Fig. 1 does not show this, we have photographed individual pulses of Pulsar 2 which show a well-resolved third subpulse at a time which would fall at time 22 msec in Fig. 1. A majority of Pulsar 2 pulses contain no third subpulse, and have an overall pulse width of 32 msec. The six pulses averaged to give the composite pulse shape for Fig. 1 contain two pulses in which there is a well-resolved third subpulse. However, the tails of those pulses not containing the third subpulse cause the composite pulse to show no clear third subpulse.

Pulsar 4 is quite interesting. About two-thirds of its pulses contain two well-resolved subpulses and resemble very closely the pulse shown in Fig. 1. The remaining one-third of its pulses are single and resemble the pulse of Pulsar 3. In those pulses containing two subpulses, weak emission can be seen occasionally during the time interval between the two subpulses, but most of the pulses show a complete absence of emission during this period. Extensive data taken 6 April 1968, but not yet reduced quantitatively, show that the separation in time between the two major subpulses varies by as much as 12 msec, and is typically about 5 msec longer than the separation shown in Fig. 1.

Whereas Pulsar 1 emits all three subpulses with similar weights, Pulsar 2 favors the first and second subpulses, and Pulsar 4 favors very greatly the first and third subpulses.

3) The shape and width of the first subpulse in Pulsars 1, 2, and 4, and the pulse of Pulsar 3 are nearly identical.

4) There is no existing evidence for weak pulsed emission either before or after the well-defined pulse onset and completion in any of the pulsars.

The second subpulse of Pulsar 4 is extremely short. No attempt to correct for time-constant smoothing has been done in Fig. 1. However, the shape of the second subpulse is largely a result of the 3-msec time constant. A correction for time constant shows that the second pulse persisted only about 4 msec, and is thus possibly associated with an emitting region less than 1200 km in size.

The simple pulse shape of Pulsar 3 is observed unaltered in all pulses from this object. No instance of complex structure or multiple pulsing has yet been observed with this object.

The most striking aspect of these pulse shapes is the presence of a basic morphology in pulse timing and pulse shapes. This shows, as might be expected, that similar physical phenomena are occurring in all the known pulsars. More significantly, it shows that acceptable theories of pulsars require stable and systematic mechanisms and geometries; theories which invoke random processes or structures of random geometry to explain the complex pulse structure appear prohibited. Thus for example, the proposal that the complex pulse structure is a result of gravitational focusing of radiation from several stellar flare regions (*3*) seems eliminated.

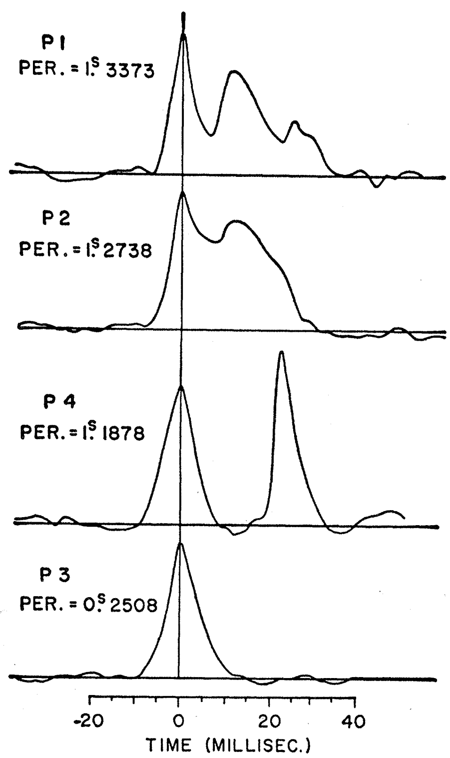

Fig. 1. Pulse structure of Pulsars 1 through 4. Ordinate is flux density, with all pulse shapes normalized so that the peak at time zero has the same intensity. The structure of Pulsar 1 is obtained from three oscillograms obtained 6 March 1968 at 111.5 Mhz radio frequency with a time constant of 1 msec and bandwidth of 25 khz. The results for Pulsar 2 are from six oscillograms taken 1 April 1968 at 111.5 Mhz with a 3-msec time constant and 50 khz bandwidth. The results for Pulsar 4 are from a single oscillogram taken 31 March 1968 at 111.5 Mhz with a 3-msec time constant and 50 khz bandwidth. The results for Pulsar 3 are from a single oscillogram taken 31 March 1968 at 195 Mhz with a 1-msec time constant and 125 khz bandwidth.

The well-defined and nearly identical shape of the first subpluses of the four pulsars suggests that attempts to understand the pulse shapes should best begin with this most stable aspect of the pulsar pulse. Our data are quite inadequate to lead to a unique model, of course. However, it is interesting to see if any simple models can reproduce the first subpulse.

One particular model of interest is one in which a thin spherical shell is simultaneously excited at all points. This model is close to what might be expected in the case of a neutron or white-dwarf star undergoing radial pulsations and possessing an atmosphere of very small height. The difference in arrival time of radiation from different parts of the shell is taken into account. With such a model, the trailing edge of the first subpulse can be approximated if we assume that the radiation is excited abruptly to full intensity and then decays exponentially. The finite rise time of the leading edge is then a result of the differences in light travel time from different parts of the shell to earth. However, with these circumstances the computed shape of the leading edge of the pulse differs drastically from the observed leading edge. The fit is so bad that the results are not presented here.

Another model which does lead to satisfactory results consists of a small central object surrounded by a large radiating and radio transparent spherical shell. The shell is of such a size that the light travel time across the shell is much less than any observed time scale, therefore less than a few milliseconds. It is assumed that the diameter of the spherical shell is much greater than that of the central object. In this model, satisfactory results are obtained in the case where a disturbance causing radio emission is propagated outwards with spherical symmetry from the central object at a velocity much less than light velocity, that is, a shock wave or Alfvén wave. The additional reasonable assumption is made that this disturbance upon arrival at any point in the shell

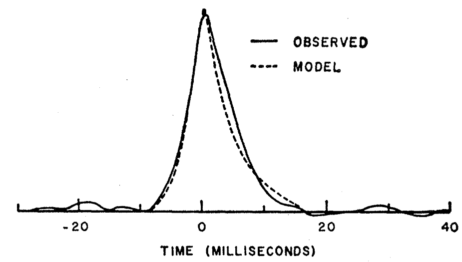

Fig. 2. Comparison between the observed pulse shape for Pulsar 2 and the theoretical shape predicted by a model (see text).

causes radiation which rises immediately to peak intensity and then decays exponentially. The somewhat unrealistic simplifying assumption is made that the volume emissivity of this emission is the same everywhere in the shell; the data do not yet justify a more complicated assumption. With these circumstances, the radio emission from the object prior to t_s, the time of arrival of the disturbance at the outer boundary of the shell, is given by:

$$S = K\,(2a^3 - 2a^2t + at^2 - 2a^3\,e^{-t/a}, \quad t < t_s. \qquad (1)$$

Here K is a constant, a is the time constant for the decay of the radiation, and t is time, with t equal to 0 being the instant at which the disturbance is emitted by the central object. The radio emission after t_s is given by

$$S = K\,[(2a^3 - 2a^2t_s + at_s^2)e^{\,t_s/a} - 2a^3] \times e^{-t/a}, \quad t > t_s. \qquad (2)$$

Since the value of the bracketed expression in Eq. 2 is a constant, the values of a and K can be found from fitting an exponential curve to the trailing edge of the pulse. From our data for Pulsar 3, this gives a value of about a equal to 5 msec, although the fit is not too good; t_s must be the time of maximum radio emission in this model. Since t equal to 0 is the time of emission onset, the Pulsar 3 data require that t_s equal 11 msec. There are then no free parameters in computing Eq. 1. With parameters so derived, the radio emission to be expected from this model is computed from Eqs. 1 and 2. The results are plotted in Fig. 2 along with the data for Pulsar 3, for which the observations best define the shape of the first subpulse.

As can be seen in Fig. 2, this model predicts a leading edge for the pulse which is in remarkable agreement with the observed leading edge. The fit of the trailing edge is not as good, but it is satisfactory in view of the simplicity of the model. Although this model is certainly not unique, it suggests that models of this type should be explored in attempting to interpret pulsars. If this model is correct, it shows that the diameters of the emitting region and the central object are very much less than the distance given by ct_s, and therefore much less than 3300 km. This is consistent with the limit suggested by the width of the final subpulse of Pulsar 4. This model is most consistent with those concepts of pulsars in which the central object is a pulsating star.

F. D. DRAKE
H. D. CRAFT, JR.
Arecibo Ionospheric Observatory, Cornell University, Arecibo, Puerto Rico

References and Notes

1. F. D. Drake, *Science* **160**, 416 (1968).
2. A. Hewish, *Cen. Bur. Astron. Telegrams Circ. 2064*, 29 March 1968.
3. W. C. Saslaw, J. Faulkner, P. A. Strittmatter, *Nature* **217**, 1222 (1968).
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Parameters of the Plasma Affecting the Radiation of Pulsar 1

Abstract. *Analysis of the relation between time delay and frequency for pulses from Pulsar 1 shows that the dispersive region of the ray path must exceed 300 astronomical units and have an average electron number density less than 8000 per cubic centimeter and average magnetic field strength less than 2×10^{-3} gauss. These requirements almost guarantee that the observed dispersion takes place in the interstellar medium.*

One of the remarkable features in the recent observations of pulsars is the high degree of accuracy with which the arrival time t_1 and t_2 of pulses at different radio frequencies ν_1 and ν_2 satisfy the condition

$$t_1 - t_2 = B\left(\frac{1}{\nu_1^2} - \frac{1}{\nu_2^2}\right)$$

where B is a constant proportional to the total electron content along the path from source to receiver. In fact, data taken at Arecibo between 40 and 430 Mhz for the source located in the constellation Vulpecula shows that this relation is satisfied to an accuracy of about 1 part in 3000 at 40 Mhz (*1*). However, as the relation is an approximation based upon the assumption that the radio frequency greatly exceeds both the plasma and cyclotron frequencies in the ionized interstellar gas, we shall show that the absence of any sizable deviations from this law can be used to establish upper limits on the average electron density and magnetic field along the path of propagation and, from this, lower limits on the extent of the ionized region.

When one retains first-order corrections to the expressions for the travel time of a pulse through a uniform (collisionless) plasma with electron number density n_e and magnetic field strength B_o, one finds that

$$t_1 - t_2 = B\left(\frac{1}{\nu_1^2} - \frac{1}{\nu_2^2}\right)(1 + T_1 + T_2)$$

where

$$T_1 = 3\nu_p^2 (\nu_1^2 + \nu_2^2) / 4\nu_1^2 \nu_2^2$$

and

$$T_2 = \pm 2 f_c \cos \gamma (\nu_2^3 - \nu_1^3) / \nu_2 \nu_1 (\nu_2^2 - \nu_1^2),$$

with ν_p, f_c, and γ the plasma frequency, cyclotron frequency, and angle between the magnetic field and the direction of wave propagation, respectively. From the data at Arecibo over frequencies between 40 and 430 Mhz, we conclude that T_1 and T_2 must be less than 3×10^{-4}. Hence, from T_1 we find

$$n_e < 8000 \text{ electron/cm}^3$$

while (assuming cos γ is of order unity), we have from T_2 that

$$B_o < 2 \times 10^{-3} \text{ gauss}$$

Although these estimates assume a uniform plasma, one can easily show that for a nonuniform plasma where n_e equals $n_{eo} + \delta n_e$, the condition on the average electron number density, n_{eo}, becomes even more restrictive since one obtains $n_{eo} + \langle(\delta n_e)^2\rangle / n_{eo} <$ 8000 cm^{-3}, while the magnetic field condition is modified somewhat and becomes simply $\langle n_e B_o \cos \gamma\rangle / n_{eo} <$ 2×10^{-3} gauss.

The upper limit on average electron number density together with the value of 3.84×10^{19} cm^{-2} obtained for $n_{eo} L$ shows that L must exceed 5×10^{15} cm $\cong$ 300 astronomical units. This result eliminates the possibility of the dispersion taking place in a stellar corona. Although an H II region has been observed in the source area at Arecibo, it appears far too small to provide the needed electron content. Hence, it seems almost certain that the dispersion is taking place in the general interstellar medium.

One final point that arises from the expression for time delay is that the time difference at a single frequency between the ordinary and extraordinary waves is given, to lowest order in B_o, by

$$\Delta t = \frac{4 B f_c \cos \gamma}{\nu^3}$$

From the above results one should expect $\Delta t < 15$ μsec (at 430 Mhz), which is considerably less than the observed pulse width of 37 msec. This, plus the fact that the observed pulse shape is qualitatively the same at all frequencies (*2*), suggests that the shape cannot be caused by a difference in arrival time of the two magnetoionic waves.

B. S. TANENBAUM
G. A. ZEISSIG
F. D. DRAKE
Arecibo Ionospheric Observatory, Cornell University, Arecibo, Puerto Rico

References and Notes

1. F. D. Drake, E. J. Gundermann, D. L. Jauncey, J. M. Comella, G. A. Zeissig, H. D. Craft, Jr., *Science* **160**, 503 (1968).
2. F. D. Drake, *Science* **160**, 416 (1968).
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Thermally Driven Rossby-Mode Dynamo for Solar Magnetic-Field Reversals

Abstract. *There is increasing interest in the possible existence of large eddies or "Rossby waves" in Sun's convection zone and photosphere. It is shown that many flows of this type, driven by an equator-pole temperature difference, act as hydromagnetic dynamos to produce magnetic fields that periodically reverse. The periods and field amplitudes agree with solar phenomena within an order of magnitude.*

Ward (*1*) postulates the existence of a "Rossby type" general circulation of the solar photosphere, in which large horizontally flowing waves or eddies (larger in dimensions than sunspot