The Rapidly Pulsating Radio Source in Vulpecula

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The discovery of the rapidly pulsating radio source in the constellation Vulpecula (*1*) has revealed the existence of a new class of objects with extraordinary characteristics. Most remarkable is the property that these objects radiate brief pulses of radio emission periodically with a rate of repetition more nearly constant by far than that of other known astronomical objects. Because of this, we, along with others, have come to call the objects "pulsars." The characteristics of the pulse radiation contain many unique properties undoubtedly associated with physical phenomena previously unobservable. They also make possible certain measurements and accuracies in measurement quite beyond reach heretofore.

Attempts to observe the Vulpecula pulsar (right ascension $19^h19^m36^s$, declination $+21°47'$, 1950.0) were commenced at frequencies of 430 and 611 Mhz on 29 February 1968 with the 1000-foot (304.8-m) telescope. These first attempts failed because of inaccuracies in the then-published position of the source and the facts that the radiation is intrinsically weaker and the periods of activity relatively short at these higher frequencies. Attempts to observe the object at 111.5 Mhz on 2 March 1968 were immediately successful. The pulsar is observable at all times on that frequency with the Arecibo telescope, and often the ratio of signal to noise on individual pulses exceeds 100. Successful measurements of the source have now been made at frequencies of 40.12, 73.8, 111.5, 195, 430.0 and 611 Mhz. An ensemble of experiments has been conducted on this and the three other known pulsars to measure the most obvious characteristics of the radiation. We now present the results of the early observations of the Vulpecula pulsar and their implications. The results from other pulsars will be presented later.

Time Variations

There are two conspicuous time variations in the pulse amplitudes. One is a variation from pulse to pulse, therefore in the interpulse interval of 1.3372795 seconds, which is much greater at the lower than at the higher frequencies. For example, this variation is about 10 to 1 at 73.8 Mhz, 5 to 1 at 111.5 Mhz, and less than 2 to 1 at 430 and 611 Mhz. Our understanding of the cause of differing times of pulse arrival at different frequencies (described below) allows us to establish unambiguously the arrival of the same pulse at several radio frequencies.

It is found that the relationship between successive pulse amplitudes is not retained from one radio frequency to another. Even differences in radio frequency of as little as 3 Mhz cause significant decorrelation in the relative intensity of successive pulses. Although some of this variation in amplitude is due to interplanetary scintillations, the Arecibo results on interplanetary scintillations in general indicate that only a small portion of the observed variation can be due to this cause. We have concluded that the bulk of this variation is created outside the solar system, and probably in the source.

The second readily observed time variation is a long-term variation in the mean intensity of the pulse. Typically, the source becomes active, giving a lengthy series of intense pulses, and then becomes intrinsically weak for a time interval which is typically about three times longer than the period of intense radiation. The variation in mean amplitude is at least a factor of 5 on all frequencies. However, this phenomenon is only quasi-periodic and is clearly not a periodic phenomenon. Furthermore, the periods of intense activity become longer at the higher radio frequencies. A period of intense activity may last of the order of seconds at 40 Mhz, of the order of 1 minute at 73.8 and 111.5 Mhz, and of the order of an hour at 430 Mhz. These observations are consistent with the results obtained at Cambridge and Jodrell Bank (*1, 2*). Lengthy simultaneous observations at 111.5 and 73.8 Mhz, and less extensive simultaneous observations at 40 and 430 Mhz, again show no time correlation between the timing of periods of intense radiation at two different radio frequencies. This behavior is similar to that observed in the interplanetary scintillations, but with a much longer time scale. It appears that a possible cause is scintillations in plasma either near the source or along the path of radiation. Considerably more analysis of these variations and of the pulse-to-pulse variations will be necessary before a precise quantitative description can be given.

A third time variation, with a time scale of the order of milliseconds, is observed within the individual pulses. The individual pulses often consist, in fact, of three well-defined subpulses following one another at 12-msec intervals, but with all radiation occurring within a sharply defined 37-msec interval. The onset and completion of this 37-msec interval occur at precisely the basic interval of 1.3372795 seconds. There is no existing evidence for pulsed radiation occurring outside the 37-msec interval. This intrapulse variation seems clearly to be intrinsic to the source. It gives an upper limit to the source of 11,000 kilometers and a possible limit of 1200 kilometers, subject to certain qualifications given in (*3*) and by Morrison and Sartori (*4*). The pulse shapes of other pulsars have similar properties, but with some major differences (*5*).

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Spectrum

The radio spectrum of the mean pulse intensity is difficult to determine because of the long-term variations in flux density. One spectrum has been presented (*2*). Of interest to both the physics of the source and observatories contemplating observation of the object is the peak flux density observed in individual pulses. In Fig. 1 are the peak flux densities observed at Arecibo. These pulse amplitudes can be expected to occur within a 10-minute interval at frequencies of the order of 100 Mhz, but only at intervals of several hours at the high- and low-frequency limits of the spectrum.

The dotted line in Fig. 1 is a crude fit to the points. It has a slope of -1.5, considerably steeper than the typical value of -0.8 observed in nonthermal radio sources, but not as steep as the values more negative than -2 observed in some solar noise bursts. No individual pulses show this precise spectrum because of the lack of time correlation in pulse amplitudes at different radio frequencies. Also interplanetary scintillations operate to enhance the maximum-pulse amplitude on the lower frequencies. However, this spectrum is adequate to rule out thermal radiation as a possible source of the emission, but it still permits all known nonthermal mechanisms, such as synchrotron radiation, cyclotron radiation, and plasma oscillations.

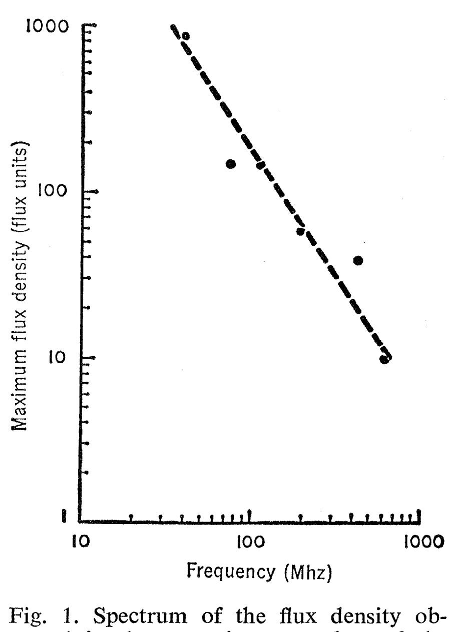


Fig. 1. Spectrum of the flux density observed in the most intense pulses of the Vulpecula pulsar. Flux densities are accurate to 10 percent. The dotted line has a slope of -1.5.

The spectrum makes observations difficult at both high and low frequencies. At high frequencies, the low flux density limits the signal-to-noise ratio. At the lower frequencies, particularly below 73.8 Mhz, the very great radio-noise level created in the telescope by galactic radiation more than overcomes the steeply rising spectrum, again producing a low signal-to-noise ratio. This will not be so serious with pulsars located farther from the galactic plane. At Arecibo, the optimum frequencies with regard to signal-to-noise ratio are near 100 Mhz, and for this reason most of the existing observations have been made near that frequency.

Variation in Pulse Arrival Time with Frequency

Hewish *et al.* (*1*) noted that the time arrival of the pulses is later on lower frequencies than on high and suggested that this delay was caused by electrons along the line of sight to the pulsar. To investigate this, simultaneous observations with accurate timing have been made at 73.8 and 111.5 Mhz, at 72.3 and 75.3 Mhz, at 110.0 and 113.0 Mhz, and at 40.12 and 430.0 Mhz; all observations were made with quartz crystal filters to define the observed frequencies (Table 1). The results of the first two measurements give directly the drift rate of the pulse radio frequency as a function of frequency ν and are plotted in Fig. 2 along with the Cambridge value (*1*). The theoretical relation to be expected if the drift is caused by intervening electrons is:

$$\left(\frac{d\nu}{dt}\right)_{\text{pulse}} = \frac{\nu^3 c}{\int \nu_p{}^2 \, d\ell} \qquad (1)$$

where c is the velocity of light, ℓ is the distance to the pulsar, and ν_p is the plasma frequency at various points along the line of sight. The plasma frequency, ν_p, equals $8.98 \times 10^{-3}\ n_e{}^{1/2}$, when n_e, the electron density, is given in electrons per cubic centimeter. The line drawn in Fig. 2 is a fit of relation 1 to the points. The experimental points follow the theoretical curve, showing that in fact intervening electrons are the cause of the pulse delay. The same conclusion has been reached in (*2*).

This conclusion permits us to determine which observed pulse at one frequency is to be associated with a pulse observed at another frequency. This association cannot be done by inspection because of the lack of intensity correlation from one frequency to another. However, the accuracy with which the sweep rate can be predicted at all frequencies is so high that no ambiguity in pulse identification occurs. By this method of pulse identification, the time delays at the more widely separated frequencies have been established. The results for the measurements near 100 Mhz are given in Fig. 3, and all the data can be combined to construct the relation of pulse arrival time and frequency for this pulsar given in Fig. 4. From this final result, the relation can be obtained for the Vulpecula pulsar

$$\left(\frac{d\nu}{dt}\right)_{\text{pulse}} = -9.689 \times 10^{-6}\ \nu^3 \text{ Mhz/sec} \qquad (2)$$

when ν is in Mhz.

An important conclusion can be drawn from the fact that the delays in pulse arrival are so accurately accounted for by an intervening plasma cloud: The initial radio emission at the pulsar occurs on all frequencies simultaneously. Our data indicate that all observed frequencies are emitted at the same instant with relative delays no greater than 8 msec between 40 and 430 Mhz. This result can be vitiated only by the unlikely existence of an emission mech-

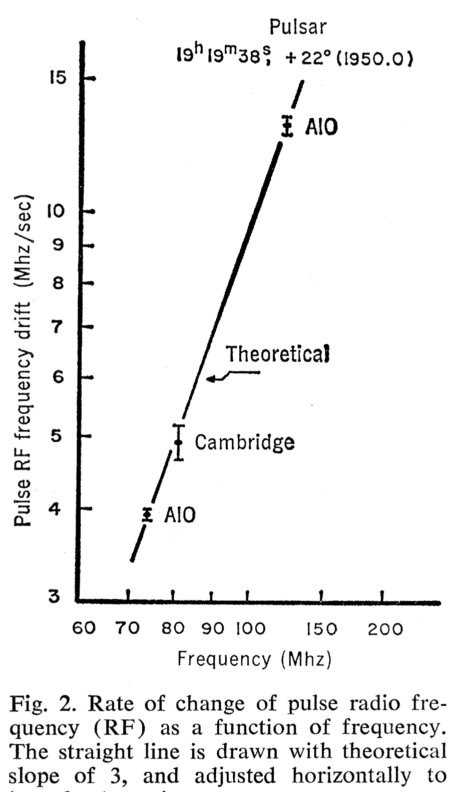


Fig. 2. Rate of change of pulse radio frequency (RF) as a function of frequency. The straight line is drawn with theoretical slope of 3, and adjusted horizontally to best fit the points.

anism which itself follows the relation 1.

It is impressive that pulses are delayed by as much as 32 seconds. Our results permit the prediction that any pulses at optical frequencies should precede those at 430 Mhz by 0.279 second.

Electron Content in the Space between the Pulsar and Earth

The total number of electrons per square centimeter along the line of sight can be determined from Eq. 1. However, rather than use the frequency drift rates, it is more accurate to use the actual time differential $(t_{\nu_1} - t_{\nu_2})$ in pulse arrival times between two frequencies ν_1 and ν_2. The frequencies should be as widely spread as possible, and ν_1 should be as low as will give satisfactory results. The appropriate equation is obtained from integrating Eq. 1 to obtain

$$\int_{\text{Earth to Source}} n_e \, d\ell = \frac{2.4808 \times 10^4 \, c \, (t_{\nu_1} - t_{\nu_2})}{\left[\frac{1}{\nu_1^2} - \frac{1}{\nu_2^2}\right]} \quad (3)$$

Inserting values from Table 1, we obtain the results of Table 2.

These results demonstrate the power of these measurements to give, for the first time, the number of electrons in the line of sight with extreme accuracy. The method utilizes a physical phenomenon whose quantitative description is free of requirements for information on usually weak parameters, such as the electron temperature, and is free of assumptions other than the good one that all frequencies are much higher than the plasma and cyclotron frequencies anywhere in the plasma. The method's accuracy is borne out by the fact that the above determinations, with greatly different pairs of frequencies being used, give the same results to about 0.1 percent. The values above differ from the values in (*2*) by about 0.5 percent.

The value of $\int n_e d\ell$ obtained is about 10^6 times a typical value for the daytime terrestrial ionosphere. This appears to rule out a planetary ionosphere as the location of the plasma. The value of $\int n_e d\ell$ is about ten times that of the solar corona ae sunspot maximum, and about 1 percent of that for a very bright galactic ionized hydrogen (H II) region.

Observations of this region at Arecibo show the presence of a faint H II region with a maximum brightness temperature of about 1°K at 430 Mhz. However, this is quite inadequate to provide the required electrons, even with favorable geometry, and so an H II region may be ruled out.

This leaves at least a stellar corona, the general interstellar electrons, or combinations of these as candidates for the location of the plasma. However, the change in projected electron density of less than 0.2 percent, and probably less than 0.1 percent over a period of 23 days seems smaller than would be expected with a stellar corona. Continued measurements of the projected electron density seem highly desirable. In any case, it presently appears that interstellar electrons are very likely the source of the electrons.

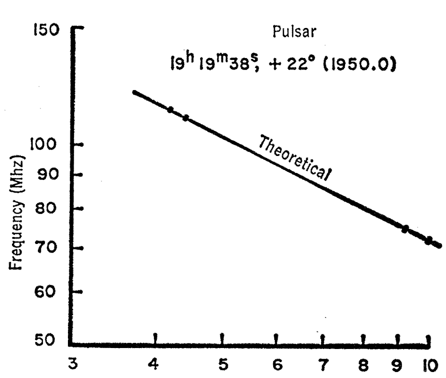
The fact that radio emission traverses the plasma at the lowest frequency where pulses are observed permits the setting of a lower limit on the size of the plasma body creating the pulse delay. Thus the observations of pulses at 40 Mhz implies that the critical frequency is never higher than 40 Mhz. As shown in (*10*), the observation that Eq. 3 is never violated significantly requires the maximum plasma frequency everywhere to be much less than 40 Mhz, since near the critical frequency relation 3 becomes inaccurate. Therefore, with $\nu_p \ll 40$ Mhz, $n_e \ll 2 \times 10^7$ cm^{-3}, and the extent of the plasma is much greater than 2×10^7 km or much greater than 30 solar radii. This result again argues that the intervening plasma is not primarily a stellar corona. The electrons are then in the interstellar medium, and their number may be used to estimate the distance to the pulsar (*1*). A typical electron density of 0.1 electron per cubic centimeter gives a distance of about 130 parsecs.

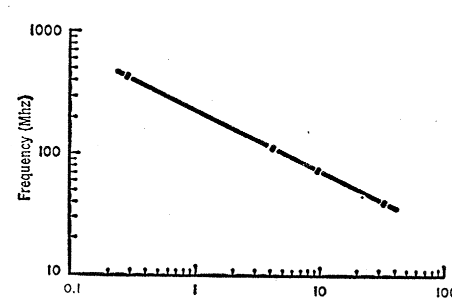
Table 1. Variation in pulse arrival time with frequency. The "delay" is the delay in pulse arrival time at low frequency with respect to the pulse arrival time at high frequency.

Date	High frequency (Mhz)	Low frequency (Mhz)	Delay (sec)	$\left(\frac{d\nu}{dt}\right)_{\text{pulse}}$ (Mhz/sec)
5 March 1968	75.3	72.3	0.761 ± 0.005	3.94
5 March 1968	113.0	110.0	0.227 ± .005	13.2
5 March 1968	111.5	73.8	5.328 ± .005	
22 March 1968	430.0	40.12	31.768 ± .003	
28 March 1968	430.0	40.12	31.765 ± .003	

Table 2. Electron content in the space between the pulsar and the earth.

Date	High frequency (Mhz)	Low frequency (Mhz)	$\int n_e d\ell$ (cm^{-2})	Mean error (cm^{-2})
5 March 1968	111.5	73.8	3.840×10^{19}	$.004 \times 10^{19}$
22 March 1968	430.0	40.12	3.837×10^{19}	$.001 \times 10^{19}$
28 March 1968	430.0	40.12	3.836×10^{19}	$.001 \times 10^{19}$





Figs. 3 and 4. Delay in pulse arrival times at frequencies between 70 and 115 Mhz [Fig. 3 (left)] and between 40 and 430 Mhz [Fig. 4 (right)]. The line drawn has the theoretical slope of −0.5 and is fitted to the points. The errors in the points are too small to show.

The Nature of the Pulsar

Several alternative interpretations of the pulsar can be offered. The interpretations to date have all been dominated by the apparent small size, less than 11,000 kilometers, of the disturbance-emitting object. The procedure has been to seek out all known or hypothesized astronomical objects which might be this small, and to make them candidates. The possible flaw in this approach, of course, is that we have not yet observed or imagined all the objects in space of such small dimensions. Keeping this in mind, the following possibilities are offered:

1) Signals from an intelligent civilization. The precise timing of the pulses, their amplitude modulation, and particularly the amplitude modulation with individual pulses are all what might be expected of an intelligent signal. One can see great utility in the pulse timing for purposes of space navigation, and in the intrapulse modulation for purposes of information communication in the presence of scintillations. The fact that there is more than one known pulsar (*1*) does not argue against this interpretation, despite statements to the contrary.

However, there are two strong arguments against this interpretation. First, the spectrum of the radiation is very broad and most intense at the lowest frequencies. Such a spectrum has no recognizable practical advantage, and in fact would have great disadvantages in that much power is present at frequencies where galactic noise would act to mask the signal strongly. The transmission of power over such a wide band of frequencies would be enormously wasteful. Furthermore, the spectrum is close to what is observed in natural sources. Second, if the distance of the object is of the order of 100 parsecs, and the pulse power is radiated isotropically, the power radiated in strong pulses is of the order of 10^{22} watts. This power level is about 10^{10} greater than the entire electrical generating capacity of contemporary terrestrial civilization. Even if we allow for great advance over our present technology, the power inferred seems much too high to be a plausible manifestation of advanced technology. No reasonable beaming of the radiated power will reduce the required power to a plausible value. It is our opinion that intelligent origin is very unlikely.

2) The result of pulsations of a neutron star. As has been noted by Thorne and Ipser, Cameron, and others (*6, 7*), the typical pulsation periods of neutron stars are much shorter than the observed pulse period. Although models of neutron stars can be constructed which would have the observed period (*8*), such objects are unstable (*6*) and would not develop a steady pulsation.

3) The result of pulsations of a white dwarf star. As shown by Thorne and Ipser (*6*), the shortest permissable fundamental pulsation periods of white dwarfs approach, but do not equal by about a factor of two, the observed pulsation period. It has been argued (*6, 7*) that a strong pulsation in the first overtone might be expected as a result of hydrogen burning in the outer layers of a white dwarf. This would provide both the proper pulsation period and a source of energy to maintain the pulsations. In such cases some variation in the period between pulses may be expected, and a search for this is important. No theory has been given as to how such a pulsation could lead to intense radio emission with the observed complex pulse structure and with power emitted per unit area equivalent to 0.1 the brightness of the solar surface at all wavelengths (*3*), all from the very limited atmosphere of a white dwarf. Nevertheless, this remains an attractive candidate.

4) The results of rotation of a neutron star. If a normal optical star conserves angular momentum while contracting to the dimensions of a neutron star, rotation periods of the order of 1 second will result. This short rotation period would maintain a fixed value to a very high precision, thus reproducing two of the most striking characteristics of the pulsar. Gold has stressed this (*9*) and called attention to the fact that such objects can be expected to possess very strong magnetic fields since the original stellar magnetic flux is conserved during contraction. This magnetic field will co-rotate with the star at distances sufficiently close to the star. Gold has noted that at some distance the co-rotating field achieves a velocity approaching that of light. This will result in the acceleration of particles to high energies and shear of the magnetic field. The accelerated particles can be expected to emit intense radio emission. The exact phenomenology of the magnetoplasma in the field-shearing region has yet to be determined. A particular difficulty with this hypothesis is the extremely well-defined pulse shape, with its substructure; this would seem an unlikely result of the mechanism. Nevertheless, the model associates the precise short pulsation period with the fixed rotation period which is perhaps to be expected in a neutron star.

5) A binary star consisting of two neutron or white dwarf star components. A binary star consisting of two neutron or white dwarf star components of mass of the order of one solar mass and separated several thousand kilometers will have an orbital period of the order of 1 second. The velocity of the components will be of the order of 1 percent of the velocity of light. Such a system will again give a nearly fixed period. In view of the intense magnetic fields of these stars, it is to be expected that they will evolve into a configuration in which the stars have rotation periods synchronous with the orbital period and with magnetic poles of opposite sign aligned along the line between the two stars. In this case there will be an intense, nearly uniform magnetic field between the stars in which the lines of force are nearly parallel. Particles injected into this field will radiate strongly. In particular, if the stellar orbits are slightly elliptical, the periodic approach and recession of the stars from one another in a frame rotating with the stars will cause a variation in the strength of the magnetic field which will be extremely effective in accelerating particles by the betatron process. If these particles are accelerated to relativistic energies, which is very likely, they will radiate synchrotron radiation which will be highly concentrated in directions very close to a plane perpendicular to the line between the stars. The radiation pattern then projects on the sky as essentially a rotating great circle, causing any observer to observe two short pulses, uniformly spaced in time, for each orbital revolution. Again, however, this model does not directly lead to the complicated intrapulse structure observed.

The difficulties with this model include at least the question of how a binary system could involve such a small orbit. Since it very likely started with normal star components, the initial orbital period must be much longer. There appears to be no known means to reduce the orbital energy except perhaps through gravitational radiation. However, gravitational radiation will not lead to the required small orbit in the age of the galaxy. F. Pacini has suggested that close neutron star binaries may be created directly by centrifugal force fission of contracting stars, which would resolve this problem.

A further difficulty is that gravitational radiation may cause the orbit to shrink rapidly once an orbital period of the order of 1 second is reached. This would result in a decrease in the pulsation period with time, a feature which can be examined observationally with great precision. However, it has been suggested by Bondi (*11*) that free-falling particles do not radiate gravitational radiation; if so, this model becomes quite attractive. It is possible that there are orbits free of gravitational radiation, analogous to those molecular orbits free of electromagnetic radiation. This has also been suggested by Saslaw, Faulkner, and Strittmatter (*12*). It is clearly of great importance to achieve a better understanding of gravitational radiation.

6) A gravitational lens effect. It has been suggested by Saslaw, Faulkner, and Strittmatter (*12*) that the pulsed radiation is the effect of gravitational focusing by members of a neutron star binary. The difficulties caused by gravitational radiation are as with the binary model just given. In addition, this model will not give the well-defined intrapulse structure known to exist.

It is clear that none of the proposed pictures of the pulsar explains well the already known observational data. There is obviously a great opportunity here for further work.

New Observational Abilities and Practical Applications

Further studies of pulsars will undoubtedly lead to new observational capabilities. It is of interest to note the following already apparent abilities:

Measurement of motion of a very distant object. The precise period of the pulses leads to the ability to detect changes in the length of the line of sight from a telescope to a pulsar. A constant velocity component relative to the earth along the line of sight is not detectable, since this simply alters the intrinsic pulse period by a constant increment which cannot be determined since we do not know the intrinsic pulsation period at the pulsar. However, variations in line of sight velocity, hence nonlinear changes in distance with time do alter the observed pulse period, making such changes measurable. This has been noted by Hewish *et al.* (*1*), who have already detected the effect of the orbital motion of the earth in their data.

Since the absolute time of pulse arrival can be measured to a millisecond with less than 10 minutes of observation, and probably to 0.1 msec when careful digital analysis is used, a deviation from constant velocity along the line of sight of the order of 30 kilometers can be detected. It is remarkable that such a small motion can be detected in such a distant object. Utilization of this ability will in time reveal whether the pulsar is alone in space or is in orbit around a second body. One striking consequence of this ability to measure deviations from linear motion is that it should be possible in about 1 year's time to detect the galactic rotation of a pulsar which is far from the sun and at a different distance from the galactic center. The gravitational force of the galaxy causes an object 10 kiloparsecs from the center of the galaxy to deviate from linear motion about 100 kilometers per year.

Time service. The precise timing of the pulses provides a new time service which may be useful in some circumstances. Since the pulses are best observed at very high frequencies, no correction for propagation effects is necessary, thus giving an advantage in some situations over the present terrestrial time services. Again, measurements of a number of pulses can provide absolute time to an accuracy of a fraction of a millisecond. The pulses of the Vulpecula pulsar have already been observed successfully at 144 Mhz by F. S. Harris at Arecibo with the use of a very simple 50-foot paraboidal antenna costing about $500.

Measurement of projected electron density. As has been noted, the measurement of the pulse arrival time versus frequency can give measurements of the electron content between earth and source to an accuracy of at least five significant figures. As the distances to pulsars become known, this will allow the plasma distribution in the galaxy to be established accurately with great detail. In time, the temporal variations in the interstellar electron distribution will be detectable.

Clearly the pulsars are not only objects of great interest in themselves; they also provide the means to study other important processes in space.

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