Pulsar Radiation Mechanisms: What Are the Critical Experiments?

This is a report of a joint Australian–United States symposium.

R. N. Manchester

A great deal of progress has been made toward reaching an understanding of pulsars since their initial discovery in late 1967. For example, their identification with rotating neutron stars possessing strong magnetic fields ($\sim 10^{12}$ gauss) is now generally accepted. However, no such consensus has been reached on the mechanism by which the rotational energy is transformed into the presumably beamed radiation that we observe as pulses. The purpose of this symposium was to provide a forum for discussion of the various models for the emission mechanism that have been proposed, and to decide which observations or "critical experiments" are likely to be the most important in choosing among these proposed models.

The symposium, held at Stanford University, Palo Alto, California, from 21 to 25 January 1974, was attended by a total of 31 participants (*1*), including 7 from Australia. It opened with a review of the existing observational literature by G. R. Huguenin in which the characteristics of, and distinctions between, the integrated pulse profile, subpulses, and microstructure were stressed. Contributions on recent observational results were divided between two sessions, the first dealing with total-intensity characteristics and the second with polarization properties. Papers of particular interest given in the first of these sessions included those by P. A. Hamilton and D. C. Backer on the radio-frequency spectra of pulsars. Results show that most pulsars have spectra which are steeper at higher frequencies, the dependence at about 1 Ghz generally being between ν^{-1} and ν^{-3}. Four or five pulsars (out of a total of about 25 observed) have power law spectra, and about the same number are observed to have a rather sharp low-frequency cutoff in the range 200 to 500 Mhz. J. H. Taylor and J. M. Sutton described observations of pulse intensity fluctuations, showing that the modulation index is generally quite different for different components of a given pulsar. For example, in the Crab pulsar, the radio precursor is relatively stable whereas the main pulse is highly modulated. Among the more important observations presently being made are those of pulse microstructure—that is, structure within a subpulse. T. H. Hankins and B. J. Rickett presented recent results obtained with their coherent dedispersing technique which showed that, although several pulsars (PSR 0950+08, PSR 1133+16, and PSR 2016+28) have microstructure with a characteristic width of about 0.05 percent of the period, for PSR 0834+06 and PSR 1919+21 the characteristic width is about twice this value, and for PSR 1237+25, PSR 1929+10, and PSR 2020+28 there appears to be a complete absence of microstructure. They also showed that in PSR 0950+08 the microstructure is correlated over a frequency interval in excess of 200 Mhz. This result places important constraints on the emission mechanism and also opens up the possibility of extremely precise determinations of pulse dispersion.

The first extensive observations of the polarization of individual pulses were reported by J. M. Rankin (results from Arecibo Observatory, Puerto Rico) and R. N. Manchester (results from National Radio Astronomy Observatory, West Virginia). Rankin described data for several pulsars in which the polarization characteristics are related to drifting subpulses rather than the integrated profile, and Manchester discussed the various ways in which depolarization of integrated pro-

Table 1. Observed properties of pulsars.

	Observed properties common to nearly all pulsars
1)	Integrated pulse profile has equivalent width of about 5 percent of the period.
2)	Integrated profile for all Stokes parameters is stable in phase and shape.
3)	Integrated profile usually has multiple components separated by up to 10 percent of the period.
4)	Components of the integrated profile have different radio-frequency spectral indexes.
5)	Radio-frequency spectral index is -2 ± 1 above about 500 Mhz.
6)	Apparent source brightness temperature is greater than 10^{25}°K.
7)	Subpulses are of typical width 1 to 2 percent of the period, are often highly polarized, and have bandwidth in excess of 100 Mhz.
8)	Pulse intensity is deeply modulated on time scales from the subpulse duration to years.
	Important properties observed in some but not all pulsars
1)	Interpulses and emission bridges between components are observed.
2)	Pulse fluctuation spectra have periodic features, different for different components.
3)	Drifting subpulses are observed, in the most prominent cases drifting from the trailing edge to the leading edge of the integrated profile.
4)	Microstructure of characteristic width less than 0.1 percent of the period is seen in several pulsars.
5)	Strong linear polarization with systematic variation of position angle through the integrated profile is common.
6)	For certain components of the integrated profile, the subpulse position angle is restricted to orthogonal angles.
7)	A maximum in the radio-frequency spectrum is often observed in the range 50 to 1000 Mhz.
8)	Infrared, optical, x-ray, and γ-ray pulse emission is observed from the Crab Nebula pulsar.

At the time this meeting report was prepared the author was associate professor of astronomy, Department of Physics and Astronomy, University of Massachusetts, Amherst. His present address is Division of Radiophysics, Commonwealth Scientific and Industrial Research Organization, P.O. Box 76, Epping, NSW 2121, Australia.

files can occur, and in particular the observation that subpulse polarization is frequently confined to two modes having an orthogonal position angle. The properties of the southern pulsar PSR 1055 − 51 were described by P. M. McCulloch. This pulsar is of interest as it has a short period (0.197 second) and has a profile remarkably similar to that of the Crab pulsar including a strong interpulse situated approximately 40 percent of the period from the main component.

In the final session devoted to observational results Manchester discussed some aspects of pulse timing measurements, reporting the detection of proper motion of PSR 1133 + 16 and a period discontinuity in PSR 1508 + 55. Period irregularities observed in the Crab and Vela pulsars were discussed by Rankin and P. E. Reichley, respectively. The optical and radio polarization characteristics of the Crab pulsar were compared by D. C. Ferguson, and M. J. Disney described a search for optical pulsars in the southern hemisphere.

The first theoretical review was by M. A. Ruderman, who discussed the conditions likely to exist at the neutron star surface, concluding that, because of the extremely strong magnetic field, ions are likely to be bound very tightly in a crystalline lattice and hence difficult, if not impossible, to remove from the surface. Following this, F. C. Michel reviewed theoretical discussions of the pulsar magnetosphere, making a distinction between models in which conditions are essentially vacuum and those in which the magnetic field is dominated by plasma effects. I. Lerche described propagation of light through shearing media, pointing out that, if the plasma refractive index is significantly different from unity near the light cylinder, substantial deformation of ray paths would occur and it would be difficult for radiation to escape the magnetosphere.

Models for the pulse emission mechanism may be divided into two categories, those in which the emission region is located near the light cylinder and those in which it is closer to the neutron star. In a session devoted to models in the first of these categories, T. Gold, F. G. Smith, and Michel described features of their models. Subsequent discussion centered on the degree of success of these models in accounting for the observations. In a similar session, models in the second category were described by P. A. Sturrock, W. J. Cocke, and Ruderman. A full session was devoted to discussion of the question "Where is the emission region?," during which the chairman, Michel, rated proposed emission mechanisms according to the degree that they had been shown to be consistent with the observations. Models in the first category, such as that of Gold, which have corotation Lorentz factors of 10^6 or more, can account for micropulse structure, but have more difficulty in accounting for the observed characteristics of structure of longer time scales. Light-cylinder models proposed by Smith and others, which have corotation Lorentz factors of less than 10, have natural explanations for observed subpulse characteristics but not for pulse microstructure. All models in the first category have some difficulty in accounting for the form and stability of the integrated pulse profile. They also suffer from a lack of general theoretical development compared to models in the second category, particularly that of Sturrock, which is essentially unique in having a relatively complete self-consistent theoretical description. Properties of the integrated profile are, in general, accounted for by models in which the emission originates in the vicinity of a magnetic pole near the surface of the star, but an explanation for smaller-scale structure is not at present included in such models. No satisfactory explanation for the drifting subpulse phenomenon exists in any model.

Table 2. The standard pulsars.

Standard	Secondary standard	Representative properties
PSR	PSR	
0031−07	2016+28	Drifting subpulses
0525+21	2045−16	Long period
0531+21		Short period, optical emission
0950+08		Microstructure
1133 + 16	1237+25	"Double" integrated profile
1642−03	0823+26	"Single" integrated profile
1929+10		High polarization

The Critical Experiments

A list of "critical experiments," that is, experiments which have the potential of defining the pulse emission processes in pulsars, was compiled during the symposium. Investigations of the following pulse properties were considered to be of great importance:

1) The amplitude and frequency statistics of pulse microstructure. Does microstructure represent a beam pattern or amplitude modulation? Can the effects of coherence be detected?

2) Stokes parameters for individual subpulses measured simultaneously at several widely spaced frequencies. What is the spectrum of a subpulse? Are the shape, polarization, and longitude of subpulses frequency-dependent?

3) All Stokes parameters for pulse microstructure. What is the relation between microstructure and subpulse polarization? Are large swings of position angle observed within micropulses?

4) The amplitude and fractional polarization statistics for subpulses whose position angle is orthogonal to the mean angle.

5) Subpulse and microstructure properties of the radio emission from the Crab pulsar. This experiment may help to show how typical the Crab pulsar is and also to define the relation between the main pulse and the interpulse.

6) Long-term intensity variations in pulsars. How are these variations related to the question of eventual turning-off of pulsars? What is the relation between intensity variations in main pulses and interpulses?

7) Long-term intensity variation of the Crab pulsar optical emission. Is it related to the pulsar period?

8) Shape, intensity, and polarization of the Crab pulsar integrated profile in the infrared, ultraviolet, and low-energy x-ray region. Determination of the nature of the cutoff in the infrared and the spectral shape between the optical and x-ray regions may show whether or not the emission mechanism is the same at optical and x-ray frequencies.

A discussion session entitled "What are the critical experiments?" represented the culmination of the week's presentations and discussions. The chairman, J. E. Gunn, began by listing ideas on the most important general areas in which observations could help define the emission mechanism in pulsars. In subsequent discussion this list was expanded and ideas for important specific experiments were developed and discussed (see box). These observations will surely help to establish the nature of the pulse emission mechanism in pulsars. The importance of several theoretical problems (in particular, the structure of the magnetic field and the distribution of particle flow within the pulsar magnetosphere) was also emphasized during the discussion.

Because of the great quantity and diversity of observational data available, it is often unclear which are the "typical" properties of pulsars and which are unusual or exceptional. To alleviate this situation, the observers at the symposium compiled a list of properties which appear to be fundamental to the pulse emission mechanism and also common to essentially all pulsars. This list, together with a list of important properties seen in only some pulsars, is given in Table 1.

As a further aid to both observers and theoreticians, a group of seven pulsars was chosen which exhibits most of the important properties of pulsars. Additional criteria for these "standard" pulsars, which are listed in Table 2 together with five secondary standards, were that they be observable at most of the major observatories and also be relatively strong. It is expected that observers will concentrate their efforts on these pulsars, and that theoreticians will find the list useful in giving a small group of "typical" pulsars for comparison with theories.

Notes

1. Participants at the symposium were J. G. Ables and M. M. Komesaroff, CSIRO, Division of Radiophysics; D. C. Backer, Goddard Space Flight Center; W. J. Cocke and D. C. Ferguson, University of Arizona; J. Cordes, T. H. Hankins, and B. J. Rickett, University of California (San Diego); M. J. Disney, Australian National University; M. Elitzur and J. E. Gunn, California Institute of Technology; T. Gold, Cornell University; P. A. Hamilton and P. M. McCulloch, University of Tasmania; S. Hinata and D. H. Roberts, University of Illinois; G. R. Huguenin, R. N. Manchester, and J. H. Taylor, University of Massachusetts; I. Lerche, University of Chicago; A. G. Lyne and F. G. Smith, University of Manchester; F. C. Michel, Rice University; V. Petrosian and P. A. Sturrock, Stanford University; R. M. Price, Massachusetts Institute of Technology; J. M. Rankin, University of Iowa; P. E. Reichley, Jet Propulsion Laboratory; M. A. Ruderman, Columbia University; and J. M. Sutton and A. E. Vaughan, University of Sydney.

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