# Part 7

# Observations of Pulsed Emission

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# Radio Pulse Observations of Neutron Stars: A Review

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**Abstract.** This paper presents a review of recent advances in those observations of radio pulsars which are relevant to the understanding of "where" and "how" the radio signals are generated in the magnetosphere of the neutron star. These include (i) results from simultaneous multi-frequency observations, (ii) emission geometry studies of multi-component pulsars, (iii) results from drifting and nulling pulsars, (iv) constraints from single pulse statistics and (v) progress in giant pulse studies.

## 1. Introduction

Though neutron stars were discovered from observations of the radio pulses they emit, and much has been learned from studies of different aspects of these radio signals, we do not as yet understand exactly *where* and *how* in the neutron star magnetosphere these radio waves are produced. This review concentrates on those aspects of radio pulse observations which are crucial to this problem. The basic observational result that pulsar signals typically have a very narrow duty cycle, coupled with the basic model of a rotating neutron star, indicates that the radiation comes from a small, localized region of emission on or above the neutron star's surface. Can observations tell us more precisely where this region is located and what is its structure? What is the basic seed of the activity that produces the energetic particles that we believe produce the radio radiation? How can we observationally try to discriminate between existing models of the emission mechanism and provide new insight that can help theorists in their work? Described below are some recent results from observations that are pertinent to these issues.

## 2. Deciphering the Polarization Signature

Early perspicacious work by Radhakrishnan & Cooke (1969) showed that the pulsar radio source must be located in the polar regions of a dipole-dominated magnetosphere of the neutron star. Their interpretation of the systematic rotation of the linear polarization angle that is seen for several pulsars, as being the signature of the projected B-field direction of the dipolar field lines, forms one of the corner-stones of our understanding of radio pulsars. It led to the development of the semi-empirical polar cap model, which provides a useful framework



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for much of our basic understanding. However, there was a stage when the universality of this model was threatened by the discovery of complicated position angle curves for several pulsars (e.g. Manchester, Taylor & Huguenin 1975), which did not match with predictions. The situation was rescued by the discovery (Backer, Rankin & Campbell 1976) of orthogonal polarization modes (OPM) and the realisation that each of the OPM follows the rotating vector model. This reaffirmed our faith in the polar cap model, but left us with the enigma of understanding OPMs. Are OPMs disjoint or simultaneous? Are they intrinsic to the emission process? What is the role of propagation effects? Answers to these questions are important not only for understanding the pulsar emission mechanism, they also have some bearing on how we process polarization data to disentangle the OPMs, as highlighted recently by McKinnon & Stinebring (2000).

Simultaneous multi-frequency single pulse observations are a powerful way to probe many of the issues related to pulsar polarization and OPMs. Recent work by Karastergiou et al. (2001, 2002, 2003) shows the following (see also Karastergiou et al., these proceedings) :
(i) polarized radiation is less correlated across frequency than the total intensity;
(ii) sense of circular polarization in single pulses can change between two frequencies;
(iii) though OPMs show a spectral dependence, the same polarization mode tends to occur at both frequencies at a given time;
(iv) there is a significant amount of correlation between the circular polarization and OPMs, but it also has a frequency dependence, becoming weaker at higher frequencies.
These results indicate a significant role of a frequency-dependent mechanism affecting the radiation, such as propagation effects through the magnetosphere (see also Petrova, these proceedings).

## 3. Understanding the Structure of the Emission Beam

The fact that average profiles often show multiple, separate components of emission in the pulse window reflects that the polar cap consists of several distinct regions of emission. Where in the magnetosphere are these regions located and how are they arranged? In the radial direction, based on the increasing separation of individual components (and overall broadening of the profile) with decreasing frequency, we believe that the emission originates at larger heights for lower frequencies, while following the same set of dipolar field lines — referred to as the "radius-to-frequency mapping" (RFM) model (Cordes 1978). However, there are alternate models that assume a constant height of emission and propose plasma effects in the magnetosphere to explain the profile broadening (e.g. Barnard & Arons 1986).

Similarly, the case of transverse distribution of the emission regions across the polar cap also has competing interpretations — the "conal" and "patchy" beam models. The conal beam model (Rankin 1983a, 1983b, 1990, 1993) proposes that there are two distinct types of emissions — core and conal — with observationally distinguishable properties. The core radiation is thought to originate close to the magnetic axis of the pulsar and comes from lower altitudes

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in the magnetosphere than the conal emission, which is thought to originate in a set of concentric hollow cones centered on the magnetic axis. The patchy beam model (e.g. Lyne & Manchester 1988; Manchester 1995), on the other hand, argues for no fundamental difference between core and conal emission, with the observed differences being a consequence of difference in location of the emission regions with respect to the magnetic axis. Further, this model claims that the component locations within the beam are randomly distributed rather than organized in the form of one or more hollow cones. This conflict is further heightened by recent results from statistical analyses, some of which argue in favor of the conal beam model (Mitra & Deshpande 1999; Kijak & Gil 2002), and others in favor of the patchy beam model (Han & Manchester 2001).

It is important to discriminate between these competing models, as they have important implications for the underlying models for radio emission. For example, pulsar profiles with multiple cones of emission are a natural consequence of emission models which postulate the presence of concentric rings of sparks in the vacuum gap just above the neutron star surface as the seed activity that drives the pulsar emission mechanism (e.g. Gil & Sendyk 2000; also Ruderman & Sutherland 1975). A patchy pulsar emission beam would require some different or additional physics for explanation.

Two issues important for resolving this conflict are: an accurate determination of the total number of emission components for a pulsar and the significance of their arrangement within the pulse window. Traditionally, the former has been done using different methods of decomposing the average profile into individual components, most often by fitting multiple Gaussians (e.g. Kramer et al. 1994). However, recent work by Gangadhara & Gupta (2001) and Gupta & Gangadhara (2003) has shown that analysis of single pulse data may be a more fruitful method for determination of components that are weak and/or emit intermittently, as well as those that occur in proximity to strong components. Using their "window-threshold" technique, Gangadhara & Gupta (2001) detect as many as 9 emission components in the data from PSR B0329+54, independently at 325 MHz and 606 MHz. Further, they find that the 9 components are arranged 4 on either side of the central core component, lending support to a picture of 4 nested hollow cones of emission for this pulsar. More interestingly, they find an offset between the center of each of the 4 conal components and the center of the core, with the core lagging behind in longitude. This offset increases systematically in going from the innermost to the outermost cone and, for a given cone, the offset also increases from 606 MHz to 325 MHz.

Gupta & Gangadhara (2003) have extended this kind of study to another half dozen well-known pulsars and found new emission components in most of them. The total number and location of the components they find supports the nested cone model. Further, they find that all these pulsars also show the systematic lag of the core with respect to the cone centers. These authors interpret their findings as evidence for retardation and aberration, in the pulsar magnetosphere, of the conal emission beams. By modeling these effects, along with a detailed consideration of the emission geometry, they come up with a formulation that allows estimates of the emission height for each cone and also the location on the polar cap of the field lines associated with the cone. Their results show the following:

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(i) for a given cone, the lower-frequency radiation comes from a higher altitude than the higher-frequency radiation — a direct confirmation of the RFM model (see also Mitra & Rankin 2002 for detailed study of the frequency evolution of conal beams). The inferred emission heights range from $\sim$ 200 to $\sim$ 2000 km ($\sim$ 0.3% to 4.3% of the value of the light cylinder radius);
(ii) for multiple cones at a given frequency, the emission altitude increases systematically from the innermost to outermost cone;
(iii) the conal emission does *not* originate at or near the last open field line region of the magnetosphere — the emitting regions lie well within this polar cap boundary; further, there is some evidence that the polar cap location of multiple cones increases systematically from the innermost to outermost cone.
Extension of such studies to a larger sample of pulsars should provide significant statistical constraints on the structure of the emission beam.

From an analysis of simultaneous dual frequency data on PSR B0329+54, taken with the GMRT at 238 and 612 MHz, Gil et al. (2002) find that the longitude separation of subpulses at the two frequencies is less than that for the corresponding components in the average profile. At first sight, this appears to be in direct conflict with the RFM model. However, Gil et al. (2002) show that this difference is a natural consequence when the single pulse events are distributed along a conal ring of emission (characterized by a fixed height at a given frequency), rather than confined to individual patches corresponding to the peaks in the average profile. This is yet another example of the potential of simultaneous multi-frequency observations.

## 4. New Light from "Drifting" Pulsars

The phenomenon of drifting subpulses in pulsars (e.g. Backer 1973) is widely thought to be an important key to understanding how pulsars shine. From measurements of $P_2$ and $P_3$ — the longitude separation between successive drift bands and the time interval between recurrence of successive driftbands at a given pulse longitude, respectively — it is possible to estimate the number and drift rate of subbeams (or sparks) in the conal beam. These can be compared with quantitative predictions of the theoretical models.

However, there are problems in the interpretation of the observations that make this comparison difficult. Often the observed drift rates are not stable with time. Even when the value of $P_3$ is stable and can be determined reliably, it may not reflect the true value, due to the effect of aliasing produced by our finite rate of sampling (once per pulsar period) of the phenomenon. Furthermore, the value of $P_2$ is affected by the drift rate and by the viewing geometry. Consequently, quantitative interpretations of the observations have remained somewhat uncertain and difficult, till recently. However, some interesting new results have energized this field of inquiry.

Vivekanand & Joshi (1997, 1999) and Joshi & Vivekanand (2000) report on a detailed study of the drifting behavior of PSR B0031–07, including the interaction between nulling and drifting. They confirm the three drift modes for this pulsar, and find that $P_2$ is a function of the drift rate.

Deshpande & Rankin (1999, 2001; also Rankin, Suleymanova & Deshpande 2003), from a clever analysis of the subpulse modulation properties of PSR

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B0943+10, show that the aliasing problem can be resolved for this particular pulsar. By interpreting the features seen in the unfolded fluctuation spectrum, obtained by continuously sampling the gated sequence that the observations naturally provide, they show that the primary feature seen in the normal fluctuation spectrum of this pulsar is a first order alias of the true frequency. This yields a value of $P_3 = 1.87P_1$. Further, from the modulating sidebands around the primary feature, they infer the presence of 20 subbeams in the conal beam. Hence, the total circulation time of the subbeam pattern, $P_4$, is shown to be $37.35P_1$, or 41 s (see also Gil & Sendyk 2003).

van Leeuwen et al. (2002, 2003) have concentrated on PSR B0809+74, which shows a very regular drift pattern, with some small but interesting changes when a null occurs. From a careful analysis of the post-null drift rate speed-up, van Leeuwen et al. (2003) show that the observed smooth driftbands are not compatible with any kind of an aliased drift rate. Hence, they conclude that the observed drift rate is the true drift rate. Further, from a consideration of the number of subpulses seen in individual pulses and the ratio of the subpulse width to the subpulse separation, they conclude that there must be more than 15 subbeams for this pulsar. Hence, $P_4$ works out to be more than 200 s.

Gupta et al. (2004) have recently completed a detailed study of PSR B0826–34. This pulsar shows subpulse emission over almost the entire pulse period and has a complex pattern of subpulse drift — including apparent reversals of drift direction (Biggs et al. 1985), which cannot be explained by most theoretical models. From an analysis of a 500 pulse sequence from the GMRT at 318 MHz, Gupta et al. (2004) show that there is clear evidence for 6–7 drift bands across the main pulse component. The drift behavior is not a linear pattern, but is more irregular, with significant changes in drift rate, including apparent changes in the direction of the drift. Nevertheless, these variations are not abrupt but relatively smooth, and are also highly correlated across all the drift bands. From their analysis, Gupta et al. (2004) show that this pulsar is very close to being an aligned rotator: $\alpha$, the angle between the magnetic and rotation axes, needs to be less than 5°, and is more likely to be about $2.^{\circ}5$. As a result our line of sight samples the radiation from a large fraction of a single conal ring, resulting in the wide profile and multiple drift bands. Further, the authors show that the observed drift behavior can be understood if the drift rate is aliased such that during one rotation period, a subpulse drifts to reach the location of the adjacent subpulse, or a multiple thereof (i.e. $P_3 = P_1/k$, where k is an integer); and if there are small ($\approx 4\%$) variations in the drift rate about this mean value. From their detailed model, Gupta et al. (2004) show that for the simplest solution, the number of sparks in the conal ring needs to be 14. Correspondingly they find $P_3 = P_1$ and $P_4 = 14P_1 = 25.9$ s. These results bring PSR B0826–34 within the realm of pulsars that can be qualitatively understood in the paradigm of existing models (e.g. Ruderman & Sutherland 1975; Gil & Sendyk 2000).

However, a quantitative comparison between the results from the three pulsars above and the predictions of the Ruderman & Sutherland (1975) model shows that in all the three cases, the observed circulation times are much larger than the model's predictions; i.e., the drift is much slower than the predictions. Modified versions of this model, which include the effects of partial charge flow in the vacuum gap (Cheng & Ruderman 1980), are required to explain the

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observations (see Gil, Melikidze & Geppert 2003). In such models, the surface temperature of the neutron star plays a crucial role in regulating the charge flow and potential drop across the gap and the observed variations in drift rates for PSR B0826–34 could be explained by small variations of this temperature. Thus it appears that these new results are providing useful insights for the improvement of the theoretical models.

As a final note on the topic of drifting subpulses, Edwards & Stappers (2003) report the detection of drifting subpulses for at least two millisecond pulsars. Even though the signals are too faint to detect individual pulses, the authors, using statistical processing techniques, are able to determine the presence of pulse-to-pulse intensity variations in six pulsars; and for two pulsars, they are able to show that the modulation phase apparently varies systematically across the pulse, indicating the presence of drifting subpulses. This adds one more feature to the list of observational properties of millisecond pulsars that are in common with those of normal pulsars.

## 5. Results from Statistical Studies of Single Pulse Data

Weak pulsars cannot be studied for single pulse properties using traditional methods, due to insufficient signal to noise ratio for the individual samples. The problem becomes worse for high temporal resolution studies and especially for the case of millisecond pulsars. Such data can be analyzed using ensemble-averaging techniques to uncover single pulse emission properties, as exemplified for the case of drifting subpulses in millisecond pulsars (Edwards & Stappers 2003).

Jenet, Anderson & Prince (2001), have used such techniques to detect pulse-to-pulse amplitude variations and shape variations. They find that PSR B0823+26 shows expected fluctuations for these quantities, consistent with the results from other methods. In contrast, for PSR B1937+21 they find that, except for the narrow region of pulse phase where the giant pulses for this pulsar are known to occur (see next section), the ensemble-averaged statistics show no evidence for pulse-to-pulse modulation and change in shape, i.e. there is a complete lack of temporal substructure. What is the cause of this difference? The authors speculate that the fluctuations may be due to a smaller number of "emission events" in the on-pulse region, or they may develop due to propagation processes in the pulsar magnetosphere.

A probably related issue is the evidence for lower intensity modulation indices for core components vis-a-vis conal components reported several years ago by Weisberg et al. (1986). Application of such techniques to a large number of pulsars (e.g. Jenet & Gil 2004) holds the promise of providing new insights into the emission mechanism.

## 6. Advances on the "Giant Pulse" Front

For a long time, the Crab pulsar was the sole known example of a pulsar producing giant pulses. In recent years, a surge of activity in this area has seen several pulsars added to the list (Romani & Johnston 2001; Johnston & Romani 2003; Joshi et al., these proceedings). In addition, there is growing evidence for "giant

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micropulses" in some pulsars (Kramer et al. 2002; Johnston & Romani 2002). Kinkhabwala & Thorsett (2000), from a detailed multi-frequency study of PSR B1937+21, show that the giant pulses from this pulsar last only $\sim$1–2$\mu$s and are emitted only in narrow ($\leq 10\mu$s) windows of pulse phase located on the trailing side of the main and interpulse regions. They also find that the frequency spectrum of the giant pulses is slightly steeper than that of the normal emission. Many of these aspects of the study of giant pulses are covered in more detail by Johnston & Romani (these proceedings).

Meanwhile, the Crab continues to establish new milestones in giant pulses. In a remarkable observational effort, Hankins et al. (2003) have studied the pulsar with 2 nanosecond time resolution at 5.5 and 8.6 GHz using the Arecibo Observatory. They find a characteristic width $\approx$ 200 ns for the giant pulses at 5 GHz, but show that the individual pulses exhibit substructure down to the resolution limit. They come up with the following conclusions about the source of these giant nanopulses:
(i) the equivalent brightness temperature is $10^{37}$ K;
(ii) the energy density is comparable to the mean energy density of the magnetospheric plasma;
(iii) the time scale and brightness temperature values are incompatible with coherent curvature and maser emission models, but are in agreement with the predictions of the plasma turbulence models (but see also Gil & Melikidze, these proceedings, for an alternate interpretation of the data).

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