# Part 4
# Radio Properties

## Section B
## Pulse Polarisation

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# Pulsar Polarization, Emission, and Beaming

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**Abstract.** This paper discusses observational and analytical questions pertaining to the pulsar emission problem. A short outline of the area is given for those new to the subject. Some of the literature pertinent to pulsar polarization, emission and beaming, which has appeared over about the last five years is mentioned. There is a short discussion of efforts to carry out polarimetric observations of higher quality, and finally, there is a short discussion of recent work by the author and her colleagues.

## 1. Introduction

In this paper we will discuss the properties of pulsar signals which appear to bear most critically on the physics of pulsar radio emission, their emission beam geometry, polarization, and temporal modulation. So far, this discussion has generally been confined to the slower "normal" pulsars, because most millisecond pulsars appear even more complicated that the slow pulsars in their emission characteristics.

Observationally, pulsar signals provide an exceptionally rich area of study, and many different phenomena have been identified which are presumably closely connected with the basic physical processes by which pulsars generate their radio frequency emission. Even the emission physics of the "normal" pulsar population is yet poorly understood. Theorists have made very great efforts to understand, the basic physics involved in pulsar emission, but all efforts to build a comprehensive global model have so far failed. Indeed, the "exotic" physical conditions, difficult geometry, and extreme non-linearity of the pulsar emission problem combine to make it one of the more challenging physical problems in contemporary astrophysics.

Given the difficulty of constructing a fundamental physical emission model, a semi-empirical "polar-cap" emission model, first outlined by Radhakrishnan & Cooke (1969) and Komesaroff (1970), has proven useful as a conceptual "cartoon", both as an observational framework and an important influence on theoretical efforts. Indeed, this is the model by which most workers in the field visualize pulsars, and considerable efforts have now been made to refine and quantify this phenomenological model, both as an observational aid and as a tool for theoretical model building.

Within this "polar-cap" model, we have tended to see the component structure of average profiles in terms of emission beams rotating with the star, their geometry determined by the pulsar's magnetic field configuration. The rich phenomena of subpulses and micropulses that modulate individual pulses are then apparently due to particle or plasma motions within this overall magnetic field structure. Most pulsar radiation appears to be emitted in directions tangent to the magnetic field at distances of no more than a few tens of stellar radii. Following Radhakrishnan & Cooke the radiation appears tied to the projected direction of the magnetic field, although there is overwhelming observational evidence for emission both parallel to and perpendicular to the planes containing the nearly dipolar field lines along which the emitting particles apparently move.

For many years all efforts to connect this, basically observational "polar-cap" model, in detail, with the available theory have proved frustrating. Simple geometric ideas inherent in the rotating vector model (RVM) of the linear polarization angle, first given by Radhakrishnan & Cooke—which should provide fundamental information about the sightline orientation relative to a pulsar's rotation and magnetic axes—have proven difficult and unreliable to interpret. Of the bewildering zoo of subpulse and micropulse phenomena, which are unfortunately often characteristic of only a narrow group of stars (*i.e.*, drifting subpulses, giant pulses, subpulse memory,...), not one has been found amenable to accurate, reliable theoretical understanding in its own right.

Finally, over the last five years or so, this bleak situation is beginning to change. A variety of observational, theoretical and phenomenological techniques have enlarged what appears to be reliably known about pulsar emission, and herald a cautious optimism that meaningful further progress on the pulsar emission problem can be made in the next few years. The remainder of this paper will a) briefly mention some recent published work (within about the last five years) which seems especially pertinent to this project, b) discuss developments in polarimetry technique, and c) report on some of the work which the author and her colleagues have carried out over the same interval.

## 2. Recent Published Work

We now have what appear to be reliable estimates of the basic emission geometry of many pulsars—that is, $\alpha$, the angle between the rotation and magnetic axes and $\beta$, the impact angle of the sightline with the magnetic axis. Not one, but three different techniques now exist for determining $\alpha$. Lyne & Manchester (1988) developed a method which uses the polarization-angle (PA) traverse together with profile-width data to circumvent the difficulties encountered in interpreting the RVM, and efforts have continued to sort out the PA traverses of particularly difficult pulsars (*i.e.*, see Gil & Lyne 1995).

Blaskiewitz, Cordes & Wasserman (1991) have then given a relativistic model for the polarization which takes into account its effects on the PA traverse and applied this analytical technique to new Arecibo observations of excellent quality.

Rankin (1990) has reported an independent technique based on the observed widths of *core* components. The latter technique stems from the observation that these *core* components have apparent angular dimensions very close to that of the magnetic polar cap—that is, about $2.45° P^{-1/2} \csc\alpha$. Remarkably, all three methods give similar values of $\alpha$ for most pulsars.

Moreover, we now seem to have a fairly secure understanding of the conal beam structure which is implied by pulsar average profiles. With the value of

$\alpha$ better known, it is possible to estimate $\beta$ from the steepness of the linear polarization position-angle traverse, and on this basis to compute the angular dimensions of the conal emission beams. The results of such a study for a population of some 150 pulsars (Rankin 1993a,b) showed, surprisingly, that there are two distinct conal emission beams with dimensions (to the outer half-power point) $\rho_{inner} = 4.33°P^{-1/2}$, and $\rho_{outer} = 5.75°P^{-1/2}$. Again, we see that the dimensions of these beams scale as $P^{-1/2}$ and are thus closely tied to the bundle of "open" field lines which define the polar cap.

Several new studies have now confirmed the double form of the conal emission beam. Gil, Kijak, & Seiradakis (1993b) carried out new observations of a somewhat different population of pulsars with the Bonn telescope at both 1.4 and 10.55 GHz and found a discrete double-conal width behavior using both the half-power and 10 percent width values. Kramer *et al* (1994) and Kramer (1994) then studied an overlapping population at 1.4, 4.75, and 10.55 GHz using a sophisticated fitting technique and obtained similar results.

Recent efforts at Bonn to study pulsars at extremely high frequencies have resulted in the first detections at mm wavelengths. Wielebinski *et al* (1993) reported on the detection of four pulsars, and polarimetry has now been conducted on groups of pulsars both at 10.55 GHz (Xilouris *et al* 1995a) and at 32 GHz (Xilouris *et al* 1995b). This latter paper, together with a shorter report (Xilouris *et al* 1994) find evidence that the characteristics of pulsar emission change significantly at the highest frequencies. See Xilouris' contributions to these proceedings.

Thorsett (1991) has conducted a new study of the frequency dependence of average profiles and found that all fit a function $\Delta\theta = A\nu_{-a} + \Delta\theta_{min}$. Gil *et al* (1994) have carried out a major new study of the moding, microstructure and drifting in pulsar 1822–09, and several other studies examine and/or model the properties of subpulse beams within the framework of the hollow-cone model (Gil 1992; Gil *et al* 1993a; Gil *et al* 1995; and Gil & Krawczyk 1996).

Arons (1993) has explored some of the structural and evolutionary consequences of non-dipolar magnetic fields and supports the premise that kinematic modeling of average profile widths suggests that "normal" pulsar magnetic fields remain close to dipolar all the way down to the neutron-star surface. Further, McKinnon (1993) has extended Biggs (1990) work on the geometry of the polar cap and suggested a somewhat different manner of interpreting the distribution of $\alpha$ values.

Weatherall and Eilek (1994) have examined theoretical models leading to the creation to pair plasmas responsible for radio emission and conclude that only those pulsars with significant core emission meet the necessary criteria. They then raise the question of a second emission mechanism responsible for the conal emission. Moreover, Asseo (1995) has found a plasma instability, which she calls the 'finite-beam' instability, which operates most efficiently close to the neutron-star surface. She argues that this phenomenon provides a good candidate for the observed core emission. See their respective talks in this volume.

## 3. Polarization Technique

The measurement of polarization is a technique of incalculable value in the study of pulsars. How much poorer our subject would be without the ability to distinguish all of the different dimensions of polarization in the pulsar signals which reach us, the linear polarization and its angle as well as the circular. Polarization has been an important aspect of our discussion about pulsars since near the time of their discovery; however, it is not clear that we have always carried out these measurements well.

Pulsars provide a particularly challenging context for polarimetry. We require all of the polarization information simultaneously and at a high data rate, and, pulsars are among the very most highly polarized sources known to astronomy. These circumstances conspire to virtually insure that even the best designed radio telescopes will distort the polarization state of the signals they are used to measure.

Although there are many ways which, in principle, telescopes can distort polarization, one seems most fundamental and problematic. It has been known for more than 20 years, but practical techniques to correct it have been slow in coming. This is the cross-coupling which occurs in any dual polarization feed. However, carefully such a feed is designed to distinguish two orthogonal polarizations, actual feeds have structures which break their symmetry and result in some of the power being mutually "cross coupled" in the receivers connected to them.

Whether one is thinking in terms of orthogonal circular or linear feeds, the effect is the same, the desired purely circular (or linear) response to the incident signals becomes elliptical, and this elliptical response degrades the specification of the Stokes parameters. Of course, no instrument is perfect, but the effect of cross-coupling is particularly insidious; the degradation of the Stokes parameters goes as the square root of the *voltage* cross-coupling.

Some of the best constructed feeds have measured isolations (or cross couplings) of about 25 db, meaning that there will be a 12 db or 8% distortion in the Stokes parameters. In practice, because pulsars are usually more linearly than circularly polarized, it is the circular which is most affected by the cross-coupling. In this example, circular polarization at a level of about 4% would be uncertain in the presence of 50% linear polarization. A great deal of the circular polarization measured in pulsar signals falls in this approximate range. We simply have to do better.

At Arecibo we have long been aware of this situation, the problem has been what to do about it. A mathematical model for the cross-coupling in circularly polarized channels was developed by Stinebring *et al* (1984) Four instrumental parameters, two cross-coupling amplitudes (which are closely related to the feed ellipticities) and two phases (which, in turn, are closely related to the orientation of the ellipses) are required to completely specify the instrumental distortion. We did not then know how to determine all of these quantities, and so we could only partially correct our 21 cm observations under certain assumptions.

Over the last three years we have learned not only how to determine all four quantities, but how to determine them as a function of frequency across the bandpass. The details of this instrumental development effort will be described in a forthcoming publication (Rankin, Rathnasree & Xilouris 1996), and we believe that our 1992 Arecibo observations represent some of the best calibrated polarimetry every carried our with that instrument.

## 4. Work in Progress

We now briefly review some of the early results from a 1992 series of Arecibo average and individual-pulse observations. More than 20 pulsars were observed at 430 and 1400 MHz using the Arecibo 40-MHz correlator in a gated single-pulse mode (Perillat 1988) for the first time.

A new study has been carried out on the stabilization rate of average profiles (Rathnasree & Rankin 1995). To investigate the physical processes governing the approach to a stable profile, the pulse-to-pulse variations were divided into three parts: variations arising from the changes in the intensity, phase, and width of the maximum. The rate of stabilization is seen to vary from pulsar to pulsar, and a correlation with other pulsar properties give some insight into the processes governing the variations of individual pulses. The stabilization rate for the polarized emission was also studied and was found to be slower than that for the total intensity.

We have carried out a new study of the polarization modes in pulsar 0823+26 (Rankin & Rathnasree 1996). Remarkable structure is revealed in the secondary mode which appears to represent a pair of conal outriders, and geometric calculations confirm that they have the right dimensions to be an outer cone. On the basis of this identification, we are able to speculate more fruitfully about the significance of the pulsar's postcursor component. It seems that 0823+26 has a very nearly equatorial geometry, in that both magnetic poles and the sight-line all fall close to the rotational equator of the star. We thus associate the postcursor component with emission along the trailing bundle of equatorial field lines. Interestingly, there is significant correlation between the secondary-mode outriders and the postcur emission.

Rathnasree (1996; see also Rathnasree these proceedings) has examined the individual pulses of pulsar 1929+10 and interpreted them as representing the emission from individual particle bunches. Fits of the expected angular distribution to subpulses are good, and the distribution of $\gamma$ values obtained is also interesting.

We have used our October 1992 observations to study the intensity dependence of linear polarization in about 20 pulsars (Rathnasree & Rankin 1996) at 430 and/or 1400 MHz. After carefully correcting our individual-pulse sequences for statistical polarization, we find that most pulsars exhibit a significant positive correlation between intensity and fractional linear polarization. Another recent study at very high frequency (Xilouris *et al* 1994), which also seems to have included careful corrections, finds a negative correlation. Can it be that the polarization statistics of most pulsars change with frequency in a similar manner?

Individual-pulse observations of pulsar 0943+10 at a frequencies of 102 and 430 MHz have revealed subtle changes in the linear and circular polarization distributions associated with the pulsar's change from its B mode to its Q mode (Suleymanova *et al* 1996). A slow attenuation of the dominant component over

18 minutes occurred before and for some time after the sudden enhancement of radiation associated with the weaker trailing component.

Finally, we explore the geometry and polarisation behaviour of pulsar 1929+10 using a variety of different techniques (Rankin & Rathnasree 1996b). This pulsar is known to emit over virtually the whole of its rotation cycle, so its polarisation-angle behaviour is particularly intriguing. The characteristics of the two polarisation modes are particularly interesting in this pulsar, both because the primary mode so completely dominates the secondary and because the structure seen in the secondary mode appears to bear importantly on the question of the pulsar's basic emission geometry. Many of these features are illustrated in the top panel of Fig. 1

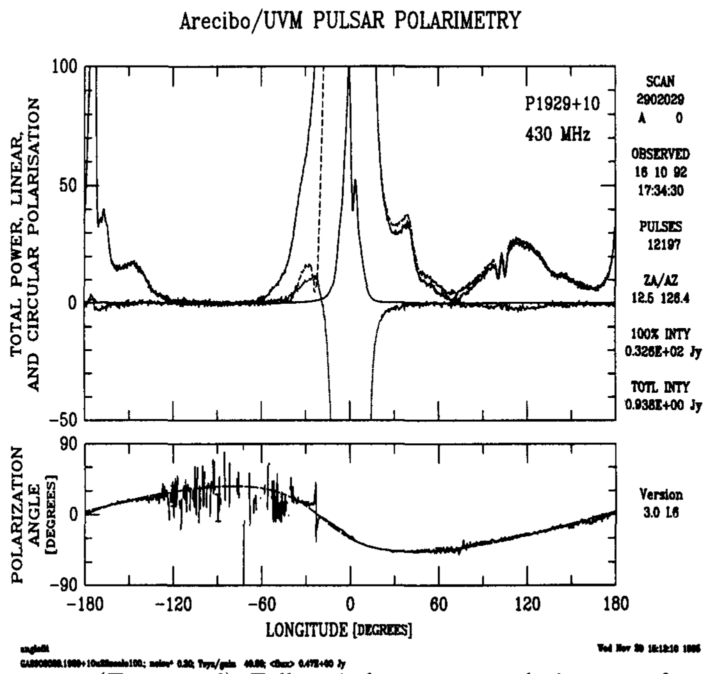


Figure 1. (Top panel) Full-period, average polarimetry of pulsar 1929+10 at 430 MHz. The total-power is plotted first at full scale and then at an expanded scale of 100, so that only features below 1 percent of the main-pulse amplitude are now visible. The linear and circular polarisation are then plotted at the expanded scale. (Bottom panel) Least-squares fit to the polarisation PA traverse. The polarisation mode change on the main-pulse leading edge has been rectified by a 90° rotation and the transition region following it unweighted. Then all points with intensities greater than 0.005 of the peak intensity were also unweighted (see text). Note the poor fit in the main- and interpulse regions. Note also that the inflection point of the fitted curve falls at about $-18°$ longitude.

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Least-squares fits to the polarisation-angle traverse fit poorly near the main pulse and interpulse and have an inflection point far from the centre of the main pulse. This fit is shown in the bottom panel of Fig. 1; the fit is the dashed curve. The poorness of the fit casts doubt of the use of the RVM to determine the values of the magnetic inclination angle $\alpha$ and impact angle $\beta$.

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