3.3 POLARIZATION OF PULSARS

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Abstract. A survey is given of the polarization properties of pulsars. Many pulsars, although showing pulse-to-pulse variations in polarization, have a stable mean polarization characteristic. Several pulsars like 0833–45 show changes in the position angle of linear polarization across the pulse which can be interpreted as due to the changing direction of the magnetic field as envisaged in the oblique magnetic dipole model of pulsars. Faraday rotation measurements when taken with dispersion measures yield values for the interstellar magnetic field of several microgauss.

In the first few months following the discovery of pulsars, observations made simultaneously with orthogonally polarized antennas showed that, at least at long wavelengths, individual pulses may be quite strongly polarized (Lyne and Smith, 1968). This polarization is in general elliptic, and the sense and degree of polarization vary strongly from pulse to pulse (Taylor, 1968). From these early observations it was by no means clear whether there would be a characteristic average profile for the polarization of the pulsar emission. Stated in another way, early observations had shown that each pulsar possesses a characteristic average intensity profile (the I Stokes parameter, or something closely related to it), but it was not clear whether similar non-zero profiles existed for the Q, U and V Stokes parameters.

This question was clarified by the discovery of the strongly polarized emission from PSR 0833 – 45. At decimeter wavelengths this object shows very much less pulse-to-pulse intensity variation than do other pulsars; thus it may be studied by the conventional technique of rotating a single linearly polarized antenna. With other pulsars there is always some doubt whether successive averages taken in this way may be meaningfully compared, although the technique has been used successfully for several objects by Komesaroff *et al.* (1970). It is far more convincing to use a polarimeter in which all four Stokes parameters are recorded simultaneously, and such devices have been used for observations at Green Bank, Goldstone, Jodrell Bank, Parkes, and Arecibo.

The radiation from PSR 0833–45 at decimeter wavelengths has almost 100% linear polarization, and the angle of polarization rotates by nearly 180 degrees during each pulse. This rather startling discovery was made independently by Ekers and Moffet at Goldstone (Ekers *et al.*, 1969; Ekers and Moffet, 1969) and by Radhakrishnan *et al.* (1969) at Parkes. The latter authors suggested a compelling explanation for the rotation of the polarization angle as a consequence of the changing direction of the magnetic field in the oblique magnetic dipole model of a pulsar. This explanation was elaborated in a subsequent paper (Radhakrishnan and Cooke, 1969). The emission is presumed to be linearly polarized with the polarization parallel to the projection of the magnetic field normal to the line of sight to the emitting region. As the magnetic polar region passes the line of sight, this direction rotates through as much as 180°. A quantitative

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model for such emission is given by Komesaroff (1970). The concentration of emission in the vicinity of a magnetic pole of a rotating neutron star follows from the electrodynamic model calculated by Goldreich and Julian (1969) in which they show that a stream of energetic particles will be ejected from such a region.

Even after the discovery of the polarized emission from PSR 0833 − 45 it was not clear whether other, more variable pulsars would have stable polarization averages, but this is in fact the case, as has been shown by Ekers and Moffet (1969); Komesaroff *et al.* (1970); Morris *et al.* (1970); and Manchester (1970). Because of the pulse-to-pulse variation, the degree of polarization is necessarily less than 100%, at least in the strong parts of the pulses. Manchester (1970) finds that in the wings of the pulses the average degree of polarization often approaches 100%. A uniform rotation of position angle during the pulse is often seen, although sharp discontinuities of position angle do occur. In PSR 2045 − 16 (Morris *et al.*, 1970) and in PSR 1237 + 25 (Manchester, 1970) these are interpreted as evidence that a single magnetic pole passes very nearly across the line of sight. Ekers and Moffet (1969) observed a jump in angle of 90° during a part of the pulse from CP 1133. This was interpreted in terms of a model with two magnetic polar regions contributing to the pulse. The reality of this phenomenon is in doubt, since it was not confirmed in the more sensitive observations of Manchester (1970), although these were at a very different wavelength.

Polarization observations may help to explain what is happening in pulsars with complex intensity profiles. In both PSR 2045 − 16 and PSR 1237 + 25 the change in the polarization angle is much more regular than the change in the intensity, with the discontinuity in position angle coming near the most prominent minimum in the intensity average. Morris *et al.* (1970) interpret this as a relative minimum of the intensity in the immediate vicinity of the magnetic pole with more intense emission in a hollow cone around the projected direction of the pole (Komesaroff *et al.*, 1970). Other complex pulses such as CP 0328 (Clark and Smith, 1969; Ekers and Moffet, 1969) do not appear to be so simple.

While an appreciable degree of circular polarization is often seen in individual pulses, the average circular polarization is usually quite small, although Ekers and Moffet (1969) have reported an appreciable average circular polarization in PSR 1749 − 28.

We have heard some discussion at this conference about whether the emission from the Crab pulsar shows a variation of position angle during the pulse. Campbell *et al.* (1970) find that at 430 MHz no rotation takes place. The precursor is 100% polarized while the main pulse and interpulse are about 30% polarized. Observations made at Jodrell at 408 MHz and presented at this conference by Schönhardt (1970) indicate a rotation of about 60° within the main pulse. The matter is clearly an important one and should be cleared up by observations with higher time resolution.

There is also some dispute about the polarization of individual giant pulses from the Crab. Graham *et al.* (1970) found about 70% linear polarization for these, while Rankin and Heiles (1970) found about 25% linear and 10% circular to be typical. Heiles *et al.* (1970) found that the sense of circular polarization is different for giant pulses which occur before or after the center of the average main pulse.

Where linear polarization is present, Faraday rotation can be measured. In reporting their detection of polarized emission from pulsars, Lyne and Smith (1968) pointed out the possibility that measurements of Faraday rotation and dispersion could be combined to give a measure of the mean galactic magnetic field component along the line of sight to the pulsar. The rotation measure is $RM \propto \int n_e \mathbf{B} \cdot \mathrm{d}\mathbf{s}$, while the dispersion measure is $DM = \int n_e \, \mathrm{d}s$. Thus $RM/DM = \langle B_{\|} \rangle$, the average component of B parallel to the line of sight and weighted by the electron density.

Such a measure was first obtained by Smith (1968a, b) for CP 0950, CP 0328 and AP 2015+28. For nearby pulsars the rotation measure will be small, and the effects of the ionosphere are not negligible (Roger and Shuter, 1968). Faraday rotations measured over narrow frequency intervals seem to be subject to errors, perhaps introduced by the interstellar scintillation. Thus Smith's first value for CP 0328 was 50% high (Goldstein and Meisel, 1969; Staelin and Reifenstein, 1969). Also Morris *et al.* (1970) find a rotation measure for PSR 0628−28 between 2650 and 1720 MHz of +22 rad m^{-2}, which differs from Vitkevitch and Shitov's (1970b) value of 45 rad m^{-2}, which was measured over narrow intervals near 86 and 110 MHz.

TABLE I

Magnetic Fields Determined from Pulsar Faraday Rotations

Object	l	b	RM rad m^{-2}	DM cm^{-3} pc	$\langle B_{\|} \rangle$ μG	Ref.*
CP0328	145	− 1	−63	26.8	+2.8	1,9
NP0527	184	− 7	|36|	51.2	|0.9|	1
NP0532	185	− 6	(−25)	56.8	(+0.55)	2
PSR0628-28	237	−17	+22	35	−0.6	3
			|45|	34.4	|1.6|	4
CP0808	140	+32	|12|	5.8	|2.5|	5
PSR0833-45	264	− 3	+33	53	−0.73	6, 7
CP0950	229	+44	<|0.5|	3.0	<|0.2|	8
AP2015+28	68	− 4	−30	14.2	+2.0	9

* 1. Staelin and Reifenstein (1969); 2. Verschuur (1969); 3. Morris *et al.* (1970); 4. Vitkevitch and Shitov (1970b); 5. Vitkevitch and Shitov (1970a); 6. Ekers *et al.* (1969); 7. Radhakrishnan *et al.* (1969); 8. Smith (1968a), 9. Smith (1968b).

This method has since been applied by various authors to determine the magnetic field in the directions of eight pulsars, as shown in Table I. Also given are the galactic coordinates, the rotation measure and the dispersion measure. Where the sign of the Faraday rotation is known it is given; a positive sign for the magnetic field implies **B** directed from the source towards the observer. Exempting the low value for CP 0950 because of doubt about the ionospheric contribution, the fields range from 0.55 to 2.8 μG. This seems likely to represent the typical interstellar magnetic field better than the higher values measured from the Zeeman splitting of the 21 cm absorption features produced by cold, dense clouds of hydrogen. There is reason to believe that the fields may have been amplified as these clouds condensed (Verschuur, 1969). The field given in Table I for NP 0532 assumes that the Faraday rotation observed for the Crab Nebula as a whole is applicable to the pulsar, since the rotation of the pulsar emission has not yet been measured. The field for CP 0808 comes from the observations of Faraday fading given by Vitkevitch and Shitov (1970a) and is fairly uncertain since the implied rotation measure is only 12 rad m^{-2}. For PSR $0628-28$, values of $\langle B \rangle$ are given corresponding to the two conflicting observations of RM as mentioned before.

Observations of the polarization of the pulsar emission have given important clues about the nature of these objects. Further work will surely assist in constructing detailed models of the emission process. It will be important to compare changes in the pulse shape with changes in the polarization at different frequencies and to examine the relation between the polarization and the short time scale structure of individual pulses. In addition the measurement of Faraday rotation gives information about the interstellar magnetic field which cannot be obtained in any other way.

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Discussion

L. Mestel: Can I underline Dr. Moffet's remark about the comparison between the magnetic field estimates from the ratio of rotation measure and dispersion measure, and the Zeeman measurements? A magnetic field strength is significant only when one knows the associated matter density. Verschuur's Zeeman measurements refer to moderately dense H I clouds, with the magnetic field appropriately amplified. The self-gravitation of the clouds may be sufficient to balance the outward force exerted by the distorted magnetic field. So far from there being any glaring contradiction, I feel that the evidence is at least qualitatively in agreement with what one expects from hydromagnetics.

F. C. Michel: I think it unprofitable to impose upon theoretical models morphological features exhibited by only a small fraction of pulsars. You have shown polarisation sweeps by about 10% of the pulsars, but what about the rest – is the sweep really a general effect?

A. T. Moffet: I think that in all cases where good data have been obtained on pulsars with fairly simple pulse shape a regular sweep of position angle has been found.

R. N. Manchester: Approximately 60% of pulsars observed show a continuous swing of position angle across the pulse.

M. M. Komesaroff: I would like to point out that the observations of Morris, Schwarz and Cooke made at 11 cm showed an identical sweep in position angle (except for a constant shift) with those of Manchester at 75 cm.

R. N. Manchester: This result shows that differential Faraday rotation between components of pulse is essentially zero, the $\Delta RM = 0.10 \pm 0.23$ rad/m^2.

J. Sutton: A search for short period pulsars in Cas A, Tycho's supernova and 3C 58 was conducted at 408 MHz using the 300 ft radio telescope at Green Bank. The beamwidth was 34′. Data were taken with bandwidths of 100 and 500 kHz, and recorded digitally at 1000 samples per second. The search involved Fourier analysis of groups of 16000 points. The data were analysed 4 times, smoothing to effective sample intervals of 1, 4, 16 and 64 msec. The dispersion limit due to bandwidth broadening was approximately $40\,P$ electrons cm^{-3}, where P is the period in msec. Within the period and dispersion limits, upper limits on the fraction of energy from Cas A in pulsed radiation is $\sim 0.2\%$. Similar limits for Tycho and 3C 58 are $\sim 1\%$.