III. RADIO OBSERVATIONS OF PULSARS

PULSAR POLARIZATION

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I. INTRODUCTION

Over ten years ago Radhakrishnan and his coworkers in Australia detected a smooth variation of the electric vector through 90° during the brief pulses from the Vela pulsar. This observation led to the hypothesis that pulsar radiation is beamed along a magnetic pole. While subsequent observations gave ample support to this model, we find that less than half of the pulsars have average profiles which are consistent with the magnetic pole hypothesis. Statistical analyses of individual pulse polarization data now reveal that the average profiles obscure the basic nature of linear polarization in pulsars: two orthogonal modes are typically present, and individually these modes agree with the magnetic pole model. We explain the occurrence of orthogonal modes by a simple geometry for the polarized subpulse beam in relation to the magnetic axis. Theoretical models for subpulse polarization invoke both a combination of emission mechanism effects and propagation effects. We conclude with directions for further research.

II. OBSERVATIONS OF AVERAGE PULSE PROFILES

The radiation from the Vela pulsar, 0833-45, exhibits nearly 100% linear polarization, and has a position angle which decreases uniformily through 90° during merely 18° of rotation (fig. 1b). Radhakrishnan and Cooke (1969) proposed that this rapid angle variation was a consequence of observing radiation beamed along a magnetic pole with the electric vector parallel to the instantaneous projection of the field lines (fig. 1a). In this model beaming is produced by particles accelerated to relativistic speeds along polar field lines which connect the stellar surface to the interstellar medium. The relativistic particles are guided along diverging field lines and radiate by curvature acceleration. Details of the production of complete linear polarization, as in Vela, and of circular polarization in other objects are left unspecified.

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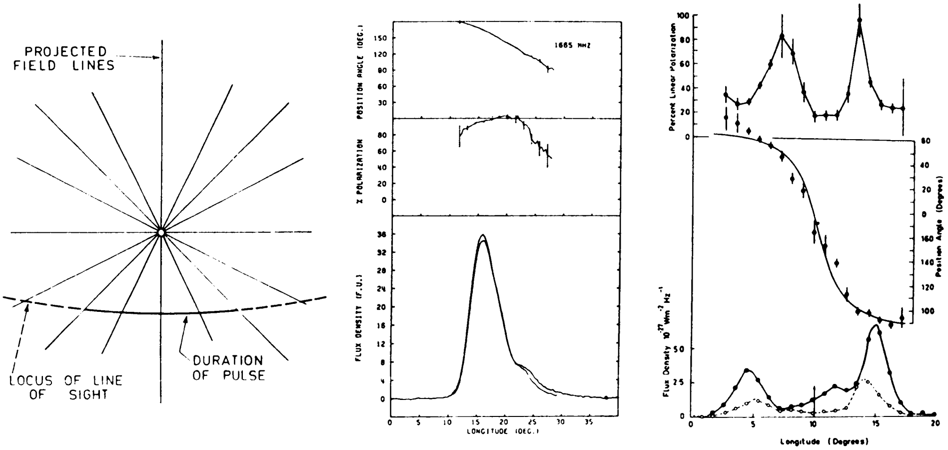

(a) Magnetic Pole (b) 0833-45 (c) 2045-16

FIG. 1 (a) Representation of magnetic pole model (Radhakrishnan and Cooke 1969); (b) Vela pulsar at 1670 MHz (Manchester 1971b); (c) PSR2045-16 at 2700 MHz (Morris et al. 1970).

The proposed magnetic axis for Vela would pass within 7°3 of the observer's line of sight assuming an inclination near 90°. The magnetic pole hypothesis predicted that pulsars would be observed with impact angles less than 7°3 and, consequently, polarization angle variations as large as 180°. These variations were soon observed, and they agreed with near mathematical precision to the magnetic pole model: 2045-16 with an impact angle of 1°5 (fig. 1c, Morris et al. 1970) and 0525+21 (Manchester 1971a).

In the first comprehensive pulsar studies 75% of the pulsars displayed monotonic variations of polarization angle in their average profiles (Manchester 1971b, Lyne et al. 1971). These variations were consistent with the magnetic pole model. However, the higher sensitivity of the more recent Arecibo Polarization Survey (APS) has reduced the fraction of objects whose average profiles conform to the model. More than half of the pulsars in our statistical study (Backer and Rankin 1980; APSVI) have nonmonotonic angle variations with longitude; in addition, several objects identified as monotonic show small deviations of the angle from the smooth curve predicted by the model. In many pulsars classed as nonmonotonic the average profiles are characterized by abrupt changes of polarization angle which exceed one radian in merely one degree of rotation.

III. INDIVIDUAL PULSE POLARIZATION OBSERVATIONS

Statistical summaries of individual pulse polarization data have led us to an explanation for the curious behavior of the average polarization angles discussed above (APS VI). The most valuable summary

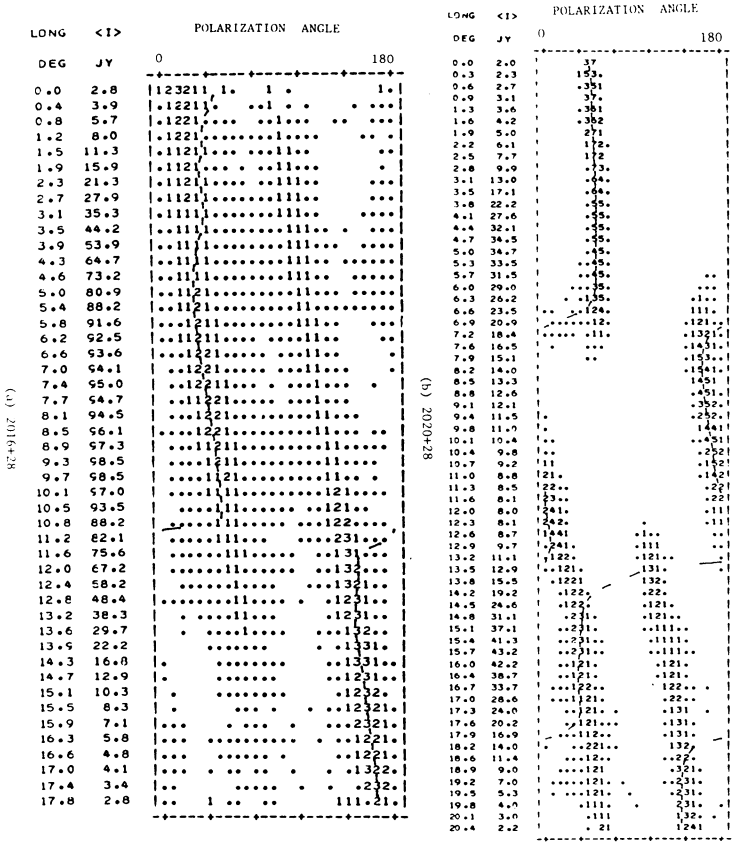

FIG. 2 Histograms of frequency of occurrence of polarization angle in units of 10%; decimals correspond to 1-5% interval. Longitudes and total intensity profiles are tabulated in degrees and Janskies, respectively (APS VI).

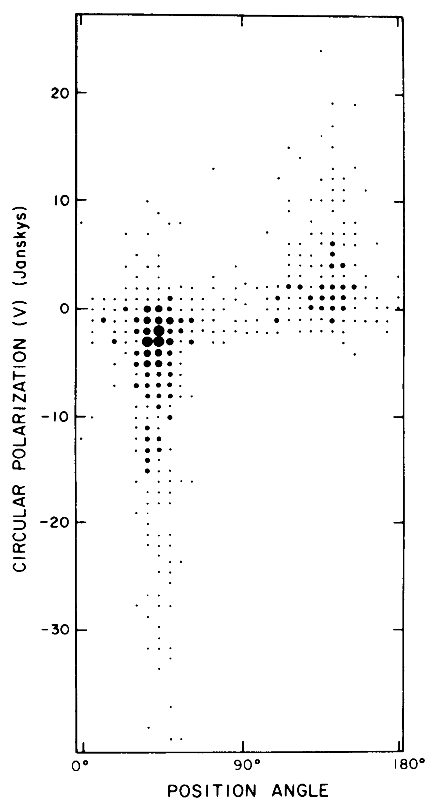

FIG. 3 Correlation of circular polarization with position angle for 2020+28. Size of symbols indicates occurrence probability (APS V).

is a two dimensional histogram of the frequency of occurrence of polarization angles at each longitude sampled. Two important features are observed in these histograms:

(1) Two orthogonal, linear polarization modes are active at one longitude or another in nearly every object. Orthogonal modes in subpulses have also been investigated by Manchester et al. (1975).

(2) The individual modes display monotonic variations of angle with longitude which are consistent with the magnetic pole model.

We conclude from the statistical summaries that in all pulsars we are observing radiation beamed along the magnetic pole. An unspecified mechanism results in electric vectors either parallel or perpendicular to the projected field lines. Both modes may be present along any line of sight, and the dominant mode may switch within the average pulse window.

We present in figure 2 the individual-pulse angle histograms for two pulsars with nonmonotonic average angle profiles. In figure 2a we find that the orthogonal mode in 2016+28 are active at all longitudes. An abrupt change in the dominant mode, as indicated by the average angle, occurs at 11° longitude. The deviation of the average angle from the peak of the histogram on the leading edge indicates that non-orthogonal modes of radiation are summed; the sum of strictly orthogonal modes is polarized either at θ or at $\theta + \Pi/2$ depending only on the relative intensities (Cordes et al. 1978; APS V). We note here for future discussion both that 2016+28 is dominated by drifting subpulses (Drake and Craft 1968), and that the orthogonal polarization angles appear in a systematic pattern coupled to the subpulse modulation (APS data and Manchester et al. 1975).

The average profile of 2020+28 contains three abrupt changes in angle (longitudes 6°.9, 13°.5 and 17°.9 in fig. 2b) which clearly result from switches between the orthogonal modes (APS V). The position angles of both increase monotonically through 100° with a morphology consistent with the magnetic pole hypothesis. The second component of 2020+28 (12°-20°, note intensity scale in fig. 2b) is distinguished from the first (0°-8°) both by nearly equal probabilities for the two polarization modes and by periodic intensity modulation near two rotation periods (Backer et al. 1975, APS II). In component II the occurrence of orthogonal modes is coupled to the subpulse modulation as in 2016+28. We present below a geometrical model for subpulse modulation with equally probable polarization modes in these two pulsars.

Statistical analyses revealed two additional features of the polarized radiation in component II of 2020+28. The two linear modes in component II are precisely correlated with opposite signs of circular polarization (fig. 3, APS V). The polarization modes are then completely orthogonal. Also we find that one mode displays a wider range of total intensity than the other. The total intensity correlation is related to the systematic appearance of modes within the subpulse modulation pattern.

IV. SUBPULSE POLARIZATION MODEL

The observations presented above suggest a model wherein the subpulse is composed of several regions. These regions are dominated by alternating modes of polarization. The partial polarization observed at any moment indicates either that the modes themselves are partially polarized (with milliradian angular resolution), or both modes are generated along the line of sight with comparable intensity. The orientations of the regions are fixed relative to the projected field lines. In the objects with drifting subpulses we envision that subpulse beams circulate around the magnetic axis (Ruderman 1976) presenting different cuts through the beam as time progresses. Figure 4 shows a possible configuration of subpulse beams (a,c, and e) circulating about the magnetic axis: a main lobe of polarization is centered on the subpulse intensity peak and extends along the projected field line (−), and two sidelobes dominated by orthogonal polarization (+) are situated symmetrically on either side. The observer records the pulse sequence labeled A-E in figure 4. Candidate subpulse beams labeled h and i were not consistent with our observations of 2016+28. In pulsars without drifting subpulses the subpulse beams are observed at a fixed orientation, and the radiation thus consists mainly of a single mode.

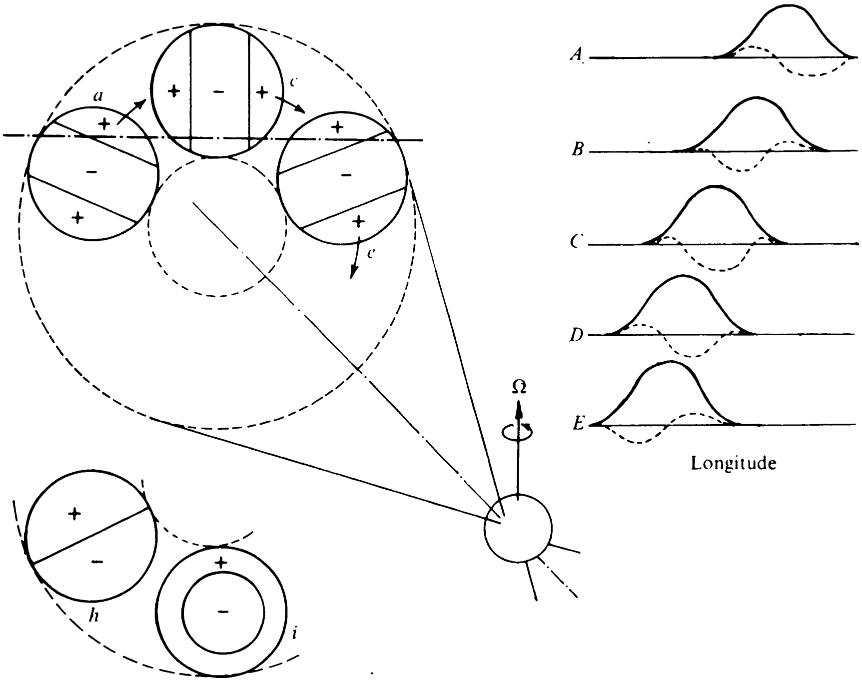

FIG. 4 Subpulse Polarization Model. Schematic of subpulse beams distributed around magnetic axis on left; observed total intensity (solid) and linear polarization (dashed) on right.

Cheng and Ruderman (1979) discuss propagation of the normal modes of radiation in a magnetoactive plasma. Their study suggests that the observed rich variety of polarization properties can be incorporated into the magnetic pole hypothesis. They describe how the polarization of a subpulse ray will be ordered by adiabatic walking as the magnetic field diverges from the ray in the near pulsar magnetosphere. The evolution of the ray polarization in the pulsar magnetosphere can produce both the wide range of observed polarization fractions and circular polarization with plausible physical parameters. Cheng and Ruderman also suggest that orthogonal modes of polarization are produced by two emission mechanisms: linear acceleration and curvature acceleration. In their model a delicate balance of physical conditions produces subpulse beams with regions of alternating polarization modes as proposed in figure 4 (APS IV).

Melrose (1978) has presented an independent analysis of the propagation of orthogonal modes from the emission site. He suggests that systematic polarization in subpulse beams is a consequence of propagation in the anisotropic medium: the ray path and the wave normal diverge by different amounts for orthogonal modes of propagation. This effect would show very strong frequency dependence.

V. CONCLUSION

In conclusion, I would like to suggest several directions for future research:

(1) Are the position angle rotations of linear polarization modes always axially symmetric?
(2) How do we explain polarization modes not separated by $\Pi/2$?
(3) Does the sense of circular polarization always correlate with the two linear modes?
(4) Is there a predominant mode which is aligned (or perpendicular to) the projected field?
(5) Is the frequency dependence of subpulse polarization consistent with current notions on propagation in the pulsar magnetosphere?
(6) Are the objects with nearly constant polarization angles throughout the pulse consistent with the magnetic pole model?
(7) Do micropulses have a characteristic polarization profile?

REFERENCES

Backer, D.C., Rankin, J.M., and Campbell, D.B.: 1975, Astrophys. J. 197, pp. 481-487 (APS II).
Backer, D.C., Rankin, J.M., and Campbell, D.B.: 1976, Nature 263, pp. 202-207 (APS IV).
Backer, D.C. and Rankin, J.M.: 1980, Astrophys. J. Suppl. 42, pp. 143-173 (APS VI).
Cheng, A.F. and Ruderman, M.A.: 1979, Astrophys. J. 229, pp. 348-360.
Cordes, J.M., Rankin, J., and Backer, D.C.: 1978, Astrophys. J. 223, pp. 961-973 (APS V).

Drake, F.D. and Craft, H.D. jr.: 1968, Nature 220, pp. 231-235.
Lyne, A.G., Smith, F.G., and Graham, D.A.: 1971, Monthly Notices Roy. Astron. Soc. 153, pp. 337-382.
Manchester, R.N.: 1971a, Astrophys. J. Letters 167, pp. L101-L105.
Manchester, R.N.: 1971b, Astrophys. J. Suppl. 23, pp. 283-322.
Manchester, R.N., Taylor, J.H., and Huguenin, G.R.: 1975, Astrophys. J. 196, pp. 83-102.
Melrose, D.B.: 1978, Australia-USSR-USA Symposium on Pulsars and Supernova Remnants, Sydney.
Morris, D., Schwartz, U.J., and Cooke, D.J.: 1970, Astrophys. Letters 5, pp. 181-186.
Radhakrishnan, V. and Cooke, D.J.: 1969, Astrophys. Letters 3, pp. 225-229.
Ruderman, M.A.: 1976, Astrophys. J. 203, pp. 206-208.

DISCUSSION

RUDERMAN: How closely can polarization in individual subpulses approach 100%?

BACKER: The subpulses of the Vela pulsar seem to be 100% linearly polarized.

TAYLOR: For many pulsars the subpulses are more than 95% polarized.