Part IX

Polarization phenomena

Friday afternoon. Session Chair: Dick Manchester

- How is the coherent radio-frequency emission produced and why is it depolarized?
  - ⋆ Polarization phenomena
    - ∗ Observations of subpulse modulation and polarization as they relate to particular emission processes.
    - ∗ Observations of the polarization-modal structure of pulsar profiles and subpulses.
    - ∗ Discussions of radiative transfer and propagation effects in the pulsar magnetosphere.
    - ∗ Polarization models and depolarization mechanisms.

The final session of formal papers was initiated by a superb review entitled, Polarization of pulsar radiation, *by V. Radhakrishnan, in which he has summarized a number of the most important observations of polarized pulsar emission and showed where a number of problems exist in their interpretation.*

THE POLARIZATION OF PULSAR RADIATION

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Introduction

The numerous discussions that took place at the colloquium have reemphasized the primary importance of polarization observations and their interpretation for understanding the magnetospheric structure and the radiation mechanisms of pulsars. I have tried to take them into account in the summary at the end of this written version of my review of polarization phenomena, where I also attempt to address some of the questions raised by both observers and theorists as to what message polarization has for the planning of future observations and for the development of theories to explain pulsar radiation mechanisms. Because I feel it is relevant I shall begin with a little history to put things in perspective.

Early history

It is interesting that polarization taught us nothing new about cosmic radio sources for the first thirty years or so of radio astronomy, and it is only in more recent times that such studies have revealed aspects that were otherwise inaccessible. A notable exception was the radio emission from Jupiter whose character was governed by a magnetic field with an origin elsewhere than in the currents associated with the motions of the particles themselves. Its energy density was far greater than that of the particles gyrating in it, and unlike in the case of other non-thermal radio sources, words like equipartition had no meaning. The consequence was that polarization observations of the decimetric radiation from Jupiter provided an instant picture of its magnetic field with the inclination and rotational period just falling out of the analysis (Morris and Berge 1962).

Well before the discovery of pulsars, neutron stars (even more compact bodies than planets) had been predicted to have extremely high magnetic fields whose form was still less likely to be affected by the presence of any particles. Of course, no one had any idea whether there would be any particles there, or what they would do, before the discovery of the radio emission from them. But after this, a simple study of the polarization characteristics of just one very strong pulsar (Vela) revealed a remarkable resemblance to the case of Jupiter, barring the differences in rotational period, duty cycle and inclinations of the magnetic dipole to the line of sight and the rotational axis. It may be noted that even if the intensity of the radiation had been constant with time, the polarization would have revealed the period of rotation. But the observed short duty cycle combined with the rapid sweep of the polarization-position angle led to the association of the radio emitting region with the field close to the magnetic pole of the neutron star.

The observations on Vela suggested a simple dipole for the form of the magnetic field, and comparison of observations at different frequencies suggested that there was no internal Faraday rotation in the pulsar magnetosphere. *If there had been any, the amount of Faraday Rotation would have varied with the aspect of the neutron star, and the sweeps of the linear polarization across the pulse at different frequencies could not have been perfectly matched by interstellar Faraday rotation.*

This absence of internal Faraday rotation provided a strong motivation for a one-to-one correspondence between the instantaneous plane of polarization at any given longitude within the pulse window and the projection of the magnetic dipole. Bearing in mind the enormous strength of the expected magnetic field, and the almost 100% polarization of Vela (much greater than expected for synchrotron radiation), an attractive candidate for the emission mechanism was radiation by relativistic particles due to the acceleration associated with their moving along the curved field lines emanating from the polar region. This was the first time in any context that such a radiation mechanism had been considered—because of the super strong magnetic fields expected—and it is now widely referred to as 'curvature' radiation. The coherence required to account for the high brightness temperatures estimated was glossed over, but formed the subject of subsequent discussion by a number of authors over the years beginning with Komesaroff (1970). It was many years before it was pointed out, as discussed by Melrose in 1980 at Bonn and again at this meeting, that there exist fundamental theoretical objections to the very possibility of *coherent* curvature radiation.

It should perhaps be clarified that these theoretical objections should not be misunderstood to mean that charged bunches moving along curved field lines (and held together artificially) will not coherently produce curvature radiation. The objection in the theorists' language, is to the assumption that an 'instability' exists which can lead to self-sustaining charge distributions of the required kind along the field lines. And the basis for the objection is the demonstration that such an instability is less than likely (Blandford 1975, Melrose 1981).

In the early observations, the polarization referred to is that of the average pulse. The enormous body of observations now available on the polarization of dozens of pulsars and particularly studies of individual pulse sequences show that the story is far from this simple, but it is remarkable how much progress was made based on this picture. I shall summarize the possible implications further on.

Subsequent developments

Everything we have learned about pulsars from the study of their average linear polarization assumed that the radiation was due to the acceleration associated with highly relativistic charges moving along the curved polar field lines, or had similar characteristics. If this were indeed so, then all of the radio radiation should have been highly linearly polarized and the sweep of the position angle should always follow the 'S' type of curve derived on the assumption of a dipole field. If the field were distorted due to the presence of higher order components, or sweeping back due to rotation, it would have deviations in it from the calculated curve; but the radiation would still be highly linearly polarized, and in particular, any given longitude would be uniquely associated with a given position angle. In fact, studies particularly of individual pulses have indicated otherwise almost from the earliest pulsar polarization observations. To sum up what I would call the most serious discrepancies from the simple picture, (a) the percentage of the linear polarization could change all the way from 0 to 100% across the pulse, (b) many pulsars showed a significant amount of circular polarization towards the middle part of the pulse, and worst of all (c) a given longitude on the pulse profile could be associated with widely different position angles of the linear polarization. This was a bit rough and took us back to square one, particularly item (c) which appeared to be direct observational evidence that the plane of polarization was in some sense independent of the direction of the magnetic field in the radiating region. And this despite the fact that we are dealing with a magnetic field whose strength is so great that no conceivable plasma could distort it near the surface in any way, and whose source (for example, currents in the superconducting core) could not conceivably vary over the time scales we are discussing. Consequently, these unquestionable observations of the flippancy in the polarization behavior must find an explanation in the workings of the plasma even when confined in a superstrong and static magnetic field of simple configuration.

This diversity of polarization behavior appeared at first to be a hopeless jungle. Careful investigations by Backer, Rankin and others have, however, vastly improved the situation. The classification of pulsar behavior achieved by Rankin in a series of papers devoted to this exercise shows considerable order and provides a possible basis for the meeting of theory with observations. The breakthroughs relevant in this context are (a) the identification of core and conal emission with different spectral and polarization characteristics, and the recognition of (b) the existence of orthogonal modes of linear polarization, and (c) the association of circular polarization, of the kind seen in many pulsars which changes sign in midpulse, with core radiation encountered in more central cuts of the line of sight through the magnetic polar regions.

By orthogonal modes is meant the possibility that at any given longitude the plane of polarization can be one of two perpendicular or nearly perpendicular states, the operative one at any instant being governed by some variability as yet not understood. This explains many things; sharp jumps in the polarization sweep pattern are merely the manifestation of the operation of the orthogonal mode in some regions of the pulse window. The existence of both modes at the same time, or rapid transitions between them, will lead to a reduction in the percentage polarization all the way down to nearly zero, as seen in many cases.

If these two modes correspond to planes of polarization which are either parallel or perpendicular to the direction of the magnetic field, this restores the intimate connection between the direction of the polarization and the magnetic field. But any acceptable theory for the emission mechanisms of pulsars must allow for the existence of these orthogonal modes of linear polarization. In fact, the origin of these modes and also that of the circular polarization must be explained. We have heard several such attempts in this meeting, but I suspect that the last word has yet to be said on this matter.

Summary (hopefully of use for future reference)

The following series of statements are summaries of various aspects as I see them. The format is intended to make it easy to agree or disagree with the views expressed on specific items or issues, and

I would like to think that the progress made in the next five or ten years when pulsar researchers meet again can be measured by the number of these statements that have been explained, corrected, refuted, *etc.*, *i.e.*, are no longer valid in their present form.

Observed *vs.* expected characteristics

1. The extraordinary diversity of polarization behavior observed in a large number of pulsars to date stands in violent contrast to the simple and systematic pattern seen in Vela and interpreted in terms of a rudimentary model for its magnetospheric structure and its emission mechanism. The crisis today, over twenty years later, is that theory has produced nothing more *useful* to compare observations with in order to interpret them. This reflects the immense difficulties experienced in producing models which satisfy electrodynamics and resemble pulsars at the same time. As a result most current work on theories of the radiation mechanism is at the global model stage and far from local modelling where detailed comparison with either stationary or non-stationary phenomena can be made. Ruderman and co-workers are exceptional in that their work has come closest to enabling comparison of observations and theory. An important corollary (which runs counter to some remarks made at the colloquium) is that more and more detailed radio observations are NOT what is needed to help with theoretical modelling.

2. The study of single pulses, subpulses and micro-structure has shown that more than one position angle, ellipticity and percentage of polarization can be associated with any particular longitude within the pulse window.

3. In the picture of curvature radiation close to the polar cap, the polarization expected is pure linear for highly relativistic particles, or bunches of them. For low values of the γ of the particles (or bunches) one would expect a slight decrease in the percentage of the linear polarization due to smearing, and also the presence of sign-changing circular polarization correlated with the sense of the linear polarization-angle sweep as discussed by Radhakrishnan and Rankin (1990), henceforth RR. But the presence at the same longitude of clearly different position angles for the linear polarization has no place whatever in this scenario. The shock delivered to the 'fundamentalist believers' by the widespread existence of such other allowed polarization angles was strangely, however, softened by Backer and Rankin's (1980) discovery that the polarization angles tended to differ by the maximum (!) possible extent, namely 90°. This enabled them to allow easily for the so called 'orthogonal' flips and restore the sanctity of the 'S' curves so useful in determining impact parameters, angles of inclination of the magnetic dipole, *etc.* It also encouraged a back-to-the-womb slumber for those who were not kept awake by the problem of producing radiation with the electric vector perpendicular to the field lines in a region where the particles are all in their lowest Landau levels.

4. The above has serious consequences. In models where both modes of polarization are *generated* in the inner magnetosphere, as in that of the Lebedev group (Beskin, Gurevich, and Istomin 1988a), an electromagnetic wave with its electric field perpendicular to the magnetic field of the star must be created in a region where the permitted motion of the plasma is only along the field lines! (My best attempt to visualize this is in terms of the distribution and motion of charge patterns along neighboring field lines conspiring to create 'transverse' electric fields.) Visualizations apart, if such 'orthogonal' radiation can in fact be generated, then the observed average linear polarization sweeps, complete with flips, are accounted for in this model, leaving the interpretation of the S curves in terms of the projected field lines exactly the same as in the curvature radiation model.

5. In the Georgian model (Kazbegi, Machabeli, and Melikidze 1992a) this difficulty is avoided by generating the radiation further out in the magnetosphere where the field has become weak enough to allow gyration of the particles around the field line, *i.e.*, transverse motions. In the Australian model (Rowe 1992) the accent has been on obtaining the required coherence to match the observed brightness temperatures and no mention is made of the expected polarization characteristics.

6. There is no reason why polarization-angle sweeps could not have other explanations—as in the Georgian model—than in terms of the field configuration close to the polar cap. But it is hard to believe that in this model (where the radiation occurs in a region where the field is weak enough to allow transverse motion of the particles, and hence where sweep back must be significant) the polarization patterns can be matched as nicely as with different impact parameters close to the magnetic pole.

7. It was reported at this meeting that millisecond pulsars have brought no significant surprises or new clues in their polarization behavior. This may mean that the high spin rates are compensating the very low field strengths to create similar conditions

in the magnetosphere. But the enormous reduction in the light cylinder distance will surely increase sweepback effects, and lower frequency observations should show evidence of this.

8. It would appear from the foregoing that any theoretically acceptable radiation mechanism for pulsars would have to mimic curvature radiation in its average polarization properties in so far as to reflect the geometry of the star's magnetic field close to but at increasing distances from the polar cap for lower frequencies of observation.

Dipole interpretations

9. Disregarding these difficulties, literal interpretation by observers of the polarization-angle sweep (corrected for orthogonal modes) in terms of the projection of the field lines in the radiating region has become more (not less) widespread over the years. It has been used to determine impact parameters, dipole inclination angles, radius-to-frequency mapping, and to resolve the question of whether an interpulse is associated with the same or opposite magnetic pole as the main pulse.

10. The ability to estimate the dipole inclination angles provides an interesting constraint on theories of the evolution of the magnetic field. Debate continues to rage on whether the field decays with pulsar age or, for example, aligns itself with the rotational axis. Polarization measurements give us no clue as to the strength of the magnetic field, but as I just said they can tell you about alignment. And as we heard from Bhattacharya (1992) earlier in this conference, there is observational evidence *against* a decay of $\sin\alpha$ in timescales $\lesssim 10^8$ yr.

11. Two extreme examples of the literal interpretation of the polarization-angle sweep are its applications by Lyne and Manchester (1988) to conclude that only parts of the polar cap (patches) are operative in many pulsars, and by Cordes (1992) in estimating the altitude of the emission region by allowing for the minute amounts of sweep back of the field lines expected at that altitude. These applications rely heavily on the assumption of a truly dipolar field; the presence of small amounts of multipolar components at low altitudes could lead to a misinterpretation. See below.

Non-dipolar fields

12. We know that "patchiness" of some sort *MUST* exist from the evidence of (a) single pulses which vary considerably from the average pulse, and (b) the fact that average profiles of pulsars are distinguishable one from the other by asymmetries and other characteristics not explicable in terms of the impact parameter alone. This coding which determines the FACE of each pulsar must be stored in some manner on or near the polar cap of the neutron star. My considered opinion is that it must be field irregularities over the polar cap at low altitudes which affect the average production of particles which flow out from that region. Such higher order components of the field are in fact a vital ingredient in the model of Ruderman and Sutherland (1975).

13. An observational test would be to find less kinkiness in the polarization-angle sweep at lower frequencies if they are generated farther from the surface. This may be discernible in spite of the sweep back effects which should be more pronounced at lower frequencies as the latter will only cause a SMOOTH deviation from a strict dipolar geometry.

14. Rankin (1990) has emphasized that the polarization angle behavior of core components is disorderly, meaning that the position-angle curves cannot be interpreted in terms of a single vector model. As core radiation is believed to come from close to the polar cap, low-altitude field irregularities would be the most natural explanation for this behavior.

15. Mode changing observed in many pulsars is the sudden change from one average intensity distribution over the polar cap to another. The long term stability of each of these individual intensity patterns when operative, and their distinctness from each other, require the pattern details to be stored somewhere permanently. Low-altitude deviations from dipole field geometry again appear to be the most likely way of doing this. Small changes in the polarization-sweep curves for the two modes noted in a few cases could then be explained as due to changes in the emphasis of the local field geometry over different parts of the polar cap.

16. The very fine analysis by Krishnamohan and Downes (1983) of the radiation from Vela showed that, even in this case where the pulsar was the archetype, there were clear deviations from a strict dipole geometry. They reconciled their observations with a simple dipole by postulating that the emission 'components' in different longitude ranges within the pulse window originated at different altitudes where the field lines would diverge by different amounts. I suggest the alternative explanation that at their high frequency of observation (2.3 GHz) all the radiation comes from (the same) low altitude,

and that the deviations are due to small multipole contributions to the field geometry close to the surface.

17. In the cases of interpulses arising from opposite magnetic poles in a near perpendicular rotator, deviations from a strict 180° separation of the main and interpulse have always been suggestive of the presence of non-dipolar components of the field. If so, here again, I would expect the separation of the pulses at lower frequencies to deviate less from 180° than those at higher frequencies. In the Lyne and Manchester (1988) picture, some (or all) of the deviation from 180° would be ascribable to non-symmetric patches on the opposite polar caps; Lyne drew my attention to one case where the partial polarization-angle sweeps in the main and interpulses support this interpretation.

Rapid changes

18. Sieber rightly regretted the lack of attention at this meeting to short time-scale phenomena and suggested that their study might be important for understanding the radiation mechanism. What is observed is tremendous variability in the total intensities and in the polarization behavior as a function of both time and longitude. It is reasonable to assume that there must be variability in the particle production process itself, but its relation to the generation of radio emission and the polarization properties thereof are still as much of a mystery as they have always been. The difficulties are the separation of polarization properties into those related to the emission mechanism and those due to modifications in propagation through the magnetosphere, and in knowing whether the non-stationary behavior is telling us about the emission or propagation mechanisms.

19. The average profile washes out all sorts of apparently interesting variations of polarization associated with micro-pulses, sub-pulses and single-pulses, but leaves us with something that has the great virtue of repeatability and hence warranting interpretation in terms of (near) permanent attributes of the particular pulsar. And as mentioned earlier this can be interpreted as the field configuration in the radiating region.

Propagation effects

20. The rapid swings of polarization-position angle often seen associated with subpulses and micropulses clearly cannot reflect the field configuration but must be associated with either the emission or propagation processes. A very natural interpretation would be dispersion in the anisotropic magnetosphere of the 'wide' frequency bands associated with 'narrow' time-scales of the duration of the radiation. A study of the senses of the sweeps and the range of polarization state change and their possible correlation with the time duration of the feature would be a way to investigate their origin. A propagation origin for such rapid polarization changes would show a frequency dependence that one would not expect in models such as those invoking the passage of the line of sight across the radiation cones associated with the motion of single bunches or charge sheets.

21. An alternative (to *e.g.* §4) possible explanation for the orthogonal linear mode is also in terms of a propagation origin, assuming that the radiation is generated with its electric field strictly parallel to the field lines. Cheng and Ruderman (1979) have discussed this possibility in detail in connection with 'adiabatic walking'. In passing through the outer magnetosphere where retardation and sweep back have introduced (at least) a slight inclination of the local magnetic field with respect to the electric vector, conversion of some fraction of the energy to the orthogonal linear mode will be possible. The two allowed modes into which the incident radiation is split will be orthogonal to each other, but the combination should be tilted somewhat with respect to the field lines in the region of origin of the radiation. As the presence and degree of such conversion could well be a function of longitude, this could lead to distortions of the sweep curve as measured over the whole pulse window.

22. Given the possibility of mode conversion mentioned above, one may draw two other conclusions. If the delay introduced between the two modes before escaping the magnetosphere is less than the effective coherence time of the radiation under study, they can recombine to form some general elliptic polarization. On the other hand, if the introduced delay is much longer, this will result in a depolarization of the radiation. This would be maximal for equal strengths in the two orthogonal modes and proportionately less otherwise. Note that this is somewhat different from the usual explanation for the depolarization of the linear, which is either *radiation* of two incoherent orthogonal modes, or a rapid flipping back and forth between the two modes which gets averaged out in the observations.

23. As in the case of emission mechanisms, theoretical attempts to model propagation effects have provided nothing readily usable to compare with

available observations or to guide the planning of future ones. The difficulty again lies in the immensity of the exercise involved and the assumptions that have to be made regarding the content of the magnetosphere (see for example Barnard and Arons 1986).

Circular polarization

24. Based on considerations of the field geometry in the propagation region such as discussed in §20 and §21 above, RR have proposed that symmetric (non sign-changing) circular polarization could well be a propagation effect, whereas the sign-changing variety is most likely a radiation characteristic of low γ bunches moving along the curved field lines at low altitudes. Some counter-examples to the linear-circular signature correlation on which this was based were presented late in the colloquium. If these are confirmed, a possible explanation could be in terms of low γ particles (or bunches) moving not along the gently curved field lines of a dipole as assumed by RR but along more sharply and randomly curved field lines close to the polar cap as suggested in §14.

25. Note however that any explanation such as §24 of the circular polarization, not to mention that for the widely accepted linear polarization sweeps, requires a high degree of coherence to account for the intensities and therefore violates the theoretical arguments (and proofs) cited by Melrose (1992) against the possibility of coherence in curvature radiation. A satisfactory explanation must be based on an emission mechanism which will both mimic the polarization characteristics of curvature radiation as mentioned in §8, and also be backed by a proof of the existence of the instability required to build up the coherence to the degree seen in pulsar radiation.

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