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A NEW MODEL FOR THE EMISSION GEOMETRY IN PSR 0950+08

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ABSTRACT

We propose that the angle between the magnetic and rotation axes in PSR 0950+08 is small, that the hollow radiation beam is highly elongated in the north-south direction (referred to the rotation axis) and extends beyond the rotation pole, and that the line of sight to Earth, which passes between the magnetic and rotation axes, intersects the same beam twice, on either side of the rotation pole, to produce the main and interpulse. The model fits the observed polarization angle variation well and explains most of the puzzling features noted in the interpulse. The geometry is distinctly different from that commonly invoked for double component pulsars.

Subject headings: pulsars — radiation mechanisms

I. INTRODUCTION

The radio pulsar PSR 0950+08 has an interpulse emission with many puzzling features which cannot be explained by current models. The bridge of emission between the main and interpulse (Hankins and Cordes 1981, hereafter HC) with a monotonic polarization angle variation (HC; Rankin and Benson 1981) rules out a two-pole model. However, the alternative hollow cone single-pole model of interpulses (Manchester and Lyne 1977) runs into difficulties over the marked asymmetry in many properties between the main and interpulse as well as the remarkable frequency independence of their separation (HC). HC have discussed the pros and cons of various possible models for this pulsar and argue that modified single-pole models, with nearly aligned magnetic and rotation axes, are the most promising candidates. We present here a single-pole model with certain novel features. The beam is much elongated along the meridian and straddles the rotation pole. Consequently, the line of sight intersects the same beam twice, at different offsets from the magnetic pole. Our model is in better agreement with polarization angle observations than other models. It also naturally explains the many apparently conflicting observations discussed above. If our model is correct, it gives new insight into the shape of pulsar beams, which could lead to a better understanding of pulsar physics.

II. THE MODEL

The model we present here for PSR 0950+08 is the result of our attempt to fit the excellent 430 MHz polarization angle variation observations of Backer and Rankin (1980). Their presentation of the data in the form of a histogram enables us to avoid complications from orthogonal radiation modes (Manchester, Taylor, and Huguenin 1975; Backer, Rankin, and Campbell 1976). Figure 1 shows the variation of the mean polarization angle θ with pulse longitude φ in one of the orthogonal modes in the main pulse and the interpulse.

We assume that the pulsar emission occurs above the magnetic poles of a rotating neutron star and that the polarization of the radio radiation reflects the orientation of the magnetic field at the point of emission (Radhakrishnan and Cooke 1969). We further assume that the magnetic field pattern is purely radial when projected on a plane perpendicular to the magnetic axis (as for a magnetic dipole). Backer and Rankin (1980) argue that there is strong evidence in their polarization data for the validity of these assumptions. We also assume that the pulsar emission at each frequency occurs at a constant height above the magnetic poles in a region well inside the light cylinder. This "radius-to-frequency" mapping of pulsar emission (Komesaroff 1970; Cordes 1978) simplifies the emission geometry by restricting it to two dimensions and also avoids complications from differential aberrations and time delays. However, a recent study by Björnsson (1982) highlights the fact that three-dimensional pulse emission geometries are also possible.

Let α be the angle between the magnetic and rotation axes and β the angle between the line of sight to Earth and the rotation axis. Also, let θ_0 be the position angle in the sky of the projected direction of the pulsar rotation axis and φ_0 the pulse longitude at which the line of sight comes closest to the magnetic pole. The variation of the polarization position angle θ with pulse longitude φ in the Radhakrishnan-Cooke model is then given by (Manchester and Taylor 1977, eq. [10–24]).

$$\tan(\theta-\theta_0)=\frac{\sin\alpha\sin(\varphi-\varphi_0)}{\cos\alpha\sin\beta-\sin\alpha\cos\beta\cos(\varphi-\varphi_0)}. \tag{1}$$

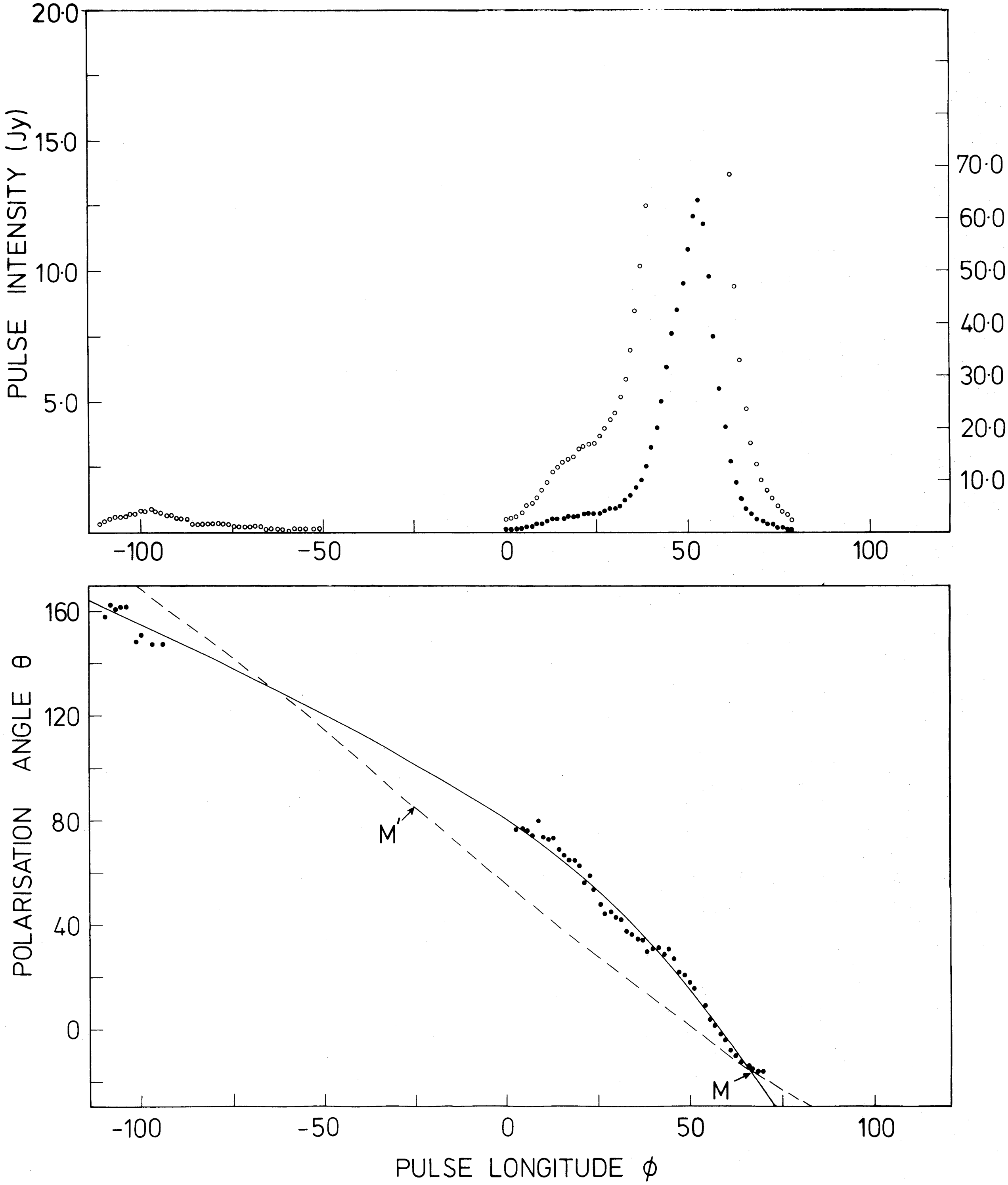

FIG. 1.—Least squares fit of the polarization angle variation across the main and interpulse of PSR 0950+08. The filled circles are mean polarization angles calculated from the detailed experimental results of Backer and Rankin (1980). The solid line is obtained with $\alpha = 10°$, $\beta = 5°$, M being the point of closest approach to the magnetic pole. The rms misfit in polarization angle is 3°.8. The dashed line, which corresponds to the best fit hollow cone model with $\alpha = 30°$, $\beta = 5°$ and magnetic pole at M′, is seen to be a distinctly poorer fit. For comparison the integrated pulse profile is also shown.

We have made a least squares fit of the data in Figure 1 to a polarization angle variation of the above form by simultaneously optimizing the four unknown parameters α, β, φ_0, and θ_0. The solid line shows the fit corresponding to the best model, with $\alpha = 10°$, $\beta = 5°$. The point M represents the closest approach to the magnetic pole and corresponds to (φ_0, θ_0). We note two key features of this model: (*a*) Since both α and β are small, the line of sight is always close to one magnetic pole; it is therefore a single pole model with nearly aligned rotation and magnetic axes, as anticipated by HC. (*b*) The point M lies within the main pulse; hence the geometry, which is discussed in greater detail below, is quite different from the hollow cone model of interpulses (Manchester and Lyne 1977), where M should lie midway between the main and interpulse. We find that the least squares fit is very sensitive to the ratio β/α, fairly sensitive to the location of M (φ_0 could be moved a few degrees on either side provided θ_0 was also suitably adjusted) and quite insensitive to the value of α (which can lie between $0°$ and $\sim 25°$). The fit with the hollow cone model is found to be poor for all combinations of parameters tried. The dashed curve in Figure 1 shows one of the better hollow cone models with $\alpha = 30°$, $\beta = 5°$, and (φ_0, θ_0) corresponding to M′.

Figure 2 shows the geometry of the beam in our best fit model of PSR 0950+08 as viewed down the rotation axis. The main and interpulse are indicated by thick lines on the line-of-sight circle. A qualitative argument shows that this model is consistent with the polarization data. Narayan and Vivekanand (1982) have demonstrated that a monotonic polarization angle variation of the type shown in Figure 1 with no reversal in the sign of the slope implies that the line of sight must pass between the rotation and magnetic axes. Further, equation (1) shows that the derivative $|d\theta/d\varphi|$ attains its maximum value at the closest approach of the line of sight to the magnetic axis and vice versa. Although the polarization data of PSR 0950+08 shown in Figure 1 are unclear in this regard, the observations of Rankin and Benson (1981) for the same pulsar show rather unambiguously that $|d\theta/d\varphi|$ is larger in the main pulse than in the interpulse. Hence the locations of the main and interpulse on the line-of-sight circle are determined. In short, given our assumptions, the qualitative features of the geometry shown in Figure 2 are plausible even without having to do a least squares fit. We still have the freedom to draw the shape of the beam. To our mind, the most natural way to arrange the beam is to center it on the magnetic axis and elongate it in the "north-south" direction (north is defined with respect to the rotation axis) so that it extends well beyond the rotation pole and crosses the line of sight on the other side to make the interpulse. The dashed line in Figure 2 shows a possible beam outline. Since the outer extremities of the main and interpulse have been selected to have the same

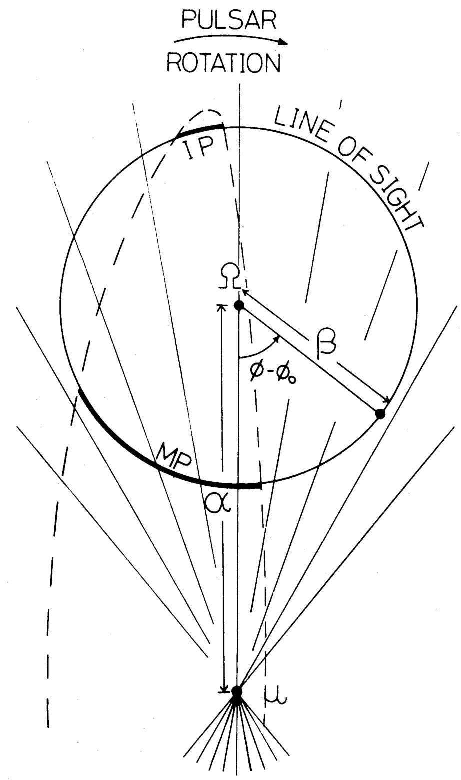

FIG. 2.—Proposed geometry of PSR 0950+08 projected down the rotation axis. The figure is to scale and shows the relative projected positions of the rotation axis Ω, the magnetic axis μ, the main pulse MP, and the interpulse IP, corresponding to the least squares fit of Fig. 1. The magnetic field lines are great circles but have been represented as radial straight lines. The dashed line is our suggestion for the shape (constant intensity contour) of the beam. Note the extreme elongation in the north-south direction.

intensity (~ 0.6 Jy at 430 MHz), this may be considered a constant power contour. We note that the north-south dimension of the beam is more than 5 times larger than the east-west dimension.

Apart from fitting the polarization observations, the above model explains many of the other puzzling features noted in PSR 0950+08. (*a*) The pronounced difference in intensity between the main and interpulse can be explained as arising because the main pulse is much closer to the magnetic pole. (There is some observational evidence, e.g., Narayan and Vivekanand 1982, 1983, that, apart from the hollow portion of the pulsar beam, the radio intensity falls off monotonically with increasing latitude offset between the line of sight and the magnetic pole.) Also, the splitting of the main pulse into two components at low frequencies (HC) can be explained by invoking an elliptic hollow conical beam with a frequency dependent size. The interpulse, being a peripheral cut of the beam, is not expected to bifurcate. (*b*) The main and interpulse half-power widths as well as the separation of the main pulse components could have frequency dependence, for example due to radius to frequency mapping (Komesaroff 1970; Cordes 1978). However, the main-to-interpulse separation is expected to be frequency-independent in our model as it is a geometrical quantity (see Fig. 2). This is in accord with observations (HC). (*c*) The bridge of emission between the main and interpulse with a monotonic polarization angle variation (HC; Rankin and Benson 1981) is natural since, as Figure 2 shows, the line of sight is always close to the beam. The bridge is expected to be stronger between the main pulse and the previous interpulse than the postinterpulse (in conformity with the observations of HC). (*d*) The similarity of microstructure morphology (Hankins and Boriakoff 1981) and the correlation of pulse intensities between the main and interpulse (HC) are consistent with our single pole model. The fact that the intensity of the interpulse follows the main pulse and not vice versa might mean that changes take place first near the center of the beam and then propagate outward. (*e*) The anomalously large width of the main pulse (78°) is consistent with the polar line of sight (small values of α and β).

The model does not automatically explain the 155° spacing between the main and interpulse. The beam has to be displaced to one side of the magnetic pole as in Figure 2. This rather unnatural feature may be caused by obscuration of part of the beam on one side. It could also occur due to sweep back of the magnetic field lines as the pulsar rotates, though in this case the analysis becomes complicated since the location at which radiation is sampled no longer follows the circular line-of-sight curve of Figure 2. We note in this connection that if we relax the assumption of radius-to-frequency mapping, then the 155° spacing can be explained by a time delay due to the interpulse radiation being emitted from closer to the neutron star. The altitude differential needed is $0.44 r_L$, where r_L is the light cylinder radius. This is only a small fraction of the distance from the neutron star surface to the light cylinder along the line-of-sight direction, which is $11.5 r_L$ for $\beta = 5°$.

III. DISCUSSION

The least squares fit we have made of the polarization angle variation in PSR 0950+08 is based on the Radhakrishnan-Cooke model coupled with radius-to-frequency mapping. Although the evidence so far seems to be in favor of this picture, this limitation should be kept in mind. If some of our assumptions are relaxed, the variation of polarization angle with pulse longitude may cease to be of the form (1), and it is not clear how the results will change. The case for a nearly aligned rotator model is probably still strong, but the shape and location of the beam in Figure 2 may possibly change. However, we note that our model does not rely solely on the polarization observations. Since it explains most of the other puzzling observations as well, we feel it must be correct in many of its details. If so, there are some important implications for our understanding of pulsars in general.

The most striking feature of the model is the large elongation of the beam. By means of least squares fits on other polarization angle observations, Narayan and Vivekanand (1982) estimated large values for the latitude offset $|\alpha - \beta|$ in several pulsars. This might imply that elongated beams are the rule rather than the exception. There is further support for this in a statistical study of the total polarization angle swing in pulsars (Narayan and Vivekanand 1983; see also Jones 1980). However, current theories of pulsar electrodynamics (based on the polar cap model) conventionally assume circular or near-circular beams. It is not clear how these theories can be reconciled with the large elongation we propose in PSR 0950+08 (it should be noted that the elongation ratio, which is > 5 in our model, is determined essentially by β/α and is very tightly constrained by the least squares fit). In many pulsar theories, the beam dimensions are determined by the last "closed" magnetic-field lines (Goldreich and Julian 1969). For pulsars with aligned magnetic and rotation axes (our model is a nearly aligned case), the beam cross section should be circular while for "orthogonal" pulsars it should be elongated (in the *east-west direction*!). Nondipole magnetic field configurations might possibly explain the beam shape. Barnard and Arons (1982) included quadrupole field configurations and found that pulsar beams are elliptical in general. However, since the beams seem to be always elongated in the north-south direction (Jones 1980; Narayan and Vivekanand 1982, 1983), this would require a preferred orientation for the quadrupole axis with respect to the rotation and dipole axes, and it is not clear why it should be so.

The beam in our model extends on either side of the rotation pole and intersects the line of sight at nearly diametrically opposite regions. This unusual geometry would be rather unnatural in the light cylinder model of pulsar emission (e.g., Smith 1977).

For the first time we have a pulsar where the line of sight intersects the same beam at two different distances from the magnetic pole. We find further confirmation that the radio intensity falls away with increasing line of sight offset from the magnetic pole along the meridian and that nearer cuts give double component pulses while farther cuts give only a single component.

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