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TOWARD AN EMPIRICAL THEORY OF PULSAR EMISSION. V. ON THE CIRCULAR POLARIZATION IN PULSAR RADIATION

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ABSTRACT

We have examined the circular polarization associated with pulsar emission phenomenologically. Virtually all circular polarization is observed in *core* components—that is, in core-single (S_t) profiles and in the central components of triple (T) and five-component (M) profiles. Two extreme types of circular signature are identified in the observations: (*a*) an antisymmetric type wherein the circular polarization changes sense in midpulse, and (*b*) a symmetric type wherein it is predominantly of one sense.

We find that circular polarization of the antisymmetric type is strongly correlated with the sense of rotation of the linear position angle. Transitions from positive (LH) to negative (RH) are found to accompany negative (clockwise) rotations of the position angle and vice versa.

In the general framework of models in which the radio power is curvature radiation emitted by charge bunches constrained to follow field lines, the linear polarization is intrinsic to the emission mechanism and is, furthermore, a purely geometric property independent of the polarity of the magnetic field or of the sign of the charges. The correlation we find then requires that the antisymmetric circular polarization is also a purely geometric property of the emission process. Curvature radiation will have significant net circular polarization if there are gradients in the emissivity over angular scales comparable with the emission cone of a single charge (i.e., γ^{-1}, where γ is the Lorentz factor of a charge bunch). The observation of significant circular polarization therefore implies that $\gamma < 20$ for the core emission. Furthermore, no net circular polarization is produced if the emissivity is circularly symmetric about the magnetic dipole axis. The sign of the correlation we have discovered is consistent with an emission region more extended in longitude than in latitude (referred to the rotation axis).

Subject headings: polarization — pulsars

I. INTRODUCTION

Within the apparently overwhelming diversity of the polarization behavior of pulsars, there are characteristic features or "signatures" which provide both clues and constraints for models of the radio emission mechanism. The earliest such signature to be recognized was a smooth rotation of the plane of linear polarization through the pulse of 180° or less. Its interpretation led to a simple and widely accepted model for the radio emission (Radhakrishnan and Cooke 1969; Komesaroff 1970)—namely, that it was curvature radiation by the ultrarelativistic particles streaming from the magnetic polar-cap regions of a rotating neutron star. Vela was the archetype of this model, because the integrated pattern of its highly linearly polarized, but simple pulse shape had great stability. In many of the major attempts at pulsar theory that followed (e.g., Sturrock 1971; Ruderman and Sutherland 1975), other aspects like pair production, coherence of the radiation and its temporal variability, pulsar lifetime, etc., were addressed and modeled, but the polarization sweep, and curvature radiation as the emission mechanism, were taken over intact from the simple polar-cap model.

If the radio emission mechanism were indeed curvature radiation due to ultrarelativistic particles streaming along the strong magnetic field lines, the polarization position angle should vary monotonically in a sort of " S " curve given by the model and observed in many pulsars studied to date. Further, the radiation should be almost totally linearly polarized as it is in Vela. However, there is no room in this picture for substantial amounts of unpolarized radiation, for circular polarization, or for sudden jumps in the position angle. All these have been observed in pulsars since their discovery, as also variations in the number and shape of pulse components. It was an attempt to systematize this extraordinary diversity observed in pulse profiles which was the basis for Rankin's empirical approach (1983*a*, *b*, 1986), which in turn led to the identification of a number of pulse characteristics that were not at all, or poorly, appreciated before. Among these were the recognition of core and conal components whose properties differed from each other and whose presence in a given pulsar depended both on intrinsic properties of the pulsar and on viewing geometry. In particular, it is with core emission that (*a*) the presence of circular polarization and (*b*) rapid transitions of the position angle[1] are associated.

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[1] Evidence is accumulating to the effect that the two "orthogonal" polarization modes correspond to the respective core and conal types of emission. The rapid, about 90° transitions (Backer and Rankin 1980; Stinebring *et al.* 1984) in the polarization angle are then due to changes in the dominance of the core and conal emission. Often these transitions were found to be associated with the *conal* components of triple and multiple profiles, and therefore they were viewed as a characteristic of conal emission. Pulsars with stronger core emission, however, exhibit modal transitions closer to the center of the profile (pulsar 0329+54 is such an example [Bartel *et al.* 1982] as is 1604−00 in Rankin 1988). Core and conal emission thus appear to be orthogonally polarized, a position also advocated by Gil (1986).

From a study of a large number of pulsars, Backer and Rankin (1980) were able to show that when allowance was made for the (very nearly) orthogonal position angle jumps, the "sweep" of the position angle corresponded precisely with that expected from the magnetic pole curvature radiation model. This restored the intimate connection between the polarization position angles and the directions of the projected polar field lines. But it also established that pulsars could, if they pleased, radiate waves with the electric vector *perpendicular* to the projected magnetic field direction, although all charges in the strong field region near the star are restricted to move only *along* the field lines! To deal with this, and other "aberrations" from the type of polarization behavior exemplified by Vela but found in very few other pulsars, Cheng and Ruderman (1977) proposed "adiabatic walking" as the explanation. The emitted polarization is modified in passing through the magnetoactive plasma, and this propagation effect was suggested as a universal recipe to explain the whole variety of polarizations observed. Spatial and temporal variations of the plasma density in the outer regions of the magnetosphere could, in principle, give rise to all the variations seen in the polarization of pulsar radiation.

An alternative explanation of the 90° position angle flips is a natural outcome of a theory of pulsar radio emission by Beskin, Gurevich, and Istomin (1988), in which waves are excited in a relativistic electron-positron plasma flowing along curved magnetic field lines. Unstable curvature plasma waves grow rapidly in strength and are then transformed through nonlinear effects into two transverse electromagnetic waves which leave the magnetosphere and constitute the observed radio radiation. Their polarizations are exactly parallel and perpendicular to the projected polar magnetic field lines tangential to the line of sight. The excitation of one of these modes, the extraordinary one, is shown to require a particular combination of period and period derivative to lie in a certain range which corresponds, in fact, with the observation of strong *core* emission in such pulsars.[2] The polarization position angle flips are attributed to the excitation (or extinction) of one or another of the two modes predicted by the theory. An important point to note here is that when both emission modes are present, the resultant radiation will be partially polarized and the plane of polarization will be that of the dominant mode. This is simply the net effect of the radiation emitted at the source and not the result of propagation through the medium.

An explanation of the radio radiation and polarization characteristics of pulsars has also been attempted by Kazbegi *et al.* (1988). These authors purport to show that the mechanism proposed by Beskin, Gurevich, and Istomin is incorrect and will not work. Interestingly, however, their alternative theory which invokes cyclotron and Cherenkov resonances also predicts the two orthogonal polarization modes observed in the radiation from many pulsars. In this work, there is no mention whatever of circular polarization. The Beskin, Gurevich, and Istomin treatment, on the other hand, mentions circular polarization, but only as a modification of the linearly polarized component of the radiation in traversing the regions where cyclotron resonance can play a part. Thus, as far as circular polarization is concerned, both the Beskin, Gurevich, and Istomin theory and the adiabatic walking discussed by Cheng and Ruderman are alike in ascribing it to propagation effects in regions of the pulsar magnetosphere outside the emission regions. Before considering whether this could be a satisfactory explanation of the observational evidence, we shall discuss first the observed signatures associated with circular polarization in pulsars.

II. CIRCULAR POLARIZATION SIGNATURES

From the earliest observations, we have known that the radiation from many pulsars contains detectable circular polarization. Although the amounts were generally small and always much less than the degree of linear polarization, one of the first clear signatures to be noted (Clark and Smith 1969) was the changing of the sense, or handedness, of the circular polarization at some point within the pulse. The accumulation of detailed observations over the years has established the existence of this signature in a large fraction of pulsars which show circular polarization. When it is most clearly defined, there is a single transition from right to left, or vice versa, which takes place very close to the center of the pulse (as shown for pulsar 1859+03 in Fig. 1). In other pulsars, this signature is not as

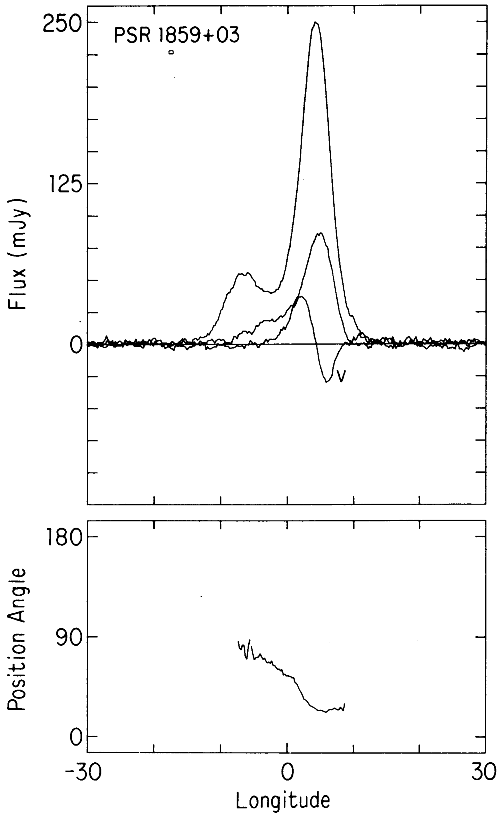

FIG. 1.—Polarization profile for pulsar 1859+03 at 1412 MHz (from Rankin, Stinebring, and Weisberg 1989). The total intensity (Stokes parameter I) is the outside curve, the total linear polarization [Stokes parameter $L = (Q^2 + U^2)^{1/2}$] the interior, positive-going curve, and the circular polarization (Stokes parameter V) the positive- and negative-going curve (labeled by a "v"). The core component provides a good example of the antisymmetric type of circular polarization. Note how the handedness changes sign near the maximum power point of the core emission. The linear polarization angle $\Phi[=\frac{1}{2}\tan^{-1}(U/Q)]$ is plotted on a separate scale in degrees and shows variation in the position angle as a function of the longitude within the pulse.

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[2] The Beskin, Gurevich, and Istomin parameter Q distinguishes strongly between the core-dominated and conal-dominated species of pulsars as discussed in Rankin (1990).

well defined, and in a very few, two transitions between senses take place within the pulse window.[3]

An extreme example of a different kind of signature is PSR 1702−19. The circular polarization reaches 60% at 408 MHz, and only right-hand circular emission occurs in both the main pulse and the recently found interpulse (Biggs *et al.* 1988). The forms of both the circular and linear polarization bear a resemblance to the total-intensity profile in that they all peak roughly in the middle of the window (see Fig. 2). The circularly polarized profile is nearly as wide as the total-intensity profile, has a single peak at its center, and falls off symmetrically to zero close to the edges of the pulse window. In those pulsars which show the sense-reversing signature, the percentage circular polarization would have been *zero* just where PSR 1702−19 has a *maximum* for this quantity.

These examples provide clear evidence for two distinctly different types of distribution of circular polarization within the pulse. If we suppose that both kinds could exist concurrently, the distorted (antisymmetric) sense-reversing signatures seen in several pulsars appear as simply due to the addition of a small amount of single-sense (symmetric) circular polarization. Such an example is shown in Figure 3. The evidence on hand thus indicates two clear signatures which probably represent extreme cases when appearing alone without any contribution from the other. We shall assume this and proceed to argue that the presence of a single sense of circular polarization (symmetric) over the whole pulse could well be due to propagation effects in the pulsar magnetosphere as discussed above, but the other kind (antisymmetric) cannot be so explained and must be the manifestation of a different kind of radiation mechanism.

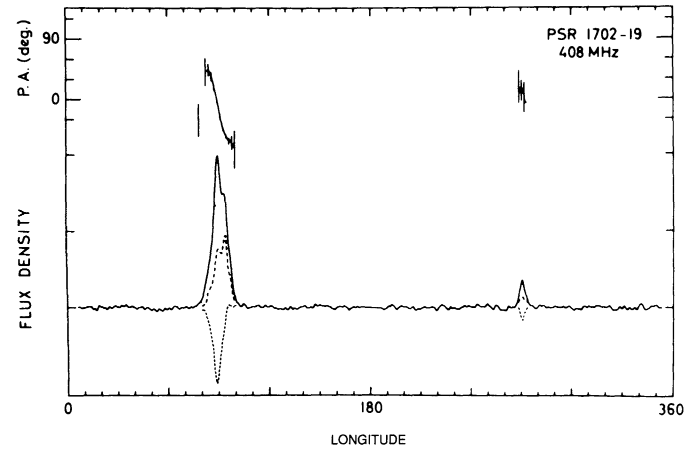

FIG. 2.—Polarization profile for pulsar 1702−19 at 408 MHz (from Biggs *et al.* 1988). The total intensity (I) is the solid curve, the total linear polarization (L) is the dashed interior curve, and the circular polarization (V) is the dotted negative-going curve. The linear polarization angle Φ is plotted on a separate scale above the others. Both the main-pulse profile and the interpulse profile provide good examples of the symmetric type of circular polarization. The fractional circular polarization of this pulsar reaches 60%.

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[3] Pulsar 1541+09 provides the only good example of two transitions of the circular polarization; the effect is observed both at 430 MHz (Rankin 1983*a*) and at 1400 MHz (Rankin, Stinebring, and Weisberg 1989). Pulsar 1839+09 in the latter paper also appears to have two transitions.

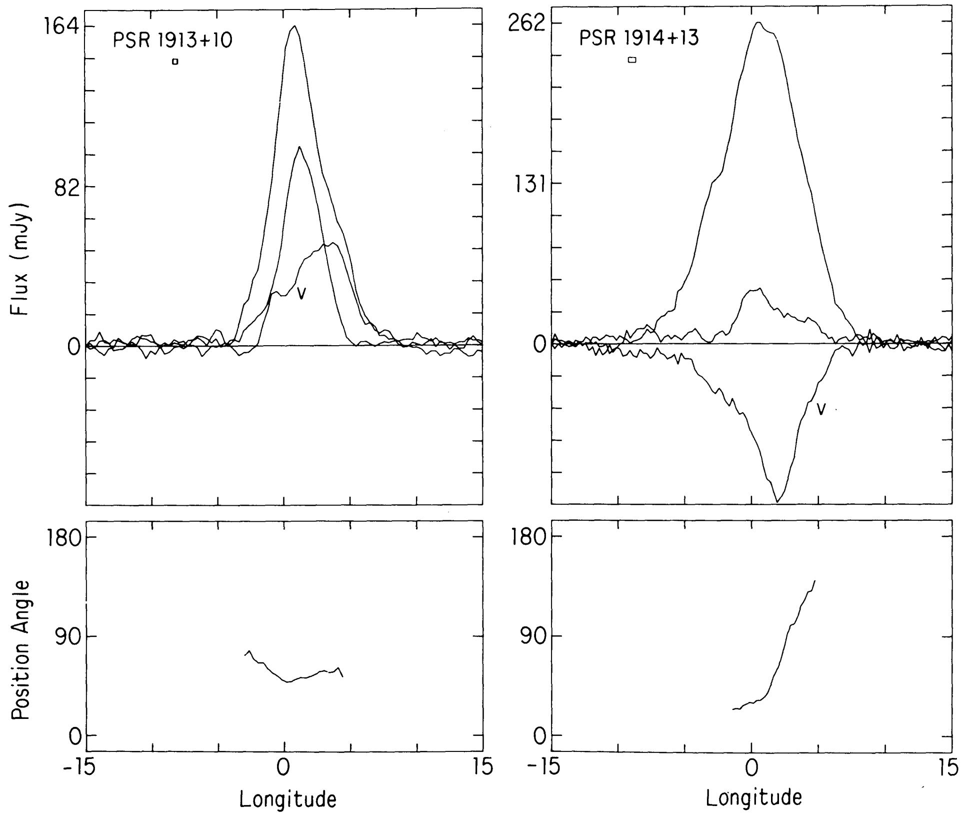

FIG. 3.—Polarization profiles (as in Fig. 1) for pulsars 1913+10 and 1914+13 at 1412 MHz (from Rankin, Stinebring, and Weisberg 1989). These stars exhibit circular signatures (curves labeled by a "v") which appear to be admixtures of both the symmetric and antisymmetric types of circular polarization.

III. PROPAGATION ORIGIN FOR CIRCULAR POLARIZATION

We shall assume that, as in the theoretical models discussed above, pulsar radiation is emitted tangentially to the field lines on which the particles are moving. We shall also assume that the radiation emitted from the source region is linearly polarized with its plane either strictly parallel, or perpendicular, to the projected magnetic field line. Figure 4 gives a simple diagram showing where the propagation effects take place—that is, beyond the source region in a volume of plasma located along the line of sight to the observer. Let us for the moment neglect both the effects of radiation travel time and also the sweepback of the open field lines as they approach the light cylinder. Then the field lines that the radiation will intersect will also lie in the plane containing the radiating field line, i.e., the plane of the paper in Figure 4. Note that this is the plane containing the magnetic dipole and the observer, regardless of the longitude of observation within the pulse window.

As seen in the diagram, the magnetic field in the propagation region will make an angle to the direction of the radio waves. This will introduce a small component of the magnetic field perpendicular to the direction of the radiation. But this component will be either precisely parallel (or perpendicular) to the electric field in the radiation, depending on which of the linear polarization modes discussed earlier is operative. Therefore, this alone does not introduce the asymmetry necessary for converting linear to circular polarization in the propagation region. It is only when radiation travel time and sweepback of the field lines is taken into account that a perpendicular component of the magnetic field at some other angle can appear and give rise to the conversion. In Figure 4, this would mean that the field lines in the propagation region do not lie in the plane of the paper, but are now inclined at some small angle to it, either coming out or going into the paper, depending on the direction of rotation of the star, and in the *same* sense at *all* longitudes within the few degrees width of the pulse. The amount of conversion will involve the strength and angle of the magnetic field and the sign and magnitude of the charge density. As Cheng and Rüderman (1979) and Beskin, Gurevich, and Istomin (1988) have pointed out, the effects of electrons and positrons in a pair plasma will not cancel each other out exactly if their energy distributions are different. They are indeed expected to differ somewhat depending on the particular sign of the electric field in the acceleration regions.[4] Variations in the charge density within the pulse window could also cause the conversion efficiency of linear to circular polarization to vary, but it seems difficult in this picture to see how the handedness of the circular polarization can change precisely at the center of the pulse. For these reasons, a propagation origin for the presence of the antisymmetic variety of circular polarization appears very unlikely. On the other hand, the (symmetric) circular polarization pattern seen in PSR 1702 − 19 appears to be just what one could expect if propagation effects were indeed responsible.

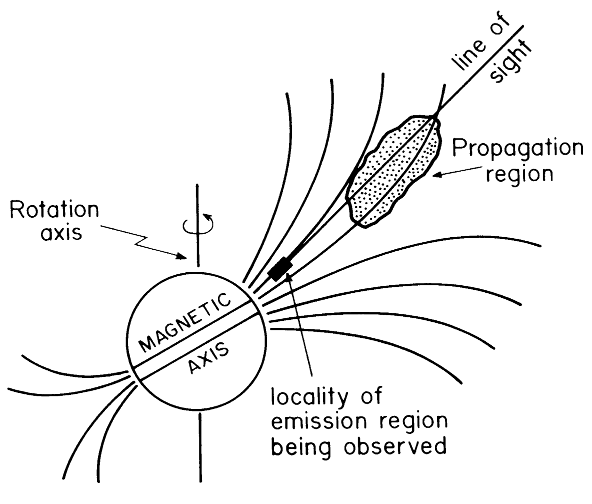

FIG. 4.—Geometry of the emission and propagation regions within the pulsar magnetosphere. Neglecting retardation and nondipolar contributions to the field, the field lines threading the emission and propagation regions will lie in a common plane containing the line of sight and the magnetic dipole—irrespective of pulsar longitude. In the particular case illustrated in this figure, which corresponds to the center of the pulse, this plane will also contain the rotation axis.

IV. GEOMETRIC ORIGIN FOR CIRCULAR POLARIZATION

For the reasons discussed just above, one is led to conclude that the antisymmetric type of circular polarization must be associated with the radiation mechanism itself. As we mentioned in the beginning, the most characteristic signature of the linear polarization of pulsars was attributed to the geometry of the field lines. If the antisymmetric circular polarization also has an origin in the field geometry, it is possible that there is a correlation between the linear and circular signatures. For this purpose, we have examined all the published and unpublished polarimetry available to us. The characteristic signatures of both linear and circular polarization are perceptible in some 20 pulsars as summarized in Table 1. We give the pulsar name, the profile species according to the classification scheme of Rankin (1983*a*), the sense of the circular and linear signatures, the frequencies of observation, and pertinent references. For the circular signature, we state merely whether the sense reverses from positive to negative (LH to RH), " +/−," or the reverse, " −/+," and for the linear signature, we state whether the rotation is positive (ccw) or negative (cw) on the plane of the sky. Less certain observations are enclosed in parentheses. Ideally, we would like to identify the sense of the signatures on the basis of their consistent behavior over a broad frequency range, but the observations are often neither extensive enough nor of sufficiently high quality. Moreover, the linear signature is often not complete enough to judge its reliability.[5] Therefore, we denote for each star whether our identification is "weak," "okay," or "strong" in these terms.

The majority of pulsars in Table 1 (some 16 of 25)—and all of those denoted as "strong"—exhibit a positive, anticorrelated relation between their circular and linear signatures. That is, when the circular polarization changes sense from positive to negative, the polarization angle exhibits a clockwise (negative) rotation. This behavior is well illustrated by pulsar

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[4] There is also the possibility of ion emission from the polar caps which would introduce an asymmetry, because of their mass difference, not found in a pair plasma.

[5] This is a particular problem with core-single pulsars which often have very clear circular signatures, but confused and unreliable linear ones. It appears that the linear polarization of core components cannot be interpreted according to RC/K (see Rankin 1990). Sometimes, however, unresolved conal "outriders" on the edges of core-single profiles at 400 to 1000 MHz provide enough conal associated linear intensity to overcome the intrinsically distorted linear signatures of the core emission. Therefore, we have only included core-single (S_t) pulsars in Table 1 when the linear signature of their outriders was unmistakable.

TABLE 1

ELLIPTICAL POLARIZATION TRAJECTORIES OF PULSAR AVERAGE PROFILES

STAR	SPECIES	POLARIZATION TRAVERSE Circular	Linear	FREQUENCIES (GHz)	REFERENCES	COMMENTS
			Anticorrelated Circular and Linear Signatures			
0355+54......	S_t	(+/−)	cw	2.7	1, 2	Weak: only one observation; circular weak
0826−34......	M?	−/+	ccw	0.61, 0.41	3	Strong
1237+25......	M	+/−	cw	1.7	4	Strong: consistent circular angle behavior clear in abnormal mode
1508+55......	T	+/−	cw	1.6, 0.41	2, 5	Strong
1541+09......	T	+/−/+	cw/ccw	1.4, 0.43	6, 7	Strong; both senses of circular correlation
1604−00......	T	(+)/−	cw	1.4, 0.43	7, 8	Okay
1700−32......	T	−/+	ccw	1.6	2	Strong, but only one observation
1737+13......	M	+/−	cw	1.4	7	Strong, but only one frequency
1821+05......	T	+/−	cw	1.4	7	Strong, but only one frequency; modal change in comp. 1
1839+09......	S_t	(+/−)	cw	1.4	7	Weak; only one observation; possibly two sense reversals
1857−26......	M	+/−	cw	2.7, 1.6 0.63, 0.27	2, 5, 10, 11	Strong
1859+03......	$S_t(T_{1/2})$	+/−	cw	1.4	7, 10	Okay; no complete linear signature
1905+39......	M	(+/−)	cw	0.41	12	Weak; one observation; small negative circular leading
1907+03......	T/M	+/−	cw	1.4	7	Okay; only one observation
1913+16......	T	−/+	ccw	1.4	13, 14	Strong, but only one frequency
1913+167.....	T/M	(+/−)	cw	1.4	7	Weak; small negative circular leading; circular inconsistent
1919+14......	T?	+/−	cw	1.4, 0.43	7, 15	Strong
2003−08......	T	+/−	cw	1.7	16	Strong, but only one frequency
2045−16......	T	(+/−)	cw	0.41	5, 9, 10	Weak; poor circular observation
2111+46......	T	+/−	cw	2.7, 1.7, 0.41	2, 12	Strong
			Correlated Circular and Linear Signatures			
0329+54......	T	−/+	(cw)	1.7	4	Okay; consistent circular; linear signature distorted by moding
1055−52......	T	(+)/−	ccw	0.63, 0.17	9, 11	Weak; little positive circular

REFERENCES.—(1) Morris *et al.* 1980. (2) Morris *et al.* 1981. (3) Biggs *et al.* 1985. (4) Bartel *et al.* 1982. (5) Manchester 1971. (6) Rankin 1983. (7) Rankin, Stinebring, and Weisberg 1989. (8) Rankin 1988. (9) Manchester, Hamilton, and McCulloch 1980. (10) McCulloch *et al.* 1978. (11) McCulloch, Hamilton, and Manchester 1983. (12) Lyne 1983. (13) Cordes, Wasserman, and Blaskiewicz 1990. (14) Stinebring 1980. (15) Rankin and Benson 1981. (16) Xilouri *et al.* 1989.

2111+46 in Figure 5—note that the circular polarization is plotted RH-LH, the opposite of the usual convention. Although not all the entries in Table 1 show the same sense of correlation, the observational evidence clearly favors the existence of an association between the linear sweep and the sense of the midpulse reversal of the circular. Combining the two and treating the polarization as elliptic, there is a clear pattern in the way this changes across the pulse.

The sign of the slope of the position angle depends both on the direction of rotation of the neutron star (which we cannot determine independently) and on whether the line of sight cuts the magnetic polar cap on the equatorial or the polar side of its rotational axis. But the correlation found above excludes any dependence of the handedness of the circular component on the polarity of the magnetic field, or on the sign of the effective charge of the radiating particles. This appears to be compelling evidence that the origin of this type of circular polarization is as much a geometric effect as the sweep of the linear polarization across the pulse. We must, therefore, seek a radiation mechanism that can be reconciled with the observations of the circularly polarized radiation of the antisymmetric kind.

V. A POSSIBLE RADIATION MECHANISM

To detect any circularly polarized radiation at all from the motion of charges, singly or collectively, they must move along curved paths and be viewed from the side, so to speak. For highly relativistic particles, the radiation is confined to a very narrow cone with its axis tangential to the instantaneous motion of the particle. The polarization of the radiation can be purely linear only at the center of the cone, and maximum circular polarization will be seen when the line of sight is roughly halfway between the axis and the edges of the cone furthest from the plane of motion of the particle. At a given instant, one will receive radiation from all those field lines whose tangents make an angle to the line of sight less than the half-angle of a radiation cone.[6] The net circular polarization

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[6] Björnsson (1984) has studied the properties of a three-dimensional distribution of source-region polarization directions as they accrue along any particular direction of propagation. While he assumes a highly relativistic particle population and thus does not specifically discuss circular polarization, his conclusion that the observed polarization phenomena are "due primarily to the geometry of the source and not to radiative transfer effects or properties of the emission mechanism " is very similar to our own.

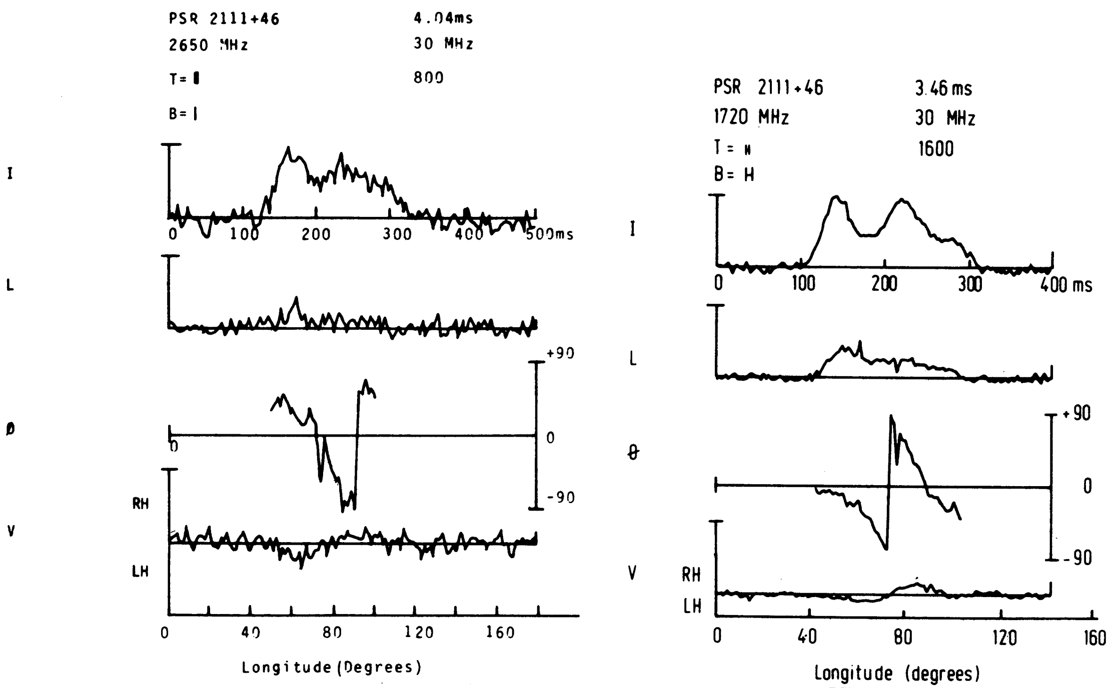

FIG. 5.—Polarization profiles for pulsar 2111+46 at 2650 and 1720 MHz (from Morris *et al.* 1981). The *I*, *L*, Φ, and *V* curves are plotted as a function of longitude. The circular polarization changes sense from positive to negative (+/−), while the linear polarization angle exhibits a clockwise (negative) rotation. (Note that the circular polarization is plotted RH-LH, the opposite of the usual convention.)

observed will therefore be the vector addition of the contributions from *all* the field lines which are in view. In the source region close to the star, the diagram of Figure 4 represents the field line geometry along the radiation path at *all* longitudes within the pulse. The only thing that varies during the pulse is the separation of the line of sight from the magnetic pole, but the symmetry as far as the field lines are concerned is unchanged. A different observer could have a larger or smaller impact parameter (distance of closest approach); from the evidence of many pulsars, however, we would surely expect every observer to see the circular polarization going through zero and changing sign at the center of the pulse. *The antisymmetric pattern of circular polarization is therefore direct evidence that beams from such pulsars cannot have circular symmetry.* Something that does break the symmetry is, of course, the rotational axis, and the fact that the circular goes through zero when the line of sight passes closest to the magnetic pole is direct evidence that the distribution of radiation around the magnetic polar direction is different in longitude and latitude. In other words, there must be a *steep and nonradial gradient in the intensity of the radiation from the different polar field lines, to give a net circular polarization.* And to produce the observed percentage of circular polarization, the angular scale size for variation of the intensity must be of the order of the cone angle itself. Further, to account for the sense of the observed correlation between linear and circular signatures, the gradient should be greater in latitude than in longitude.

The three panels of Figure 6 illustrate the relationship between the intensity gradient of the radiation and the elliptical polarization. In the circularly symmetric case (*a*), there is no gradient in the emission along azimuthally (or circumferentially) adjacent field lines, and thus no net circular polarization is produced. For the latitudinally-extended situation in (*b*), there is a net circular polarization in the four quadrants of the polar-cap region as indicated. The particular sightline trajectory depicted represents a positive (ccw) rotation of the linear polarization angle and a transition from LHC (+) to RHC (−) polarization. Either taking the sightline traverse above the magnetic axis or reversing its direction again results in circular/linear correlations of +/− with ccw or −/+ with cw—the opposite of what is observed. On the other hand, the longitudinally extended case in (*c*) produces just the circular/linear correlations which are observed, that is, +/− with cw or −/+ with ccw. This latter configuration of the intensity distribution could well be a consequence of the non-circularly symmetric distribution of the $\boldsymbol{E} \cdot \boldsymbol{B}$ electric field around the magnetic poles due to the tilt of the dipole with respect to the rotational axis.

The width of components within the integrated pulse profile is a measure of the gradient in the total intensity. This angle, which is a few degrees, is far larger than the narrow radiation cones associated with ultrarelativistic particles with high Lorentz factors. The radiation in question simply cannot be produced by particles, or bunches of them, moving at ultrarelativistic speeds. More precisely, we require the pattern of charge density to have a γ of the order of or less than the reciprocal of the pulse width (i.e., $\gamma < 20$). Such motion along the curved field lines would produce substantial amounts of radiation at large angles to the field lines, and at any given longitude of observation one would be "viewing" a patch of field lines of the same order of magnitude, but, of course, smaller than the size of the polar cap. Michel (1987) independently has been thinking along similar lines. He has considered the circular polarization of pulsars and suggested that emission from particles with a low γ in "isolated flux tubes" might be responsible.

It should be pointed out that the elongation (in longitude) of the radiating region deduced above is just the opposite of that (elongation in latitude) found for pulsar beams in general by Narayan and Vivekanand (1983). But their analysis of the

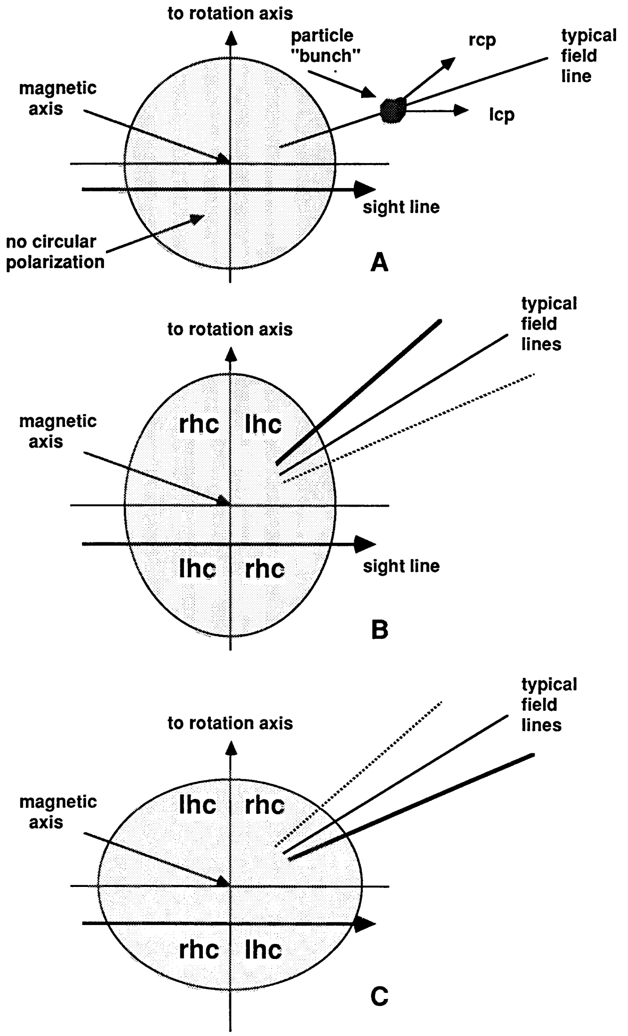

FIG. 6.—Schematic of polar-cap emission regions comparing characteristics of (*a*) circular, (*b*) latitudinally extended, and (*c*) longitudinally extended configurations. The perimeter represents an isointensity contour. The magnetic axes pass perpendicularly through the center of each diagram. Bold arrows represent a typical trajectory of the sight line. Because of its complete azimuthal symmetry, configuration (*a*) cannot produce circular polarization. LH and RH circular polarization emitted by a typical particle "bunch" will be cancelled by identical bunches on adjacent field lines. The latitudinally-extended configuration in (*b*) produces net circular polarization owing to the gradient of emission on adjacent field lines. It implies a circular/linear correlation of +/− with ccw (as shown) or −/+ with cw, contrary to what is observed. (*c*) The longitudinally-extended configuration also produces net circular and implies a circular/linear correlation of −/+ with ccw (as shown), or +/− with cw in agreement with the observations.

sweep rates of the position angle of the linear polarization refers mainly to the *conal* radiation observed at much larger angles from the magnetic polar axis. The antisymmetric type of circular polarization discussed here is associated with *core* emission originating closer to the magnetic polar direction and to the polar-cap surface. The connection, if any, between these orthogonal elongations of core and conal emission is as yet obscure.

VI. THE CASE OF PSR 1702−19

We return to a discussion of PSR 1702−19 because its polarization characteristics are so unusual and interesting that they warrant more detailed attention. As noted by Biggs *et al.* (1988), the most striking characteristic is the very high circular polarization (approximately 60% at 408 MHz) in both the main pulse and interpulse—the highest found in any pulsar. We discussed earlier that there is only a single handedness of circular all the way across the pulse, which was the basis for our taking it as a prototype of the symmetric kind. Moreover, all the evidence indicates that the pulsar's dipole is roughly perpendicular to the rotation axis, and that we are observing the radiation from both magnetic poles, because we also are located close to the equatorial plane.[7] Let us examine this situation a little more closely.

It is generally assumed that the radiation from both magnetic poles of a pulsar would have the same characteristics. If the magnetic dipole had been truly perpendicular to the rotational axis, one would expect both pulses (main and interpulse) to have equal strength independent of the "latitude" of the observer. The fact that the interpulse is much weaker would require a deviation in the standard picture to make one pulse appear weaker than the other[8]—both the magnetic axis from perpendicularity and of the observer from the rotational equatorial plane. Although the signal-to-noise for the interpulse position angle curve in Figure 2 (taken from Biggs *et al.*) is marginal, the sweep appears to be in the same sense as in the main pulse. This indicates that the line of sight to the observer is at a greater angle to the rotational equatorial plane of the pulsar than the magnetic dipole. The 100° or so sweep of the linear position angle across the main pulse is a measure of the impact parameter, that is, the displacement of the locus of the line of sight from the main pulse magnetic pole. The line of sight would be a little more displaced from the interpulse magnetic pole in order for the interpulse to have both a much weaker intensity and a smaller sweep of the position angle, as observed.

We have a major problem, however, with the above picture because of the circular polarization. There is primarily the question of the very high percentage in both main pulse and interpulse which we shall come to later. But the most extraordinary aspect, in the context of the present work, is that the sense of the circular polarization is the *same* for both the main pulse and the interpulse. In the spirit of the argument advanced in an earlier section regarding the antisymmetric type, it can be stated with equal confidence here that a geometric origin is inconceivable for the symmetric shape of the circularly polarized profiles observed in PSR 1702−19. The determining factors for RH versus LH circular polarization can thus only be the combination of the polarity of the magnetic field and the sign of the effective charges in the propagation region.

We know that the polarity of the magnetic field has to be opposite for the two poles, and to see the same sense of circularity would therefore require that the signs of the effective charges are also opposite in the two cases. Given a pair plasma with equal numbers of e^+ and e^- particles, the effective charge will depend on the energy distributions of these two, caused by the sign of the $\boldsymbol{E} \cdot \boldsymbol{B}$ field, and according to the above argument, this should be different for the two poles. On the other

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[7] This evidence is summarized in the Appendix of the foregoing paper (Rankin 1990). Furthermore, the widths of core components in 1702−19 and other pulsars with interpulses are interpreted in terms of simple dipolar geometry, and all are found to have a nearly orthogonal relationship between their magnetic and rotational axes.

[8] Polarization angle fitting according to the RC/K model supports this conception of the emission geometry (Lyne and Manchester 1988).

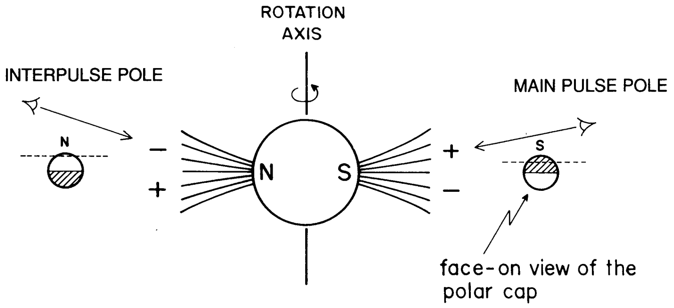

FIG. 7.—Possible two-pole emission geometry of pulsar 1702−19. In the special case of the perpendicular rotator, the electric field over each polar cap is split and has opposite signs above and below the rotational equator. A line of sight just above (or below) the rotational equator will therefore see opposite signs of electric field in the two polar caps. Because the sight line traverse for the interpulse is further from the (interpulse) magnetic pole, its profile has both a smaller intensity and a shallower sweep of the linear polarization angle than that of the main pulse.

hand, we know from first principles that for magnetic dipoles aligned with the rotational axis, or tilted at moderate angles to it, the polarity of the induced electric field will be the *same* at both magnetic poles. We are hence faced with observational evidence that at least one of our premises in the foregoing discussion was wrong.

A possible and interesting resolution of the difficulty is illustrated in Figure 7. If we assume that the magnetic dipole is almost perpendicular to the rotation axis, the electric field will be as shown in the figure (see, e.g., Sturrock 1971). With the line of sight tilted from the equatorial plane by a small angle (as indicated by the linear polarization position angle sweep in the main pulse), it will cut the other polar cap in a region where the electric field is oppositely directed. Assuming that pair plasma can be generated in both these regions, and that the energy distributions of the two types of particles are modified by the sign of the electric field, we thus have a plausible explanation for the observations.

It should be noted that in the original Ruderman and Sutherland (1975) model, only negative charges (electrons) could be pulled off the surface of a neutron star. And according to this model, pulsar action could only be expected in that fraction of all neutron stars in which the relative directions of spin and magnetic moment were appropriate. There have, however, been later developments in regard to the validity of the assumptions that led to this conclusion (see for example, Jones 1981). Further, theories regarding the way currents flowing out of a pulsar are balanced by those flowing in are very complicated, to say the least, and one is still far from a proper understanding (e.g., Michel 1982). But given that the configuration of the electric field for this geometry will be as illustrated in Figure 7, we could turn the argument around and treat the observations of PSR 1702−19 as evidence that pair plasma *can* be generated over polar-cap regions with *either* sign of $\boldsymbol{E} \cdot \boldsymbol{B}$ electric field. If this is so, it also means that pulsar action can be expected from all neutron stars irrespective of the relative orientations of their spin and magnetic moments.

The other remarkable aspect of PSR 1702−19 referred to earlier is the very high percentage of circular polarization observed. If, as we have surmised, this represents an unusually high conversion efficiency of linear to circular in the outer magnetosphere, this could imply a much higher particle density in the propagation regions than for other pulsars. We cannot refrain from speculation that this might be a natural consequence of the near perpendicularity of the magnetic dipole to the rotational axis. Since particles move along the magnetic field lines, their location in the outer magnetosphere will be determined by the sweepback of the field lines around the rotation axis of the pulsar. In the special case of a perpendicular dipole, the particles will tend to remain in the rotational equatorial plane. Radiation emitted tangentially to the field lines near the magnetic poles will also be in this plane, and this particular geometry will therefore lead to a much greater column density in the outer magnetosphere than for other inclinations of the magnetic dipole. If this is indeed the explanation, a prediction is that the amount of propagation-induced symmetric circular polarization should show a correlation with the tilt angle of the dipole.

VII. SUMMARY

Two extreme types of circular polarization signature are identified in the observations: (*a*) an antisymmetric type wherein the circular polarization changes sense in midpulse, and (*b*) a symmetric type wherein it is predominantly of one sense. We find that circular polarization of the antisymmetric type is strongly correlated with the sense of rotation of the linear position angle. This correlation requires that the antisymmetric circular polarization is also a purely geometric property of the emission process and is highly suggestive of curvature radiation from core-emitting charge bunches with $\gamma < 20$. The sign of the correlation we have discovered is consistent with an emission region more extended in longitude than in latitude. We attribute the symmetric type of circular polarization to propagation effects in the outer magnetosphere and predict a correlation of its magnitude with the tilt angle of the magnetic dipole to the rotation axis.

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