THE ASTROPHYSICAL JOURNAL, 352:247–257, 1990 March 20

TOWARD AN EMPIRICAL THEORY OF PULSAR EMISSION. IV. GEOMETRY OF THE CORE EMISSION REGION

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Received 1989 March 13; accepted 1989 September 16

ABSTRACT

The core-component widths of pulsars with interpulses are studied in an effort to define the geometric properties of the core emission region. The results are then applied to a large population of core-single (S_t), triple (T), and five-component (M) pulsars which all have core components.

Core-component widths are intimately related to the polar-cap geometry at the stellar surface. A simple mathematical expression,

$$W_{\rm core} = 2\overset{\circ}{.}45 P^{-1/2}/\sin\alpha ,$$

established through the study of two-pole interpulsars, indicates that the core-component widths depend only upon the pulsar period P and α, the angle between the rotation and magnetic axes of the star.

The relationship can then be used to estimate α in any pulsar with a core component. Values of α are estimated for about 110 core single (S_t), triple (T), and five-component (M) pulsars. The histogram of α values for core-single pulsars ranges from about 15° to 90° and peaks sharply at about 35°. A similar histogram for triple and five-component stars also peaks at about 35°, but it is broader with α values ranging down to 3°. These stars also exhibit a second peak at 90°.

These results have important implications for the nature of the core radiation process. Core emission appears to come essentially from the stellar surface, filling the entire polar-cap "gap" region where particle acceleration is thought to take place.

Subject heading: pulsars

I. INTRODUCTION

The foregoing papers in this series reach a single overarching conclusion: pulsars divide into distinct classes or species. The morphological characteristics of *polarized* average profiles were first studied with particular reference to their formal *evolution* with radio frequency (Rankin 1983*a*, *b*, hereafter Papers I and II), and five distinct species were delineated. In a subsequent work, this classification system was related to certain collective properties of pulse sequences, mode changing, drifting subpulses, and pulse nulling (Rankin 1986, hereafter Paper III).

In summary, two distinct classes of "single" profile are delineated: the "conal" and the "core" (designated S_t). Pulsars of this latter core single type, which are of most interest to us below, are found to exhibit properties similar to those encountered in the central components of triple (T) stars, which also have a pair of outriding conal components. That is, the core components of both species are often labeled by circular polarization of symmetrically alternating sense. Similarly, "multiple" or five-component (M) profiles are observed which have a central core component between a double set of conal outriders.

Core components and especially the triple profile emerge as most generally prototypical of pulsar emission. Some 70% of the observed pulsar population has core emission components. And the contrasting polarization signatures of the outriding conal components and the quasi-axial core component of triple profiles strongly suggest that two different physical mechanisms are involved in pulsar emission.

The isolated core components of stars with core-single (S_t) profiles display little ordered modulation, nor do they null or show evidence of any sort of mode changing. Many have featureless ("white") fluctuation spectra, whereas others exhibit low-frequency ("red") features (15–50 periods per cycle) with which no orderly drift is apparently associated. Similarly, the core components in triple (T) and multiple (M) profiles also show these longitude-stationary, low-frequency fluctuations.

With regard to age, the core single (S_t) pulsars are by far the youngest, triple (T) stars are of intermediate age, and the remaining species (S_d, D, cT, and M) are all relatively old.[1] We then have the picture that young (S_t) pulsars emit a bright, steady core beam. As they age, their conal emission becomes prominent at ever lower frequencies (T stars), and the emission of the oldest species is then primarily conal throughout their spectrum.

All these circumstances underscore the centrality of the core beam and suggest that it is in some sense primary. Geometrically, the relatively small angular width of core components argues that they are generated at much lower heights than the conal emission.

The quantitative exploration of the geometry of core radiation in § III is the essence of this paper. An analysis is first made of the properties of core emission in pulsars with interpulses and then extended to other stars—resulting both in the surprising conclusion that core emission is emitted close to the stellar surface and in providing a technique for estimating the angle between the magnetic and rotational axes. The results

[1] The systematic age difference of the various species can be seen both in their spin-down age values and in their galactic z-distribution. S_t pulsars have an average z height of only about 160 pc, and T stars have a height of 210 pc, whereas the others (S_d and D, cT, and M) have average heights of between 300 and 350 pc.

TABLE 1

Pulsars with Established Classification

PSR	B_{12}/P_2	$1/Q$	Class
Core Single Stars			
0105+65	2.53	1.07	St
0136+57	23.4	5.39	St
0154+61	3.87	1.59	St
0355+54	34.0	6.95	St
0540+28	32.2	6.99	St
0611+22	40.8	8.55	St
0626+24	4.30	1.49	St
0740−28	61.0	11.1	St
0823+26m	3.47	1.25	St
0833−45m	426	49.2	St
0835−41	2.94	1.14	St
0906−49m	113	17.4	St/$T_{1/2}$
0940−55	8.81	2.74	St
0942−13	0.51?	0.27?	St
0959−54	4.22	1.63	St
1154−62	7.85	2.37	St
1240−64	8.94	2.58	St
1449−64	22.0	4.96	St
1556−44	7.76	2.25	St
1557−50	27.0	5.86	St
1641−45	14.9	3.95	St
1642−03	5.53	1.79	St
1702−19i	12.6	3.33	St
1706−16	4.90	1.68	St
1736−29m	15.5	3.96	St?
1736−29i	...	...	St?
1747−46	1.81	0.77	St?
1749−28	6.91	2.18	St
1839+09	4.44	1.50	St
1842+14	6.04	1.88	St
1844−04	15.8	4.27	St/T?
1859+03	5.21	1.78	St($T_{1/2}$)
1900+05	3.26	1.24	St
1900+01	5.63	1.92	St
1907+02	2.42	1.00	St
1907+10	10.8	2.95	St
1907−03	4.21	1.45	St
1911−04	2.73	1.08	St
1913+10	15.4	4.02	St
1914+13	12.9	3.37	St
1915+13	31.7	6.67	St
1924+16	9.63	2.89	St
1927+13	2.92	1.14	St
1929+10i	10.0	2.71	St
1929+20	14.9	3.77	St
1930+22	140	21.3	St
1933+16	11.5	3.16	St
1946+35	4.45	1.57	St(T)
1953+29	12.0	2.17	St
1953+50	3.16	1.17	St
2002+31	2.82	1.23	St/T
2053+36	5.88	1.75	St
2113+14	1.87	0.75	St?
2217+47	4.24	1.48	St
2255+58	10.9	3.02	St
Conal Single Stars			
0031−07	0.71	0.37	Sd
0320+39	0.16	0.13	Sd
0628−28	1.95	0.86	Sd
0643+80	1.47	0.69	Sd
0655+64	0.31	0.17	Sd
0809+74	0.28	0.18	Sd
0818−13	1.06	0.53	Sd
0820+02	0.40	0.24	Sd
0826−34i	0.40	0.25	Sd/cT?
0943+10	1.66	0.75	Sd
0950+08m	3.83	1.26	Sd?
0950+08i			Sd?
1540−06	1.58	0.69	Sd?
1612+07	1.17	0.57	Sd
1923+04	1.43	0.66	Sd
1940−12	1.36	0.63	Sd
2016+28	0.95	0.44	Sd
2021+51	4.60	1.57	Sd/T?
2043−04	0.64	0.36	Sd
2110+27	1.24	0.60	Sd
2148+63	1.78	0.71	Sd
2303+30	0.86	0.46	Sd
2310+42	1.67	0.67	Sd?
2315+21	0.60	0.34	Sd
Conal Double Stars			
0148−06	0.38	0.24	D
0301+19	0.70	0.39	D
0525+21	0.88	0.51	D
0751+32	0.61	0.34	D
0818−41	0.41	0.23	D
0834+06	1.82	0.82	D
0957−47	0.53	0.29	D
1133+16	1.52	0.70	D
1601−52	0.96	0.46	D
1906+09	0.42	0.24	D
1911+09	...	...	D
1924+14	0.31	0.20	D
1942−00	0.71	0.38	D
2044+15	0.36	0.22	D
2154+40	0.98	0.51	D
2306+55	1.40	0.60	D
2323+63	0.99	0.51	D
Conal Triple Stars			
1633+24	1.02	0.47	cT
1845−01	4.31	1.53	cT
1918+19	1.29	0.59	cT
1944+17	0.54	0.28	cT
Triple Stars			
0329+54	2.40	0.96	T
0450+55	7.82	2.31	T
0450−18	5.97	1.95	T
0531+21pm	3470	239	$T_{1/2}$?
0656+14	31.6	7.10	T
0736−40	5.60	1.78	T
0906−49i	113	17.4	T?
0919+06	13.2	3.60	T
1055−52m	27.9	6.04	T
1112+50	0.75	0.41	T
1221−63	22.3	5.10	T
1451−68	2.35	0.86	T
1508+55	3.57	1.33	T
1541+09	1.03	0.49	T
1558−50	10.5	3.20	T
1604−00	2.04	0.80	T
1700−32	0.63	0.35	T
1702−19m	12.6	3.33	T
1727−47	17.1	4.72	$T_{1/2}$
1742−30	14.9	3.88	T?
1804−08	2.59	0.88	T
1818−04m	5.45	1.84	T
1821+05	0.73	0.38	T
1822−09m	10.9	3.25	$T_{(1/2)}$
1826−17	14.1	3.65	T?
1907+00	2.32	0.97	T
1907+03	0.61	0.36	T/M

TABLE 1—*Continued*

PSR	B_{12}/P_2	$1/Q$	Class
Triple Stars			
1911+13	2.41	0.94	T
1913+16	6.56	1.68	T
1913+167	0.31	0.21	T/M
1914+09	11.4	3.05	$T_{1/2}$
1916+14	11.5	3.54	T?
1917+00	1.95	0.87	T
1919+14	4.99	1.69	T?
1920+21	2.59	1.07	T
1926+18	...	...	T
1929+10m	10.1	2.71	T
1952+29	0.16	0.11	T/M
2003−08	0.46	0.25	T
2020+28	6.89	2.09	T?
2045−16	1.22	0.62	T
2111+46	0.84	0.43	T
2224+65	5.58	1.89	$T_{1/2}$
2319+60	0.79	0.45	T
2327−20	1.03	0.53	T
Multiple Stars			
0523+11	1.29	0.54	M?
0621−04	0.88	0.45	M
0826−34m	0.40	0.25	M
1039−19	0.65	0.36	M
1237+25	0.61	0.34	M
1737+13	1.70	0.74	M
1738−08	0.52	0.32	M?
1745−12	4.50	1.50	M?
1831−04	2.85	1.02	M
1857−26	0.84	0.41	M
1905+39	0.53	0.31	M
1910+20	0.96	0.52	M/T?
1919+21	0.75	0.41	M?
2028+22	1.90	0.79	M?
2210+29	0.70	0.38	M

NOTES.—"i" stands for interpulse, "m" stands for main pulse, and "p" means the precursor; it is interpreted here as a core component (see Appendix).

are discussed in § IV, and the Appendix discusses the emission geometry of the known interpulsars.

First, however, I must digress in § II to discuss the classification of a large group of pulsars. In a subsequent paper, I will return to the emission geometry of the conal radiation.

II. PULSAR CLASSIFICATION

In order to explore the geometry of pulsar emission, we require a population of pulsars whose classification has been well established. Such a population has been accumulating over the last few years. A number of stars were given as examples of particular species in Paper I in the course of delineating the original criteria for classification. Paper III extended these criteria and explicitly tabulates the classes of some 60 stars. Also, a number of further identifications have been made in the course of presenting the results of 21 cm (Rankin, Stinebring, and Weisberg 1989, hereafter RSW) and 18 cm (Xilouri *et al.* 1990, hereafter XRSS) polarization observations. These classifications are collected in Table 1 and, apart from a very few cases, are identical to the designations given in the above papers.

A principal difficulty in classifying pulsars has been that of distinguishing between core (S_t) and conal (S_d) single stars. For other species, the profile form often provides enough information to determine the star's class. Thus, if a profile is well observed, we usually do not confuse a conal double and a triple profile. But for the S_d and S_t stars, the profile form gives no help in differentiating between the two single classes. Using the criteria of Paper I, observations over a wide frequency range were required to determine whether a single profile developed outriders at high frequency or bifurcated at low frequency. Or, alternatively, polarimetry was required to identify the characteristic circular polarization frequently exhibited by the core species or linear polarization associated with the conal variety. Paper III then added the criterion that *drifting* subpulses are often associated with conal single stars and "white" fluctuation spectra are associated with the core variety. There are many pulsars in the two single groups, and their classification has required much more extensive information than is required for the other species. Thus, for many single stars we have simply not had adequate information to determine their classification.

Study of the groups of stars classified in Paper III and RSW, however, provides a further criterion for distinguishing between the two single species. It was noted in Paper III that core and conal single stars occupy different regions of the $P-\dot{P}$ diagram. It now appears that their distinct distributions are related to the differing acceleration potentials available to the stars in their polar-cap regions. Goldreich and Julian (1969) and Sturrock (1971) calculate the acceleration potential for the situation in which the magnetic and rotation axes are aligned, finding it is proportional to the quantity B_{12}/P^2, which in turn is proportional to $\dot{P}^{1/2}/P^{3/2}$ (the square of this quantity is also related to the total luminosity of the pulsar). Calculated values of this parameter for the stars classified in Paper III and RSW distinguish clearly between the core and conal species: core-single (S_t) stars exhibit values greater than about 2–3, and conal single (S_d) stars exhibit values ranging between about 0.2 and 2–3. It is interesting that this parameter is quite similar to the one ($B_{12}/P^{13/8}$) delineating the "turn-off line" in Ruderman and Sutherland (1975) and that indeed we find no stars with a value less than 0.16.

On this basis, a number of further stars have been added to the identifications from Paper III and RSW, and classifications for a total of about 160 pulsars are listed in Table 1 along with their respective values of the parameter B_{12}/P^2.

Subsequently, I discovered that Beskin, Gurevich, and Istomin (1986, 1988, hereafter BGIa and BGIb, respectively) define the parameter $Q = 2P^{11/10}\dot{P}_{-15}^{-4/10}$, first to distinguish modes of plasma flow in the polar-cap region of their model (BGIa), and then to discriminate between emission modes which they identify with the core and conal mechanisms of Paper I (BGIb). The parameter $1/Q$ is also given in Table 1, and it is apparent that values greater than unity are associated with core-single stars, whereas conal single and double stars virtually always have values less than 1.

Finally, it is consoling that in the few cases where the specified classifications in Table 1 are at odds with the B_{12}/P^2 or $1/Q$ values, the stars involved are well known for their peculiarities and hybrid properties: PSRs 0950+08 and 2021+51 are somewhat problematical conal single stars, having attributes of the core-single class as well. Similarly, PSR 2020+28 is a very strange conal double, and I have followed RSW in classifying it as a triple. Clearly, there are also angular factors affecting the acceleration potential which we cannot yet properly take into account.

III. THE WIDTHS OF CORE COMPONENTS

The widths of core components show an intriguing period dependence. The half-power width of the 2.1 s core-single star, PSR 2002+31, is little more than 2°, whereas the 6 ms pulsar, 1953+29, has a core width of some 40°. The width of these components is intimately related to the polar-cap geometry of the emission region and therefore deserves detailed study in the subsections that follow.

a) Core Components in Pulsars With Interpulses

Twelve pulsars with interpulses are now known which exhibit core emission in their main-pulse and/or interpulse profiles. Historically, such "interpulsars" have been deemed important, because only for these few stars can we hope to glean any direct information about their basic emission geometry—that is, the angle α between their magnetic and rotation axes and the angle ζ that our line of sight makes with the rotation axis of the star. [$\beta(=\zeta-\alpha)$ is the angle the line-of-sight trajectory makes with the magnetic axis.] Even for these stars, the interpretation has not been entirely straightforward, because interpulses clearly arise *both* because the two axes are nearly orthogonal (two-pole model) *and* because they are closely aligned (single-pole model; Manchester and Lyne 1977; Narayan and Vivekanand 1983).

I have not previously attempted profile classifications for the interpulse pulsars because several present significant difficulties. However, the Appendix discusses the speciation and, whenever possible, the interpulse geometry of each of these 12 stars which have core components. The results of this discussion are summarized in Table 2, which gives the parameters B_{12}/P^2 and $1/Q$, the main-pulse and interpulse classifications, the interpulse separation, and an indication of whether our sightline passes through one or both polar emission regions. From this summary, we draw the following conclusions.

1. Fourteen interpulsars have classifiable profiles, of which 12 (those listed in Table 2) exhibit core emission.

2. Most of these stars have core-single (S_t) or triple (T) profiles, large values of B_{12}/P^2, and an overall geometry wherein the magnetic and rotation axes are nearly orthogonal. Thus their interpulses are associated with a second polar emission region. For some half of these pulsars, it was also possible to make at least a tentative classification of their interpulse profile.

3. One very interesting pulsar, 0826−34, seems to have a five-component (M) main-pulse profile, a small value of B_{12}/P^2, and a nearly aligned geometry. The interpulse of this star seems to have a conal single (S_d) or perhaps a conal triple (cT) profile.

4. The two remaining pulsars with interpulses, 0950+08, and 1944+17, have conal profiles and their spin and rotation axes appear to be nearly aligned. The latter also has a very low value of B_{12}/P^2.

Six of the pulsars in Table 2 have core components whose width (i.e., full width at half-maximum) can be measured with reasonable accuracy: the 0531+21 precursor, the 0823+26 main pulse, the 0833−45 main pulse, the 0906−49 interpulse, the central component of the 1702−19 triple main pulse (by measuring the width of its associated circular polarization) and interpulse, and the 1929+10 interpulse. Wherever possible, measured widths at higher and lower frequencies were interpolated to 1 GHz, and these values are given in Table 3.

When fitted against period, the core widths of the six interpulsars in Table 3 exhibit a surprisingly accurate power-law relation. A least-squares fit to these values yields the result that

$$W = 2.^\circ 45/P^{0.50}\ . \qquad (1)$$

and the fitted width is also given in the table. The core components of the other interpulsars in Table 2 also have widths comparable to those given by the above relation, but they cannot be determined so accurately.

This core width–period relationship has a very simple interpretation in terms of the magnetic field structure of the pulsar. Assuming a dipolar magnetic field, the angle ρ between the field line tangent and the magnetic axis is

$$\rho \approx 3/2(r/\mathscr{A})^{1/2} = 3/2r^{1/2}r_p/R^{3/2}\ , \qquad (2)$$

here r is the emission height, measured from the center of the star. The polar cap is delineated by the set of "open" field lines which do not close within the velocity-of-light cylinder, and the parameter $\mathscr{A}$ takes the value R^3/r_p^2 on this last open field line, where r_p and R are the polar-cap radius and stellar radius, respectively (Gil 1981; Kuz'min and Dagkesamanskaya 1983).

$\mathscr{A}$ is also equal to $cP/2\pi$ on the last open field line, where P is the pulsar period and c is the velocity of light. Then, taking the core-component width as twice the field line tangent angle ρ for interpulsars and R as 10 km, we find that in degrees,

$$W_{\rm core} = 2\rho \approx 2.^\circ 49(r/R)^{1/2}/P^{1/2}\ , \qquad (3)$$

Let us now compare the empirical relationship for W in equation (1) with the geometrically derived expression in equa-

TABLE 2

INTERPULSARS WITH CORE COMPONENTS

Star	P	B12/P2	1/Q	Profile Class Main	Int'plse	Sep	Poles	Refs.
0531+21	0.0331	3454	238.5	T1/2	?	146	two	Rankin et al. (1970)
0823+26	0.5307	3.44	1.25	St/T1/2	?	179	two	RB; RSW
0826-34	1.8489	0.40	0.25	M	Sd	197	one	Biggs et al. (1985)
0833-45	0.0892	424	49.2	St	n/a	n/a	two	Downs et al. (1973)
0906-49	0.1068	113	17.4	T1/2	T	180	two	D'Amico et al. (1988)
1055-52	0.1971	27.9	6.04	T	?	154	two	McCulloch et al (1976)
1702-19	0.2990	12.6	3.33	T	St?	181	two	Biggs et al. (1988)
1736-29	0.3229	15.5	3.96	St?	St?	~180	two?	Clifton and Lyne (1986)
1818-04	0.5981	5.51	1.84	T	?	225	two	Perry and Lyne (1985)
1822-09	0.7690	10.9	3.25	T(1/2)	St	187	two	MGSBT; FW
1855+09	0.0054	11.8	2.12	T?	T?	~200	two	Segelstein, et al. (1986)
1929+10	0.2265	10.1	2.71	T	St	187	two	RB; RSW

TABLE 3

INTERPULSARS WITH MEASURABLE CORE COMPONENT WIDTHS

Pulsar	Period (s)	Core Width[a] (measured)	Core Width (fitted)	References
0531+21p	0.0331	13°.5 ± 1°.0	13°.47	Boriakoff and Payne 1973
0823+26m	0.5301	3.38 ± 0.1	3.37	Hankins and Rickett 1986
0833−45m	0.0892	8.18 ± 0.3	8.20	McCulloch *et al.* 1978; Manchester, Hamilton, and McCulloch 1980
0906−49i	0.1068	7.5 ± 0.4	7.50	D'Amico *et al.* 1988
1702−19i	0.2990	4.5 ± 0.3	4.48	Biggs *et al.* 1988
1929+10i	0.2265	5.15 ± 0.1	5.15	Rankin and Benson 1981; Rankin, Steinberg, and Weisberg 1989

[a] Observed values are referred to 1 GHz.

tion (3). Both equations have a $P^{-1/2}$ term, and thus it appears that the period dependence of the core width is geometrical in origin. Furthermore, in order to reconcile the two expressions, the ratio of the emission height (from the center of the star), r, to the stellar radius, R (=10 km) must be nearly unity in equation (3). This in turn suggests that *the core emission comes from very near the stellar surface*. In other words, two-pole interpulsars have core-component widths which are virtually identical to the total angular spread of their open–field line tangents at the stellar surface. Indeed, it is surprising that this simple dipole model fits so well.[2]

Most pulsars, of course, do not have interpulses, and therefore we have no means to estimate α or ζ. In this general situation, we must consider how an emission beam of angular radius ρ about the magnetic axis projects onto the sightline direction. Following Gil's (1981) description of the spherical geometry, the angular width of the sightline's traverse through the emission cone, $\Delta\psi$, is given by

$$\Delta\psi = 4 \sin^{-1} \left\{\frac{\sin [(\rho/2) + (\beta/2)] \sin [(\rho/2) - (\beta/2)]}{\sin \alpha \sin \zeta}\right\}^{1/2} , \tag{4}$$

where $\beta = \zeta - \alpha$. If β is small, however, the relation reduces to $\Delta\psi = 4 \sin^{-1} [\sin (\rho/2)/\sin \alpha] \approx 2\rho/\sin \alpha$, and α is of course close to 90° for two-pole interpulsars.

Combining this α dependence with the period dependence deduced above, we have

$$W_{\rm core} = 2°.45 P^{-1/2}/\sin \alpha . \tag{5}$$

Apparently, this simple relationship describes the angular width of core emission beams as 1 GHz. The relationship depends only on the pulsar period (which determines the height of the velocity-of-light cylinder and thus the polar-cap radius) and the angle α (which enters in considering how much of a rotation cycle the core beam occupies).

In deriving equation (5), the angle β has been ignored, and there are apparently deep reasons why it is possible to do so. β strongly affects the observed widths of conal beams, but its effect on the width of core components may be quite weak. In effect, equation (4) describes the width of a beam with discrete edges. The core beam, however, exhibits a more gradual distribution of angular intensity. In fact, the angular intensity distribution of the core beam is almost certainly well approximated by a bivariate Gaussian function,

$$I(\beta, \varphi) \propto \exp -[(\beta - \beta_0)^2/2\rho_\beta^2 + (\varphi - \varphi_0)^2/2\rho_\varphi^2] ,$$

whose breadth (FWHM) is invariant along any set of parallel paths (although in general the latitudinal scale ρ_β can be different than the longitudinal scale ρ_φ). Thus, the angular width of core beams can be only weakly dependent on the centrality of the traverse.

Another important point to emphasize here concerns the polarization angle behavior of core components: In a word, it is disorderly, meaning that *it has not been possible to interpret the linear polarization angle traverse of core components on the basis of the single-vector model* (Radhakrishnan and Cooke 1969, hereafter RC; Komesaroff 1970, hereafter K70). The single-vector model appears to describe the linear angle behavior of conal emission very adequately (when allowance is made for the "orthogonal modes"). There is no single instance, however, where it has been clearly and successfully applied to core emission. Several good examples of such disorderly polarization-angle behavior can be found in RSW: 1900+01, 1933+16, 1946+35, 2053+36, and 2113+14.

The result of this circumstance is that *the polarization-angle behavior of core components seems to provide no reliable information about the impact angle* β. Even in those cases where the angle behavior appears to be more orderly—usually assuming a shallow, approximately linear traverse—estimates of β, pertaining to the core component, give strange results.[3]

There are at least three reasons why the core emission may not typically exhibit polarization angle behavior which can be understood in terms of the single-vector model: (*a*) the emis-

[2] Several investigators have studied the pulse-width distribution of pulsars as a function of period. Kuz'min and Dagkesamanskaya (1983), in particular, have given a geometrical analysis having much in common with the arguments made here; although my own initial conclusions were reached independently, their work has challenged my thinking positively. Only in applying their analysis to the entire pulsar population did the Kuz'min and Dagkesamanskaya study miss finding the present results, for only core components have consistent angular widths by virtue of their pencil-beam shape and emission at or near the surface of the star.

[3] Let us take 1915+13 in RSW, for instance. Its measured pulse width is 6° (see Table 4), and if we use eq. (5) to estimate α, we obtain a value of 68°. Then we can use the relationship

$$R = |d\chi/d\varphi|_{\rm max} = \sin \alpha/\sin \beta ,$$

where χ and φ are the polarization angle and longitude, respectively, to estimate β. R is 6°/° for this star, and we obtain β = 11°.3—which is nearly 4 times the value of ρ! If the beam shape were Gaussian, this would imply an intensity reduction, relative to the beam center of 10^6—this is not reasonable.

Geometrical interpretation of the shallow, linear traverses associated with core components according to the RC/K70 model represents one major source of confusion in Lyne and Manchester's (1988) recent work. They are forced to interpret many such pulsars as "partial *cones*"! While profiles with partial conal emission are undoubtedly possible, RSW's classification work indicates that they are rather rare in the overall pulsar population.

sion is not a single vector, but rather the superposition of many polarization vectors; (*b*) core emission is produced by a distinct radiation mechanism which is not necessarily polarized along the projected field direction; (*c*) core and conal emission occur together so often in the centers of profiles that their different properties may distort any underlying core signature that might be interpretable in the usual terms. Beskin, Gurevich, and Istomin (1988) associate core emission with a direction *perpendicular* to the projected field direction, and in a companion paper (Radhakrishnan and Rankin 1990, hereafter Paper V), we shall argue that core emission *must* be a superposition of many polarization vectors.

b) *Core-Single Pulsars*

The measured width (FWHM) of 50 pulsars with core-single (S_t) profiles are given in Table 4. The accuracy of these core-component width measurements is quite variable. Wherever possible, measurements were made of profiles at frequencies both above and below 1 GHz, and the values interpolated to estimate the 1 GHz value (including information such as that in Paper II). For some stars, however, multifrequency observations were unavailable, and so the interpolation procedure could not be applied uniformly. For yet another group, the quality of the available observations was poor, with the effect that the width value is less accurate and probably somewhat overestimated. The varying significance of the values in Table 4 reflects these considerations, and references are given therein to the sources used to determine the component width of each star.

Figure 1 then gives a plot of these half-power widths as a function of period. The points corresponding to the interpulsars (*filled symbols*) as well as several other stars are labeled, and a line showing the fitted widths of the interpulsars (eq. [1]), is indicated. The plotted core width values exhibit a rough inverse-period dependence. The most important feature of the diagram, however, is the minimum width defined by the four interpulsars. Several other pulsars—most notably the 6 ms pulsar 1953+29—have core widths just in excess of the interpulsar minimum, but none have smaller widths.

We can interpret the core width/period relationship in Figure 1 as deriving primarily from the polar-cap geometry, and as such it should be well described by equation (4) above. Only two factors apparently determine the 1 GHz width of a core component: (*a*) the extent of the polar-cap emission region at the stellar surface, which goes as $2\overset{\circ}{.}45P^{-1/2}$, and (*b*) the angle between the magnetic axis and the rotation axis, α.

Assuming that the angular width of all core emission is determined by the angular extent of the open field lines at the stellar surface, then equation (4) can be inverted to estimate the magnetic orientation angle α. Table 4 gives values for the angular diameter of the polar cap ($2\overset{\circ}{.}45/P^{1/2}$) as well as α values computed by comparing them with the measured core widths. A histogram of the α values is then given in Figure 2. The angles range between some 15° and 90° and have a median value of about 35°. The "pileup" at 90° suggests that perhaps the angles have been slightly overestimated, but probably by no more than 5°.

The population of core-single pulsars in Figure 2 has been divided into two subgroups of 25 according to their spin-down age ($P/2\dot{P}$). The younger group (*solid bars*) has a mean log age of 5.6, whereas the older one (*striped bars*) has a mean log spin-down age of 6.7. The older group shows a weak tendency toward alignment, which is probably not significant at this level of analysis. In any case, it will be interesting to compare

TABLE 4

Core Widths of Core-Single Pulsars

PSR	Class	Wcore (deg.)	Wcap (deg.)	Alpha (deg.)	Refs.	PSR	Class	Wcore (deg.)	Wcap (deg.)	Alpha (deg.)	Refs.
0105+65	St	5	2.2	26	MGSBT; Ba81; MIS	1842+14	St	8.2	4.0	29	RSW;Ba81; WABCBF
0136+57	St	7	4.7	42	Ba81; LM; MIS; XRSS	1844-04	St/T?	6	3.2	32	MGSBT
0154+61	St	6.0	1.6	15	Ba81	1859+03	St(T1/2)	5.25	3.0	35	RSW
0355+54	St	8	6.2	51	MSFB; Ba81; LM; MIS	1900+05	St	6.8	2.8	25	RSW
0540+23	St	8.6	4.9	35	RSW; RB	1900+01	St	4.4	2.9	41	unpublished 1400/430
0611+22	St	7.5	4.2	34	MGSBT; RB; LM	1907+02	St	4.1	2.5	37	RSW; RB†
0626+24	St	7.2	3.5	30	RSW; WABCBF	1907+10	St	6.1	4.6	49	RSW; RB
0740-28	St	10	6.0	37	MHM; MHMA	1907-03	St	6.3	3.4	33	Lyne (1983)
0823+26m	St	3.38	3.4	84	RSW; HR; RB	1911-04	St	~3.0	2.7	64	M71
0833-45m	St	8.18	8.2	90	MHM; MHMA	1913+10	St	4.3	3.9	64	RSW
0835-41	St	3.7	2.8	50	MHM; MHMA	1914+13	St	6	4.6	50	RSW
0940-55	St	7	3.0	25	MHM; MHMA	1915+13	St	6.0	5.6	68	unpublished 1400/430
0942-13	St	4.6	3.2	45	LM; Ba81	1924+16	St	5.7	3.2	34	RSW; RB
0959-54	St	3.9	2.0	32	MHM; MHMA	1929+10i	St	5.15	5.1	88	RSW; RB
1154-62	St	13	3.9	17	MHM; MHMA	1929+20	St	5.3	4.7	63	RSW; GR
1240-64	St	7.2	3.9	33	MHM; MHMA	1930+22	St	6.5	6.4	83	Hankins (1986); GR
1449-64	St	8.5	5.8	43	MHM; MHMA	1933+16	St	5.25	4.1	51	RSW; unpublished 430
1556-44	St	9	4.8	32	MHM; LM; MHMA	1946+35	St(T)	5.5	2.9	32	RSW; RB
1557-50	St	7.0	5.6	53	MHM	1953+29	St	40	31.4	52	SBCDW
1641-45	St	6.7	3.6	33	MHM	1953+50	St	5.8	3.4	36	Ba81; MIS
1642-03	St	4.2	3.9	70	M71; MHMA	2002+31	St/T	2.24	1.7	49	RSW; RB
1702-19i	St	4.5	4.5	85	Biggs et al. (1988)	2053+36	St	9.35	5.2	34	RSW; WABCBF
1706-16	St	5.5	3.0	33	MGSBT; Ba81	2113+14	St?	7.4	3.7	30	RSW; WABCBF
1749-28	St	5.0	3.3	41	MGSBT; MHMA	2217+47	St	5	3.3	42	MGSBT; LGS
1839+09	St	~4.5?	4.0	62	RSW;Ba81; WABCBF	2255+58	St	10?	4.0	24	MGSBT; DLS

† The longitude scale on 1907+02 in RB is in error by a factor of 2.

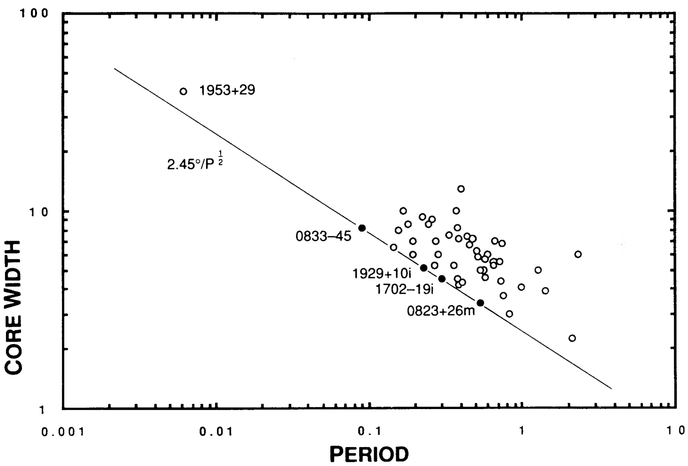

FIG. 1.—Half-power profile width of 50 core-single (S_t) pulsars as a function of period. The symbols of a few prominent pulsars are labeled, and those with interpulsars are indicated by a filled symbol. The indicated curve is $2°45P^{-1/2}$ (see text).

this distribution for core-single (S_t) pulsars with that of other species below.

c) Triple and Multiple Pulsars

The widths of the central core components of pulsars with triple (T) and five-component (M) profiles are given in Tables 5 and 6. Again, the varying precision of the values in the tables reflects the quality and extent of the observations available. Also, the presence of the adjacent conal components in these profiles often made measurement difficult, resulting in the necessity to specify estimates in a number of cases (e.g., $\sim 6?$). References are given to the profiles consulted, and the measurements were interpolated wherever possible to a frequency of 1 GHz.

A plot of these 59 half-power widths is given as a function of period in Figure 3. Pulsars with triple profiles are indicated by triangular symbols, and the the M stars are indicated with squares. Filled symbols are used to indicate the interpulsars which, along with several other prominant stars, are explicitly identified. A curve indicating the fitted widths of the interpulsars (eq. [1]) is again superposed. The core-width values of

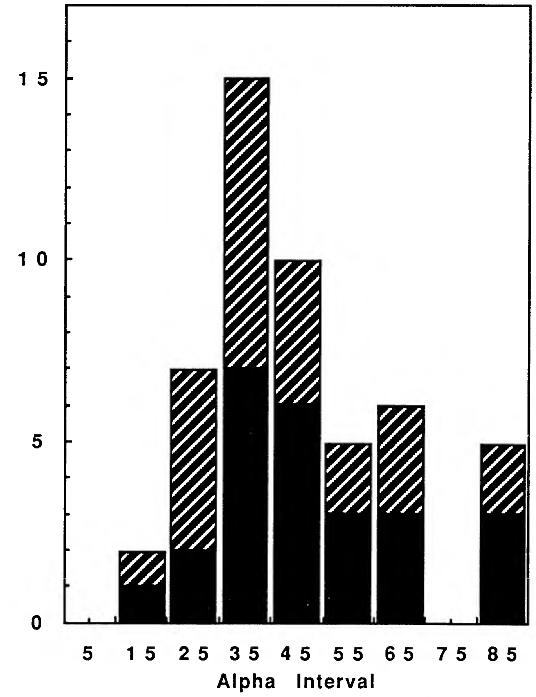

FIG. 2.—Histogram of inferred α values for 50 core-single (S_t) pulsars. The population is divided into two equal groups, a younger group (*solid bars*) whose mean log spin-down age is 5.6, and an older group (*striped bars*) whose mean log age is 6.7.

TABLE 5

CORE WIDTHS OF TRIPLE PULSARS

PSR	Class	Wcore (deg.)	Wcap (deg.)	Alpha (deg.)	Refs.	PSR	Class	Wcore (deg.)	Wcap (deg.)	Alpha (deg.)	Refs.
0329+54	T	5.5	2.9	32	M71; LSG	1821+05	T	5.4	2.8	32	RSW; WABCBF
0450+55	T	~7.2	4.2	36	Ba81; MIS; XRSS	1822-09m	T	2.8	2.8	86	FW; MGSBT; MHMA
0450-18	T	~7?	3.3	28	MHM; MHMA	1826-17	T?	~9?	4.4	29	MGSBT; MHM
0531+21p	T1/2	13.5	13.5	86	BP	1907+00	T	2.43	2.4	89	RSW; RB
0656+14	T/St	~8	3.9	30	unpublished 430	1907+03	T/M	~15?	1.6	6	RSW; HR; WABCBF
0736-40	T	~14	4.0	17	MHM; MHMA	1911+13	T	4.4	3.4	50	RSW; GR
0906-49i	T	7.5	7.5	89	D'Amico et al (1988)	1913+16	T	~14	10.1	46	TW
0919+06	T	~5?	3.7	48	unpublished 1400/430	1914+09	T1/2	6?	4.7	52	RSW; RB
1055-52m	T	≤6	5.5	~90	MHM; MHAK; XRSS	1916+14	T?	~3.5?	2.3	40	MGSBT; RSW; RB
1112+50	T	4.6	1.9	24	MGSBT; Ba81	1917+00	T	2.18	2.2	85	RSW; RB
1221-63	T	~6?	5.3	61	MHM; MHMA	1919+14	T?	~8?	3.1	23	MGSBT; RSW; RB
1451-68	T	~11.5	4.8	25	MHM; MHMA; HMAK	1920+21	T	3.4	2.4	44	RSW; RB
1508+55	T	5	2.8	35	MGSBT; M71; LSG	1926+18	T	3.9	2.2	35	FBWBC
1541+09	T	~32	2.8	5	RSW; Paper I	1929+10m	T	~5	5.1	[90]	RSW; RB
1558-50	T	~4?	2.6	41	MHM; MHMA	1952+29	T	4.8	3.8	51	MGSBT; RSW; RB
1604-00	T	5.1	3.8	48	RSW; Rankin (1988)	2003-08	T/M	10	3.2	19	Ba81; XRSS
1700-32	T	4	2.2	34	MHM; MHMA	2020+28	T?	4?	4.2	85	SCRWB; CRB
1702-19m	T	4.5	4.5	85	Biggs et al. (1988)	2045-16	T	4.0	1.7	26	MHM; M71; MHMA; HMAK
1727-47	T1/2	5	2.7	33	MHM; MHMA	2111+46	T	11.7	2.4	12	MGSBT; Lyne (1983)
1747-46	T?	~3.5?	2.8	54	MHM; MHMA; HMAK	2224+65	T1/2	9.5	3.0	18	MGSBT; Ba81
1804-08	T?	~7	6.1	60	XRSS	2319+60	T	~6?	1.6	16	WF; Lyne (1983)
1818-04m	T	~3.2?	3.2	82	SRW; M71; MHMA	2327-20	T	~2?	1.9	73	MGSBT; MHMA

TABLE 6

Core Widths of Five-Component Pulsars

PSR	Class	W_{core}	W_{cap}	Alpha	References
0523+11	M?	~4°.2?	4°.1	78°	RSW; WABCBF
0621−04	M	~6	2.4	24	Ba81
0826−34m	M	~40?	1.8	3	Biggs *et al.* 1985
1039−19	M?	~4?	2.1	31	LM
1237+25	M	~2.7?	2.1	51	M71; BMSH
1737+13	M	~4.1	2.7	42	RSW; RWS; WABCBF
1738−08	M?	~4?	1.7	25	Ba81; LM
1745−12	M?	~4?	3.9	77	XRSS
1831−04	M	~23	4.5	11	Ba81; XRSS
1857−26	M	~8	3.1	23	MHM; MHMA
1905+39	M	~4?	2.2	33	Ba81; Lyne 1983; XRSS
1910+20	M/T?	3?	1.6	33	RSW; RB
1919+21	M	~3?	2.1	45	PW; C75
2028+22	M?	~3.5?	3.1	62	RSW; Hankins 1986
2210+29	M	~4.3	2.4	35	Wolszczan 1987

the seven triple interpulsars (*filled triangles*) all fall accurately on this curve within their measurement or estimation errors. By contrast, the core-width value for 0826−34m (*filled square*), which has an aligned geometry, falls furthest from the curve.

Again, the core width/period relationship in Figure 3 can be interpreted geometrically according to equation (4) to estimate the angle between the magnetic axis and the rotation axis, α. Here the accuracy is much reduced, but values so determined are again listed in Tables 5 and 6 and plotted in the histogram of Figure 4. The α values for the T (*filled bars*) and M (*striped bars*) stars range more widely than for the S_t stars above. The median value is still about 35°, but the distribution is flatter, and a larger fraction are very nearly aligned ($\alpha \le 20°$).

The α distributions for the triple and five-component pulsars are very similar despite differences in mean log age (6.6 and 7.3, respectively). For α values less than about 60°, where measurement errors are least significant, the histograms are nearly identical. Even above 60°, the distributions are not necessarily different, because the angles for the three M stars (0523+11, 1745−12, and 2028+22) are poorly determined—indeed, probably overestimated—and could thus just as easily fall in the 85° bin. It would be interesting to look for interpulses in these three pulsars.

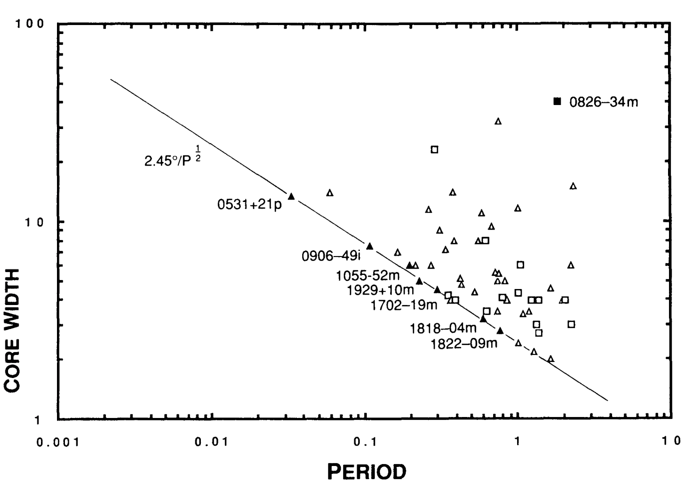

Fig. 3.—Half-power core-component widths of 44 triple (T) pulsars (*open triangle symbols*) and 15 five-component (M) pulsars (*open square symbols*) as a function of period. The symbols of a few prominent pulsars are labeled, and those with interpulses are indicated by a filled symbol. The indicated curve is $2°.45P^{-1/2}$ (see text).

IV. DISCUSSION

We have studied the properties of core emission in core-single (S_t), triple (T), and five-component (M) pulsars. In each group, the interpulsars exhibit core-width values which are given quite accurately by the expression $2°.45P^{-1/2}$, whereas the others have core widths in excess of this value by a factor of $\sin^{-1}\alpha$.

On this basis, the angle between the rotation and magnetic axes, α, has been estimated for a population of more than 100 pulsars. Pulsars with core-single profiles show a strong preference for α values around 35°, with the observed values ranging

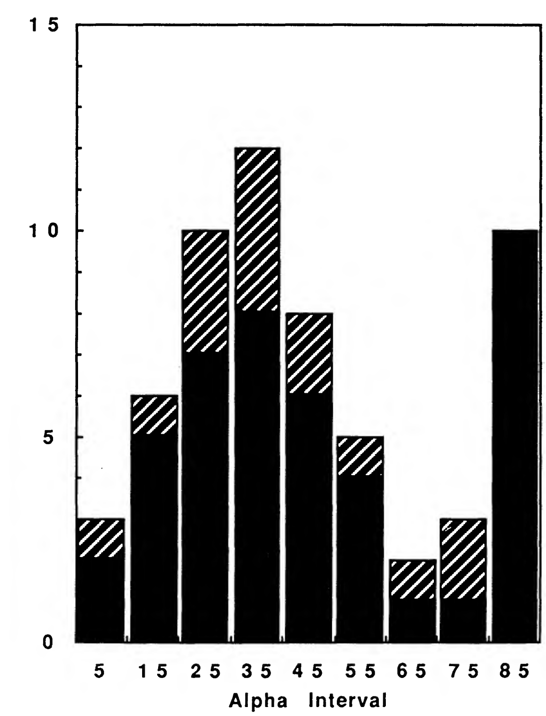

Fig. 4.—Histogram of inferred α values for 44 triple (T) pulsars and 15 multiple (M) pulsars. The first group (*solid bars*) has a mean log age of 6.6, and the second (*striped bars*) has a mean log age of 7.3.

from a low of about 15° to some 65°, and then a possible secondary peak around 90°. The α distribution for triple and five-component stars also peaks around 35°, but the values are more broadly distributed between essentially 0 (3°) and 70°—with a strong secondary peak at 90°.

These results do not suggest any simple statements about the evolution of α with spin-down age. Core-single pulsars are, of course, typically much younger (mean log spin-down age, 6.1) than M stars (7.3), with triple (T) pulsars lying somewhere in between (6.6). The α distributions of the younger and older subgroups of core-single pulsars (mean log ages 5.6 and 6.7, respectively) in Figure 2 show little difference, but the distributions for both the T and M stars in Figure 4 are less peaked around 35°. Also noteworthy are the apparent secondary peaks around 90°. If core-single pulsars evolve into T and M stars, a substantial proportion seem to assume a more orthogonal geometry as well as a more aligned configuration.

Obviously, it would be very interesting to use these α values to study the properties of the conal emission in these three species of pulsars—in core-single stars which have conal outriders at higher frequencies, and in triple and five-component pulsars throughout the spectrum. I will return to this task in a later paper in this series, and we shall see that they also have a surprisingly orderly behavior.

These results have important implications for the nature of the core radiation process, which constitutes some 60%–70% of all pulsar emission. On the basis of the simple geometrical model used above, we apparently must regard the core emission as being physically emitted at very low altitude above the stellar surface—indeed, essentially *at the stellar surface*. There are, of course, other possibilities if some of the assumptions above (such as that the core emission process operates over the whole of the angular region defined by the open field lines) are invalid, but the surprising accuracy of the geometric model in accounting for the core widths of the interpulsars argues strongly for a model that operates at the stellar surface.

A core emission process operating essentially at the stellar surface could be located within the "gap" region, where the particles ultimately responsible for the conal curvature radiation are apparently accelerated. Thus, it is conceivable that both the core and conal emission stem from the same particle bunches and acceleration process. To the extent that the core emission is the primary process of the two, it may play a role in bunching or otherwise facilitating the conditions necessary for the same particles to emit conal curvature emission at a much greater height along their flight.

In an accompanying paper, Radhakrishnan and Rankin (1990), we discuss the characteristic circular polarization associated with core emission and conclude that its properties are also closely associated with the nature of the polar-cap geometry.

The overall picture of the pulsar radiation process which we have begun to develop in this series of papers is in strong disagreement with the views recently outlined by Lyne and Manchester (1988). The forms and positions of the emission components within average profiles appear to be direct manifestations of the *geometry* of the polar-cap emission region. Indeed, the conclusion that core radiation is emitted throughout the polar-cap region near the star implies that each core component is a composite of emission over many (or most) areas of the polar cap, not just from a single "hot spot." Throughout, Lyne and Manchester's use of the terms "core" and "conal" are frequently at odds with the meanings developed in the present series of papers, leading to the construction of categories which confuse the distinct characteristics of core and conal components.

Theoretically, efforts are being made in the Soviet Union to understand the distinction between core and conal emission in terms of different modes of propagation and plasma flow within the polar-cap emission region (BGIa, b; Kazbegi *et al.* 1988, Kazbegi, Machabeli, and Melikidze 1988). Additionally, several other writers have suggested quite different mechanisms for the core emission (Qiao 1988: Wang, Wu, and Chen 1988). It seems premature as yet to attempt to evaluate these efforts in any detail.

I wish to thank V. Radhakrishnan, C. S. Shukre, and J. Gil for helpful discussions and Don Backer, Tim Hankins, Curt Michel, Dan Stinebring, and Joel Weisberg for their comments on the manuscript. I further wish to acknowledge grants from the Vermont EPSCoR Program, the Cottrell Fund of the Research Corporation, and the Graduate College of the University of Vermont in partial support of this work. Arecibo Observatory is operated by Cornell University under contract to the National Science Foundation.

APPENDIX

CLASSIFICATION OF PULSARS WITH INTERPULSES

0531+21.—The Crab pulsar's three profile features, the precursor, the main pulse, and the interpulse (Rankin *et al.* 1970), exhibit almost no polarization angle rotation (Campbell, Heiles and Rankin 1970), strongly indicating two-pole emission. Classification, however, is more difficult: The precursor, by virtue of its softer spectrum (Boriakoff and Payne 1973) and steadier modulation (Heiles, Rankin, and Campbell 1970), should probably be regarded as a core component, and its linear polarization is so nearly complete that any circular signature would be disrupted by instrumental cross-coupling (Rankin, Campbell, and Spangler 1975). If we then interpret the precursor as the star's core component, the overall precursor-mainpulse profile could be seen as a one-sided triple ($T_{1/2}$) form, but the spacing is large and we have little independent basis (polarization or modulation?) for identifying either the main pulse or the interpulse as conal features.

0823+26.—The main pulse is readily identified as a core component by virtue of its circularly polarized signature, and the weak interpulse may be one also (RSW). The overall main-pulse–postcursor complex might again be regarded as a $T_{1/2}$ profile, but the 30° spacing is again rather large. Polarization angle modeling (e.g., Lyne and Manchester 1988, hereafter LM) strongly indicates that the magnetic and rotation axes are nearly orthogonal, α being close to 90°.

0826−34.—This star's exceedingly wide profile is suggestive of a nearly aligned rotator (Biggs *et al.* 1985), and polarizing-angle modeling seems to bear this out (LM). At first glance, the main pulse appears to have a conal double profile, but its circularly polarized signature suggests that we are actually seeing a five-component (M) profile with merged components—a conclusion which is supported by the five discernable "subpulse paths" in individual pulse sequences (Biggs *et al.* 1985, Fig. 2). The interpulse, which only appears at 1400 MHz, seems to have a conal single (S_d) form.[4]

0833−45.—The Vela pulsar is a core-single (S_t) pulsar. It is single at 600 MHz and below (Hamilton *et al.* 1977; McCulloch *et al.* 1978, hereafter MHMA) but appears to have at least one outrider at higher frequencies (Downs, Reichley, and Morris 1973). The trailing outrider is quite clearly discernible at 21 cm and becomes progressively stronger at shorter wavelengths. Unfortunately, there are no reliable profiles available in the literature above 2400 MHz, so that the high-frequency evolution of this important pulsar's profile is as yet uncertain. Its linear polarization is again so high that instrumental cross-coupling would presumably disrupt any circular signature. No radio interpulse is found in this star, and so its overall emission geometry is uncertain. Despite their complexity, however, the X-ray and γ-ray profiles together with the radio emission suggest that a two-pole model is probably appropriate for this star.

0906−49.—This star was recently discovered by D'Amico *et al.* (1988) in the course of a search for millisecond pulsars at Molonglo. Only one total-power profile at 843 MHz is available. But for a trailing-edge feature at the 15% level, the main-pulse shape is almost single; this feature is probably a conal outrider. The interpulse, which is about 20% of the main-pulse amplitude, has prominent central component flanked by what appear to be conal outriders. Polarimetry at several frequencies is required to make a certain classification, but both the main-pulse and interpulse profiles seem to be dominated by bright core components; thus, the main pulse appears to have a core-single (S_t) profile, and the interpulse has a triple (T) profile.

0950+08.—This pulsar is the prototype single-pole interpulsar following the analysis of Narayan and Vivekanand (1983), and polarization angle modeling (e.g., LM) strongly reiterates this conclusion. The main-pulse profile has a standard conal single (S_d) form, and in most respects the interpulse appears to be a member of the same class (RSW).

1055−52.—The main pulse exhibits a well-resolved triple form (MHMA), and its central feature has a somewhat softer spectrum than the outer components (McCulloch *et al.* 1976). The linear polarization is virtually complete, so that no reliable circular signature is expected. Clearly, we should regard the main pulse as having a T profile. The existing interpulse observations are inconsistent and provide no obvious interpretation. The pulsar's magnetic and rotation axes are almost certainly nearly orthogonal; polarization angle fitting (LM) has produced spurious results, probably because of an unresolved $\approx 180°$ angle transition associated with the central component.

1702−19.—A recently discovered interpulse in this pulsar has been reported by Biggs *et al.* (1988). Both main pulse and interpulse are conspicuous for their strong ($\geq 60\%$) circular polarization. The main pulse has a central core component and a closely spaced pair of conal outriders, making it a probable member of the triple (T) class; on the other hand, the interpulse appears single and therefore appears to have a core-single (S_t) profile. Position angle modeling (LM), as well as the precise interpulse–main pulse spacing ($181° \pm 1°$), strongly indicates that the angle between the magnetic and rotation axes, α, is close to 90°.

1736−29.—This star is among the pulsars discovered by Clifton and Lyne (1986). Both its main pulse and strong interpulse appear narrow and single, but the one available 21 cm profile is of poor quality. The star's period and spin-down, however, clearly mark it as core dominated, and thus we have every reason to expect that it will have either triple or core-single profiles and a nearly orthogonal emission geometry.

1818−04.—The main pulse of this star is a member of the triple (T) species, although many observations do not resolve it well enough at meter wavelengths to clearly show its three closely spaced components. The profile exhibits some circular polarization but no characteristic signature. The interpulse reported by Perry and Lyne (1985) is exceedingly faint, and nothing can be said about its classification. Although the star's weak linear polarization provides little polarization angle information, the component spacing and lack of unpulsed emission suggest that the magnetic and rotation axes are nearly orthogonal.

1821−24.—Only one rough total-power profile, which appears to have both a main-pulse and interpulse, is available for this pulsar (Lyne *et al.* 1987). No classification can be made at this time.

1822−09.—The main pulse has a highly asymmetric triple ($T_{1/2}$) profile, as discussed at length in Rankin (1986); component 1 is conal and component 2 is a composite of leading and trailing features, the earlier of which seems to be the core component (see FW). The interpulse observations are very weak, but its profile is composite and the strongest feature appears to be a core component. No modeling of the position angle has been reported for this star, but the spacing and lack of baseline emission suggest that the magnetic and rotation axes are nearly orthogonal.

1855+09.—This 5.3 ms binary pulsar was discovered by Segelstein *et al.* (1986). Its ostensibly double main pulse shows both the sense-reversing circular signature associated with a core component and the S-shaped, $\leq 180°$ polarization angle traverse indicative of a conal component pair. Apparently, we should regard the main pulse as a triple (T) with a superposed core and conal component. The evolution of the star's profile is as yet unclear, because only 1400 MHz observations are now available. Polarization angle modeling has thus far been inconclusive, owing to what appear to be modal shifts under both the main pulse and interpulse. It would be surprising, however, were the star's magnetic and spin axes not nearly orthogonal.

1929+10.—The main-pulse profile consists of a core component closely flanked by one or possibly two sets of conal outriders (Hankins and Rickett 1986, hereafter HR), so that the central core component is not readily distinguishable. The interpulse consists of a strong core component flanked by weak conal emission (RSW). Again, the linear polarization is too great to expect reliable circular labeling.[5]

[4] It is interesting to speculate that, in this closely aligned geometry, conal spreading might result in this conal single interpulse becoming continuous at low frequency, with the effect that we would "miss" it.

[5] Indeed, the strong negative circular associated with both the main pulse and interpulse as reported by Rankin and Benson (1981) and republished by LM is undoubtedly due to instrumental cross-coupling (Rankin, Campbell, and Spangler 1975).

The question of whether a one- or two-pole model is correct for this star is quite interesting. Polarization angle modeling based on the observations of Rankin and Benson (1981) has given quite inconsistent results, essentially because the observed polarization angle traverse of the main pulse is so slow ($-1^\circ\!.5/^\circ$). Narayan and Vivekanand (1982) find α large, indicating a two-pole model, but they also obtain an implausibly large value of β. LM, on the other hand, find α small, indicating a single-pole model, but their analysis leads to the wildly improbable result that the angular radius of the emission cone is some 90°. Moreover, were we seeing emission from a single pole, we should expect to see some change in the main-pulse–interpulse separation with frequency due to conal spreading (as we *do* see in 0826 − 34!), but no such effect is observed in 1929 + 10 (Hankins and Fowler 1986).

The resolution of this paradox is probably that the polarization angle undergoes an unresolved $\approx 180°$ transition during the main pulse (as in 1237 + 25), which leads to a large α value and a two-pole model. Indeed, some high-quality profiles do show a small departure from linearity under the central component, which may well be a remnant of this transition (e.g., see RB). Against this interpretation is the low-level emission between the main pulse and interpulse identified by Hankins (1983) and by Perry and Lyne (1985). The pulsar 1929 + 10, however, is both intrinsically bright and the second closest known pulsar—thus, we may be able to discern detailed features of its emission that would be far too weak in more distant pulsars.

1937 + 21.—Very little can be said about the classification of this exceedingly important pulsar. High-quality polarization measurements are available at both 430 and 1400 MHz (Stinebring *et al.* 1984), but the profile forms present severe problems in classification. Presuming that we are dealing with a two-pole interpulsar, both the main-pulse and interpulse profiles are too narrow to be core-single profiles. On the other hand, it would be very surprising if such a fast pulsar exhibited prominent conal emission (B_{12}/P^2 is 162 for this star!!).

1944 + 17.—This star has an unusual conal triple (cT) profile (RSW), and a weak interpulse is reported by Hankins (1984). The polarization angle information provides little geometrical insight, but the rather wide main and interpulse profiles with their broad wings suggest that the spin and magnetic axes are closely aligned.

1957 + 20.—This star is the most recently discovered millisecond pulsar. The first published profile (Fruchter, Stinebring, and Taylor 1988) shows what appear to be a pulse and interpulse, but little can be said about their classification at this time.

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