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TOWARD AN EMPIRICAL THEORY OF PULSAR EMISSION. VI. THE GEOMETRY OF THE CONAL EMISSION REGION

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ABSTRACT

This paper presents an empirical analysis of the geometry of the conal emission region for a total population of some 150 pulsars for which an adequate body of observations now exists. It continues the analysis begun in a previous paper that explored the geometry of the core emission region and provided a means of estimating the angle α between the rotation and magnetic axes of pulsars with core components. The various pulsars are thus divided into groups according to their morphological classification, and those species that have core components are treated first.

Special consideration is given to the five-component (M) class and to those other, entirely conal species which are closely related to it, the conal triple (cT) and the conal quadruple (cQ). An adjunct appendix discusses the classification of these "double-conal pulsars"—that is, the nearly 20 M pulsars as well as the four known cT stars and the five cQ candidates.

The conal emission geometry of this group of five-component (M) stars is considered first. Their two pairs of conal components suggest that both an "inner" and "outer" hollow conal beam is emitted. For each pulsar several geometrical parameters are calculated: The angle α between the rotation and magnetic axes of the star is computed from the core width, the impact angle β from the steepness of the polarization-angle traverse, and the radius of the conal emission beam ρ from these quantities as well as the measured width of the conal component pair $\Delta\Psi$. Finally, the emission height r is simply scaled according to the dipolar geometry of the "last open" field lines.

The conal emission radii of the five-component M pulsars exhibit a behavior which is striking in its orderliness: The "inner" and "outer" radii have the following dependencies at 1 GHz, $4.^{\circ}3P^{-1/2}$ and $5.^{\circ}8P^{-1/2}$, respectively, where P is the pulsar period. As both the conal radii and the core width scale as $P^{-1/2}$, the emission height (at a given frequency) is found to be independent both of the pulsar period and the magnetic inclination angle α. The "outer" cone then appears to be emitted at a 1 GHz height of about 220 km, and, if the "inner" cone is also emitted on this same set of field lines, its emission height is about 130 km.

The other species also exhibit great regularity in their conal emission geometry. Virtually all of the core-single (S_t) pulsars which develop conal outriders at high frequency have a conal geometry which corresponds to the "inner" cone of the M stars. The triple (T) pulsars also have a conal emission geometry which closely matches that of the five-component pulsars; they divide in roughly comparable numbers between those which emit an "inner" and those which emit an "outer" cone.

The final three, entirely conal classes entail additional difficulty because they lack a core component; therefore α cannot be directly determined. For these pulsars reference is made to the work of Lyne & Manchester, and, where possible, α-values were used which were close to those determined in their study. Generally, the cT and cQ pulsars seem to have conal geometries which are compatible with their classification—that is, they represent more peripheral sight-line trajectories through a double-conal emission pattern. Finally, among the conal double (D) and single (S_d) pulsars most appear to emit "outer" cones, although a handful appear to have an "inner" conal emission geometry.

It is not yet clear why some pulsars have an "inner" conal emission geometry, others an "outer," and still others have both an "inner" and an "outer" geometry. Only the pulsar rotation period appears to distinguish, statistically, between these various groups. Pulsars with "inner" cones are generally faster, those with "outer" cones much slower, and the group of five-component (M) pulsars (which emits both cones) falls in between the other two.

A major unanswered question is whether the "inner" cone is emitted at a lower height along the same group of peripheral field lines that produce the "outer" cone (as has been assumed, for purposes of calculation, in this analysis), or whether it is emitted at some greater height along a group of more interior field lines. Several different circumstances which might be capable of producing two conal emission beams are reviewed.

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1. INTRODUCTION

In the foregoing papers of this series (Rankin 1983a, b, 1986, 1990; Radhakrishnan & Rankin 1990, hereafter Papers I–V, respectively), the characteristics of pulsar profiles have been studied in an effort to understand the basic nature of their radio-frequency emission processes. Two distinct types of emission component were identified, *conal* and *core*. One of the most common types of profile, the triple (T), then consists of a central core component preceded and followed by a conal component pair (i.e., conal "outriders"). Both types of emission appear closely associated with the bundle of field lines immediately surrounding the magnetic axis of the pulsar (the so-called open field lines which define the "polar-cap" region). The core emission is emitted in a "pencil" beam relatively close to the stellar surface, and the conal emission forms a hollow-conical beam which is radiated at a height of some 10^8 cm.

In Paper IV we determined that the widths of the core components are intimately related to the polar-cap geometry at the stellar surface. A simple mathematical expression (see eq. [1]) established through the study of two-pole interpulsars indicates that the half-power width of a core component depends only upon the pulsar period P and α, the angle between the rotational and magnetic axes of the star. This relationship can then be used to estimate α for any pulsar with a core component.[2] Values of α were estimated for a number of core-single (S_t), triple (T), and five-component (M) pulsars and were found to range between about 3° and 90°, peaking sharply at about 35°.

In this paper we turn our attention to the geometrical properties of the conal emission. Historically, we have had no reliable means of estimating the magnetic colatitude α, and this circumstance has greatly impeded study of the geometry of the conal radiation beam.[3]

For those pulsars with both core *and* conal emission, however, we are now in a position to use the core-width relation to determine α, so that we can fully analyze the radius and orientation of the conal beam. In the sections that follow, we begin with a study of the five-component (M) pulsars, the core-single (S_t) and triple (T) stars, and then extend the results as far as possible to those species which lack a core component. As usual, however, we must first give some attention to classification, in this case to the five-component (M) stars and to those other classes of pulsars with double-conal profiles, the conal triple (cT) and the conal quadruple (cQ).

An Appendix and eight tables are mentioned below, but because of their length these have been published separately (Rankin 1993). They will be referred to, however, as if they are physically a part of this paper. The discussion in the Appendix is summarized in Figure 1, and the details of the analysis in the tables is plotted in various of the figures. A general reader then need not refer to them, but those readers interested in specific pulsars, their classification, or the implications of classification on the geometrical questions discussed below should have access to the Appendix and tables.

2. CLASSIFICATION OF PULSARS WITH DOUBLE-CONAL PROFILES

We have long known that certain odd pulsars had profiles with five emission components. Pulsars 1237+25 and 1857−26 are the best known cases, but a number of other stars have "boxy" profiles which appear to consist of about five closely spaced components. Evidence has been accumulating, however, to the effect that these pulsars have just five components and that they constitute a distinct species with highly coherent characteristics (see Rankin 1992).

Consideration of the characteristics of these profiles shows that the central component (III) is a core component with all the usual properties of antisymmetric circular polarization, a relatively steep spectrum, and "red" fluctuation characteristics. Furthermore, the remaining four components are most easily understood as representing two concentric conal zones—an "outer" (components I and V) and an "inner" (components II and IV) zone, respectively—again with the usual S-shaped traverse of the linear position angle, a relatively flat spectrum, and orderly, rapid pulse modulation.

Recognition of these double-conal profiles as a distinct observational phenomenon is important for two reasons. First, the five-component (M) profiles represent the highest degree of profile complexity that the pulsar emission process is apparently capable of producing. *We have no good examples of profiles with six or more components and very few candidates of pulsars with just four-component profiles.* Second, the implication of *two* conal emission zones is surprising theoretically. A single hollow-conal emission region follows as one of the most fundamental ramifications of polar-cap geometry, and a number of pulsar emission theories envision just such a configuration. The general occurrence of two (and only two!) pairs of conal components then challenges us positively to reexamine our suppositions.

Proceeding, however, on the strength of the observational evidence that the five-component profiles provide, we can draw a cartoon of the composite double-conal/core emission beam and consider what other kinds of profile patterns or morphologies might result from it. Such a diagram is given in Figure 1.

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[2] While this appears to be true, it is not always easy to measure the width of a core component accurately. Because the core component occupies a central position within the profile, very frequently there are other components so closely adjacent to the core that its "wings" are not discernible. Also, some core components are "notched" and narrowed at meter wavelengths by the "absorption" phenomenon (see Paper II).

[3] In principle α can be measured from the character of the polarization-angle traverse, but in practice the linear angle behavior is much more dependent upon β, the impact angle of the sight line, than upon α.

Lyne & Manchester (1988) have developed an interesting technique for estimating α which takes into account both the polarization-angle trajectory and the angular width of the conal emission pattern. Using this method, they studied the linear polarization-angle behavior of some 160 pulsars and have obtained estimates of α for more than 100.

In application, however, their method has produced results (and certainly interpretation) which must be approached with some caution. First, it depends upon classifying the pulsar population into physically meaningful categories, and, despite using terminology reminiscent of that in Paper I, their classification is quite problematic. Their rigid adherence to the Radhakrishnan & Cooke (1969) model led them to posit radiation from "partial cones," the existence of which in any number is doubtful. Second, for purposes of calculation, they assume a period dependence for the conal beam ($\rho = 6.5P^{-1/3}$, their eq. [6]), which now appears incorrect from several different points of view.

We shall see below that many of the α-values estimated by Lyne & Manchester are in close agreement with those calculated in this paper. Others, however, are wildly different, and, when so, the reason can usually be traced to issues of classification.

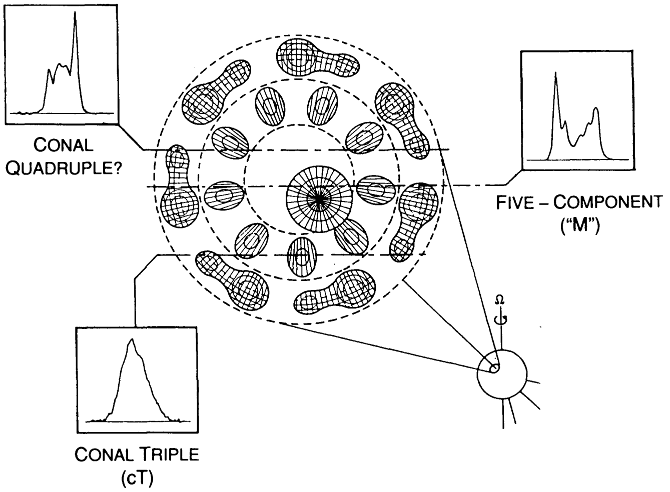

FIG. 1.—Schematic diagram showing the possible profile forms that follow from the double-conal emission geometry. Two conal emission zones and a core beam are indicated. In addition to the five-component (M) profiles, entirely conal profiles with either three or four components can be produced, depending upon the centrality of the sight-line traverse. There is also the possibility that the sight line will cut the "outer" cone tangentially, but this situation results in a conal single profile indistinguishable from that produced by a single "outer" conal beam.

Two circular conal zones and a core beam are indicated.[4] Sight lines which cross close to the magnetic axis make an oblique traverse through both conal zones and generally encounter the core beam also, resulting in the usual five-component (M) profile. However, it is also possible that the sight line will miss the core beam or that it will be relatively weak or absent. As shown in the figure, this would produce either three- or four-component, entirely conal profiles. A few examples of stars with conal triple (cT) profiles have been identified (Hankins & Wolszczan 1987), and several other pulsars with possible conal quadruple (cQ) profiles will be discussed below.

There are several reasons why five-component profiles were not earlier recognized as a distinct species. First and foremost, many M profiles have a "boxy" shape in which individual components are not easily identified. Experience now shows that (at higher frequencies) most M stars have closely spaced or even merged components and, if either the signal-to-noise ratio (S/N) is poor or the resolution degraded, it may not even be clear that the profile *has* components! The squarish, "boxy" shape of such profiles is thus important, because no other species assumes this form—and in every case studied in detail so far, the structure has been the same, two pairs of conal components and a central core component.

This "boxy" form is most pronounced at high frequency because of conal narrowing. The "outer" cone generally seems to narrow more rapidly than the inner, so that above 1 GHz the pairs of leading and trailing components tend to become merged. The exemplars, $1237+25$ and $1857-26$, clearly show this behavior; at high frequency the former's components are difficult to distinguish, and no existing high-frequency profile resolves the latter pulsar's profile into components at all.

Another issue is that both $1237+25$ and $1857-26$ evolve toward triple forms below about 400 MHz. Study has shown that components II and IV have flatter spectra than I and V—consequently, by about 100 MHz the "inner" conal components are hardly detectable. This behavior has misled some investigators to conclude that such profiles had *variable* numbers of components. Rather, the observations indicate that *all known pulsar profiles have a fixed number of components, each with somewhat different spectra.* This is a very different matter and has wholly different implications about the character of the pulsar emission process.

Similarly, the core component typically exhibits a steeper spectrum than either pair of conal components, and sometimes subsides altogether at high frequency. This circumstance has led to the perception that some pulsars have four-component profiles—and, indeed, one need only to look at some of the M stars at moderately high frequency to see examples. As noted above, some candidate (cQ) stars have been identified, but none of these is as yet so well studied that a core-emission feature can be entirely excluded. The absence of conal-quadruple profiles might imply that core radiation is never absent in pulsars with double-conal emission, but we cannot yet draw this conclusion with certainty.

The "absorption" phenomenon can further confuse the component count: at meter wavelengths some pulsars have an "unresolved double" core component which becomes single again at both higher and lower frequencies ($0329+54$ provides a good example; see Papers II and III). No one has yet explained why such components become "notched"—typically between about 200 and 800 MHz—but the observational evidence for the effect is very clear.

Nearly 20 pulsars have now been identified which appear to be members of the five-component (M) class. Their designations, along with some other relevant information, are given in Table 1. With three exceptions the list is identical to the one given in Paper IV (Table 1), but seven new stars have been added. Again, it is worth noting that these pulsars represent a physically coherent group; their acceleration potentials (scaling as B_{12}/P^2 [or as $1/Q$ in the work of Beskin et al. 1986, 1988, see Paper IV]) are generally low, their spindown ages moderately large, and most lie at rather high Galactic latitude, also suggesting that they are old.

3. CONAL EMISSION IN PULSARS WITH FIVE-COMPONENT PROFILES

It may seem strange to begin our study of the conal emission geometry by first looking at the pulsars with five components. Given, however, that they apparently reflect the full phenomenological potential of the emission process, they will then also provide the most geometrically comprehensive subjects of study.

We shall proceed first by determining α, the angle between the magnetic and rotational axes. In Paper IV we studied the characteristics of those pulsars with interpulses—which also had core components—and derived a simple relation between the 1 GHz half-power width of their core component $W_{\rm core}$ and the angle α as follows

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

where P is the pulsar period.

Here this calculation is not entirely straightforward, because the width of the core component of many M stars is not at all easy to determine. The core component of these stars tends to

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[4] This figure is similar to one which appeared earlier in Paper I. The conal zones are here drawn circular as there is no longer any strong evidence for the latitudinally extended elliptical beams suggested by Narayan & Vivekanand (1983). Indeed, evidence is now accruing that pulsar beams are elongated in the longitudinal direction (Paper V; Biggs 1991; McKinnon 1992), but the assumption of a circular beam appears quite adequate for the current analysis.

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be resolvable only at about 600 MHz and below, and we need to determine its width at 1 GHz, where the components of many M pulsars are merged into the usual "boxy" form. Nonetheless, in most cases it is possible to make a surprisingly accurate estimate or educated guess. A number of these pulsars have well-resolved core components at around 600 MHz, and one can extrapolate to 1 GHz with reasonable accuracy. Even in cases where the core component is barely identifiable (i.e., owing to component merging or observations with low S/N), one can place an upper limit or estimate how wide it might be, given the configuration of the other components. Therefore, the core-width values in Table 1 have different uncertainties depending upon how well resolved a particular pulsar's core component is (see the notes to Table 1).

A further indication of the reliability of these estimates will come when the component structures of many pulsars have been modeled as the result of a series of Gaussian-shaped contributions. Wu, Xu, & Rankin (1992) have carried out such an analysis for pulsar 1451−68, and the benefit of their work is included in Table 1, although direct measurement here indicates a value slightly smaller than that obtained from the fitting. In any case such modeling would, I believe, generally corroborate the values given here.[5]

We now turn to the geometry which applies to the conal emission region. This geometry is depicted in Figure 2. Assuming a dipolar magnetic-field configuration, we take the conal emission region to be roughly circularly symmetric about the polar axis.[6] The problem of determining the radius ρ of the conal emission beam then reduces to a relation of spherical geometry (Gil 1981) involving β and $\zeta[=\alpha+\beta]$, the impact angles of the sight line with respect to the magnetic and rotation axes, respectively, and $\Delta\psi$, the full 1 GHz width of the conal emission pattern in longitude, measured between the outside half-power points of the profile:

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

To the extent that the polarization angle χ as a function of longitude φ (exclusive of polarization-mode changes) follows the single-vector model (Radhakrishnan & Cooke 1969; Komesaroff 1970),

$$\tan\chi = \frac{\sin\alpha\sin\varphi}{\cos\alpha\cos\zeta\cos\varphi-\sin\alpha\sin\zeta}\,,$$

the maximum rate of polarization-angle rotation at the center of the profile provides a means of estimating the magnitude of β as follows:

$$\sin\beta = \sin\alpha/|d\chi/d\varphi|_{\max}\,. \tag{3}$$

The sign of β must be determined from the form of the position-angle traverse and was taken positive whenever significant "flattening" was observed in the wings of the profile (Narayan & Vivekanand 1982). In any case, as long as $|d\chi/d\varphi|_{\max}$ is not close to unity, this sign has a small effect on the calculations which follow.

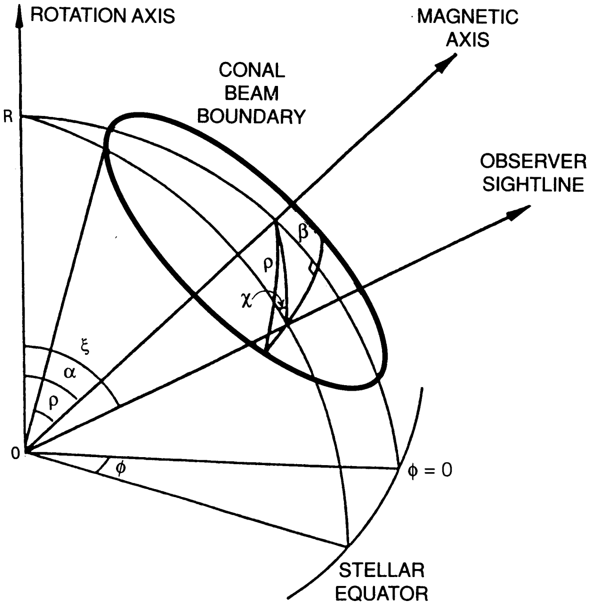

FIG. 2.—Geometry of the conal emission region (after Manchester & Taylor 1977).

Taken together these relations can be used to solve for ρ as follows:

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

The various values pertaining to the conal emission geometry for the group of five-component (M) pulsars are listed in Table 2: the derived α-values, $|d\chi/d\varphi|_{\max}$, and the half-power widths of the respective "inner" and "outer" conal component pairs. These latter values refer to the distance between the two outside half-power points of each conal outrider pair, and where possible are interpolated to 1 GHz in keeping with our general practice. Note that the $\Delta\psi_{\text{outer}}$ values are generally quite accurate, whereas the $\Delta\psi_{\text{inner}}$ are much less so owing to the proximity of the "outer" components. Columns in the table also give the derived β-value, the conal emission radii, ρ_{inner} and ρ_{outer}, and the ratios $\beta/\rho_{\text{inner}}$ and $\beta/\rho_{\text{outer}}$.

First of all, note that the values in Table 2 are plausible in qualitative terms. For most of the stars the sight line makes a relatively central traverse through the "outer" emission cone; this is shown clearly by the $\beta/\rho_{\text{outer}}$ values which generally are well less than 0.6. Only three pulsars have larger values (1952+29, 2028+22, and 2310+42), and each of these stars has a profile wherein the core component and/or the "inner" pair of conal components are difficult to distinguish. Perhaps we would have been better advised to regard the latter two pulsars as having conal quadrupole (cQ) profiles. Similarly note that the "inner" traverses as measured by $\beta/\rho_{\text{inner}}$ are somewhat less central and that the two most tangential (of those which could be estimated) are again 1952+29 and 2310+42.

Leaving aside for the moment questions regarding the geometric interpretation of these *two* pairs of conal components, let us examine the width values which are plotted as a function of pulsar period in Figure 3. The ρ_{outer} values are plotted as

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[5] Interestingly, two pulsars (1237+25 and 1952+29) have apparent core widths at meter wavelengths which are impossibly small—less than $2.45/P^{1/2}$. Closer examination shows that both almost certainly represent cases of "absorption" (see Paper II). In the case of 1237+25 the absorption "notch" can be seen in some "abnormal" mode profiles, and its "resolved-double" shape probably in part explains why the core component trails the center of symmetry of the profile.

[6] This assumption, of course, is at slight variance with both calculations (i.e., Sturrock 1971) and our own results in Paper V. It is a matter of little consequence here, however.

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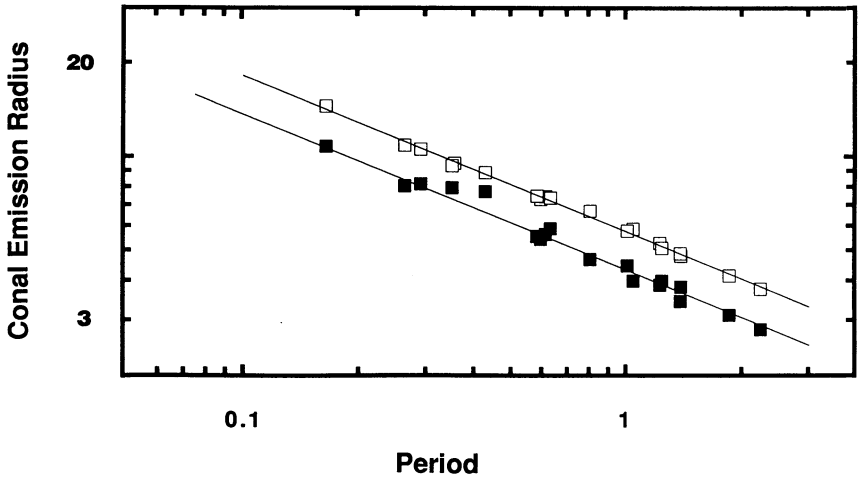

FIG. 3.—Conal radius ρ as a function of period for the "inner" (*solid symbols*) and "outer" (*open symbols*) conal zones of five-component (M) pulsars. The dotted curves $4^{\circ}.3P^{-1/2}$ and $5^{\circ}.8P^{-1/2}$ are indicated.

open square symbols and the $\rho_{\rm inner}$ as filled squares, respectively. The orderly behavior of the M class of pulsars is particularly evident here. Both the period and pulse width values span nearly an order of magnitude, but the emission-cone radii fall within less than a factor of 4 and exhibit a shallow inverse-period relationship.

Least-squares fits to the emission-cone radii in Figure 3 yield the following relationships

$$\rho_{\rm outer} = 5^{\circ}.75P^{-0.50} \quad \rho_{\rm inner} = 4^{\circ}.33P^{-0.52} , \tag{5}$$

where the formal 1 σ uncertainties in the magnitudes and indices are about $\pm 0^{\circ}.1$ and ± 0.01, respectively. More realistic error estimates are difficult to determine, given all of the estimates and uncertainties which have gone into the calculation; however, they probably do not increase the formal errors by more than a factor of 3 and might be less.

Interestingly, the emission-cone radii exhibit a period dependence very like that of the core components above, and at 1 GHz the "outer" and "inner" radii differ by a factor of about 4/3. On the assumption that these conal emission-zone radii are also bounded by the last "open" field lines at some height above the stellar surface, we can estimate this height by comparing the conal emission beam radius with that of the core beam, which we have argued reflects the emission geometry at the stellar surface. On any given dipolar field line the height is proportional to ρ^2, thus $r_{\rm cone}/r_{\rm core} = (\rho_{\rm cone}/\rho_{\rm core})^2$. Using equation (1), the core emission beam radius is $2^{\circ}.45/2P^{1/2}$, then

$$r[{\rm km}] = 10(\rho/1.225P^{-1/2})^2 = 6.66\rho^2 P , \tag{6}$$

where $r_{\rm core}$ is assumed to be 10 km.

The results of these calculations are given in Table 2. The 1 GHz values of $r_{\rm outer}$ and $r_{\rm inner}$ fall narrowly around 220 and 130 km, respectively. That the emission radii of both the conal and core beams scale accurately as $P^{-1/2}$ suggests that the 1 GHz height of the conal emission is independent both of rotational period and of magnetic inclination angle α. It is striking again how remarkably homogeneous this group of M pulsars is.

In concluding this discussion on the five-component pulsars, let us now turn to the question of how the conal emission radii and emission heights change with radio frequency. Unfortunately, among the group of 18 pulsars in Tables 1 and 2, only three, 1237+25, 1451−68, and 1857−26, have been observed over a sufficiently wide frequency range to study this evolution in detail; and for only two of these, 1237+25 and 1451−68, can we trace the "inner" components over a significant range of frequency—in the first case because they are relatively well resolved and in the latter by virtue of the component-fitting work of Wu et al. (1992).

The measured values of the conal widths and the resulting estimates of the conal radii and emission heights as a function of frequency are given in Table 3. The values of α and β used here are identical to those given in Tables 1 and 2. Pulsar 1237+25 gives the most complete picture. Observations are available between 49 and 4870 MHz, and the bulk of these (all except those at 278 and 178 MHz; MHMb) are Arecibo observations of exceptionally high sensitivity and resolution (Hankins, Rankin, & Stinebring 1992). Over this nearly seven-octave range the "outer" conal emission radius changes by almost a factor of 2, whereas the "inner" conal emission radius varies much less steeply. Quantitatively, least-square fits to the emission radii values in Table 3 have the following dependencies: $3^{\circ}.41f_{\rm GHz}^{-0.08}$ and $5^{\circ}.04f_{\rm GHz}^{-0.15}$, respectively. Throughout this range, the emission height of the "outer" cone varies by more than a factor of 3 from some 170 km at 4870 MHz to about 600 km at 49 MHz. The height of the "inner" cone radiation changes more narrowly between some 90 km at 4870 MHz and 160 km at 111 MHz. Fits to these values result in the following expressions: $r_{\rm outer}$ and $r_{\rm inner}$ equal 234 km $f_{\rm GHz}^{-0.27}$ and 107 km $f_{\rm GHz}^{-0.15}$, respectively.

Results for pulsars 1451−68 and 1857−26 are also given in Table 3. Between 170 MHz and about 2 GHz the "outer" conal emission radii have indices of −0.18 and −0.15, respectively; whereas in both cases the "inner" ones appear to have a less steep dependence, but cannot be accurately measured. For 1451−68 between 170 and 1612 MHz we find fitted emission-height values of 208 km $f_{\rm GHz}^{-0.36}$ and 115 km $f_{\rm GHz}^{+0.08}$, respectively. Note that there is really no evidence for a change of the "inner" conal emission height at all, in that the 1612 MHz value is the least reliable of the group. Finally, we find a fitted dependence of 249 km $f_{\rm GHz}^{-0.30}$ for the emission height of the "outer" cone of 1857−26 over a frequency range of 170–2650 MHz.

For seven other pulsars in Table 2, it was possible to estimate the frequency dependence of the radius of the "outer" cone between two low frequencies. Four of the pulsars have been observed at 200 MHz or below and the remainder at some higher frequency. The mean index for these pulsars was again very close to that found for the three stars discussed above, -0.14 ± 0.02.

The very different frequency dependencies of the "inner" and "outer" conal emission heights of these double-conal pulsars are notewothy and appear well founded in the observations. Not only does it point to rather different circumstances of emission, but also—because this behavior implies an overlapping of the "inner" and "outer" cones at higher frequency—it begins to suggest quantitatively why so many M pulsars seem to have "boxy," "squarish" profiles with poorly distinguished components above 1 GHz.

4. CONAL EMISSION IN PULSARS WITH CORE-SINGLE PROPERTIES

Let us now consider the core-single (S_t) pulsars. It may again seem paradoxical to investigate *conal* emission in a class of pulsars which, at meter wavelengths, emit almost entirely core radiation. Many of these stars, however, develop conal outrider pairs at frequencies above 1 GHz, and so it will be interesting to see how the geometrical properties of the conal beams of these stars compare with the double-conal pulsars considered in the foregoing section.

Proceeding as above, we first determine α by measuring the width of the core component and applying equation (1). Given the "single" form of S_t profiles below 1 GHz, the core component width is identical to the overall profile width, and so the 1 GHz interpolated width can sometimes be determined with an accuracy only dependent on the sensitivity and frequency extent of the observations. Of course, not all core-single pulsars exhibit distinct conal components at high frequency, and for a few of those that do, only a single conal component is apparent. Therefore, out of a population of 49 S_t pulsars which have been identified, only 22 have high-frequency profiles which are clearly triple in form, and thus suitable for this study. Table 4 gives the designations of these pulsars along with the derived α-values and other data which will be discussed below. The specification of the estimated errors in the core-width values follows the convention in Table 1.

Turning now to the geometrical characteristics of the conal emission, estimates of the sweep rate $|d\chi/d\varphi|_{\max}$ and measurements of the outside half-power width of the conal component pairs are also given in Table 4. Where possible, these latter values were interpolated to 1 GHz in keeping with our general practice, but, given the usual pattern of profile evolution in S_t pulsars, most are based on a 21 cm observation. The table also gives estimates of β derived from equation (3). Again, the sign of β was chosen positive if any flattening of the polarization-angle traverse could be discerned and negative otherwise, but in all cases the traverses are sufficiently steep that the sign has little effect on the calculations which follow.

Equations (4) and (6) were used to compute values of the conal radius ρ and emission height r, and these values are given in some of the final columns of Table 4. These results are again plausible in qualitative terms. The conal radii fall between about 4° and 14°, and the values of β/ρ have a somewhat larger range than for the double-conal pulsars above. Four of the pulsars in the table have β/ρ close to unity—0136+57, 0740−28, 0833−45, and 1112+50—and all of these stars exhibit high-frequency profiles in which the conal outriders are closely merged with the central core component, compatible with a more nearly tangential traverse of the sight line through the conal emission beam.

The 1 GHz conal emission-radius values for this group of S_t stars are plotted against pulsar period in Figure 4. Most of the values exhibit a very orderly inverse dependence on period, again suggesting that the conal emission radius is independent both of rotational period and of magnetic inclination angle α. Indeed most fall on or near the lower of the two curves plotted in the figure, which represent the 1 GHz "inner" and "outer" conal emission radii of the five-component (M) pulsars as found above in equation (5). Three other stars fall well off this curve. Two of them, 0823+26 and 1933+16, have conal emission radii which appear to lie on the upper curve. The other, pulsar 1914+13, has a computed ρ-value of only 5°3, whereas other core-single pulsars in this period range have values closer to 8°.

Given that most of the ρ-values follow the same $P^{-1/2}$ scaling as does the core beam, the height of the conal emission at 1 GHz will be constant, independent of the period. Apart from the three irregular stars mentioned above, the computed

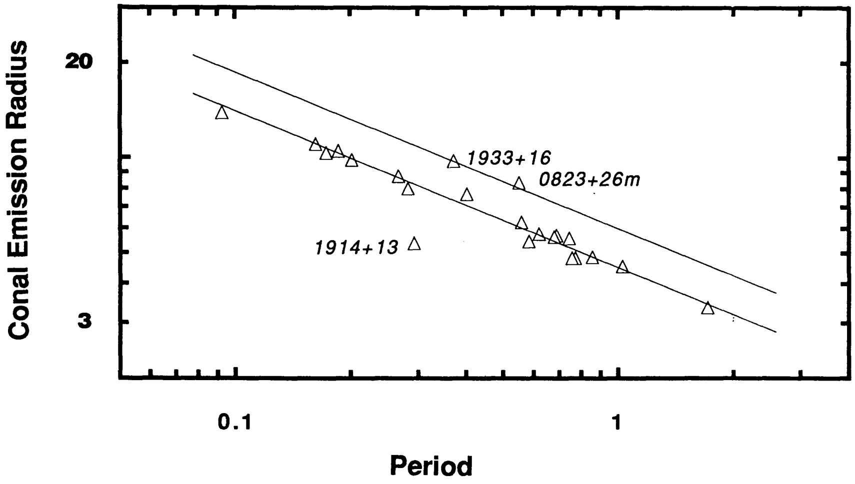

FIG. 4.—Conal radius ρ as a function of period for a group of core-single (S_t) pulsars which have well-developed conal outriders at frequencies above 1 GHz. The fitted curves 4°3$P^{-1/2}$ and 5°8$P^{-1/2}$ are indicated. Several pulsars are identified whose conal beam radius falls well off the "inner" curve.

heights in Table 4 fall around 125 km, which is indistinguishable from the 130 km value given above for the 1 GHz conal emission height of the "inner" conal beam of the five-component pulsars. By circumstance core-single pulsars do not exhibit conal emission at lower frequencies, and thus we cannot trace the frequency dependence of the size of the conal beam for this group of stars.

Table 4 exhibits very clearly that some core-single pulsars develop conal outriders at high frequency and others do not. Generally, the existence of conal emission features is apparent at 21 cm if at all, so that we need not inspect observations of arbitrarily high frequency to answer the question. For a few of the pulsars in the table, a 21 cm observation is either poor or missing to that a question remains, but for most of the stars a good case can be made one way or another. Of the 49 S_t pulsars in the table, 27 show evidence of conal emission at high frequency, and 16 exhibit no such evidence—thus somewhat more than one in every three core-single pulsars appears to remain single throughout the spectrum.

Why is it that some S_t pulsars remain single and others evolve into triple or double forms at high frequency? Statistically the "conal emitting" and "not conal emitting" populations in the table are identical in period, spindown, spindown age, surface magnetic field, acceleration potential B_{12}/P^2, luminosity, and total spindown power dE/dt. They do, however, exhibit a significant difference in magnetic geometry—the "not emitting" group being more nearly aligned (i.e., a smaller α-value) than the one that does. The "emitting" group has a mean α-value of $50^\circ \pm 4^\circ$, whereas $\langle\alpha\rangle$ is only $35^\circ \pm 4^\circ$ for "not emitting" the group. The physical reason for such a difference in the value of α is not yet clear; let us, however, keep it in mind as we explore the conal geometry of the other pulsar species.

5. CONAL EMISSION IN PULSARS WITH TRIPLE PROFILES

We now turn to the final species which exhibits both core and conal components in its profiles, the triple (T) pulsars. Unlike the core-single class which was just discussed, the T stars have profiles with both a core component and a conal outrider pair at meter wavelengths—and indeed frequently throughout most of the spectrum. Unlike the M stars the triple class exhibits only a single pair of conal components, indicative of a single hollow-conical beam of emission.

Following the procedure of the foregoing sections, we determine α by measuring the 1 GHz width of the core component and applying equation (1). For the triple pulsars, as for the M pulsars discussed above, the core width is frequently difficult to measure, given the proximity of the adjacent conal components. The core-component widths in Table 5 then represent a mix of cases wherein, on the one hand, a value could be measured quite accurately and interpolated to 1 GHz or, on the other, where only an educated estimate was possible upon close inspection of the profiles at frequencies adjacent to 1 GHz, usually 1400–1700 MHz and/or 400–600 MHz. Overall, the values in the table appear to be reasonably reliable; in almost all cases the core component could be discerned clearly, so at worst the errors committed were usually of the order of $\pm 0\overset{\circ}{.}5$. Again, the error estimates in these core-width values are specified using the convention of Table 1.

Now turning to the conal geometry, values of the sweep rate $|d\chi/d\varphi|_{\max}$ and measurements of the outside half-power width of the conal outrider pair are given in Table 5. Where possible, these latter values were also interpolated to 1 GHz as above. Calculations of β derived from equation (3) are also given, the sign chosen positive if any flattening of the polarization-angle traverse could be discerned and negative otherwise. The traverse of the polarization angle is here again usually quite steep, so that the sign of β generally had little effect on the computations.

As earlier, equations (4) and (6) were used to calculate values of the conal radius ρ and emission height r. The final columns of Table 5 give these these values, and we note that $3\overset{\circ}{.}5 < \rho < 17^\circ$ with $|\beta/\rho|$ generally less than 0.7. Only a few pulsars have larger β/ρ-values, and these pulsars are predictably the ones with high frequency profiles in which the three components are most difficult to distinguish.

Figure 5 gives a plot of the conal radii for this group of T pulsars as a function of pulsar period. Curves representing the 1 GHz "inner" and "outer" conal radii of the five-component pulsars (eq. [5]) are indicated as before. One can see immediately that most of the values again show an orderly dependence of period. Only two pulsars, 1822−09*m* and 1929+10*m*,

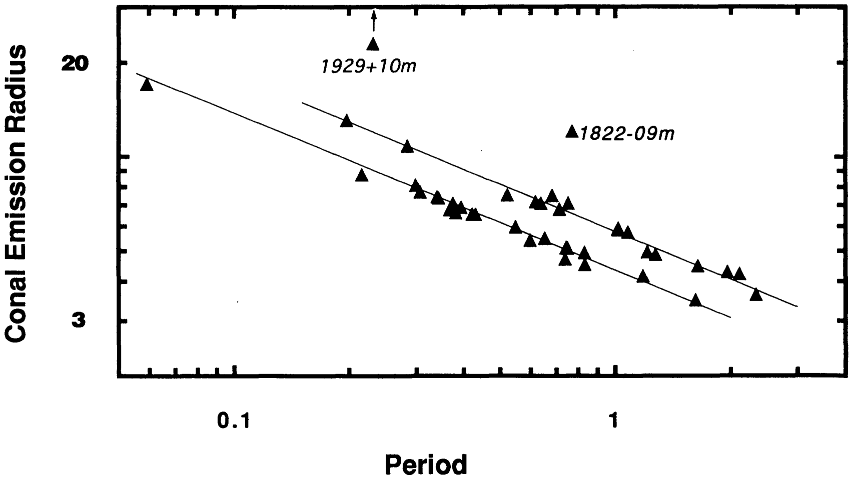

Fig. 5.—Conal radius ρ at 1 GHz as a function of period for the triple (T) pulsars. The fitted curves $4\overset{\circ}{.}3P^{-1/2}$ and $5\overset{\circ}{.}8P^{-1/2}$ are indicated. Two pulsars with highly disparate values of the conal beam radius are identified.

have ρ-values which are incompatible with the others. Here the ρ-values are distributed in comparable numbers near each of the two curves corresponding to the "inner" and "outer" conal beams of M pulsars.

In that virtually all of the ρ-values fall on one of the two $P^{-1/2}$ curves of equation (5), the height of the conal emission at 1 GHz will take one of two values and be otherwise independent of the period. And, indeed, the computed heights in Table 5 fall around 125 and 220 km, which again are indistinguishable from the values given for the five-component pulsars above.

Interestingly, Figure 5 suggests that the triple pulsars divide into two subgroups—that is, a "wide" and a "narrow" category, depending upon which of the two curves of equation (5) describes their conal geometry. Of the 48 pulsars in the table, 24 are found in the "narrow" category and 15 in the "wide." At this level of analysis, however, the conclusion that the triple (T) pulsars fall into "wide" and "narrow" categories is by no means proven. As the various notes to the table make clear, the overall quality and completeness of the observations available is now simply insufficient. Some of the pulsars can thus be "pushed" into one category or the other by small changes in their various parameters, but a number of T stars have well-determined values, and the resulting ρ-values fall quite "firmly" near one or the other of the two curves.

At first consideration, the possibility that the T stars divide into "wide" and "narrow" categories may seem surprising. However, the double-conal emission geometry of the five-component (M) pulsars raises the question immediately: if the conal emission process is observed to operate in two specific geometrical configurations in one case, which (if either) of these configurations corresponds to the conal emission observed in pulsars with a single cone? And what physical circumstances determine whether the conal emission is radiated in an "inner" or "outer" cone? The two populations in the table are statistically identical in spindown, spindown age, surface magnetic field, acceleration potential B_{12}/P^2, luminosity, total spindown power dE/dt, and magnetic inclination angle α. The only parameter which distinguishes between the two groups in a statistically significant manner is the period, which is 0.56 ± 0.07 s for the "inner" group and 1.06 ± 0.16 s for the "outer." Again, it is not clear physically why this should be so, but it is worth noting that the group of S_t pulsars with observed ("inner") conal outriders has a mean period value of 0.48 ± 0.07 s, whereas the M pulsars with both conal beams have a mean period value of 0.86 ± 0.13 s.

An attempt was made to study the frequency dependence of $\rho(\propto f^{-a})$ for the pulsars in Table 5. Given the difference in behavior of the "narrow" and "wide" cones of the five-component pulsars discussed above, it would certainly be interesting to see if the respective "narrow" and "wide" groups of triple pulsars exhibit any analogous difference. In practice the state of the observations is such that this question is not easy to answer. A handful of triple pulsars (i.e., 0329+54) have been studied extensively, and a large body of observations spanning a considerable frequency range are available in the literature. Restricting analysis to these stars, many of the "wide" triples have steeper frequency indices than do the "narrow" ones. For many others, however, the observational evidence is more limited, and one is often reduced to looking for changes between, for instance, 430 and 300 MHz profiles. It was possible to compute indices for 18 of the pulsars in Table 5, but less than half of these are at all well determined. Formally, no difference was found in the respective mean indices of the two groups, but the question is not at all closed.

6. CONAL EMISSION IN PULSARS WITH ENTIRELY CONAL PROFILES

Let us now consider the final several profile species which have conal emission components, but no core component. These are the familiar conal single (S_d) and double (D) classes as well as the conal triple/conal quadrupole (cT/cQ) classes. Many stars of these species are most exemplary of conal emission by virtue of their individual-pulse modulation characteristics, but for the purposes of the present study their lack of the core component presents a major difficulty.

For each of the groups discussed above, the existence of a core component provided the possibility of determining the magnetic inclination angle α. For these entirely conal species the form and scale of the profile provides no direct information about the orientation of the magnetic axis. Such information is implicit, however, in the linear polarization angle traverse, and Lyne & Manchester (1988) have used this polarization-angle information to estimate α-values for many of the pulsars in the groups below. While the conclusions and some of the methods of this paper are problematic (see footnote 2), it is just for such entirely conal profiles that one might expect their analysis to be best motivated and useful.

Accordingly, the analysis in the following subsections must proceed somewhat differently and entail somewhat different questions: Whenever possible values of the magnetic inclination will be taken close to those given by Lyne & Manchester, (1988) so that the basic features of the conal geometry can be determined as above. The question, then, is whether values of ρ and r can be found which are compatible with the values determined for the core/cone species in the foregoing sections and whether the requisite α-values are then in general agreement with LM.[7] If such agreement is poor or no α estimate is available, then the question is whether any value of α results in a conal configuration compatible with equations (5) and (6).

6.1. *Pulsars With Conal Triple and Quadruple Profiles*

Table 6 gives the designations of nine pulsars which appear to have a double cone configuration and no core component. As discussed earlier these pulsars are apparently near relatives of the five-component (M) class but represent more tangential trajectories which miss the core beam. Figure 1 shows that there are two possibilities for such profiles: (1) the conal triple (cT) configuration wherein the sight line cuts the "inner" cone tangentially, so that the "outer" cone is resolved into a conal component pair, but the "inner" cone appears single, and (2) the conal quadruple (cQ) situation wherein a somewhat more central traverse of the sight line resolves both emission cones into conal component pairs.

The pulsars in the table divide about equally between those with conal triple and conal quadruple profiles. Three of these, pulsars 1633+24, 1845−01, and 1918+19, we first identified as members of the cT class by Hankins & Wolszczan (1987),

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[7] Precise agreement is neither expected nor meaningful since Lyne & Manchester (1988) assumed in their analysis that $\rho \propto P^{-1/3}$. It is not easy to see how to rectify this assumption as to do so requires knowledge of the question we are trying to answer—that is, which of the two conal beams is involved.

and a fourth 1944+17 was so classified in Paper IV; only 2154+40 then has been added here.[8]

Four additional stars may well have conal quadruple profiles, although each one must be regarded as tentative at this time. Well-observed 409 MHz profiles of 1738−08 and 2319+60 were published by Lyne & Manchester (1988), and in both cases they were the first meter-wavelength profiles available for these stars in the literature. Both profiles appear to have four components. It is possible that lower frequency observations will yet reveal the existence of a core component, in which case we probably should regard them as members of the five-component (M) class. Both appear to be good cQ candidates, however, considering that no M pulsar is presently known whose core component is not discernible at around 400 MHz.

Pulsar 1919+21 may also be a member of the conal quadruple class. This is most easily seen in the paper of Prószynski & Wolszczan (1986) wherein four discontinuous stationary modulation patterns are visible around 400 MHz. Cordes's (1975) study also illuminates how steadier modulation associated with core emission fills out the center of the profile. The weakest of the four cQ candidates is 2315+21, whose classification rests on the 21 cm observation of Rankin, Stinebring, & Weisberg (1989). Sensitive meter-wavelength profiles are needed to confirm the nature of this pulsar's structure.

Additional columns in Table 6 give the estimated width of the core component, the angular size of the polar cap, the required α-value, and the α-value determined in Lyne & Manchester's (1988) study. Obviously, no core component was discernible in any of these stars, but we have retained the procedure of calculating this angle from equation (1) so as to keep before us the question of whether the expected size of a core component is reasonable in terms of our ability to identify it.

Values of the sweep rate $|d\chi/d\varphi|_{\max}$ and measurements of the outside half-power width of each conal component pair are also given in Table 6. These latter values were as usual interpolated to 1 GHz where possible. Computations of β based on equation (3) are again tabulated, the sign chosen according to whether the polarization-angle curve was discernibly flattened. Again the polarization-angle traverses were usually sufficiently steep that the sign of β has little effect on the computed values of ρ and r.

The resulting ρ-values are both given in the table and plotted (as square symbols) in Figure 6. It is immediately clear that solutions are possible which produce values falling quite close to the curves obtained above for the five-component (M) pulsars (eq. [5]). Furthermore, these solutions require α-values which are within a few degrees of those obtained by Lyne & Manchester (1988).[9]

Five of the nine pulsars in this group have been observed at 102 MHz, so it was possible to explore the frequency dependence of the "outer" conal beam radius. Another three have both 430 and 610 MHz profiles available. The mean spectral index was again −0.15, but the standard deviation was greater 0.07. This is because two of the pulsars, 2154+40 and 2315+21, have very steep indices, −0.33 and −0.46, respectively, whereas some other pulsars, 1845−01 and 1919+21 (see Paper II), have small positive indices.

6.2. *Pulsars With Conal Double Profiles*

Exactly the same procedure was followed with the group of conal double (D) pulsars in Table 7. Of the 18 pulsars listed, adequate observations were available for 13. Solutions were then found near the "inner" or "outer" cone curves of equation (5) at α-values near those given by Lyne & Manchester (1988). For most of the pulsars the α-values are very close; in only one case is the discrepancy as large as 10°. Again, these pulsars have ρ-values which divide about equally between those corresponding to an "outer" (6) and an "inner" (7) cone. Note also that $|\beta/\rho|$ is generally less than 0°.5, indicating fairly central traverses of the sight line, although there are several conspicuous exceptions.

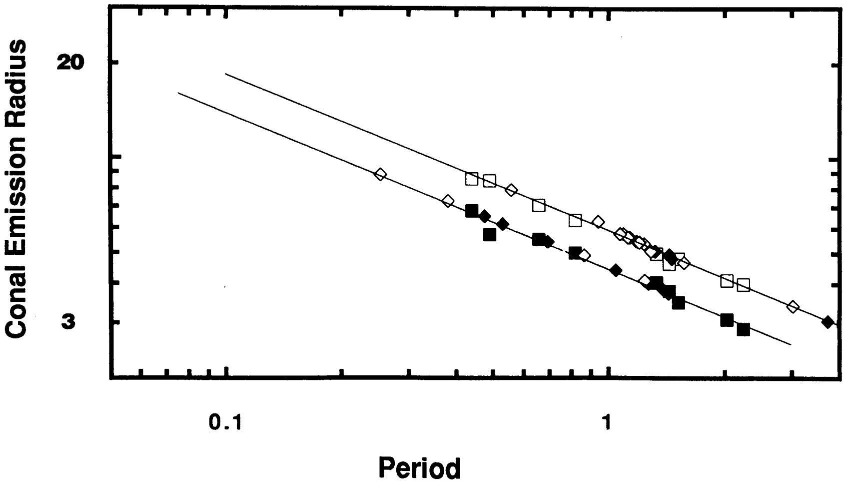

FIG. 6.—Conal beam radius ρ as a function of period for groups of pulsars with: (*a*) conal triple (cT) and conal quadruple (cQ) profiles, "inner" zone (*solid square symbols*) and "outer" zone (*open square symbols*); (*b*) conal double (D) pulsars (*solid diamond symbols*), and (*c*) conal single (S_d) pulsars (*open diamond symbols*).

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[8] Subsequent observations suggest that 1633+24 has a conal triple profile at higher frequencies, whereas at meter wavelengths its profile is quadruple. This is just as one might expect if the cones become appreciably bigger at lower frequencies. See the discussion for this pulsar in the notes to Table 6.

[9] Calculations are also carried out in the table to explore the possibility that pulsar 1929+10*m* is actually a member of the cT class. It is possible to obtain a solution near one of the values (15°) estimated by LM. There are still strong arguments, however, that this pulsar is a two-pole interpulsar with a magnetic inclination angle near 90°. Furthermore, the radii of the two cones must be nearly identical and the impact angles β/ρ implausibly near unity.

Clear criteria for placing a given pulsar on the "inner" or "outer" curve are often lacking for these conal double pulsars, so they do not provide as a group strong independent evidence either for the existence of double cones or for the proportion of pulsars falling into the group or another. This said, there is some statistical difference in the periods of those pulsars with "inner" (0.98 ± 0.15 s) versus "outer" (1.30 ± 0.05 s)[10] cones.

It was possible to study the frequency dependence of ρ for a number of the conal double pulsars. Eight of the pulsars in Table 7 have been observed at frequencies of 102.5 MHz or lower, and of these, four each were assigned to the "inner" and "outer" groups. Those with "outer" cones had a mean spectral index of -0.20 ± 0.02, whereas those with an "inner" cone were virtually identical at -0.19 ± 0.07.

6.3. *Pulsars With Conal Single Profiles*

The final group of pulsars are those with conal single profiles which are listed in Table 8. The profiles of these stars represent tangential trajectories through a conal emission beam, and nothing about the form of the profile indicates whether it is produced by an "inner" or an "outer" beam—or indeed whether the pulsar emits other radiation interior to it. Therefore these profiles could be near relatives of either the conal double (D), the five-component (M), or even the triple (T) species, and we have no ready means to distinguish which.

The calculations presented in Table 8 verify that solutions can be found for these pulsars near the "inner" or "outer" curves of equation (5). Of the 20 pulsars listed adequate information was available on 15 so that the conal geometry calculations could be carried out. Of these 11 *seem* to represent "outer" cones and four "inner" cones, although our ability to make this distinction here is quite weak.

Note that the $|d\chi/d\varphi|_{\max}$ values for these pulsars are generally quite small, corresponding to larger values of both β and $|\beta/\rho|$. Indeed only three of the latter values fall below 0.9, which is reasonable given our expectation that these S_d pulsars will have highly tangential sight-line trajectories. The required α-values generally agree quite well with those found by Lyne & Manchester (0818−13 being a significant example to the contrary), but the latter were available for only 6 of the 15 stars.

Again we make no claims here for our correctness in assigning pulsars to the "inner" and "outer" categories. Nonetheless, the "inner" group has a somewhat smaller mean period (0.69 ± 0.23 s) than the "outer" one (1.30 ± 0.19 s).

This all said, the analysis for the S_d pulsars appears much less satisfactory than that given above for the various other species. There appear to be two principal reasons for this situation:

1. Because, for the S_d pulsars, the sight line does not necessarily pass through any intensity maximum of the conal emission beam (that is, radially inward of the conal beam peak), we have no observational indication of where the sight line *does* intersect the conal beam. Therefore we can have no ready assurance that the half-power points of the S_d profiles correspond to those, say, of the D stars. Thus the entire analysis for this group may be skewed toward smaller values of α, because our measured values of $\Delta\psi$ are larger than they would be if we could reference them to the actual half-power points of the conal beam.

2. Many of the $|d\chi/d\varphi|_{\max}$ values are very small, $\lesssim 2°/°$. Of course we expect that this will be so for pulsars with nearly tangential sight-line trajectories. However, there is some evidence that drifting subpulses both depolarize the profile and flatten the position-angle curve. The value of $|d\chi/d\varphi|_{\max}$ is virtually unmeasureable for many S_d pulsars because the aggregate linear polarization is so small. Undoubtedly this was a factor in the smaller fraction of S_d pulsars whose α-values could be determined in Lyne & Manchester's (1988) study and thus are available for comparison in the present one. The question remains, however, whether the $|d\chi/d\varphi|_{\max}$ values are "geometrical" for these pulsars or whether they are distorted by the subpulse drift phenomenon.

For both of these reasons, it was not possible to assess the frequency dependence of ρ and r meaningfully, although more than half of the pulsars in the sample have been observed at or below 100 MHz (Malofeev, Izvekova, & Shitov 1989). When calculating the spectral indices, however, only a few pulsars yielded reasonable results, and these are just the pulsars with the smallest values of $|\beta/\rho|$. Most others have calculated index values of between 0.0 and -0.05. Indeed, the inconsistent results obtained in this attempt reiterate that the results for the conal single pulsars are less firm than for the other species considered above.

7. DISCUSSION

That some pulsars radiate two concentric conal emission beams now hardly seems arguable. Nearly 20 stars are now known which are very probably members of the five-component (M) class, and members of two other species—the conal triple (cT) and conal quadruple (cQ) pulsars—have been identified which are closely related. Thus at least 6% of the pulsar population have profiles which evidently indicate an emission beam geometry consisting of two concentric cones of radiation.

Because many of these double-conal profiles also have core components, it has been possible to first calculate α, the angle between the rotation and magnetic axes, and then use these and other measured values to compute the radii of the conal emission beams. Surprisingly, these radii are found to follow two simple scaling rules: $4\overset{\circ}{.}3P^{-1/2}$ for the "inner" conal beam corresponding to components II and IV, and $5\overset{\circ}{.}8P^{-1/2}$ for the "outer" one calculated for components I and V.

In that the conal emission beams have the same $P^{-1/2}$ dependence as the core beam, the height of the conal emission region proves to be independent both of period and of magnetic inclination angle α. It is not independent of frequency, however; the outside half-power points can be identified with the "top" of the emission region, and for 1 GHz these occur at about 220 km for the "outer" beam and 130 km for the "inner" one. This near constancy of the 1 GHz emission height is a remarkable circumstance, and it is not clear what physical causes conspire to make it so. The field-line curvature, for instance, is proportional to $(rP)^{1/2}$, so that as a pulsar slows down the beam radius apparently decreases in inverse proportion to increasing field-line curvature.

If then some pulsars radiate conal beams in two particular, well-defined configurations, do other pulsars exhibit similar beam geometries or is their configuration importantly differ-

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[10] The period of pulsar 0525+21 was taken as 1.25 s in this calculation so as not to bias the results.

ent? Just what then are the conal beam configurations of each of the several profile species? Virtually all of the core-single (S_t) pulsars (which develop conal outriders at all) radiate a conal beam which apparently corresponds to the "inner" cone of the five-component pulsars; whereas the triple (T) pulsars appear to include examples of conal emission corresponding to both the "inner" and "outer" conal beams. Finally, among the remaining entirely conal species (D and S_d) the results are less certain, but the majority appear to have "outer" cones although some "inner" ones can also be identified.

What determines physically whether a particular pulsar emits an "inner" and/or "outer" cone? No clear answer to this question can yet be given, but among a number of obvious parameter combinations only the period tends to distinguish between the various groupings: Core-single (S_t) pulsars (with outriders) and triple (T) pulsars with "inner" cones have the shortest mean periods, 0.48 ± 0.07 and 0.56 ± 0.07 s, respectively. Five-component (M) pulsars (which emit both cones) are next with an average period of 0.86 ± 0.13 s, and then the triple pulsars with an "outer" cone have a mean period value of 1.06 ± 0.15 s. Finally, the purely conal pulsars with "outer" beams are all of rather long mean period—that is, 1.22 ± 0.22, 1.30 ± 0.05, and 1.30 ± 0.19 s for the cT/cQ, D, and S_d groups, respectively.

The core-single (S_t) pulsars are interesting in their own right because some ($\sim 65\%$) develop conal outriders at high frequency, and others ($\sim 35\%$) do not. For these two groups there is a statistically significant difference in the magnetic inclination angle, those which do not develop conal outriders tending to be more closely aligned ($\langle\alpha\rangle = 35° \pm 4°$) than those that do ($\langle\alpha\rangle = 50° \pm 4°$). Why this should be so is also not clear. It is possible that the relative efficiency of core and conal emission depends in some way on the inclination angle α. It is also possible that the conal outriders tend to become less detectable in more aligned configurations for purely geometrical reasons.

In any case there should be a few S_t pulsars which do not develop a well-resolved pair of conal outriders because the sight line cuts the conal beam tangentially (i.e., $\beta \sim \rho$). Such a pulsar would then have a profile consisting of a single core component at meter wavelengths which evolved into a single superposed core/conal component at high frequency. Not surprisingly, no good candidate for such a pulsar is now known, but careful study will be required to make a case for such a configuration.

None of this addresses the question of why there should ever be two—and apparently only two!—zones of conal emission at all. The circumstance of two concentric conal zones of emission is surprising theoretically. Most theories have in one way or another envisioned that a hollow conical beam would be associated with the group of maximally curved peripheral field lines which remain "open"—that is, those that do not close within the velocity-of-light cylinder. Geometrically this group of field lines is unique; and thus within this scenario two distinct emission cones do not even seem possible. Nor have we observers been much more ready to embrace the idea, despite our long awareness that five-component pulsars did exist. The semiempirical paradigm of Radhakrishnan & Cooke (1969) as elaborated by Komesaroff (1970) predisposed many of us to think in terms of the simplest possible geometries. Of all pulsar astronomers who have grappled with the problems presented by such exemplars as 1237+25 and 1857−26 over the years, only Oster & Sieber (1977) seem to have seriously considered the possibility of two concentric conal emission beams, although Hankins & Wright (1980) explored a spiral geometry which is not too far different.

The question of why there are two conal emission zones cannot now be answered, but we can discuss what are some of the possibilities. If we suppose that the "outer" emission cone is produced by charged particles propagating along the most peripheral "open" field lines at some height, then the "inner" cone can be interpreted in two possible ways: (1) It is also emitted along this "last" bunch of "open" field lines, but at a lower height above the surface of the star. This is the interpretation we have made for purposes of calculation in the foregoing analysis, but it is not the only one—nor necessarily the correct one. (2) the "inner" cone can be emitted along some more central group of field lines at a height comparable to, or even greater than, that of the "outer."

The first interpretation does appear more plausible because the dimension of the conal beam is apparently firmly tied to the dimension of the "open" field line region or, what is the same, the dimension of the polar cap. To abandon this expectation for the "outer" of the two conal beams is to ignore the fundamental geometrical significance of the polar cap and reduce the significance of equation (1) to that of mere coincidence.

It is then the agency which constrains the "inner" conal beam to a particular, well-defined dimension which remains perplexing. If interpretation (1) is correct, we must wonder why particle bunches radiate at the same frequency at *two* well-determined heights—a question that becomes all the more urgent given the expectation that bunching will have something to do with the local plasma frequency and that this plasma frequency will almost certainly decrease monotonically with height. If, on the other hand, interpretation (2) is correct, then some geometrical or physical circumstance must favor radiation along a particular set of field lines well inside the "last open" ones.

Several different possibilities come to mind:

1. *Distinct particle currents.*—Electron, positron, and even ionic currents apparently occur in the "open" field line region. It is not clear, however, whether these currents are spatially segregated at the height of the conal emission region, as envisioned by Sturrock (1971), or consist of a single overall current with particles of either charge moving in both directions. If the particle currents are spatially segregated, this might provide the kind of circumstance needed to fix the dimension of the "inner" conal beam. The particular particle current responsible for the "inner" beam would presumably be constrained by the overall electrodynamics of the magnetosphere and in turn fixed in relation to the underlying surface of the neutron-star polar cap. Somehow this possibility seems too facile, however; would not more pulsars show evidence of two conal emission zones were this the case?

Even if the particle currents are not segregated, the existence of several distinct particle currents might facilitate bunching—and thus radiation—at more than one height. Clearly the electron and positron currents need not be the same, owing both to the action of the "gap" and the characteristics of the resulting cascade. Thus the various inward- and outward-going currents of positrons and electrons can differ both in energy and density.

2. *Cascade phenomenology.*—All pulsars are thought to accelerate a primary particle population in the polar-cap "gap" region, but the radio emission must come from a much

less energetic secondary plasma. Apparently, this secondary plasma is created by quanta, radiated by the primary particles, which pair-produce on nearby field lines. The details of the process are not well understood. Certainly some particular field lines (at particular heights) will be much more copious emitters of quanta than others, and similarly some other field lines will be more highly suited than others as sites for the resulting production of electron-positron pairs from the quanta. If most of the primary quanta are produced on some of the "last" "open" field lines—as seems plausible given their larger curvature—then certain interior field lines may be left with much greater concentrations of secondary plasma than adjacent ones. Such a scenario might provide a reason why certain interior field lines appear to radiate with an angular pattern which is smaller than, but closely tied to, the dimensions of the "last open" field lines. Shukre & Radhakrishnan (1982), in a somewhat different context, have looked into the problem of just how the avalanche occurs, but further analysis is required to understand what the plasma distribution on the "open" field lines might be.

3. *Plasma-wave propagation modes.*—Several groups of theorists (e.g., Beskin et al. 1986, 1988; Kazbegi et al. 1988; Kazbegi, Melichidze, & Machabeli 1988; Asséo, Pellat, & Sol 1983; Asséo, Pelletier, & Sol 1990) have begun to consider the possible modes of plasma-wave propagation in the ultra magnetic polar-cap region near the neutron star. Some modification of the picture that the emission occurs in a direction tangent to the "last open" field lines and reaches us directly holds the possibility of rationalizing the double-cone phenomenon. The modes which produce the respective "inner" and "outer" emission cones cannot, however, differ markedly in polarization. No great difference is observed in the fractional linear polarization of the two pairs of conal components, and the polarization-angle traverse is continuous across the conal components, arguing that all have a linear-angle orientation which is determined by the projected magnetic field direction. What is often different between the component pairs is the relative strength of the respective orthogonal polarization mode; cross-polarized power is virtually always stronger in the "outer" emission cone and results in some linear depolarization, whereas several examples of pulsars are known which exhibit no detectable secondary mode contribution to the "inner" cone emission.

What further observational evidence can be brought to bear on the questions pertaining to the nature of the two conal emission zones? First, it appears that while the subpulse modulation period P_3 is virtually identical for the "inner" and "outer" conal component pairs, each exhibits fluctuations which are independent in phase. The repeating sequence of strong subpulses associated with the several components of 1237+25, for instance, attracted the attention of Hankins & Wright (1980) and gave rise to their spiral drift model. If, indeed, the subpulses have their origin in a pattern of discharges which drift azimuthally within the polar cap region (Ruderman & Sutherland 1975), then the comparable P_3 values suggest that both cones are excited by the same set of "sparks." What then remains mysterious is why a given spark sometimes excites one cone and not the other. This general picture of the subpulse modulation pattern rests so narrowly on pulsar 1237+25 (Backer 1970, 1973) and to a lesser extent on 1737+13 (Rankin, Wolszczan, & Stinebring 1988), however, that a more comprehensive observational foundation is desperately needed. There is thus still a rich potential in individual-pulse studies of double-cone pulsars.

If the "inner" and "outer" cones are emitted at different heights, aberration and retardation may produce both shifts in the separation of the two conal zones with frequency and small offsets in the linear polarization angle associated with the two conal component pairs. Unfortunately, these effects now appear to be quite small; if the emission height difference is only about 10^7 cm (rather than 10^8 cm as had earlier been estimated), retardation delays will be only of the order of $\sim 200\ \mu$s.

Finally, it will be interesting to see over time how many other pulsars are found which exhibit double-cone characteristics. For instance, Wu et al. (1992) fitted Gaussian components to a pulsar, 1451−68, which appeared merely triple and found strong evidence for five components. McKinnon & Hankins (1992) have carried out a similar analysis for pulsar 0329+54—which has seemed the very prototype of a pulsar with a triple profile—and have come to a very similar conclusion. There are indeed some obvious examples of pulsars which have been classified as triple but which, on closer inspection, may well prove to have a double-conal profile (e.g., 1745−12 [Xilouris et al. 1990], 1907+03 and 1913+167 [Rankin et al. 1989]).

It is further noteworthy that virtually every double-conal pulsar appears to undergo profile mode changes. We can then ask what happens to the double-conal structure of the profile as a result of transitions from the normal to the abnormal mode. Studies have been carried out for both 1237+25 (Bartel et al. 1982) and 1737+13 (Rankin et al. 1988) which indicate that the double-conal structure remains virtually unaltered as a result of mode changing, but such studies very much need to be carried out for a variety of other pulsars with double-conal profiles.

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