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# Core emission in classical conal double pulsars

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**ABSTRACT**

While core emission is a general feature of pulsar radio emission and indeed dominant in many stars, the few pulsars with "classic" double profiles have often been regarded as entirely conal, despite some evidence suggesting that their "intrapulse" regions have different properties. Here, we undertake single pulse analyses of this central emission in pulsars B0525+21, B0301+19 and B1133+16 using sensitive observations from the Arecibo instrument at both 327 and 1400 MHz. We identify "core flares" persisting for a dozen or so pulses in B0525+21 and small populations of central subpulses that appear "corelike" in all three stars. These central subpulses tend to be most detectable when the surrounding conal emission is less strong, such that the core and conal structures have aggregate intensities that are not dissimilar. The aggregate width of the putative core feature in each pulsar agreed roughly with the expected angular width of its respective polar cap. Those pulsars with "classic" double profiles tend to have large polarization position-angle gradients, reflecting sightline traverses with impact angles close to their magnetic axes—indeed, just the geometry that would favor detection of core emission near the centers of their profiles.

**Key words:** – pulsars: general, core emission, individual (B0301+19, B0525+21, B1133+16)

## 1 INTRODUCTION

The small population of radio pulsars with wide double profiles has exerted a strong influence on conceptions of pulsar emission. Their 'S'-shaped polarization-angle (hereafter PPA) traverses, broadening with wavelength (*i.e.,* "radius-to-frequency mapping"), steep outer and shallow inner edges, and edge depolarization [*e.g.,* see Hankins & Rankin (2010); Mitra & Rankin (2002); Rankin & Ramachandran (2003)] have gained them special notice since shortly after the pulsar discovery. This conal double configuration lies at the very center of geometrical classification efforts and their empirical interpretation [Radhakrishnan & Cooke (1969); Komesaroff (1970); Backer (1975); Rankin (1983; hereafter ET I)]—and this was the only type of pulsar emissivity that the Ruderman & Sutherland (1975) theory attempted to account for physically. Following this long record of study and interpretation, we will refer to such pulsars as exhibiting "classic" double profile forms.

We now know that pulsar emission profiles are generally more complex than these "classic" double forms would indicate, showing consistent geometrical evidence of two concentric hollow conical emission regions as well as a central core beam [*e.g.,* Rankin (1993a,b; hereafter ET VIa,b); Mitra & Rankin (2011)]. In particular, the "intrapulse" region falling in between the leading and trailing components of such "classic" double profiles has long raised questions: the emission in this area seems not to be comprised entirely of the "tails" of the two bright conal components, nor does it ever seem to form a "component" in its own right. Most such interpretations have been based entirely on average-profile methods. In a few cases fluctuation-spectral techniques have indentified distinct long period modulation features in this region, suggesting that the "intrapulse" emission was not conal and thus possibly core in character [see Rankin (1986) and the references there cited]; however, more recent studies have

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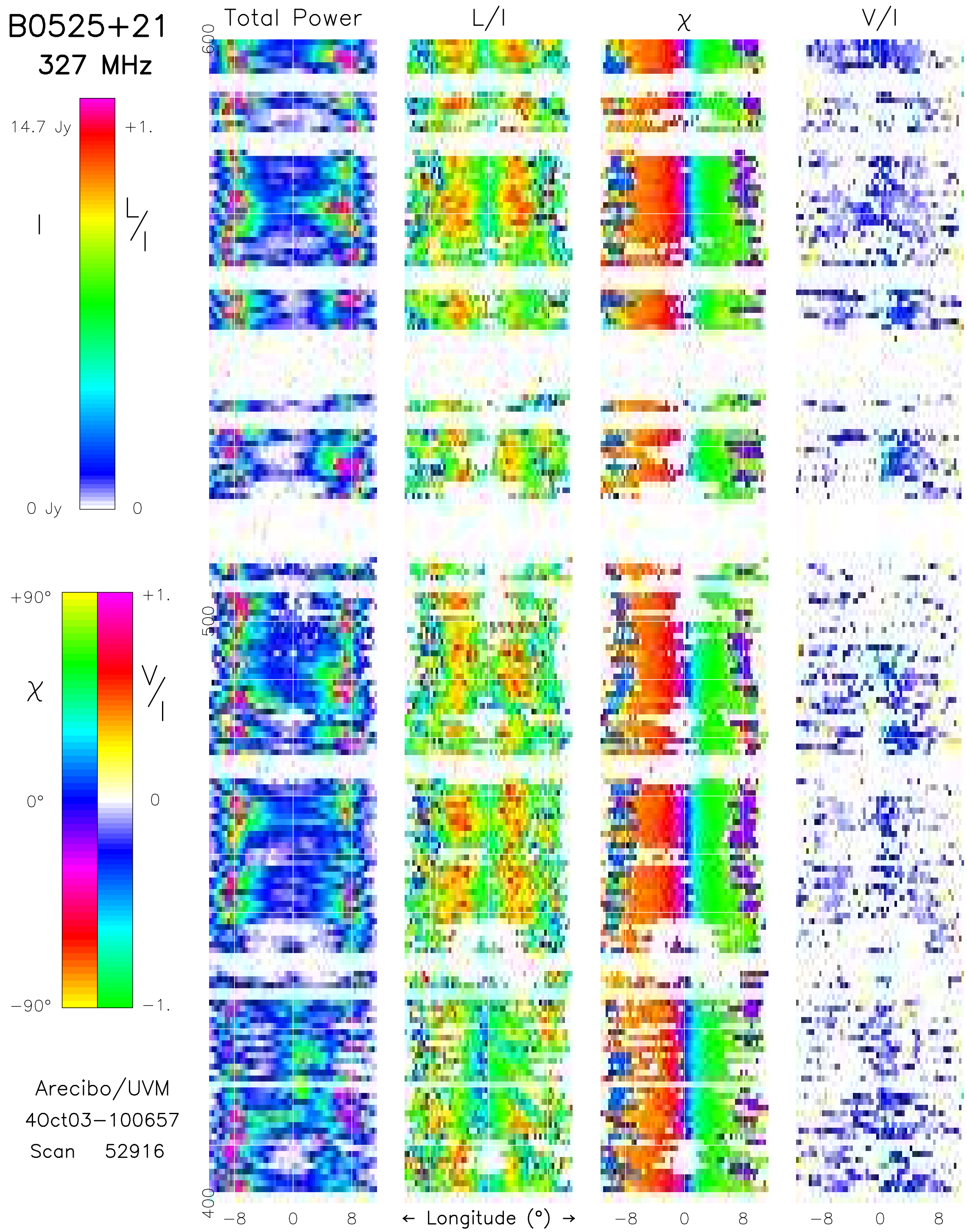


**Figure 1.** A rare "core flare" seen in the "classic" conal double pulsar B0525+21 during pulses 414-435 at 327 MHz on 2003 October 4 (bottom of LH column). The 200-pulse polarization display shows this unusual behavior clearly: generally, bright emission is seen only in the leading and trailing conal components, not often in the center of the profile nor forming a distinct peak. No other such "flare" was seen in the rest of this observation, but occasional weak subpulses are found near the center of the profile (*e.g.*, , pulses 444 and 591). The total power $I$, fractional linear $L/I$, polarization position angle $\chi$, and fractional circular polarization $V/I$ are colour-coded in each of four columns according to their respective scales at the left of the diagram. Note also that $\chi$ and $V/I$ change hardly at all during the "flare"; rather the central region appears depolarized in the $L/I$ column. Both the background noise and interference levels of this observation are exceptionally low with the former disappearing into the lowest intensity white portion of the $I$ color scale.

**Table 1.** Observational parameters

| Pulsar | RF (MHz) | Date (m/d/yr) | Length (pulses) | Res. (°) |
|---|---|---|---|---|
| B0301+19 | 1420 | 07/17/2003 | 2163 | 0.27 |
| | 327 | 01/08/2005 | 1729 | 0.19 |
| B0525+21 | 1420 | 10/01/2009 | 1441 | 0.20 |
| | 327 | 10/4/2003 | 636 | 0.35 |
| | 327 | 09/30/2009 | 1505 | 0.36 |
| B1133+16 | 1400 | 08/03/2003 | 1010 | 0.31 |
| | 327 | 05/02/2005 | 1342 | 0.39 |

tended to associate these features with periodic nulling (Herfindal & Rankin 2007, 2009).

Here we undertake a full investigation of the "intrapulse" emission in the few bright stars with "classic" conal double (**D**) profiles visible with the Arecibo telescope. We have access to sensitive pulse-sequence (hereafter PS) polarimetry in two different bands, therefore we can much more fully investigate the single pulse properties of this emission. Overall, we find evidence for core emission in the "intrapulse" region—that is, core emission that is not necessarily weak but so sporadic that it contributes little to the total average profiles. In §2 we describe our observations, and in §3 we present the results of our analyses. §4 we gives a summary and discussion of our results.

## 2 OBSERVATIONS

The observations were carried out using the 305-meter Arecibo Telescope in Puerto Rico. All of the observations used the upgraded instrument with its Gregorian feed system, 327-MHz (P band) or 1100-1700-MHz (L band) receivers, and Wideband Arecibo Pulsar Processors (WAPP[1]). The ACFs and CCFs of the channel voltages produced by receivers connected to orthogonal linearly (circularly, after 2004 October 11 at P band) polarized feeds were 3-level sampled. Upon Fourier transforming, some 64 or more channels were synthesized across the passbands with about a milliperiod sampling time. At P band 25-MHz bands were used prior to 2009 and 50 MHz thereafter. Three bands centered at 1170, 1420 and 1520 MHz were available at L band, and the lower three were often free enough of RFI such that they could be added together to give an effective 300-MHz bandwidth at nominally 1400 MHz. Each of the Stokes parameters was corrected for interstellar Faraday rotation, various instrumental polarization effects, and dispersion. The date, resolution, and the length of the observations are listed in Table 1.

[1] http://www.naic.edu/∼wapp

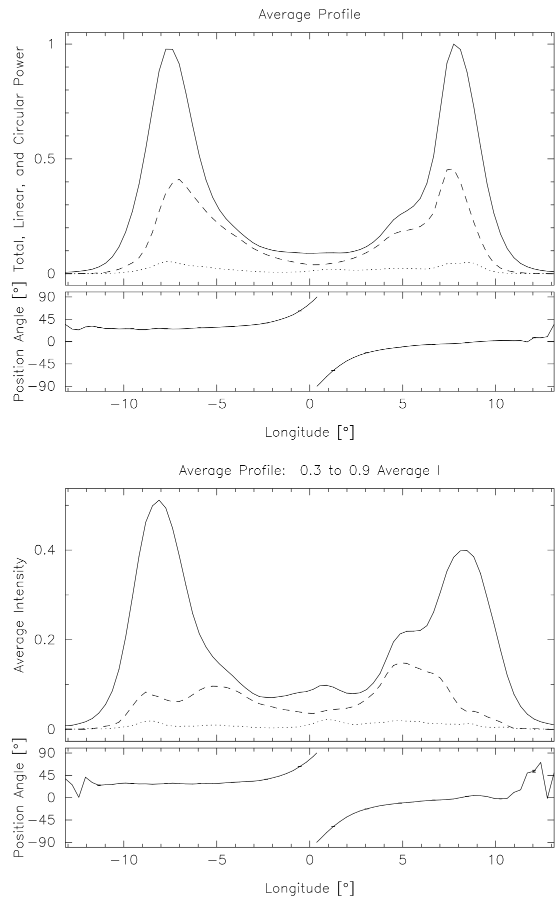


**Figure 2.** Total average profile of pulsar B0525+21 at 327 MHz (**top**) comprised of 1505 pulses together with a low intensity partial profile (**bottom**) comprised of 370 non-consecutive pulses having intensities falling between 0.3 to 0.9 <*I*>. Note the emergence of a new profile feature near longitude 0. Both panels display the total power, total linear polarization ($L$ [$=\sqrt{Q^2+U^2}$]; dashed) and circular polarization $V$ (dotted) as well as (lower panel) the linear polarization angle ($PPA$ [$=\frac{1}{2}\tan^{-1}(U/Q)$]).

## 3 ANALYSES

During the course of some earlier investigations we had noticed occasional strong subpulses near the profile centers of bright pulsars well known for their conal double profiles and 'S'-shaped PPA traverses. In that these subpulses almost always occurred singly, they were readily dismissed as probably part of a "tail" distribution associated with the two bright conal components. However, a possible "core flare" in a short early observation of pulsar B0525+21 kindled a more serious interest: here any core activity seemed doubly unlikely, first because the star had a "classic" conal double profile and second because of its long 3.7-second rotation period.

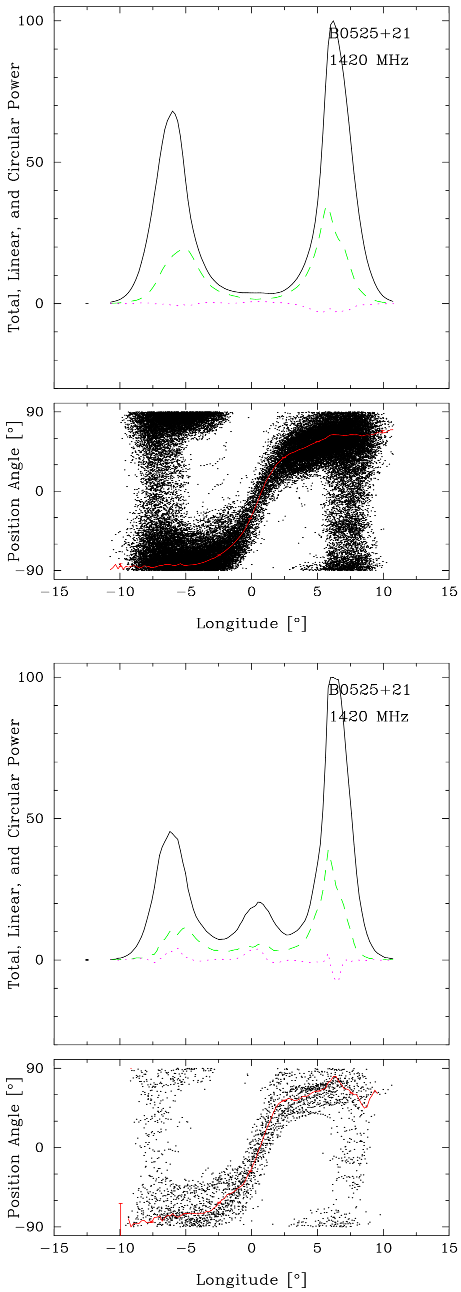


**Figure 3.** Total average profile of B0525+21 at 1420 MHz (**top**) and a partial average profile (**bottom**) as in Fig. 2, comprised of 1441 and 39 pulses, respectively. The partial profile was created by assembling those individual pulses with significant power and peaks in the region around the profile center.

Figure 1 gives a 200-pulse polarization display of this early observation of pulsar B0525+21, and the putative "core flare" can be seen near the bottom of the LH (total power) column during pulses 414-435. No other such emission structure is seen in the remainder of the short 636-pulse observation; though emission is seen in the center of the profile, sometimes in the form of weak subpulses that peak in this region, but often also as emission that "spills over" from that of the conal components. Note also that the polarization characteristics of the emission change little during the "core flare": the PPA and circular polarization imperceptibly; the only clear change is in the fractional linear where the center of the profile appears somewhat more depolarized as if the "flare" represented secondary polarization-mode power.

We have waited some time to undertake this study because we wanted to conduct much longer observations of B0525+21, and these became possible only toward the end of 2009. In the meantime we encountered preliminary evidence that similar effects might occur in other "classic" conal double pulsars, and we present analyses below of both B0301+19 and B1133+16. Some work was also carried out on several weaker stars with prominent conal double profiles, but the lower signal-to-noise ratio (hereafter S/N) prevented our obtaining clear results.

Overall, we had available 4-6 observations of each of the three pulsars (as opposed to the ones explicitly used here listed in Table 1). We found that the "core flaring" behavior in B0525+21 was unusual, but that an episode similar to the one in Fig. 1 could be found in most PSs of a similar length. However, the remaining two stars, B0301+19 and B1133+16, behaved differently in that no good examples of successive subpulses in the "intrapulse" region were encountered in any of the PSs. Consequently, each pulsar required a somewhat different analysis method to study its weaker central subpulses in the presence of the strong surrounding conal emission.

### 3.1 Pulsar B0525+21

Figure 2 displays a total average profile as well as a low-intensity partial profile, both of B0525+21 at 327 MHz. The latter is comprised of 370 pulses with intensities ranging from 0.3 to 0.9 <I>. Clearly, these pulses are not usually consecutive. The small new peak in the center of the partial profile occurs at just the position where core-emission components sometimes occur. This feature closely coincides with the S-shaped swing of the PPA, whose steepest gradient falls at about 0° longitude. In fact, the somewhat asymmetic feature peaks near +1°, and note that there is a weak inflection in the total average profile at just this point. Possibly such features have been missed because they were "swamped" by other emission in this region. The observed steep PPA traverse through nearly 180° indicates that our sightline passes directly across the center of the emission region, close to the magnetic axis along which core beams are thought to be emitted; indeed, modeling suggests that this "impact angle" $\beta$ is here only 0.6°(ET VI). Note that the partial profile, in $I$ and $L$, gives a clear indication of inner and outer conal component structure as well. There is even a hint of weak antisymmetric $V$ centered on the putative weak core component.

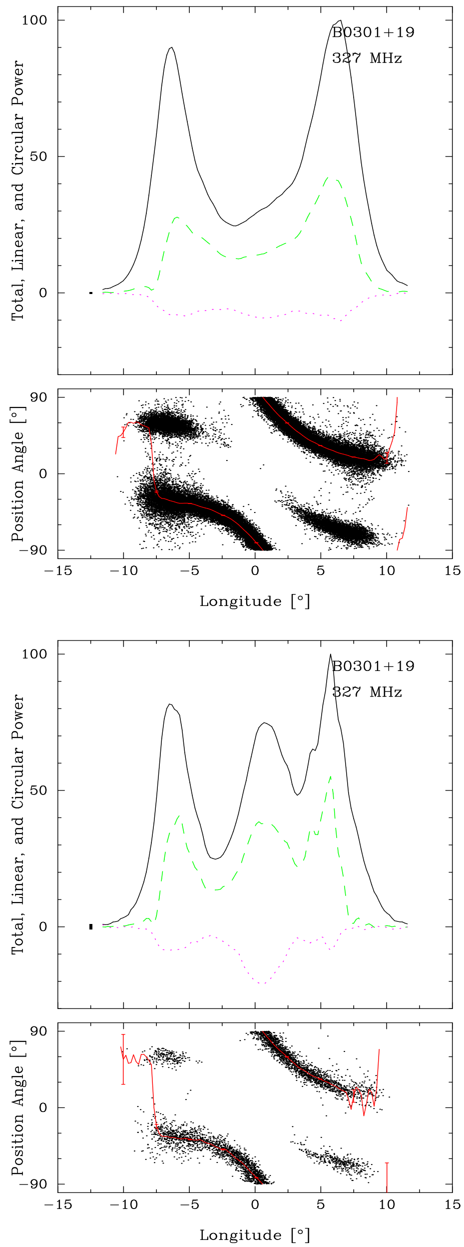


**Figure 4.** Pulsar B0301+19 at 327 MHz: total average (1729-pulse) profile (**top**) and a 93-pulse partial average profile (**bottom**) as in Fig. 3. Again, this partial profile is comprised of non-consecutive pulses that have clear intensity peaks in the ±4° "intrapulse" region. Note that here these central subpulses exhibit intensities comparable to those in the conal regions.

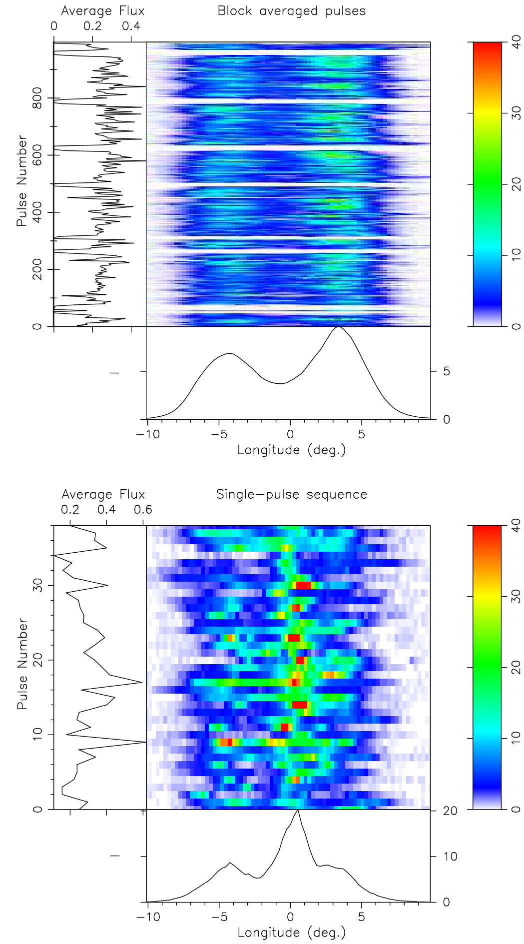


**Figure 5.** Pulsar B0301+19 at 1400 MHz: A 1000-pulse sequence (**top**) in 4-pulse averages and an artificially ordered 39-pulse subsequence (**bottom**), both with their corresponding average profiles (lower panels). The total profile exhibits two well resolved components with substantial power in the "intrapulse" region. A number of single pulses with clear peaks in the central region are collected in the bottom display.

We have also searched for possible core-associated subpulses at L band, and our results can be seen in Figure 3. Core emission is usually relatively weaker at higher frequencies and, apart from being narrower, the B0525+21 L-band total profile differs mainly by having a weaker "intrapulse" bridge. This lack of power in this central region frustrated our attempts identify weak central emission using the same method as for the P band above. Here, the partial profile was created by identifying those single pulses having total-power peaks in the central ±3° region. Again, we see a clear central feature just where we would expect to find a core component, falling close to the PPA steepest gradient point.

Interestingly, a reasonable estimate for the width of these putative core features in B0525+21 is between 3 and 4° longitude. In that core components seem to reflect the full angular width of the polar cap (ET IV), this value squares well with a polar cap diameter of 1.3° viewed at a magnetic colatitude $\alpha$ of 21°—that is, 3.6°.

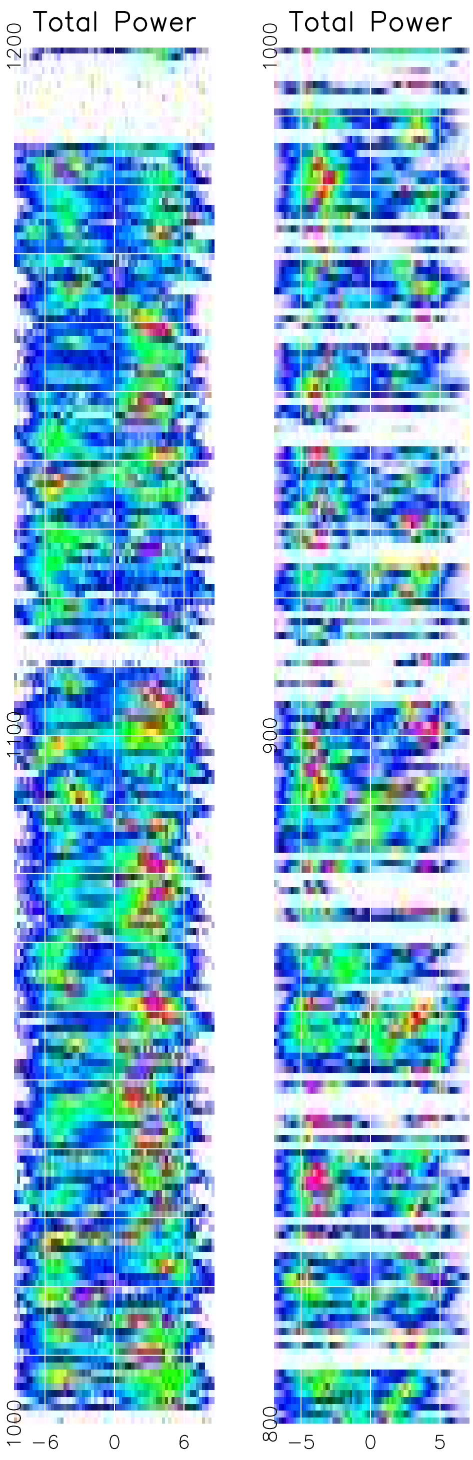


**Figure 6.** Color intensity coded, 200-pulse sequences of B0301+19 (**left** at 1420 MHz) and B1133+16 (**right** at 327 MHz) showing relative scaling in the total power. Careful inspection of each image will show examples of subpulses that peak close to the center of their respective profiles. Such activity is seen throughout our observations. The horizontal scale is in degrees of longitude.

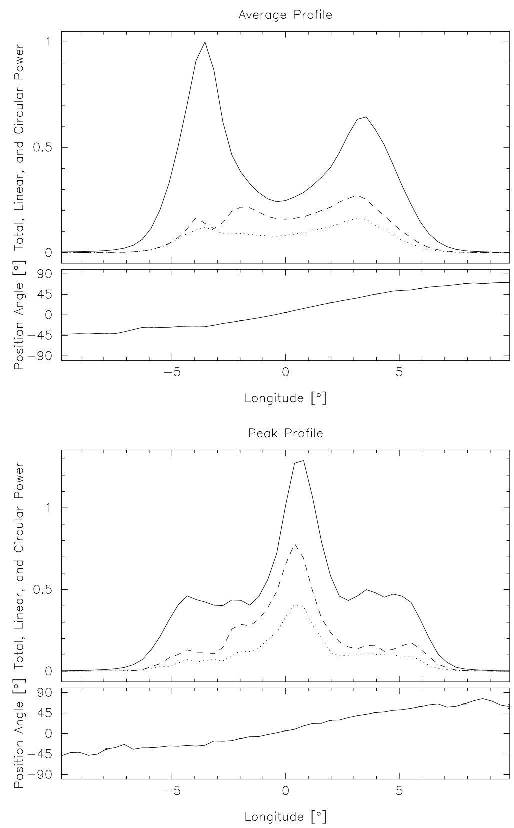


**Figure 7.** Pulsar B1133+16, both at 327 MHz: 1342-pulse total average profile (**top**) and 26-pulse partial profile (**bottom**). The partial profile shows the aggregate of pulses that have significant peaks in the "intrapulse" region of the star's profile.

### 3.2 Pulsar B0301+19

Figure 4 displays the total average profile and a partial profile of B0301+19 at 327 MHz. Here our effort was more difficult because the "intrapulse" region often shows power that is clearly associated with the "tails" of the leading and trailing conal components. The partial profile was thus constructed using a method similar to that in Fig. 3—that is, identifying pulses with significant peaks in the central $\pm 3°$region. While we obviously expect these 93 pulses to show a peak in the central region of the profile coinciding with the steepest portion of the PPA around $+1°$ longitude, note that the aggregate intensity of these putative core subpulses is very comparable to those in the conal region. Further, note that the "core" peak lags the center of the conal component pair by about half a degree, roughly what might be expected for the effects of aberration/retardation.

A close study of this star at L band also reveals emission in the center of the profile, although here again we may expect that any core emission will be relatively weaker. Figure 6 (left) displays a total power PS that illustrates the difficulties of analysis. Here, significant central emission often seems to persist for a few pulses, and the longitude interval that is usually clear of conal subpulses is little more than $\pm 2^{\circ}$wide. Figure 5 then shows a 1000-pulse interval in four-pulse averages and a few of the averages unsurprisingly show clear peaks in the "intrapulse" region. Then, some of the strongest examples of single pulses with central peaks are assembled into the artificial 39-pulse non-consecutive PS in the bottom display of Fig. 5 with its corresponding average profile in its lower panel. Again, the triple character of this partial profile is fully expected as is the necessary dominance of the central component. What is significant is that the half-power width of the putative core is some $2.5^{\circ}$, well less that the width of the intrapulse region and that the central peak lags the center of conal components as in the P band partial profile above.

Both our difficulties and results are more understandable in terms of B0301+19's emission and sightline geometry. Its impact angle $\beta$ of some $1.7^{\circ}$together with its probable inner cone emission (ET VI) results in a profile that is more closely spaced with less well resolved peaks. Accordingly, its expected polar cap diameter of $2.1^{\circ}$is viewed at a magnetic latitude $\alpha$ of some $30^{\circ}$, implying a core width of some $4^{\circ}$in decent agreement with the rough measurement above.

### 3.3 Pulsar B1133+16

The images of B1133+16 at 327 MHz in Figure 7 show the total average profile (top) and a 26-pulse partial profile (bottom). As in Figs. 3 and 4 above, the partial profile was constructed by identifying those single pulses having peaks within the "intrapulse" region. While this region is only some $\pm 2^{\circ}$wide, close inspection of Fig. 6 shows that subpulses tend to fall within pairs of inner and outer conal regions as well as the central region, making it easier to identify this small population clearly. The partial profile appears to bear out this overall fivefold structure, being comprised of single pulses with necessarily weaker conal emission; whereas the double structure of the total profile reflects all the very bright conal subpulses with strong "tails" into the "intrapulse" region. The peak in the central region of the partial profile appears where the emission bridge is usually observed. This "new component" is highly linearly polarized and coincides with the steepest part of the PPA traverse. A few examples of single pulses with peaks in this central region can be seen in Fig. 6 (right). Some further examples of subpulses peaking in the profile center were also found at 1520 MHz and these are shown in Figure 8, where the tendancy of emission to fall into five relatively discrete regions assisted us in identifying the 87 pulses that comprise the partial profile.

Pulsar B1133+16 is one of the brightest pulsars in the northern sky, and its geometry has been studied by many groups. Its relatively shallow PPA traverse implies a larger sightline impact angle of $4.1^{\circ}$, thus its narrow "intrapulse" bridge despite its primarily outer cone emission (ET VI). Similarly, the expected polar cap diameter is $2.2^{\circ}$which viewed at an $\alpha$ of $46^{\circ}$implies a core width of some $3^{\circ}$—agreeing decently with the feature forms in Figs. 7 and 8.

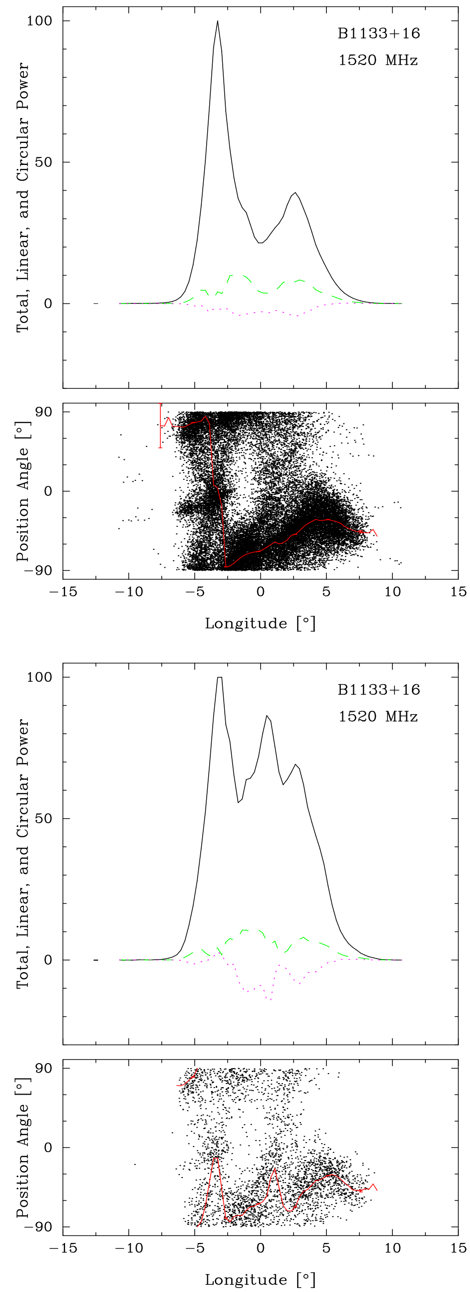


**Figure 8.** Pulsar B1133+16 at 1520 MHz: 1010-pulse average profile (**top**) and an 87-pulse partial profile (**bottom**) as in Fig. 3. Here again we see that some central subpulses have aggregate intensities comparable to the weaker population of conal subpulses adjacent to them.

## 4 SUMMARY AND DISCUSSION

Individual-pulse observations of the “classic” conal double pulsars B0525+21, B0301+19 and B1133+16 were investigated in detail using several different techniques in an effort to understand the character of their central “intrapulse” emission. Several preliminary studies had suggested weak core emission might be detectable in this region, motivating this larger effort. A summary of the results is as follows:

- Populations of individual subpulses were identified in the central regions of these “classic” conal double pulsars that are difficult to regard as having a conal origin.
- Each star exhibited subpulses peaking in the central region during intervals when the surrounding conal emission was weak or absent.
- In each case the longitude distribution of this central population of subpulses was narrower than the width of the “intrapulse” region examined.
- “Core flares” were positively identified in pulsar B0525+21 (and less prominently in B0301+19 and B1133+16) wherein the central region became active continuously for a few pulses.
- The aggregate widths of features comprised of this central emission agree well with the expected polar cap widths of core components.
- Central subpulses are more irregular than weak: such emission is most readily identifiable when the surrounding conal emission is weak; however, the partial profiles show that its intensity is then comparable to the residual conal emission.

These populations of central subpulses, detected in pulsars B0301+19, B0525+21 and B1133+16 at both 1400 and 327 MHz, exhibit aggregate characteristics very similar to those of core components. We also examined B0751+32, B2044+15 and B1924+14, and these other stars with “classic” conal double profiles exhibited similar properties, but their smaller signal-to-noise ratios made it difficult to assemble clear enough evidence to present here.

Overall, this central emission so closely resembles core emission both dynamically and geometrically that we believe it very difficult to understand it otherwise. Indeed, the idea that core emission might be found in the “intrapulse” bridge regions of conal double pulsars is not new; these regions are so difficult to understand in conal terms that one of us speculated upon it previously in ET I. What is new here is a thorough single-pulse based investigation of this “bridge” emission. Clearly, such techniques can be applied to other similar pulsars lying outside Arecibo’s declination range.

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