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Millisecond Pulsar Radiation Properties

D. C. Backer *Astronomy Department, University of California, Berkeley, CA 94720*

Abstract. Two investigations of millisecond pulsar radiation are discussed: average total intensity pulse morphology and individual pulse to pulse fluctuations. The average emission profiles of millisecond pulsars are compared with those of slower pulsars in the context of polar cap models. In general the full.widths of pulsar emission regions continue to widen inversely with period P as $P^{-(0.30-0.5)}$ as expected for dipole polar cap models. Many pulse components are very narrow. The period scaling of pulsar profiles – separations and widths – can tell us about the angular distribution of radiating currents. An investigation of individual pulses from two millisecond pulsars at 430 MHz shows erratic pulse to pulse variations similar to that seen in slow pulsars. PSR B1937+21 displays occasional strong pulses that are located in the trailing edge of the average profile with relative flux densities in the range of 100 to 400. These are similar to the giant pulses seen in the Crab pulsar.

1. Introduction

Why are some neutron stars pulsating radio sources? While no one knows the answer with any degree of certainty, many observations and theoretical inquiries are consistent with the neutron star polar cap model. In this model radiation, which is created in currents driven outward along field lines that connect to the interstellar medium, is relativistically beamed, along those field lines. The radiation is linearly polarized with a position angle parallel (or perpendicular) to the projection of the curved field lines. The Radhakrishnan & Cooke (1969) explanation of the monotonic sweep of linear polarization across the Vela pulsar's average pulse profile in terms of this polar cap model provided the cornerstone upon which most subsequent work has been based.

As a pulsar spins faster the separation between tangents to the outermost field lines which connect to the interstellar medium spreads in proportion to $P^{-0.5}$ for a simple dipole geometry when measured at the *same* altitude. If pulsar radiation fills a fixed fraction of this 'open' field zone, then we could expect a similar scaling of observed pulse width, measured in angle not time, with period. A dependency of emission altitude on period can, of course, alter this relation. While the pulse width–period relation has been studied by many scientists since the early days of the pulsar discovery, the most convincing demonstration that this simple dependence is present comes only when objects with similar sight line / dipole axis / spin axis geometry are compared (*e.g.,* Backer 1976, 1984; Lyne & Manchester 1988 (LM88); Rankin 1990 (R90)). These studies proceed with the assumption that in any pulsar we observe a random cross section of a common pulsar two-dimensional beam pattern. We can piece together what this looks like with a statistical study.

The frequency dependence of pulse profiles is slight for slow pulsars, but does aid in the identification of pulse morphology. Pulse components have individual spectra, and component widths and separations generally decrease with increasing frequency with logarithmic index of around -0.25 (*e.g.,* Rankin 1983; Hankins & Rickett 1987; Thorsett 1991). The interpretation of this frequency dependence as the result of radius to frequency mapping of the altitude of emission in polar cap models is more controversial than the polar cap model itself.

What emerges from these studies is that the central component of the beam has a steep spectrum, and typically displays sign reversal of circular polarization. This is surrounded by a hollow cone of emission, or something approximating this morphology. The perimeter of the conal emission is probably circular (LM88). The sizes of the emitting cone and the core are 6.5° (LM88) and 2.5° (R90), respectively, for a period of 1 s. These values as well as conal component widths grow with $P^{-0.33 \text{ to } -0.5}$. Conal component widths are roughly a fraction 0.15-0.4 of the cone width, or about 2° at 1 s.

That millisecond pulsars, with rotation periods 100-1000 times smaller than the slow pulsars, pulse with any similarity to the slower pulsars is remarkable. Evidently, the radio emission mechanism in all neutron stars depends mostly on processes in the relativistic current structure *in the rotating frame*, and not on the speed of rotation itself. Of course, we believe that it is the rotation and oblique orientation of dipole field that are responsible for inducing the emf that drives this strong polar current. We would like to relate the polarization properties, the period dependence of pulse morphology, and the frequency dependence of pulse morphology of millisecond pulsars to polar cap models, or other models of the magnetospheric radiating current structure (Chen & Ruderman 1993). However, at this time observations are sparse (*e.g.,* Thorsett & Stinebring 1990), and often have poor resolution and/or low snr. In section 2 I report on my understanding of the pulse width – period relation in comparison to the 'expected' $P^{-0.33 \text{ to } -0.5}$ scaling discussed above. Multi-frequency polarization observations in the future will be particularly important to aid in assessing the relationship between millisecond pulsar pulse morphology and the simple ideas we currently have for polar cap models. In section 3 I will discuss the results of an individual pulse study of millisecond pulsars with attention given primarily to the strong pulses seen in radiation from PSR B1937+21.

2. Pulse Width – Period Relation

In my 1984 summary of the pulse width – period relation for pulsars I showed that pulse widths of single peaked pulse profiles and double peaked profiles follow an inverse period relation down to periods of 6 ms with a dependence of approximately $P^{-0.35}$, somewhat flatter than the constant altitude dipole model would predict. These two categories are roughly identifiable with Rankin's conal and core emission, respectively. LM88 include a few millisecond period pulsars in their study of a large body of slow pulsar data, and find a similar relation; Manchester (1990) again comes to the same conclusion with the addition of a few more millisecond pulsars. However the millisecond pulsar profiles are difficult to interpret. There are often many components which are spread widely across the period. As stated earlier, interpretation in terms of core and conal morphology is difficult to impossible owing to the limited frequency coverage and the absence of polarization data.

At present levels of resolution and sensitivity there seem to be unusually narrow components in millisecond pulsars (Fig.1) with full widths at half intensity of 10-20°. For example, the three shortest period pulsars in Figure 1 have components with widths, in angle, at least as narrow as those in the two longest period objects when account of scattering and instrumental effects (see caption) are considered. These narrow components were labeled 'cusp' emission in my 1984 paper. This study pointed out that the components of B1937+21 are remarkably narrow, and perhaps linked to the equally remarkably narrow main and inter pulse of the Crab pulsar which are only 4° wide. We can hope to learn more about the distribution of radiating currents in the polar cap by extending comprehensive pulse morphology statistical studies to millisecond pulsars.

Of the 16 millisecond (field) pulsars considered, six showed prominent interpulses or possible interpulses (B1821-24, B1855+09, B1937+21, B1957+20, J2019+2425, J2322+2057), although, as stated, more complete studies are required for firm identification. Several millisecond pulsars display simple double pulse morphology which one might associate with conal emission scaled to larger opening angles (J0751+18, B1953+29, J2235+1506, J2317+1439). These have larger component widths and separations that corroborate the period scaling, but they are too few in number to make a firm estimate on the exact power law index. This is particularly so owing to the strong selection of objects, and exclusion of what does not fit the paradigm. The three components in PSRs J0613-02 and B1821-24 shown in Figure 1 suggest a possible identification with core/cone emission. However, the central components in both of these as well as PSR B1957+20 (Fruchter *et al.* 1990) have relatively flat spectra in contrast to the reverse for standard core/cone components.

3. Strong Pulses from PSR B1937+21

Investigations of slow pulsars, starting with strip chart recordings of the very first pulsar B1919+21, revealed the erratic behavior of individual pulse emissions which stands in sharp contrast to the extremely stable average pulse profiles required for precise timing of neutron star rotations. The origin of pulse to pulse fluctuations is no better understood than the origin of any radio emission although no one is surprised that the extreme conditions required for coherent radio emission are not steady from one instant to the next. Given the large ratio of periods between the slow pulsars, whose pulse to pulse fluctuations were extensively studied in the 1970's, and the millisecond pulsars, Shauna Sallmen and I were interested in studying the statistics of individual pulses of millisecond pulsars to see if there were similarities in time scales or angle scales as well as the general level of modulation. Some Information was provided by Wolszczan (1984) who reported on the strongest pulses from B1937+21. More recently Johnston *et al.* (1993) presented a string of pulses from the very strong, nearby pulsar J0437-4715.

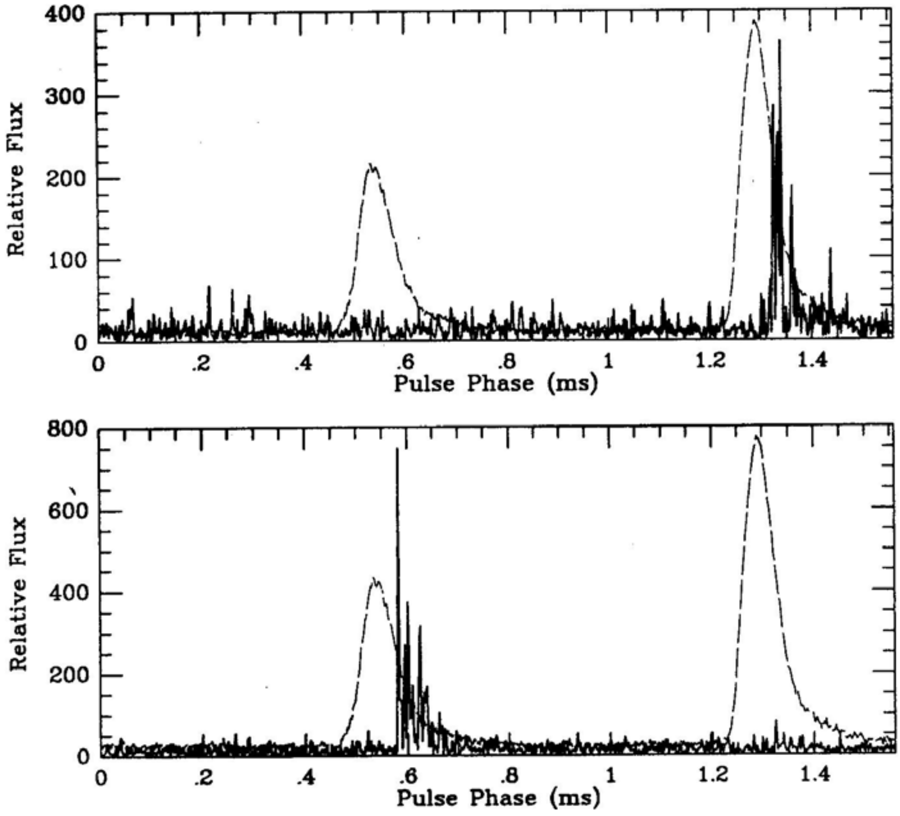

Figure 1: Average pulse profiles from pulsar timing array observations at the NRAO 42m telescope near 800 MHz. Ordinates are pulse phase in ms, and abscissas are flux in Jy. Typical bandwidth is 20 MHz and integration times range from 2-40 h. Resolution is typically 0.009 P except for B1937+21 where it is 0.016. Interstellar scattering contributes to the width of narrow components in B1821-24. Pulsar B1257+12 has a sharp component within the central pulse which is particularly prominent in 430 MHz data.

Our data were obtained at the Arecibo Observatory in November 1992 as part of a low frequency dispersion measure monitoring project. The present study has focused on 430 MHz observations of B1534+12 and B1937+21. Complex voltages in a 250 kHz band from othogonally polarized feeds were recorded with sampling at 500 kHz. For B1534+12 data was recorded for a window centered on the pulse while for the 1.6ms pulsar B1937+21 data was recorded for 8 pulse periods and then 3 pulse periods were skipped. The data was analyzed with software dedispersion in predetection and postdedection algorithms. Histograms of pulse energies were formed to explore the level of modulation. The B1534+12 data was extremely strong, and the histogram showed a high level of modulation. There is similarity between the form of this histogram and that seen for the relatively short period pulsar B0950+08.

The B1937+21 data did not have as high a snr, but its histogram revealed a handful of pulse energies that were above 10 times the mean energy. Separate histograms for the two peaks in the pulse profile – the main pulse and interpulse – showed strong pulses in both. These seemed to form a distinct population reminiscent of the giant pulses of the Crab pulsar. Evidently these were typical of the pulses that Wolszczan (1984) had located. We went back to the raw data and extracted the pulses with full time resolution. Figure 2 displays two of the strong pulses, one at location of each pulse component. Surprisingly all the strong pulses are located on the trailing edge of the average pulse components. This makes their pulse energies 100-400 times that of the average.

One striking feature of both the average pulse and the strong pulses is that they are stretched out by interstellar scattering. In the single screen model of interstellar scattering the impulse response of the interstellar medium is an exponential. Any true pulse structure will be seen convolved by this temporal filter. Most curiously the strong pulses are located in just the part of the average pulse that is stretched out by the interstellar impulse response convolution, But we can't ascribe the strong pulses to scattering since the time scale for the diffraction pattern to change, which occurs as the earth-pulsar line of sight moves through an isoplanatic patch, is many seconds at 430 MHz while the strong pulses are there in one pulse and not in the next pulse or even the intervening interpulse. Furthermore, while we await 1400 MHz data for detailed analysis, we can conclude from the work of Wolszczan (1984) that the presence of strong pulses at both 1400 and 430 MHz would also argue against an interstellar propagation mechanism.

The data in Figure 1 show several spikes whose significance must be judged against the low number of degrees of freedom summed in construction the plot. What is expected for the narrow band impulse response of the interstellar medium has not been studied. We expect to see noise with the number of degrees of freedom being defined by the time-bandwidth product and an envelope given approximately by the exponential function. This is roughly what we see. Thus, what was emitted by the pulsar could be even stronger and as sharp as a microsecond. Higher frequency observations are required to escape the distortion of interstellar propagation. The instantaneous impulse response of the interstellar medium may not be a simple exponential, but rather individual paths may be turned on with a range of delays and a range of amplitudes of scattered radition. This would lead to non noise like fluctuations in these individual pulses. We are exploring these possibilities.

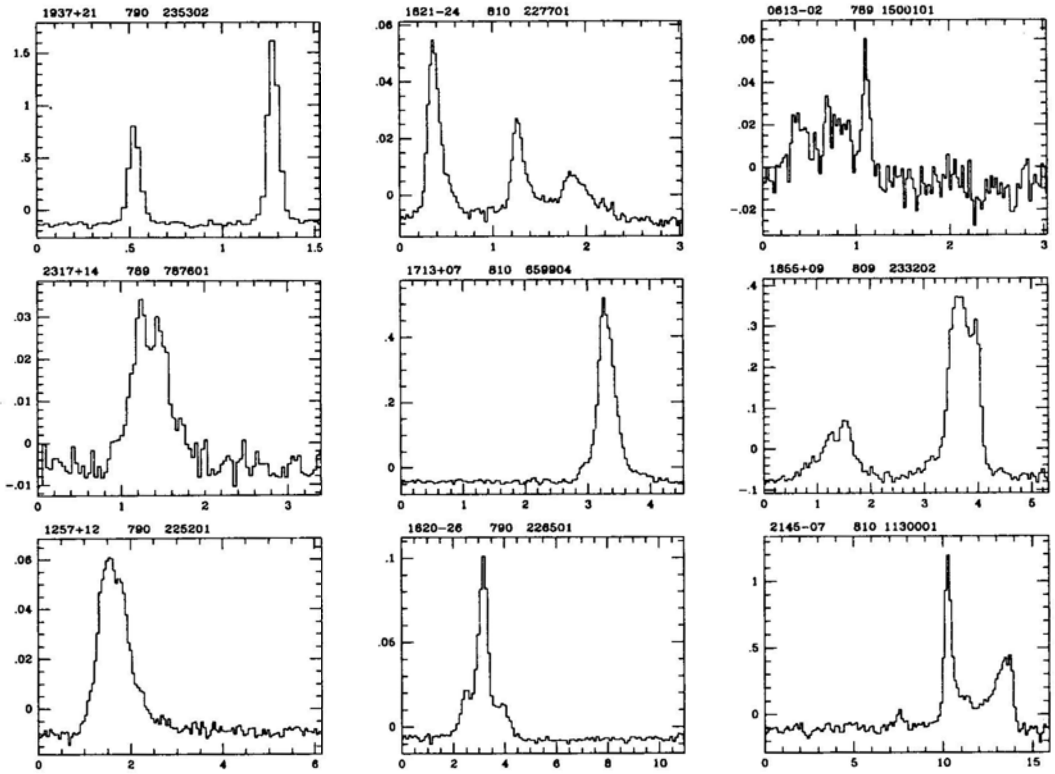

Figure 2: Two strong pulses from PSR B1937+21 at 430 MHz from observations at the Arecibo Observatory with 250 kHz bandwidth. Dashed line gives the average pulse profile from a total of four minutes of data. The stretching of main and inter pulses is the result of interstellar scattering. All strong pulses are observed to follow the peak flux of average pulse profile by about one pulse width. The fluctuations of these individual pulses is dominated by statistical noise. The individual pulses appear to have an envelope which is also scattered as expected.

The delay of the strong pulses from the average may provide a clue to their special origin. The delay of strong pulses after the average, which is of order 25 microseconds, corresponds to a few km of vacuum light travel time which is somewhat smaller than a stellar radius. Is this scale comparable to the size of the emission region? Perhaps some feedback condition in the emission region sets up a high gain, in the sense of a maser, oblique path which fires off an extra intense microwave beam.

Certainly it has been a special pleasure to bring this curiosity of 'light' in nature to the Raman Research Institute wherein many such curiosities have been unraveled by its distinguished directors and colleagues. I trust that there will be many more to come.

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