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A New Model for the Beams of Radio Pulsars

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With the discovery of new classes of radio-emitting neutron stars, such as RRATS and the radio emitting magnetar, understanding the structure and geometry of pulsar beams is becoming central to the interpretation of the observations. We have developed a model, whereby radio emission at a particular frequency arises from a wide range of altitudes above the surface of the star, which can account for the large diversity found in the average profile shapes of pulsars. We demonstrate how a change in the range of emitting heights can account for the differences between pulse profiles of young, highly energetic pulsars and their older counterparts. Monte Carlo simulations are used to demonstrate the match of our model to real observations.

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1. Introduction

Interest in the dynamic radio sky has recently increased, partially due to newly discovered objects and partially to the exciting prospects opened up with next generation instruments with wide fields of view. One class of variable radio sources which has been known for the past 40 years is pulsars, and drawing on our understanding of their dynamic nature can lead to a better understanding of new types of transient objects. In this paper, we introduce a model for the beams of radio pulsars, a model which we believe can account for much of the phenomenology seen in the observations. We use the model to generate a large number of artificial pulsar profiles and statistically compare them to recently acquired, high quality pulsar data. We believe the simplicity of the model to be one of its main strengths, in particular for a better theoretical understanding of the radio emission process.

Average pulsar profiles, made up from the summation of several thousand single pulses, are highly stable over decades of observing. Each pulsar has its own unique profile consisting of a (usually small) number of Gaussian-shaped components (Kramer et al. 1994), and even a cursory examination of the many hundreds of profiles available in the literature shows that they come in a bewildering variety of forms. This variety owes partly to the shape of the pulsar beam and partly to the geometry of the star and the relative orientation to the observer. Unfortunately, it is very difficult to determine the viewing geometry, and therefore also the true pulsar beam shape. Nevertheless, over the years many different attempts have been made to classify the integrated profiles into groups with well defined characteristics. Two different ideas have emerged, each with their own pros and cons. In the work of Rankin and co-workers (Rankin 1983; Rankin 1993; Mitra & Rankin 2002), emission is recognised as arising from near the magnetic pole of the star ('core' emission) and in concentric rings around the pole ('cone' emission). This is a natural explanation for symmetric pulse profiles and for profiles with an odd number of components. In contrast, Lyne & Manchester (1988) argue that the emission cone is patchy with emission occurring at random locations in the beam convolved with an annular 'window function'. This more obviously explains the asymmetry seen in many profiles (Han & Manchester 2001).

2. Pulsar phenomenology

Despite the large variety in pulsar profiles, there is a small number of observational facts which any phenomenological model should reproduce. These are

- **single component profiles:** A large fraction of the observed pulsar profiles consist of a single component.
- **evidence for conal emission:** In the profiles that are not single, symmetry is often present (e.g. PSRs B1133+16 and B0525+21), indicating that the emission originates from a ring centered on the magnetic pole.
- **the period-width relationship:** Rankin has shown good evidence that the profile width, W, depends on the pulsar period, P, as $W \propto P^{-0.5}$. This result implies that the height at which a pulsar emits is largely independent of its period (Rankin 1993).
- **the emission height versus pulse longitude:** A small number of authors in the past have proposed that the emission height at a particular frequency is not constant but varies with

Table 1: Profile classification for 283 pulsars

$\log\dot{E}$	Single	Double	Multiple	Total
>35.0	54%	38%	8%	26
33-35	47%	23%	30%	93
32-33	48%	22%	30%	74
<32	49%	21%	30%	90

pulse longitude (e.g. Krishnamohan & Downs 1983, Gangadhara & Gupta 2001, Mitra & Rankin 2002). The combination of these results is a key result which breaks the long-held assumption that emission at a given frequency arises from a uniform height above the pole.

- **the simplicity of young pulsar profiles:** Johnston & Weisberg (2006) showed that the profiles of a group of young pulsars can be reproduced simply by postulating a single, rather wide, cone of emission located relatively high in the magnetosphere following an earlier idea by Manchester (1996). This is in contrast to older pulsars where complex, multi-component profiles are often observed.
- **that cones are not fully illuminated:** The Lyne & Manchester (1988) model for pulsar beams suggests that the emission within the beam boundary occurs in patches with essentially random locations.
- **that complex profiles have complex position angle (PA) swings:** It is very noticeable that many complex profiles often show strong deviations from the standard rotating-vector-model picture. The natural explanation here is that overlapping components at different heights cause a distortion of the observed PA swing (Karastergiou & Johnston 2006).
- **that profiles get wider with decreasing observing frequency:** The so-called radius to frequency mapping (RFM) idea is that lower frequencies are emitted higher in the magnetosphere than higher frequencies which naturally results in wider observed profiles due to the dipolar configuration of the magnetic field lines. Thorsett (1991) postulated a width-frequency law which essentially accounts for the fact that pulse widening only really occurs at frequencies below $\sim$1 GHz; above this value the pulse width is constant.

3. Classification of the profiles

We have recently obtained polarization data on more than 250 pulsars, using an unbiased sample of pulsars in the southern sky strong enough to give high signal to noise profiles in less than 30 minutes at the Parkes radio telescope (Karastergiou et al. 2005; Karastergiou & Johnston 2006; Johnston et al. 2006, Karastergiou & Johnston 2007). We devised a simple classification scheme by visual inspection of the profiles. Profiles were classified into ‘single’, ‘double’ and ‘multiple’ component profiles, and then sorted by their spin down energy, $\dot{E}$, with the results listed in Table 1.

In Table 1, we see a striking result. The highly energetic pulsars (which are also the young and fast rotating pulsars) have roughly a 60:40 split between single and double component profiles, and show very few complex profiles. In contrast, the older, slower spinning, less energetic stars do have

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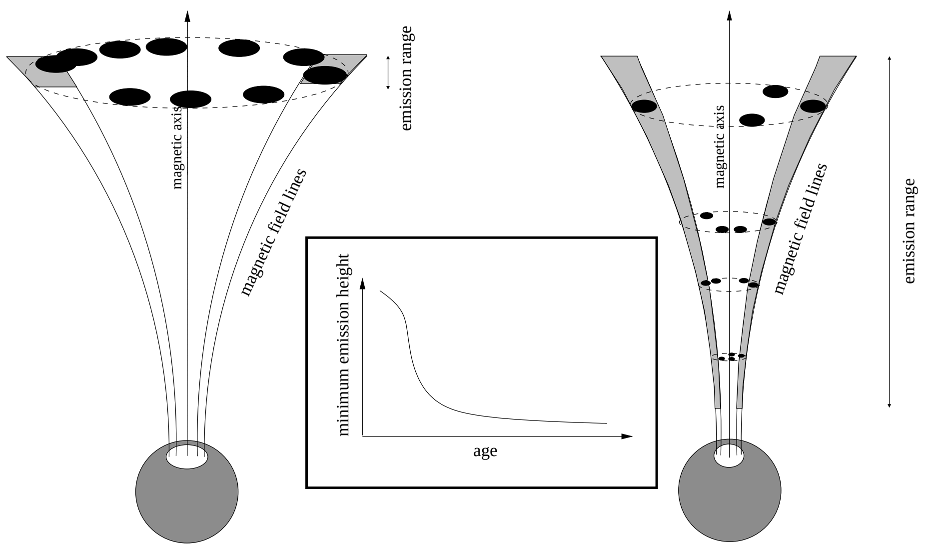

Figure 1: A cartoon of the proposed model. On the left we show the model for young pulsars with emission arising from a patchy conal ring over a narrow range at high altitudes. On the right, the case for older pulsars is shown. Here, the polar cap is smaller and emission at a given frequency arises from close to the surface to a height of $\sim$1000 km in a series of discrete patchy rings. The middle panel shows the proposed variation in the minimum emission height with increasing characteristic age, increasing period and decreasing $\dot{E}$
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complex profiles and the split between single, double and multiple component pulsars is roughly 45:25:30. Furthermore, there appears to be a rather abrupt transition where complex profiles are formed at $\dot{E} \sim 10^{35}$ ergs^{-1}. After this transition point, the relative fractions stay constant. In the following, when we refer to young pulsars, we mean young/short-period/highly-energetic pulsars on one side of this transition point, as opposed to older, slower and less energetic pulsars.

4. A simple beam model

In an attempt to understand the observational evidence and reconcile the nested cone models of Rankin with the patchy models of Lyne & Manchester in a simple way, we postulate a beam model which has the following ingredients:

- radio emission originates from field lines close to the outer edge of the beam, forming an emission cone;
- the conal beam is patchy;
- the maximum altitude of emission, in all pulsars, is set to $\sim$1000 km at a frequency of $\sim$1 GHz; typical maximum emission heights from the literature range from $\sim$10 to $\sim$1000 km above the stellar surface (Blaskiewicz et al. 1991, Mitra & Li 2004);
- the minimum altitude of emission is large for young pulsars (similar to the maximum altitude) and small ($\sim$20 km) for older pulsars;
- emission arising from discrete locations within the entire range of emission heights is possible at a given frequency;

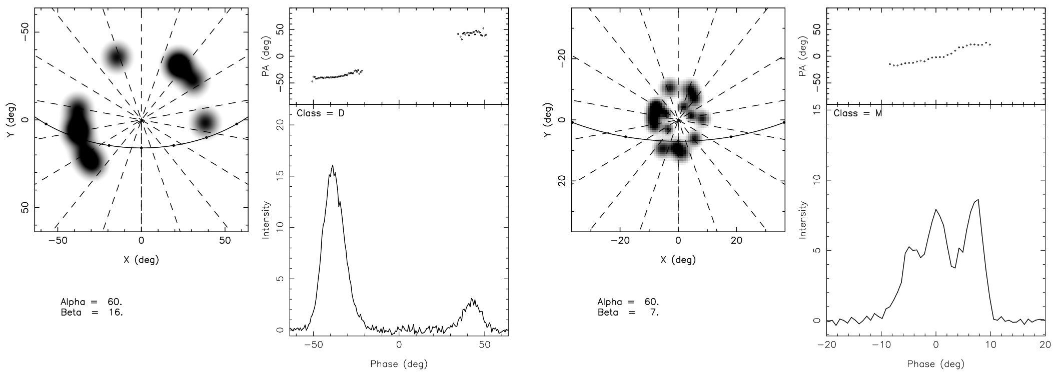

Figure 2: Artificial beams and profiles generated for a young pulsar with period of 100 ms (left) and an older pulsar with period of 1000 ms (right). The beam is shown from above the magnetic pole, and the line of sight is also depicted. Note the narrower patches originating from lower altitudes in the beam depicted on the right. Above the pulse profile, we show the polarization PA obtained according to the model. Deviations from the simple RVM are caused by overlapping patches. Longitude zero depicts the magnetic pole crossing.

- the polarization PA of each patch is tied to the magnetic field line at the centre of that patch.

Figure 1 illustrates the model which naturally reproduces virtually all the observational phenomenology outlined in section 2. In particular, in older pulsars, the large range of allowable heights gives rise to apparent "nested" emission zones resulting in a complex profile. The width of a patch of emission at a given height is a key parameter for the model. Mitra & Rankin (2002) measure component widths as a function of emission height in a variety of double component pulsars. We use their equation to assign a patch width based on emission height

$$w_p = 2.45^o \Delta s \sqrt{\frac{H}{10 \cdot P}}, \tag{4.1}$$

with $\Delta s = 0.2$ and H expressed in km.

5. Results

A large number of numerical simulations have been performed to constrain the remaining free parameters, namely the active altitudes and the patches per emission height. These consist of "creating" patchy beams according to the model. Each beam is then systematically cut with 300 different lines of sight, spanning a reasonable range of α and β. This results in a "clean" profile for each line of sight, to which an amount of Gaussian noise is applied before passing it through an automated classification process to determine whether the generated profile is single, double or multiple. Following this procedure, we check what fraction of the artificially generated profiles are single, double or multiple for a given combination of emitting heights and patches per height. This test also results in a predicted beaming fraction, that is the fraction of pulsars we would expect to detect given a certain beam configuration.

5.1 Young, highly energetic pulsars

The observational data suggests that over 50% of the profiles in this category comprise of a single component. The rest are almost all symmetrical doubles and only a very small number of

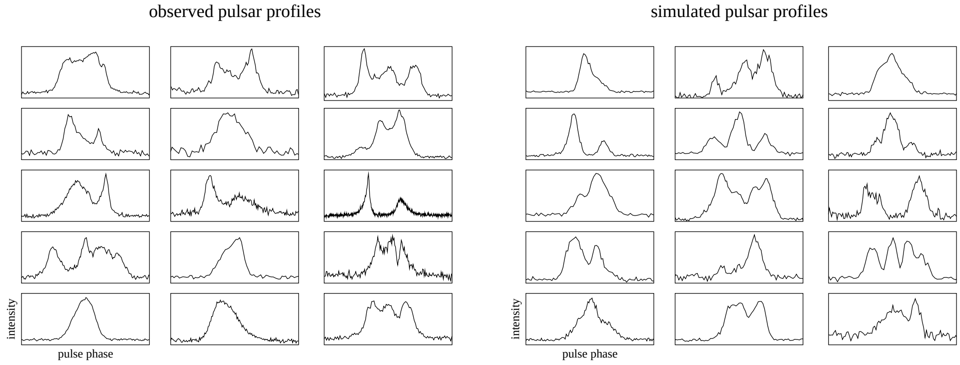

Figure 3: The left panel shows fifteen profiles randomly selected from our database of pulsar polarization data obtained at 1.4 GHz with the Parkes radio telescope. These show the usual variety of phenomenology such as multiple components and components of various width, amplitude and shape. On the right are fifteen simulated profiles according to our model. Although a direct one-to-one comparison is not our intention here, the same sort of profile variety as exists in the real data is clearly reproduced.

multiple component profiles exist (see Table 1). Evidence that emission from such objects generally arises from high altitudes has been presented in Johnston & Weisberg (2006) and we therefore limit our range of emission heights from 950 to 1000 km. However, the fraction of single profiles also forces the total number of patches to be rather small, so that the line of sight will intersect only one patch on half of the observed cases. We find the best value to be 10 patches in total, at a single emission height. For this group, we find the beaming fraction to be around 30%. An example of a simulated artificial beam and profile from this group can be seen in the left hand panel of Figure 2.

5.2 Older pulsars

In contrast to young pulsars, this group a large fraction of multiple component profiles (see Table 1) but this fraction does not appear to change with $\dot{E}$. In our model, we attribute this diversity to the wide range of active emission heights at a given frequency. We find that we can reproduce the statistics as long as we permit at least 3 active heights, and a number of active patches per height roughly ranging from 2 to 7, depending on the number of heights. We obtain the best match to the observations when the total number of patches is $\sim$16$\pm$4 (example, for 4 active heights, 3-5 active patches per height). Pulsars with periods of 0.2 s have a beaming fraction of around $\sim$18%, whereas only $\sim$5% of 2 s pulsars would be detected, similar to results obtained from population studies (Tauris & Manchester 1998). An example of a simulated artificial beam and profile from this group can be seen in the right hand panel of Figure 2.

A visual inspection of the artificial profiles yields a strong affirmation of a hollow cone of emission, with many symmetrical double profiles, as well as other characteristic shapes often seen in the data. To illustrate these points, Figure 3 shows a comparison between randomly selected, artificial pulse profiles and real observational data.

5.3 Radius-to-frequency mapping - RFM

It is possible to simply add RFM to our model, following ideas from Rankin & Mitra (2002). They interpreted the earlier work of Thorsett (1991) and showed that the height of emission has a

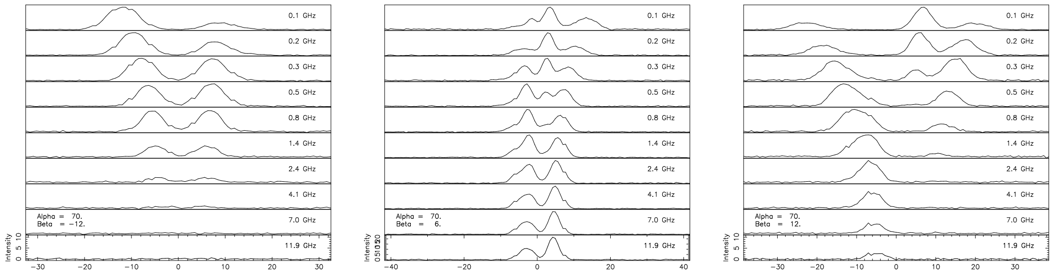

Figure 4: Three examples of simulated profiles at 10 different observing frequencies. As a consequence of equation 5.1, the pulse profile becomes narrower at higher observing frequencies. In all cases there are substantial profile shape changes between low and high frequencies. The middle and right hand panels show that the smaller, lower altitude patches seen towards the centre of the profile have an apparently steeper spectral index than the outrider components, similar to what is observed in the known pulsars. The panel on the left demonstrates how geometry hampers high frequency observations, as the line of sight no longer intersects the pulsar beam.

functional form

$$H_\nu = K \cdot \nu^{-2/3} + H_0, \tag{5.1}$$

with K and H_0 picked to ensure little evolution of the profile width above $\sim$1 GHz. In our model, we compute H_ν for every created patch. Figure 4 shows three examples obtained for our implementation of RFM, where the profile width changes with frequency. Note the apparent change of the component amplitude ratios as a function of frequency, which purely of geometric origin as originally suggested by Sieber (1997).

6. Conclusions

We have developed a beam model for the radio emission from pulsars, where emission is generated at more than one discrete height at a given frequency. The emission occurs in a ring close to the last open field lines. Emission from a given ring is patchy. Following extensive numerical simulations, we have derived parameters for the model which best reproduce the features of the observational data. The model yields

- the simple profiles of young, energetic pulsars as opposed to more complex profiles of the older population;
- a wide variety of simulated profiles which closely resembles the observations;
- an explanation for the number of single-component profiles through the patchiness of the ring structure at a given height;
- a complex PA angle profile for complex profiles, as in the observed data;
- RFM behaviour consistent with the observations;
- beaming fractions as a function of period which are consistent with other studies.

From a theoretical point of view, the idea that emission arises only from near the last open field lines is appealing. Our model requires a successful theory that gives rise to emission at many heights at a particular frequency rather than emission at many locations across the polar gap. As the emission properties are tied somehow to the plasma conditions, one could postulate a varying plasma density along the vertical extent of the emission tube as a possible explanation for multiple emission heights.

In summary we have produced a simple beam model of pulsar radio emission, which can generate average pulse profiles in accordance with the most current observational constraints. Its main features are that it postulates emission over a wide range of emission heights rather than over a wide range of beam longitudes as in previous models and that it largely replicates the observational data. More details on the model and the simulations can be found in Karastergiou & Johnston (2007).

References

[1] Blaskiewicz M., Cordes J. M., Wasserman I., 1991, ApJ, 370, 643

[2] Gangadhara R. T., Gupta Y., 2001, ApJ, 555, 31

[3] Han J. L., Manchester R. N., 2001, MNRAS, 320, L35

[4] Johnston S., Karastergiou A., Willett K., 2006, MNRAS, 369, 1916

[5] Johnston S., Weisberg J. M., 2006, MNRAS, 368, 1856

[6] Karastergiou A., Johnston S., 2007, MNRAS, 380, 1678

[7] Karastergiou A., Johnston S., 2006, MNRAS, 365, 353

[8] Karastergiou A., Johnston S., Manchester R. N., 2005, MNRAS, 359, 481

[9] Kramer M., Wielebinski R., Jessner A., Gil J. A., Seiradakis J. H., 1994, A&AS, 107, 515

[10] Krishnamohan S., Downs G. S., 1983, ApJ, 265, 372

[11] Lyne A. G., Manchester R. N., 1988, MNRAS, 234, 477

[12] Manchester R. N., Wide beams from young pulsars (or one pole for all). pp 193–196

[13] Mitra D., Li X. H., 2004, A&A, 421, 215

[14] Mitra D., Rankin J. M., 2002, ApJ, pp 322–336

[15] Rankin J. M., 1983, ApJ, 274, 333

[16] Rankin J. M., 1993, ApJ, 405, 285

[17] Sieber W., 1997, A&A, 321, 519

[18] Tauris T. M., Manchester R. N., 1998, MNRAS, 298, 625

[19] Thorsett S. E., 1991, ApJ, 377, 263

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