Enlarging the Parameter Space and our Understanding of The Radio Emission of Millisecond Pulsars

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Abstract. The understanding of pulsar radio emission demands a close look at all regions of the huge parameter space present for pulsar observations. In this review we concentrate on the space given by the range of observed pulse periods, spanning four orders of magnitude. A comparative study of the emission properties of millisecond pulsars and normal pulsars, both at radio and high energy frequencies, promises to shed light on the still poorly understood emission theory.

1. Introduction

The search for a theoretical framework that is able to explain the radio emission of pulsars, has been largely unsuccessful. This is due to the difficulty to include all the different phenomena and time scales observed in radio pulsars into a working model. It is essential to isolate the bigger picture, and one way of doing this, is to enlarge the parameter space. Rather than making the picture even more complicated by more observations that are difficult to explain, the aim must be to study the emission properties by pushing the known parameter space to new boundaries to provide solid and obvious constraints.

The parameter space relevant for pulsar radio emission is large. Obvious parameters are the period and its increase, determining important values like magnetic field, or potential drop above the surface. Further parameters are time resolution, frequency coverage in the radio, but also from the radio regime to high energies, eventually simultaneously, and sensitivity. A large neglected part of the parameter space in pulsar studies is that of observing length – quite naturally as many time allocation committees do not appreciate long-term projects. However, some new phenomena will only be discovered, when sources – not only pulsars, that is — are monitored for a long time span. In this review I will concentrate on the period space, and the implication that can be derived from studying emission of millisecond pulsars. For the other aspects, the reader may be referred to other contributions (e.g. Karastergiou et al.) or recent literature (e.g. Kramer et al. 2002).

2. Millisecond Pulsars

Despite a manifold increase in the number of known pulsars, the smallest period of any known pulsar is still that of PSR B1937+21 discovered by Backer et al. (1982) with 1.56 ms. As a consequence of their small periods millisecond pulsars (MSPs) are surrounded by magnetospheres which are 6 to 7 orders of magnitude more compact than those of slower rotating pulsars. Inferred magnetic fields close to the surface of MSPs are 3 to 4 orders weaker than in normal pulsars. In contrast, charges at these regions experience an accelerating potential similar to that of normal pulsars. The impact of the different environment on the emission processes in MSPs magnetospheres has been a question addressed already shortly after their discovery. With the plethora of MSPs detected over the years, a better understanding of not only MSPs (as radio sources and tools) but slower rotating (normal) pulsars as well. Recent addressing the radio emission of pulsars are those by Kramer et al. (1998, Paper I) on spectra, pulse shapes and beaming fraction, by Xilouris et al. (1998, Paper II) on polarimetry of 24 MSPs, by Salin et al. (1998) and Stairs et al. (1999) on multi-frequency polarimetry, by Toscano et al. (1998) on spectra of Southern MSPs, by Kramer et al. (1999b, Paper III) on multi-frequency evolution, and Kramer et al. (1999a, Paper IV) on profile instabilities of MSPs. A number of contributions can also be found in the proceedings of IAU Colloquium 177.

2.1. Flux Density Spectra

Prior to the investigations leading to Paper I it was commonly believed that the spectra of millisecond pulsars were steeper than those of normal pulsars. It was demonstrated in Paper I that the distribution of spectral indices for MSPs is in fact not significantly different, finding an average index of $-1.76 \pm 0.14$ (Paper III). The initial impression was due to a selection effect, since the first MSPs were discovered in previously unidentified steep spectrum sources. Results presented in Paper III also suggest that most spectra can be represented by a simple power law,
Fig. 1. Distribution of spectral indices for normal pulsars and MSPs, measured in a frequency range below 2 GHz. Note that all data have been derived from distance limited samples in order to avoid selection effects (see text for details).

i.e. clear indications for a steepening at a few GHz as known from normal pulsars are not seen.

It is interesting to note that the current data suggest a similar mean flux density spectrum but the distribution spectral indices seems to be somewhat narrower for MSPs than for normal pulsars (Fig. 1).

2.2. Radio Luminosity

When comparing the spectra and radio luminosity of normal pulsars and MSPs, one has to take extra care that selection effects do not bias the result. The sample of MSPs in the galactic plane is limited by scattering effects, resulting in the discovery of mostly nearby MSPs. In contrast, normal pulsars are also affected by scattering, but the longer period allows their detection to larger distances. It is therefore useful to compare only a distance limited sample that can be assumed to be sampled adequately. A distance of 1.5 kpc is appropriate, as outlined in Paper I. As a result one obtains that MSPs are slightly less luminous, being also slightly less efficient in converting spin-down luminosity into radio emission (Fig. 2).

Bailes et al. (1997) pointed out that isolated MSPs are slightly less luminous than those in binary systems, pointing towards a possible relation between radio luminosity and birth scenarios. We have compared a distance limited sample of normal and MSP and came to a similar result with the MSPs as a whole being weaker sources than normal pulsars.

2.3. Pulse Profiles – Complexity, Interpulses and Beaming Fraction

For a long time it was also believed that MSP pulse profiles are more complex than those of normal pulsars. Using a large uniform sample of profiles for fast and slowly rotating pulsars, we showed in Paper I that the apparent larger complexity is due to the (typically) larger duty cycle of MSPs. MSP profile can hence studied in greater detail, facilitating the recognition of detailed structure. In fact, blowing up normal pulsar profiles in a similar manner leads to very similar profiles. A quantitative proof is given in Paper I, while Fig. 3 provides an illustration.

Despite this similarity, there is a profound difference to the profiles of normal pulsars! Additional pulse features like interpulses, pre- or post-cursor are much more common for MSPs. While only ~2% of all normal pulsars are known to show such features, we detect them for more than 30% of all (field) MSPs. They also appear at apparently random positions across the pulse period than we see for normal pulsars (Fig. 4). Their frequent occurrence and location makes one wonder — given the similarity of the main pulse shapes otherwise — whether these compo-
One interpretation of these additional pulse features is related to a model first put forward for some young pulsars by Manchester (1996), who interpreted some interpulses as the results of cuts through a very wide cone. This is an interesting possibility also for MSPs, since their beam width appears to be much smaller than predicted from the scaling law derived for normal pulsars. The beam width of normal pulsars, $\rho$, i.e. the pulse width corrected for geometrical effects (see Gil et al. 1984), follows a distinct $\rho \propto P^{-0.5}$ law (e.g. Rankin 1993, Kramer et al. 1994, Gould 1994). Using polarization information to determine the viewing geometry and also applying statistical arguments, we calculated $\rho$ (at a 10% intensity level) for MSPs and showed (Paper I) that they are not only much smaller than the extrapolation of the known law to small periods, but that — under the assumption of dipolar magnetic fields — the emission of some MSPs seems to come even from within the neutron star — a really disturbing result! While we discuss the possibility of non-dipolar fields and the used the polarization information below, one explanation would be that (perhaps below a critical period) the emission beam does not fill the whole open field line region (“unfilled beam”). The situation improves a bit when we
Fig. 5. The beam radius, $\rho$, for normal pulsars and MSPs. MSPs do not follow the scaling law of normal pulsars (here Gould 1994) but their beaming fraction is much smaller. For MSPs with interpulses an “inner” relationship is indicated.

Another explanation of the additional pulse features could be the possibility that so-called “outer gap” emission is responsible (see Paper II). A number of MSPs are detected as X-ray sources (see contribution by Becker) and those with magnetospheric emission are probably detected by emission created in the outer magnetosphere, i.e. “outer gaps” (see contribution by Romani). As MSPs have very compact magnetospheres, the usual location of radio emission in some distance to the star could well coincide with the location of outer gaps, enabling the detection of “classical” polar-cap radio emission and that of outer gaps at the same time. This is similar to the circumstances probably responsible for the additional high-frequency components seen in the Crab pulsar (Moffett & Hankins 1996).

Finally, it should be pointed out that the much smaller beam width has consequences for population studies, which usually utilise the $\rho - P$ scaling as found for normal pulsars. The failure of this law leads to an overestimated
beaming fraction and an underestimation of the birth rate of recycled pulsars (see Paper I).

2.4. Polarization Properties

The radio emission of MSPs shows all polarization features known from normal pulsars, i.e. circular polarization which is usually associated with core components, linear polarization which is usually associated with cone components, and also orthogonal polarization modes (see Paper II, Sallmen 1998, Stairs et al. 1999). Despite the qualitative similarities, the position angle (PA) swing is often strikingly different. While normal pulsars show typically a $S$-like swing, which is interpreted within the rotating vector model (RVM; Radhakrishnan & Cooke 1969), the PAs of many MSPs often appear flat (see e.g. Fig. 6). This could be interpreted in terms of non-dipolar fields, but Sallmen (1998) noted that larger beam radii lead to a larger probability for outer cuts of the emission cones, i.e. flatter PA swings according to the RVM. Although one should bear in mind the limitations of the $\rho$-scaling law and another caveat discussed later, this interpretation justifies the geometrical interpretation of the data. Magnetic inclination angles derived from RVM fits are important for binary evolution models and determinations of the companion mass (Fig. refincl).

2.5. Frequency Evolution

The radio properties of normal pulsars show a distinct frequency evolution, i.e. with increasing frequency the profile narrows, outer components tend to dominate over inner ones, and the emission depolarises. The emission of MSPs, which at intermediate frequencies tends to be more polarized than that of normal pulsars (Paper II), also depolarises at high frequencies (Fig. 8; Paper III). Simultaneously, the profile width hardly changes or remains constant (see Fig. 9). This puts under test attempts to link both effects to the same physical origin (i.e. birefringes). In fact, many profiles also exhibit the same shape at all frequencies, while others evolve in an unusual way, i.e. the spectral index of inner components is not necessarily steeper, so that a systematic behaviour as seen for normal pulsars is hardly observed. This can be understood in terms of a compact emission region, an assumption further supported by a simultaneous arrival of the profiles at all frequencies. We emphasize that we have not detected any evidence for the existence of non-dipolar fields (Paper III).
2.6. Profile and Polarization Instabilities

The amazing stability with time of MSP profiles has enabled high precision timing over the years. However, in Paper IV we discussed the surprising discovery that a few MSPs do show profile changes caused by an unknown origin. These time scales of these profile instabilities are inconsistent with the known mode-changing. In particular, PSR J1022+1001 exhibits a narrow-band profile variation never seen before (Paper IV), which could, however, be the result of magnetospheric scintillation effects described by Lyutikov (2001). With the pulse shape the polarization usually changes as well, and hence this effect is possibly related to phenomena which we discovered in Paper II. Some pulsars like PSR J2145–0750 (Paper II) or PSR J1713–0747 (Sallmen 1998) show occasionally a profile which is much more polarized than their usual pulse shape. In the case of PSR J2145–0750, the PA changes from some distinct (though not S-like) swing to some very flat curve. This is a strong indication that some of the flat PA swings discussed above may not be of simple geometrical origin alone.

3. Summary and Conclusions

The emission properties of millisecond pulsars are in many respects similar to those of slowly rotating pulsars. However, there are a few remarkable differences like additional profile components and a very week frequency evolution for most MSPs, which can be attributed to the smaller, compact magnetosphere. The additional pulse components may be representatives of outer gap emission, providing an interesting link to the X-ray properties of MSPs. This motivates a close inspection of their joint radio and high energy characteristics. Results of this work in progress will be presented elsewhere.

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