Session 10

Galactic distribution and evolution of neutron stars

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The Galactic Millisecond Pulsar Population

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Abstract. Among the current sample of over 2000 radio pulsars known primarily in the disk of our Galaxy, millisecond pulsars now number almost 200†. Due to the phenomenal success of blind surveys of the Galactic field, and targeted searches of *Fermi* gamma-ray sources, for the first time in over a decade, Galactic millisecond pulsars now outnumber their counterparts in globular clusters! In this paper, I briefly review earlier results from studies of the Galactic millisecond pulsar population and present new constraints based on a sample of 60 millisecond pulsars discovered by 20 cm Parkes multibeam surveys. I present a simple model of the population containing $\sim 30,000$ potentially observable millisecond pulsars with a luminosity function, radial distribution and scale height that matches the observed sample of objects. This study represents only a first step towards a more complete understanding of the parent population of millisecond pulsars in the Galaxy and I conclude with some suggestions for further study in this area.

Keywords. stars — neutron; methods – statistical

1. Introduction

Millisecond pulsars have been the subject of intense discovery over the past few years. Thanks to the current generation of large-scale pulsar surveys, we find ourselves in an era where we have large samples of both millisecond and normal pulsars and, in particular for millisecond pulsars, there are many opportunities to learn about the population of objects as a whole based upon the ones we see. The contributions by Keith, Ng, Lazarus and Lynch elsewhere in these proceedings provide the latest status of these searches, and further details can be found in Lorimer (2011). These discoveries are due to the modern surveys having low-noise receiver systems with a large fractional bandwidth and employing state-of-the-art digital data acquisition systems which are now close to optimal (e.g. DuPlain *et al.* 2008), as well as substantial computing resources using sophisticated search processing algorithms which can largely remove radio-frequency interference and combat the effects of binary motion during the observation. In addition, multiple analyses of the data often result in additional discoveries (e.g. Keith *et al.* 2009; Eatough *et al.* 2010; Mickaliger *et al.* 2012).

Along with the current generation of ongoing pulsar surveys at Green Bank, Parkes, Arecibo and Effelsberg, a key set of surveys that provide the backbone for much of the current population analyses are the Parkes multibeam surveys. These groundbreaking experiments were carried out using analog filterbanks and had substantially better sensitivity to millisecond pulsars compared to previous efforts. The main surveys of interest here are the Galactic plane survey (Manchester *et al.* 2001), the Swinburne intermediate (Edwards *et al.* 2001) and high-latitude (Jacoby *et al.* 2009) pulsar surveys, the high latitude survey (Burgay *et al.* 2006) and Perseus arm survey (Burgay *et al.* 2012) as well as

† For my list of Galactic millisecond pulsars, see http://astro.phys.wvu.edu/GalacticMSPs

a deep multibeam survey of the northern Galactic plane (Lorimer, Camilo & McLaughlin 2013). In spite of their good sensitivity, these surveys were ultimately limited by a number of selection effects which bias their pulsar samples and need to be accounted for by population analyses. These selection effects include the inverse-square law, pulse dispersion and scattering, pulsar intermittency, interstellar scintillation and also binary motion. For further details of these effects, the interested reader is referred to earlier reviews on this subject (Lorimer 2009, 2011).

2. Overview of modeling approaches

Although early efforts to correct for observational selection were done via analytical treatments (e.g. Gunn & Ostriker 1970), nowadays this is best done in a Monte Carlo fashion to create realizations of the true of the underlying pulsar population which are then searched using models of survey detection thresholds which account for propagation in the interstellar medium. The contribution by Cordes in this volume describes current work to update the so-called "NE2001" electron density model (Cordes & Lazio 2002) which is currently used to model the propagation effects in these population syntheses. The reader is also referred to recent work on this subject by Schnitzeler (2012).

From statistical analyses of samples of artificial pulsars that satisfy the criteria for detection, it is possible to generate and optimize models for the pulsar population which inform us about the underlying distribution functions and make predictions for future survey yields. Although a variety of different approaches have been employed, the Monte Carlo simulations follow two basic strategies. In the "snapshot" approach, no assumptions are made concerning the prior evolution of pulsars. Instead, the populations are simply generated according to various distribution functions (typically in Galactocentric radius, R, height with respect to the plane, z, spin period, P and luminosity, L) which are optimized in order to find the best match to the sample. Alternatively, one may carry out "evolution" approaches where the model pulsars are evolved forward in time from a set of initial distributions. Software to carry out both approaches has been developed by a number of groups and some of this is freely available†.

The snapshot approach was applied to the normal pulsar population by Lorimer *et al.* (2006) who were able to derive best-fitting probability density functions in R, L, z and P for the present-day population of objects. One result of this work was that the radial distribution of pulsars could not be decoupled from the radial distribution of free electrons in the pulsar distribution. For the evolution approach on the normal population, the current state-of-the-art is the work of Faucher-Giguère & Kaspi (2006) who generated excellent fits to the pulsar P-$\dot{P}$ diagram using a model in which the luminosity has a power-law dependence on P and $\dot{P}$. In their optimal model, L scales as $P^{-1.5}\dot{P}^{0.5}$, i.e. the square root of the spin-down luminosity. One interesting result from this paper is that the luminosity function of the present-day pulsar population appears to be log-normal in form. The smooth tails of this distribution (which are integrable over all luminosities to give a finite result) offer a distinct advantage over previous studies which parameterized the luminosity as a power law which is divergent and requires a somewhat unphysical minimum luminosity. Similar results were found by Ridley & Lorimer (2010). The log-normal form of the luminosity distribution has subsequently been adopted as a starting point by a number of other studies (e.g., Boyles *et al.* 2011; Bagchi *et al.* 2011 and Chennamangalam *et al.* 2012; see also these proceedings).

† For example, the PSRPOP software package at http://psrpop.phys.wvu.edu has modules to carry out both the snapshot and evolution approaches

3. Previous studies of the millisecond pulsar population

One of the first efforts to quantify the millisecond pulsar population was the work of Kulkarni & Narayan (1988) who used a $V/V_{\rm max}$ approach to estimate the number of similar objects to those observed by surveys at that time. With a sample of only three millisecond pulsars, their study was subject to large uncertainties, but it began a significant discussion on the so-called "birthrate problem" for millisecond pulsars. Based on their results Kulkarni & Narayan (1989) claimed that the birthrate of millisecond pulsars was substantially greater than that of their proposed progenitors, the low-mass X-ray binaries. This problem has largely disappeared as better constraints have become available from larger samples (Lorimer 2009). Rathnasree (1993) attempted to synthesize the population of millisecond pulsars from low-mass X-ray binaries by carrying out Monte Carlo simulations to model their evolution since birth. The current state of the art of this approach is discussed in the contribution by Tauris in this proceedings.

A prescient paper by Johnston & Bailes (1991) demonstrated that the local population of millisecond pulsars revealed by all-sky surveys at ~ 0.4 GHz should be largely isotropic. This work, and early discoveries of two recycled radio pulsars at high Galactic latitudes (Wolszczsan 1990) inspired a number of 400 MHz pulsar surveys during the 1990s which led to a sample of about 30 objects by the end of the decade. During that time, studies of the scale height, velocity distribution and luminosity function were performed (Lorimer 1995; Cordes & Chernoff 1997; Lyne *et al.* 1998) and it was found that the local (within a few kpc) millisecond pulsar population potentially observable was comparable in size to the equivalent population of normal pulsars. One conclusion from these studies is that the populations of millisecond and normal pulsars are consistent with a single velocity distribution applied to all neutron stars at birth (Tauris & Bailes 1996).

4. A new analysis of the millisecond pulsar population

We are now in an era where significant further understanding of the millisecond pulsar population should be possible in the coming years. As a starting point, I present here a snapshot analysis of the sample of millisecond pulsars detectable by the Parkes multibeam surveys prior to the current high time-resolution universe surveys (see Keith's contribution in this proceedings, and Keith *et al.* 2010). The total number of millisecond pulsars from these surveys now numbers 58. This number turns out to have more-or-less asymptoted, but may still increase further thanks to a number of new discoveries† by reanalyses of the Parkes multibeam survey of the Galactic plane.

Using the snapshot approach, I have developed a model (hereafter referred to as model A) which has the following parameters: (i) a log-normal luminosity function with an identical mean and standard deviation (i.e. −1.1 and 0.9) to that found by Faucher-Giguère & Kaspi (2006). This function was found to be consistent with recycled pulsars in globular clusters recently by Bagchi *et al.* (2012); (ii) a manually-tweaked period distribution with a peak at 3 ms; (iii) an exponential scale height with a mean of 500 pc; (iv) a Gaussian radial distribution with a standard deviation of 7.5 kpc. The period distribution was arrived at by initially choosing periods from a distribution which is uniform in $\log P$ between 1 and 30 ms. I adjusted the relative weighting of the bins to arrive at a distribution which most closely matches the observed sample. The z distribution was motivated by my earlier results (Lorimer 1995) based on the low-frequency surveys.

† Data analysis by the Einstein@Home team has so far discovered 23 sources including one highly dispersed millisecond pulsar, while Mickaliger *et al.* (2012) have recently announced the discovery of five further millisecond pulsars.

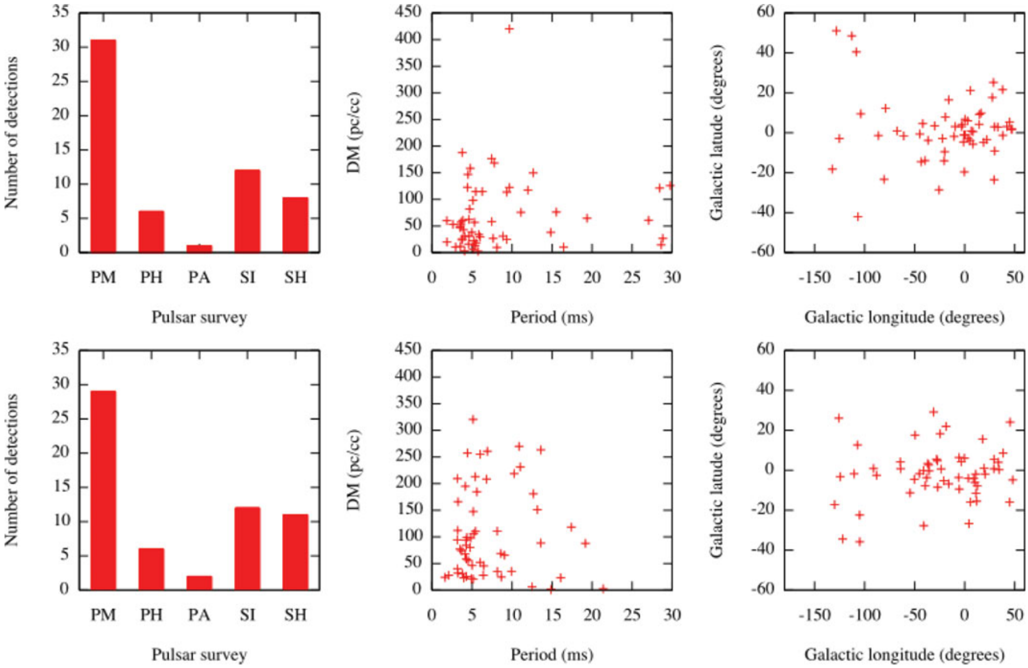

Figure 1. The sample of millisecond pulsars detected in the five major surveys (top panels) confronted with the equivalent distributions from model A shown in the lower panels (see text).

Model	Modification compared to model A	$\mathcal{Q}_{\rm KS}$	$\chi^2_{\rm nobs}$	$N_{\rm Galaxy}$
A	None	–2.3	0.7	31,700
B	Mean of log-normal reduced to –1.2	–2.1	1.3	36,000
C	Uniform surface density over the disk	–7.1	2.8	2,670
D	Cordes & Chernoff (1998) spin period distribution	–12.8	1.1	43,700
E	100 pc vertical (z) scale height	–4.9	8.1	21,000
F	1 kpc vertical (z) scale height	–3.1	1.3	40,800
G	6.5 kpc radial (R) scale length	–2.6	0.5	30,800
H	8.5 kpc radial (R) scale length	–3.4	0.9	31,800
I	Gaussian spin period distribution	–6.0	0.4	28,700

Table 1. Summary of the simulation results obtained from our snapshot modeling of the millisecond pulsar population. From left to right we list the model, base-10 logarithm of the combined Kolmogorov Smirnoff probability ($\mathcal{Q}_{\rm KS}$), the reduced chi-squared value ($\chi^2_{\rm nobs}$) and the number of potentially observable millisecond pulsars in the Galaxy ($N_{\rm Galaxy}$).

As can be seen in Fig. 1, this model provides a reasonable match to the observed sample. I define reasonable in this context in terms of a comparison of the observed and predicted survey yields and also by looking at the observed distributions of spin period, P, dispersion measure, DM, Galactic longitude, l, and Galactic latitude, b. In Table 1, along with the total number of potentially observable‡ I tabulate two figures of merit for this model: $\mathcal{Q}_{\rm KS}$ and $\chi^2_{\rm nobs}$. The former is the base 10 logarithm of the product of the four individual Kolmogorov-Smirnoff (KS) tests between P, DM, l and b. The latter is the reduced χ^2 computed from the observed and predicted numbers of pulsars.

‡ These are the number of pulsars in the model Galaxy whose beams intersect our line of sight — i.e. uncorrected for beaming effects.

Also listed in the Table are the equivalent numbers for a number of other models B–I. The approach I took here was to investigate the impact of each assumption made in model A by changing it, but keeping all other assumptions constant. In model B, to show the impact on the choice of luminosity function on the results, I made only a small change to mean of the log-normal function, i.e. –1.1 to –1.2. The figures of merit are comparable to model A, but the number of pulsars increases by about 14%. For model B, to show that the sample does require a radial dependence on number density, I generated pulsars assuming constant number density on the plane throughout the model galaxy. Here, both figures of merit are substantially poorer due to the gain in number of detections at higher Galactic longitudes. The number of pulsars required in the model is substantially reduced, since it is now much easier to detect the population at larger R. Models G and H, where the scale length is varied by ± 1 kpc from the value in model A show that our ability to constrain the scale length is currently not very good. In model D, I adopt the Cordes & Chernoff (1997) spin period distribution. Although the relative survey yields are satisfactory, this distribution predicts a substantial fraction of millisecond pulsars with $P < 2$ ms which is much higher than that observed. A similar result is found using a Gaussian period distribution (model I) with a mean of zero and a standard deviation of 10 ms†. Reducing the scale height of the population in model E to 100 pc substantially worsens the agreement with the observed data, while increasing the scale height to 1 kpc (model F) has less of an effect.

5. Suggestions for further work

The analysis presented here will be described further in a forthcoming Parkes multi-beam survey paper. It represents a first step towards a more detailed understanding of the millisecond pulsar population in the Galaxy. Further work is encouraged to account for the following subtleties not included here. Of particular interest are studies of the motion of millisecond pulsars in the $P - \dot{P}$ diagram and the relationship to the low-mass X-ray binary population. The work of Kiziltan & Thorsett (2010) and Tauris *et al.* (2012) relates directly to the first issue. Further work in this area, along the lines of the population syntheses carried out by Story *et al.* (2007) seem to be the next logical step. Significant progress is now being made in modeling the binary evolutionary steps and predicting distributions for orbital parameters for the binary population (see, for example, Belszcynski *et al.* 2008). Combining all these elements into an all-encompassing synthesis of the millisecond pulsar population which accounts (as far as possible) for the observational selection effects is now a major goal of future studies. On the road to such a lofty goal, past experience with the normal pulsar population (see, for example, Lorimer 2009) suggests that it will be extremely profitable to break up the steps into a number of smaller problems. One such example is the radio-selected sample of millisecond pulsars revealed by *Fermi* (Ray *et al.* 2012). A careful study of the selection effects impacting this sample should now be undertaken in order to fully understand the impact of these discoveries on our knowledge of the millisecond pulsar population.

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† Only the positive periods from this distribution are used for this model!

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Discussion

Keane: Pulsar surveys are not exhaustively searched. Is there any means to account for this in your modeling?

Lorimer: There is a “fractional completeness” parameter in psrpop that can be tweaked.

Ransom: We heard earlier in the week for millisecond pulsars that there might be some interesting spectral dependencies. How easy would it be to add in the larger 350 MHz surveys into this modeling?

Lorimer: Not too difficult. We just need the information describing the sky coverage of these surveys. What you then need to do is to add the pulsar spectra to your models, but that will hopefully teach you something about that. [Note added in write-up: see the contribution by Youling You *et al.* in these proceedings]

Heras: For the 20% of millisecond pulsars which are isolated, are there any differences between this population and those that are members of binary systems?

Lorimer: As far as I am aware (and I looked at this last a few years ago), there are no significant differences in the population of isolated or binary millisecond pulsars in terms of P, L, spatial distribution etc. What I think is interesting is whether the binary population syntheses can match that 20% isolated millisecond fraction that we currently observe. That remains to be seen.