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Gamma Rays from Millisecond Pulsars

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Abstract. We estimate the contribution of millisecond pulsars to the diffuse gamma-ray background of the Galaxy, and show that a significant fraction of the Galactic background may originate from them. A small number of the unidentified COS-B point sources may, in fact, be millisecond pulsars. It is argued that several hundred millisecond pulsars may be detectable as point sources by the GRO satellite.

Key words: Pulsars, millisecond—gamma-ray emission—diffuse gamma-ray background

1. Introduction

Although the existence of a Galactic gamma-ray background is now well established (see, *e.g.* Ramana Murthy & Wolfendale 1986), its true nature is still controversial. In particular, it is not clear how much of this emission comes from unresolved discrete sources. According to some authors (*e.g.* Bloemen *et al.* 1984) the entire diffuse background can be accounted for by gamma-rays produced in the interaction of cosmic rays with the diffuse gas in our Galaxy. On the other hand, Higdon & Lingenfelter (1976) and Harding (1981) have argued that discrete sources may make a substantial contribution to the background.

Two of the strongest gamma-ray sources that have been detected so far are the Crab and Vela pulsars; both are young and rapidly spinning (Hillier *et al.* 1970; Albats *et al.* 1972, 1974). This has led to the expectation that the population of pulsars may be rather important in this context. In one of the earliest estimates of the contribution of pulsars to the gamma-ray background Harding (1981) came to the conclusion that a significant fraction of the observed emission may, in fact, originate from pulsars. The main features of the pulsar contribution as computed by Harding (1981) are:

1) the spectral shape of the integrated pulsar emission is very similar to that of the observed background, and

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2) the distribution of the pulsar gamma-rays in galactic latitude is narrower than that of the observed background. Harding estimates that at a latitude of ~15°, the pulsar contribution to the flux may be ~10 per cent.

The expected gamma-ray emission from the population of pulsars depends sensitively on the period distribution of these pulsars, since the gamma-ray luminosity is expected to be a strong function of the rotation period. In the estimates of Harding, most of the contribution to the total emission comes from fast pulsars ($P < 100$ ms). However, recent studies of pulsar statistics (Vivekanand & Narayan 1981; Chevalier & Emmering 1986; Narayan 1987) strongly suggest that the majority of pulsars must be born spinning relatively slowly compared to the Crab and Vela pulsars (initial periods > 0.15 s). A similar conclusion has been arrived at by Srinivasan, Bhattacharya & Dwarakanath (1984) from an analysis of the statistics of pulsar-produced supernova remnants. It is important to mention in this context that the results of the recent sensitive surveys to detect short-period pulsars (Stokes *et al.* 1986) are fully consistent with the above conclusions.

However, in the past few years a new population of pulsars, namely, the *millisecond pulsars*, have been discovered. It has been argued (Srinivasan 1989a) that these can make a substantial contribution to the gamma-ray luminosity of the Galaxy. By virtue of their short rotation periods, millisecond pulsars are expected to be fairly strong sources of gamma-rays (Usov 1983). Indeed, there are reports of detection of Very High Energy gamma-rays from two of these millisecond pulsars (Chadwick *et al.* 1985, 1987). Moreover, it is very likely that there is a large number of such pulsars in the Galaxy. In the next section we summarize the reasons for expecting a large population of millisecond pulsars. In Section 4 we estimate the contribution of the millisecond pulsars to the gamma-ray background.

2. The population of millisecond pulsars

It is now generally accepted that millisecond pulsars have been spun up due to accretion in binary systems. Spin-up of a neutron star to such short periods can occur if two conditions are met:

1. The neutron star should have a rather low magnetic field $\lesssim 10^9$ gauss.
2. The neutron star must accrete at least $\sim 0.1\, M_\odot$ of material from its companion. This can happen if the mass transfer phase lasts 10^7 yr or more.

The last condition can be fulfilled only if the companion of the neutron star has a rather low mass $\lesssim 1\, M_\odot$. These stars have a long evolutionary timescale, and can sustain mass transfer for the required length of time (Webbink, Rappaport & Savonije 1983). During the mass transfer phase, such a system will be a strong source of X-rays. Several such objects are known in the Galaxy, and they are commonly called Low Mass X-ray Binaries (LMXBs). At the end of the mass transfer phase these systems are expected to leave a low mass ($\lesssim 0.3\, M_\odot$) white dwarf in a circular orbit around the spun-up neutron star. The confidence in this scenario has grown because three of the four millisecond pulsars discovered in the Galactic disc are in binaries, and have the expected orbital characteristics (Table 1). The remaining one, namely PSR 1937+21, does not have a binary companion at present, but it is likely that the relativistic wind

Table 1. Millisecond Pulsars in the Galactic disc.

PSR	P (ms)	$\log \dot{P}$	$\log B$ (G)	P_{orb} (days)	e	likely comp. mass ($M_\odot$)
1855+09	5.4	−19.8	8.5	12.33	2.1×10^{-5}	0.2–0.4
1937+21	1.6	−19.0	8.6	—	—	—
1953+29	6.1	−19.5	8.6	117.35	3.3×10^{-4}	0.2–0.4
1957+20	1.6	−19.9	8.1	0.38	0.001	0.022

[from Srinivasan 1989b]

from the millisecond pulsar has evaporated away its companion star, as is happening in the recently discovered eclipsing millisecond pulsar PSR 1957+20 (Fruchter, Stinebring & Taylor 1988).

Since LMXBs are the most likely progenitors of millisecond pulsars, the space distribution of millisecond pulsars is expected to be similar to that of LMXBs. The scale height of LMXBs from the Galactic plane is about 300 pc, consistent with that of an old population of stars. However, the millisecond pulsars discovered so far lie very close to the Galactic plane. While PSR 1957+20 has a z-distance of ~ 100 pc, the other three lie within only ~ 25 pc of the plane. The reason for this clustering of the observed millisecond pulsars close to the Galactic plane can be traced to the fact that the sensitive millisecond pulsar surveys have so far been done only near the plane. In other words, the proximity of these pulsars to the plane is a selection effect. By implication, there must be many more observable millisecond pulsars away from the Galactic plane which are still to be found. In addition, the observed millisecond pulsars lie within a narrow range of galactic longitudes between 40° and 65°; again because the most sensitive surveys using the Arecibo telescope have been conducted only over this longitude range. A simple geometrical scaling which takes into account this factor, and the scale height, predicts a total of about 10^4 millisecond pulsars in the Galaxy (Bhattacharya & Srinivasan 1986). If one takes into account additional factors like luminosity selection effects *etc.*, the predicted number could be as large as $\sim 10^6$ (Kulkarni & Narayan 1988). The results of the Princeton-Arecibo survey (Stokes *et al.* 1986) are consistent with these predictions.

This expected number of millisecond pulsars is much larger than the number of LMXBs in the Galaxy, which is estimated to be ~ 100 (McClintock & Rappaport 1985). If millisecond pulsars are descendants of LMXBs, then their total number mentioned above implies that the lifetime of millisecond pulsars must be at least a factor of 10 higher than that of LMXBs. The typical lifetime of an LMXB is estimated to be about 10^8 yr, and therefore the above argument implies a lifetime $> 10^9$ yr for a millisecond pulsar (see Kulkarni & Narayan 1988 and Coté & Pylyser 1989 for a detailed discussion of birthrates of millisecond pulsars and LMXBs). Such a long lifetime for millisecond pulsars is possible only if the magnetic fields of old neutron stars do not continue to decay over timescales on the order of 10^7 yr inferred for normal pulsars, but asymptotically reach a minimum value (Bhattacharya & Srinivasan 1986; van den Heuvel, van Paradijs & Taam 1986). Bhattacharya & Srinivasan (1986) suggested that the 'residual field' for old neutron stars in low mass binaries may be $\sim 4 \times 10^8$ gauss. It turns out that the derived magnetic fields ($\propto \sqrt{P\dot{P}}$) of all the four millisecond pulsars in the galactic disc are close to this value. In what follows we shall assume that all *millisecond pulsars* have this magnetic field. We shall also assume that all these pulsars are spun up to a minimum period of ~ 1.5 ms, and then begin to slow down due to pulsar activity after the mass transfer ceases. As the magnetic field of the pulsar does not decay any further, the period derivative $\dot{P}$ is inversely proportional to the period P, and the period distribution of these pulsars takes the form $N(P) \propto P$. This distribution would extend up to a $P_{\max} \sim 10$ ms, because that is the maximum period which a pulsar with an initial period ~ 1 ms would have slowed down to in the age of the Galaxy.

3. The gamma-ray luminosity of millisecond pulsars

To estimate the collective contribution of millisecond pulsars to the gamma-ray background, we need to know the gamma-ray luminosity of a millisecond pulsar as a function of its rotation period and magnetic field. So far no explicit model has been constructed for the gamma-ray emission from millisecond pulsars. However, at least two different models exist for the gamma-ray emission from normal pulsars, which can be extrapolated to the case of low field millisecond pulsars to get an idea about their gamma-ray luminosities. One of these models (Harding, Tademaru & Esposito 1978) attributes the gamma-ray emission to the curvature radiation photons escaping from near the polar cap, while the other model (Cheng, Ho & Ruderman 1986a, b) traces the origin of gamma-rays to a combination of synchrotron radiation and inverse Compton effects in the 'outer gap' of the pulsar magnetosphere. Both models make similar predictions for the luminosity and the spectrum of the Crab and the Vela pulsars. Thus it is difficult to choose between these two models. When extrapolated to millisecond pulsars, however, the predictions of the two models differ significantly. Confirmed detection of gamma-rays from millisecond pulsars will therefore allow us to distinguish between these two alternative mechanisms. Since this has not been possible so far, we shall explore the consequences of both these models.

In the model of Harding, Tademaru & Esposito (1978), the gamma-ray luminosity of a pulsar scales with its magnetic field and rotation period according to the following relation:

$$L_\gamma(>100\ \mathrm{MeV}) = 1.2 \times 10^{35}\, B_{12}^{0.95}\, P^{-1.7}\ \mathrm{photons\ s^{-1}}$$

where B_{12} is the magnetic field of the pulsar in units of 10^{12} Gauss, and P its rotation period in seconds. Using 4×10^8 Gauss as the value of the magnetic field of millisecond pulsars, we find

$$L_\gamma(>100\ \mathrm{MeV}) = 9 \times 10^{36}\, P_{\mathrm{ms}}^{-1.7}\ \mathrm{photons\ s^{-1}} \qquad (1)$$

where P_{ms} is the rotation period in milliseconds.

In the 'outer gap' model of Cheng, Ho & Ruderman (1986a,b), the gamma-ray luminosity $\dot{E}_\gamma$ of a pulsar is a fraction of the rate of loss of its rotational energy, $\dot{E}_{\mathrm{rot}}$. If the magnetic field and the rotation period of the pulsar are near those of Vela, then this ratio is $\sim 10^{-2}$. But, in their model, if the parameter $\eta \equiv (B^{-2}P^5/B_{\mathrm{Vela}}^{-2}P_{\mathrm{Vela}}^5)$ for the pulsar is $\gtrsim 10^{-2}$, then the gamma-ray efficiency, *i.e.* $\dot{E}_\gamma/\dot{E}_{\mathrm{rot}}$, rises to unity. If the value of η is smaller than this, then the gamma-ray efficiency will be η times that of the Vela pulsar. Since the value of $\dot{E}_{\mathrm{rot}}$ is proportional to B^2P^{-4}, we find that in this "low-efficiency-regime" the gamma-ray luminosity $\dot{E}_\gamma \propto P$. When applied to millisecond pulsars, this leads to the luminosity relations:

$$\left.\begin{array}{ll}\dot{E}_\gamma=8.3\times10^{32}\,P_{\rm ms}\,{\rm erg\,s^{-1}}, & P_{\rm ms}<6\\ \dot{E}_\gamma=6.4\times10^{36}\,P_{\rm ms}^{-4}\,{\rm erg\,s^{-1}}, & P_{\rm ms}>6\end{array}\right\}$$

Assuming a E^{-2} photon spectrum from ~100 keV to ~3 GeV (as computed by Cheng, Ho & Ruderman (1986b) for the Vela pulsar), these luminosities can be translated to the photon production rates:

$$\begin{array}{l}L_\gamma(>100\,{\rm MeV})=5\times10^{35}\,P_{\rm ms}\,{\rm photons\,s^{-1}},\ P_{\rm ms}<6\\ L_\gamma(>100\,{\rm MeV})=4\times10^{39}\,P_{\rm ms}^{-4}\,{\rm photons\,s^{-1}},\ P_{\rm ms}>6.\end{array}\qquad(2)$$

Given the photon production rates (1) and (2), we can now calculate the gamma-ray emissivity due to millisecond pulsars in the following manner.

4. Contribution of millisecond pulsars to the gamma-ray background

The space distribution of millisecond pulsars is modelled as a decaying exponential both in galactocentric radius R and height z from the Galactic plane, with scales R_0 and z_0 respectively:

$$\rho(R,z)=\frac{N_{\rm tot}}{4\pi R_0^2 z_0}\exp\left(-\frac{R}{R_0}-\frac{|z|}{z_0}\right)\qquad(3)$$

where $\rho(R,z)$ is the number density of millisecond pulsars at R, z and $N_{\rm tot}$ is the total number of millisecond pulsars in the Galaxy. In accordance with the space distribution of population II systems, reasonable choices for R_0 and z_0 would be 4 kpc and 300 pc respectively (Kulkarni & Narayan 1988).

The normalized period distribution $\rho_{\rm p}(P)$ of millisecond pulsars is given by:

$$\rho_{\rm p}(P)=\frac{2P}{P_{\rm max}^2-P_{\rm min}^2}$$

according to the arguments presented in Section 2. With $P_{\rm max}\sim10$ ms and $P_{\rm min}\sim1.5$ ms, this distribution simplifies to

$$\rho_{\rm p}(P)=2\times10^{-2}\,P_{\rm ms}.\qquad(4)$$

The gamma-ray emissivity may then be written as

$$\varepsilon_\gamma(R,z)=\left[\frac{1}{4\pi}\int_{P_{\rm min}}^{P_{\rm max}}L_\gamma(P)\,\rho_{\rm p}(P)\,{\rm d}P\right]\rho(R,z).\qquad(5)$$

The quantity in the square brackets is independent of position, and depends only on the assumed emission model. Therefore, for the two models of gamma-ray emission outlined above, we write

$$\left.\begin{array}{l}\varepsilon_\gamma^{\rm HTE}(R,z)=q^{\rm HTE}\,\rho(R,z)\\ \varepsilon_\gamma^{\rm CHR}(R,z)=q^{\rm CHR}\,\rho(R,z)\end{array}\right\}\qquad(6)$$

where q is a shorthand notation for the quantity in square brackets in (5), HTE stands for the model of Harding, Tademaru & Esposito (1978) and CHR for that of Cheng, Ho & Ruderman (1986a, b). Carrying out the integral over the period distribution, we have

$$q^{\mathrm{HTE}} = 4.3 \times 10^{34}\ \mathrm{photons\ s^{-1}\ sr^{-1}}$$

$$q^{\mathrm{CHR}} = 1.13 \times 10^{35}\ \mathrm{photons\ s^{-1}\ sr^{-1}}.$$

The gamma-ray intensity at earth due to millisecond pulsars as a function of galactic longitude l and latitude b can now be estimated by integrating ε_γ over the line of sight through the Galaxy. We have carried out this integration numerically following the procedure outlined by Harding (1981). Our results are presented in Figs 1 and 2.

Fig. 1 shows the latitude profile at $l = 0°$ of the gamma-rays expected from millisecond pulsars, for an assumed total number $N_{\mathrm{tot}} = 5 \times 10^5$. The results for two emission models—namely, the outer gap model due to Cheng, Ho & Rudermann (CHR) and the curvature radiation model due to Harding, Tademaru & Esposito (HTE) are shown, and a comparison is made with the gamma-ray intensity from "normal" pulsars as estimated by Harding.

There are two points to be noted from this diagram. First, the contribution of millisecond pulsars to the gamma-ray background may exceed that of the standard pulsars by a large factor. Second, the effective "width" of the latitude profile of the contribution due to millisecond pulsars is about twice that due to "normal" pulsars. This is in spite of the fact that normal pulsars have a scale height ~400 pc, larger than

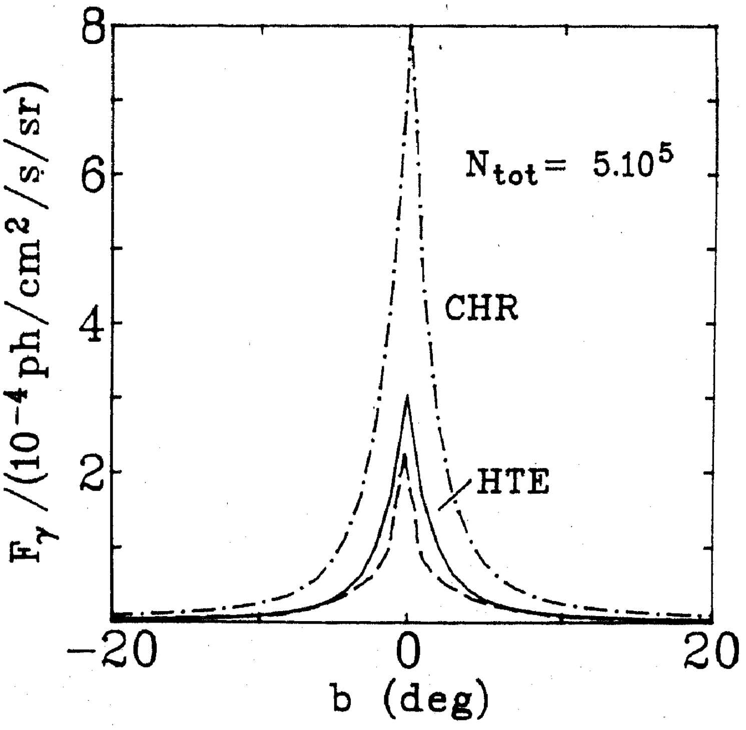

Figure 1. Estimates of the specific intensity of gamma-rays (>100 MeV) produced by millisecond pulsars plotted against the galactic latitude (for $l = 0°$). A total number of 5×10^5 millisecond pulsars in the Galaxy has been assumed. The solid line shows the results obtained using the curvature radiation model of Harding, Tademaru & Esposito (1978) and the dash-dotted line uses the outergap model of Cheng, Ho & Ruderman (1986). The dashed line at the bottom shows the contribution due to "normal" pulsars as estimated by Harding (1981).

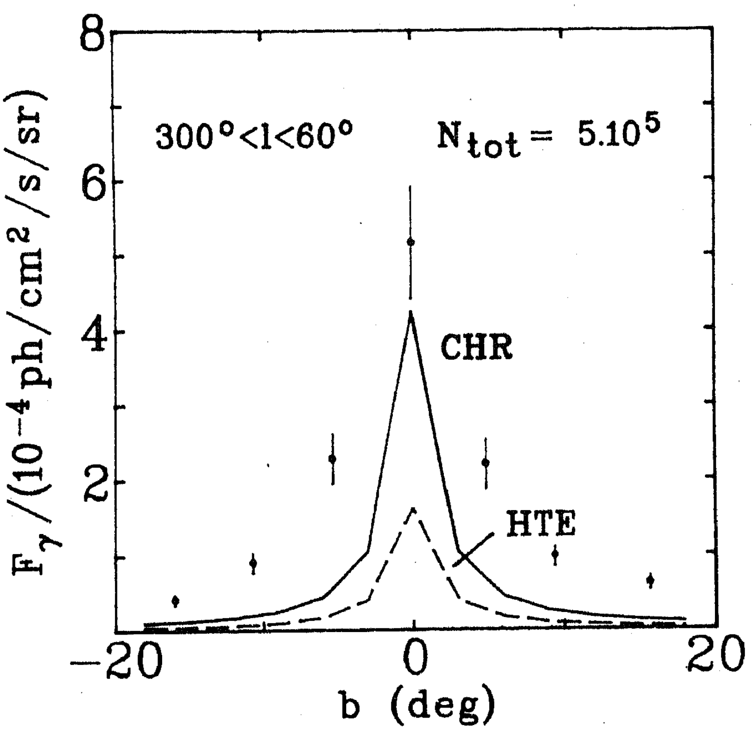

Figure 2. The estimated contribution of millisecond pulsars to the diffuse gamma-ray background is compared with the intensities observed by SAS-2 at different galactic latitudes (Fichtel, Simpson & Thomas *et al.* 1978). Results for two different magnetospheric models, as in Fig. 5, are shown. Both the data and the theoretical estimates are averaged over ±60° in Galactic longitude around $l = 0°$.

that assumed for millisecond pulsars. The reason for this is that although normal pulsars have a large scale height, the younger short-period ones among them are expected to be very close to the Galactic plane. Since these short-period pulsars dominate the gamma-ray production, the latitude profile is rather narrow. In the case of millisecond pulsars, even the "young" ones have a large scale height ~300 pc, since this is the scale height of their progenitors. Further, even if a millisecond pulsar is born near the plane, it can migrate to a couple of hundred parsecs away from the plane before slowing down appreciably. Thus the latitude profile of the γ-ray intensity from millisecond pulsars merely reflects their tapering population.

Fig. 2 compares these predictions with the diffuse γ-ray background intensities observed by SAS-2 (Fichtel, Simpson & Thompson 1978). The data points represent the diffuse gamma-ray specific intensity at different galactic latitudes, averaged over the galactic longitude range 300° through 0° to 60°. The expected contribution of millisecond pulsars averaged over the same longitude range is also shown for the two emission models CHR and HTE. As we can see, a good fraction of the background emission near the Galactic plane may originate from millisecond pulsars. At higher latitudes, the millisecond pulsars can still account for 20–25 per cent of the observed emission.

However, as mentioned above, much of the diffuse gamma-rays near the Galactic plane may originate due to the interaction of cosmic rays with the interstellar gas. If it were possible to obtain a firm lower limit to this contribution, then the argument may be turned around to place an useful upper limit on the number of millisecond pulsars in the galaxy.

5. Detectability of millisecond pulsars as point gamma-ray sources

So far we have discussed the net contribution of millisecond pulsars to the diffuse gamma-ray background. In this section we briefly discuss the interesting question as to what fraction of the millisecond pulsars are likely to be detected as point sources; in particular whether some unidentified COS-B sources could in fact be millisecond pulsars. It is to be noted, however, that the gamma-ray luminosity (above 100 MeV) of a millisecond pulsar is predicted to be less than or on the order of a few times 10^{33} erg/s, more than an order of magnitude less than the inferred luminosities of the unidentified COS-B sources (Bignami & Hermsen 1983). Thus, to be detected as an individual source, a millisecond pulsar must be situated very close to the Sun. A Monte Carlo study done by us shows that depending upon the magnetospheric model used, one expects $\sim$(2 to 7) $\left(\frac{N_{\rm tot}}{5.10^5}\right)\left(\frac{f}{0.2}\right)$ millisecond pulsars to be detectable by COS-B above a flux limit $\sim 1 \times 10^{-6}$ photons $\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$ (f is the gamma-ray beaming factor, *i.e.* the fraction of the sky swept by the gamma-ray beam of a millisecond pulsar). This number is likely to be even smaller since the detection threshold is higher in the directions towards the inner Galaxy, where most of the unidentified COS-B sources are situated. Nevertheless we wish to make the following observations.

1. According to our estimates, none of the *known* millisecond pulsars are likely to have been detected by COS-B.
2. But some of the unidentified COS-B sources may, in fact, be millisecond pulsars not yet detected as radio pulsars.

The prospects, however, look much brighter with the Gamma Ray Observatory to be launched in the near future since it will have a sensitivity of about 20 times higher than that of COS-B and also a better sky coverage (Kanbach *et al.* 1988). The Monte Carlo study mentioned above predicts that $\gtrsim 300\left(\frac{N_{\rm tot}}{5.10^5}\right)\left(\frac{f}{0.2}\right)$ millisecond pulsars should be detectable by GRO as point sources.

6. Conclusions

By virtue of their short rotation periods, millisecond pulsars are expected to be fairly strong sources of gamma-rays. Based on the existing magnetospheric models for normal pulsars, we have estimated the contribution of millisecond pulsars to the diffuse Galactic gamma-ray background. It seems possible that a good fraction of the background emission near the Galactic plane, and about 20–25 per cent of that at higher galactic latitudes is contributed by millisecond pulsars.

It is quite likely that a few of the unidentified COS-B sources may be as yet undetected millisecond pulsars. We predict that the GRO satellite scheduled to be launched soon should be able to detect >100 millisecond pulsars as point sources.

It should be noted that the above predictions are based on extrapolations of magnetospheric models constructed for normal pulsars. Until such models are computed specifically for millisecond pulsars, these estimates are to be viewed with some caution.

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