Radio-loud and radio-quiet gamma-ray pulsars from the Galactic plane and the Gould Belt

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We present recent results of a pulsar population synthesis study in the polar cap model that includes the Parkes Multibeam Pulsar Survey, realistic beam geometries for radio and γ-ray emission from neutron stars born in the Galactic disc as well as the local Gould Belt. We include nine radio surveys to normalize the simulated results from the Galactic disc to the number of radio pulsars observed by the group of selected surveys. In normalizing the contribution of the Gould Belt, we use results from a recent study that indicates a supernova rate in the Gould Belt of 3 to 5 times that of the local region of the Galactic plane leading to ~100 neutron stars born in the Gould Belt during the last 5 Myr. Our simulations include the dynamical evolution of the Gould Belt where neutron stars are produced in the plane of the Gould Belt during the past 5 Myr. We discuss the simulated numbers of radio-quiet (those below flux threshold of radio surveys) and radio-loud, γ-ray pulsars from the Galactic disc and the Gould belt observed by γ-ray telescopes EGRET, AGILE and GLAST. They suggest that about 35 of the unidentified EGRET sources could be (mostly radio-loud) γ-ray pulsars with 2/3 of them born in the Galactic disc and 1/3 in the Gould Belt.

1. INTRODUCTION

While it continues to be a major challenge to identify the 150 EGRET unidentified γ-ray sources [1,2], the multi-wavelength approaches [3] have succeeded in identifying a few of these objects. Pulsars are believed to be an important class of the EGRET unidentified γ-ray sources. The largest group of EGRET sources appears to be AGNs [2]. A group of 45±6 unidentified sources [4] have been spatially correlated with the location of the Gould Belt, which is a nearby structure of OB stars having produced about 100 supernova explosions during the past 5 Myr [5,2]. However, such a large number suggests that nearly half of the anticipated 100 neutron stars from the Gould Belt are detectable by EGRET as point sources. We anticipate that the Gamma-ray Large Area Space Telescope (GLAST) will be able to determine whether many of these unidentified sources are radio-quiet γ-ray pulsars. GLAST will have the sensitivity and the ability to perform blind period searches required to identify nearby radio-quiet γ-ray pulsars.

Since the EGRET error boxes are quite large (1 degree), and it has not been possible to identify many of these sources, a statistical analysis of pulsar characteristics from a population synthesis study can provide important information on the likelihood that many of these unidentified sources are radio-quiet γ-ray pulsars. Such simulations also provide predictions for upcoming γ-ray telescopes like AGILE and GLAST. The ratio of radio-loud to radio-quiet γ-ray pulsars is an important parameter that will help to discriminate between pulsar models. The polar cap model [6,7] predicts that the radio and γ-ray emission results from common field lines that are tied to the magnetic polar cap, the size of which is defined by the last open field lines. As a result, the polar cap model predicts strong correlations between radio and γ-ray pulse profiles. Since the beams significantly overlap, the polar cap model predicts a large number of radio-loud γ-ray pulsars. However, the weaker off-beam γ-ray emission allows for some number of radio-quiet γ-ray pulsars. On the other hand, the outer gap model [8,9] predicts that the region where γ-ray emission takes place is many stellar radii from the surface near the light cylinder, along the null charge surface. The γ-ray emission from these regions tends to be anticorrelated with the radio emission; therefore, the outer gap model predicts a greater number of radio-quiet γ-ray pulsars. While the detections of GLAST may lead to a much larger number of unidentified γ-ray sources, it will detect a statistically significant number of radio-quiet and radio-loud γ-ray pulsars that may help resolve the location of the emission region in the pulsar magnetosphere.

2. SIMULATION - ASSUMPTIONS

Our simulations are based on previous studies [10,11] with the additional contribution from the Gould Belt. Our current results represent an improvement over our previous study [12] of pulsars from the Gould Belt that assumed a simple geometry for the γ-ray beam and no consideration for radio emission. We have now included the geometry of the core and cone radio beams as well as the slot gap geometry as discussed more fully in [11]. For neutron stars born in the Galactic plane, we assume a constant birth rate over the past 1 Gyr, while for the Gould Belt the oldest neutron stars are assumed to be 5 Myr. The Gould Belt is assumed to be 26.4 Myr [5] with a

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recent supernova rate of the 2 to 5 times the local rate. The age of a neutron star is randomly selected back to 5 Myr, and the shape of the Gould Belt at that time is determined by an evolution model [5]. The location of the neutron star is chosen uniformly over the disk of the Gould Belt.

We then evolve the neutron stars in the Galactic potential to the present. We find that in order to reproduce the distribution of the pulsars in the $\dot{P}-P$ diagram shown below in Figure 1a, we have to assume that the magnetic field decays with a constant of 2.8 Myr. For the radio beam geometry and luminosity, we have assumed the model of [13] as well as their supernova kick velocity distribution. The geometry of the γ-ray beam is theoretically motivated by the work of [14,15] who describe the γ-ray emission from the slot gap. The initial period of the pulsars is assumed to be a flat distribution from 0 to 500 ms with an initial magnetic field described by two Gaussians. We have included all-sky threshold maps for EGRET and AGILE and a more recent estimate than was used in [11] for GLAST thresholds (Grenier, private communication) indicated in Table 1.

Table 1: GLAST Thresholds

$\|b\| < 5^o$ and $\|l\| < 45^o$	1.1×10^{-8} photons/(cm2·s)
$\|b\| < 5^o$ and $\|l\| > 45^o$	6.0×10^{-9} photons/(cm2·s)
$\|b\| > 5^o$	3.0×10^{-9} photons/(cm2·s)

3. RESULTS

We normalize the number of neutron stars that are simulated in the plane in our select group of nine radio surveys (including the Parkes Multibeam pulsar survey) to the number of pulsars (978) that have actually been detected by these surveys. We have included the information associated with each of these radio surveys that is required to obtain the flux threshold for each survey (see [11]). With this normalization, we are able to predict the neutron star birth rate in the plane. The normalization for the Gould Belt is based on simulating 100 neutron stars in the Gould Belt during the past 5 Myr. We are then able to predict the number of radio-quiet and radio-loud γ-ray pulsars from the plane and from the Gould Belt seen by

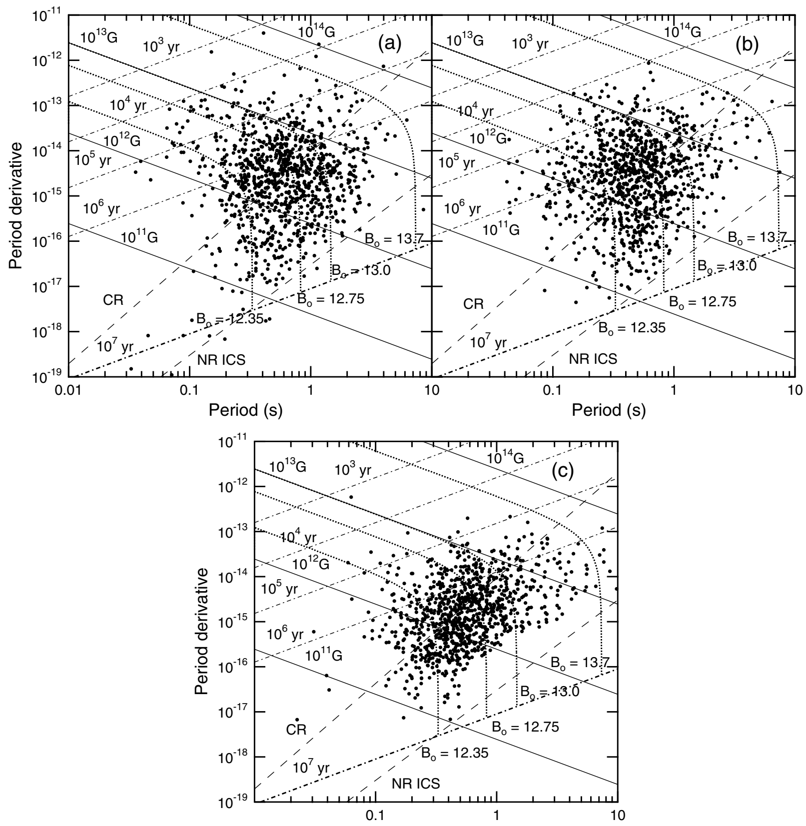

Figure 1: The distribution of 978 radio pulsars detected (1a) by a select group of surveys, same number of pulsars simulated from the plane (1b) and the same number simulated from the Gould Belt (1c) assuming magnetic field decay constant of 2.8 Myr. The solid lines represent the lines of constant dipole magnetic field of 10^{11}--10^{14} G, assuming no field decay. The dotted curves represent the paths of four 10^7 yr old pulsars with the indicated initial magnetic fields (Log), the dot-dashed lines show the lines of constant age assuming an initial period of zero seconds, and the dashed lines indicate the curvature radiation (CR) and nonresonant inverse Compton scattering (NRICS) death lines to the right of which pairs are no longer produced by these mechanisms.

various instruments. We show in Figure 1 the distribution of 978 detected radio pulsars (1a) by the selected group of surveys, the same number of simulated radio pulsars from predicts only a total of 10 radio pulsars from the Gould Belt. The Gould Belt pulsars occupy a similar place as the plane pulsars in the diagram except that they have an age limitation of 5 Myr. The small number of pulsars beyond the 5 Myr age line is a result of the fact that the line represents the age of the pulsar with an initial period of zero seconds; while in the simulation we have assumed a flat distribution in period from 0 to 500 ms.

In order to predict an adequate birth rate and a distance distribution matching the observed distribution of radio pulsars, we had to reduce the radio luminosity of [13] by a factor of 80 in order to have a supernova rate similar to recent findings of $2.5^{+0.8}_{-0.4}$ per century with 85% arising from massive stars [17]. While it may be possible to tailor the radio luminosity model with a complicated dependence on the period and period derivative to account for the the plane (1b) and from the Gould Belt (1c). While we do not expect 978 pulsars from the Gould Belt, we show this number to see the overall distribution. The simulation overall distribution, field decay leads quite naturally to the upside-down funnel-shaped distribution of the detected pulsars seen in the diagram.

In Figure 2, we compare the indicated characteristics between detected pulsars (shaded histograms) and simulated pulsars (open histograms). To improve the statistics and smoothness of the simulated histograms, we run the simulation until the number of simulated pulsars detected by the radio surveys is equal to ten times the number of detected pulsars and then renormalize accordingly. As seen in the comparisons, the model simulation over predicts the number of pulsars with short periods, large period derivatives, and large distances. However, overall the agreement of the simulation of pulsars from the Galactic plane is fairly good.

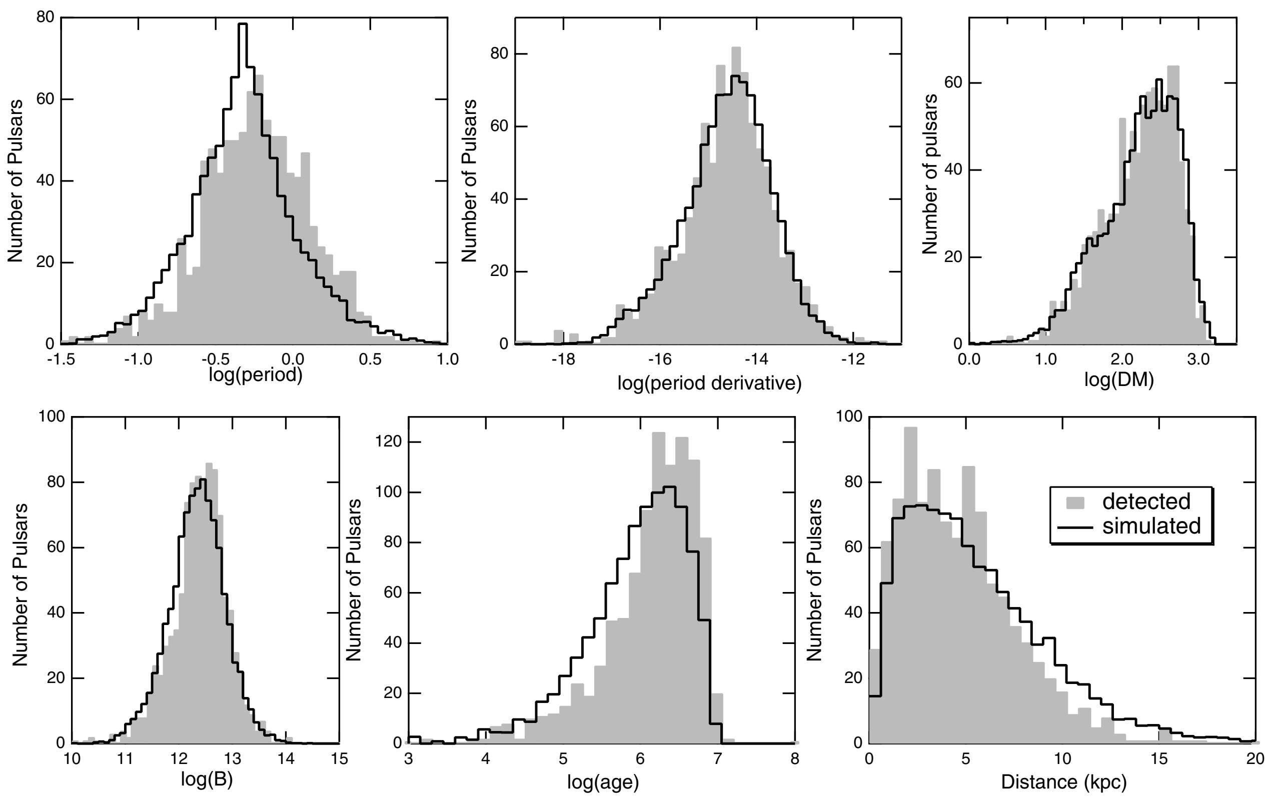

Figure 2: Distributions of various pulsar characteristics indicated as detected pulsars (shaded histograms) and simulated pulsars (open histograms) from the Galactic plane.

In Figure 3, we present the distribution of pulsars in the $\dot{P}-P$ diagram of the known γ-ray pulsars detected by EGRET (a) and of those simulated for EGRET (b), AGILE (c) and GLAST (d), in which radio-loud γ-ray pulsars are shown as dots and the radio-quiet γ-ray pulsars are indicated by crosses. Young pulsars have higher γ-ray luminosities, which decrease as they approach the curvature pair death line where curvature radiation is no longer able to produce electron-positron pairs. Pulsars below the curvature pair death line are still able to produce pairs via nonresonant inverse Compton scattering of the thermal soft X-ray emission from the stellar surface. However, below the nonresonant inverse Compton scattering line, pulsars no longer produce pairs and become radio-quiet.

In Table 2, we present the simulated γ-ray pulsar statistics for radio-quiet and radio-loud γ-ray pulsars as detected by various instruments as well as the ones that

EGRET detected. The numbers to the left are those from the Galactic plane and those added on the right represent the contribution from the Gould Belt. The last column represents the ratio of radio-loud to radio-quiet γ-ray pulsars. Our simulation predicts that EGRET should have detected 26 radio-loud and 9 radio-quiet γ-ray pulsars, AGILE should detect 48 radio-loud and 20 radio-quiet γ-ray pulsars, while GLAST, with increased sensitivity, should detect 288 radio-loud and 356 radio-quiet γ-ray pulsars from both the plane and the Gould Belt. For pulsars from the plane, the ratio of radio-loud to radio-quiet γ-ray pulsars goes down with GLAST, as GLAST begins to see pulsars that are further away than current radio telescopes can detect, thereby, seeing more γ-ray pulsars that escape radio detection.

Table 2: Simulated γ-ray Pulsar Statistics

Source	**Number of γ-ray pulsars (plane+Belt)**		**Ratio RL/RQ**	
	Radio-Loud	**Radio-Quiet**	**Plane**	**Gould Belt**
Det. EGRET	6+2	0+1		2
Sim. EGRET	23+3	6+3	3.8	1.0
Sim. AGILE	45+3	16+4	2.8	0.8
Sim. GLAST	284+4	249+7	1.1	0.6

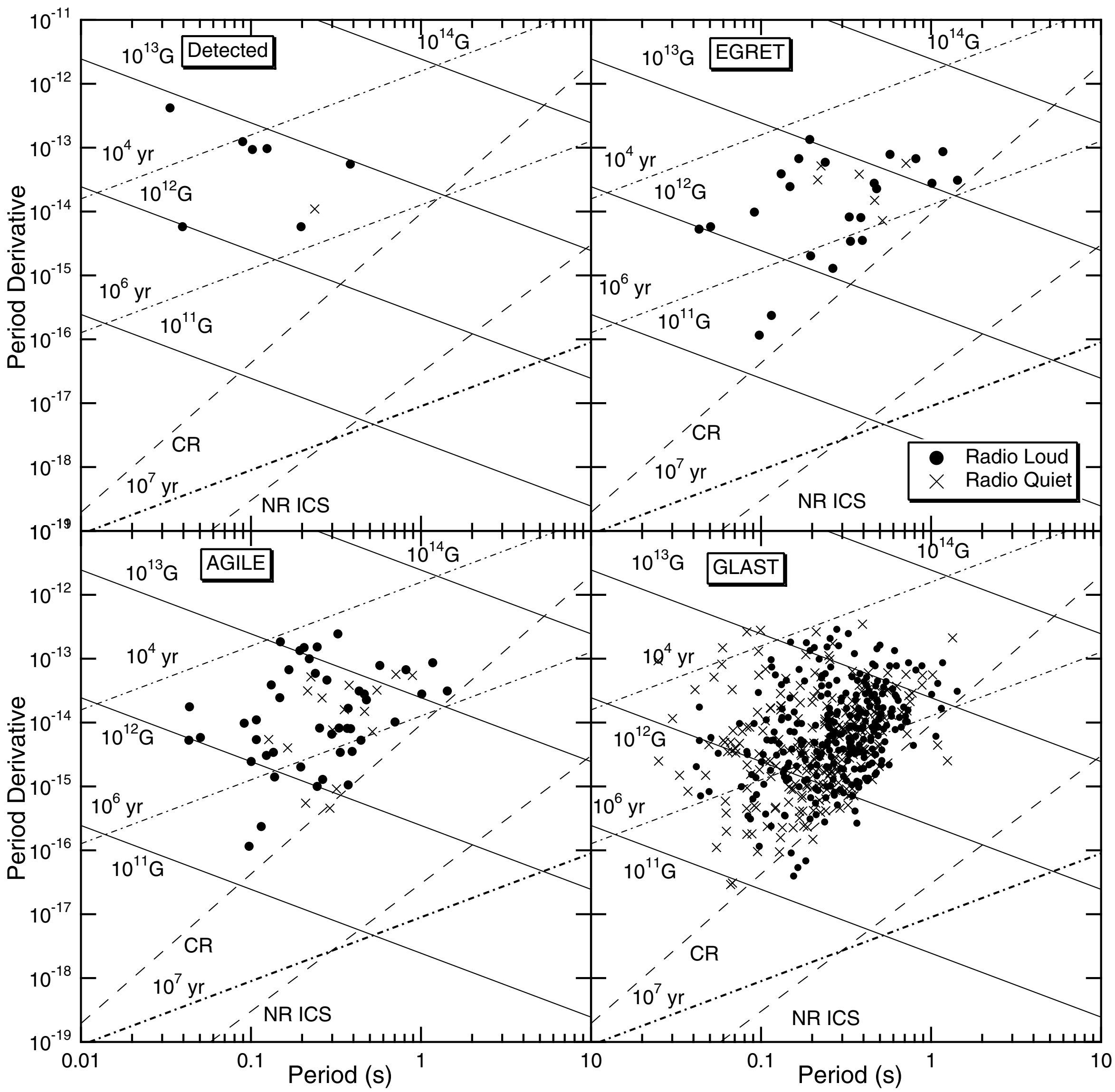

Figure 3: Distributions of radio-quiet (crosses) and radio-loud (dots) γ-ray pulsars (a) detected by EGRET, and simulated for (b) EGRET, (c) AGILE, and (d) GLAST, assuming a field decay constant of 2.8 Myr. Dashed lines represent the death lines for curvature radiation (CR) and for nonresonant inverse Compton scattering (NRICS). Dot-dashed lines represent the indicated pulsar age, assuming field decay, and solid lines represent the traditional magnetic surface field strength, assuming a constant dipole spin-down field.

Currently there are about 53 detected radio pulsars within about 28 of EGRET error boxes with about 4 pulsars detected using deep searches. So there are between 18-25 reasonably gamma-ray-bright radio pulsars [15] within EGRET error boxes and 8 previously detected γ-ray pulsars giving a total of about 32 radio-loud γ-ray point sources that EGRET has detected. Our simulation predicts a total of 26 radio-loud γ-ray pulsars, which includes a contribution of 3 from the Gould Belt. In addition, our simulation indicates that there should be about 9 Geminga-like radio-quiet γ-ray pulsars with 3 of these being contributed by the Gould Belt. A total number of only 6 γ-ray pulsars from the Gould Belt is significantly smaller than the 45 EGRET unidentified sources that have been previously correlated with the Gould Belt.

In order to explore the correlation of the Galactic position of γ-ray pulsars with the current location of the Gould Belt, we show in the Aitoff projections radio-quiet (crosses) and radio-loud (dots) γ-ray pulsars simulated for EGRET (a) and GLAST (b) in Figure 4. It is clear that there is a correlation especially for simulated radio-quiet γ-ray pulsars from the Gould Belt. We understand that there is a difficulty in detecting nearby radio pulsars, as radio astronomers look for a dispersion signal above the local red noise that may identify it as a pulsar (Roberts, private communication). However, we have not included such a filter in our simulation. As a result, we may be over estimating the number of nearby radio pulsars, and, therefore, due to the normalization of the pulsars from the plane, underestimating the number of γ-ray pulsars.

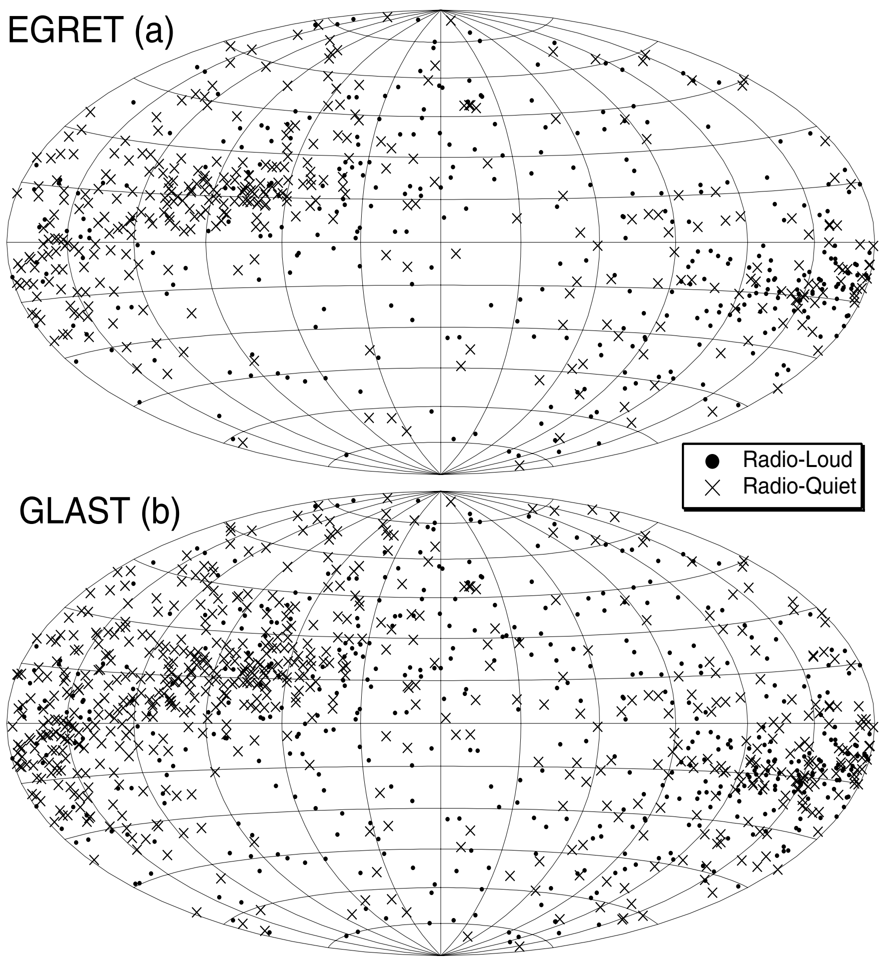

Figure 4: Aitoff plots of radio-quiet (crosses) and radio-loud (dots) γ-ray pulsars simulated for EGRET (a) and GLAST (b). The number of pulsars contributed by the Gould Belt is exaggerated to show the correlation of Galactic position and the location of the Belt.

The radio-loud γ pulsars have smaller impact angles than radio-quiet γ-ray pulsars. However, γ-ray pulsars, either radio-quiet or radio-loud, must be younger in order to have sufficient γ-ray flux to be detected.

A central assumption that is built into the radio geometry and luminosity model of [13] is that the ratio of the core to cone peak fluxes varies as the reciprocal of the period, so that short period pulsars are core dominated and, due to their small emission region (small solid angle), are harder to observe. On the other hand, the off beam curvature radiation of the γ-ray emission is much broader. Since the young neutron stars of the Gould Belt are fairly close, they are more easily detected in the γ rays than in radio due to the larger γ-ray solid angle. Therefore, radio-quiet γ-ray pulsars from the Gould Belt will have large impact angles (β) so that the viewer will miss the radio beam, but detect the off-beam γ-ray emission. Radio-loud γ-ray pulsars have smaller impact angles in order to see the radio core beam and the on-beam γ-ray emission. This viewing geometry has a larger radio and γ-ray luminosity. As a result, radio-loud γ-ray pulsars are older and have larger distances than radio-quiet γ-ray pulsars.

4. CONCLUSIONS

We present the results of a population synthesis study of radio and γ-ray pulsars from both the Galactic plane and the Gould Belt. The details of the simulation of pulsars from the plane are presented in [11]. There is a general consensus that many of the EGRET unidentified γ-ray sources are pulsars, some of which must come from the Galactic plane and some from the Gould Belt. A significant number of EGRET error boxes have been found to contain one or more radio pulsars. We present some preliminary results in which neutron stars from the plane and the Gould Belt are treated consistently within the same set of assumptions. Consistent with the polar cap model, we find that the number of radio-loud γ-ray pulsars detectable by EGRET dominate over the radio-quiet γ-ray pulsars and even more so for pulsar detectable by GLAST. This is in stark contrast to the outer gap model in which radio-quiet γ-ray pulsars dominate over radio-loud ones as indicated in the studies of [8,9,16]. Such model simulations indicate that GLAST may have the ability to then distinguish between these models, settling a long-standing debate over the location of the region within the neutron star magnetosphere where electrons are accelerated.

Our simulation indicates that the Gould Belt contributes 20% of the total number (6 out of 35) of simulated γ-ray pulsars that EGRET should have detected as point sources. Our simulations find that the positions of γ-ray pulsars from the Gould Belt do indeed map to the present location of the Gould Belt in a similar fashion as the positions of γ-ray pulsars from the plane map to the Galactic plane. This result is expected as γ-ray pulsars must be young to be γ-ray bright, and, therefore, must not have moved very far from their birth location. However, nine γ-ray pulsars simulated from the Gould Belt is significantly smaller than the 45 EGRET unidentified sources that have been correlated with the Gould Belt. It may be that perhaps some of these are from the Galactic plane.

The ratio of radio-loud to radio-quiet γ-ray pulsars may serve as an important diagnostic to discriminate between polar cap and outer gap models. Due to the very different geometries of γ-ray emission, the polar cap and the outer gap models make significantly different predictions of this ratio. In this study, we have used the slot gap geometry of the polar cap model for γ-ray emission, which is concentric to the assumed radio beam geometry, thereby yielding many radio-loud γ-ray pulsars. The outer gap with its γ-ray emission anticorrelated to the radio emission produces many more radio-quiet pulsars. Therefore the polar cap and the outer gap models predict ratios of radio-loud to radio-quiet γ-ray pulsars of 2.8 and 0.27 [16], respectively.

However, there are other uncertainties that must be settled. These include further understanding of the ratio of the radio core to cone flux in radio pulsars, as well as the inclusion of the caustic γ-ray component [18,19]. While the results of the simulation do depend on a number of assumptions, there is a clear indication that polar cap and outer gap models predict significantly different ratios of radio-loud to radio-quiet γ-ray pulsars for EGRET but more so for GLAST.

Acknowledgments

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