

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

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Abstract: We present recent results of a population synthesis study in the slot gap 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 in the Gould Belt during the last 5 Myr. Our simulations include the evolution of the Gould Belt during the past 5 Myr. We discuss the simulated numbers of radio-quiet (below threshold of radio surveys) and radio-loud, γ -ray pulsars from the Galactic disc and the Gould belt observed by 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.

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Introduction:

- ~ 150 unidentified EGRET γ -ray sources
 - largest group of EGRET src = AGNs but pulsars believed to be an important class too
 - 45 ± 6 unid. sources spatially correlated to the location of the Gould Belt – Grenier (2000) (a nearby structure of OB stars that produced ~ 100 NS over the last 5 Myr, see next slide)
 - GLAST \rightarrow are these unid. sources radio-quiet γ -ray pulsars?
 - difficulty to identify sources in large EGRET error boxes
- \rightarrow statistical analysis of pulsars characteristics from a population synthesis
- \rightarrow predictions for AGILE / GLAST
- \rightarrow radio-loud/radio-quiet ratio to help in the discrimination of pulsar emission models:
- polar-cap model - Daugherty & Harding (1996)
 - outer-gap model - Romani et al. (1995)

The Gould Belt:

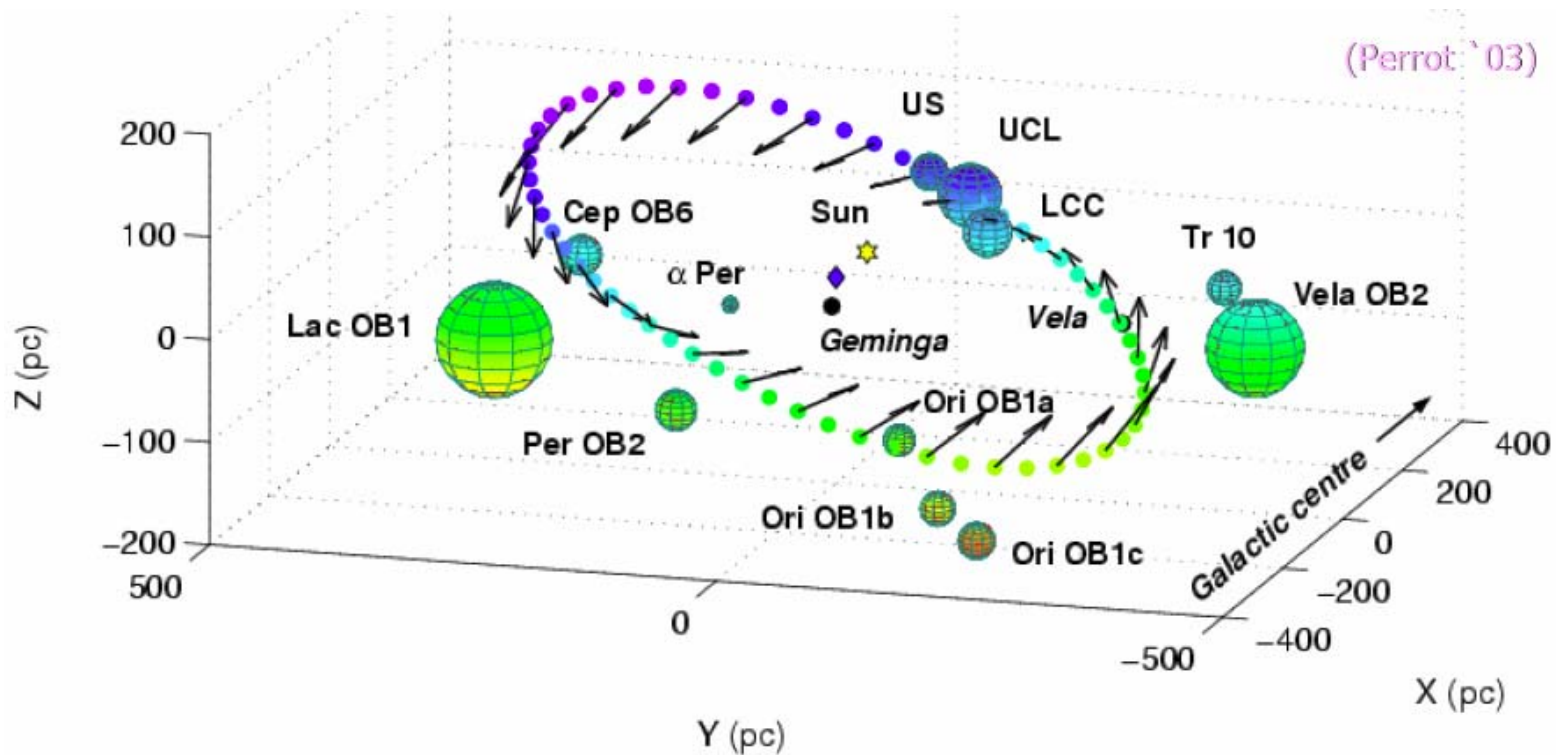


Figure 1 - The structure of the Gould Belt at the present time indicating a 3D view of the shockwave and velocity field relative to the LSR. Spheres indicate OB associations with radii equal to their size (de Zeeuw et al. 1999). The location of the center of the Belt and the Sun are indicated with a diamond and star, respectively.

A nearby starburst region, 26.4 ± 0.4 million years old, with a recent supernova rate of 20 neutron stars per Myr during the past 5 Myr – Grenier (2004)

Background:

In previous radio and γ -ray simulations (Gonthier et al. 2004) within the polar cap model, we have used:

- The Galactic potential by Paczynski (1990)
- The Parkes Multibeam Pulsar Survey - Manchester et al. (2001)
- The new distance model of Cordes & Lazio (2003) – distances are $\sim 20\%$ smaller compared to old model
- The radio beam geometry and luminosity of Arzoumanian, Chernoff & Cordes (2002)
- The radius-to-frequency mapping for the conal beam as described by Mitra & Deshpande (1999)
- The γ -ray beam geometry and luminosity from the slot gap described by Muslimov & Harding (2003)
- an all sky threshold for AGILE (A. Pellizzoni, private communication)
- an all-sky threshold for EGRET (I. Grenier, private communication)

Instrument	Radio-loud γ -ray pulsars	Radio-quiet γ -ray pulsars	Ratio RL/RQ
EGRET	19	7	2.7
AGILE	37	13	2.8
GLAST	344	276	1.2

yielding a neutron star birth rate of 1.38 neutron stars per century

Improvements:

The following improvements have been implemented:

- Improved flux thresholds for GLAST (I. Grenier, private communication)

GLAST Flux Thresholds	
in Plane $\rightarrow b < 5^\circ$	11.0×10^{-9} photons.cm ⁻¹ .s ⁻²
out of Plane $\rightarrow 5^\circ < b < 45^\circ$	6.0×10^{-9} photons.cm ⁻¹ .s ⁻²
out of Plane $\rightarrow b > 45^\circ$	3.0×10^{-9} photons.cm ⁻¹ .s ⁻²
pulsed emission	5.0×10^{-8} photons.cm ⁻¹ .s ⁻²

- A more realistic Galactic potential (mass model 2) of Dehnen & Binney (1998) (W. Dehnen private communication)
- An improved adaptive stepsize Runge-Kutta – Cash-Karp (Numerical Recipes)
- The addition of neutron stars born in the expanding Gould Belt, following the dynamical evolution of this structure – Perrot & Grenier (2003)
- An adjusted radio luminosity to obtain a supernova rate of 2.13 per century in the Galaxy in order to agree with the findings of Tammann et al. (1994)

Emission geometry for the slot gap model: Muslimov & Harding (2003)

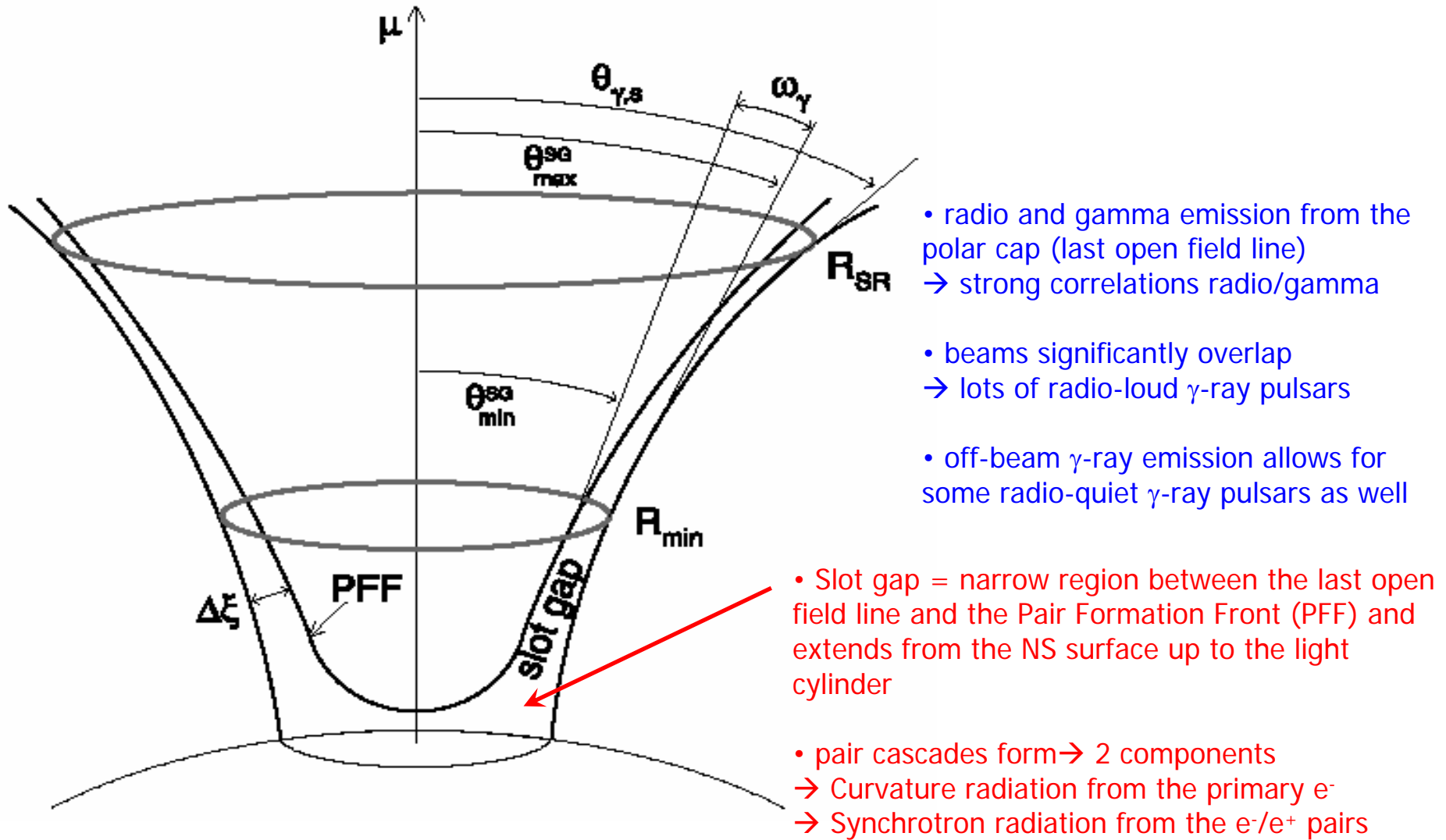


Figure 2

Gonthier et al. (2004)

Emission geometry for the outer gap model: Romani & Yadigaroglu (1995)

γ -ray emission located far from the surface, near the light cylinder (along the null charge surface)
→ Tends to be anticorrelated to the radio emission → lots of radio-quiet γ -ray pulsars

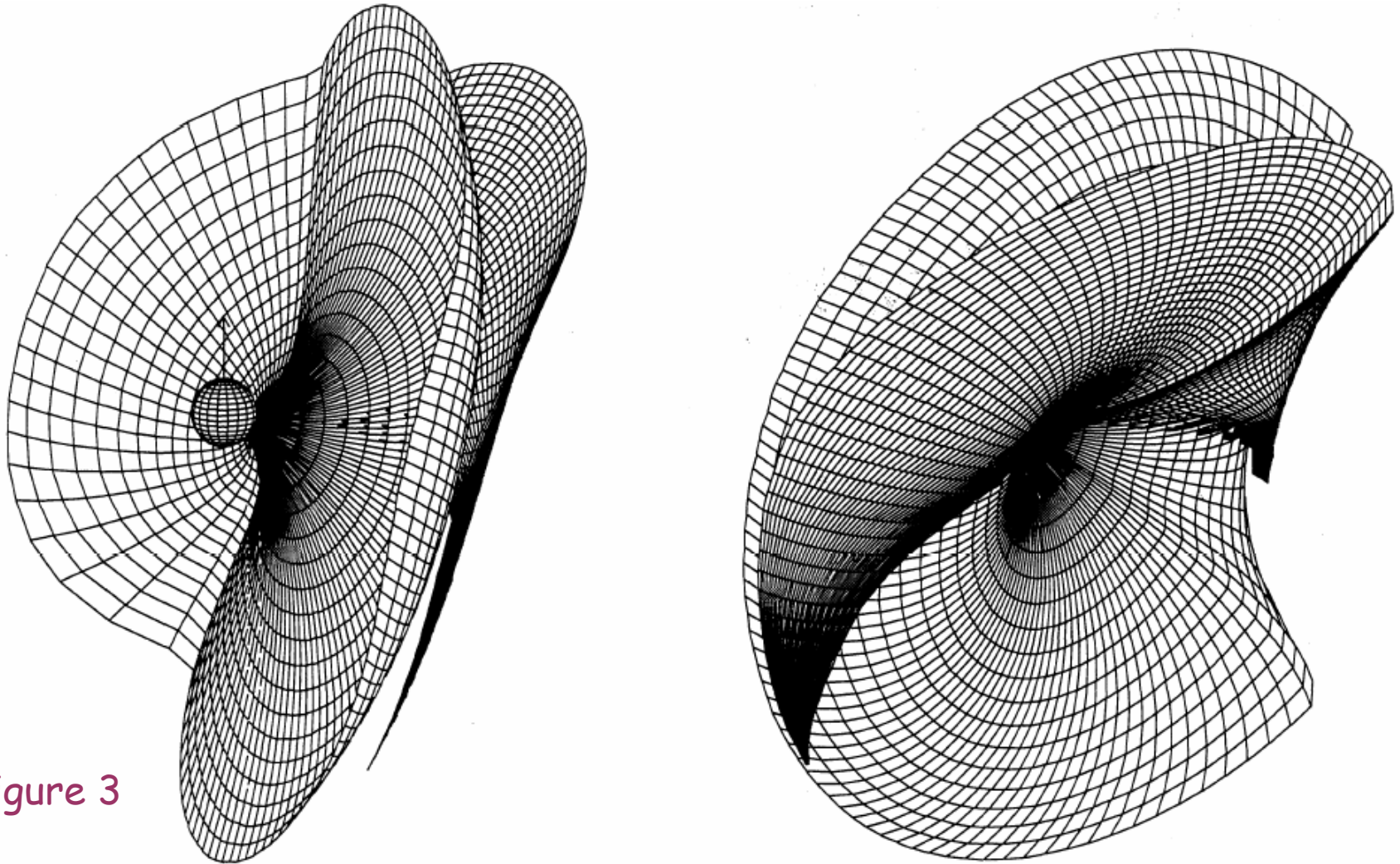


Figure 3

FIG. 1.—Two views of the surface of last closed field lines, cut at $1.2r_{LC}$ for an $\alpha = 70^\circ$ rotator (see text). The gap lies above the null charge surface, inside the open field line region. We show the illuminated section of the gap upper surface. The observed pulsar γ -rays are beamed along this surface. The neutron star's radius is increased to $0.1r_{LC}$ for clarity. A computer animation of this geometry is available from the authors.

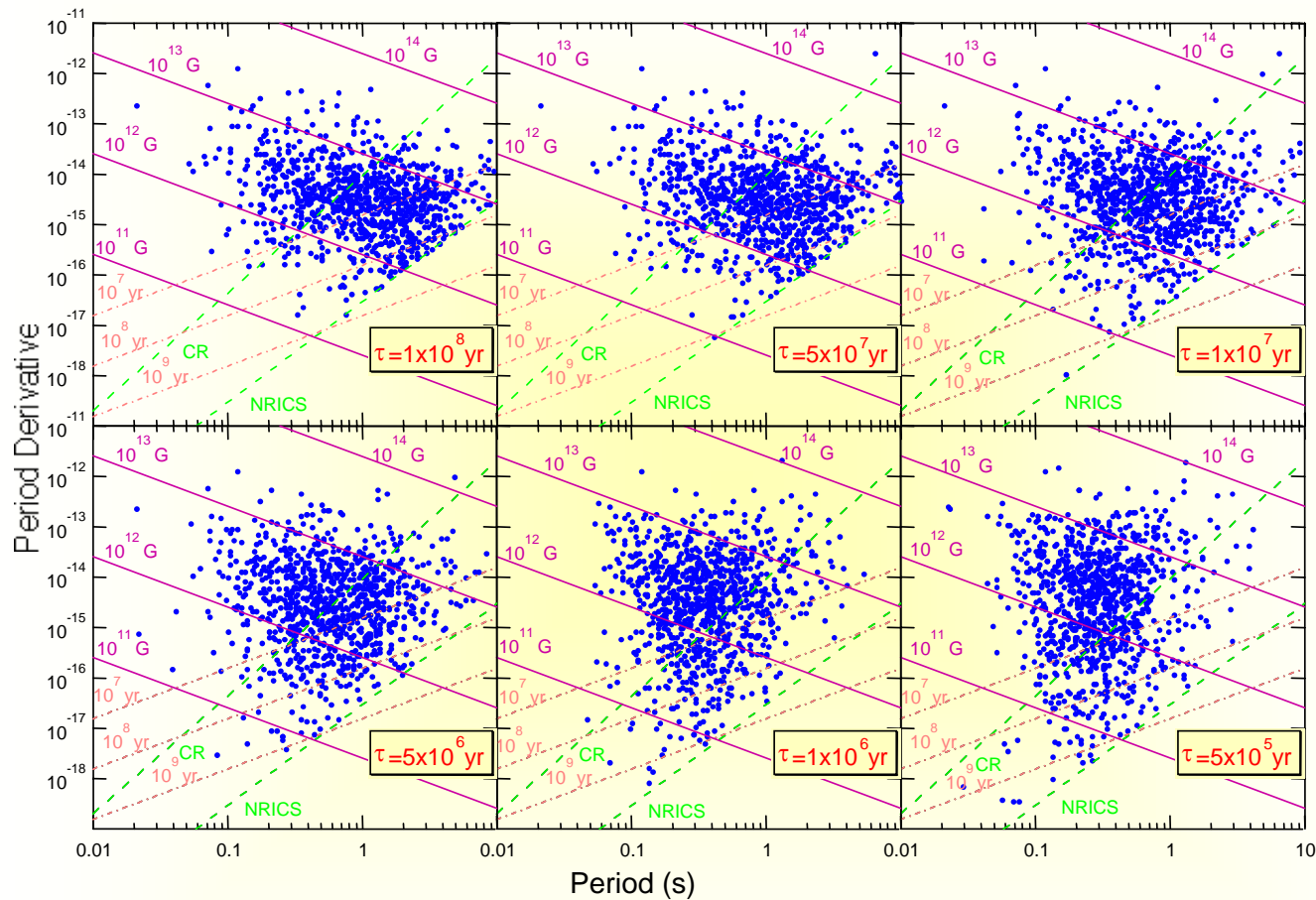
Assumptions:

- Uniform birth rate back to:
 - 1 Gyr for the Galactic disc distribution of Paczynski (1990)
 - 5 Myr for the expanding Gould Belt region of Perrot & Grenier (2003)
 - assumed to be 26.4 Myr old
 - SN rate 2 – 5 times the local rate → birth in the GB disc → evolved in the Gal. Potential
- Birth period – flat distribution of 0 to 150 ms
- Birth magnetic field described by Gaussians

Parameters for initial magnetic field distribution			
Gaussian	Log(Mean)	Log(Width)	Weight
Low field	12.6	0.5	2
High field	13.0	0.8	1

- Magnetic field decay constant of 2.8 Myr (P-Pdot diagram) – Gonthier, Van Guilder & Harding (2004)
- Normalization of the simulation
 - Galactic disc - to 978 radio pulsars actually detected by nine radio pulsar surveys including the Parkes Multibeam Pulsar Survey
 - Gould Belt – to 100 supernovae having taken place during the last 5 Myr

Why magnetic field decay?



adopted value
2.8 Myr

Figure 4 - Simulations of radio pulsars for the indicated magnetic field decay constant τ , from Gonthier, Van Guilder & Harding 2004. Pair curvature and inverse Compton scattering death lines are shown as dashed green lines. Orange-dot-dashed lines represent the indicated pulsar age, assuming no field decay. Solid magenta lines show the indicated magnetic surface field strength, assuming a constant dipole spin-down field.

Radio Pulsars from the Galactic Disc

model favors
short P, large Pdot, large distances

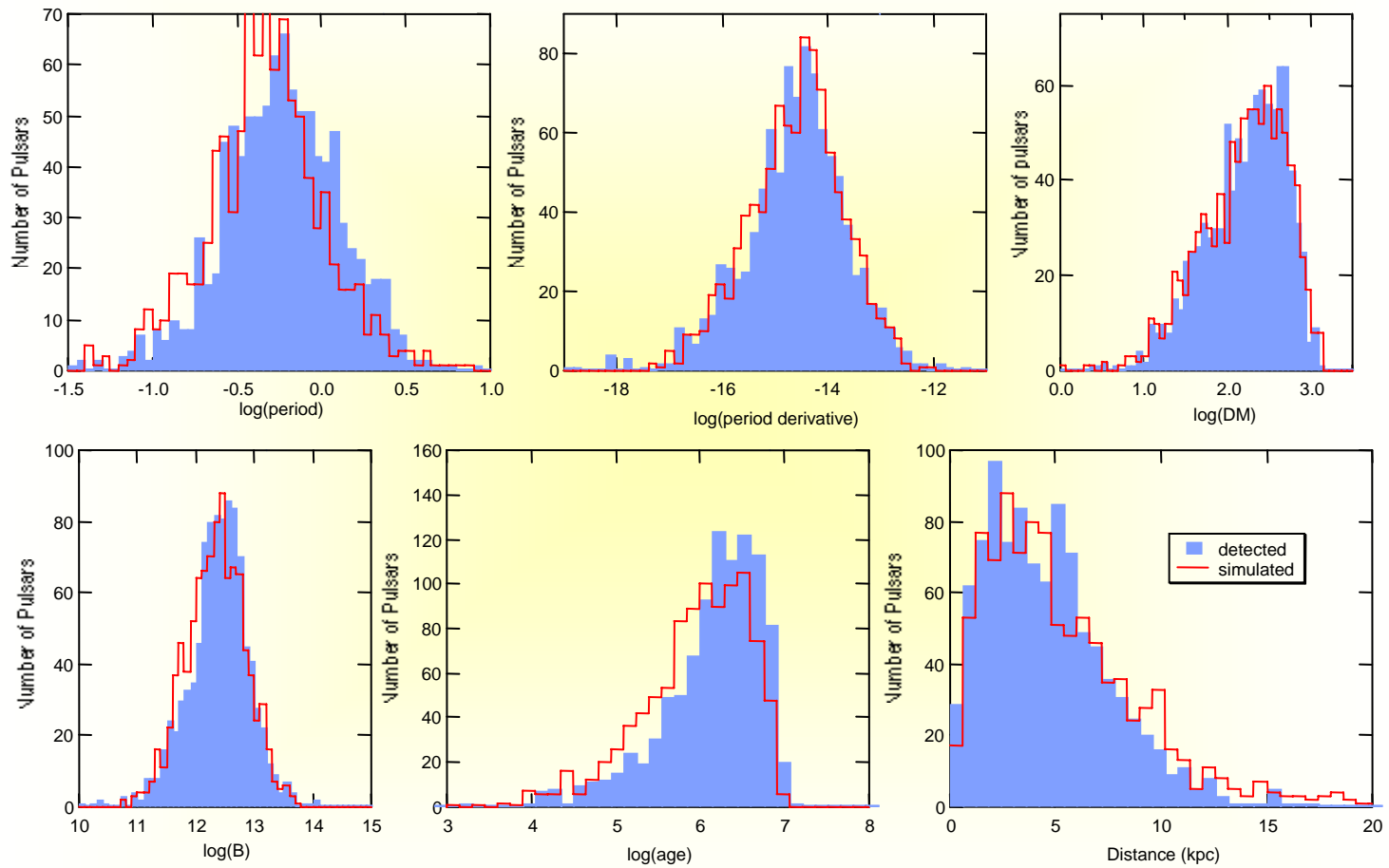


Figure 5 - Distributions of various pulsar characteristics. Detected pulsars are represented by blue solid histograms, while simulated pulsars are shown in red histograms.

Radio Pulsars from the Galactic Disc

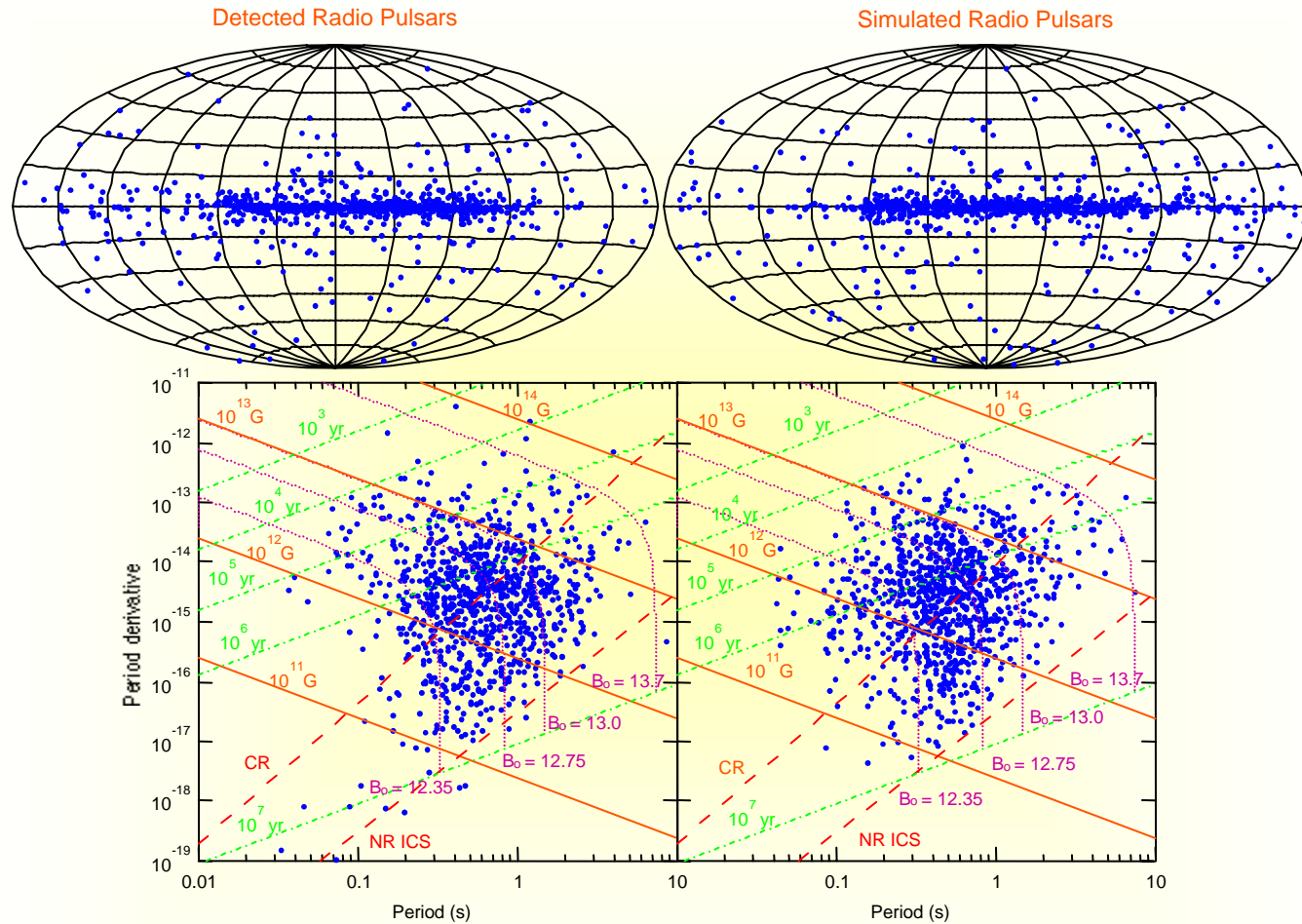
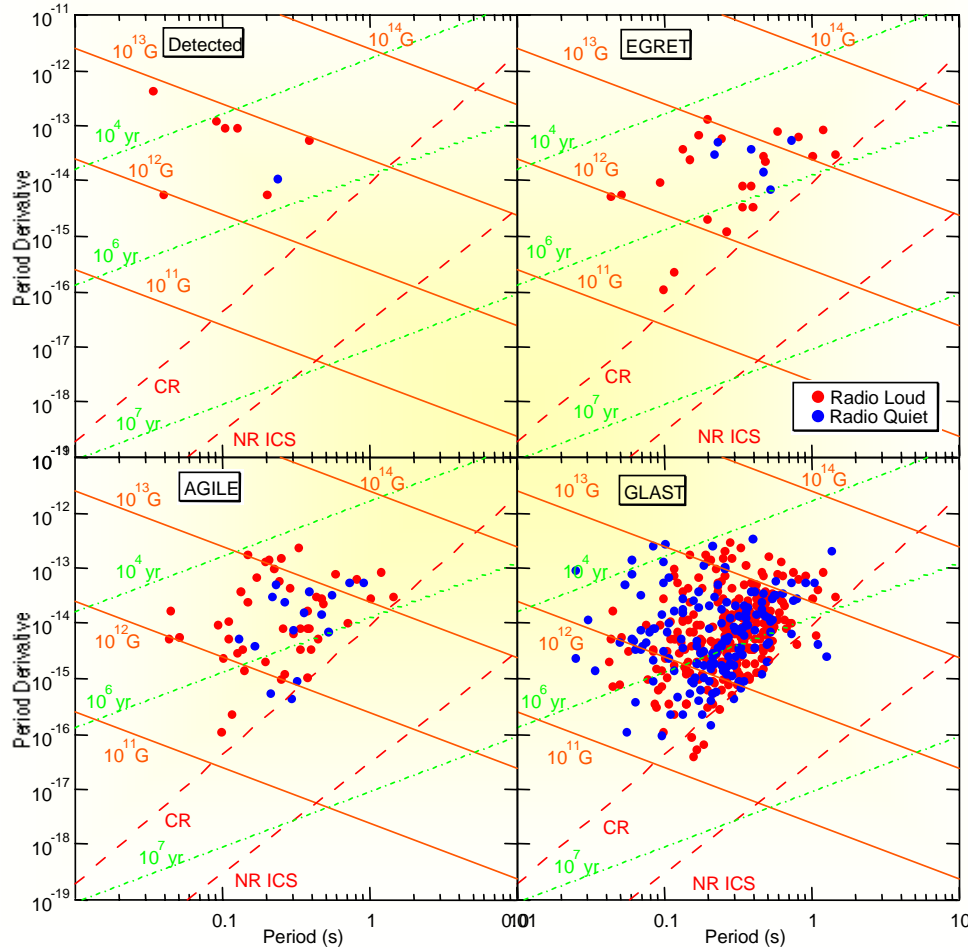


Figure 6 - (Top) Aitoff plots of (left) 978 detected and (right) 978 simulated radio pulsars from the Galactic disc. **Pair curvature** and **inverse Compton** scattering death lines are shown as dashed red lines. Green dot-dashed lines represent the indicated **pulsar age**, assuming a field decay constant τ of 2.8 Myr. Solid brown lines show the indicated **magnetic surface field** strength, assuming a constant dipole spin-down field. Magenta dotted curves depict the indicated **field strengths** assuming a decay constant of 2.8 Myr.

Gamma - ray Pulsars from the Galactic Disc



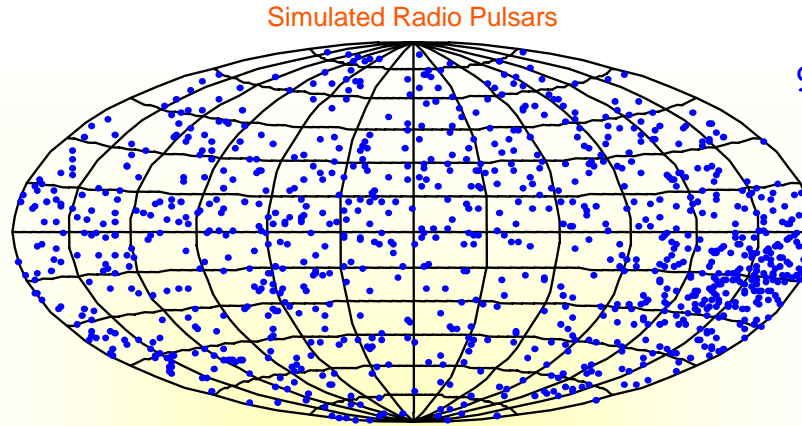
Younger pulsars
→ higher γ luminosity
which
decreases approaching
curvature death line

below CR death line:
→ pairs still produced via
nonresonant inverse
Compton scattering of the
thermal X-ray emission
from the surface

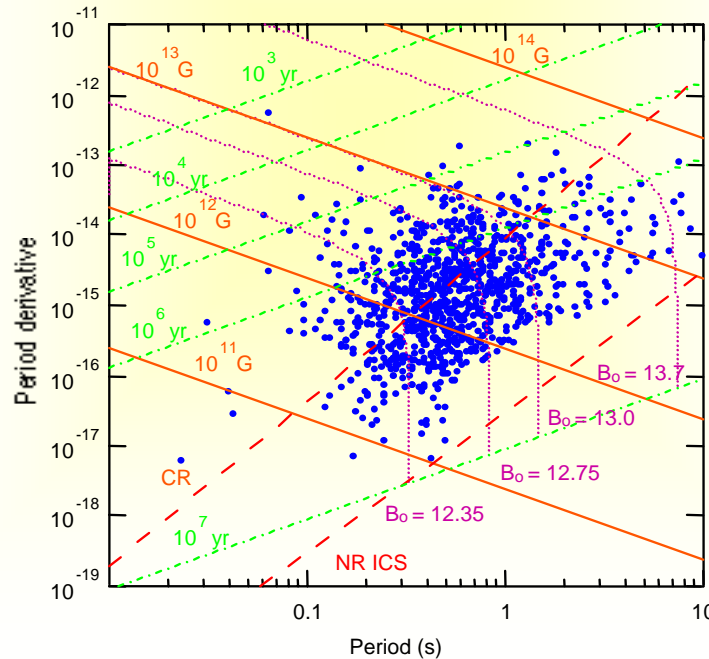
below NR ICS death line:
→ no pair production

Figure 7 - Distributions of radio-loud and radio-quiet gamma-ray pulsars (top left) detected by EGRET, simulated for (top right) EGRET, (bottom left) AGILE, and (bottom right) GLAST.

Radio Pulsars from the Gould Belt



978 simulated radio pulsars from the Belt useful to see the overall distribution



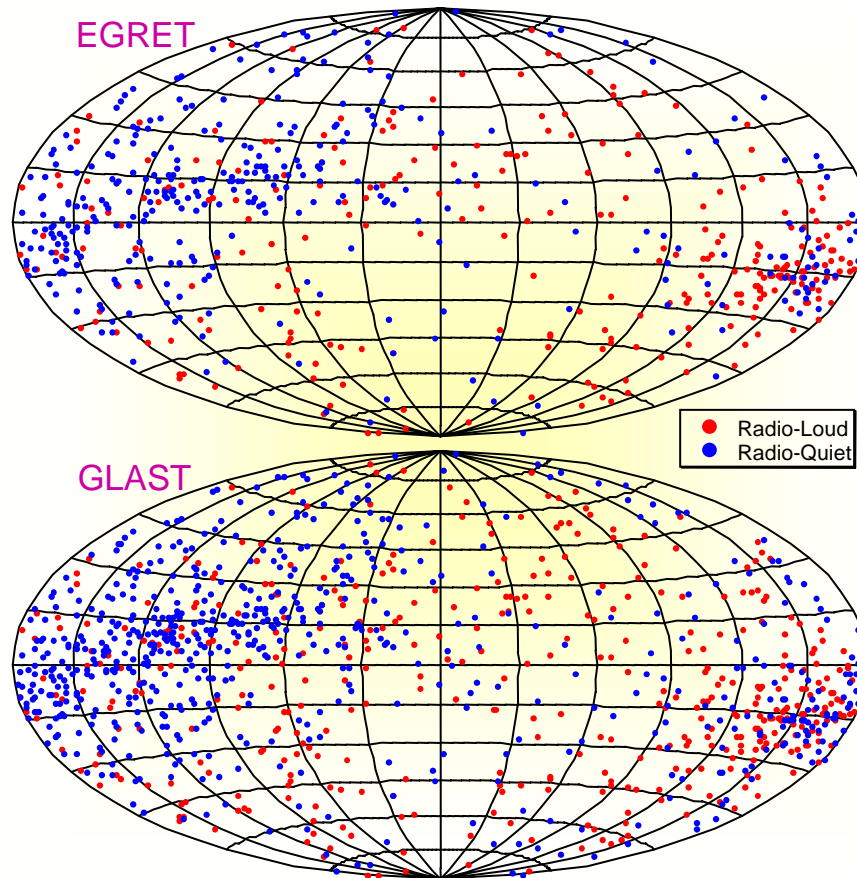
same distribution as plane pulsars but 5 Myr age limitation

5 Myr line for pulsars with $P_{ini} = 0$ while $0 < P_{ini} < 150$ ms

Not normalized to 100 neutron stars, i.e. to 10 observable radio pulsars

Figure 8 - Aitoff plot and P-Pdot diagram of an arbitrary number of simulated radio pulsars from the Gould Belt. Pair curvature and inverse Compton scattering death lines are shown as dashed red lines. Green-dot-dashed lines represent the indicated pulsar age, assuming a field decay constant of 2.8 Myr. Solid-brown lines show the indicated magnetic surface field strength, assuming a constant dipole spin-down field. Magenta dotted curves depict the indicated field strengths assuming a decay constant of 2.8 Myr.

Spatial Distribution of Gamma-ray Pulsars from the Gould Belt



clear correlation with GB for
radio-quiet γ -ray pulsars
which are
closer and younger
than radio-loud ones

Figure 9 - Aitoff plots of an arbitrary number of radio-quiet and radio-loud gamma-ray pulsars from the Gould Belt simulated for (top) EGRET, and (bottom) GLAST. Radio-quiet pulsars are closer and younger than radio-loud ones as a result of the fainter off-beam gamma-ray emission seen at large impact angles away from the radio beam (see Figure 10).

Selection of the Viewing Geometry and Age of Pulsars from the Gould Belt

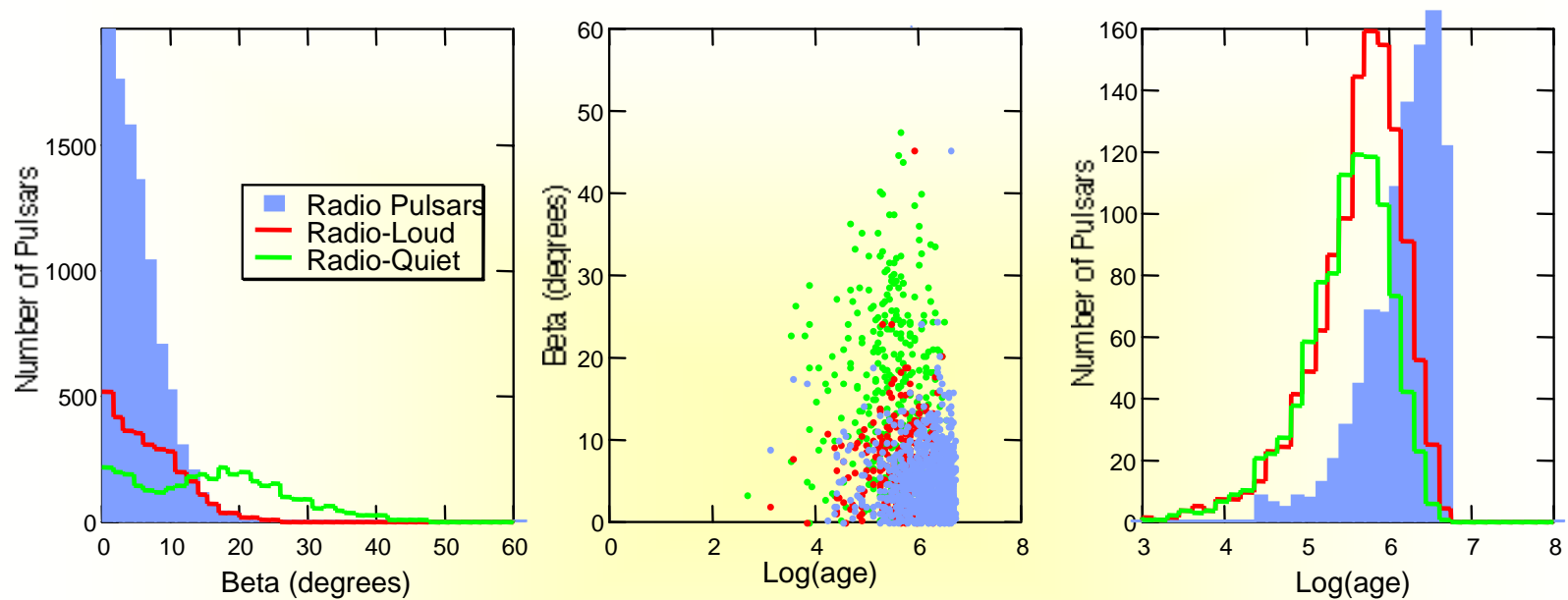


Figure 10 - Distributions of (left) impact angle β , and (right) age of an arbitrary number of (red) radio-loud, (green) radio-quiet gamma-ray pulsars, and (blue) radio pulsars from the Gould Belt. The middle figure is the correlation of the impact angle and the age of the corresponding pulsars.


- radio and radio-loud γ -ray pulsars \rightarrow smaller β than radio-quiet γ -ray pulsars
- γ -ray pulsars (radio-loud and radio-quiet) \rightarrow younger (need sufficient γ -ray flux to be seen)
- radio-quiet γ -ray pulsars \rightarrow much larger β than radio-loud γ -ray pulsars

Characteristics of Radio-loud and Radio-quiet Gamma-ray pulsars from the Gould Belt (GB):

- radio geometry and luminosity model assumes that short-period pulsars are core-dominated
 - short-period pulsars have a small emission region (solid angle)
 - harder to observe
- off-beam curvature radiation of the γ -ray emission is much broader
- the young neutron stars from the GB are close
 - more likely to be detected in γ than radio (larger gamma solid angle)
 - **radio-quiet** γ pulsars from the GB have a large impact angle β
 - the observer will miss the radio-beam but detect the off-beam γ emission
 - **radio-loud** γ pulsars from the GB have a smaller impact angle β
 - the observer will see the radio beam and the on-beam γ emission
 - **radio-loud** γ pulsars have a larger radio and γ luminosity
 - **radio-loud** γ pulsars are older and seen at larger distances than **radio-quiet** ones

Gamma-ray Pulsars from the Galactic Disc and the Gould Belt

Instrument	Radio-loud γ -ray pulsars		Radio-quiet γ -ray pulsars		Ratio RL/RQ
	Plane	Gould Belt	Plane	Gould Belt	Total
Detected (EGRET)	6 (7 possible)	2 (Vela & 0656+14)	0	1 (Geminga)	8-9
EGRET	23	3	6	3	2.9
AGILE	45	4	16	3	2.6
GLAST	249	4	159	6	1.5



- There are about 25 EGRET error boxes that contain radio pulsars (Parkes Multibeam Pulsar Survey) that could have been observed by EGRET as γ -ray point sources (Harding & Muslimov, 2004)
- EGRET has observed 9 and possibly 10 γ -ray pulsars.
- The simulation is in reasonable agreement with this findings.
- The simulation predicts that only 6 of the 45 ± 6 EGRET unidentified sources that have been correlated to the Gould Belt (Grenier 2000) could be pulsars from the Gould Belt.

Polar Cap and Outer Gap Models - Ratio of Radio-loud to Radio-Quiet γ -ray Pulsars

- Due to the very different beam geometries of γ -ray emission, the polar cap and outer gap models make significantly different predictions of the ratio of radio-loud to radio-quiet γ -ray pulsars
- In this study, we have used the slot-gap geometry in the polar cap model for the γ -ray emission, which is concentric to the assumed radio beam geometry.

	Outer gap model – Cheng 2004				Slot-gap polar cap model			
	Gould Belt		Plane		Gould Belt		Plane	
Gal. lat.	< 5°	> 5°	< 5°	> 5°	< 5°	> 5°	< 5°	> 5°
Radio-loud	1	4	12	4	0.2	2.5	14	9
Radio-quiet	2	13	40	22	0.4	2.8	1	5

Ratio of radio-loud to radio-quiet γ -ray pulsars	
Outer gap model – Cheng 2004	Slot-gap polar cap model
0.27	2.78

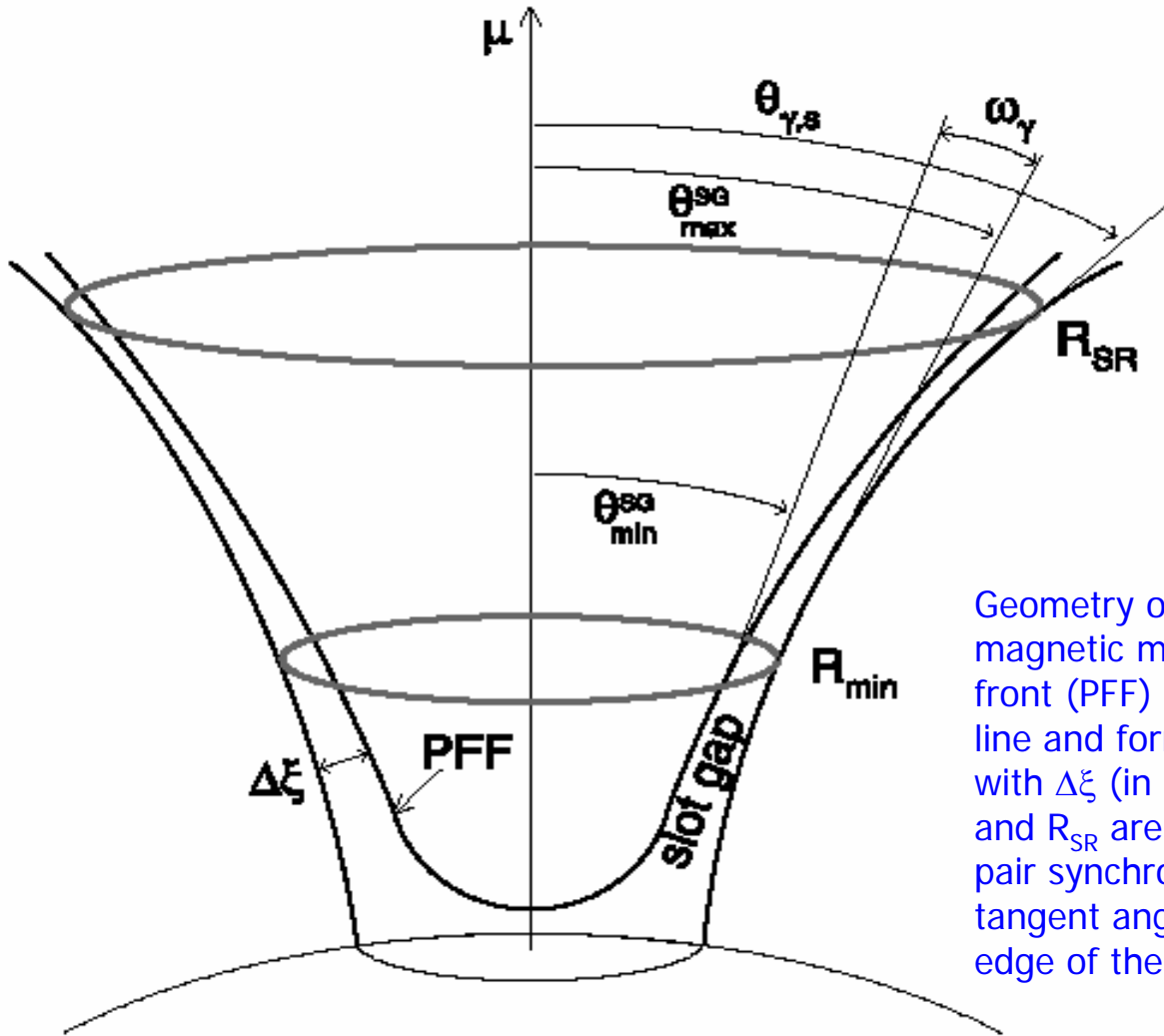
The ratio of radio-loud to radio-quiet γ -ray pulsars is 10 times larger in the slot gap polar cap model than in the outer gap model.

References:

- Arzoumanian, Z., Chernoff, D.F., & Cordes, J.M. 2002, ApJ, 568, 289
- Cheng, K.S. 2004, Multiwavelength Approach to EGRET Unidentified Gamma- ray Sources, Cheng, K.S. and Romero, G.E., editors, Kluwer Academic Publishers, Dordrecht, in press
- Cheng, K.S et al. 2000, ApJ, 537, 964
- Cordes, J.M. & Lazio, T.J.W. 2002, preprint (astro-ph/0301598)
- Daugherty, J.K. & Harding, A.K. 1996, ApJ, 458, 278
- De Zeeuw, P.R. et al. 1999, AJ, 117, 354
- Dehnen, W. & Binney, J. 1998, MNRAS, 294, 429
- Dyks, J., & Rudak, B., 2003, ApJ, 598, 1201
- Gonthier, P.L. et al. 2002, ApJ, 565, 482
- Gonthier, P.L., VanGuilder, R. & Harding, A.K. 2004, ApJ, 604, 775
- Grenier, I.A. 2000, A&A, 364, L93
- Grenier, I.A. 2004, Proc., The Young Local Universe, astro-ph/0409096
- Harding, A.K., Gonthier, P.L., Grenier, I.A., & Perrot, C.A. 2004, Advances in Space Research, 33, 571
- Harding, A.K. & Muslimov, A.G. 2004, Multiwavelength Approach to EGRET Unidentified Gamma-ray Sources, Cheng, K.S. and Romero, G.E., editors, Kluwer Academic Publishers, Dordrecht, in press
- Manchester, R.N. et al. 2001, MNRAS, 328, 17
- Mitra D. & Deshpande, A.A. 1999, A&A, 346, 906
- Muslimov, A.G. & Harding, A.K. 2003, ApJ, 588, 430
- Perrot, C.A. & Grenier, I.A. 2003, A&A, 404, 519
- Tammann, G.A. et al. 1994, ApJS, 92, 487

The End

Emission geometry for the slot gap model: Muslimov & Harding (2003)



Geometry of the slot gap emission relative to the magnetic moment vector μ . The pair formation front (PFF) curves upward near the last open field line and forms the inner boundary of the slot gap with $\Delta\xi$ (in units of the polar cap half-angle). R_{\min} and R_{SR} are the minimum and maximum radii of pair synchrotron radiation. $\theta_{\text{SG}_{\min}}^{\text{SG}}$ and $\theta_{\text{SG}_{\max}}^{\text{SG}}$ are the tangent angles to field lines at the inner and outer edge of the slot gap at R_{\min} .

Figure 2

Gonthier et al. (2004)