GALACTIC SOURCES WITH THE *FERMI* LARGE AREA TELESCOPE

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The Large Area Telescope began orbiting the Earth on NASA's *Fermi* satellite on June 11, 2008, scanning the entire sky eight times per day since August. A major objective for the LAT is to characterize the large variety of GeV gamma-ray sources in the Milky Way. The emission is the by-product of charged particle acceleration to energies of GeV, TeV, and beyond. Acceleration occurs in the shocks where winds and jets collide with their surroundings, as well as across the voltage drops in pulsar magnetospheres. Many of the different Galactic GeV source classes involve either massive stars, or the remnants thereof. I will review the Galactic sources seen using the *Fermi* LAT after the first months of the sky survey.

1 Introduction

Milky Way particle accelerators have something for everybody. Astrophysicists fascinated by the mechanisms at work in a variety of types of shocks, jets, accretion flows, and rotating magnetospheres are the first concerned. But those keen on the larger scale dynamics of our Galaxy, from which to extrapolate to galaxies in general, cannot ignore these emitters as they reflect on how energy in the Galaxy is shared between the particle and photon fluxes. And finally, particle physicists bent on solving the Dark Matter puzzle need first to master the pesky foreground created by the great wealth of galactic gamma-ray sources.

The Large Area Telescope (LAT) on the *Fermi* satellite is a fabulous tool and is sparking a giant leap forward in our understanding of all of the above. The LAT is described by L. Latronico (these proceedings). Two aspects of the LAT performance are worth repeating. First, the good single-photon angular resolution combined with the large effective area and excellent charged particle rejection combine to give source localisation good enough to separate many confused sources, and is even close enough to the size of a radio-telescope lobe, or an X-ray telescope field-of-view, to simplify follow-up searches for counterparts. Second, the huge field-of-view (a fifth of the sky at a given moment), again combined with the high sensitivity, makes the sky-survey strategy possible. Imaging the whole sky 8 times per day means not only that LAT users don't need to compete for time to view their favorite objects, but also that undervalued pieces of the sky also get written to disk, and especially, that source *variability* will be seen. The LAT is truly a discovery-oriented telescope.

Table 1 lists some classes of Galactic GeV gamma-ray sources. It is striking that massive stars are present, directly or indirectly, in most of the categories. When they are still "alive", they produce intense charged-particle winds that create shocks in the dense regions where they tend to be found, such as OB associations or open clusters, long predicted to be particle accelerators, and baptised SNOBs, for "supernovae near OBs" [1,2]. The heavy elements are created in these stars. For

Table 1: Some different kinds of Galactic gamma-ray sources

Category	Sub-category	Accelerator type
Supernova remnants (SNR)		Expansion shocks
Pulsar Wind Nebulae (PWN)		Wind shocks
Massive stars	OB associations	Wind shocks
	WR stars	Wind shocks
X-ray binaries	micro-Quasars	Jets & shocks
	binary pulsars	Beams & winds
Pulsars	Young, radio-loud	Huge voltages
	Young, unknown in radio	Huge voltages
	Old (millisecond)	Huge voltages
Clusters	Globular clusters	Multi-pulsars?
	Open clusters	Wind shocks?

>9 solar masses, when the hydrogen fuel gets used up, core-collapse leads to a type II supernova explosion. The bread-and-butter of Galactic high-energy astrophysics consists of the three main leftovers from these disasters, namely, supernova remnants (SNRs), pulsar wind nebulae (PWNs), and pulsars.

Pulsars dominate the list of identified galactic sources and will be discussed below. In these proceedings, please see the contributions by D. Parent, M. Kerr, and A. Caliandro about young, radio-loud gamma-ray pulsars ; by F. Giordano for the gamma-ray pulsars discovered through the blind period search ; and by L. Guillemot for the discovery of a population of millisecond pulsars, with honorable mention for globular clusters.

2 Swan Song

To focus this sampling of early LAT results for Galactic sources I will mostly limit myself to the Cygnus region, illustrated in Figure 1. Furthermore, since most of the quantitative results are presented by other LAT team members elsewhere in these proceedings, I'll indulge the reader in a little astro-tourism suitable for summer evenings in mid-northern latitudes.

Vega is a very bright star near the zenith, to the right in the figure. Nearby is the "northern cross", the name of the asterism at the heart of the Cygnus constellation. The long-necked swan is flying along the Milky Way – visible here in gamma-rays – towards the Galactic center, in Sagittarius, near where Scorpio grazes the southern horizon. The Swan's head is the star Albireo, its tail is Deneb. The Figure includes a few Messier catalog objects, as well as the first pulsar discovered by Hewish & Bell in 1967, PSR B1919+21.

The small circles in the Figure are gamma-ray sources from the Bright Sources List [3] described by J. Ballet (these proceedings). The radius corresponds to the 95% Confidence Level for the source localization. Not shown in the figure are the several EGRET 3^{rd} catalog sources (hereafter "3EG"), most of which were unidentified [4]. The largest category of identified LAT sources is the gamma-ray pulsars: as many are visible within 20° of Cygnus as EGRET saw for the whole sky.

Most prominent in Figure 1 is the diffuse emission along the plane itself, the result of high-energy charged cosmic rays interacting with interstellar gas and dust, a separate topic covered by G. Johannesson in these proceedings. This said, one of the goals of the study of discrete gamma-ray sources is to unveil the origin of these cosmic rays.

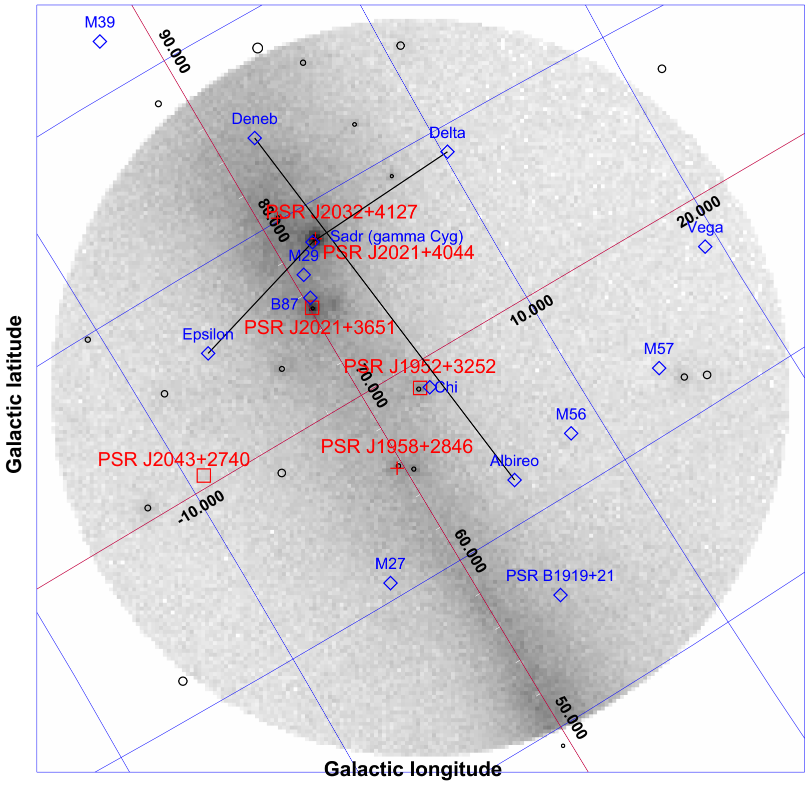

Figure 1: The Cygnus region. The grey-scale counts map shows six months of LAT > 0.1 GeV gamma-rays. The circles are the 95% C.L. radii of Bright Sources List objects. Crosses show gamma-ray pulsars found using radio ephemerides, while squares show gamma-ray pulsars found in the blind period search. Diamonds show some bright stars, Messier objects, the open cluster Berkeley 87 ("B87", see text), as well as the first pulsar discovered 42 years ago, PSR B1919+21. The coordinate scales are in degrees, galactic longitude decreases from the Swan's tail to its head.

Clusters and Associations, with and without shocks

2.1 OB associations

The gamma-ray-selected pulsar PSR J2032+4127 lies in the middle of Cygnus OB2. The name "OB" refers to the hot, blue spectral types of the many young, massive stars found grouped together [a]. The (previously) unidentified source 3EG J2033+4118 overlaps Cyg OB2 nicely. Cyg OB2 is also spatially associated with a famous TeV source, first reported by the Hegra collaboration at Moriond in 2001 (G. Rowell), and discussed extensively for years thereafter [5]. (The rapporteur was Yours Truly [6].) The TeV discovery was important because it was the first ever serendipitous discovery of a TeV gamma-ray source by an atmospheric Cherenkov detector. Furthermore, it was an apparent break in the monopoly then held by SNRs as the principal candidate source class to explain the origin of cosmic rays. The basic idea is that particle acceleration occurs in the shocks between the stellar winds. The "energy budget" argument supporting SNRs as the origin of the cosmic radiation applies nearly as well to these sorts of objects: supernovas are more powerful, but shorter-lived. Integrated over their lifetimes, OB associations fall only about an order-of-magnitude shy of the putative SN contribution to the cosmic ray energy budget. The uncertainties in the population numbers could conceivably even the footing further.

The LAT discovery of a gamma-ray pulsar that might be physically associated with Cygnus OB2 gives pause: could it be that the GeV/TeV gamma-ray source is *not* the shock of stellar winds after all? Ongoing radio and X-ray searches using the accurate LAT ephemeris could conceivably reveal a PWN [7], in which case instead of being a prototype of a new class, Cyg OB2 would turn out to be "just another" case of a pulsar giving GeV emission, and the surrounding PWN providing the TeV signal, as in the Crab (see M-H Grondin, these proceedings).

2.2 Open Clusters

Open clusters are another type of stellar grouping where massive stars are close enough together, and the interstellar medium is dense enough, that particle acceleration in shocks can occur. (Famous open clusters are the Pleiades and the Hyades, both visible by eye near the Crab, straddling Taurus and Orion.) In particular, the open cluster Berkeley 87 is shown in Figure 1. Bednarek [5] and earlier authors had predicted that shocks from the winds of massive Wolf-Rayet [b] stars could be the source of the GeV gamma-ray source reported by EGRET.

The discovery of gamma-ray pulsations from PSR J2021+3651 by the LAT [8] (M. Kerr, these proceedings), as well as by AGILE [9], means that this scenario is not dominant for this previously unidentified 3EG source. The LAT upper limit on off-pulse emission was primarily intended to search for GeV gamma-rays from the Dragonfly PWN, but it is interesting to note that the upper limit is at approximately the same level as Bednarek's prediction for the emission by the shocked winds. With increased statistics, the LAT will continue to search for off-pulse emission. It will then be a challenge to distinguish between the PWN and the open cluster as the source. The LAT localization will likely be up to this challenge in this case.

Berkeley 87 illustrates an element for understanding another problem: that of the pulsar distances d, so critical to understand their luminosity $L_\gamma = 4\pi f_\Omega d^2 h$ and thus the efficiency $\eta = L_\gamma/\dot{E}$ with which the rotational kinetic energy of neutron stars is converted to radiation in the magnetosphere. (The *"beam correction factor"* f_Ω and the spin-down energy $\dot{E}$ are discussed in Section 3, and h is the integral energy flux.) For pulsars within several hundred parsecs, parallax measurements can give accurate distances. But most known pulsars are farther, and more model-sensitive distance estimators must be used. The primary tool-of-choice is the Cordes and Lazio NE 2001 model for the free electron density throughout the Milky Way [10], which converts the measured radio

[a] The modern mnemonic for the stellar spectral types OBAFGKM is "Only Boys Accepting Feminism Get Kissed Meaningfully", from hottest to coolest.

[b] Professor Rayet founded the Bordeaux Observatory in 1893.

Dispersion Measure (DM) into a distance for a given pulsar direction ("line-of-sight"). The model uses average electron densities averaged over fairly broad swaths of the sky. For most directions, the typical distance uncertainty is ±40%. *However*, in many cases the distance can be wrong by a factor of a few! (Han, in these proceedings, addresses current knowledge of Galactic B-field and electron distributions.)

The gamma-ray pulsar PSR J2021+3651 suffers from this distance problem [8]. For its DM of 370 electrons per pc/cm^3 the nominal distance given by NE2001 is 12.1 kpc, yielding $\eta > 100\%$ for reasonable beaming models! The line-of-sight coincides with the edge of Berkeley 87. A back-of-the-envelope calculation [c] suggests that 35 electrons per pc/cm^3 could be due to the open cluster. The NE2001 distance decreases to 10.7 kpc after subtracting the "extra" electrons. This is still several times farther than argued for this pulsar and illustrates the type of work that needs to be done to obtain reliable pulsar distances.

2.3 Globular Clusters

Globular clusters (GCs) are quite different than either open clusters or OB associations. They are systems nearly as old as the Galaxy itself, judged in part by the high metal content of the stars residing therein. GCs contain many recycled pulsars (millisecond pulsars, MSPs). An important LAT result is the discovery that MSPs efficiently convert their rotation energy into GeV gamma-rays [11,12] (see also L. Guillemot, these proceedings). He also describes the LAT discovery of the globular cluster 47 Tuc as a steady gamma-ray source, and lists the MSPs known in many other GCs. There is a good chance that the LAT will be able to see pulsations from the individual MSPs in GCs.

Supernova Remnants and Pulsar Wind Nebulae

Three SNR/PWN systems are apparent in the Cygnus region (Figure 1). The γ Cygni SNR shares its name with the bright star Sadr. About half-way from Sadr to Albireo lies the variable star χ Cygni, near the SNR called CTB 80, at the heart of which lies the EGRET pulsar PSR B1951+32. Finally, the "Dragonfly" PWN surrounds PSR J2021+3651, mentioned above.

Pulsations have been discovered in the blind period search for γ Cygni [13]: a traditional SNR thus reveals that it probably has a PWN as well, coincident with 3EG J2020+4017. More generally, the many TeV PWNs discovered these last years, mainly by H.E.S.S., also host GeV pulsars, as shown by the LAT. See M-H Grondin (these proceedings) for ongoing work on the Kookaburra and Vela X PWN's.

X-ray binaries

The LAT clearly sees GeV gamma-ray emission from the high-mass X-ray binary LSI +61 303, modulated at the 26.5 day orbital period [14] (A. Hill, these proceedings). This object is a TeV source, and is one of the classic "micro-quasars". The basic idea of a μquasar is that accretion from the companion star is analogous to the accretion from the torus onto the supermassive black hole that occurs in a "real" quasar, that is, in an active galactic nucleus. Both would then produce jets wherein high-energy emission would occur. Afficionados of μquasars argue that these smaller, closer systems allow exploration of the key ideas applied to AGNs. LS 5039 is another μquasar for which evidence of a GeV gamma-ray signal is mounting.

However, in a classic paper called "Micro-quasars: Pulsars in Disguise?", G. Dubus [15] deconstructs the observational evidence that lead to the μquasar paradigm and explores the idea that a pulsar in orbit around a suitable companion could equally well explain the data in some cases. Pulsars, and massive stars, are both thus once again at the heart of the explorations of high-energy

[c] performed by S. Bontemps

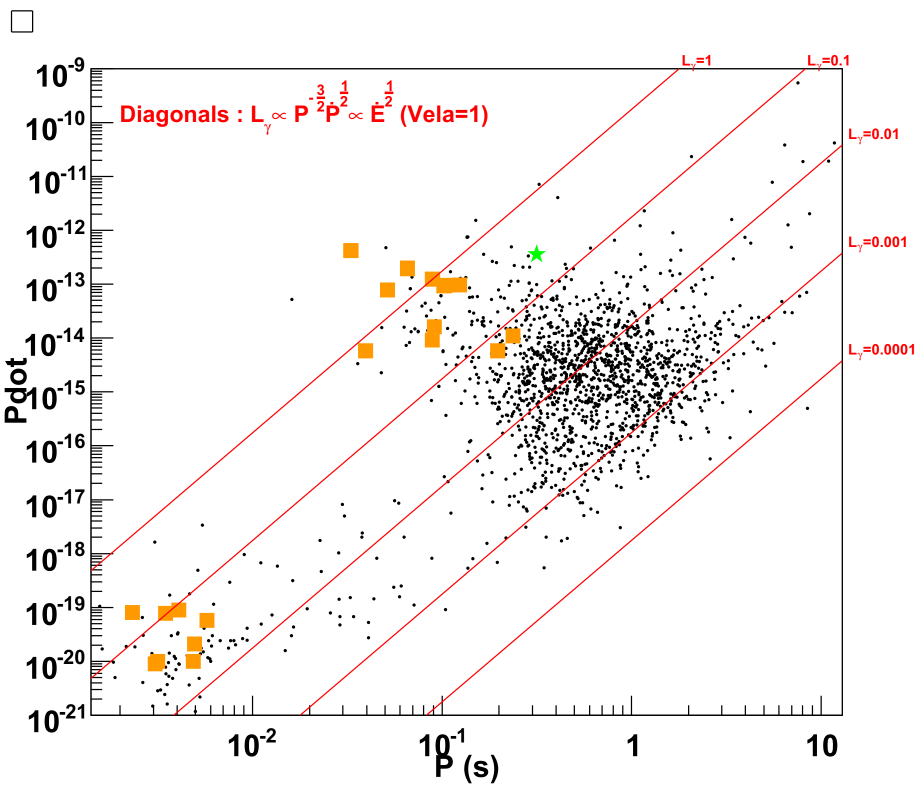

Figure 2: Period derivative versus period (seconds) of most known pulsars. Gamma-ray pulsars found by the *Fermi* LAT using rotation parameters from radiotelescopes are shown as squares, while those discovered by the blind period search are stars (only CTA 1's parameters are published so far). A total of about 50 gamma-ray pulsars have been detected, publications are in progress. Black dots show the remainder of the pulsars from the ATNF database. Diagonal lines show constant $\sqrt{\dot{E}}$, normalized to the Vela pulsar ($\dot{E} = 7 \times 10^{36}$ erg/s).

Galactic sources. As LAT data accumulates we will be able to address these issues more and more directly.

3 Gamma-ray pulsars

Pre-launch predictions for the number of gamma-ray pulsars that the LAT would detect ranged from about 100 to several hundred, and a substantial radio timing campaign was organized [18]. The differences stem from the emission model (how efficiently is the neutron star's kinetic energy of rotation transformed into high energy radiation by the electromagnetic braking process? How wide are the beams that sometimes sweep the Earth?) as well as the population model (how many neutron stars are there within a given distance of the Earth, that is, what is the supernova rate in our part of the Galaxy?). As of this writing (April, 2009), the LAT has chalked up fifty 5σ detections. These are the 6 EGRET pulsars, the 3 marginal EGRET pulsars, the new pulsars found in the blind period search [13] , and 8 millisecond pulsars [11,12]. The remaining are young radio pulsars [8,16,17], half of which are still unpublished.

Figure 2 is the standard $\dot{P} - P$ diagram, for the 1794 pulsars from the ATNF database [d], nearly all of which are radio pulsars. P is the rotation period, in seconds, and $\dot{P} = \frac{dP}{dt}$ is the rate at which the rotation slows due to electromagnetic braking. The rate at which the kinetic energy of rotation is lost by the neutron star is $\dot{E} = 4\pi^2 I\dot{P}/P^3$, where the standard value for the moment of inertia used is $I = 10^{45}$ gm-cm^2. Diagonal lines of constant $\sqrt{\dot{E}}$ are shown, to illustrate predictions that $L_\gamma \propto \sqrt{\dot{E}}$, normalized to Vela [19]. The position of CTA 1 is shown, and soon there will be 15 more stars [13].

The figure shows that $\dot{E}$ alone does not predict which pulsars give detectable gamma-ray pulsations. Normalizing for the distance-squared reduces the scatter, but the mix of gamma-ray bright and dim pulsars for a given $\dot{E}$ remains. The distance ambiguities discussed above are only part of the story. The geometry of the radio and gamma-ray beams is another.

Figure 3 shows the 3-dimensional gamma-ray emission predicted by a pulsar emission model (left), as well as a projection across a given line-of-sight from the Earth (right). The beams are very narrow in longitude but extended in latitude, called *"fan-like"*. To infer the total energy output in gamma-rays of the pulsar from the energy flux measured by the LAT, we use a *"beam correction factor"* f_Ω which is, for a given model and set of pulsar parameters, simply the ratio of the integrals of the two figures, normalized to 4π. Most past work has assumed a 1 sr beam (a $\sim 30°$ half-angle for a cone), which yields $f_\Omega = 1/4\pi \simeq 0.1$, corresponding to polar cap emission. Observations increasingly favor gamma-ray emission from near the pulsar light cylinder, as for example in the outer gaps or slot gaps, where the beam is broad like in the figure, and $f_\Omega \simeq 1$. This framework was developed in [20] and briefly repeated in some of the LAT pulsar papers already cited [8].

The models also predict the shapes and relative phase of the radio pulse profiles, and predict spectral parameters such as the cut-off energies. We are well-armed to compare the increasing number of LAT pulsar measurements with model predictions and expect a signficant step forward in the fundamental understanding of neutron star emission as a consequence.

4 Conclusions

Half-way through the *Fermi* LAT one-year all-sky survey, a large number of EGRET unidentifed sources have already been unambiguously associated with objects known at other wavelengths. Often, they are pulsars. Other Galactic objects which are clearly identified at GeV energies with the LAT are globular clusters and high-mass X-ray binaries. Solid identifications as pulsars means that other hypotheses have to be put aside, at least of the level of intensity that was within the reach of EGRET, and thus, just for the time being.

[d] http://www.atnf.csiro.au/research/pulsar/psrcat/

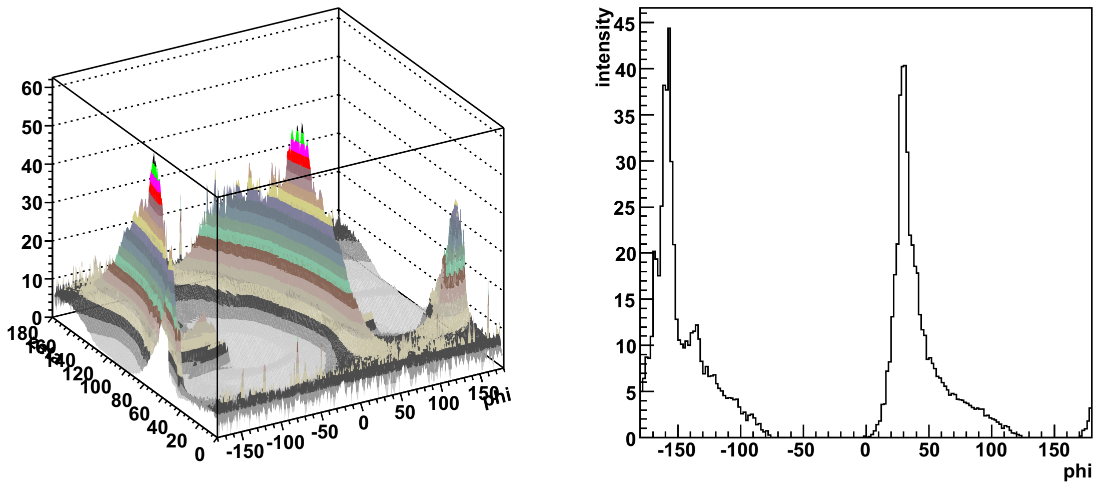

Figure 3: Simulated gamma-ray "fan-like" beam in a "slot gap" model, courtesy of A. Harding. Left: ζ versus ϕ, in degrees, where ϕ is the neutron star longitude (more commonly known as the rotation phase), and ζ is the latitude relative to the neutron star rotation axis – the line-of-sight from the neutron star to a terrestial viewer selects a value of ζ. Right: Projection along $\zeta = 80^\circ$. The *"beam correction factor"* f_Ω is the ratio of the integrals of the two plots, normalized to 4π.

Since pulsars can be easily identifiable sources they are also easy to subtract, to open the way to analysis of more subtle objects. The nebulae sustained by pulsar winds are a second wave of objects to be scrutinized, also relatively easy to identify. As each of the many components of the Galactic gamma-ray emission is mastered and subtracted, fainter and fainter ones will come to light. Emission by the shocks in stellar winds will likely be detected, at some level. And beyond that? All guesses are fair, and we have another 9.5 years to follow through.

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