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GALACTIC VARIABLE SKY WITH EGRET AND GLAST

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The characteristics of the largely-unidentified Galactic sources of gamma rays that were detected by EGRET are reviewed. Proposed source populations that may have the correct spatial, spectral, luminosity, and variability properties to be the origins of the EGRET sources are also presented. Finally, the prospects for studying Galactic gamma-ray sources with the GLAST LAT are reviewed.

Keywords: Milky Way; gamma-ray

1. Introduction

The Energetic Gamma-Ray Experiment Telescope (EGRET) on the *Compton* Gamma-Ray Observatory provided a tremendous advance in high-energy gamma-ray astronomy. The number of known gamma-ray sources was increased from ∼20 to ∼300,[1] and although the positional determinations generally were not accurate enough to permit identifications of counterparts, overall average properties of the underlying source populations could be inferred.

The distribution of the sources on the sky suggests that a large fraction of the EGRET sources are clearly within the Milky Way. Few sources were observed deeply enough or often enough for variability to be detected with high confidence but overall many of the Galactic sources detected by EGRET are probably variable.

Several plausible candidate populations for Galactic sources have been described in the literature. All are related in one way or another to massive star formation or remnants of massive stars.

This paper provides a summary of the properties of the EGRET sources as well as of the likely underlying source populations. The potential for GLAST to advance the study of variable Galactic sources and source populations is also illustrated.

2. Properties of EGRET sources

The 3EG catalog has 271 sources, the majority of which were unidentified at the time of the production of the catalog and a few of which were known to be either transient (a solar flare) or probably spurious (e.g., point sources near the Vela pulsar that pulse in phase with it)[1] . The distribution of the sources on the sky suggested perhaps 3 populations: isotropic (presumably extragalactic), Galactic disk, and Galactic halo.

The isotropic component included the ∼70 gamma-ray blazars that had been identified at the time, and since then likely blazar counterparts have been proposed for most of the high-latitude EGRET sources.[2,3]

The Galactic halo sources, which were also characterized as 'faint' and 'steady' (see below), were initially proposed to be correlated with Gould's Belt, the relatively nearby star-forming regions that ring the sky[4,5] and not actually associated with the halo of the Milky Way. In this model the sources were considered most likely to be gamma-ray pulsars, the only identified Galactic population of gamma-ray sources. Deep searches of the error boxes for these sources for radio pulsars were subsequently undertaken, essentially unsuccessfully (e.g., Ref. 6).

More recently, the existence of these halo sources as point sources of gamma rays has been called into question based on a re-evaluation of the diffuse gamma-ray emission of the Milky Way.[7] The diffuse emission is a relatively bright background against which gamma-ray point sources must be detected. Owing to the limited statistics and angular resolution of EGRET data, the emission is typically modeled rather than inferred directly from the observations. Models for the diffuse emission based on interactions of cosmic rays with interstellar gas (as traced by observations of the 21-cm line of H I and the 2.6-mm line of CO, as a surrogate for H_2) and the interstellar radiation field have been very successful in describing the large-scale features of the gamma-ray sky. At intermediate latitudes, however, recent studies of infrared emission from interstellar dust suggest that some interstellar gas not previously accounted for (presumably H_2 that is not being traced by CO) is present at signficant levels.[7] Indeed a survey of 'infrared excess' clouds finds a large fraction to be undetectable in CO.[8] The reanalysis by Grenier & Casandjian of the EGRET data with a model of diffuse emission that includes infrared excess clouds suggests that the great majority of the faint, steady halo sources were misidentified diffuse emission.[9]

The Galactic disk component of the EGRET sources is relatively narrowly distributed around the Galactic equator. The scale height ($< 2°$) and distribution in longitude suggest a characteristic distance of 1-6 kpc,[10] i.e., not even as great as the distance to the Galactic center. The corresponding luminosities are $(1-15)\times 10^{35}$ erg s^{-1}, or $\sim$100 $L_{\odot}$.[10] These sources and their potential origins are subject of the next sections.

2.1. *Variability of EGRET sources*

The limited sensitivity of EGRET relative to the characteristic fluxes of Galactic sources made short-term (scale of days) variability difficult to measure. A systematic search by Wallace et al.[11] found only 2 examples of possibly-significant day-scale flares; notably 3EG J0241+6103 (a possible counterpart to the microquasar LS I $+61^{\circ}$ 303) apparently doubled its flux for a $\sim$2-day interval.

On somewhat longer time scales of 1-2 weeks, the duration of a typical EGRET viewing period, the fluxes and upper limits published in Ref. 1 for each source can be used to estimate variability. Several authors have analyzed variability of the EGRET sources with this method, e.g., Refs. 12–14. As Reimer[15] points out, the resulting measures of variability were not always consistent between approaches, which differed notably in how upper limits were treated.

Typically, the variability index for a given source in the 3EG catalog is not very prescriptive about whether the source is variable. When the sources are considered as classes, then some plausible conclusions may be reached. For example, Nolan et al.[14] find that the identified blazars are signficantly variable sources and the pulsars (averaged over many spin periods of course) are not. Nolan et al. find that among the low-latitude sources, a large fraction of those toward the inner Galaxy (with $|l| < 55^{\circ}$) are significantly variable, with estimated dispersion of measured fluxes greater than 70% of the average flux. This distribution is consistent with the general direction of massive star-forming regions in the inner spiral arms of the Galaxy.

For the variable EGRET sources, Roberts et al. point out that time scales of variability shorter than months imply angular sizes of less than $1'$, and that particle acceleration happens on this time scale as well.[16]

3. Candidates for variable Galactic sources

In this section, plausible (and published) classes of variable Galactic sources are described; all can produce sources of the required luminosities. In this context, rotation-powered pulsars are not considered to be variable sources; see the contribution by M. Razzano elsewhere in this volume.

3.1. *X-ray binaries: microquasars/microblazars*

X-ray binaries are close binary systems of a pulsar and a star, so-named because they are strong and variable X-ray sources. In high-mass X-ray binaries (HMXRB), the companion is an early-type star, with strong stellar winds. In low-mass X-ray binaries (LMXRB) the companion is less massive ($< 2.5\ M_\odot$) and accretion onto the pulsar is via Roche lobe overflow.

Several hundred XRBs are known in the Milky Way.[17,18] More have recently been discovered in hard X-ray observations with Integral;[19] these 'cocooned' binary systems are completely obscured by intervening interstellar gas at softer X-ray energies.

The distributions of HMXRB and LMXRB on the sky are significantly different.[20] The HMXRB are more tightly confined to the Galactic equator; LMXRB have a broader distribution in Galactic latitude and are not as tightly correlated with star-forming regions. Just as EGRET did not detect all of the GeV sources of gamma rays in the Milky Way, the known XRBs are flux limited; the Grimm et al.[20] sample includes all XRBs that reached a flux of 5 mCrab for the All-Sky Monitor of RXTE during the first 5 years of the mission. No complete census exists of XRBs; the gamma-ray manifestations detected by the LAT may well be a 'deeper' sample.

Microquasars are XRBs with relativistic radio jets, and the name 'microquasar' is intended to suggest an analogy with active galaxies, in which accretion onto a supermassive black hole powers jets on a much larger scale. (Carrying this analogy further, a microblazar would be a microquasar with a jet aligned with the line of sight to the earth; see below.) The inferred population of relativistic electrons in the jet of a microquasar can produce gamma rays through scattering of synchrotron photons in the jet (synchrotron self-Compton scattering) or perhaps more likely inverse Compton scattering of ultraviolet photons from the companion star.

The protypical microquasar is LS 5039, a HMXRB in which the companion is an O7 star. (See Sect. 3.4 for an alternative interpretation of the source.) The microquasar identification and association with EGRET source 3EG J1824-1514 were proposed by Paredes et al.[21] As Paredes et al.[22] point out LS 5039 should be intrinsically variable in high-energy gamma rays owing to the high eccentricity ($e = 0.41$) of the orbit, which causes the accretion rate onto the compact object and the intensity of the stellar radiation field in its vicinity to vary.

Variability at the 4.1 d period of LS 5039 was not seen in the EGRET data for 3EG J1824-1514, although the limited coverage and sensitivity of the EGRET observations of this source are not particularly constraining and periodic variations are also superimposed on variability of the jets. Variations of the jets are not periodic, but in general for microquasars the transition to a high (X-ray) luminosity state seems to be associated with launching relativistic ($\Gamma > 2$).[23]

In addition, in microquasars, absorption effects in the atmosphere of the companion star, or in its wind, or even eclipses by the companion could also introduce modulation of the gamma-ray emission at the orbital period.

For microblazars, relativistic boosting is another source of intrinsic variability. Kaufman Bernado et al.[24] point out that the accretion disk (and jet) of microquasar/blazar will precess if the orbit of the companion star is not coplanar with the disk.

Paredes[25] published a list of 15 known or suspected microquasars in the Milky Way. Only 2 or 3 of these (LS I +61° 303, LS 5039, and Cygnus X-3) are potential counterparts to EGRET sources, and each of these is a HMXRB. LMXRBs are disadvantaged relative to HMXRBs as gamma-ray sources owing to the greatly decreased intensity of the UV radiation fields of the stellar companions. Grenier, Kaufman Bernado, & Romero[7] considered LMXRBs as potentially forming a population of variable, intermediate latitude gamma-ray sources. Their conclusion was that inverse Compton scattering of radiation external to the jet would not be sufficient for producing EGRET gamma-ray sources, although synchrotron self-Compton emission in the jets together with microblazar alignment of the jets might be feasible.

3.2. *Plerions: pulsar wind nebulae*

Plerions, also known as pulsar-powered nebulae or pulsar-wind nebulae, are 'filled-center' supernova remnants (SNR). A few dozen are known in the Milky Way; the Crab is the prototypical plerion but their properties vary widely owing to differences in, e.g., age of the SNR. A plerion can be identified as such via imaging X-ray observations without finding the pulsar driving the nebula. Searches of the error boxes of EGRET sources have yielded several plerions that are prospective high-energy gamma-ray sources (e.g., Refs. 27,28).

The mechanism for producing high-energy gamma-ray emission is likely to be synchrotron emission from electrons accelerated in the shock between the pulsar wind and interstellar medium.[29] The time scale for cooling via IC scattering is too long to be consistent with day-scale variability. Interaction with nearby molecular clouds, via Bremsstrahlung scattering, also can be ruled out owing to variability considerations. Roberts[29] reports that the 'best' candidate gamma-ray sources among pulsar wind nebulae are those for which the nebulae are ram pressure confined, meaning for which the pulsars have large space velocities. The reasoning is that compression and amplification of the magnetic field in the bow shock increases the maximum energy that electrons can achieve.

3.3. *Binary plerions*

As Dubus has pointed out, binary systems of plerions with early type stars may also be sources of high-energy gamma rays.[30] Actually, PSR B1259-63, a millisecond pulsar with a B0Ve companion in a 3.4-yr orbit has been detected at periastron by the H.E.S.S. ground-based gamma-ray telescope at energies >100 GeV.[31] Dubus pointed out that in LS 5039 and LS I+61°303 the resolved radio structures had not yet been demonstrated to be relativistic jets, and the masses of the compact objects in these sysetms were not known well enough to know whether they were not neutron stars. In the mechanism proposed by Dubus, the electrons accelerated in the pulsar wind nebula produce gamma rays by inverse Compton scattering on the optical-ultraviolet radiation field of the companion star. Binary plerion systems would necessarily be periodic gamma-ray emitters.

3.4. *Isolated black holes*

Punsley describes how rapidly-rotating, charged black holes could produce jets as a product of gravitohydrodynamic coupling of the magnetosphere to the rotating black hole.[32] The particles in the jet could emit high-energy gamma rays via inverse Compton scattering or possibly synchroton self-Compton scattering. In these systems, unlike rotation-powered pulsars, the magnetic field would be aligned with the rotation axis, so they would not pulsate. Variability on short time scales would be possible, e.g., from wobbling of the jet or a change of the injected spectrum of electrons.

4. Prospects for studying variable Galactic sources with the LAT

The Large Area Telescope (LAT) is the principal instrument on the GLAST mission, under development for launch in late 2007; the instrument and its performance are described in Ref. 33. For the present topic, the most relevant aspects are the large effective area (>8000 cm^2), very large field of view (>2 sr), and the frequent, uniform coverage of the sky that the LAT will achieve. The LAT has no consumables, unlike EGRET, and the systematic uncertainties in flux measurements should be much less.

All of these considerations bode well for great advances in the study of variable Galactic gamma-ray sources with the LAT. The potential is illustrated in Fig. 1 via a simple simulation of a periodic source with properties like those expected for LS I +61° 303. This relatively-bright source against the relatively faint diffuse background in the outer Galaxy is probably a best case, but the example illustrates what will be possible for such a source in only weeks of surveying the sky; the design life of the mission is 5 years and the goal for operations is 10 years. The LAT certainly should 'see' much deeper into the Milky Way than EGRET was able to.

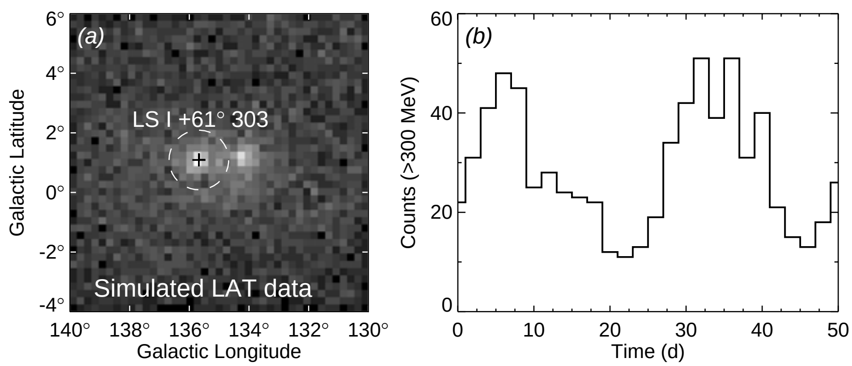

Fig. 1. Simulated LAT observation of the region around LS I +61° 303. The simulation is for the equivalent exposure of a 55-day sky survey. (*a*) Distribution of gamma rays with energies >300 MeV. The simulation includes a realistic model of the diffuse and point-source emission of the sky, and LS I +61° 303 has the flux of its potential counterpart 3EG source and a 26-day period with fairly strong modulation. (*b*) Counts per day for the region within the dashed circle (radius 1°).

5. Conclusions

Sources of gamma rays in the Milky Way are numerous and the evidence from EGRET is that many low-latitude sources (i.e., associated with Population I objects) are variable on time scales of days to months. Good candidates exist for variable Galactic sources - pulsar wind nebular, XRB (microquasars), or both (plerion binary systems). The variable Galactic gamma-ray sources will be much better characterized, more numerous, and it is to be hoped better understood, when GLAST is operational.

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