



Gamma-ray Large Area Space Telescope



Galactic Variable Sky with EGRET and GLAST

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Outline

- What do we know from EGRET?
- What source classes are plausible?
 - Characteristics of these sources
- How will the performance of the GLAST LAT compare with EGRET for Galactic sources?
 - Instrument characteristics, observing strategy
 - Simple simulation



EGRET All-sky Map



- ~1.4 My, ~60% interstellar emission from the MW
- ~10% are cataloged (3EG) point sources

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Results from EGRET: Point Sources



- 3EG catalog (Hartman et al. 1999) has 271 sources, almost all of them real, most unidentified, flux limit ~1 × 10⁻⁷ cm⁻² s⁻¹ (>100 MeV)
- A large fraction of the sources is Galactic



Accumulated updates

- ~10 3EG sources are known to be spurious, including several in the vicinity of Vela that were found to pulsate at the frequency of Vela
- Many of the unidentified high-latitude sources now have reasonably secure blazar counterparts (Sowards-Emmerd et al. 2003)
- Also Grenier et al. (2005) finding that with a proposed (previously-unknown) component of celestial diffuse emission, many of the 'faint persistent' sources in the inner Galaxy (aka Gould Belt) sources disappear



Distributions of Unidentified Sources

- Again, the great majority of EGRET Galactic sources are unidentified
- Two populations are recognizable from the distributions – narrow and wide latitude
 - Modulo the nonuniformity of exposure, increased diffuse intensity at low b, latitude-dep. significance threshold, uneven sampling in time and flaring bias (Reimer 2001)
- Positional correlations with Pop I have been found (e.g., Romero et al. 1999 and many others, probably starting with Sturner & Dermer 1995)



White: 3EG catalog Grey: Reimer analysis of Phase 1-4



What do we know from EGRET about unidentified Galactic sources?

- Typical luminosity ~ (1–15) × 10³⁵ erg s⁻¹ (isotropic) for an EGRET Galactic point source (characteristic distance 1–6 kpc), Mukherjee et al. (1995)
 - F(>100 MeV) ~ 5 × 10⁻⁷ cm⁻² s⁻¹ for 10³⁵ erg s⁻¹ at 1 kpc (depends on spectral index, of course)
- Variability time scales of ~<months limit angular sizes to ~1' for typical few kpc distances (Roberts et al. 2001)
- And of course also need to accelerate particles on this time scale
 - Gamma-ray production mechanisms are well understood; particle acceleration less so



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



Best examples of day-scale variability of Galactic 3EG sources in the systematic analysis of Wallace et al.



Variability statistics of EGRET sources

- On scales of viewing periods (1-2 weeks, typically), the fluxes in the 3EG catalog (Hartman et al. 1999), which are listed for every viewing period for which a source was in the FOV, have been used to estimate variability
 - McLaughlin, Torres, Tompkins (Nolan) et al.

Distribution of variability index for 3EG sources with $|b| < 6^{\circ}$.





EGRET Unidentified Sources

- Cautions about definition of populations by source properties as determined from EGRET data
 - Differences, e.g., in how upper limits are handled
 - Recent summary by Han & Zhang (2005) tries to combine variability measures
- Nevertheless, as a class, low-latitude unidentified EGRET sources tend to be variable

- Any useful spectral characterization?
 - **No**





Candidates for variable Galactic sources*

- X-ray binaries microquasars/microblazars
- Plerions pulsar wind nebulae
- Sort of both binary plerions (Dubus)
- Isolated, rotating, magnetized black holes (Punsly)
- What about the Galactic center?
- Populations, luminosities, variability characteristics

*Not including rotation-powered pulsars (M. Razzano after the break)



XRBs in the MW

- Close binary system of pulsar and star strong and variable Xray sources (surprise)
- HMXRB companion is early-type star, strong stellar winds
- LMXRB companion is less massive (<2.5 Mo), Roche lobe xfer
- ~Hundreds in MW (Liu et al. 2000, 2001 & more discovered with INTEGRAL)



Filled circle: HMXRB Open circle: LMXRB

Grimm et al. 2002



XRBs in the MW (2)

- From the flux limit of EGRET and the characteristic distances of the EGRET unidentified sources we can infer that EGRET did not detect all of the GeV sources of gamma rays in the MW
- The known HMXRBs are flux limited, too, and no complete census for the Milky Way exists yet



(The Grimm et al. sample contains all XRBs that reached 5 mCrab for the ASM of RXTE at some point during the 1st 5 yrs of the mission.)

Grimm et al. 2002



Microquasars

- X-ray binaries with relativistic radio jets
- Prototype high-energy gamma-ray emitter: HMXRB LS 5039, NS/BH with O7 companion, ~3 kpc distant
- Microquasar identification and gammaray counterpart proposed by Paredes et al. (2000)
- VLBA + VLA show radio jets
- Inferred relativistic electron population and UV photons from O7 can provide IC gamma rays in addition to SSC
 - Can plausibly produce a relatively stable gamma-ray flux
 - Electrons in jet IC scatter UV photons from early-type companion star
- Apparently associated with 3EG J1824-1514 (16°, -1°)



Paredes et al. (2000)

18 AU



Variability of microquasars

- Regarding LS 5039, *P* = 4.1 d (Paredes et al. 2003):
 - "The high eccentricity of LS 5039 [e = 0.41] provides both, a variable accretion rate along the orbit implying a variable rate of electrons injected into the jet, and a variable radiation energy density close to the compact object. Hence, it is predicted a variability in the γ -ray luminosity correlated with the orbital period, which may hopefully be detected by INTEGRAL and/or GLAST."
- Also, absorption effects in the binary or the wind of the binary, or eclipses, can provide a periodic modulation
- Massi (2004) finds periodicity in EGRET flux for LS I +61°303 with P = 27.4 ± 7.2 d, consistent with the 26.49 d period of the binary; plus the ~2 flares seen by EGRET occur during periastron



Tavani et al. (1998)



Variability of microquasars (2)

- Jets are intrinsically variable related to accretion rate
 - Transition to high (X-ray) luminosity state seems to be associated with launching relativistic (Γ > 2) jets (Fender & Maccarone 2003)
- 'Microblazar' effect (Mirabel & Rodriguez 1999) – microquasars with jets nearly aligned with the line of sight.
 - When $\phi \leq 10^{\circ}$, flux boosted by 8 Γ^3
 - Kaufman Bernadó et al. (2002) study microblazar mechanism as a way to make variable unidentified sources

Non-coplanar orbit of companion star
can cause the disk to precess – resulting ,
in ~20% duty cycle for flaring out of ~O(100)-day period





Microquasars in the Milky Way

• Paredes (2005)

Name	INTE 30-50 keV (significance)	GRAL ^(a) 40-100 keV (count/s)	BATSE 20-100 keV 1 (significance)	(b) 160—430 keV (mCrab)	$\begin{array}{c} \text{COMPTEL}^{(c)} \\ 1-30 \text{ MeV} \\ \text{(GRO)} \end{array}$	$\begin{array}{l} \mathrm{EGRET}^{(\mathrm{d})} \\ > 100 \ \mathrm{MeV} \\ (\mathrm{3EG}) \end{array}$	Others ^(e)
		High I	Mass X-ray Binarie	es (HMXB))		
★ LS I +61 303	_	_	5.2	5.1 ± 2.1	J0241+6119?	J0241+6103?	
V4641 Sgr	_	-	-	-	_	_	
k LS 5039	_	_	10.7	3.7 ± 1.8	J1823 - 12?	J1824 - 1514?	
SS 433	13.5	< 1.02	21.7	0.0 ± 2.8	_	_	
Cygnus X-1	676.6	66.4 ± 0.1	1186.8	924.5 ± 2.5	yes	_	\mathbf{S}
Cygnus X-3	122.7	5.7 ± 0.1	197.8	15.5 ± 2.1	_	-	O, T?
		Low 1	Mass X-ray Binarie	es (LMXB)			
Circinus X-1	_	_	3.8	0.3 ± 2.6	_	_	
XTE J1550-564	8.6	0.6 ± 0.07	17.1	-2.3 ± 2.5	_	_	
Scorpius X-1	111.6	2.3 ± 0.1	460.6	9.9 ± 2.2	_	_	
GRO J1655-40	_	_	40.6	23.4 ± 3.9	_	_	0
GX 339-4	21.9	0.55 ± 0.03	89.0	580 ± 3.5	_	_	\mathbf{S}
$1 \ge 1740.7 - 2942$	147.3	4.32 ± 0.03	92.4	61.2 ± 3.7	_	_	\mathbf{S}
XTE J1748-288	_	_	-12.4	_	_	_	\mathbf{S}
GRS 1758-258	135.9	3.92 ± 0.03	74.3	38.0 ± 3.0	_	_	\mathbf{S}
GRS 1915+105	144.9	8.63 ± 0.13	208.8	33.5 ± 2.7	_	-	S, T?

Notes:

^(a) The first IBIS/ISGRI soft gamma-ray galactic plane survey catalog (Bird et al. 2004).

^(b) BATSE Earth occultation catalog, Deep sample results (Harmon et al. 2004).

^(c) The first COMPTEL source catalogue (Schönfelder et al. 2000).

^(d) The third EGRET catalog of high-energy γ -ray sources (Hartman et al. 1999).

^(e) S: SIGMA instrument onboard GRANAT satellite; O: OSSE; T: TeV source.

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What about the LMXRBs?

- What LMXRBs have going against them as high-energy sources: Much less intense stellar radiation field with lower T_{eff} & less intense X-ray emission from disk
- Grenier, Kaufman Bernado & Romero (2005) propose LMXRBs as counterparts to variable intermediate latitude sources
 - They conclude (sensibly) that IC scattering of radiation external to the jet is not sufficient to produce EGRET gamma-ray sources
 - SSC in the jet together with small viewing angle (microblazar) are still feasible



Plerions as gamma-ray sources

- Pulsar-powered nebulae, pulsar wind nebulae (PWN) 'filled-center' SNRs
 - ~30 known
 - Crab is prototype, but wide range of properties (related to age, magnetic field, ...)
- A plerion can be identified as such without finding the pulsar driving the nebula
 - E.g., X-ray synchrotron nebula reported by Oka et al. (1999) possibly assoc. with an unidentified EGRET source (2EG 1811-2339/3EG J1809-2328, a significantly variable EGRET source)
 - Now (thanks to Chandra imaging) the 'Mouse'





PWN as gamma-ray sources (2)

- Roberts et al. (1999) 'Rabbit' and Halpern et al. (2001) also report prospective plerions found in searches of an EGRET error box
- Most likely synchrotron emission from shock accelerated electrons (from pulsar wind interaction with shell or ISM)
 - IC cooling time scales are not short enough
 - Variability time scales would be too long if Bremsstrahlung emission in nearby molecular clouds

•Roberts (2005): Best candidate PWN counterparts for EGRET sources are all ram pressure confined – highvelocity pulsars

-Crab unpulsed flux is variable in the 70-150 MeV range (de Jager et al. 1996) on ~week (viewing period) time scales; cutoff around 25 MeV

-Compression & amplification of magnetic field in bow shock would increase E_{max} for the highvelocity PWN

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Another GeV emission mechanism for HMXRBs

- Interaction of pulsar wind with wind of the companion star (Dubus 2006)
- Careful argument that in LS 5039 and LS I +61°303 the resolved radio structure has not been shown to be relativistic jets
 - And might instead plausibly be, say, a pulsar wind interacting with the wind of the massive companion star
- Also, the masses of the compact objects in these XRBs are not known well enough to say whether they are not neutron stars
- PSR B1259-63 is prototype (ms pulsar with B0Ve companion in 3.4 yr period orbit)
 - HESS detection of VHE emission during periastron (Aharonian et al. 2005)
 - Not seen by EGRET during periastron (Tavani 1996) but may have been due to sensitivity limitation



Another mechanism (2)

 The GeV gamma-ray emission is under-predicted by this model, but various approximations made in the calculation leave room for adjustment





Isolated Black Holes



from ISM

Vacuum Electrodynamic Sheath



Galactic Center (3EG J1746-2851)

• Even without anything particularly exotic, plenty of evidence for particle acceleration, SNR, stellar winds,...



- Its position is not consistent with (0,0) (Hooper & Dingus 2002)
- Nolan et al. (2003) analysis suggested variability, but systematic uncertainties are large
- Pohl (2005) re-analysis of EGRET data finds no significant variability (beyond ~30% systematic uncertainty)

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Unofficial Derived LAT Capabilities

[Old & based on early estimates of response functions consistent with 'Goal' performance in the Science Requirements Document]

	EGRET	LAT
Point Source Sensitivity (5σ, >100 MeV)	~5 × 10 ⁻⁸ cm ⁻² s ⁻¹	3 × 10⁻⁹ cm⁻² s⁻¹ (at high gal. latitude for 1-year sky survey, for photon index of -2)
Source Location Determination	15´	0.4 [*] (1σ radius, flux 10 ⁻⁷ cm ⁻² s ⁻¹ >100 MeV, 1-year sky survey, high <i>b</i>)
Splitting 1 × 10 ⁻⁷ cm ⁻² s ⁻¹ sources	75´	6´
Resolving 5 × 10 ⁻⁷ cm ⁻² s ⁻¹ extended sources	90´ min (7.5° max)	5´

For flaring or impulsive sources the relative effective areas (~6x greater for LAT), FOV (>4x greater for LAT), and deadtimes (>3 orders of magnitude shorter for LAT) are relevant as well

Exposure (per year, in any direction) ~ $3 \times 10^{10} \text{ cm}^2 \text{ s}$ (~>1 GeV)

More **fine print**: *E*⁻² sources, EGRET: 2-week pointed obs. on axis, LAT: 1-year sky survey, flat highlatitude diffuse background

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Even more fine print

- Dependence on spectral index, spectral break, intensity of celestial diffuse emission, and the residual charged particle background is significant
 - Increase the flux limits by factor ~4-5 for low latitudes



• Event classification and reconstruction (along with the particle background model and attitude profiles) are still being refined



Some GLAST simulations

- Unfortunately, no actual data (one big advantage that EGRET retains over the LAT)
 - In the meantime, LAT simulation tools have become increasingly sophisticated – point and extended sources with spectral and temporal variations can be 'observed'





- LAT flux limits will be >10x deeper than EGRET
 - Roughly speaking this corresponds to >10x greater area of the Galactic disk over which the LAT will detect sources
 - [Will LAT discover distant HMXRBs that are not in X-ray catalogs?]
- Owing to the scanning sky coverage and the large FOV, the return time is very short and sampling of light curves will be very uniform
- LAT has no consumables and flux checks with bright pulsars will be nearly continuous (day scale anyway), so limitation of EGRET variability studies from systematic uncertainties will be less



- Simple 'Data Challenge 2' simulation (55 days, realistic everything else) with LS I +61° 303 inserted as a periodic source
 - 26.5 d period, 80% modulation (assumed), and flux consistent with one of the brighter EGRET measurements (1 x 10⁻⁶ cm⁻² s⁻¹ >100 MeV, Γ = 2.19)



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- Sources of gamma rays in the Milky Way are numerous and evidence from EGRET is that many low-latitude sources (Pop-I associated) are variable on time scales of days to months
- Good candidates exist for variable Galactic sources
 - PWN, XRBs (microquasars), or maybe both
- And will be much better characterized and understood (and more numerous) with the LAT



Backup slides



• Braje et al. (2002) Mouse

