Modelling the Milky Way in Gamma Rays for GLAST

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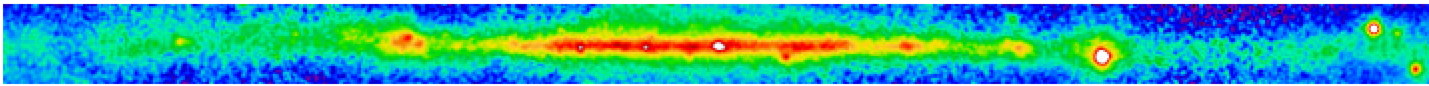


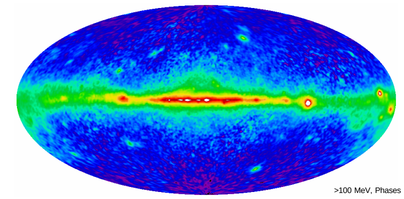
Intensity >300 MeV observed by EGRET for |b| < 10°.

Abstract

The Milky Way is a bright, diffuse source of high-energy gamma rays that are produced in cosmic-ray interactions with interstellar gas and radiation. An accurate, detailed model of this emission will be important for analysis of the data from the Large Area Telescope (LAT) under development for launch by NASA on GLAST in 2006. The LAT will study the sky in the 20 MeV-300 GeV energy range. Owing to its angular resolution, ranging from 3° to 0.1° with energy, and because of the limited photon statistics, a model of the pervasive interstellar emission is needed in order to determine accurate positions for gamma-ray point sources as well as to distinguish them from unresolved interstellar clouds. The model will depend on surveys of neutral and ionized gas and of continuum emission from the infrared through the optical. In this poster, we will describe how the model will be developed and what might be learned from LAT data about the interstellar medium and radiation field of the Milky Way and cosmic-ray origin and propagation in the light of results from the previous gamma-ray instrument, EGRET. Regarding the astronomical inputs, the challenges in developing the model include inverting spectral line surveys into 3-dimensional distributions of gas, accounting for the cold neutral gas, and modelling the interstellar radiation field. In addition models for the sources and propagation of cosmic rays based on current theory will be required. None of these issues is unique to the LAT model development, and our object is to identify and adopt the best approaches.

High-Energy Gamma-Ray Astronomy

The history of gamma-ray astronomy is relatively short. The technical challenges for detecting gamma rays in the 20 MeV–10 GeV range are great; the gamma rays must be detected above the atmosphere by instruments that convert them to positron-electron pairs which are tracked with charged particle sensors and absorbed in a calorimeter. The fluxes of gamma rays are low and achievable areas and angular resolutions for gamma-ray detectors have been modest by the standards at lower energies. This increases the need for a good model of the diffuse emission (see below). The few pioneering missions are being followed up with more sensitive instruments; the Large Area Telescope (LAT) is to be launched by NASA on the GLAST mission in 2006 (**Table 1 & Fig. 5**).



>100 MeV, Phases 1-5

Figure 1. All-sky map in Galactic coordinates of the intensity of >100 MeV gamma rays. The data are from the EGRET instrument on CGRO. The bright band at low latitudes is diffuse interstellar emission from the Milky Way. Emission from nearby interstellar cloud complexes at intermediate latitudes is also prominent. The bright point sources conspicuous at low latitudes are gamma-ray pulsars.

Instrument	Years	Ang. Res. (100 MeV)	Ang. Res. (10 GeV)	Energy Range (MeV)	A_{eff} Ω (cm^2 sr)	# of Gamma Rays
OSO-3	1967–1968	18°	–	>50	1.9	621
SAS-2	1972–1973	7	–	30–10,000	40	~10,000
COS-B	1975–1982	7	–	30–10,000	40	~2 × 10^5
EGRET	1991–2000	5.8	0.5°	30–10,000	750	1.4 × 10^6
AGILE	2005–	4.7	0.2	30–50,000	1500	4 × 10^6/yr
GLAST LAT	2006–	3.5	0.1	30–300,000	25,000	1 × 10^8/yr

Table 1. Comparison of characteristics of past gamma-ray missions with those under development. In its first few weeks of operation, the LAT should double the number of detected celestial gamma rays in its energy range. The first year of the LAT mission will be devoted to a sky survey.

Origin and Utility of Diffuse Emission

Diffuse interstellar emission from the interaction of cosmic rays with interstellar gas and photons makes the Milky Way the most prominent source at high energies, representing more than 60% of the integrated flux of the sky at energies above 30 MeV.

- **Galactic cosmic rays** are directly measured only within the solar system. For cosmic rays, the diffuse gamma-ray emission may be considered a measure of the distributions of cosmic rays across the Galaxy. In particular, sources of cosmic rays (interacting with the interstellar medium and radiation field) are of great interest.
- For the **interstellar medium**, study of the gamma-ray emission can yield information about the calibration of molecular mass in CO clouds and of the interstellar mass in general, as well as on the reliability of kinematic distance determinations. Useful limits on dark baryonic matter, e.g., cold molecular gas, can also be obtained.
- The diffuse gamma-ray emission at energies >10 GeV is particularly sensitive to the **interstellar radiation field** (see below).
- The limited angular resolution and photon statistics have also long made modelling of the diffuse gamma-ray emission of the Milky Way important as defining the ‘background’ against which **gamma-ray point sources** are detected. Many known or suspected classes of sources, e.g., pulsars, microquasars, and supernova remnants, are certainly Galactic, and must be detected against the bright, structured diffuse emission of the Milky Way.
- The apparently-isotropic **extragalactic diffuse emission** must be detected against the brighter foreground emission of the Milky Way

Components of the Model

In high-energy gamma-ray astronomy, owing to the poor angular resolutions of the detectors and the limited statistics, most astronomical analysis (e.g., the detection and characterization of point sources) is via parametric studies using a maximum likelihood analysis. Even study of point sources requires a good model of the diffuse interstellar gamma-ray intensity. The LAT collaboration will develop a model of the interstellar emission; this model will be made available through the GLAST Science Support Center.

Such a model requires the 3-dimensional distributions of interstellar gas ($?_{ISM}$) and the distributions and spectra of the interstellar radiation field (ISRF, $?_{ISRF}$), and cosmic-ray electrons and protons ($?_{CR,e}$ and $?_{CR,p}$). The gamma-ray production mechanisms (Bremsstrahlung, inverse Compton scattering, and decay of secondary p^0 from hadronic interactions) are well understood (at the 10% level) (see **Fig. 2**), and the radiative transfer is simple, as the interstellar medium is essentially transparent to gamma rays. The diffuse intensity may be written as

$$I(l,b,E)=\iint r_{CR,p}(E',s)q_{p^0}(E,E')r_{ISM}(s)dE'ds+$$

$$\iint r_{CR,e}(E',s)[q_B(E,E')r_{ISM}(s)+q_{IC}(E,E')r_{ISRF}(s,E')]dE'ds$$

where q_{p0} is the emissivity of p^0-decay gamma rays, q_B the Bremsstrahlung emissivity, q_{IC} the inverse Compton emissivity, and s is the distance along the line of sight in the direction (*l, b*). The above equation is somewhat of an oversimplification for the inverse compton (IC) emission, as the directional dependence of the IC emissivity (Moskalenko & Strong 2000) is not indicated, and the gamma-ray emissivity of ionized gas is greater than for neutral gas. Both of these refinements will be incorporated in our model.

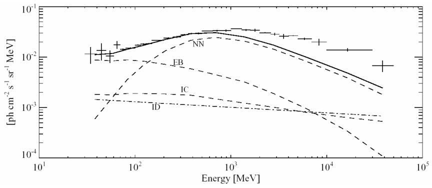
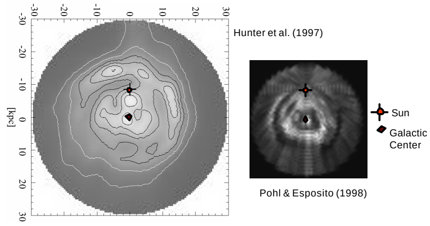


Figure 2. Spectrum of the inner Milky Way (|l| < 60°, |*b*| < 10°, point sources subtracted) from EGRET data. Indicated are the modelled contributions from Bremsstrahlung (eB), inverse Compton scattering (IC), p^0 decay (NN) calculated from the EGRET team’s model of the diffuse emission. The results, including the excess from the observations at energies >1 GeV are discussed in Hunter et al. (1997).

Motivations for a new Interstellar Emission Model for the LAT

The model that was developed for analysis of EGRET data (Bertsch et al. 1993; Hunter et al. 1997) was quite successful overall but needs revision for analysis of LAT data.

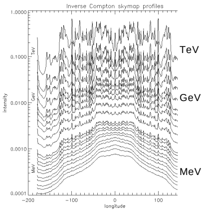
- Now or in the foreseeable future, several surveys of the atomic, molecular, and ionized components of the ISM with **better calibration, higher-resolution, or greater coverage** will be available.
- Inversion of spectral line surveys to derive the distribution of gas $?_{ISM}$ is known to be problematic for a number of reasons and we wish to explore **new approaches for resolving the kinematic distance ambiguity** and coping with sysematic non-circular motions, including tuning the inversion based on the observed gamma-ray intensity (**Fig. 3**).
- At large scales, the EGRET model deviates in some directions from the observed intensities, especially at high latitudes and at high energies (>1 GeV). Such large-scale deviations are inconsequential for point-source analysis but are relevant for studies of cosmic rays and also for **determining the diffuse extragalactic component**.
- At low latitudes, where the diffuse emission is the most intense, the LAT model will require **greater angular resolution** than the EGRET model (~0.5–1°). We need to be able to estimate total interstellar column densities on angular scales within which many molecular tracers are becoming optically thick (**Table 1**).
- Also, some special directions on the sky, for example the **Galactic center and anticenter and the tangent directions of spiral arms**, are both intrinsically difficult to model and of great interest scientifically. With recently-available infrared data and surveys of tracers of dense molecular gas, we will refine the approach for modelling these regions.
- The interstellar emission model for the LAT must also **extend to much higher energies** than EGRET (~300 GeV vs. ~10 GeV), so the interstellar radiation field $?_{ISM}$ must be modelled over a broader energy range.
- The ISRF must also be modelled in the vicinity of **massive star-forming regions**, where the energy density in visible-UV radiation is great.
- **Models of cosmic ray production and propagation** have become more sophisticated and more data now exist about cosmic rays in the solar vicinity to constrain the models (see below). Analysis of EGRET data indicated that Arm-interarm contrasts in cosmic rays are important to the model on kpc scales (e.g., Digel et al. 2001).



Hunter et al. (1997)

Pohl & Esposito (1998)

Figure 3. Distributions of surface densities of interstellar gas from two published studies of the diffuse gamma-ray emission of the Milky Way. The surface densities were derived from surveys of interstellar gas but made different assumptions about the rotation curve and the resolution of the distance ambiguty. The resulting distributions differ in many respects.



Inverse Compton skymap profiles

Figure 4. Intensity profiles for inverse Compton emission for an assumed SNR rate of 3/century and a random distribution in the inner Galaxy (Strong & Moskalenko). At higher energies, the individual cosmic-ray sources become discrete and the specifics of the source distribution become more relevant.

Cosmic-Ray Production and Propagation

Cosmic rays are accelerated in interstellar shocks, primarily in supernova remnants it is commonly believed. All all but the highest energies, they are confined by the Galactic magnetic field and diffuse with a long escape time to pervade the Galaxy. The energy loss rate for cosmic-ray electrons is much greater than for protons, and the distribution of electrons, especially at >GeV energies, is much more dependent on the details of the locations and ages of the supernova remnants (e.g., Pohl & Esposito 1998; **Fig. 4**) .

A variety of approaches have been used in gamma-ray astronomy to calculate the distribution of cosmic rays $?_{CR,e}$ and $?_{CR,p}$ across the Galaxy: coupling to interstellar gas (e.g., Hunter et al. 1997), propagation models (e.g., Strong, Moskalenko, & Reimer 2000; Pohl & Esposito 1998), or fitingt via adjustable emissivities to the diffuse gamma-ray emission (e.g., Strong & Mattox 1996). We are evaluating the approach to be used for the LAT interstellar emission model. Regardless, the method will be iterative, informed by the LAT data itself, e.g., regarding the distribution of cosmic-ray sources near enough to add detectable structure to the diffuse emission.

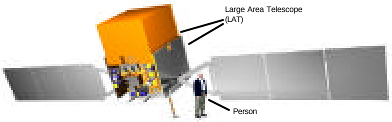
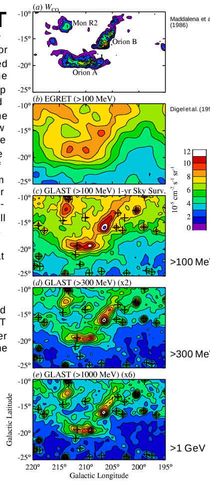


Figure 5. The LAT and the GLAST spacecraft. GLAST will also carry a gamma-ray burst monitor, the GBM instrument. For more information about GLAST, see http:/glast.gsfc.nasa.gov. The LAT home page is http://www-glast.slac.stanford.edu. Image source: L. Klaisner (SLAC).

Prospects for the LAT

The practical implications for the superior angular resolution and sensitivity of the LAT for the study of interstellar emission are illustrated in **Figure 6** , which compares a CO map of the Orion molecular clouds with the EGRET map and simulated LAT maps from the planned one-year sky survey. The point sources in the LAT simulations are artificial and all below EGRET’s sensitivity limit. The LAT will resolve structure in the diffuse emission on degree scales, and largely solve the problem of distinguishing gamma-ray point sources from the diffuse emission of (in many cases) their parent molecular clouds. Variations of cosmic-ray density and molecular mass calibration will be revealed on degree scales with LAT data. The value of ^{12}CO as a mass tracer for molecular hydrogen will be tested with great sensitivity.



(*a*) W_{CO}

(*b*) EGRET (>100 MeV)

(*c*) GLAST (>100 MeV) 1-yr Sky Surv.

(*d*) GLAST (>300 MeV) (x2)

(*e*) GLAST (>1000 MeV) (x6)

Maddalena et a (1986)

Digel et al. (199

Figure 6. The Orion region in CO and gamma-ray emission, actual data for EGRET and simulated data for the LAT. At higher energies, the LAT observations will map the Orion region in considerable detail.

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