Small Molecular Clouds at High Latitudes as Gamma-Ray Sources for GLAST*

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The sensitivity of the Large Area Telescope (LAT) on the forthcoming GLAST mission will be so much greater than previous high-energy γ-ray missions that small molecular clouds at intermediate and high Galactic latitudes ($|b| > 10°$) will be detected in the light of diffuse γ-ray emission from cosmic-ray interactions. These clouds are small, typically subtending less than 1° with masses ∼10–100 solar and distances ∼150 pc, and many are only now being discovered with sensitive, well-sampled, unbiased surveys of CO away from the Galactic equator. On the order of 100 such clouds will be detected by the LAT. Most will be near the detection limit (which depends on angular size) and many will in fact be detected but unresolved by the LAT, i.e., indistinguishable from point sources. We present predictions for the detectability of recently-cataloged clouds. As a γ-ray source class, they will clearly have a Galactic distribution and be steady emitters, but identifications of these sources as molecular clouds rather than potentially more exotic γ-ray phenomena will require more extensive and finely-sampled CO surveys at high latitudes.

1. INTRODUCTION

Cosmic-ray interactions in interstellar gas are a well known source of high-energy diffuse γ-ray emission. In fact, approximately 60% of the celestial γ-rays detected by the EGRET instrument on the Compton Gamma-ray Observatory originated with cosmic-ray interactions in interstellar clouds, making the Milky Way a bright foreground for point sources of γ-rays. The scale height of the densest, largely molecular, interstellar hydrogen is only about 70 pc, and so the vast majority of the molecular gas in the Milky Way is within a few degrees of the Galactic equator on the sky. Molecular hydrogen at interstellar conditions is very difficult to detect directly, and the J=1–0 line of CO, the second most abundant molecule, has become the standard surrogate tracer of molecular gas. No complete, well-sampled CO survey of the high-latitude sky exists and only recently have details of the tail of the distribution of molecular gas at high latitudes started to become known.

The Large Area Telescope (LAT, Fig. 1), under development for launch in 2007 on the Gamma-ray Large Area Space Telescope (GLAST) mission will have much greater sensitivity than EGRET. Depending on spectrum, the LAT will detect sources 20 or more times below the flux limit of EGRET. At these levels, what would be undetectable and ignorable small-scale features of diffuse emission for analysis of EGRET data become quite relevant for LAT data analysis.

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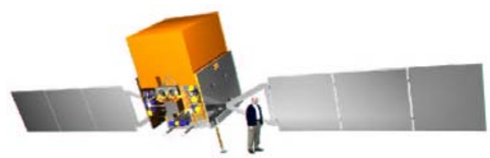

Figure 1: The LAT and the GLAST spacecraft. The dimensions of the LAT are approximately $1.8 \times 1.8 \times 0.75$ m. GLAST will also carry a gamma-ray burst monitor, the GBM instrument. The LAT home page is http://www-glast.slac.stanford.edu. Image source: L. Klaisner (SLAC).

In this poster, we use results from a sensitive new survey of molecular gas at high Galactic latitudes by Dame & Thaddeus [1] to estimate the numbers of small molecular clouds that will be detected by the LAT. The new survey is unique for its sensitivity to small molecular clouds because the grid spacing was 0.25°. Other surveys of the high-latitude sky have extended to higher latitudes (e.g., [2, 3]) but with 1° sampling. The great majority of the newly-found clouds have diameters less than 1°.

2. FLUXES OF CLOUDS IN GAMMA-RAYS

An interstellar cloud that is not a site of massive star formation can be considered a passive target for cosmic rays. The hadronically-generated γ-ray number luminosity can be computed as (see, e.g., [4, 5])

$$I_\gamma(E) = \int n(r) q_\gamma(E) dV \sim (M/m_p) q_\gamma, \qquad (1)$$

where r represents the position within the interaction region V, M is the mass of gas, m_p is the proton mass, n is the number density, and q_γ is the γ-ray emissivity. The γ-ray flux is then $F(>100\ \mathrm{MeV}) \sim 2.4\times10^{-9}(M/10M_\odot)(D/100\mathrm{pc})^{-2}\ k$ photons cm^{-2} s^{-1}, where D is the distance to the cloud and k is the enhancement factor of cosmic rays. The numerical factor takes into account electron bremsstrahlung (see, e.g., [6]). For local high-latitude clouds, we assume no enhancement, $k = 1$, so that the cosmic-ray spectrum is the same as the proton flux measured in the neighborhood of the Earth.

In estimating hydrogen masses, we do not include atomic hydrogen associated with the molecular clouds. The atomic gas is typically more smoothly distributed than the molecular gas on angular scales of degrees. (And diffuse γ-ray emission from high-latitude H I is already included in models of the diffuse emission of the Milky Way that are used for analyzing γ-ray data.) Relatively limited ($\sim$15 deg^2) mapping of intermediate latitudes at $9'$ resolution with the GBT [7] has shown that, even without dense molecular cores, the interstellar H I has a clumpy distribution but at the typical distances of the H I, these clumps could not be detected individually by the LAT.

The molecular masses of each cloud can be estimated under the usual assumption of a proportionality between the velocity-integrated CO intensity and the H_2 column density, $X = N(\mathrm{H_2})/\mathrm{W_{CO}}$. We use the value $X = 1.8\times10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$, derived from an intercomparison of large-scale far-infrared, 21 cm, and CO surveys [8]. The precise γ-ray fluxes of these clouds are difficult to estimate owing to the known wide variations of X in high-latitude molecular clouds.

Expressed in terms of its integrated intensity in the CO line, S_{CO}, the mass of molecular hydrogen is $M[\mathrm{M_\odot}] = 8.60\ S_{\mathrm{CO}}$ [K km s^{-1} deg^2] $(D/100\mathrm{pc})^2$ [9]. The factor 8.60 incorporates the value of X assumed; the correction for the contributions from He and heavier elements is removed here, because the γ-ray emissivity that we use (see below) already corrects for their contributions to the overall cross sections by relative abundance.

3. DETECTABILITY OF CLOUDS IN GAMMA-RAYS

In order to estimate which clouds the LAT will be able to detect and spatially resolve, we simulated observations of idealized, disk-shaped sources against an isotropic background intensity typical of the Milky Way at high latitudes (2×10^{-5} cm^{-2} s^{-1} sr^{-1}, >100 MeV, photon spectral index -2.1). We simulated a 1-year sky survey as planned for the first year of the mission after instrument checkout. The sources were assumed to have a spectrum consistent with the local

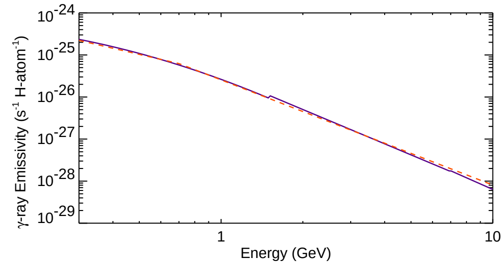

Figure 2: For our study of the detectability of high-latitude molecular clouds, we assumed that their γ-ray spectra are that of the emissivity from π^0 decay for the local spectrum of cosmic-ray protons. The parameterization given by Bertsch et al. [10] is shown as the solid curve. The broken power-law approximation used in our simulations is dashed. For the simulations of detectability only γ-rays with energies >300 MeV were used; for γ-rays below this limit, the PSF is so broad that they contribute little to the sensitivity for detecting or resolving these clouds.

γ-ray emissivity (primarily from π^0 decay in the range >100 MeV [10]; Fig. 2), as for the calculation of fluxes presented above.

As Figure 3 illustrates, the criterion for detectability by the LAT cannot be based solely on expected flux. For faint extended γ-ray sources, detectability will depend rather strongly on angular size. Preliminary response functions for the LAT, consistent with the performance requirements [11], were used for the simulation. The actual limits and angular sizes can be expected to change somewhat when final response functions become available.

Resolving a source (distinguishing it from a point source) requires better statistics (i.e., more γ-rays) than detecting it; thus the flux limit for detecting a source is lower than the limit for resolving it. With further simulations we mapped the regions of detectability and resolvability in the flux-angular size plane (Fig. 4), where we have also overlaid the new Dame & Thaddeus molecular clouds, which are in the range $|b| = 10°$ - $30°$, $l = 0°$ - $230°$.

Sources in the lightest shaded region of Figure 4 are both detectable and resolvable, i.e., distinguishable from point sources. In the intermediate shaded region sources are detectable but not distinguishable from point sources. Even if the expected location, extent, and shape of a source (disks in the case of the simulations) are known, if it lies within this region it is indistinguishable from a point source. Many of the clouds that are detectable will not be resolvable (i.e., not distinguishable from point sources). In particular, any detectable cloud with flux less than $\sim$8 $\times10^{-9}$ cm^{-2} s^{-1} (>100 MeV) will not be resolvable.

Resolving a cloud of course unambiguously establishes it as a diffuse source. The diffuse nature of the clouds might also be inferred from variability studies - they should be steady - or from their relatively soft

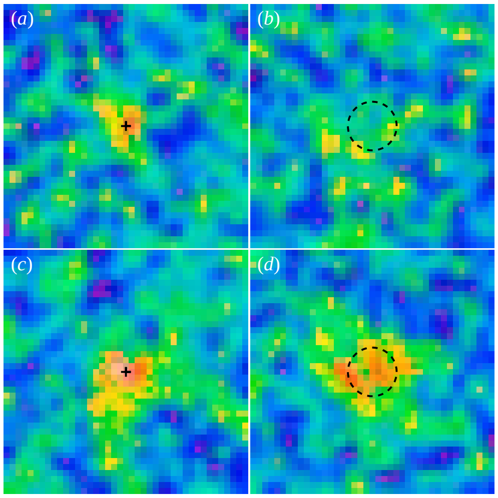

Figure 3: Illustration of the limits of the resolving power of the LAT. The images are simulated γ-ray intensity maps ($4^\circ \times 4^\circ$) for LAT observations of isolated sources against the diffuse background intensity at high latitudes. The simulation is based on preliminary response functions for the LAT, the exposure is that of the planned 1-year scanning survey of the sky, and the sources are assumed to have spectra consistent with the local γ-ray emissivity (see text). (a) Point source with flux 5×10^{-9} cm^{-2} s^{-1} (>100 MeV). The position of the source is indicated by the cross. (b) Disk-shaped source with 1° angular diameter and the same flux as (a). The circle indicates the position and extent of the source. The source is not detectable. (c-d) are as for (a-b) except with a source flux of 1×10^{-8} cm^{-2} s^{-1} (>100 MeV). The images have been smoothed slightly to reduce statistical fluctuations; each $0.1^\circ \times 0.1^\circ$ pixel typically contains 2 γ-rays.

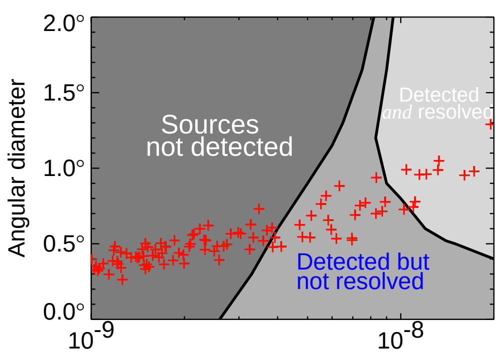

Figure 4: The limiting fluxes for sources with a given angular diameter to be detected and resolved by the LAT. The heavy-drawn lines indicate the boundaries for detecting and/or resolving a source at the 5σ level. The boundaries were derived from simulations using preliminary response functions for the LAT, for a 1-yr sky survey. The crosses are individual high-latitude molecular clouds in the new survey of Dame & Thaddeus [1], in the range $|b| = 10^\circ$-30°, $l = 0^\circ$-230°. The catalog contains 20 clouds that have greater fluxes and angular diameters than the limits of this plot (and many others below the flux limit shown).

spectra at high energies (the local γ-ray emissivity falling as $\sim E^{-2.75}$ in the GeV range). However, variability and spectral studies for faint sources such as these small clouds will not be particularly constraining. We expect that many of these γ-ray sources would be unidentified if they were not already cataloged as molecular clouds.

4. CONCLUSIONS

The properties of the molecular clouds discovered in the new survey of Dame & Thaddeus [1] suggest that approximately 140 high-latitude clouds will be detected in the LAT sky survey. Based on the coverage of the survey and where the clouds are in Figure 4, we estimate that approximately half of these will be detected but will not be bright enough to be angularly resolved. These clouds, if not otherwise incorporated in a model of the diffuse γ-ray emission of the Milky Way, would appear to be faint (unidentified or incorrectly identified) point sources. This is motivation for extending the coverage of the high-latitude sky with CO surveys in preparation for the GLAST mission. A more detailed version of this work has been published since the Symposium [12].

Acknowledgments

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