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Galactic Diffuse Emissions

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Abstract. Interactions of cosmic rays with interstellar nucleons and photons make the Milky Way a bright, diffuse source of high-energy γ-rays. Observationally, the results from EGRET, COMPTEL, and OSSE have now been extended to higher energies by ground-based experiments, with detections of diffuse emission in the Galactic center reported by H.E.S.S. in the range above 100 GeV and of diffuse emission in Cygnus by MILAGRO in the TeV range. In the range above 100 keV, INTEGRAL SPI has found that diffuse emission remains after point sources are accounted for. I will summarize current knowledge of diffuse γ-ray emission from the Milky Way and review some open issues related to the diffuse emission – some old, like the distribution of cosmic-ray sources and the origin of the 'excess' of GeV emission observed by EGRET, and some recently recognized, like the amount and distribution of molecular hydrogen not traced by CO emission – and anticipate some of the advances that will be possible with the Large Area Telescope on GLAST. We plan to develop an accurate physical model for the diffuse emission, which will be useful for detecting and accurately characterizing emission from Galactic point sources as well as any Galactic diffuse emission from exotic processes, and for studying the unresolved extragalactic emission.

Keywords: gamma rays, cosmic rays, diffuse background, interstellar medium, gamma ray telescope
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INTRODUCTION

This paper presents a brief review of γ-ray emission from interstellar processes in the Milky Way, and what we hope to learn from the Large Area Telescope on GLAST. Nuclear line and positron decay emission are not considered here. In the GeV energy range the diffuse emission is a useful diagnostic of Galactic cosmic rays and the interstellar medium. Even if it were not, it needs to be modeled accurately anyway; as Casandjian & Grenier have demonstrated (these proceedings), adoption of a new component for the model of diffuse emission has serious implications for the detections of faint point sources in the EGRET data. Accurately modeling the diffuse emission is important, too, for determining accurate coordinates for point sources and of course is also important for measuring the extragalactic diffuse emission.

THE MILKY WAY AS A DIFFUSE SOURCE OF GAMMA RAYS

That the Milky Way should be a bright source of γ-rays in the $\sim$100 MeV–GeV range was long predicted (e.g., [1]). Our galaxy is a large, barred spiral (type SBbc), and so has intrinsic advantages for producing γ-rays by interstellar processes. The spiral density waves induce ongoing massive star formation in the interstellar medium, the massive stars in one way or another ultimately are the sources of cosmic rays, and the Milky Way is massive enough to provide a large confinement time for cosmic rays.

The Milky Way was detected by OSO-3 in 1967-68 [2] and the observations were correctly interpreted to support a diffuse origin for the gamma rays [3]. The bright diffuse emission from the Galactic plane was seen by SAS-II [4] and COS-B [5], and the nearby giant molecular cloud complex in Orion was also studied quantitatively with COS-B data [6]. Knowledge of the Galactic diffuse emission in the 100 MeV–10 GeV range advanced greatly with the improved point-spread function and effective area (and limited residual background of charged particles) of the EGRET instrument on the Compton Gamma-Ray Observatory (1991-2000).

The primary production processes for γ-rays are pion decay from cosmic-ray proton-nucleon collisions, inverse Compton scattering (on the interstellar radiation field) and Bremsstrahlung scattering of cosmic-ray electrons. The radiative transfer for γ-rays in the 100 MeV–100 GeV range is particularly simple. The Milky Way is essentially transparent at these energies. Stars do not matter at all in terms of the diffuse γ-ray emission. They contain the great majority of the gas, but have a small fluctuation and are quite optically thick; if the hydrogen in the sun emitted γ-rays

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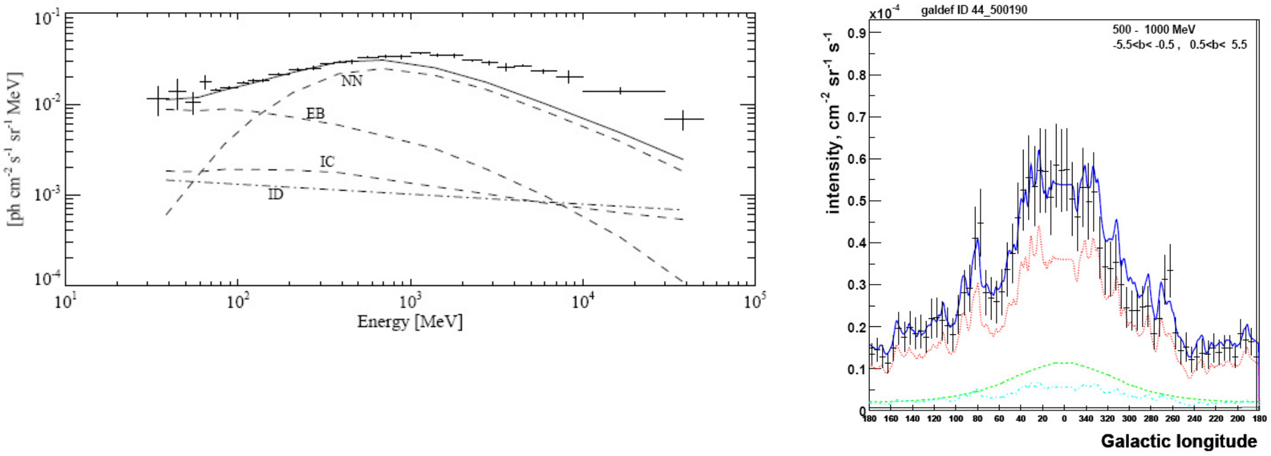

FIGURE 1. *left* Spectrum of the inner Milky Way ($|l| < 60°$, $|b| < 10°$) observed by EGRET. The curves are electron Bremsstrahlung (EB), inverse Compton (IC), isotropic (extragalactic) diffuse emission (ID), and π^0 decay from nucleon-nucleon interactions (NN) from the EGRET team's model [7]. The intensity has been multiplied by E^2 to display energy flux per decade. *right* Longitude profile of EGRET intensity (500–1000 MeV, point-source subtracted) for low latitudes compared with the 'optimized' model by Strong et al. [8]. In order from lowest to highest the curves are ID, EB, IC, NN, and sum for the model.

at the average interstellar rate, the γ-ray flux of the Sun would be approximately 14 orders of magnitude greater than its actual albedo emission.

The central challenge for understanding the diffuse emission is deducing the line-of-sight distributions of gas, of cosmic rays, and of the interstellar radiation field (ISRF) from our in-plane perspective. That the basic understanding of the diffuse emission from the Milky Way is sound is illustrated in Figure 1, which shows the spectrum of the inner Milky Way and the longitude profile across the Milky Way from two studies with EGRET data. The model fits are seen to fairly closely describe the observations. The deviations are not insignificant - and are topics in the sections below - but the important point is that in an absolute sense the observed diffuse intensities are consistent with what we know about the densities of cosmic rays, the distribution of interstellar gas and radiation, and the γ-ray production processes.

DIFFUSE EMISSION AT HIGHER AND LOWER γ-RAY ENERGIES

Before continuing with a discussion of issues related to the 100 MeV–100 GeV range, let us briefly consider the observations of diffuse gamma-ray emission outside this range. At energies $\gg$100 GeV most of the luminosity of the Milky Way appears to come from discrete sources, e.g., plerions, rather than from interstellar processes. The H.E.S.S. array of atmospheric Cherenkov telescopes has detected diffuse emission within a few degrees of the Galactic center, but the observed intensity relative to the column densities of interstellar gas indicate that the detection was possible only because the density of cosmic rays in the inner $\sim$250 pc is several times greater than typical across the Milky Way [9], [10]. The recent results from the Milagro water Cherenkov experiment indicate that Galactic 'hot spots', possibly somewhat extended, are being detected but that they are associated with regions of massive star formation, in particular in Cygnus [11].

At lower energies, the INTEGRAL SPI instrument has resolved much of the emission into point sources, although an apparently-diffuse continuum probably dominates in the range immediately below 1 MeV, predominately from inverse Compton (Knoedlseder, these proceedings; see also [12]). The contribution from unresolved sources, such as Anomalous X-ray Pulsars, may be significant, but is unknown at this point; the diffuse spectrum seen by INTEGRAL is lower than that found by OSSE, but presumably the SPI instrument is resolving more of the point-source contribution.

INTERSTELLAR GAS

Most of the interstellar gas is in the form of atomic (H I) and molecular hydrogen. H I can be observed directly in the light of the 21-cm hyperfine transition. Under interstellar conditions, H_2 cannot be detected directly and most commonly its presence is inferred from observations of the 2.6-mm rotational transition of CO. The ionized component of the interstellar medium is difficult to observe directly, because it is so diffuse. The scale height is large ($\sim$1 kpc) and the density is low ($\sim$0.02 cm^{-3}) [13]. Dispersion measures toward pulsars, together with distance estimates, can be translated into density distributions. The detailed model of Cordes & Lazio [14] is commonly adopted for the 3-dimensional structure. The interstellar medium is also presumed to include a proportion of He (mass fraction 27%), distributed like the neutral gas. Emissivities implicitly include the He fraction.

A few issues regarding the interstellar gas and current approaches for addressing them are summarized below.

Galactic structure and distance determinations: Differential rotation of the Milky Way causes easily measured distance-dependent Doppler shifts in the CO and H I lines from the interstellar medium. These shifts can be used as an indicator of distance, albeit with many caveats - including the existence of non-circular (streaming) motions, the internal velocity dispersions of approximately self-gravitating giant interstellar clouds, a near-far ambiguity within the solar circle, and the loss of kinematic resolution toward the Galactic center, anticenter, and at large Galactocentric distances in any direction.

As a result of the above considerations no unique solutions exist for the 3-dimensional distribution of gas. Although the spiral nature of the disk of the Milky Way is well established, e.g., through observations of tangent points of the inner spiral arms, no consensus exists on the specific arrangement of arms.

Local interstellar clouds & Dark gas: Interstellar gas at Galactic latitudes greater than $|b| \sim 10^\circ$ is nearby on a Galactic scale, with typical distances $\sim$100 pc or less. On this scale pc-scale details matter for the distribution of gas (and hence for the γ-ray intensity distribution). Although several large, local molecular cloud complexes each subtend more than 100 deg^2 [15], the high-latitude sky is remarkably devoid of molecular gas, or at least largely free from CO emission. The filling factor is $\sim$1–3 % [16]. Many of the molecular cloud complexes known at high latitudes were found using the 'infrared excess' method. Recently, however, a uniformly sampled, sensitive survey with the 1.2-m CfA telescope [17] has found dozens of small (degree-scale or less), previously-unknown molecular clouds. Estimates of column densities for these clouds based on CO emission are quite uncertain, owing to physical conditions that are quite different from the larger, denser molecular clouds in the Galactic plane [18]. However, many of the newly-found clouds certainly will be detectable by the LAT.

The question of CO as a tracer of H_2 at high latitudes has another dimension. Recently, determination of a residual component of infrared emission (a tracer of interstellar dust) that is not correlated with CO intensity or H I column density, has been interpreted as evidence for H_2 that has no associated CO emission [19]. The column densities of the 'dark' gas inferred to be associated with the infrared residual is sufficient to account for the fluxes of many faint, apparently-steady EGRET sources at intermediate laitudes (Casandjian & Grenier, these proceedings).

X-ratio and metallicity: Strong et al. [20] proposed a plausible explanation for at least part of an apparent discrepancy between the distribution of cosmic-ray sources and the distribution of cosmic rays. For previous studies of diffuse γ-ray emission, the proportionality $X = N(\mathrm{H}_2)/W_{\mathrm{CO}}$ was assumed to be the same across the Galaxy. However, X is expected to depend fairly strongly on metallicity Z; the dependence may be as steep as Z^{-1} or $Z^{-2.5}$. The gradient of metallicity in the vicinity of the solar circle is approximately 0.04–0.07 kpc^{-1} in log Z. Although even with sharply increased X ratios the overall abundance of molecular gas relative to atomic gas remains small beyond the solar circle, as Strong et al. point out, the general increase of gas densities has the effect of allowing steeper gradients of γ-ray emissivity, more in line with expectations from the inferred distribution of supernova remnants.

INTERSTELLAR RADIATION FIELD

The ISRF of the Milky Way must be inferred indirectly from stellar population counts and tracers of interstellar dust (which scatters and also absorbs and re-radiates in the infrared). Porter has constructed a detail model for the large-scale ISRF, including its essential anisotropy, using current understandings for the stellar populations and dust (see Porter et al. in these proceedings). Recently, Orlando & Strong have considered the inverse Compton emission from the intense ISRF in the immediate vicinities of early-type stars [21]. Some γ-ray 'haloes' from these stars or OB associations may be detectable by the LAT.

COSMIC RAYS IN THE MILKY WAY

The intensities of cosmic rays can be measured directly only in the solar system, and at low energies even these are subject to large corrections for solar modulation. Calculations of the intensities of diffuse γ-ray emission necessarily rely on methods for defining the densities of cosmic rays across the Milky Way. Three approaches have been used for analysis of EGRET data.

Cosmic-ray propagation codes, e.g. GALPROP [8], derive the distribution of cosmic rays by propagating them in a model Milky Way, using cosmic-ray source distributions and injection spectra and diffusion coefficients, etc. that are constrained by observations, e.g., of isotopic ratios in cosmic-ray species. The propagation calculations include interactions and loss (escape) of the cosmic rays and are continued until a steady state is reached. This approach offers the most direct connection to the physics of the production and propagation of cosmic rays but necessarily has many parameters, although most are constrained.

Another approach is to build into the calculation of γ-ray intensities the assumption that cosmic rays are coupled to interstellar gas on some characteristic length scale. This approach is motivated by the work of Parker [22], who found that the Galactic magnetic fields are coupled to the interstellar gas. The diffuse emission model of the EGRET team [23], [7] was based on this assumption and the coupling scale length $\sim$1.8 kpc [7] was found to optimize the agreement between the model and observations. One limitation is the necessary assumption of a Galaxy-wide uniform spectrum for cosmic rays; neither does it prescribe the scale height. The assumption of coupling is testable, and indications from a detailed study of the diffuse emission toward Monoceros suggest that at least the coupling scale cannot be constant [24]. But in large-scale features and most detailed structures, the assumption yields a model consistent with the EGRET observations.

The third approach is to not actually build in assumptions about the distributions of cosmic rays but instead fit γ-ray emissivities to the gas. This was first used in a study of the Orion molecular clouds in COS-B data [6], and was extended to studies of the whole plane of the Milky Way in COS-B [25] and EGRET [26] once suitable radio and millimeter-wave surveys of the gas were available. The appeal of this emmissivity-fitting approach is that propagation calculations or assumptions about coupling between gas and cosmic rays are not required. However, the z dependence of the distribution is essentially neglected.

THE GEV EXCESS

The most substantial difference between the EGRET team's model and the EGRET observations was a general underprediction of the γ-ray intensities in the range above 1 GeV, the so-called 'GeV excess' (Fig. 1). The GeV excess was present to some degree in every direction but was most prominent in a large halo around the Galactic center. Several possible explanations were considered and found to be unlikely to explain the excess, e.g., faulty production functions [27]; [28]; miscalibration of EGRET [7], unresolved point sources [29]. Strong, Moskalenko, & Reimer [8] found that in their GALPROP model calculations, the cosmic-ray spectra could be tuned ('optimized') to make γ-ray intensities consistent with the GeV excess without violating the various other constraints, notably without inconsistency with the locally-measured spectra of cosmoc rays.

UNRESOLVED POINT SOURCES

The distribution on the sky of the point sources detected by EGRET suggests that a large fraction is within the Milky Way (Hartman et al. 1999). The typical luminosities of the low-latitude sources are $\sim (1-15) \times 10^{35}$ erg s^{-1} (isotropic) and characteristic distances 1–6 kpc [30], [31]. The γ-ray luminosities of Vela and Geminga, the two brightest point sources in the 3EG catalog, are only 10^{34} erg s^{-1} and 10^{33} erg s^{-1}, their great fluxes stemming from their proximity (300 pc and 160 pc, respectively). Clearly, the Galactic sources in the 3EG catalog are flux limited at a fairly high level and not a complete sample. Intrinsically less luminous or more distant sources are presumably present but undetected.

One approach for estimating the contribution of point sources to the diffuse foreground relied on estimating the effect on the spectrum of the inner Milky Way. Hunter et al. [7] presented the spectrum (Fig. 1) and argued that the 'pion bump' feature near 68 MeV, which was in good agrement with the predictions of the EGRET model for diffuse emission, would have been washed out if unresolved point sources contributed more than 10% of the integrated flux in the energy range 30–1000 MeV.

Pohl & Esposito [29] found that pulsars could contribute significantly (up to $\sim 18\%$) in the range > 1 GeV but the distribution in latitude of the unresolved γ-ray pulsars is narrower than that of the diffuse emission. More recently, Strong [32] has shown that a simple luminosity function for Geminga-like pulsars could be adjusted to account for the GeV excess spectrally without violating any observational constraints on the numbers of pulsars.

EXPECTATIONS FOR THE LAT & CONCLUSIONS

The LAT will have superior angular resolution and effective area relative to EGRET [33] and in its first few months of operation should double the number of celestial gamma rays ever detected in the 100 MeV–100 GeV range. For diffuse studies the stability of the effective area relative to EGRET will be a great advantage as well. The improved statistics and resolution will allow testing of models for the distribution of gas, whether dark gas at high latitudes or an uncertain gradient of X-ratio much more directly with the observations.

The LAT source catalog certainly will be much deeper than EGRET's but of course the question of unresolved sources will remain. One productive approach for setting limits on the contributions from unresolved sources will be to study in detail nearby molecular clouds; Galactic sources are expected to be related to massive star formation regions, which are in turn related to molecular clouds. The nearest giant cloud complex, Orion ($\sim$500 pc), is 10–15 times closer than typical EGRET Galactic sources and so any sources in Orion will have fluxes 100–200 times greater.

The diffuse emission of the Milky Way is bright and pervasive at GeV energies and will closely studied in LAT data to answer outstanding questions regarding the distributions of cosmic-ray sources, the propagation of cosmic rays, and the molecular mass content of the Milky Way (including 'dark gas'). The LAT data also will tightly constrain the contributions of Galactic point source populations to the diffuse emission.

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