DIFFUSE GAMMA RAYS OF GALACTIC AND EXTRAGALACTIC ORIGIN:PRELIMINARY RESULTS FROM EGRET

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Abstract. The all-sky survey in high energy gamma rays (E>30 MeV) carried out by the Energetic Gamma Ray Experiment Telescope (EGRET) aboard the Compton Gamma Ray Observatory provides for the first time an opportunity to examine in detail diffuse gamma-ray emission of extragalactic origin. The observed diffuse emission at high galactic latitudes is generally assumed to have a galactic component arising from cosmic-ray interactions with the local interstellar gas and radiation, in addition to an isotropic component presumably of extragalactic origin. The galactic component can be estimated from a model of the interstellar medium and cosmic-ray distribution. Since the derived extragalactic spectrum depends very much on the success of our galactic model, the consistency of the galactic diffuse emission model is examined both spectrally and spatially with existing EGRET observations. In conjunction with this model, EGRET observations of the high latitude emission are used to examine the flux and spectrum of the residual extragalactic emission. This residual emission could be either truly diffuse in origin or could arise from accumulated emission from unresolved sources particularly in the light of EGRET observations showing the presence of numerous gamma-ray bright active galactic nuclei.

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1. Introduction

Historically, the first indication of an extended diffuse component of the high energy gamma radiation was obtained by Kraushaar *et al.*(1972) with the OSO-3 satellite. Later observations by the second Small Astronomy Satellite (SAS-2) clearly showed for the first time a strong correlation of the observed diffuse emission with column density of interstellar gas (Fichtel, Simpson & Thompson 1978; Thompson & Fichtel 1982). In addition, this correlation also indicated the presence of a residual emission at zero column density which was interpreted as not being associated with the Galaxy and hence of extragalactic origin. SAS-2 was unable to truly examine the isotropic nature of this residual emission due to the premature loss of the satellite after about 6 months of operation. The subsequent COS-B mission did not result in any additional understanding of the isotropic emission due to the high instrumental background. Neither the placement of material surrounding the instrument nor the orbit were optimized to allow observations of the weak extragalactic diffuse radiation. With more than an order of magnitude increase in sensitivity over previous experiments and a low instrumental background, EGRET, on board the Compton Gamma Ray Observatory (CGRO) provides the first opportunity to study in detail the spectrum and distribution of the extragalactic gamma-ray emission. During the early phase of the CGRO mission (April 1991 - Nov 1992), EGRET carried out the first all sky survey in high energy gamma rays (30 MeV$\leq E \leq$ 30 GeV). The most striking aspect of the all sky survey is the dominant diffuse emission from the plane of the Galaxy. In addition, numerous point sources are also observed, many of them have been identified with pulsars, molecular clouds, active galactic nuclei and a nearby normal galaxy (Fichtel *et al.*1994). Along the galactic plane, point source detection is difficult since they are embedded in the extremely strong galactic diffuse emission. Currently, the unambiguously identified point sources along the plane include, five sources identified as pulsars (PSR B0531+21 (Crab) (Nolan *et al.*1993), PSR B0833-45 (Vela) (Kanbach *et al.*1994), PSR 0630+178 (Geminga) (Bertsch *et al.*1992; Mayer-Hasselwander *et al.*1994), PSR B1706-44 (Thompson *et al.*1992) & PSR B1055-52 (Fierro *et al.*1993) on the basis of their characteristic timing signature. At high galactic latitudes point source detection capability is enhanced by the much weaker galactic emission. A total of 36 sources have been identified with a class of active galactic nuclei called blazars. In general, blazars are radio bright AGNs with flat radio spectra, strong optical polarization, often exhibit superluminal motion and show significant time variability at most wavelengths. EGRET observations have shown that for a majority of the gamma-ray luminous blazars, the gamma-ray emission dominates the bolometric

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luminosity. This important finding further strengthens the theoretical attempts to explain the origin of the extragalactic emission as a superposition of sources. Other high latitude as well as galactic point sources have also been detected by EGRET and these have yet to be identified with any *likely* candidates.

This paper briefly discusses the approach used to study the extragalactic gamma-ray background by carefully accounting for the foreground galactic emission. The level of our understanding of the galactic model is demonstrated by showing the consistency both spatially and spectrally between the prediction and EGRET observations. The observational results presented here are based on the all sky survey phase of the CGRO mission (April 1991 to Nov 1992). Details on the instrument and its capabilities are discussed by Thompson *et al.*(1993). Preliminary conclusions derived on the extragalactic gamma-ray background are also discussed.

2. Diffuse Gamma Rays of Galactic Origin

Beyond the point sources discussed above, the emission that appears diffuse in nature in the all sky survey is dominated by a strong galactic component. Diffuse emission of galactic origin strongly traces out the plane of the Milky Way including the warp in the atomic hydrogen gas disk around longitude of 90°. Apart from a possible contribution from unresolved sources such as pulsars (Bailes & Kniffen 1992), this emission is generally understood to arise from cosmic rays interacting with the interstellar gas and radiation (Bertsch *et al.*1993). Away from the plane, the galactic emission gets weaker but is non-negligible even at the poles. The detailed comparison of the model against observational data from EGRET will be discussed by Hunter *et al.*(1995) for the galactic plane and by Sreekumar *et al.*(1995) for regions at high latitudes. In order to understand and characterize diffuse gamma rays of extragalactic origin, it is important to remove the galactic component from the observed diffuse emission . Consequently, for the study of the extragalactic radiation, it is more appropriate to examine regions away from the galactic plane where the galactic contribution is weaker.

Gamma-ray observations also provide a direct way to examine the cosmic-ray distributions in our Galaxy as well as in other external galaxies. Thus in addition to the reason given above to model the galactic emission, another important goal is to use gamma-ray observations to probe the spectrum and spatial density distribution of cosmic rays in the Galaxy. The three principal gamma-ray production processes are bremsstrahlung by energetic cosmic-ray electrons, decay of neutral pions resulting from nucleon-nucleon interactions and by inverse Compton scattering of cosmic-ray electrons on the low energy 2.7K, infra-red, optical and UV photons in the Galaxy.

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Electron bremsstrahlung dominates the observed diffuse emission at energies below 100 MeV. However, above a few 100 MeV, diffuse gamma-ray emission is dominated by photons from the decay of neutral pions. While relativistic cosmic-ray electrons can be studied using radio observations, cosmic-ray protons which carry most of the energy in cosmic rays are best studied using high energy gamma-ray observations. Beyond the Milky Way, we have detected for the first time gamma-ray emission from an external galaxy the Large Magellanic Cloud (Sreekumar *et al.*1992). In addition, our observation of the Small Magellanic Cloud has provided clear evidence for the galactic origin of the bulk of cosmic rays (Sreekumar *et al.*1993). This result provides the fundamental basis to model galactic cosmic rays as being coupled to the interstellar gas (see Bertsch *et al.*,1993, for further discussion). Since the observed gamma-ray emission depends also on the density distribution of the interstellar gas, the model can be used to limit the CO to H_2 normalization factor (X-factor) used to convert the observed CO emission into molecular hydrogen column density. Prior to the launch of the Compton Observatory, the modeling of the COS-B data was carried out using a multiparameter fit to the observed emission. The analysis showed indications of a variation of cosmic-ray density with galactocentric radius as well as an upper limit of 2.3×10^{20} K km s^{-1} for the X-factor (Strong *et al.*1988). Conclusions from our analysis are discussed later on in this paper.

2.1. MODEL

The primary input parameters to calculate the galactic diffuse gamma-ray intensity include a model of the interstellar gas (neutral and ionized), photons and cosmic rays. The neutral atomic hydrogen distribution is obtained from 21-cm observations while the molecular hydrogen distribution is derived indirectly using the strength of $^{12}C^{16}O$ emission at 2.6 mm. At present, diffuse gamma-ray observations provide one of the better tools to constrain the conversion factor (X) used to derive the molecular hydrogen column density from the CO. The model uses the all sky 21-cm map of Dickey & Lockman (1990) for regions at high latitudes (above $\pm10°$) and data from the Maryland-Parkes survey(Kerr *et al.*1986), Weaver & Williams (1974) and Leiden-Green Banks survey (Burton & Liszt 1983) for the galactic plane. Along the plane, the model deconvolves the observed column density of neutral hydrogen along the line of sight using the galactic rotation curve. The molecular hydrogen density was derived from the CO data of Dame *et al.*(1987). The ionized interstellar medium is not as well determined and here we use the model of Taylor and Cordes (1993) which is based on results from pulsar observations. The cosmic rays are assumed to be closely coupled to the interstellar gas, the coupling length

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scale along the galactic plane is adjusted to best fit the EGRET observations. Additional details on the model are discussed in Bertsch *et al.*(1993). Since the interstellar neutral gas distributions have a narrow scale height (110 pc for atomic H; 60 pc for molecular H), at high latitudes, we assume the neutral gas is all local and hence the cosmic-ray density to be similar to that in our galactic neighborhood. The ionized gas is generally believed to have a larger scale height of several hundred parsecs (Reynolds 1993). Radio continuum observations have indicated the cosmic ray electron scale height to be significantly larger than that of the gas. Our model uses a cosmic ray scale height of 1 kpc and assumes a ratio of electrons to protons of 1/100, which is the generally accepted value in our galactic neighborhood. The larger scale heights lead to larger relative contributions from the ionized medium and the inverse Compton process at high latitudes. The structure and scale height of the ionized medium and the spatial distribution of the soft photons in the Galaxy (2.7K, NIR, FIR, Optical and UV) that participate in the inverse Compton process, are not well known. This introduces uncertainties in the predicted high latitude gamma-ray emission. Thus, our current results on the extragalactic background emission are also subject to these uncertainties. Efforts to improve the model in this regard are underway.

2.2. RESULTS

The observed diffuse gamma-ray emission from the plane can be compared with the model calculations of Bertsch *et al.*(1993). Figure 1 shows the longitude dependence of the observed intensity averaged over $\pm$ 10° in latitude. The solid line represents the model of Bertsch *et al.*(1993) together with an isotropic extragalactic component of 1.5×10^{-5} photonscm^{-2}s^{-2}ster^{-1}. Considering the model has only two adjustable parameters and does not force fit the observations rigorously, it is remarkable that it reproduces many of the spatial features at various longitudes which correspond to spiral arm tangent points. The assumption by Bertsch *et al.*(1993) that cosmic rays are closely tied to the interstellar gas distribution appears to have a strong basis as seen from figure 1. The latitude distribution averaged over the longitude range (90°-150°), is shown in figure 2 and shows good consistency with the model predictions. The model requires an X-factor (one of the adjustable parameters of the model) of 1.8×10^{20} K km s^{-1} or less to be consistent with the EGRET observations. The analysis also indicated that the cosmic-ray - matter coupling length scale is about (2$\pm$1) kpc in the plane of the Galaxy. The corresponding length scale derived using a typical diffuse coefficient (Ginzburg *et al.*1980) and a cosmic-ray mean lifetime of 2×10^7 years is about 3 kpc which is within the errors of our observation-

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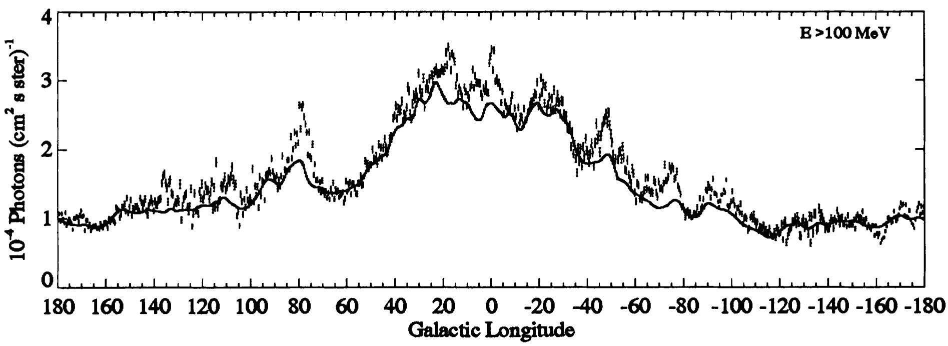

Figure 1. EGRET observations of the Galactic diffuse emission: distribution in galactic longitudes, averaged over $\pm 10°$in latitude. The solid line represents the model prediction along with an assumed isotropic component of $1.5 \times 10^{-5} photons cm^{-2} s^{-1} ster^{-1}$. Only the clearly identified sources along the galactic plane viz., the five gamma-ray pulsars are subtracted (Hunter *et al.*1995).

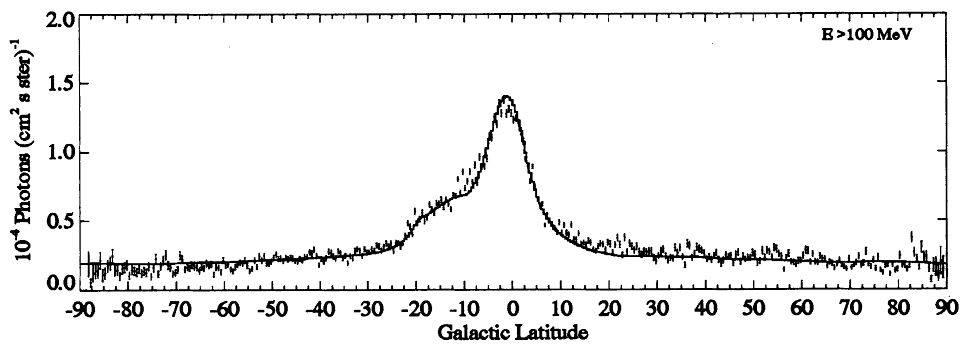

Figure 2. EGRET observations of the Galactic diffuse emission: distribution in galactic latitudes, averaged over the longitude range of 190°- 240°.The solid line represents the model prediction along with an assumed isotropic component of $1.5 \times 10^{-5} photons cm^{-2} s^{-1} ster^{-1}$. EGRET detected point sources at high latitudes have been removed. Along the galactic plane, only the five gamma-ray pulsars are subtracted from the data (Hunter *et al.*1995; Sreekumar *et al.*1995).

ally derived value. The point source analysis using a maximum likelihood method (Mattox *et al.*1995) indicates $<$ 15% of the total observed diffuse emission from the Milky Way arise from resolvable point sources. There may

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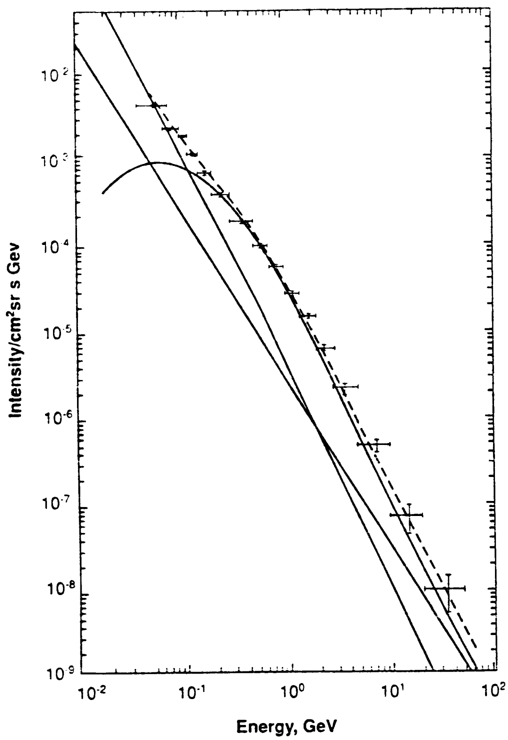

Figure 3. Galactic diffuse emission spectrum near the galactic center (from Fichtel *et al.*1993). The dashed line indicates the sum of the three components: π^0 decay, electron bremmstrahlung and inverse Compton process.

still be unresolved point sources below the detection threshold of EGRET. The spectrum from the region near the galactic center is shown in figure 3. It shows for the first time the predicted feature from gamma rays arising from π^0 decay. This is an important signature of cosmic-ray protons in the Galaxy. Thus the galactic model shows consistency both spectrally and spatially with the observed diffuse emission. Additional results on the diffuse emission from the galactic plane will be discussed by Hunter *et al.*(1995).

3. Diffuse Gamma Rays of Extragalactic Origin

The measurement of the extragalactic diffuse radiation is one of the most difficult of all high-energy measurements. This is because the intensity is low and there is no unique signature such as spatial or temporal profile to separate the cosmic signal from the various backgrounds. Not the least of these is the instrumental background produced by the interactions of ambient cosmic rays with the material in and around the detector. So two

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separate factors must be minimized, the cosmic-ray intensity and instrument and/or spacecraft material outside of the anticoincidence scintillator.

Only two instruments have been placed in orbit with these two factors designed to give a background well below the expected diffuse background intensity. These are the spark chamber telescopes flown aboard the SAS-2, and the EGRET instrument on the Compton Observatory. The SAS-2 instrument was launched into a near equatorial orbit and EGRET into the standard 28° inclination orbit for a shuttle launch. Because of the higher inclination, the Compton Observatory is kept below a 450 kilometer altitude to minimize the effects of the trapped radiation. The design of the Compton Observatory was complicated also by the discovery during the repair of the Solar Maximum Mission (SMM) satellite that space debris was more intense than expected. A penetration of the light shields surrounding the instruments could cause light leaks which could degrade or damage the photomultiplier tubes and adversely affect instrument performance. For this reason the mass in the detector aperture on EGRET, $\sim 0.19\,\mathrm{g\,cm^{-2}}$, was slightly higher than the $\sim 0.16\,\mathrm{g\,cm^{-2}}$ of SAS-2. Nevertheless, extensive preflight calibration at the Brookhaven Laboratory have indicated that the expected instrumental background of EGRET is an order of magnitude less than the intensity of extragalactic radiation derived from the SAS-2 data. The small disadvantages of EGRET are more than overcome by the much improved instrument sensitivity of well over an order of magnitude, the long exposure to high latitude regions of the sky, and broad spectral coverage (30 MeV - 30 GeV).

3.1. EXPOSURE AT HIGH GALACTIC LATITUDES

The most extensive exposure off the galactic plane to date is to the Virgo region. Over 20 weeks of exposure have been obtained in phase 1 to 3 (April 1991 to Jan 1994) and another 5 more weeks are allocated for phase 4. Furthermore, there are a number of other high latitude (+ and -) exposures, shorter in duration, that will add to the study. In order to complete the analysis of these data great care must be exercised to ensure proper normalization between different exposures and other even more subtle corrections, including subtraction of background due to discrete source and galactic diffuse contamination. This work is nearing completion, but a normalized spectrum is not yet available. Preliminary results indicate a good power law fit to the extragalactic spectrum with a slope of -(2.2 ± 0.2) (Sreekumar *et al.*1994) .

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3.2. WORK IN PROGRESS

Current work is aimed toward optimizing the subtraction of backgrounds since these and an accurate exposure calculation are crucial to obtaining a good normalized spectrum. In addition, several approaches are being taken to investigate the origins of this radiation. In particular, fluctuation analysis using a logN-logS technique as well as topological and wave packet analysis of spatial fluctuations on all scales are being explored.

4. Conclusions

We have successfully modeled the diffuse gamma ray emission from the Galaxy. The model predicted diffuse emission spectrum and the spatial distribution in galactic longitude and latitude are in good agreement with the EGRET observations. This makes it possible to remove the galactic component from the observed high latitude diffuse emission. The determination of the diffuse spectrum of the extragalactic high-energy gamma radiation is very difficult and must be done with extreme care. Instrumental response must be thoroughly understood and folded into the analysis. This work is well underway, but not yet complete. The results which currently exists suggests a power law slope of -(2.2±0.2). This is consistent with the slope of $-2.34^{+0.4}_{-0.3}$ reported by SAS-2 (Thompson and Fichtel 1982). This is also consistent with the average spectra reported for AGNs detected by EGRET and hence the spectral shape of the extragalactic emission could be explained by an accumulation of unresolved AGN emission. Future work on fluctuation analysis may shed some light on this question.

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