GAMMA-RAY OBSERVATIONS OF THE INTERSTELLAR CLOUDS IN CEPHEUS

NASA Grant NAG5-2823

IN-93
375883

Final Report

For the Period 15 December 1994 through 14 June 1998

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September 17, 1998

Prepared for

National Aeronautics and Space Administration
Washington, DC 20546

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The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

The NASA Technical Officer for this grant is Dr. Jay P. Norris, Code 661.0,
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Subcontract of Grant NAG5-2823: "Gamma-Ray Observations of the Interstellar Clouds in Cepheus"

Final Report

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1. Introduction

During the last six months of the period of performance, the diffuse gamma-ray emission from the Monoceros region was reanalyzed and one of the important conclusions was revised as a result. The reanalysis incorporated newly-available data from recent EGRET viewing periods and revealed a previously-uncataloged gamma-ray point source near the plane in Monoceros. The effect of incorporating this source in the diffuse emission model was significant, as its flux was comparable to that from a large interstellar cloud complex in the Perseus arm. In the updated model, a greatly reduced gamma-ray emissivity was found in the Perseus arm. This finding alters the previous conclusion that we had found evidence for an enhanced emissivity in the arm, which had supported the hypothesis that cosmic rays are coupled to the interstellar medium on the scale of spiral arms. Our updated findings are consistent with our previous results for the emissivity toward the Cepheus region (Digel et al. 1996), where a monotonic gradient of emissivity in the outer Galaxy was found.

The updated analysis of Monoceros was presented at the June, 1998 meeting of the American Astronomical Society, and a journal publication should be ready for submission soon.

2. Summary of Analysis

As stated before, the diffuse gamma-ray emission in Monoceros was studied in a way complementary to analyses applied to other regions, like Cepheus (Digel et al. 1996). The Monoceros region is very well suited for study of the cosmic-ray density and molecular mass calibration beyond the solar circle. The interstellar gas along lines of sight through this region is concentrated in well-defined distance ranges, permitting the diffuse gamma-ray emissions from different distance ranges to be distinguished. In the outer Galaxy, the distance of an interstellar cloud and the doppler shift of the 2.6-mm CO and 21-cm H I emission from its molecular and atomic gas are directly related; distances are inferred from measured shifts of the emission frequencies. (The intensity of the CO line is used as a tracer for the much more abundant H_2, which is difficult to observe directly at interstellar conditions.)

In the interstellar medium, high-energy gamma rays are principally produced in collisions of cosmic-ray protons and electrons with interstellar gas nuclei. The main processes are the decay of π^0 particles in cascades from proton interactions and Bremsstrahlung scattering of high-energy electrons. The gamma-rays are not absorbed by the interstellar medium, and their intensities may be interpreted in terms of the line-of-sight integral of the product of the cosmic ray and gas densities. Because cosmic-rays are smoothly distributed on scales of interstellar clouds and larger, the integral can generally be simplified to a linear combination of terms describing the column density of interstellar gas.

A model describing the diffuse emission from a given region on the sky has as free parameters the density of cosmic rays on one or more distance ranges. (In general, models are fit separately for different gamma-ray energy ranges. Owing to the different spectral characteristics of the emission from cosmic-ray proton and electron interactions, their densities may be determined separately.) Other free parameters in the model are the extragalactic isotropic intensity, the $N(H_2)/W_{CO}$ ratio on various line-of-sight distance ranges, and the positions and fluxes of gamma-ray point sources. Positions and fluxes of sources are determined iteratively, especially for uncataloged sources. First, a maximum likelihood search for point-source-like gamma-ray excesses is made using a diffuse model with no sources, then the sources identified in the search are added to the model.

2.1 Data Sets

The primary gamma-ray data set was compiled from all of the EGRET viewing periods that overlap any part of the region of interest (l = 210–250°, b = -15 – +20°). Among the more than 50 relevant viewing periods, this included viewing periods 510 and 510.5, pointed observations of the central part of this field taken specifically for this study. The average exposure in the combined dataset was 6.2×10^9 cm^2 s for $E > 100$ MeV.

As described before, to combine all of the viewing periods into a self-consistent composite dataset, special care was required. The sensitivity of EGRET varied with time, energy, and inclination angle; as the spark chamber gas aged between refills, the sensitivity declined, especially at lower energies. The standard EGRET data products include an energy-dependent scale factor to correct exposure maps for this effect. The correction factors are applied to the entire field of view of EGRET, but there is reason to expect that the sensitivity fall-off is non-uniform across the field of view, being greater at large inclination angles. Because much of the exposure toward Monoceros is at large angles, from viewing periods centered on the Crab and Vela pulsars, the relative sensitivity correction factors for Monoceros were rechecked carefully using special software written just for this purpose. Viewing period 44.0, which is well-centered in Monoceros, was adopted as the intensity standard. Twenty-four of the viewing periods that overlap Monoceros were found to have average intensities more than two standard deviations different, and their exposure maps were scaled accordingly. Because most of these discrepant viewing periods had only a small overlap with Monoceros, the net effect on the overall average exposure was small (a 3% decrease), but the exposure estimates near the edges of the field were improved significantly.

As described before, the CO spectral line data for the region of interest were taken from the composite survey of the Milky Way by Dame et al. (1987) and H I spectra for the region were compiled by combining parts of the surveys of Cleary et al. (1979), Heiles & Habing (1974), Kerr et al. (1986) and Weaver & Williams (1973), as described before. Maps of N(H I) and W_{CO} were derived for four distance ranges along the line of sight through Monoceros. Distances were derived kinematically in the usual way, on the assumption of a flat rotation curve across the outer Galaxy. The four distance ranges were denoted local (Monoceros), interarm, Perseus arm, and beyond Perseus arm.

2.2 The Model and Model Fitting

As described above, the model of the observed map of gamma-ray photons, i.e., the intensity map multiplied by the EGRET exposure map, is a linear combination of the N(H I) and W_{CO} maps, with a constant-intensity term corresponding to the isotropic emission, and terms describing point sources in the region of interest. The coefficients of the linear combination, derived from fitting the model to the observations, are interpreted as the gamma-ray emissivities and the $N(H_2)/W_{CO}$ ratios.

Likelihood analysis showed that the model required five point sources, four previously cataloged (Thompson et al. 1996), and a newly-found source. This source, which does not have a candidate counterpart at other wavelengths, was found to have approximate Galactic coordinates (215.25°, +0.75°) and an average flux of $(12.8 \pm 4.2) \times 10^{-8}$ cm^{-2} s^{-1} for $E > 100$ MeV.

The model was fit to the gamma-ray data set for several energy ranges spanning the 30 MeV – 10 GeV range of sensitivity of EGRET. Details of the fitting method, known as the maximum likelihood method, are given in Digel et al. (1996) along with citations to the original work on likelihood analysis in astronomy.

3. Highlights of the Results

As mentioned in the introduction, the incorporation of the unidentified gamma-ray source in the model significantly affected the derived gradient of gamma-ray emissivity. Much of the flux assigned to the source by the maximum likelihood model comes at the expense of emission that had previously been assigned to the Perseus arm. Instead of a increased emissivity in the Perseus arm, relative to the interarm and beyond Perseus arm regions, we now find a monotonic decrease of emissivity from the solar neighborhood. That the cosmic-ray density may be correlated with the surface density of interstellar gas on the scale of spiral arms has been conjectured theoretically (e.g., Parker 1977) but not measured directly before. (That cosmic-rays may be produced in spiral arms is not surprising, but direct observational evidence for the continued coupling to the arms once the cosmic rays have had the opportunity to diffuse has been lacking.) The Perseus arm in Monoceros has a large surface density of gas and in principle is one of the best regions for testing this conjecture, especially with the sensitivity and low background of the EGRET observations. In an earlier, complementary study of diffuse emission in the Cepheus region, in the second Galactic quadrant, the Perseus arm is much closer to the local arm and no secondary maximum of cosmic-ray density could be resolved (Digel et al. 1996).

The finding that the cosmic-ray density does not appear to be correlated with spiral arms, at least on the scale of the arms, should inform models of the diffuse gamma-ray emission for the entire Milky Way (e.g., Hunter et al. 1997). For example, the widely-used model of Hunter et al. explicitly assumes cosmic-ray–gas coupling to derive predicted diffuse gamma-ray intensities. Perhaps not surprisingly, this model over-predicts the gamma-ray intensities in the Monoceros region.

Another finding deserving emphasis is that the molecular mass calibration ratio $N(H_2)/W_{CO}$ in Monoceros, including the Mon R2 cloud, is marginally greater than in Orion. The ratio is $(1.54 \pm 0.27) \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$ in Monoceros and $(1.01 \pm 0.11) \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$ in Orion (based on the reanalysis described in a previous report). Both regions contain interstellar clouds that are relatively nearby, but the clouds in Monoceros are approximately 300 parsecs more distant. The larger ratio in Monoceros is consistent with the expectation from the general decline of the metallicity of the interstellar medium and of the temperatures of interstellar clouds with distance from the Galactic center.

In a search for significant variations of cosmic-ray density or $N(H_2)/W_{CO}$ ratio in individual interstellar clouds in Monoceros, total residual (observed minis model) fluxes from Mon R2, CMa OB1 and Maddalena's Cloud were calculated for $E > 100$ MeV. No statistically significant residuals were found; therefore, within the sensitivity of the observations, no variations are indicated. For Maddalena's cloud, a well-known large molecular cloud with unusually little star formation activity, the limits are especially poor, though, as the cloud is quite faint in gamma rays.

Details about the findings described above are presented in Digel et al. (1997) and Digel et al. (1998) and in publications in preparation.

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