GLOBAL STUDIES OF MOLECULAR CLOUDS IN THE GALAXY, THE MAGELLANIC CLOUD AND M31

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Final Report

Over the past five years we have used our extensive CO surveys of the Galaxy and M31 in conjunction with spacecraft observations to address central problems in galactic structure and the astrophysics of molecular clouds. These problems included the nature of the molecular ring and its relation to the spiral arms and central bar, the cosmic ray distribution, the origin of the diffuse X-ray background, the distribution and properties of x-ray sources and supernova remnants, and the Galactic stellar mass distribution. For many of these problems, the nearby spiral M31 provided an important complementary perspective.

Our CO surveys of GMCs were crucial for interpreting Galactic continuum surveys from satellites such as GRO, ROSAT, IRAS, and COBE because they provided the missing dimension of velocity or kinematic distance. GMCs are a well-defined and widespread population of objects whose velocities we could readily measure throughout the Galaxy. Through various emission and absorption mechanisms involving their gas, dust, or associated Population I objects, GMCs modulate the galactic emission in virtually every major wavelength band. Furthermore, the visibility of GMCs at so many wavelengths provided various methods of resolving the kinematic distance ambiguity for these objects in the inner Galaxy.

Summaries of our accomplishments in each of the major wavelength bands discussed in our original proposal are given below.

Gamma Rays

The high-energy diffuse Galactic gamma-rays surveyed by SAS-2, COS-B, and GRO are mainly produced by collisions between cosmic ray protons and interstellar gas nuclei—mainly the protons of H or H_2. Since the Galactic plane is quite transparent to high energy photons, the high energy gamma-rays trace without bias the mass distribution in both atomic and molecular clouds, with the molecular clouds—especially the GMC's—standing out as extended gamma-ray sources owing to their high density and large size. The Galactic disk seen by the gamma-ray surveys is thus the sum of the disk observed in H I and CO, and this is the reason why an intercomparison of the three types of surveys has been so fundamental and instructive.

Working closely with the Compton Observatory EGRET instrument team at NASA Goddard Space Flight Center, we developed a detailed model for the Galactic diffuse gamma-ray emission which incorporated the most recent results by our group and others on the Galactic gas distribution, and allows for coupling between cosmic rays and matter. We first compared the model with existing data from the COS-B and SAS-2 satellites (Bertsch et al. 1993) and later with the full GRO survey (Hunter et al. 1997). This work provided the best calibration of the CO-to-H_2 mass conversion factor on a Galactic scale, and demonstrated that the cosmic rays are loosely coupled with the gas on the scale of spiral arms. This coupling suggests that a dynamic balance exists between the cosmic rays, the magnetic fields, and the gravitational attraction of interstellar matter. The model has since proved extremely valuable for the identification of EGRET point sources.

We also studied the gamma ray emission from a number of individual GMCs that were sufficiently massive and close to be detected and resolved by GRO. Ophiuchus was chosen for study first because of its good exposure in existing EGRET data (owing to its proximity to the well-observed Galactic center). We were able to determine, for the first time, that the CO-to-H_2 mass conversion factor does not vary spatially across the cloud, nor with gamma ray energy. In addition, we discovered that a significant fraction of the diffuse gamma ray flux from the main cloud in Ophiuchus is actually emitted by a background source, the quasar PKS 1622-253, disproving previous claims of a cosmic ray enhancement in Ophiuchus (Hunter et al. 1994).

We subsequently extended this sort of analysis both to the more distant and massive Orion molecular complex (Digel, Mukherjee, & Hunter, 1995), and to regions in the second (Digel et al. 1995) and third (Digel et al. 1997) Galactic quadrants containing clouds in both the Local and Perseus spiral arms. The Orion cloud was of particular importance because it is the nearest Galactic GMC. Since GMCs are the main sites of massive star formation, with supernova remnants and H II regions, they are best suited to the study of cosmic-ray production, propagation, and interaction in molecular clouds. We determined that the CO-to-H_2 mass conversion factor in Orion is ~40% less that the commonly adopted Galactic average, and the high-energy cosmic-ray density ~30% less than what we derived by the same method in Ophiuchus—a surprising result given the small separation of these clouds (~0.6 kpc) compared with the kiloparsec-scales over which the cosmic-ray density is expected to vary.

In the outer Galaxy we found significant gradients in both the CO-to-H_2 mass conversion factor and the cosmic-ray density from the Solar circle to the Perseus Arm. We also found that the gamma ray emissivity of the gas is significantly less in the interarm than in the local or Perseus arms. This finding supports models of Galactic cosmic rays which assume that cosmic rays are coupled to interstellar gas. Our measurement of the cosmic-ray density in the Perseus Arm allowed us to put a firm upper limit on the amount of cold H_2 there not traced by CO; it is at most one-third the amount of atomic hydrogen, and about 10 times less than that claimed to exist in the outer Galaxy by Lequeux, Allen, & Guilloteau (1993).

X-Rays

The kinematic information inherent in the CO spectral line data provides a powerful method of locating X-ray emitting gas and discrete X-ray sources along the line of sight, since only clouds lying in front of the X-rays will produce strong absorption. Much of our research in the X-ray band was devoted to determining distances in this manner. Using ROSAT data, we identified a new Galactic supernova remnant in Sagittarius and were able to determine the distance to the remnant fairly accurately (Seward et al. 1995): a CO cloud with a velocity of 18 km s^{-1} and a kinematic distance of 2 kpc is clearly seen in X-ray absorption again the remnant, but another at 52 km s^{-1} and a distance of 4.7 kpc shows no absorption.

We applied our detailed knowledge of the inner-Galaxy gas distribution to obtain the first reliable distance estimate for a soft gamma ray repeater (SGR 1806-20), one of a class of high-energy transients which present recurrent outbursts with shorter and softer gamma ray spectrum than gamma ray bursts (Corbel et al. 1996). The SGR has an X-ray counterpart and is apparently associated with the bright H II region W31 and a massive molecular cloud ~14 kpc away. This distance estimate is important not only for constraining SGR models, but also for demonstrating the feasibility of determining distances for X-ray sources from their spectra: in the case of the X-ray counterpart to SGR 1806-20, the total visual extinction derived from its spectrum (30 mag) is in good agreement with that derived from the foreground molecular and atomic gas.

We also investigated the nature and origin of the 0.5-2.0 keV X-ray background by studying X-ray shadows cast by dense molecular clouds deep in the inner Galaxy. A mosaic of seven ROSAT PSPC pointed observations toward Galactic longitude 10° (Park, Dame, & Finley 1997) and a similar mosaic of five observations toward longitude 25° (Park, Dame, & Finley 1998) both revealed deep X-ray shadows cast by molecular clouds with kinematic distances in the range 2-4 kpc. Given the short mean free path of X-rays in the 0.75 keV band in the Galactic plane, the large percentage of the observed flux that must originate beyond the molecular clouds indicated a strong enhancement in the distribution of X-ray emitting gas in the Galactic center region, possibly associated with a Galactic X-ray bulge.

Near Infrared

Working with S. Kent (Fermilab) and G. Fazio (CfA), we developed a model of the Galactic emission in the near infrared that accounts quantitatively for the detailed anticorrelation seen between near infrared and CO along the Galactic plane in the first quadrant (Kent, Dame, & Fazio 1992). We used this model to determine the CO-to-H_2 conversion factor in the inner Galaxy, and considered the implications of the model for the structure of the inner Galaxy (Dame 1993).

We also analyzed the near-infrared map of the Galactic plane obtain by the DIRBE instrument aboard the COBE satellite. We showed that this map agrees extremely well with the one obtained previously by the IRT instrument and used for all of our pervious near-infrared analysis; this agreement was an important and reassuring result given the background problems that plagued the IRT instrument. The tight anticorrelation which we found in the first Galactic quadrant between our CO map and the IRT map is at least as tight, and perhaps more so, between CO and the more sensitive and higher angular resolution DIRBE map. Rather surprisingly, we found that the CO and near-infrared are less tightly anticorrelated in the fourth Galactic quadrant than in the first quadrant. Our modeling suggested that this is because the near-infrared disk is somewhat dimmer in the fourth quadrant, and there are fewer foreground GMCs. Both these results are consistent with the inner Galaxy bar proposed by Blitz and Spergel (1991).

Far Infrared

We made significant progress in calibrating CO as a tracer of molecular mass in the nearby galaxy M31 using a CO survey now underway with the array detector on the University of Massachusetts 14-meter telescope. We have surveyed about half of the inner disk of M31 with the U. Mass. telescope. These observations revealed several long and well defined spiral arms in M31 which contain molecular complexes that are remarkably similar in size and CO intensity to those in the Milky Way at similar galactic radii. This result implies that the overall faintness of M31 in CO compared with the Milky Way is not due to a systematic difference in the CO-to-molecular mass conversion factor but simply to a low overall gas density at radii corresponding to the Milky Way's molecular ring.

We also carried out a study of the infrared emission from the conspicuous complex of dark nebulae in Chamaeleon (Boulanger et al. 1997). Our CO observations were combined with IRAS, extinction, and H I data to study the distribution of interstellar matter in the complex. For the complex as a whole and for its largest clouds, masses computed from the far infrared emission were found to roughly agree with those derived from the CO survey using the standard Galactic value of the CO-to-H_2 conversion factor. However, among the smaller clouds the ratio between H_2 masses derived from CO and IRAS data varied by up to a factor of 10. The molecular emission was observed to be primarily associated with the 100 micron emission characterized by cold IRAS colors (low 60/100 micron flux ratio and no 12 or 25 micron emission) while the 100 micron emission with warm IRAS colors was poorly traced by CO emission.

We also studied the molecular gas associated with the infrared cirrus at high Galactic latitudes. D. Hartmann, in collaboration with L. Magnani, completed an unbiased CO survey with the CfA telescope of the entire sky accessible from Cambridge and more than 30° from the Galactic plane (Hartmann, Magnani, & Thaddeus 1997). Observations were made on a locally Cartesian 1° grid to a 3-sigma sensitivity of 0.3 K. A key objective of this work was to determine the filling factor of molecular gas at high Galactic latitudes, a measurement which is directly relevant to several important discoveries and issues raised by the IRAS and ROSAT missions. With the exception of four fairly significant aggregations of clouds (the Polaris Flare, Ursa Major, Draco, and L134), and a handful of isolated cloudlets, the Northern Galactic hemisphere was found to be largely free of molecular gas, with a filling factor of only 0.0036.

We also used the IRAS and COBE far infrared surveys in conjunction with the new Leiden-Dwingloo 21 cm survey in order to identify regions on the sky for which the infrared emission is brighter than expected from the known amount of atomic gas. We found that such "infrared-excesses" are an excellent indicator of the presence of molecular gas, and they lead us to discover about a dozen new molecular clouds in the Galactic latitude range $|b| = 10°–30°$. We have found that using the COBE/DIRBE bands at 140 and 240 microns to correct the IRAS 100 micron intensity to a constant dust temperature leads to quantitatively better predictions of H_2 column density than the 100 micron intensity alone.

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