Chapter 6

How are we to Understand the Large Scale Structure of the ISM?

WHAT DO GAMMA RAYS TELL US ABOUT THE ISM? NEW INSIGHT FROM THE COMPTON OBSERVATORY

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Abstract. Gamma-ray astronomy has become a rich field of research and matured significantly since the launch of NASA's Compton Gamma Ray Observatory in April 1991. Studies of the diffuse γ-ray emission of the Galaxy can now be performed in far more detail and extended into the MeV regime, including both continuum and line emission. These studies provide unique insight into various aspects of the interstellar medium, in particular of the cosmic-ray component. This paper gives a brief review on the diffuse Galactic γ-ray emission and summarizes early results and prospects from the Compton Observatory.

1. Introduction

The diffuse continuum γ-ray emission of the Milky Way is a unique tracer of cosmic rays. The observed radiation at energies above ~50 MeV, well studied with the SAS-2 and COS-B satellites, seems indeed largely of diffuse origin. The basic findings are summarized in Section 2. The EGRET telescope aboard the Compton Observatory (Thompson et al. 1993) enables now more detailed studies, but these are largely in progress. A preliminary comparison with the COS-B observations is presented here. At low energies ($\lesssim$ 50 MeV) an important contribution from unresolved point sources cannot be excluded. The COMPTEL telescope on board the Compton Observatory (Schönfelder et al. 1993) provides for the first time extensive imaging possibilities in the 1–30 MeV range. First findings on the diffuse

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continuum emission at these energies are discussed in Section 3. With an energy resolution of 5–8%, COMPTEL is capable of imaging in narrow energy bands, which has already proved to be of great value for studies of nuclear deexcitation γ-ray lines (Section 4). These lines either originate from nuclei of which the excited levels are populated in nuclear interactions (again providing unique information on cosmic rays) or from long lived radionuclei produced in various nucleosynthesis processes. Below ~1 MeV, in the hard X-ray / low-energy γ-ray regime, very little is known about any diffuse emission from the Galactic disk (see e.g. Gehrels & Tueller 1993 and Ramaty & Skibo 1993). This paper is limited to energies above 1 MeV.

2. High-energy gamma-ray continuum — EGRET vs COS-B

The diffuse continuum γ-ray emission of the Galaxy largely originates from interactions of cosmic-ray (CR) particles with the interstellar gas. Beyond about 100 MeV, CR protons and α-particles with energies of typically 1–10 GeV play a dominant role through the decay of π°-mesons that originate from nuclear interactions. At lower γ-ray energies, the diffuse continuum emission is largely bremsstrahlung from low-energy CR electrons (typically 1–100 MeV). Away from the gaseous disk, a third emission component may be important, namely inverse-Compton radiation, which involves the scattering of high-energy electrons ($>$ 10 GeV) on low-energy photons (mainly optical and infrared photons and the 3 K background radiation).

A comprehensive review on high-energy γ-ray studies of the Milky Way using SAS-2 and COS-B observations is given by Bloemen (1989). Recent updates are presented by Strong (1994) and Bloemen (1993).

Several γ-ray studies have been aimed at determining the radial distribution of cosmic rays in the Galaxy. This requires independent information on the distribution of the target gas particles with which the cosmic rays interact. The results from the latest and most robust analyses (Bloemen et al. 1986; Strong et al. 1988) were obtained from correlation studies with HI and CO surveys, using the velocity information as a distance indicator. Only a weak Galactocentric gradient for the relevant CR particles (mainly protons) was found. Since all potential CR sources show a much steeper radial fall-off, a large CR halo seems required to explain the weak gradient. This is hard to reconcile with CR measurements near Earth, which indicate an effective CR scale height in the solar vicinity of $\lesssim 3$ kpc (Webber et al. 1992, Bloemen et al. 1993). The lack of a strong CR gradient indicates that such a 'small' scale height can only be representative for the Galaxy as a whole if the CR source distribution has a weak gradient as well. On the other hand, the CR gradient may actually be underestimated due to hidden gas in the outer Galaxy (Lequeux, Allen, Guilloteau 1994).

Instead of adopting a CR distribution with a radial variation only, Bertsch et al. (1993) have considered a model that assumes cosmic rays to be preferentially located in regions of high gas density, based on the argument that the weight of the matter ties the magnetic fields and hence the cosmic rays to these regions (Bignami and Fichtel 1974; Fichtel and Kniffen 1984). This *coupling model* and the *gradient model* (as discussed above) appear to describe the γ-ray data equally well. This is basically due to the fact that the radial CR distribution in the gradient model (beyond a few kpc from the Galactic center) is similar to the radial distribution of the total gas surface density when smoothed over a few kpc (at least when the Columbia/CfA CO survey and the radial-unfolding method of Bronfman et al. 1988 are used). If the density of (GeV) cosmic rays and the matter density are correlated, it is indeed most realistic that this occurs on scales of a few kpc (also used by Bertsch et al.), because this is the characteristic CR diffusion path length. Melisse and Bloemen (1990) have shown that the gradient model fits the γ-ray data much better than a model in which CR and gas density are correlated on small scales of typically 100 pc, which appears to be mainly due to the small scale height of the γ-ray emitting disk inherent to this coupling model. This result is probably the most direct evidence from γ-ray astronomy for the existence of a (flat) halo distribution of GeV CR protons and confirms similar conclusions from radio synchrotron data for CR electrons (e.g. Baldwin 1976, Beuermann et al. 1985).

If independent information on the CR distribution throughout the Galaxy would be available, then γ-ray observations could be used as a tracer of the total gas column density. For some studies, the CR density is sufficiently constrained to derive meaningful information on interstellar gas components that is otherwise hard to obtain. This holds for the molecular gas and the extended warm ionized medium (the so called Reynolds layer). Valuable information on the CO-to-H_2 calibration factor has thus been obtained for the Galaxy at large (see e.g. reviews by Wolfendale 1988 and Bloemen 1989) and for regions that are of particular interest, such as the Galactic center (Blitz et al. 1985) and the Orion complex (Bloemen et al. 1984). Regarding the ionized medium (see Reynolds 1993 and references therein), it is interesting that almost half of the observed γ-ray emission at medium latitudes ($5^\circ \lesssim |b| \lesssim 20^\circ$) in the general direction of the inner Galaxy cannot be explained by CR-matter interactions if only atomic and molecular gas are involved. Although inverse-Compton emission can explain part of the excess, a significant fraction should probably be ascribed to the ionized gas which was not included in the γ-ray modeling (provided that this medium does not extend far beyond the solar circle).

Given the higher sensitivity, higher angular resolution, and lower instrumental background of the EGRET observations, the analyses previously

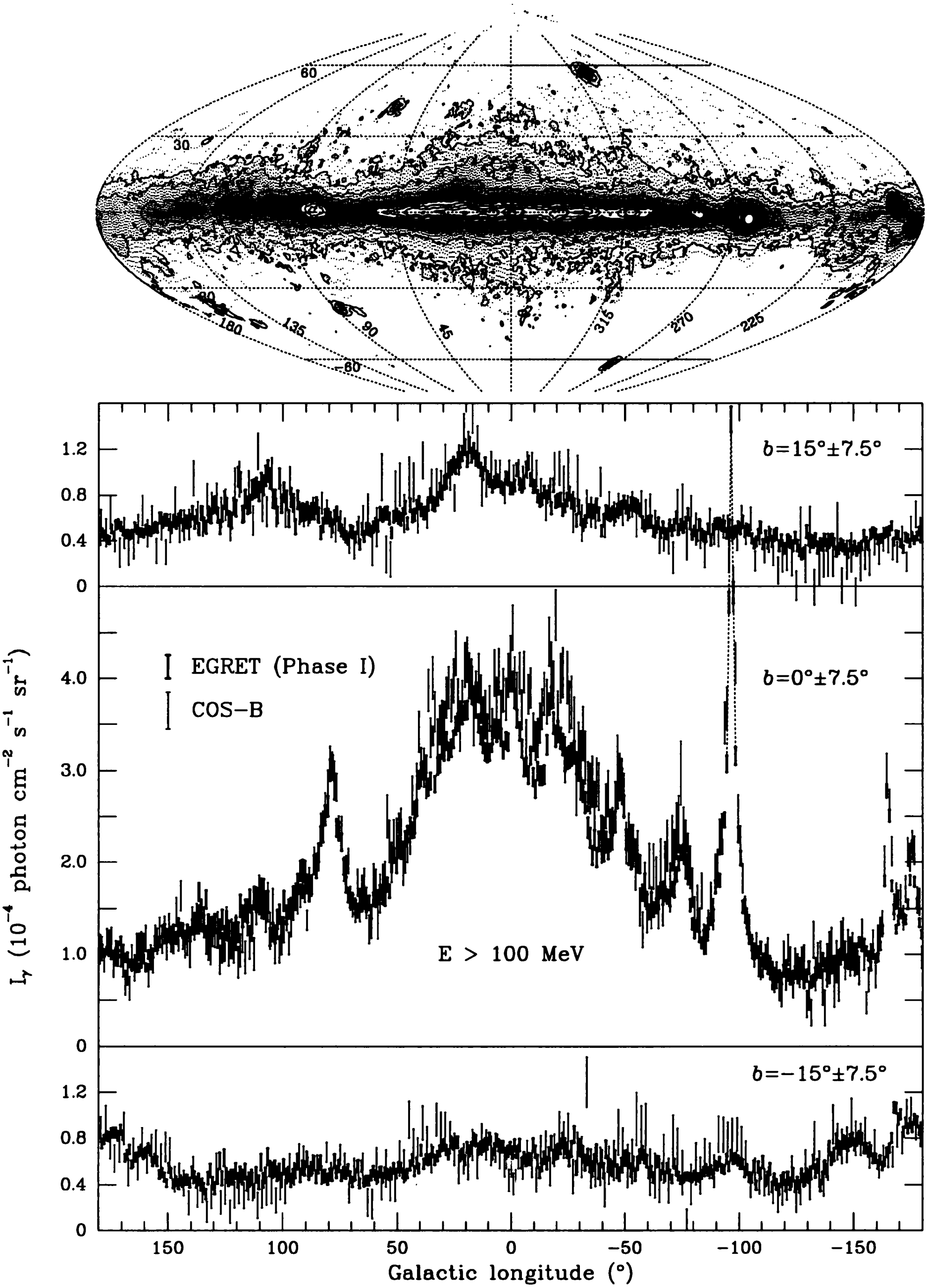

Figure 1. *Top:* Preliminary EGRET full-sky image (> 100 MeV) derived from a combination of all observations obtained during the first 18 months of the Compton Observatory mission (archival data). *Bottom:* Comparison of EGRET (archival data) and COS-B longitude profiles (> 100 MeV) for 15° wide latitude bands centered at $b = -15°$, $0°$, and $+15°$. An instrumental (on-axis) background level of 7×10^{-5} photon cm^{-2} s^{-1} sr^{-1} has been subtracted from the COS-B intensities.

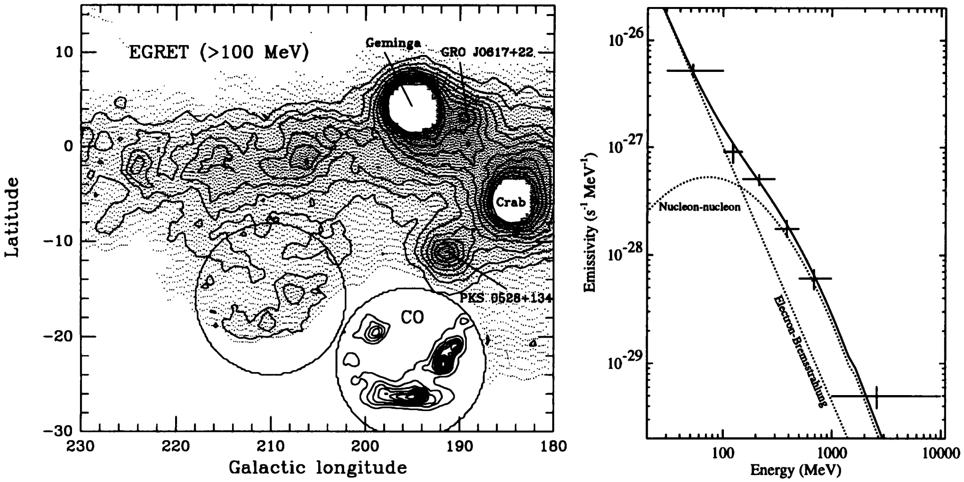

Figure 2. *Left:* EGRET image (> 100 MeV, archival data) of the Galactic anti-center, including the Orion complex (circle). Contour levels start at 8×10^{-5} photon cm^{-2} s^{-1} sr^{-1} with steps of 1.5×10^{-5}. The inset shows the Columbia CO observations. *Right:* EGRET spectrum of the Orion complex (Digel et al. 1995).

applied to the COS-B data can now be performed with higher accuracy and extended to small-scale regions and narrower energy bands. Very few results are available yet, but Figures 1 and 2 may illustrate what level of accuracy can be achieved with the EGRET observations. Figure 1 shows a comparison of the COS-B data and archival EGRET data (> 100 MeV). Since the EGRET observations are basically free of any instrumental background, whereas the COS-B observations are not, an instrumental (on-axis) background level of 7×10^{-5} photon cm^{-2} s^{-1} sr^{-1} (which appeared to be an optimum choice) was subtracted from the COS-B intensities. Long-term background variations during the COS-B mission were already accounted for in combining the individual observations — see Strong et al. 1987. Figure 1 shows that the EGRET and COS-B observations appear to be in good agreement, although the EGRET intensities seem to be systematically about 10% lower in the central radian of the Galactic disk. It should be emphasized, however, that the EGRET observations used here are considered to be preliminary. The level of detail that can be achieved with the EGRET observations is further illustrated in Figure 2, which shows a blow-up of the Galactic anti-center region, including the Orion region, together with a spectrum of the Orion complex (from Digel et al. 1995). Note that Figures 1 and 2 are based on data from the first observational phase only (about 18 months), so the statistical accuracy will significantly improve when further observations are added.

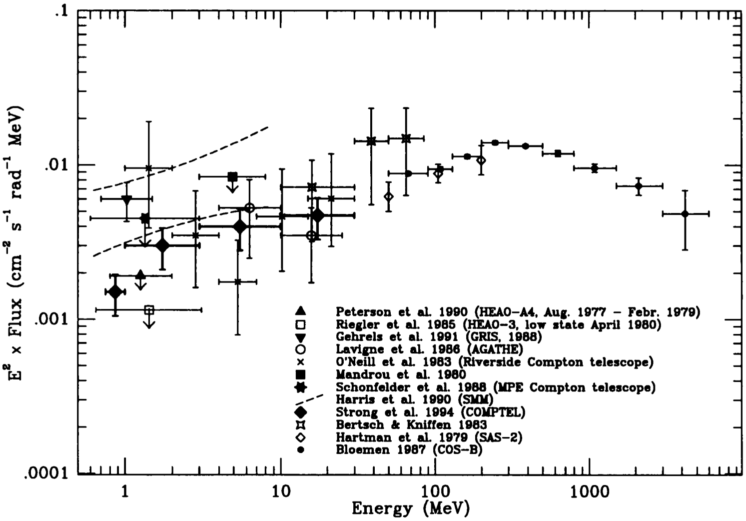

Figure 3. A compilation of flux estimates for the inner Galaxy, multiplied by E^2. An E^{-2} spectrum was assumed to calculate effective energies. The published fluxes from HEAO-3 and GRIS were converted to flux-per-radian by dividing by the FWHM of the instrument field of view. The references can be found in Bloemen et al. (1994a). The COMPTEL data points are from Strong et al. (1994).

3. Low-energy gamma-ray continuum — first COMPTEL results

For γ-ray energies < 50 MeV, our knowledge was very limited prior to COMPTEL because observations had mainly been made with non-imaging instruments with fields of view of typically tens of degrees. Figure 3 shows a compilation of flux estimates for the central radian of the Galactic disk. Preliminary broad-band images of the Milky Way obtained with COMPTEL (Bloemen et al. 1994a, Strong et al. 1994) show a structured ridge of emission along the Galactic equator (the integrated fluxes from the central radian are included in Figure 3). Starting from the assumption that the observed emission is of diffuse origin and due to electron bremsstrahlung, Strong et al. (1994) fitted a model based on HI and CO surveys and derived unique information on the low-energy CR electron spectrum ($\lesssim 100$ MeV), as shown in Figure 4. It should be emphasized, however, that the observed emission and model show distinct differences (Bloemen et al. 1994a). This may be due to an important contribution from unresolved point sources, but may also result from a very inhomogeneous distribution of low-energy CR electrons, which is largely determined by the distribution of the CR sources and the characteristics of the ambient interstellar medium. A closely related and very interesting preliminary finding from the analysis by Strong et al. is the indication for an energy dependence of the relative contribution from

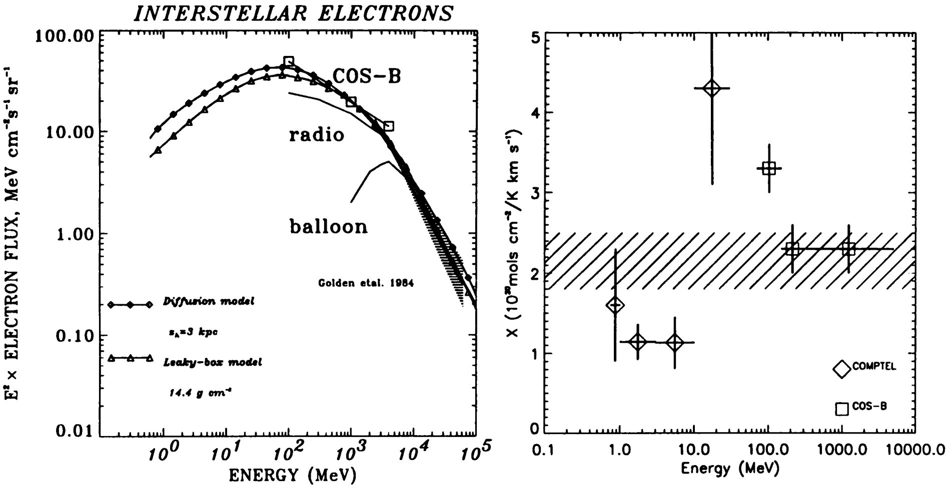

Figure 4. *Left:* Interstellar electron spectrum, illustrating the unique information that is provided by COMPTEL at low energies ($\lesssim$ 100 MeV). *Right:* Values of the "CO-to-H_2 conversion factor" derived from COMPTEL and COS-B studies, showing evidence for an energy dependence of the relative contribution from molecular clouds to the total γ-ray emission from the disk, with a peak contribution at 10-100 MeV. *From Strong et al. 1994.*

molecular clouds to the total γ-ray emission from the disk, with a peak contribution at 10-100 MeV (Figure 4). If confirmed in further analyses, this may have important implications for our understanding of the acceleration and propagation of CR electrons in/near molecular clouds.

4. Gamma-ray line emission

COMPTEL has good potentials for studies of de-excitation lines, which result from nuclear interactions and radioactive nucleosynthesis products (of which the lines from ^{26}Al and ^{44}Ti are of main interest for ISM studies).

Until recently, γ-ray lines resulting from accelerated particle interactions had been observed only from solar flares, namely the lines of ^{12}C at 4.44 MeV, of ^{16}O at 6.13 MeV, and of ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S and ^{56}Fe in the 1–2 MeV range. COMPTEL has now detected intense emission in the 3–7 MeV range from the Orion complex, which was identified with the ^{12}C and ^{16}O de-excitation lines at 4.44 MeV and 6.13 MeV (Bloemen et al. 1994b), as illustrated in Figure 5. In view of early theoretical predictions (Meneguzzi and Reeves 1975, Ramaty et al. 1979), this discovery came as a pleasant surprise, the observed flux being much larger than anticipated. So far, Orion has revealed only upper limits in the 1–3 MeV range.

Bykov and Bloemen (1994) have shown that these results may find a novel explanation in the strong overabundance of oxygen in the supernova

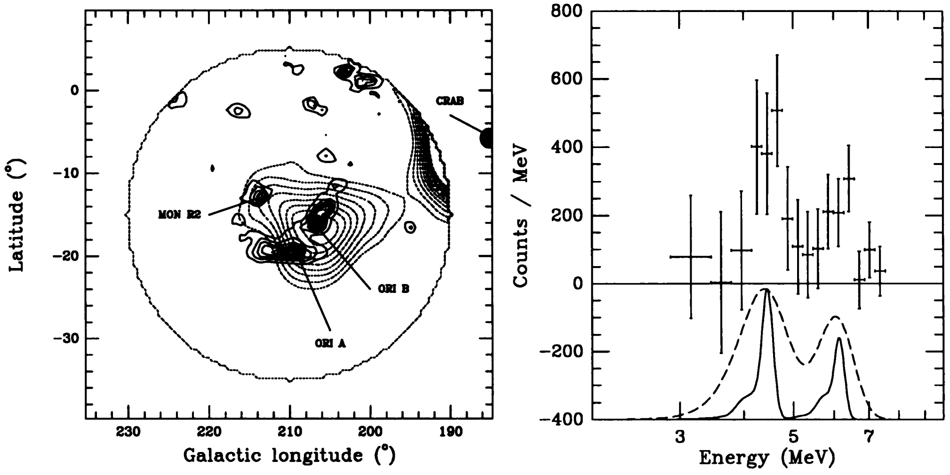

Figure 5. COMPTEL map (dotted contours) and spectrum of the Orion Complex, showing evidence for 3–7 MeV emission that can be attributed to the 4.44 MeV and 6.13 MeV de-excitation lines of carbon and oxygen following energetic nuclear interactions. The Columbia CO observations are superimposed in the map for comparison (solid contours). The excess in the upper right originates from the Crab pulsar. *From Bloemen et al. 1994b.*

ejecta from massive stars (Weaver and Woosley 1993, Woosley et al. 1993), in combination with the efficient acceleration of low-energy CR nuclei in regions with strong stellar winds and multiple supernova explosions (Bykov and Toptygin 1990, Bykov and Fleishman 1992). In this scenario, the γ-ray lines originate from energetic nuclei that are extracted from the enriched hot medium in regions of massive star formation and bombarding the ambient dense gas in clouds and shells. The width of nuclear interaction lines provides crucial information on the processes that occur, but the available COMPTEL observations of Orion are inconclusive. Detailed model spectra of the Orion region are presented by Ramaty et al. (1994). The study of nuclear interaction lines has broad applications: it provides direct insight into particle acceleration (in fact the very origin of cosmic rays), into the composition and enrichment of the ISM in regions of massive star formation (with important implications for nucleosynthesis studies), and into the role of cosmic rays in the ISM in general (such as CR ionization and heating).

The 1.809 MeV line emission from ^{26}Al ($\tau \simeq 10^6$ years) has now for the first time been mapped along the Milky Way by COMPTEL (Diehl et al. 1994, 1995a). Although the structured appearance of the observed emission (Figure 6) clearly excludes a dominant contribution from novae (Diehl et al. 1994, 1995a), alternative scenarios that have been proposed could so far not be distinguished. These scenarios largely invoke massive stars, as reviewed

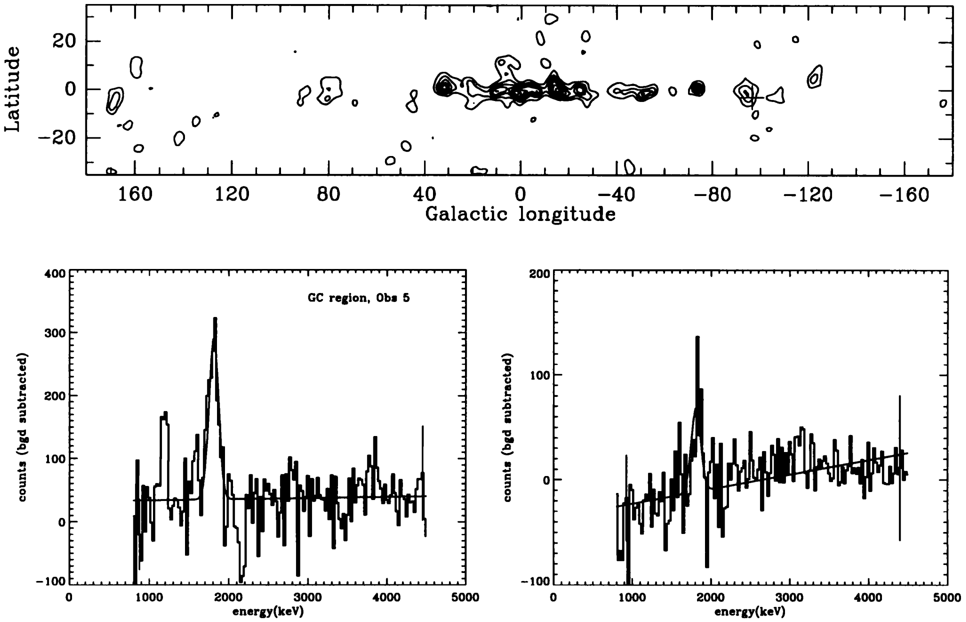

Figure 6. *Top:* COMPTEL map of the Galactic ^{26}Al 1.809 MeV emission, showing evidence for localized emission regions along the Milky Way (including a possible detection of the Vela supernova remnant at $\ell \simeq -97^{\circ}$). The continuum radiation is removed using a model derived from the observed emission at adjacent energies. *Bottom:* Examples of background-subtracted counts spectra, obtained from one single observation of the inner Galaxy (left) and a combination of available observations of the Vela region (right). Typical statistical error bars are shown. *From Diehl et al. 1995ab.*

by Prantzos (1991). Apart from a possible detection of the nearby Vela supernova remnant (Diehl et al. 1994, 1995b), essentially all other localized emission regions that can be seen in Figure 6 must be due to an ensemble of sources. The intermittent nature of massive-star formation and the 1.809 MeV line, both on time scales of typically 10^6 years, may indeed explain the structured appearance of the 1.809-MeV Milky Way, but it remains to be seen which sources are prime contributors.

The 1.156 MeV line from the decay of ^{44}Ti into ^{44}Ca ($\tau \simeq 80$ years) is not only of importance for nucleosynthesis studies, but also provides an interesting possibility to search for obscured supernovae. The prime known candidate, Cas A, was already detected by COMPTEL (Iyudin et al. 1994).

Although this paper has only provided a first glance at the COMPTEL and EGRET observations of the Galactic diffuse emission, it may be clear from the above that γ-ray studies of the ISM have great potentials. With an expected mission lifetime of 6–10 years, the Compton Observatory will provide further insight into the γ-ray sky for several years to come.

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