Assessment of Tracers of 1.8 MeV Emission

J. Knödlseder¹, R. Diehl², U. Oberlack⁵, P. von Ballmoos¹, H. Bloemen³, W. Hermsen³, A. Iyudin², J. Ryan⁴, and V. Schönfelder²

¹Centre d’Etude Spatiale des Rayonnements, CNRS/UPS, B.P. 4346, 31028 Toulouse Cedex 4, France ²Max-Planck-Institut für extraterrestrische Physik, Postfach 1603, 85740 Garching, Germany ³SRON-Utrecht, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands ⁴Space Science Center, University of New Hampshire, Durham NH 03824, U.S.A. ⁵Astrophysics Laboratory, Columbia University, New York, NY 10027, U.S.A.

ABSTRACT We examined the question of a possible correlation between 1.8 MeV emission and intensity distributions observed at other wavelengths by comparing the 1.8 MeV data to an extended set of all-sky maps, covering the entire explored wavelength range from the radio band up to high-energy gamma-rays. This analysis revealed that tracers of the old stellar population or the local interstellar medium provide only a poor description of the data. Tracers of the young stellar population considerably improve the fit. Residuals are minimized for the free-free emission map obtained by the DMR at microwave wavelengths and the 158 µm fine-structure line map of C⁺ observed by FIRAS. Within the statistics of the present data, both maps provide an overall satisfactory fit. We therefore conclude that adequate tracers of ²⁶Al sources have now been identified. Implications for ²⁶Al source types are discussed (see also Knödlseder, these proceedings).

KEYWORDS: gamma-ray lines; nucleosynthesis; massive stars; multi-wavelength analysis;

1. INTRODUCTION

The imaging telescope COMPTEL aboard the Compton Gamma-Ray Observatory (CGRO) provided the first all-sky map of the sky in the light of the 1.809 MeV γ-ray line, attributed to the radioactive decay of ²⁶Al (Oberlack et al. 1996; Knödlseder et al. these proceedings). This map shows an asymmetric emission profile along the galactic plane with peculiar features towards the direction of Cygnus, Vela, Carina and near the anticenter. It has been shown that this type of emission pattern is expected if massive stars are the dominant source of galactic ²⁶Al (e.g. Diehl et al. 1995). In order to understand the 1.8 MeV sky globally, considerable effort has been made in modelling the COMPTEL ²⁶Al data (Chen et al. 1995; Diehl et al. 1995, 1996, 1997; Knödlseder et al. 1996a). Since imaging results suggest that massive stars are among the most plausible sources of ²⁶Al, the modelling focused primarily on finding optimum tracers of massive stars in the Galaxy. As such, molecular gas models, based on the CO survey of Dame et al. (1987), and far-
infrared maps, obtained by the DIRBE telescope aboard the Cosmic Background Explorer (COBE) provide reasonable first order descriptions of the data, but significant residual emission remains towards Cygnus, Vela, and Carina when the maps are fitted to the data. Additionally, the intensity contrasts between positive and negative longitudes or the inner and outer Galaxy for these maps differ from those of the 1.8 MeV data.

Advancing the search for a satisfactory tracer of 1.809 MeV emission, we extend in this paper our set of possible tracers to an extensive database of all-sky maps, covering the entire explored wavelength range from the $\lambda \sim 10$ m radio band up to the energetic $E > 100$ MeV $\gamma$-ray photons. Since the Galaxy is transparent to $\gamma$-rays, each all-sky map of our database represents a specific hypothesis about the galactic distribution of $^{26}$Al. Hence, the results of the comparison of these maps to COMPTEL 1.8 MeV data may be interpreted in terms of these hypotheses, providing physical insight into the origin of galactic $^{26}$Al. The database and preparation of the all-sky maps is discussed in detail in a separate paper by Knödlseder et al. (1998) which gives also more details on the analysis methods used for the study. Here we update sky maps for the FIRAS far-infrared line emission at 158 $\mu$m (C$^+$) and 205 $\mu$m (N$^+$) which have become available recently (Pass 4 data products).

2. TRACER MAP COMPARISON

For the comparison, the 31 all-sky maps of the database have been convolved with the 3-dimensional COMPTEL point spread function to provide model distributions of 1.8 MeV source counts in the COMPTEL imaging data space. These source models are then fitted along with a model for the instrumental background contribution to COMPTEL data in the energy interval 1.7 – 1.9 MeV. The background model is based on the event distribution in adjacent energy intervals and has been proven to suppress most of the continuum emission in the data analysis (Knödlseder et al. 1996b). In order to reduce systematic uncertainties in the analysis the $\bar{\phi}$ distribution of the background model is adjusted by the fit (for an analysis using an alternative background model see Bloemen et al., these proceedings). After fitting, a residual analysis is performed for each map using the `software collimation’ technique (Diehl et al. 1993) and the maximum likelihood ratio test (de Boer et al. 1992). The first method provides longitude profiles of the residual emission in the raw data space while the second method results in significance maps of residual point source emission. It turned out that this residual analysis is less sensitive to systematic uncertainties in our background modelling procedure than the likelihood analysis used previously (Knödlseder et al. 1998).

2.1 Old Stellar Population

Maps in our database which are related to the old stellar population are the HEAO-1 hard X-ray map and the DIRBE near infrared maps at $\lambda \leq 4.9$ $\mu$m. The X-
FIGURE 1. Software collimator longitude scans for some of the all-sky maps. The histograms show the background subtracted 1.8 MeV counts, the solid lines show the corresponding all-sky map profiles convolved into the COMPTEL imaging data space. The reduced $\chi^2$ values for the residual longitude profiles are quoted as measures of the correlation between the 1.8 MeV and the all-sky map longitude profiles.
ray map traces the population of X-ray binaries which shows a strong concentration towards the inner Galaxy. The longitude profile for the HEAO-1 map (cf. Fig. 1) clearly demonstrates that this concentration is much stronger than that of 1.8 MeV emission. When fitted to the data, the hard X-ray maps leave significant 1.8 MeV residual emission in the outer disk regime. The near infrared maps, tracing the population of K and M giants, can not explain the 1.8 MeV data either (as an example the longitude profile for the DIRBE 2.2 µm map is shown in Fig. 1). Obviously, this population obeys a rather smooth and symmetric profile, in contrast to the structured and asymmetric distribution of the 1.8 MeV emission. Indeed, the population of K and M giants is usually modelled by a superposition of a probably bar-shaped bulge and an exponential disk with radial scale length between 1 – 3 kpc (Wainscoat et al. 1992), while fitting geometrical models to COMPTEL 1.8 MeV data suggests a larger radial scale length of 4.5 ±0.4 kpc for the galactic distribution of 26Al and no evidence for a galactic bulge component (Diehl et al. 1998).

2.2 Young Stellar Population

There are a number of maps in our database which are related to the massive, hence young, stellar population, although the relation may be quite convoluted. Molecular gas as measured in CO traces the raw material of star formation, hence it maps the potential for star formation throughout the Galaxy. Microwave data can be used to extract the distribution of galactic free-free emission arising from photoionization of the interstellar medium (ISM) by massive stars. Far-infrared continuum emission reveals the distribution of interstellar dust which has been shown to correlate with galactic H II regions in the galactic plane (Broadbent et al. 1989). Far-infrared line emission traces neutral and ionized gas cooling, related to massive star heating of the ISM by FUV photons. High-energy γ-rays arise from the interaction of cosmic-ray nuclei with the interstellar gas and show a distribution similar to that of CO (the high-energy γ-ray longitude profile as observed by COS-B has been often used as a template to determine the galactic 1.809 MeV flux).

Figure 1 illustrates that all these maps provide a reasonable first order description of the COMPTEL 1.8 MeV data. But most of them can not explain some peculiar features of the data, like the relative large 1.8 MeV emission in the southern hemisphere (l < 0°) or the emission peaks towards Cygnus (l ≈ 80°), Carina (l ≈ −75°), and Vela (l ≈ −90°). The only maps in the database which apparently explain all of the features of the 1.8 MeV data are the 53 GHz free-free emission map and the FIRAS 158 µm line-emission map. The first map was derived by Bennett et al. (1992) from microwave data taken by DMR aboard COBE using the different spatial and spectral morphology of the dominant emission processes at this frequency. Since the Galaxy is transparent at microwave frequencies, the map traces the distribution of ionized matter throughout the entire Galaxy. The second map was obtained using the FIRAS telescope aboard the COBE satellite. The 158 µm line arises from a fine-structure ground state transition of C+, and is considered as the dominant coolant of neutral interstellar gas (Tielens & Hollenbach 1985).
Galactic absorption is also negligible at this wavelength. Remaining weak residuals have to be studied carefully, as they may be related to systematic uncertainties in our instrumental background model. For example, significant residuals near the anticenter and towards the southern galactic pole area have been found to show no 1.8 MeV line feature in the spectral analysis (Knödlseder et al. 1998a).

The fitting procedure provides scaling factors for the tracer maps which allow to determine the ratio between 1.8 MeV intensities and free-free and 158 μm intensities, respectively. For the intensity ratio between 1.8 MeV and 53 GHz free-free emission we obtain $0.86 \pm 0.03 \text{ ph cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ K}^{-1}$ (free-free intensities are usually quoted in units of antenna temperature). The intensity ratio between 1.8 MeV and 158 μm line emission was determined to $12.0 \pm 0.4 \text{ ph erg}^{-1}$ (158 μm line intensities are usually given in units of erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$). From these ratios we determine the inner radian 1.8 MeV flux by integration over $-30^\circ < l < 30^\circ$ and $|b| < 10^\circ$, resulting in $(2.6 \pm 0.1) \times 10^{-4} \text{ ph cm}^{-2} \text{ s}^{-1}$ for both maps. This is consistent with flux determinations from image reconstruction using the same instrumental background model (Oberlack et al. 1998), but significantly smaller than the value found by Bloemen et al. (these proceedings) using a different background model. The discrepancy reflects our systematic uncertainties due to the instrumental background modelling procedure, which is still limiting our analysis accuracy.

2.3 Gould’s Belt

The local population of massive stars forms an inclined system with respect to the galactic plane, referred to as Gould’s Belt. It is dominated by a few associations, predominantly in the third and fourth quadrants of galactic longitude. Recent analysis based on Hipparcos data has revealed an age of 30 – 40 Myr for the system and distances between 400 and 600 pc to the individual members (Lindblad et al. 1997; Torra et al. 1997). It has been suggested earlier that nucleosynthesis activity of the massive stars in this system could lead to a distinct 1.8 MeV emission feature on the sky (Diehl et al. 1996, see also Diehl et al., these proceedings). Fitting of COMPTEL 1.8 MeV data using geometrical models for the Gould’s Belt population, however, showed no significant correlation (Diehl et al. 1997).

Our database contains 4 all-sky maps obtained by the TD1 satellite in the UV waveband which are dominated by local O and B stars, and which nicely delineate Gould’s Belt. Comparison of these maps to our data reveals that the bulk of 1.809 MeV emission is certainly not correlated to this structure (cf. Fig. 1).

3. DISCUSSION

Our multi-wavelength tracer map comparison clearly demonstrates that the 1.809 MeV intensity distribution does not correlate with the old stellar population. Proposed $^{26}$Al candidate sources among these objects are novae and low-mass AGB stars, and we conclude that those can be excluded as prolific sources of $^{26}$Al.
Apparently, the 1.809 MeV emission shows clearly the characteristics of a young stellar population which is an asymmetric emission profile along the galactic plane with regions of enhanced intensity due to galactic spiral structure and clustered massive star formation. It is remarkably, however, that COMPTEL 1.8 MeV data are best explained by tracers of the extreme Population I, i.e. tracers of very massive stars. The 53 GHz free-free emission map traces the distribution of the ionized interstellar medium which is dominantly ionized by UV photons of stars with initial masses above $\sim 20M_\odot$ (Knödlseder 1998b; see also Knödlseder, these proceedings). The 158 $\mu$m [C II] line has been shown to be an excellent tracer of OB star formation activity arising from the interface of H II regions and molecular clouds (Stacey et al. 1991). The excellent correlation of COMPTEL 1.8 MeV data with these two tracer maps strongly suggests that $^{26}$Al is also produced by very massive stars, making core-collapse supernovae and/or Wolf-Rayet stars the primary candidate sources. Small $^{26}$Al contributions from AGB stars or novae may well exist, but they are not required by the present data.

ACKNOWLEDGMENTS It is a pleasure to thank M. Leising for helpful discussions and comments. The COMPTEL project is supported by the German government through DARA grant 50 QV 90968, by NASA under contract NAS5-26645, and by the Netherlands Organisation for Scientific Research NWO.

REFERENCES

Bennett, C. L., Smoot, G. F., Hinshaw, G., et al. 1992, ApJ, 396, L7
Broadbent, A., Haslam, C. G. T., & Osborne, J. L. 1989, MNRAS, 237, 381
Chen, W., Gehrels, N., & Diehl, R. 1995, ApJ, 440, L57
Dame, T. M., et al. 1987, ApJ, 322, 706
de Boer, H., et al. 1992, in: Data Analysis in Astronomy - IV, ed. D. Gesù, 241 (Plenum Press)
Diehl, R., et al. 1993, A&AS, 97, 181
Diehl, R., et al. 1995a, A&A, 298, 445
Diehl, R., et al. 1996, A&AS, 120C, 321
Diehl, R., et al. 1997, in Proc. of the 4th Compton Symposium, AIP 410, 1114
Diehl, R., et al. 1999, in preparation for A&A
Knödlseder, J., et al. 1996a, A&AS, 120C, 335
Knödlseder, J., et al. 1996b, Proc. SPIE 2806, 386
Knödlseder, J., et al. 1998a, A&A, submitted
Knödlseder, J. 1998b, ApJ, in press
Lindblad, P. O., et al. 1997, ESA SP-402, 507
Oberlack, U., et al. 1996, A&AS, 120C, 311
Oberlack, U., et al. 1998, in preparation for A&A
Wainscoat, R. J., et al. 1992, ApJS, 83, 111
Stacey, G. J., et al. 1991, ApJ, 373, 423
Tielens, A. G. G. M., & Hollenbach, D. 1985, ApJ, 291, 722
Torra, J., et al. 1997, ESA SP-402, 513