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COMPTEL OBSERVATIONS OF THE 1.809 MeV GAMMA-RAY LINE FROM GALACTIC ^{26}Al

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ABSTRACT

The COMPTEL experiment on the *Compton Gamma-Ray Observatory* (*CGRO*) has been demonstrated to be capable of imaging the Galaxy within its field of view of about 1 steradian in the 1.809 MeV gamma-ray line originating from radioactive ^{26}Al. The combined data from the *CGRO* sky survey in 1991/1992 have been analyzed to provide a first map of the inner Galaxy in this gamma-ray line. The 1.809 MeV emission appears extended along the inner 70° of the Galactic plane, with a relatively sharp falloff outside this regime. Correlations with massive stars and supernova remnants as possible tracers of the candidate ^{26}Al sources are discussed.

Subject headings: Galaxy: structure — gamma rays: observations

1. INTRODUCTION

The 1.809 MeV gamma-ray line originating from the decay of radioactive ^{26}Al (1.04×10^6 years lifetime) had been predicted by Ramaty & Lingenfelter (1977) already as being observable proof of recent nucleosynthesis in the Galaxy. It was detected for the first time with the *HEAO-C* instrument (Mahoney et al. 1984). Many other measurements were taken since then, and the existence of the line was solidly established since 1985 with the *SMM* measurement. The formation of ^{26}Al takes place in nucleosynthesis sites such as novae, supernovae, and in the interior of massive stars (Nofar, Shaviv, & Starrfield 1991; Woosley 1986; Prantzos 1993; Paulus & Forestini 1991). As the Galactic distribution of these potential ^{26}Al sources can be inferred to some extent from measurements in other spectral regimes, imaging of the 1.809 MeV emission in the Galaxy is believed to provide crucial information on the nature of the source. Attempts to image the line emission have been reported by different groups: von Ballmoos, Diehl, & Schönfelder (1987; MPE's imaging Compton telescope), and Purcell et al. (1988; *SMM* analysis exploiting earth occultation). Limitations in sky exposure or instrumental capabilities of the various measurements (see review by Schönfelder & Varendorff 1990) have prevented a conclusive result, although, looking at all existing measurements, extended source models with a pronounced peak at the Galactic center appeared in best agreement with earlier observations.

The *Compton Gamma-Ray Observatory* (*CGRO*) with its four gamma-ray instruments (BATSE, OSSE, COMPTEL, EGRET) was successfully launched in 1991 April. The COMPTEL imaging telescope has adequate sensitivity (Schönfelder et al. 1993) to provide new insight into the origin of ^{26}Al. First 1.809 MeV results from this instrument have been reported by Diehl et al. (1993a, b). This paper presents first imaging results for the inner 2 radians of the Galactic plane in the 1.809 MeV gamma-ray line from a combination of all observations of the *CGRO* sky survey (1991 April–1992 November).

2. DATA ANALYSIS

With an instrumental energy resolution of 8.5% (FWHM) at 1.8 MeV and a high photopeak fraction at MeV energies, the 1.809 MeV ^{26}Al gamma-ray line can be identified already in the raw data from the COMPTEL scintillation detectors (see Fig. 1). The dominant features of the instrumental background are similar for all observations, with known strong instrumental background lines at 1.46 and 2.2 MeV. Therefore, an average of several high-latitude observations provides a good first-order background model for identification of the line (see Fig. 2).

The imaging analysis was performed in two different approaches:

1. Using the imaging information measured for each event, the signal from a narrow (~10°) region in the sky can be selected ("software collimation"). Variation of the selection criteria can be used to scan excess 1.8 MeV emission within the field of view. Background subtraction was performed from averages of several high-latitude observations, normalized to the instrumental 2.2 MeV line.
2. Using the full imaging response of the telescope, a sky image can be generated from the three-dimensional dataspace of measured scatter angle and direction. Two image-generation algorithms were applied:

> The "Maximum Entropy" method iteratively extracts a sky image using the three-dimensional PSF by maximizing the overall image entropy until satisfactory agreement with the data is achieved.
>
> The "maximum-likelihood" method scans the dataspace with the three-dimensional PSF, maximizing the likelihood for a hypothetical source at each scan position successively.

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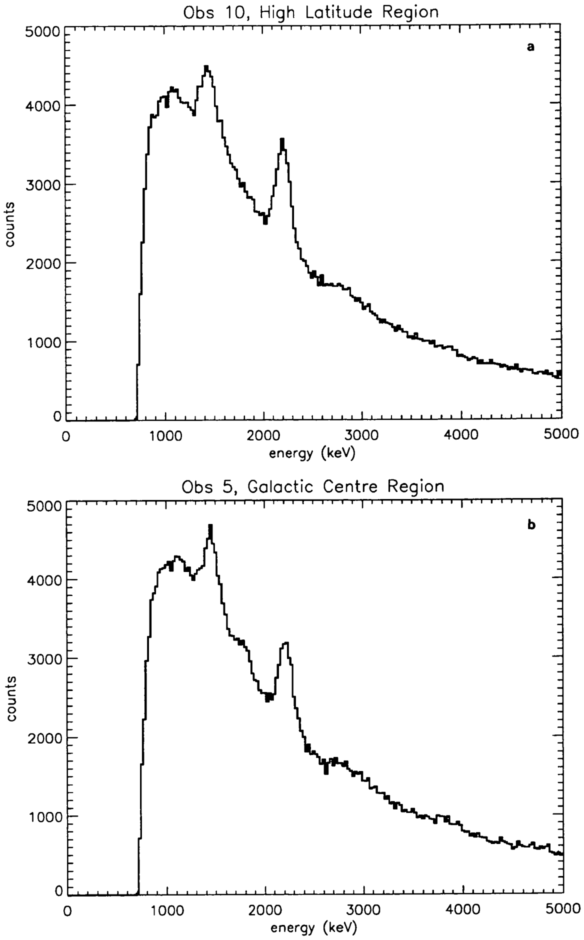

FIG. 1.—Measured energy spectra for selected regions (from two-week observations): (*a*) high-latitude observation, (pointing direction $l = 288°$, $b = 55°$); (*b*) the Galactic plane in the central region (pointed at $l = 0°$, $b = -4°$).

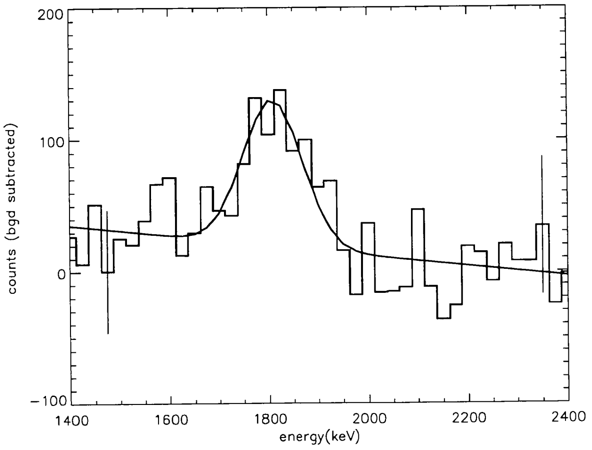

FIG. 2.—Background subtracted spectrum for the direction of the Galactic center region. A narrow selection (event circles within 3° of the Galactic center) has been applied for these data from the two-week observation no. 5. Averaged high-latitude observations were used for background subtraction.

TABLE 1

OBSERVATIONS OF THE GALACTIC PLANE AS USED IN THE IMAGING ANALYSIS

Observation Number	Name	Longitude	Latitude
2	Cyg X-1	73°3	2°51
5	Galactic center	0.07	−4.09
7.0	Cyg X-3	50.51	−8.35
7.5	G 25.0−14	24.64	−13.29
8	Vela PSR	262.99	−5.65
12	Cen A	310.76	21.97
13.0	G 25.0−14	25.04	−14.1
14	Eta Carinae	285.09	−0.76
16	Sco X-1	0.05	20.20
20	SS 433	39.69	0.75
23	Cir X-1	322.15	3.01
27	4U 1543	332.23	2.52
32	NGC 3783	284.2	22.88

Detailed background modeling in the three-dimensional data space is achieved through different methods:

Data from the same observations at adjacent energy bands are smoothed.

Data from the same observation and energy band are filtered to extract instrumental background with minimum celestial signal suppression (see Bloemen et al. 1994).

Observations from high Galactic latitudes in the same energy band are used.

The latter two background models provide a crosscheck on the 1.809 MeV line versus continuum contribution.

3. RESULTS

The Galactic plane has been observed during the *CGRO* sky survey in 23 pointings of the field of view of 1 sterad as listed in Table 1. A scan profile of excess 1.809 MeV counts in the direction of the Galactic center is shown in Figure 3, based on

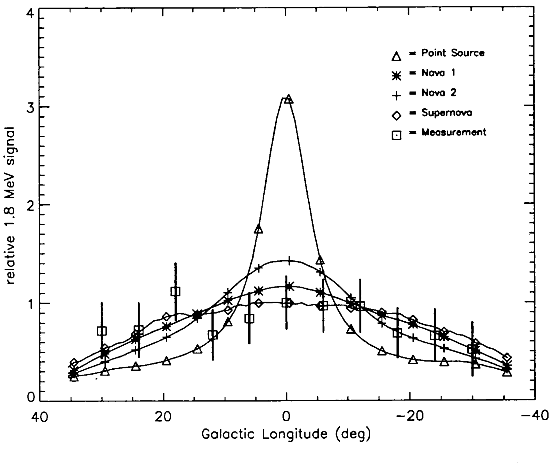

FIG. 3.—Profiles of 1.8 MeV excess counts across the region of the Galactic center. The measured profile from the 3° event circle selected data is compared to profiles derived from simulated data with the same analysis method. The models for simulations were: point source at the Galactic center, supernova-like distribution from CO measurements, and two models for nova distributions (after Leising & Clayton 1985).

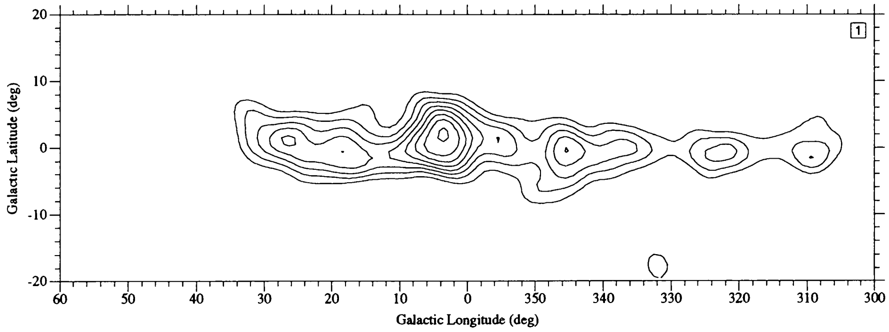

FIG. 4.—Map of likelihood ratio values for 1.8 MeV emission along the Galactic plane. All observations of the plane from the *CGRO* sky survey are combined. The peak likelihood ratio of 58 at 1°–2° corresponds to a statistical significance of greater than 7 σ for detection of 1.8 MeV emission; only contours greater than 2 σ are shown.

the three observations within the central 30 degrees. Simulations of the expected longitude profiles for a point source, supernova, and nova origin were made, using the same "software collimation" analysis to convert the simulated data into scan profiles (see Fig. 3). From this comparison, a point source alone at the Galactic center can be excluded, while all other models are compatible with these data.

Imaging analysis with the full instrument response in the three-dimensional event data space of scatter direction and scatter angle provides a more detailed map of the 1.809 MeV emission. Figure 4 presents a first maximum-likelihood map from the combined observations of the sky survey for the inner Galaxy (longitude range ± 60°). Extending the earlier results from four observations (Diehl et al. 1993b), it is evident that combining more observations results in substantial reduction of the noise in the images, confirming the basic structures of early results. The 1.809 MeV emission appears extended along the Galactic plane over a longitude range from $-35°$ to 40°; beyond this regime, the intensity drops by at least a factor of 3; the inner Galaxy emission is fairly irregular (intensity variations along the plane of $\gtrsim 50\%$) with a particularly pronounced maximum close to, but not at the Galactic center itself (the statistical probability of the maximum being the Galactic center is less than 10^{-3}, from the measured likelihood difference between the maximum of emission and 0°/0°). If all observations are combined and deconvolved with the "Maximum-Entropy" method, the 1.8 MeV image from the Galactic center region shown in Figure 5 is derived.

4. DISCUSSION

^{26}Al is believed to originate in nucleosynthesis sites such as novae, Type II supernovae, or massive stars. The conditions at these sites are required to be sufficiently hot and enriched in ^{26}Al seed nuclei such that the ^{26}Al production through e.g., the Mg-Al cycle (Woosley 1986) is effective, but on the other hand destruction of ^{26}Al due to competing neutron or proton capture reactions in such hot environments should be sufficiently small. These constraints favour nonequilibrium nuclear burning such as explosive nucleosynthesis on the surface of metal enriched O-Ne-Mg novae or in Ne-burning triggered by the shockwave of Type II supernovae (core collapse supernovae). An alternative process is core nuclear burning in massive stars with convective stellar atmospheres, where the synthesized ^{26}Al is convected away from the hot inner burning region sufficiently fast. Precise yield calculations are very difficult, as the delicate balance of nuclear reactions depends critically on temperatures and convection, hence requires calculations with adequate treatment of the hydrodynamics of the nucleosynthesis region. Therefore, the question of ^{26}Al origin can be addressed most directly from Galactic mapping of the 1.809 MeV emission, and correlation of this emission image with the Galactic distributions of the candidate sources. Due to the lifetime of ^{26}Al of $\sim 10^6$ years, integration of the individual nucleosynthesis events over this timescale is required. If the yield in an individual event is a substantial fraction of the totally observed ^{26}Al, a clumpy emission picture can be expected; on the other

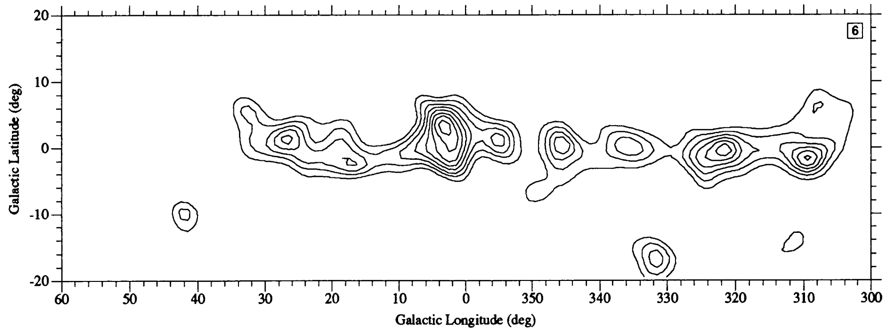

FIG. 5.—Intensity map for 1.8 MeV emission along the Galactic plane, derived from the combined plane observations of the *CGRO* sky survey. This map is the result of deconvolution with the maximum-entropy method, displaying contour levels in steps of 2×10^{-4} photons cm^{-2} sr^{-1} s^{-1} for 1° bins (with a possible systematic bias in absolute flux values from the analysis method).

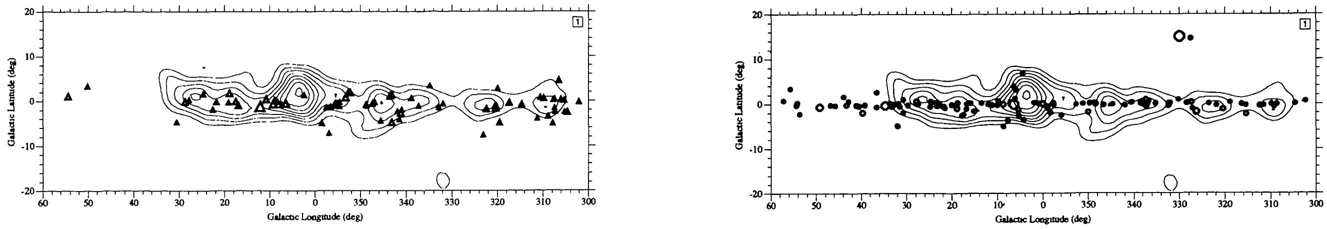

FIG. 6a

FIG. 6b

FIG. 6.—Overlays of tracers for candidate ^{26}Al sources above the likelihood map (Fig. 4). (*a*) Positions of Wolf-Rayet stars (*triangles*) (van der Hucht 1988). The symbol sizes scale with distance from the Sun. (*b*) Positions of radio supernova remnants (*circles*) (Green 1992). The symbol sizes scale with the radio flux at 1 GHz.

hand, for low individual event yields as expected for novae and massive stars in general, the emission profile should be fairly smooth.

From the COMPTEL data, smooth source models such as the classical nova model (Higdon & Fowler 1987) can be ruled out, as well as attribution of the observed ^{26}Al to a single point-like source; detailed model fitting is in progress. The overlays of our 1.8 MeV emission map for this part of the the Galaxy with Wolf-Rayet stars (cf. van der Hucht 1988, Fig. 6*a*) and with supernova remnants (cf. Green 1988, Fig. 6*b*) indicate that the Wolf Rayet stars appear to trace the 1.809 MeV emission much better than the supernova remnants as measured by their radio emission. This may be interpreted as the WR stars tracing young massive stars in the Galaxy, hence young massive stars and their supernovae (Type Ib and II) being responsible for the Galactic ^{26}Al; the supernova remnants as measured in radio emission only span a short period ($<10^5$ yr) of an ^{26}Al lifetime, and may not be a good tracer of the progenitors in general (van den Bergh 1988).

The location of the central emission peak at 1.809 MeV with its slightly positive longitude ($\sim 2°$ for COMPTEL) could provide a further test for other tracers of candidate sources: The Galactic gas distribution (measured, e.g., in CO by Dame et al. 1987, or in giant molecular complexes as sites of massive star formation, e.g., Hartley et al. 1986) with their remarkable structures in the central region of the Galaxy, or the diffuse hot gas extending out of the Galactic plane (e.g., *ROSAT* maps at 1.5 keV; Snowdon 1992); such observations of enhanced Galactic activity may be exploited to further substantiate the "massive star" origin of ^{26}Al.

5. CONCLUSIONS

First combined COMPTEL data from all observation periods of the *Compton Gamma-Ray Observatory* sky survey yield a map of the inner region of the Galaxy in the light of the 1.809 MeV gamma-ray line attributed to radioactive ^{26}Al. The image extends over a broad longitude range. Further observations in other regimes of the Galaxy are needed to put constraints on the origin of the ^{26}Al emission. It is remarkable that the clumpy emission as seen in COMPTEL data indicates the possibility of local ^{26}Al, i.e., the observed ^{26}Al is not necessarily concentrated in the vicinity of the Galactic center at distances of about 8.5 kpc. If more local ^{26}Al is observed, the ^{26}Al mass derived from the 1.8 MeV line intensity may be well below the 1–3 $M_\odot$ derived from measurements.

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