ON THE ORIGIN OF THE $^{26}\text{Al}$ EMISSION

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ABSTRACT

The Gamma-Ray Imaging Spectrometer recently observed the gamma-ray emission from the Galactic center region. We have detected the 1809 keV Galactic $^{26}\text{Al}$ emission at a significance level of 6.8 $\sigma$ but have found no evidence for emission at 1173 and 1332 keV, which is expected from the decay chain of the nucleosynthetic $^{60}\text{Fe}$. The isotopic abundances and fluxes are derived for different source distribution models. The resulting abundances are between $2.6 \pm 0.4$ and $4.5 \pm 0.7 M_\odot$ for $^{26}\text{Al}$, and a $2 \sigma$ upper limit for $^{60}\text{Fe}$ is between 1.7 and 3.1 $M_\odot$. The measured $^{26}\text{Al}$ emission flux is significantly higher than that derived from the Compton Gamma Ray Observatory COMPTEL 1.8 MeV sky map. This suggests that a fraction of the $^{26}\text{Al}$ emission may come from extended sources with low surface brightness that are invisible to COMPTEL. We obtain an $^{60}\text{Fe}/^{26}\text{Al}$ flux ratio $2 \sigma$ upper limit of 0.14, which is slightly lower than the 0.16 predicted from current nucleosynthesis models assuming that Type II supernovae are the major contributors to the Galactic $^{26}\text{Al}$. Since the uncertainties in the predicted fluxes are large (up to a factor of 2), our measurement is still compatible with the theoretical expectations.

Subject headings: Galaxy: abundances — gamma rays: observations —
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1. INTRODUCTION

Stellar nucleosynthesis produces a number of radioisotopes that are potentially observable through their gamma-ray emission. Radioisotopes with decay times that are long compared with the intervals between the events that eject them establish steady state abundances in the interstellar medium. Among these radioisotopes, the species $^{26}\text{Al}$ ($t_{1/2} = 7.2 \times 10^5$ yr) and $^{60}\text{Fe}$ ($t_{1/2} = 1.5 \times 10^6$ yr) are of particular interest since their decay times are short compared with Galactic rotation. The abundances of these species in the interstellar medium therefore serve as an important tracer of the stellar population responsible for their synthesis. The existence of Galactic 1809 keV line radiation was well established after the detections by the HEAO C and SMM spacecraft and was subsequently confirmed by different balloon- and satellite-borne instruments (see Prantzos & Diehl 1996 for a review). In spite of the enormous progress in the understanding of the 1809 keV line emission in the last few years, thanks to the sky maps obtained by COMPTEL, the main contributor to this emission is still an issue of discussion. Theory predicts that $^{26}\text{Al}$ is released into the interstellar medium by nova and supernova explosions, from winds of massive stars in the Wolf-Rayet phase, and from less massive stars in the very late stages of their evolution (in the asymptotic giant branch [AGB] phase). However, uncertainties in the models do not allow the contributions of each source to be predicted precisely (Prantzos & Diehl 1996). An important clue to this puzzle would be provided by the detection of the $^{60}\text{Fe}$ emission. The isotope $^{56}\text{Fe}$ ($t_{1/2} = 1.5 \times 10^6$ yr) decays to $^{60}\text{Co}$ ($t_{1/2} = 5.3$ yr), which then decays to $^{60}\text{Ni}$, simultaneously emitting two gamma-ray photons of energies 1173 and 1332 keV. Models predict that $^{60}\text{Fe}$ is released into the interstellar medium through supernova explosions and calculate the average $^{60}\text{Fe}$ mass yield from Type II supernovae (SNe II) to be about one-third of that for $^{26}\text{Al}$ (Timmes et al. 1995; Timmes & Woosley 1997). This implies that, if the main contributor to the Galactic $^{26}\text{Al}$ are supernovae, the 1173 and 1332 keV $^{60}\text{Fe}$ line emissions should be close to the limits of detectability of current gamma-ray telescopes. In this Letter, we present the observation of $^{26}\text{Al}$ and $^{60}\text{Fe}$ line emissions performed by the Gamma-Ray Imaging Spectrometer (GRIS). While $^{26}\text{Al}$ is clearly detected, we can derive only upper limits for the $^{60}\text{Fe}$. We obtain the fluxes and Galactic abundance of these two isotopes assuming various source distribution models, and we discuss the implications of the derived values on the current models of Galactic nucleosynthesis.

2. THE GRIS FLIGHT

The Gamma Ray Imaging Spectrometer (GRIS) is a balloon-borne high-resolution gamma-ray spectrometer consisting of an array of seven germanium detectors surrounded by a thick (15 cm) active NaI anticoincidence shield. This instrument was reconfigured with a wide-field collimator (100° × 75° FWHM field of view) and a 15 cm thick NaI blocking crystal to optimize its capability for observing diffuse gamma-ray sources such as the cosmic diffuse background and Galactic line emissions, in particular, the $^{26}\text{Al}$ and the $^{60}\text{Fe}$ radiations. The measurements reported in this Letter were made on a flight from Alice Springs, Australia, on 1995 October 24–26. The total germanium detector area and volume were 237 $\text{cm}^2$ and 1647.6 $\text{cm}^3$, respectively. The duration at flight altitude was 32 hr at an average atmospheric depth of 3.8 g cm$^{-2}$. The collimator was always pointed at the zenith. From Alice Springs, the
in the background spectrum. The derived instrumental widths to leave the line intensity as the only parameter of the fit. The no hint of these lines in the spectrum, it was more appropriate fixed at the values for narrow-line emission. Since there was the values expected from decay at rest, and the widths were For the 1332 and 1173 keV fits, the centroids were fixed at the (l = 240°) transit nearly overhead (see the top of Fig. 1). GRIS observed alternating 10 minute exposures with the blocking crystal open and closed.

3. DATA ANALYSIS AND RESULTS

The variation of the 1809, 1332, and 1173 keV line intensities measured during the flight is displayed in Figure 1. These values were calculated by fitting the GRIS data with a Gaussian plus a power-law model. The intensity, centroid, and width of the Gaussian were set as free parameters for the 1809 keV fits. For the 1332 and 1173 keV fits, the centroids were fixed at the values expected from decay at rest, and the widths were fixed at the values for narrow-line emission. Since there was no hint of these lines in the spectrum, it was more appropriate to leave the line intensity as the only parameter of the fit. The instrument energy resolution was determined precisely by fitting a line to the measured widths of many intense narrow lines in the background spectrum. The derived instrumental widths

Galactic center, the south Galactic pole, and the Galactic plane (l = 240°) transit nearly overhead (see the top of Fig. 1). GRIS observed alternating 10 minute exposures with the blocking crystal open and closed.

at 1809, 1332, and 1173 keV were, respectively, 3.4, 2.8, and 2.7 keV FWHM.

Notice that the 1809 keV drift scan shows an excess during both Galactic center transits, which is a detection of Galactic $^{26}$Al emission. Such modulation is not observed in the 1332 and 1173 keV drift-scan data. Because of the lack of imaging capabilities of GRIS, the flux of the emissions was derived by fitting the drift-scan data with a given source distribution model and taking into account the instrument response plus the effects of atmospheric absorption. Based on recent nucleosynthesis and stellar evolution models (Timmes & Woosley 1997), we have assumed that most of the Galactic $^{26}$Al and $^{56}$Fe is generated by SNe II explosions, and thus both isotopes have an identical spatial distribution. This assumption is also supported by the COMPTEL irregular profile, which favors massive stars as the source of $^{26}$Al. In order to quantify the influence of the source distribution profile on the derived fluxes, we have extended the study to several models.

Figure 2 shows the latitude-integrated flux profile for the models considered. The long-dashed line corresponds to the Galactic high-energy gamma-ray measurement performed by the COS B instrument, which has been used to fit most previous 1809 keV observations. The dotted line represents the profile derived from the 1.8 MeV COMPTEL map from 3.5 yr of observation integrated for $-10° < b < 10°$ (Oberlack et al. 1996). The solid line corresponds to the free electron distribution of Taylor & Cordes (1993), which shows the exponential spatial distribution of the features on the $^{26}$Al COMPTEL map in the addition of a Galactic bar component (Chen et al. 1996). The short-dashed curve corresponds to an exponential distribution with 4.5 kpc scale radius, which is a good representation of the stellar disk and is well fitted to the COMPTEL map (Diehl et al. 1995). Notice that the Galactic abundances are a by-product of the calculation when using three-dimensional models. The fluctuations outside the Galactic center region shown by the exponential model are due to local isolated SN events. The

![Image](https://example.com/image.png)

**Fig. 1.**—Variation of the 1809, 1332, and 1173 keV line intensities during the flight. These values include the instrumental background lines due to interactions of cosmic-ray-induced neutrons with Al and Cu in the instrument. Notice that while the 1809 keV line clearly shows a modulation due to the Galactic center transits, no significant modulation is observed for the $^{56}$Fe lines. The solid line shows the predicted scan profile assuming a COSB source model distribution. The derived fluxes are $(4.8 \pm 0.7) \times 10^{-4}$ photons s$^{-1}$ cm$^{-2}$ rad$^{-1}$ for the $^{26}$Fe emission and a combined $2\sigma$ upper limit of $6.9 \times 10^{-4}$ photons s$^{-1}$ cm$^{-2}$ rad$^{-1}$ for the $^{56}$Fe emission.

**Fig. 2.**—Longitude flux distributions considered for the flux and abundance studies presented herein. The curves are normalized to the value that fits the GRIS 1809 keV drift-scan data. The long-dashed line is based on the high-energy gamma-ray measurement performed by the COS B instrument (Mayer-Hasselwander et al. 1982). The dotted line corresponds to the longitude profile derived from the COMPTEL map (Oberlack et al. 1996). The solid and short-dashed lines have been derived from the sum of SN events generated by a Monte Carlo technique following three-dimensional models that are a reasonable fit to the COMPTEL map such as the Taylor & Cordes (1993) distribution and an exponential distribution with 4.5 kpc scale radius, respectively.
intensity and location of these are specific to the random sequence used for the generation of the galaxy model. The peaks shown in this particular distribution represent about 20% of the emission from the central radian, which gives an idea of the contribution that local sources could have on the total emission.

The fluxes and abundances resulting from the different models are displayed in Table 1. The 1809 keV line flux derived from the COS B distribution (as used in Mahoney et al. 1984) is $(4.8 \pm 0.7) \times 10^{-4}$ photons s$^{-1}$ cm$^{-2}$ rad$^{-1}$. This value is consistent with the fluxes reported by previous observations, and it constitutes the most statistically significant flux measurement performed with high-energy resolution (6.8 $\sigma$ confidence level). On the other hand, the 1332 and 1173 keV best-fit fluxes are $(1.6 \pm 4.8) \times 10^{-5}$ and $(2.5 \pm 5.5) \times 10^{-5}$ photons s$^{-1}$ cm$^{-2}$ rad$^{-1}$, which are compatible with no detection of Galactic $^{60}$Fe. The derived 2 $\sigma$ flux upper limits for 1332 and 1173 keV line emission are, respectively, $1.1 \times 10^{-4}$ and $8.5 \times 10^{-5}$ photons s$^{-1}$ cm$^{-2}$ rad$^{-1}$. Since these two photons are emitted simultaneously in every $^{60}$Fe decay, we derive a combined 2 $\sigma$ upper limit of $6.8 \times 10^{-5}$ photons s$^{-1}$ cm$^{-2}$ rad$^{-1}$. The fluxes obtained from the other models are similar to those derived from the COS B distribution. Making a joint fit to the $^{26}$Al and $^{60}$Fe drift scan, we derive an $^{60}$Fe/$^{26}$Al flux ratio 2 $\sigma$ upper limit of 0.14.

The derived fluxes and upper limits are the most significant ever measured by a high-resolution gamma-ray spectrometer and are similar to those reported by the satellite instruments SMM (Leising & Share 1994) and OSSE (Harris et al. 1997). However, we must point out that, unlike in previous observations, the error on this measurement is dominated by statistical uncertainties. The systematic uncertainties are small because the data comes from a single balloon flight, with low background and a high signal-to-background ratio. Furthermore, the count rate spectra do not show any significant background lines at the energies of interest, and the continuum background was very stable during the whole flight.

The measured astrophysical spectrum around the 1809, 1332, and 1173 keV lines is displayed in Figure 3. This spectrum was derived by subtracting the Galactic pole and Galactic plane accumulation from the sum of both Galactic center transits. Since we do not expect significant line emission from the Galactic pole and the Galactic plane ($l = 240^\circ$), the subtracted spectrum should be mostly of Galactic origin. The different energy regions were fitted with a Gaussian profile plus a constant (see the resulting fit parameters included in the figure). The 1809 keV line is well resolved, and the details of the analysis and the implications of this detection can be found in a recent work by Naya et al. (1996). The most remarkable result is the intrinsic width of the line $(5.4^{+1.4}_{-1.3}$ keV FWHM), which is approximately 3 times broader than expected from the effect of Doppler broadening due to Galactic rotation (Skibo & Ramaty 1991; Gehrels & Chen 1996). This large width implies that the $^{26}$Al is moving at velocities of greater than 450 km s$^{-1}$, and it favors models of an origin of the $^{26}$Al in supernovae or Wolf-Rayet stars rather than from the slower winds in AGB stars. However, it is not well understood how $^{26}$Al can maintain such a high speed for 10$^4$ yr. Different scenarios that can account for a broad emission have been studied, but none of them seem to provide a satisfactory explanation to the GRIS observation (Chen et al. 1997). For the $^{60}$Fe lines (Figs. 3b and 3c), only the line intensity was left as a free parameter. The best fit is consistent with no $^{60}$Fe detection, which is in good agreement with the drift-scan analysis shown previously.

### 4. DISCUSSION

The derived $^{26}$Al and $^{60}$Fe abundances and fluxes shown in Table 1 represent a valuable piece of information for the understanding of the nucleosynthetic activity in our Galaxy. Notice, however, that these values are closely related to the assumed models, which, in principle, could differ significantly from reality. The obtained $^{26}$Al abundances are significantly higher than the 1.8 $M_\odot$ reported by COMPTEL (Knödlseder et al. 1998). This discrepancy results from the $^{26}$Al emission flux derived by GRIS, which is higher than that derived by COMPTEL. Taking the measured COMPTEL longitude distribution as the model for the source distribution (see Fig. 2), we derive a flux that is $(5.4 \pm 0.7) \times 10^{-4}$ photons s$^{-1}$ cm$^{-2}$ rad$^{-1}$, which is 2.8 times higher than that derived for the inner Galaxy $l = 328, 35$ and $b = (-5, 5)$ in the COMPTEL map (Oblerlack et al. 1996). Furthermore, a comparison with the fluxes measured by all other instruments shows that COMPTEL has the lowest flux value reported (Prantzos & Diehl 1996). This suggests that a significant fraction of the $^{26}$Al emission is not shown in the COMPTEL map. This is not surprising since COMPTEL has little sensitivity to low surface brightness extended emission. In a recent study, it has been shown that the existence of dispersed $^{26}$Al from nearby SNe or $^{26}$Al confined to fragments located at medium latitudes that do not appear clearly in the map cannot be ruled out with the COMPTEL data (Knödlseder et al. 1997). A combined analysis of the GRIS and COMPTEL observations is currently being performed in order to refine the comparison of GRIS and COMPTEL results.

We have studied the effect that known local sources could have on the results. The Cygnus Loop, one of the local sources identified in the COMPTEL map, should not contribute to the observed emission since this source was well outside the GRIS field of view during the entire flight. Vela, the other local source identified in the COMPTEL map, is within the GRIS field of

### Table 1

| Model        | $^{26}$Al Flux Ratio ($10^{-4}$ photons s$^{-1}$ cm$^{-2}$ rad$^{-1}$) | $^{60}$Fe Flux Ratio ($10^{-4}$ photons s$^{-1}$ cm$^{-2}$ rad$^{-1}$) | Abundance ($M_\odot$) |
|--------------|--------------------------------------------------------------------|---------------------------------------------------------------------|------------------------|
| COS B$^b$    | $4.87 \pm 0.72 <0.68$                                              | $<0.14$                                                             | $... ...$              |
| COMPTEL$^b$  | $5.48 \pm 0.78 <0.72$                                              | $<0.13$                                                             | $... ...$              |
| Taylor & Cordes | $3.97 \pm 0.59 <0.54$                                          | $<0.14$                                                             | $2.61 \pm 0.39 <1.69$  |
| Exponential  | $4.97 \pm 0.74 <0.71$                                              | $<0.14$                                                             | $4.52 \pm 0.67 <3.11$  |

$^a$ 2 $\sigma$ upper limits.

$^b$ Abundances cannot be derived from two-dimensional models.
Fig. 3.—Net Galactic center count rate spectrum around the 1809, 1332, and 1173 keV energies. Notice the clear detection of the Galactic Alem emission at 1809 keV and the absence of a significant excess for the Fe lines. The derived intrinsic width for the astrophysical 1809 keV line is 1.45±1.3 keV FWHM, which is more than 3 times the value expected from previous theories (see a more detailed discussion in Naya et al. 1996).

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