THE ASTROPHYSICAL JOURNAL, 448:157–163, 1995 July 20

LIMITS ON GALACTIC GAMMA-RAY LINES AT 4.44 MeV AND 6.13 MeV FROM NUCLEAR DE-EXCITATION

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Received 1994 September 22; accepted 1995 January 30

ABSTRACT

Inelastic collisions of low-energy cosmic-ray protons and alpha particles with interstellar ^{12}C and ^{16}O produce relatively narrow de-excitation lines at 4.44 and 6.13 MeV (FWHM $\sim$ 100 keV); impacts of cosmic-ray ^{12}C and ^{16}O nuclei on interstellar H atoms produce broad lines at these energies (FWHM $\simeq$ 1 MeV). Such broad-line emission, at a level $\simeq 5 \times 10^{-5}$ γ (cm^2 s)$^{-1}$ at 4.44 MeV and $\simeq 3 \times 10^{-5}$ γ (cm^2 s)$^{-1}$ at 6.13 MeV, was recently reported from the Orion Nebula by the COMPTEL instrument aboard the *Compton Gamma Ray Observatory*. We have used over 9 years of data from the Gamma Ray Spectrometer experiment on the *Solar Maximum Mission* satellite to search for both narrow and broad lines from the directions of the Galactic center and anticenter, with ^{12}C* and ^{16}O* line intensities fixed in the ratios expected from theory and observed by COMPTEL. No emission was detected in either broad or narrow lines from any source. Our 3 σ upper limits on the combined emission from ^{12}C* and ^{16}O* are 8.7×10^{-5} γ (cm^2 s rad)$^{-1}$ for narrow lines from the central radian of the Galaxy, 3.0×10^{-4} γ (cm^2 s rad)$^{-1}$ for broad lines from the same direction, and 3.0×10^{-4} γ (cm^2 s)$^{-1}$ for broad lines from a point source in the direction of Orion. Our results suggest that the Galactic distribution of Orion-like sources does not follow the expected dependence on the square of the CO abundance and, in particular, that the ^{12}C and ^{16}O abundances in the cosmic rays accelerated in Orion-like sources are not proportional to the ambient CO abundance. We also place constraints on the fraction of Galactic ^{26}Al which can be due to cosmic-ray spallation reactions.

Subject headings: cosmic rays — Galaxy: center — gamma rays: observations — ISM: abundances

1. INTRODUCTION

Nuclear γ-ray lines are produced when energetic particles interact with ambient matter in the interstellar medium (ISM). The intensities and shapes of these lines provide information on the flux, energy spectrum, and composition of the cosmic rays and the density, composition, and gas-to-dust ratio of the ISM. The processes involved, and the nuclear cross sections, are discussed in detail by Ramaty, Kozlovsky, & Lingenfelter (1979, hereafter RKL). In the case where the ISM and cosmic-ray heavy-element abundances are comparable to the solar system values, the strongest features in the Galactic diffuse γ-ray spectrum are expected to be relatively narrow lines at 4.438 and 6.129 MeV from de-excitation of interstellar ^{12}C and ^{16}O, respectively. The predominant source of these photons is emission from nuclei in the ISM gas, excited by protons and alpha particles with energies of a few tens of MeV. The width of the lines is $\sim$100 keV FWHM; however, the 6.129 MeV line is also expected to include a very narrow component, of FWHM < 5 keV, arising from impacts on ^{16}O nuclei in dust grains. A third, extremely broad component (FWHM $\sim$ 1 MeV) is contributed to both lines by de-excitations of ^{12}C and ^{16}O cosmic-ray nuclei in flight, after impacts on ISM protons.[1] This very broad line component will be dominant only if the heavy-element abundances in cosmic rays are strongly enhanced over the solar system abundances.

Theoretical predictions of the strengths of the lines have mainly considered the narrow components. Uncertainties in the predictions obviously arise owing to lack of knowledge of the variation of heavy-element abundances in both cosmic rays and the ISM throughout the Galaxy (these uncertainties are taken into account in the work of RKL). Furthermore, strong adiabatic deceleration of cosmic rays generated by the solar wind (e.g., Fisk 1974) prevents near-Earth measurements of the particles below 100 MeV that are present in the ISM; however, limits can be placed on the flux of low-energy cosmic rays by the amount of ionization observed in the ISM. Estimates of the fluxes of the narrow Galactic γ-ray lines have been made by RKL and others (Meneguzzi & Reeves 1975; Higdon 1988; Silberberg, Tsao, & Letaw 1988) under different assumptions concerning the distributions of interstellar matter, the percentage of heavy elements relative to hydrogen, and flux of low-energy cosmic rays. These estimates range from about 5×10^{-6} to 1×10^{-4} γ cm^{-2} s^{-1} (in both lines) averaged over the central radian of the Galaxy, the direction from which the strongest narrow-line emission is expected.

Nevertheless, actual reports of positive detections of these lines have mainly been of the broad ones. The first measurement of the Galactic γ-ray spectrum, made by the Rice University balloon-borne spectrometer (Haymes et al. 1975) reported a positive detection. Haymes et al. (1975) interpreted

[1] Our analysis (§ 2) treats the components with widths $\sim$100 keV separately from the broad component with width $\sim$1 MeV. We refer to the former as "narrow lines" and to the latter as "broad lines."

a γ-ray line of FWHM 0.7 MeV which they found at 4.6 MeV as the de-excitation line from ^{12}C. The reported flux was $9.5 \pm 2.7 \times 10^{-4}$ γ cm^{-2} s^{-1} observed with a 13° (FWHM) aperture centered within a few degrees of the Galactic center (GC). Subsequent observations of the GC, however, yielded only upper limits. The most constraining line limits, prior to those reported in this paper, are from *HEAO 1* (Matteson, Nolan, & Peterson 1979) and from the Max-Planck-Institut für Extraterrestrische Physik (MPE) balloon-borne Compton telescope (Diehl, von Ballmoos, & Schönfelder 1988). These limits suggest that if the Rice detection were real, the source must be time variable and discrete. If such an observation by the Rice group were due to an extended source along the Galactic plane, the inferred flux would have been considerably higher, averaged over the central radian, and would be in conflict with all of the subsequent measurements. These measurements are presented in Table 1.

A positive detection of broad lines from a different direction has recently been reported by the COMPTEL experiment on board the *Compton Gamma Ray Observatory*. Bloemen et al. (1994) measured a flux $1.0 \pm 0.15 \times 10^{-4}$ γ cm^{-2} s^{-1} in the energy range 3–7 MeV from the Orion molecular cloud complex. This flux appears to be dominated by broad (FWHM $\sim$ 1 MeV) lines at 4.44 MeV and 6.13 MeV, with intensities $5 \pm 1 \times 10^{-5}$ γ cm^{-2} s^{-1} and $3 \pm 1 \times 10^{-5}$ γ cm^{-2} s^{-1}, respectively (Table 1).

In this paper we present measurements from 1980 to 1989 with the Gamma Ray Spectrometer (GRS) on NASA's *Solar Maximum Mission* (*SMM*) satellite. We have searched for emission of both broad and narrow lines from both the central region of the Galactic plane and the Orion Nebula. The limits placed on the emission of the narrow lines from the inner Galaxy at 4.44 and 6.13 MeV by interstellar ^{12}C and ^{16}O are nearly an order of magnitude lower than those obtained in earlier studies (§ 3). These limits constrain optimistic estimates of the ISM density and composition in the inner regions of the Galaxy (§ 4.1); they also constrain the possible contribution of cosmic rays to the nucleosynthesis of ^{26}Al (§ 4.3). Our upper limits on emission of the broad lines are larger, and only weakly constrain the distribution of "Orion-like" sources of 4.44 and 6.13 MeV radiation in the Galaxy as a whole (§ 4.2).

2. INSTRUMENT AND ANALYSIS TECHNIQUE

The GRS was in operation from launch in 1980 February until the reentry of *SMM* in 1989 December. Details of its design are discussed by Forrest et al. (1980). It consisted of seven 7.6 cm × 7.6 cm NaI detectors, whose electronic outputs were summed together and analyzed into 476 pulse-height channels spanning the energy range from about 300 keV to about 8.5 MeV. The NaI detectors were shielded from charged particles and external background γ-radiation by CsI and plastic scintillation counters. The spectrometer presented an effective area of $\simeq 38$ and $\simeq 27$ cm^2 to vertically incident γ-ray lines at 4.44 and 6.13 MeV, respectively; narrow lines at these energies were broadened by the instrument to widths of 170 and 210 keV (FWHM), respectively. The instrument presented a broad aperture to incident γ radiation; its angular response for photons at 5 MeV is plotted in Figure 1. Active gain control performed remarkably well over the full lifetime of the mission, allowing spectra to be accumulated over months and years without detectable broadening or shifting of spectral features.

2.1. *Data Selection*

Share et al. (1985, 1988) have discussed the use of GRS data to measure Galactic γ-ray lines from position-electron annihilation and decay of ^{26}Al. The technique basically involves the accumulation of spectra over 3 day intervals, after removing high-background segments such as orbits which intersect with belts of particles in the South Atlantic Anomaly. These spectra are fitted with models containing the line of interest, any suspected blending lines, and the underlying continuum. The amplitude of the line derived from these fits is arranged in a time series, which is fitted by the calculated response of the spectrometer to the expected source of γ-rays which transited its aperture. For a source at the GC, such transits occurred annually during a few months centered in December, as the solar-pointed axis of *SMM* passed within 6° of the center of the Galaxy; for sources toward the anticenter (AC), the transits occurred around June of each year.

In the current analysis we take into account the fact that the atmosphere of Earth is the most important source of background lines at 4.44 and 6.13 MeV. We therefore used spectra accumulated with the spacecraft axis pointed away from Earth (angles $|\theta| > 108°$ from Earth center). A representative spectrum between 3.9 and 8.5 MeV accumulated over a 3 day period, with a total live time of 32,620 s, is shown in Figure 2 (*top curve*). The Earth albedo 4.44 and 6.13 MeV lines are clearly visible, arising from leakage of atmospheric γ-radiation through the anticoincidence CsI shield.

We made a further selection from these data in order to minimize the strengths of these Earth albedo lines. From

TABLE 1

LINE MEASUREMENTS AT 4.44 AND 6.13 MeV

		Flux[a] 10^{-4} γ (cm^2 s rad)$^{-1}$				
Experiment	Target	4.44 MeV (Broad)	6.13 MeV (Broad)	4.44 MeV (Narrow)	6.13 MeV (Narrow)	Reference
Rice	GC	42 ± 12	<37	...	...	1
HEAO 1	GC	<7.7	...	<4.4	<3.3[b]	2
Apollo 16	GC	<42	...	...	...	3
UNH	GC	...	...	<13	<9.3	4
MPE	GC	<13	<13	<13	<13	5
COMPTEL[c]......	Orion	0.5 ± 0.1	0.3 ± 0.1	...	...	6

[a] All limits are 3 σ. Emission assumed to be distributed as Galactic CO (Leising & Clayton 1985) unless otherwise noted.

[b] Our estimate based on information provided in reference.

[c] Assumed point source at $l = 208°$, $b = -18°$. Units are γ (cm^2 s)$^{-1}$.

References.—(1) Haymes et al. 1975; (2) Matteson et al. 1979; (3) Gilman et al. 1979; (4) Dunphy et al. 1981; (5) Diehl et al. 1988; (6) Bloemen et al. 1994.

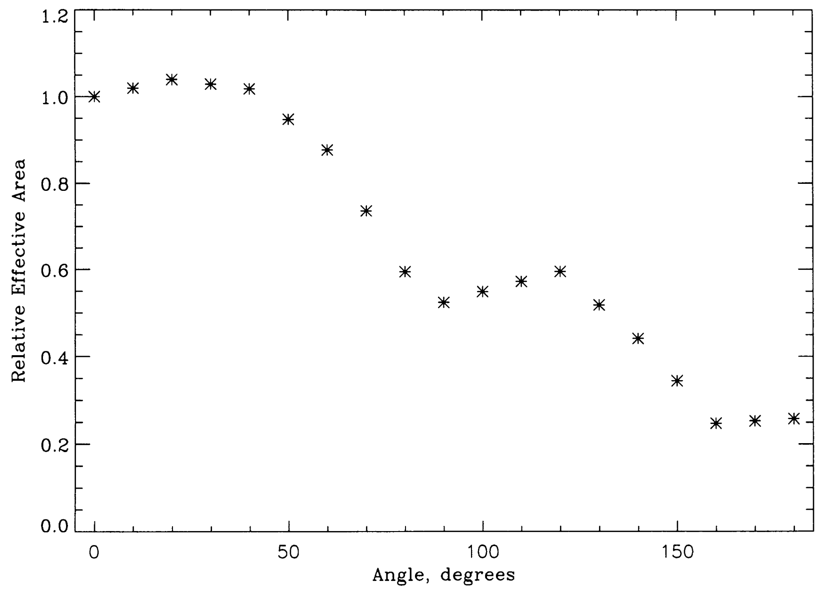

FIG. 1.—Angular response of the *SMM* GRS to incident γ-rays with energies near 5 MeV as determined by Monte Carlo calculations. The effective area at 0° incident angle is $\simeq 38$ cm^2 at 4.4 MeV and $\simeq 27$ cm^2 at 6.1 MeV.

Figure 2 (*lower curve*) it is clear that the strengths of the lines at 4.44 and 6.13 MeV are much smaller in data obtained at high cosmic-ray cutoff rigidities (> 11 GV). By using only these high-rigidity data, we found that the systematic errors in the line strengths were reduced by at least a factor 2, at the cost of reducing the sensitivity of *SMM* to a celestial source by the sacrifice of about 50% of the live time.

2.2. *Line Searches*

The model spectrum which we used to fit the 3 day spectra was derived from measurements of the Earth albedo spectrum by Letaw et al. (1989). The model contains a power law and seven line features, which are listed in Table 2. The solid curves in Figure 2 are the best fits of this model to these particular 3 day spectra after folding through the instrument response function for an incident angle of 0°.[2] The broad intrinsic width used in fitting the line features range from 70 keV to close to 300 keV and are due both to Doppler broadening and line blending.

A further reduction in the systematic errors of our measurement is expected if, instead of the two freely varying ^{12}C* and ^{16}O* lines given in Table 2, a "template" is fitted to each 3 day

[2] This angle was chosen in order to provide the proper normalization for any observed celestial lines; it has no significant impact on the fit to the atmospheric lines. Fluxes for atmospheric γ-rays are therefore relative.

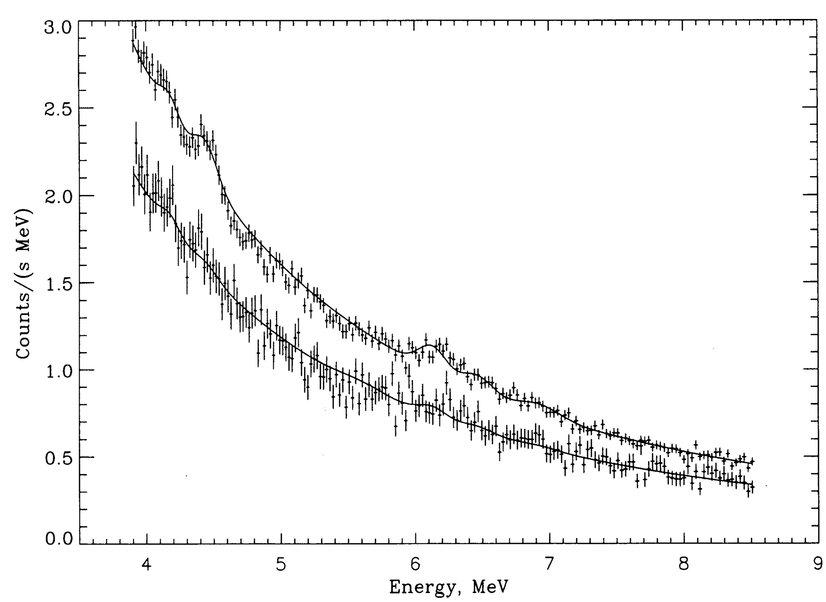

FIG. 2.—*SMM* GRS background spectra from about 3.9 to 8.5 MeV observed during the 3 day period 1980 July 1–3, with the instrument looking away from Earth ($|\theta| > 108°$). Top curve is data at geomagnetic cutoff rigidities ≥4 GV (live time 32620 s). Bottom curve is data at high rigidities only (> 11 GV, live time 7760 s). Solid curves are fits consisting of a power law and seven background lines from Table 2.

TABLE 2

LINE FEATURES FITTED TO *SMM* GRS SPECTRA

Energy (MeV)	Possible Identification
4.18	Atmospheric ^{16}O
4.44[a]......	Atmospheric ^{11}B and ^{12}C
5.10	Atmospheric ^{14}N, ^{15}N, and ^{15}O
5.60	Atmospheric ^{14}N and ^{11}C
6.13[a]......	Atmospheric ^{14}C, ^{15}O, and ^{16}O
6.46	Atmospheric ^{11}C, ^{14}N, and ^{15}N
6.93	Atmospheric ^{11}B, ^{14}C, ^{14}N, and ^{16}O

[a] The widths of these lines were varied according to theoretical and observational expectations (§ 2.2). In some cases ("template" fits) their intensities were held in a fixed ratio, for the same reason (§ 2.2).

spectrum consisting of the two lines fixed in the ratio expected from cosmic-ray impacts in the ISM. Doing this incurs the penalty of introducing a systematic uncertainty due to the error bars on the theoretical and experimental values of the 4.44 MeV:6.13 MeV line ratio. However, the range of values of this ratio, obtained from the calculations of RKL for different cosmic-ray and ISM abundances, and from the COMPTEL measurement of the two lines from Orion, is relatively small, ranging from about 1.6 (for the COMPTEL lines: Bloemen et al. 1994) to 2.4 (for RKL's case 3 in their Table 5). The atmospheric ^{12}C* and ^{16}O* line ratio measured by Letaw et al. (1989) is quite similar, so these templates are expected to fit the data adequately.

Therefore, when searching for the narrow lines, we fitted templates consisting of 4.44 and 6.13 MeV lines of width (FWHM) 112 keV and intensity ratios in the range 1.6 to 2.4. When searching for broad lines, we fitted a template in which the 4.44 MeV line was $\simeq$0.8 MeV wide, the 6.13 MeV line was $\simeq$1 MeV wide, and the ratio between the two was 1.6 (Bloemen et al. 1994).

The 3 day averaged intensities of the line features from the fits, over the entire mission, were arranged in a time series. We discovered various systematic features in these time series, of which the most important is a long-term modulation peaking in 1986, which is illustrated for one of the templates in Figure 3. We attribute this to variation of the atmospheric background caused by solar modulation of the incident cosmic radiation, which generates the lines via the interaction of secondary neutrons with nitrogen and oxygen (Letaw et al. 1989). The solid curve plotted in Figure 3 is a normalized fit of the rates from the Climax neutron monitor (obtained from Solar Geophysical Data) to the template flux, after subtraction of a constant. The good agreement confirms that the long-term trend is due to solar modulation.

We searched these time series for evidence of celestial ^{12}C* and ^{16}O* lines in the form of increases occurring each year. By fitting a GRS exposure function peaking in December of each year, we searched for emission from the GC region. The diffuse source was assumed to have the same distribution as Galactic CO emission (Leising & Clayton 1985). By independently fitting a GRS exposure function peaking in June, we searched for emission from the Orion region (treated as a point source; however, due to its broad aperture, *SMM* would detect any source[s] in the general direction of the Galactic AC). In both cases, we included the Climax neutron monitor rate time series (Fig. 3) in the fits.

2.3. *A Limitation of the Method*

The simultaneous measurement of γ-ray line intensities from two antipodal directions on the sky is clearly not possible by the methods used here. The GRS exposure function to the GC peaks in December, but any increase in count rate is measured *relative to the count rate in June*, when the contribution from a source in the AC or Orion direction would peak. In principle, two sources of equal intensity in each direction would cancel out. Our measurements of each line from each source are therefore essentially measurements of the differences GC − Orion and Orion − GC. We would expect a net positive flux from one source for one line to be accompanied by a corresponding negative flux from the other source for the same line, if the flux

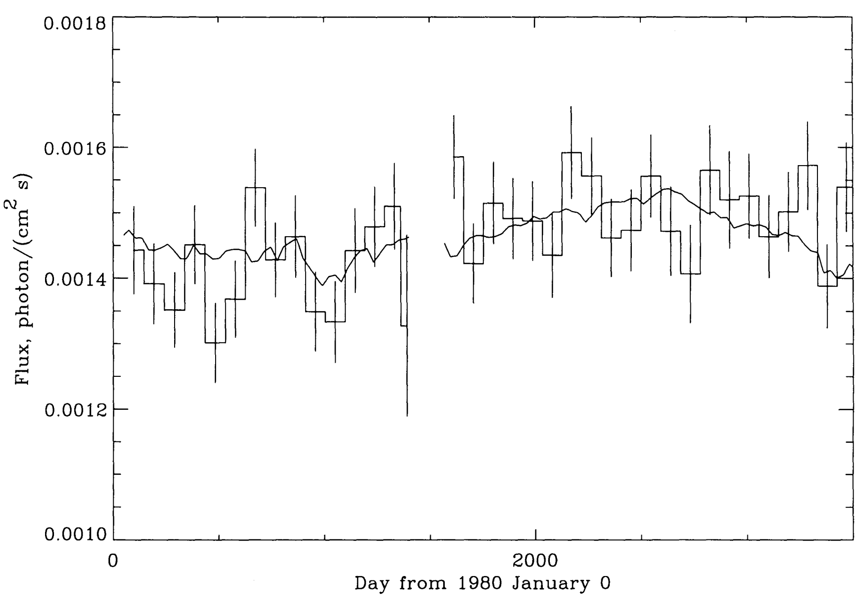

FIG. 3.—Total intensity of a template of narrow 4.44 and 6.13 MeV lines in ~96 day accumulations from 1980 to 1989 with the experiment viewing away from Earth (|θ| > 108°) and for geomagnetic cutoff rigidities >11 GV. The two lines are fixed in the ratio 1.6:1. Solid curve is Climax neutron monitor rate fitted to the data.

were real. There may also be interference between broad and narrow lines; when searching for narrow-line emission, we therefore considered as a possible source of systematic error the known emission of broad $^{12}C^*$ and $^{16}O^*$ lines from the direction of Orion, as established by Bloemen et al. (1994), by including these lines (as modulated by the GRS aperture) in the spectrum fits.

3. RESULTS

Shown in Figure 4 are the measured intensities of the narrow 4.44 and 6.13 MeV lines (fitted separately), and of the template with them fixed in the ratio 1.6:1, obtained with the spectrometer pointed away from Earth ($|\theta| > 108°$, where θ is angle between the detector axis and the center of Earth), and for cosmic-ray cutoff rigidities >11 GV. The data have been averaged over ∼48 day accumulations for clarity, and the long-term trend due to the effects of solar modulation has been removed. A source of line photons from the direction of the GC would be expected to appear as a broad increase centered in December of each year. The solid lines in Figure 4 are the calculated response of the spectrometer to a diffuse Galactic source following the distribution of CO in the Galaxy, as given in Leising & Clayton (1985); however, the GRS response is not very sensitive to the shape of any plausible Galactic distribution.

The results for these narrow lines from the GC are characteristic of our results as a whole, and we give them in some detail as examples. We measured the Galactic emission in these lines by fitting the model (*solid line*) to the data. The fluxes measured for the 4.44 and 6.13 MeV lines individually are, respectively,

$$(2.0 - 3.8) \pm 1.9 \times 10^{-5}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{rad}^{-1}\ ,$$

$$(-0.8 - 0.5) \pm 1.4 \times 10^{-5}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{rad}^{-1}\ .$$

The flux measured using the templates of 4.44 and 6.13 MeV lines is

$$(2.5 - 3.4) \pm 2.6 \times 10^{-5}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{rad}^{-1}\ ,$$

where the ranges reflect the influences of the sources of systematic error which we identified in §§ 2.2 and 2.3. We conclude that there is no evidence for a Galactic contribution in the 4.44 and 6.13 MeV time series of fluxes plotted in Figure 4.

We also see that the systematic errors are much reduced when the templates are used, even given the extra systematic error due to uncertainty in the template line ratio (§ 2.2). We therefore quote our results henceforth in terms of the fluxes in the narrow- and broad-line templates; note that these represent the *sums* of the $^{12}C^*$ and $^{16}O^*$ line fluxes.

Upper limits only were likewise found for every other combination of line type and source for which we searched. We found no evidence for emission of narrow 4.44 and 6.13 MeV lines from the direction of Orion, nor for emission of broad 4.44 and 6.13 MeV lines from either the GC or Orion. Upper limits (3 σ) on the strengths of these lines are given in Table 3. These results (obtained from the template fits) include the small systematic errors discussed above.

TABLE 3

SMM UPPER LIMITS (3 σ) ON SUM OF 4.44 AND 6.13 MeV LINE FLUXES

Source	3 σ Upper Limit ($\times 10^{-4}$): 4.44 + 6.13 MeV (Broad)	4.44 + 6.13 MeV (Narrow)	Units
GC	<3.0	<0.87	γ (cm^2 s rad)$^{-1}$
Orion......	<3.0	<1.0	γ (cm^2 s)$^{-1}$

4. DISCUSSION

4.1. *Narrow-Line Measurements*

The upper limits derived from *SMM* data given in Table 3 for a distributed source of narrow cosmic-ray induced lines

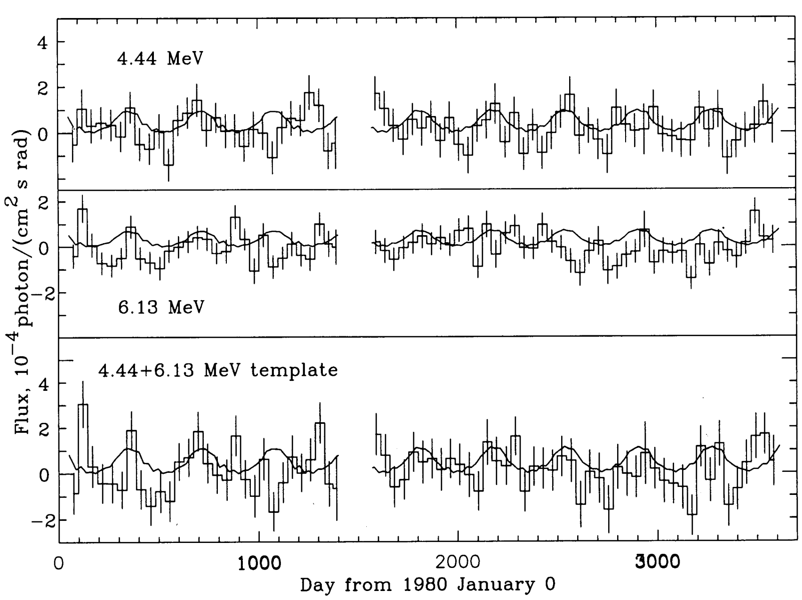

FIG. 4.—Intensities in the GC direction of (*top*) narrow 4.44 MeV and (*middle*) narrow 6.13 MeV line γ rays, and (*bottom*) a template of narrow 4.44 and 6.13 MeV lines with the intensity ratio fixed at 1.6:1. The intensities are ∼48 day accumulations after subtracting constant level plus variable contribution from solar modulation, as determined using Climax neutron monitor data plus linear trend (Fig. 3). Solid curves are expected responses to diffuse Galactic plane sources having intensities of the 3 σ upper limits obtained from the results quoted in § 3: (*top*) 7.5 × 10^{-5} γ (cm^2 s rad)$^{-1}$, (*middle*) 5.5 × 10^{-5} γ (cm^2 s rad)$^{-1}$, (*bottom*) 8.7 × 10^{-5} γ (cm^2 s rad)$^{-1}$.

toward the GC direction (8.7×10^{-5} γ cm^{-2} s^{-1} rad^{-1}) are about a factor of 9 lower than the best previous observation (Table 1). The corresponding limits implied for a broader line at 4.44 MeV are well over an order of magnitude below the line flux at 4.6 MeV, attributed to $^{12}C^*$ de-excitation, reported by the Rice group from its observation in 1974 (Table 1). This suggests that the Rice observation was either a statistical fluctuation or a systematic effect, although one cannot rule out the presence of a low duty cycle variable point source near the GC.

The limits on emission of narrow 4.44 and 6.13 MeV lines in Table 3 do not significantly constrain parameters used in calculating the diffuse flux of line γ-rays from the inner Galaxy (see references in § 1). Most of these estimates are about an order of magnitude below the limits set here. Only mild constraints are placed on enhanced abundances of elements heavier than helium in the inner Galaxy, relative to the local cosmic-ray and solar abundances. In their most optimistic case (case 3 in their Table 5), RKL estimate that the C/H and O/H ratios may be 5 times higher at a galactocentric radius near 5 kpc than they are locally. They estimate gradients of these ratios and integrate over the line-of-sight path toward the GC to obtain fluxes of 7.2 and 3.0×10^{-5} γ cm^{-2} s^{-1} rad^{-1} at 4.44 and 6.13 MeV, respectively, summing to 1.0×10^{-4} γ cm^{-2} s^{-1} rad^{-1}. The corresponding 3 σ upper limit set by the GRS is 8.7×10^{-5} γ cm^{-2} s^{-1} rad^{-1} (Table 3). This indicates that the increased metallicity in the inner Galaxy is not significantly greater than the most optimistic estimate by RKL and is probably less.

4.2. *Broad-Line Measurements*

Our upper limit of 3×10^{-4} γ cm^{-2} s^{-1} on the emission of broad lines from a point source in Orion is almost 4 times higher than the sum of the line fluxes measured by COMPTEL (Table 1) and can do little to confirm or to constrain this measurement. However, certain conclusions about the Galactic distribution of broad-line emission can be drawn when the COMPTEL measurement is combined with our results from both GC and AC (Orion) directions.

The distribution of 4.44 and 6.13 MeV broad-line emission is not expected to follow the distribution of high-energy (> 100 MeV) γ-rays, which are also cosmic-ray induced and which broadly follow the distribution of matter in the Galaxy (Bertsch et al. 1993). Whereas the γ-ray emission above 100 MeV is diffuse, as a result of the large (~ 1 kpc) length scale of the coupling between cosmic rays and matter, the lines observed by COMPTEL are clearly confined to the Orion cloud complex (Bloemen et al. 1994). Most of the target protons in the cloud will be in the form of H_2. Further, the COMPTEL measurements require the accelerated particle abundances to be strongly enriched in ^{12}C and ^{16}O, at least within the complex. The most natural assumption is that the enrichment is proportional to the C and O abundances, which (like the total matter distribution in molecular clouds) will follow the distribution of CO. The simplest assumption is therefore that the broad-line emission will be proportional to the *square* of the density of (molecular) matter, or to the product of the densities of H_2 and CO.

We can quantify the Galactic distribution of hypothetical broad-line sources by calculating the ratio (flux from GC)/(flux from AC), given that the quantities which are actually measured by *SMM* are the flux differences GC − AC and AC − GC (§ 2.3). When the COMPTEL measurement, which implies (flux from AC) $\geq 0.8 \times 10^{-4}$ γ cm^{-2} s^{-1}, is combined with our 3 σ upper limits in Table 3, it can easily be shown that[3]

$$R = \frac{\text{flux GC (central radian)}}{\text{flux AC}} < 4.7 \, . \qquad (1)$$

We compared this with the corresponding value for the square of the Galactic distribution of H_2 (Bronfman et al. 1988: the distributions of H_2 and CO are equivalent), computed after convolving with the GRS aperture. The result, (flux GC)/(flux AC) = 8.2, is not compatible with equation (1).

However, the Orion region appears to be untypically active in both forming stars and in producing cosmic rays (if the COMPTEL measurement is correct). It is possible that Orion-like objects are only a subset of all molecular clouds in the Galaxy, and that the GC-to-AC ratio is explained by one source (Orion) being both active and very nearby in the AC direction. We therefore used a Monte Carlo method to investigate the likelihood that a finite subsample (randomly selected) from the CO- or H_2-squared distribution will have a GC-to-AC emission ratio of less than 4.7, as required by equation (1). We approximated a two-dimensional map of the square of the Galactic CO emission, from the results of Bronfman et al. (1988), by about 10^5 points.[4] We assigned units of cosmic-ray induced line emission to these randomly (weighted by the CO emission from each point). We computed the ratio between the cosmic-ray induced line emission from the GC and AC, as seen at Earth after convolving with the GRS aperture. Several hundred simulations enabled us to determine, for a given number of units of emission, the fraction having GC-to-AC ratios less than 4.7.

The result is shown in Figure 5. The number of units of emission in each set of simulations is related to the probability that each point in the model Galaxy is "active" in terms of γ-ray line emission; for example, if the number of units of emission is much larger than the number of points, the probability of any point being active approaches 100%, and the GC-to-AC ratio 8.2 of the Bronfman et al. (1988) distribution is recovered—the fraction of simulations with a ratio <4.7 is then zero. As fewer units of emission are assigned, the probability of any point in the map being selected decreases, individual simulations depart increasingly from this fiducial distribution, and the fraction having GC-to-AC ratios <4.7 rises. We therefore express the abscissa of Figure 5 as the probability of a given map point (i.e., CO cloud) being active.

It appears from these results that situations with GC-to-AC ratio <4.7 are unlikely. The probability of such an outcome only becomes large (> 10%) if "active" molecular clouds are rare (≤ 3% probability); alternatively, if activity is common among molecular clouds (> 10% probability), then the probability that those in the AC direction will emit the necessary strength is small (≤ 2%). We conclude that either the γ-ray line emission from the Orion molecular cloud is an unlikely chance event, or the abundances of C and O in cosmic rays in molecular clouds are not proportional to the ambient density of CO.

[3] The ratio GC:AC is clearly largest for the minimal value 0.8×10^{-4} of AC. The maximal value of the GC flux which is compatible with this value is 3.8×10^{-4}, since our results require (GC − AC) $< 3.0 \times 10^{-4}$ (Table 3). A further increase in the GC flux would reduce the GC:AC ratio, since the numerator and denominator increase at the same rate. The maximum of the ratio GC:AC is therefore $3.8 \times 10^{-4}/0.8 \times 10^{-4}$.

[4] Each point has a characteristic linear dimension ~ 80 pc, which is comparable to the scale of the CO emission from a single cloud complex (e.g., Orion A and B) and of the γ-ray line emission detected by COMPTEL.

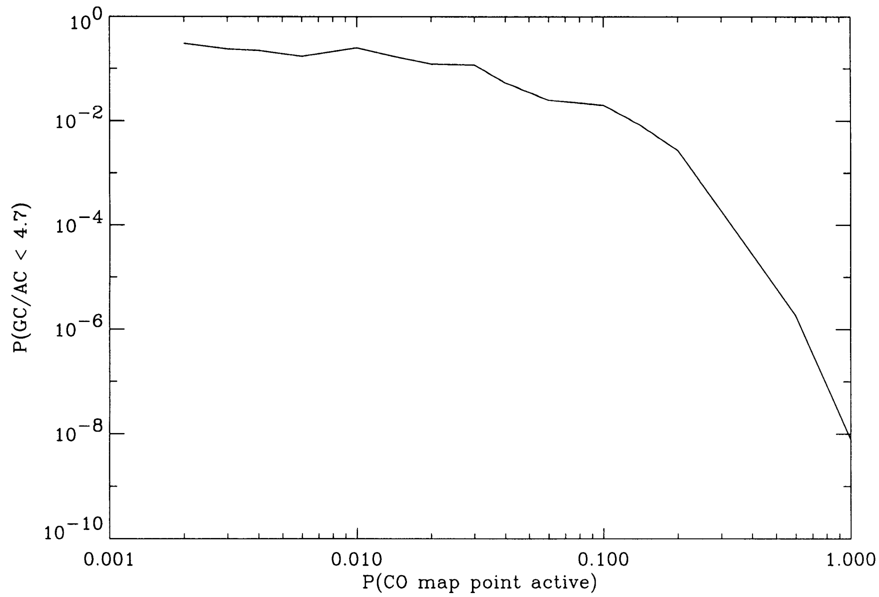

FIG. 5.—Probability of obtaining a GC-to-AC γ-ray line flux ratio >4.7 as a function of the probability of any given molecular cloud being active in producing lines (see text, § 4.2).

4.3. *Cosmic-Ray Production of* ^{26}Al

The well-known interstellar ^{26}Al β-decay line at 1.809 MeV has long been regarded as anomalously strong (Diehl et al. 1994 and references therein), relative to the nucleosynthetic sources of ^{26}Al. Recently, Clayton (1994) used the COMPTEL measurement of broad 4.44 and 6.13 MeV lines from Orion (Bloemen et al. 1994) to suggest that a substantial fraction of the Galactic ^{26}Al can be produced by cosmic-ray interactions in molecular clouds. The COMPTEL measurement implies that C and O are strongly enhanced in the cosmic rays in the Orion molecular cloud, relative to local measurements; Clayton assumes that Mg and Si are similarly enhanced and that ^{26}Al is produced by spallation reactions on Mg and Si isotopes.

As Ramaty, Kozlovsky, & Lingenfelter (1995) have pointed out, this hypothesis is inconsistent with the upper limits on the GC 4.44 and 6.13 MeV lines presented here (see also Ramaty 1994). Ramaty et al. (1995) have shown that, whatever the width of these lines, the ratio of 1.809 MeV to (4.44 MeV + 6.13 MeV) line emission from a pure spallation source (cosmic-ray interactions) can never be greater than 10^{-2}. The fluxes from the central radian of the Galaxy do not obey this limit. The ratio of the COMPTEL measurement $1.8 \times 10^{-4}\ \gamma\ cm^{-2}\ s^{-1}\ rad^{-1}$ at 1.809 MeV (Diehl et al. 1994) to our weakest 3 σ upper limit $<3 \times 10^{-4}\ \gamma\ cm^{-2}\ s^{-1}\ rad^{-1}$ at 4.44 MeV (Table 3) is >0.6. It follows that no more than $\sim 2\%$ of Galactic ^{26}Al can be produced by cosmic-ray spallation of Mg and Si. Ramaty et al. (1995) also point out that enhanced cosmic-ray abundances of Mg and Si would lead to significant emission of lines in the 1–3 MeV energy range (e.g., 1.37 MeV from ^{24}Mg* and 1.78 MeV from ^{28}Si*) which was not observed from Orion by COMPTEL (Bloemen et al. 1994 only obtained an upper limit on the flux in this energy range).

We wish to thank Steve Matz and Greg Jung for providing information on the energy and angular response of the spectrometer based on Monte Carlo calculations. Don Clayton and Reuven Ramaty provided prepublication details of their work. We are grateful to the referee Richard Lingenfelter for suggestions concerning the Galactic CO distribution, and to Jeff Skibo for providing the CO distribution in map form. This work was supported by NASA under contract DPR-W 178 08.

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