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DETECTION OF GALACTIC ^{26}Al GAMMA RADIATION BY THE *SMM* SPECTROMETER

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ABSTRACT

The gamma-ray spectrometer on the *Solar Maximum Mission Satellite* has detected a line near 1.81 MeV with a significance of $> 5\ \sigma$ in each of 3 yr when the Galactic center traversed the broad aperture of the instrument in 1980, 1981, and 1982. There was no significant variation in intensity from year to year. The Galactic center/anticenter intensity ratio is > 2.5, and the center of the emission is consistent with the location of the Galactic center. The distribution could not be measured well enough to distinguish between candidate sources, e.g., novae, supernovae, red giants, and massive stars. For an assumed source distribution which follows the > 100 MeV Galactic gamma radiation, the total flux measured in the direction of the Galactic center is $(4.0 \pm 0.4) \times 10^{-4}\ \gamma\ (\text{cm}^2\ \text{s rad})^{-1}$. The measured energy of the line is 1.804 ± 0.004 MeV. These measurements are consistent with the detection of a narrow γ-ray line from interstellar ^{26}Al by *HEAO 3* in 1979/1980.

Subject headings: gamma rays: general — nucleosynthesis — stars: novae — stars: supernovae

I. INTRODUCTION

The isotope ^{26}Al can be synthesized in novae, supernovae, red giants, and massive stars (e.g., Clayton and Hoyle 1976; Arnett 1969; Woosley and Weaver 1980; Nørgaard 1980; Cameron 1984; Dearborn and Blake 1985). Ramaty and Lingenfelter (1977) recognized that a narrow γ-ray line at 1.809 MeV from the decay of ^{26}Al ($t_{1/2} = 7.2 \times 10^5$ yr) accumulated in the interstellar medium during the past few million years might be detectable with the current generation of instruments. In 1979 the germanium spectrometer on *HEAO 3* scanned the Galactic plane and found weak evidence for the emission of this line (Mahoney *et al.* 1982). Using a refined analysis, the significance of the detection has improved to close to the 5 σ level of confidence leading Mahoney *et al.* (1984) to conclude that ^{26}Al has been detected in the interstellar medium.

The γ-ray spectrometer on the *Solar Maximum Mission Satellite* has been in operation since 1980 February. Although it was not designed for Galactic studies, the spectrometer's excellent stability, good sensitivity, and long observing period have enabled it to detect the interstellar ^{26}Al line at a significance of $\sim 10\ \sigma$. In the next section we discuss the instrument's characteristics and methods used to observe celestial sources. We then summarize the various background contributions and systematic variations which can affect the Galactic line studies. The Galactic ^{26}Al was detected by the annual increase in intensity in the spectrometer's response to a line near 1.81 MeV as the Galactic center passed through its field of view.

II. INSTRUMENT AND METHOD OF ANALYSIS

The γ-ray spectrometer on the *Solar Maximum Mission Satellite* consists of seven cylindrical 7.5 cm × 7.5 cm NaI scintillation detectors (Forrest *et al.* 1980). These detectors are actively gain stabilized, and their outputs are summed. The effective detecting area of the spectrometer at 1.8 MeV is 70 cm^2. A 2.5 cm thick annulus and a 7.6 cm thick back plate of CsI define an aperture of $\sim 130°$ (FWHM) to incident γ-rays. The axis of the detector has been pointed to within 10° of the Sun throughout the mission. A plastic scintillation detector covers the aperture and completes the 4 π anticoincidence shield for charged particles. Spectra are accumulated each 16.38 s. The instrument's gain has been so stable that spectra accumulated over months and years exhibit resolution comparable to that observed at launch (7% at 662 keV). Data have been obtained since *SMM*'s launch in 1980 February with the exception of a 4 month period prior to and immediately following the repair of the satellite in 1984 April.

We obtained the data base for the Galactic studies by accumulating 1 minute spectra along with the satellite's location and orientation. Three day accumulations of these spectra were then sorted according to the three parameters which have been found to have the most significant effect on the background radiation in the instrument. These parameters are (1) the time from the last significant transit of the radiation belts (SAA), (2) the zenith angle of the detector axis, and (3) the vertical geomagnetic cutoff rigidity for cosmic rays. Each of these parameters was divided into 10 intervals with roughly equivalent exposures. Data were only included in these sum-

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1985ApJ...292L..61S

mations for the approximately eight orbits each day which were free from significant exposure to the SAA. Both computerized and visual screening of all the data prior to the 3 day summations allowed us to remove contributions from solar flares, γ-ray bursts, geomagnetic disturbances, and times with poor telemetry transmissions.

We have used the fact that *SMM* follows the Sun along the ecliptic to search for an annual increase in the intensity of 1.81 MeV γ-rays as the Galactic center passes through the field of view. The Sun crosses the Galactic equator within 6° of the center in the latter part of December. Because of the spectrometer's large aperture, a source is observable for about 4–5 months. We require that the detected modulation agree with what is derived from folding the instrument's angular response with an ^{26}Al intensity distribution which follows the Galactic distribution of > 100 MeV γ-rays (Mayer-Hasselwander 1983). This is the same model utilized by Mahoney *et al.* (1984) to approximate the distribution of supernovae in the Galaxy. However, because of the detector's large aperture, the fit to the modulation is not very sensitive to the assumed width of the distribution. We test for any instrumental effects which might simulate the annual Galactic modulation by utilizing data obtained when Earth occulted the Galactic center region as viewed from *SMM*.

III. BACKGROUND LINES AND THEIR VARIABILITY

In order to assess the significance of any annual Galactic modulation in the intensity of 1.81 MeV line emission, it is first necessary to understand the behavior of the continuum and background lines near that energy. A detailed description of this study will be presented elsewhere. In this section we summarize the results as they pertain to the ^{26}Al observations. The two sources of background which play a significant role in the variability of the background near 1.8 MeV are the particles in the SAA and the cosmic radiation.

Our ability to uniquely identify background lines is limited by the 95 keV (FWHM) energy resolution of the spectrometer near 1.81 MeV. However, the 3.5 yr data base has permitted us to observe temporal variations which aid in identifications. The overall background spectrum in the 1.6–2.0 MeV region can be represented by a power-law continuum and a line feature near 1.78 MeV whose width exceeds the instrumental resolution. From a study of the temporal variation of the shape of this feature and likely background lines, we conclude that it is dominated by unresolved lines at ~ 1.75 MeV, ~ 1.79 MeV, and ~ 1.81 MeV. The different temporal variations of these three lines are illustrated in Figure 1, which shows their intensities averaged over the 48 day modulation caused by the orbital precession of *SMM*. The intensities were determined with a least-squares algorithm by fitting the 1.6–2.0 MeV spectral range with a power-law continuum and the three lines (each energy fixed and width fixed at the instrumental resolution). All data in orbits containing significant exposure to the SAA were excluded.

The decrease in intensity of the 1.75 MeV line feature in the overall background spectrum, shown in Figure 1*a*, primarily reflects the decreasing SAA dosage as *SMM*'s altitude dropped from 570 km to 500 km. The dashed line is a normalized fit to the intensity of the strong ^{24}Na line at 2.754 MeV produced by interactions of SAA and cosmic-ray protons and neutrons with the aluminum in the detector's housing. The agreement is excellent. A likely source of the 1.75 MeV feature is ^{119}Te (1.749 MeV, $t_{1/2}$ = 16 hr) which is produced in the instrument's CsI shield. The intensity of the underlying continuum, which is dominated by the positron decay spectrum from ^{124}I in the NaI, also follows the profile of the radioactively induced ^{24}Na line.

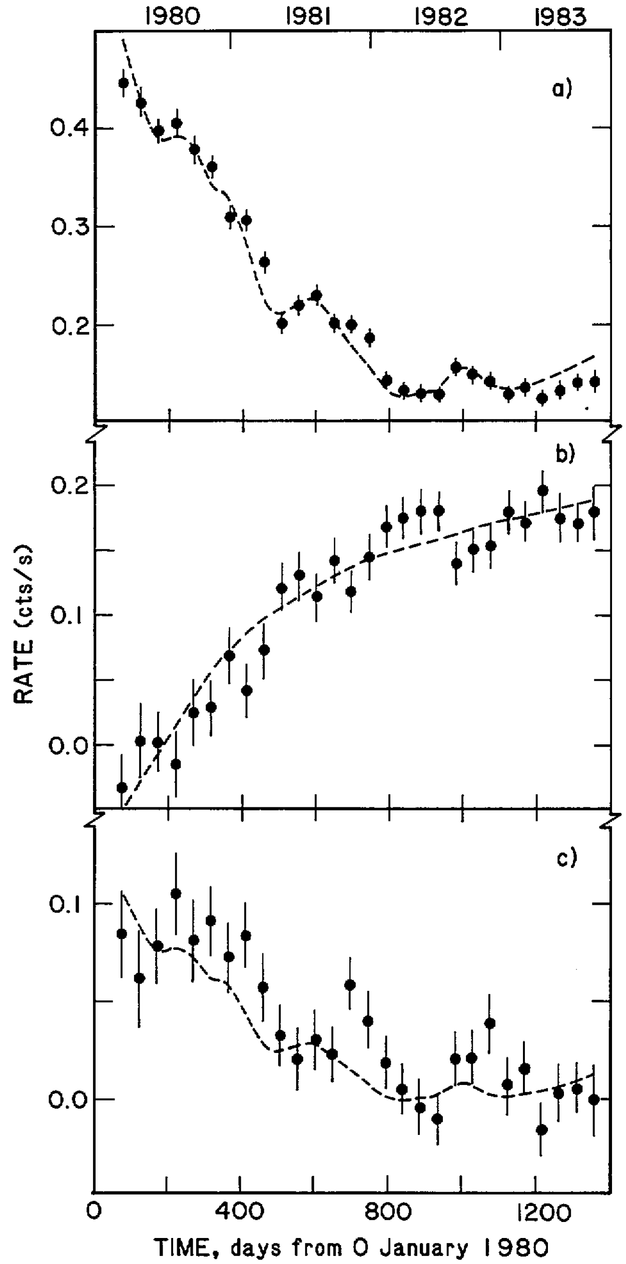

FIG. 1.—Variations in the intensities of three lines fitted to the broadened feature observed in 1.6–2.0 MeV background. All data outside of SAA orbits are included. (*a*) 1.75 MeV line; (*b*) 1.79 MeV line; (*c*) 1.81 MeV line. Curves in (*a*) and (*c*) follow the intensity variation of the instrumental background line due to ^{24}Na. The curve in (*b*) is the increase expected for production of ^{22}Na by exposure to the SAA and cosmic rays.

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1985ApJ...292L..61S

As seen in Figure 1*b*, the 1.79 MeV line feature in the background spectrum increased in intensity with time from launch. The dashed curve is a fit to the data representing the buildup in a radioactive line ($t_{1/2}$ = 2.6 yr) excited by a source proportional to the radiation dosage encountered by the detector as monitored by the ^{24}Na line intensity. The isotope ^{22}Na has a 2.6 yr half-life and is produced by spallation of aluminum in the detector's housing. The ^{22}Na decays with the emission of a positron and a 1.275 MeV γ-ray. A sum peak at 1.786 MeV results when a 0.511 MeV annihilation photon is detected simultaneously with the 1.275 MeV γ-ray. The observed line intensity is consistent with the measured 0.511 MeV and 1.275 MeV rates produced from the aluminum inside the instrument's housing.

The intensity of the background feature near 1.81 MeV, shown in Figure 1*c*, exhibits an overall decrease with time which appears to follow the trend of the ^{24}Na shown by the dashed curve. Therefore a large fraction of the contribution to the 1.81 MeV feature may come from a radioactive decay sequence. Comparing Figures 1*a*, 1*b*, and 1*c* we see that the 1.81 MeV feature contributes no more than about 25% to the complex of lines in that region. We also note the appearance of excesses in the 1.81 MeV intensity near ~ 350, ~ 700, and ~ 1050 days in Figure 1*c* in December when the Galactic center traversed the center of the instrument's aperture. In the next section we show that these excesses are due to Galactic ^{26}Al line radiation detected during portions of the *SMM*'s orbit when the Galactic center was not occulted by Earth.

IV. GALACTIC LINE RESULTS

The expected annual increase in the 1.81 MeV γ-ray line intensity as the Galactic center passes through the aperture of the spectrometer has been used to detect the ^{26}Al emission. In contrast to the data plotted in Figure 1*c*, only spectral data accumulated more than 10,000 s after the last significant passage through the SAA and with the detector axis within 72° of zenith are used to search for the Galactic emission. These sky-viewing data have been fit in the same manner as described in the previous section, i.e., with a model containing three lines (1.75, 1.79, and 1.81 MeV) and continuum in the 1.6–2.0 MeV region. The temporal variations of the lines are similar to those shown in Figure 1 with the exception that the annual modulation at 1.81 MeV is more significant, as would be expected for a celestial source, because only sky-viewing data are included.

In order to improve the significance of the fits, we reduced the number of parameters by using a model having a continuum and only two lines, fixed at 1.75 MeV and 1.81 MeV. The intensity of the fitted 1.81 MeV feature in this two-line fit is shown in Figure 2*a* as a function of time from 1980 February to 1983 September. The gradual increase is due to the growth of the nearby ^{22}Na background line (1.79 MeV) which is not resolved using this two-line procedure. Superposed is a striking increase that occurred in each of the 3 yr centered in the latter part of December. This is the time when the detector axis was pointed near the center of the Galaxy. The dashed curve represents a model having three terms: (1) a constant, (2) the buildup in intensity in a radioactive line excited by a source function proportional to the radiation dosage encountered by the detector, and (3) the calculated response of the instrument to a diffuse galactic source which follows the longitude distribution of > 100 MeV γ-rays (Mayer-Hasselwander 1983). The fitted half-life of the radioactive buildup is 2.0 ± 0.6 yr (half-life of ^{22}Na is 2.6 yr). The Galactic modulation is ~ 30% of the background. Its average amplitude is 0.030 ± 0.003 counts s^{-1}. There is no evidence for annual variability; the fitted rates are 0.031 ± 0.003, 0.031 ± 0.004, and 0.028 ± 0.005 counts s^{-1} for the three Galactic exposures in the winters of 1980, 1981, and 1982.

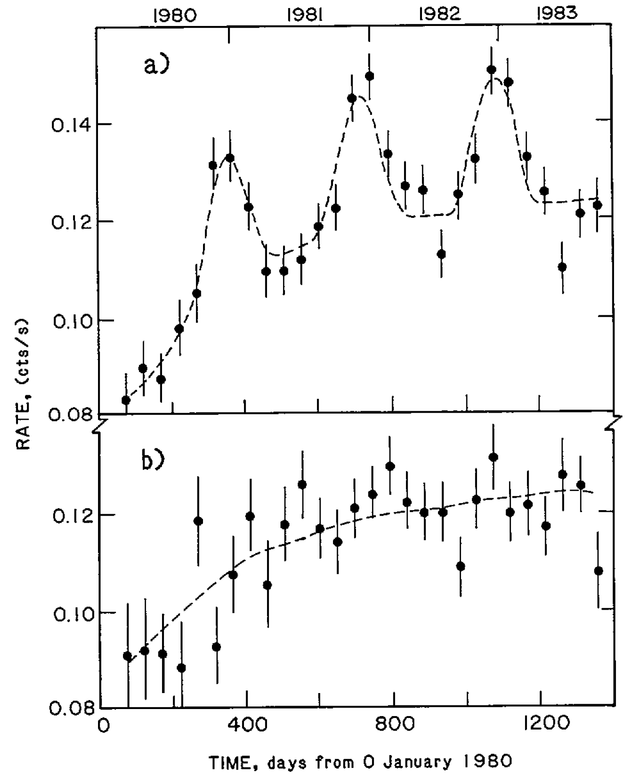

FIG. 2.—Variation in the intensity of a line at 1.81 MeV obtained when data for times > 10,000 s from the last SAA passage in the 1.6–2.0 MeV range are fit by a power-law continuum and lines at 1.75 and 1.81 MeV. The gradual increase in the 1.81 MeV intensity is due to the nearby ^{22}Na line which is not resolved in this two-line fit. (*a*) Sky-viewing data (zenith angle < 72°); (*b*) Earth-occulted data (> 108°).

In order to confirm that this modulation is a true Galactic phenomenon and not some systematic effect, we did the same analysis on different data sets. Shown in Figure 2*b* are the 1.81 MeV intensities obtained for zenith angles greater than 108° (i.e., with Earth filling a large part of the aperture). These data show the same radioactive buildup from ^{22}Na plotted in Figure 2*a*, but there is no evidence for an annual modulation. An extensive study was undertaken to identify local sources of the annual modulation. None were identified. The amplitude of the Galactic modulation did not change significantly when we restricted our data sample to reduce the instrumental background, e.g., by utilizing only data taken at high geomagnetic cutoff rigidity (> 11 GV), at times more than 20,000 s from the last passage through the SAA, or for zenith angles less than 36°. When we fitted the sky-viewing data with three lines (i.e., 1.75, 1.79, and 1.81 MeV) we obtained an average

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1985ApJ...292L..61S

amplitude of 0.038 ± 0.009 counts s^{-1} for the annual modulation at 1.81 MeV, consistent with the result obtained using only two lines. The only significant annual orbital effect that we know of is the $\pm 23°$ change in angle as the detector axis follows the seasonal variation of the Sun. This 23° change is small with respect to the instrument's 130° (FWHM) aperture and produces small background effects which are not associated with the 1.81 MeV emission. We therefore conclude that the observed annual modulation in the 1.81 MeV line feature is Galactic in origin.

We have obtained a spectrum of the Galactic line emission near 1.81 MeV by separately summing data within ± 45 days of Galactic center and Galactic anticenter transits during the 3.5 yr observing period. We then normalized the spectra by live time and subtracted the Galactic anticenter exposures from the Galactic center exposures for both zenith angles $< 72°$ and $> 108°$ (Earth-occulted data). The resulting count rate spectra from 1.6 to 2.0 MeV, not corrected for instrument response, are plotted on arbitrary scales in Figure 3. The continuum contains contributions from radioactive decay products and atmospheric photons which were not fully removed by the subtraction process due to the varying radiation environment; thus the contribution from any residual Galactic continuum cannot be assessed at present. A line near 1.8 MeV is clearly visible in the data viewing the sky, while it is not present in the data taken with Earth blocking the instrument's aperture. The fitted parameters of the line are energy = 1.804 $\pm$ 0.004 MeV, width = 102 $\pm$ 10 keV FWHM (includes instrumental broadening of 95 keV FWHM), and intensity = 0.036 ± 0.004 counts s^{-1}. The fitted energy and intrinsic line width (38^{+21}_{-38} keV FWHM) are consistent with a narrow line at 1.809 MeV from ^{26}Al. The intensity is consistent with what was obtained by fitting the time variation of the line.

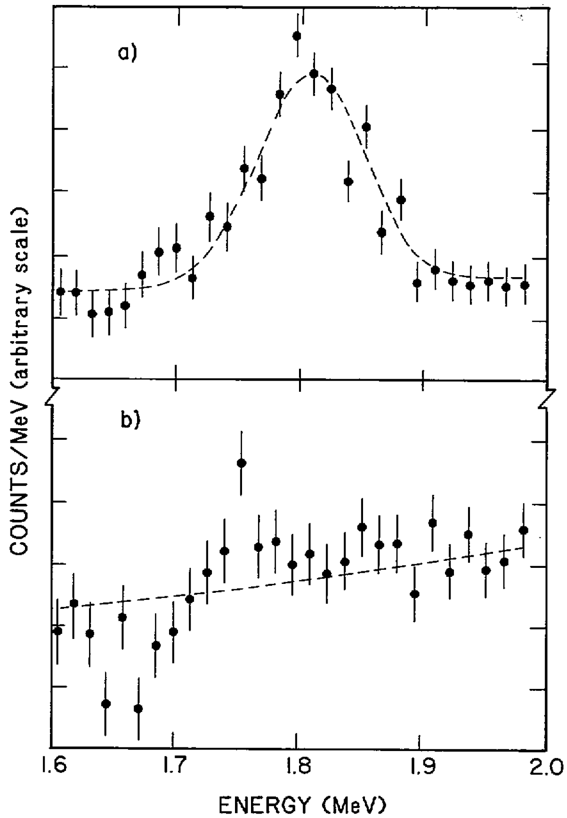

FIG. 3.—Count rate spectra, not corrected for instrument response, for the difference of Galactic center minus Galactic anticenter exposures from 1980 to 1983. (*a*) Sky-viewing data; (*b*) Earth-occulted data. The use of arbitrary scales reflects our uncertainty of the continuum intensities.

V. DISCUSSION AND SUMMARY

We have analyzed 3.5 yr of data from the γ-ray spectrometer on *SMM* and have observed an $\sim 10\ \sigma$ increase in the intensity of line radiation near 1.81 MeV when the Galactic center region traversed its aperture. Restricting data samples in order to reduce the effects of background in the instrument has no significant effect on the measured intensity of the line. All of our tests point to a celestial origin of the radiation. We have derived an energy spectrum by taking the difference between Galactic center and Galactic anticenter exposures. This difference spectrum shows the presence of a single line in the 1.6–2.0 MeV region having an energy 1.804 ± 0.004 MeV and intrinsic width 38^{+21}_{-38} keV (FWHM). This is consistent with narrow line emission at 1.809 MeV from interstellar ^{26}Al. Unambiguous identification of this line with ^{26}Al comes from the high-resolution *HEAO 3* measurements of its energy, 1808.49 ± 0.41 MeV, and width, < 3 keV (Mahoney *et al.* 1984).

The detection of interstellar 1.81 MeV line gamma radiation by both the *HEAO 3* and *SMM* spectrometers is convincing evidence for nucleosynthesis of ^{26}Al during the past 10^6 yr. It was initially believed that the integrated emission from Galactic supernovae could account for the observed γ-ray flux (Ramaty and Lingenfelter 1977); however, recent work indicates that this may not be the case (Clayton 1984; Fowler 1984). Clayton suggests that emission from dispersed novae can account for the ^{26}Al line emission, while Cameron (1984) points out that red giant stars are also a likely source. Alternatively Dearborn and Blake (1985) suggest that massive stars can synthesize and disperse a comparatively high flux of ^{26}Al.

One of the keys to determining the origin of the observed emission is its angular distribution (Leising and Clayton 1985). They find that the Galactic longitude distribution for novae is strongly peaked toward the Galactic center (> 50% are within 10° of the center). The distribution of CO, which monitors star formation and supernovae in the Galaxy, is broader and drops off in intensity only for longitudes more than 30° from the Galactic center. This distribution is similar to that observed for > 100 MeV Galactic γ-rays (Mayer-Hasselwander 1983) and that estimated for massive stars by Dearborn and Blake (1985).

The *SMM* results require a strong concentration in the direction of the Galactic center as evidenced by the striking annual modulation shown in Figure 2*a*. We have compared this modulation with calculations of the instrument's response to source distributions which either lie along the Galactic plane or are asymmetric in Galactic latitude. The centers of these distributions fall in an error box defined by 345° and 25° in Galactic longitude and $-15°$ and $+10°$ in latitude

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1985ApJ...292L..61S

(99% confidence). This is consistent with a source centered at the Galactic center. The width of the distribution cannot be defined as well with the *SMM* data. The best fit is obtained for longitude distributions which are as narrow or narrower than the observed > 100 MeV Galactic γ-rays; however, a distribution which is flat for $-90° < l^{II} < +90°$ and negligible at larger longitudes is acceptable at a confidence level of 2%.

We can also obtain a limit on the ^{26}Al emission from the anticenter direction by comparing intensities with and without Earth occultation (see Fig. 2). The result is independent of particle background, indicating that the atmosphere is not a significant source of 1.81 MeV line radiation. The 99% confidence upper limit for the 1.81 MeV line from the anticenter is 0.006 counts s^{-1}, but this needs to be corrected for leakage of the Galactic center emission through the rear of the detector. We estimate this leakage to be < 25% based on measurements of atmospheric γ-rays. From this we conclude that the anticenter flux is less than 40% of the flux of ^{26}Al line radiation from the direction of the Galactic center. For comparison, Leising and Clayton (1985) estimate that this ratio is ~ 6% for a novae distribution and ~ 17% for a CO distribution; the > 100 MeV γ-rays exhibit a slightly higher ratio, ~ 25%. We are therefore unable to use the *SMM* data to discriminate between these likely source distributions. Detailed spatial measurements will be available in a few years with the launch of NASA's *Gamma-Ray Observatory* and should enable the source of the ^{26}Al line to be determined.

The intensity of the ^{26}Al line averaged over the three *SMM* observation periods in 1980, 1981, and 1982 is 0.030 ± 0.003 counts s^{-1}. There is no evidence for any year-to-year variation in intensity. This intensity corresponds to a $(4.3 \pm 0.4) \times 10^{-4}$ γ (cm^2 s)$^{-1}$ excess in the γ-ray flux coming from the vicinity of the Galactic center. If we assume that the line emission follows the > 100 MeV Galactic γ-ray distribution (Mayer-Hasselwander 1983), this corresponds to a total flux of $(4.0 \pm 0.4) \times 10^{-4}$ γ (cm^2 s rad)$^{-1}$. This is consistent with the flux of $(4.8 \pm 1.0) \times 10^{-4}$ γ (cm^2 s rad)$^{-1}$ observed by *HEAO 3* in 1979/1980 (Mahoney *et al.* 1984).

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