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TGRS OBSERVATION OF THE GALACTIC CENTER ANNIHILATION LINE

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ABSTRACT

The Transient Gamma-Ray Spectrometer (TGRS) experiment is a high-resolution germanium detector launched on the *WIND* satellite on 1994 November 1. Although primarily intended to study gamma-ray bursts and solar flares, TGRS also has the capability of studying slower transients (e.g., X-ray novae) and certain steady sources. We present here results on the narrow 511 keV annihilation line from the general direction of the Galactic center accumulated over the period 1995 January through 1995 October. These results were obtained from the TGRS occultation mode, in which a lead absorber occults the Galactic center region for $\frac{1}{4}$ of each spacecraft rotation, thus chopping the 511 keV signal. The occulted region is a band in the sky of width 16° that passes through the Galactic center. We detect the narrow annihilation line from the Galactic center with flux = $(1.64 \pm 0.09) \times 10^{-3}$ photons cm^{-2} s^{-1}. The data are consistent with a single point source at the Galactic center, but a distributed source of extent up to ~30° cannot be ruled out. No evidence for temporal variability on timescales longer than 1 month was found.

Subject heading: gamma rays: observations

1. INTRODUCTION

Electron-positron annihilation radiation is a valuable diagnostic for studies of a variety of different types of astrophysical sources. Positrons can be produced by hot pair plasmas in the vicinity of compact objects, by nucleosynthetic processes (both hydrostatic and explosive) and by cosmic-ray interactions in the interstellar medium (ISM). A narrow 511 keV electron-positron annihilation line (~3 keV FWHM) has been observed from the general direction of the Galactic center (see Teegarden 1994 and Ramaty & Lingenfelter 1995 for recent reviews). Data from a series of balloon observations in the late 1970s and 1980s suggested that the line was variable. These same instruments had a variety of different fields of view, and it was noted (see Teegarden 1994) that the detected flux varied systematically with the size of the field of view. This implied that there was also a diffuse steady component to the narrow 511 keV emission. Subsequent satellite observations with *SMM* (Share et al. 1990) and *CGRO*/OSSE (Purcell et al. 1993, 1994) found no evidence for variability. *CGRO*/OSSE has now mapped the Galactic center region with its 3° × 11° collimator (Purcell et al. 1993, 1994). The OSSE data can be well represented by a two-component distribution consisting of a central bulge component of width ~8° combined with a disklike component. Of the total flux, ~75% is contained in the bulge component and ~25% in the disk component.

The *Granat*/SIGMA experiment reported episodes of transient broad line emission, lasting typically a fraction of a day, from the source 1E 1740.7−2942, which lies within 1° of the Galactic center (Bouchet et al. 1991; Sunyaev et al. 1991; Cordier et al. 1993). The line energy was ~480 keV, and it was broadened to ~130 keV. The features were interpreted as electron-positron annihilation radiation redshifted by the strong gravitational field of a black hole (Bouchet et al. 1991; Sunyaev et al. 1991). It has been suggested (Ramaty et al. 1992) that sources such as these can inject positrons into the ISM which can travel substantial distances before annihilating. An ensemble of such sources could be responsible for the diffuse narrow 511 keV emission from the direction of the Galactic center.

2. INSTRUMENTATION

Transient Gamma-Ray Spectrometer (TGRS) is an unshielded high-resolution 35 cm^2 germanium detector passively cooled to a temperature of 85 K (for more detail see Owens et al. 1995). Its energy range is ~20–8000 keV, and the energy resolution after launch was ~2.7 keV FWHM at 500 keV. TGRS was launched on the *WIND* spacecraft on 1994 November 1. The primary purpose of the *WIND* mission is to sample conditions in interplanetary space in the vicinity of the Earth's magnetosphere. Although in Earth orbit, *WIND* spends the great majority of the time in interplanetary space. As a consequence the environment is generally quite stable (background levels, temperatures, etc.) which lends itself quite well to the long data accumulations necessary for the analysis described in this paper. A schematic view of the detector/occulter assembly is shown in Figure 1. The main axis of the

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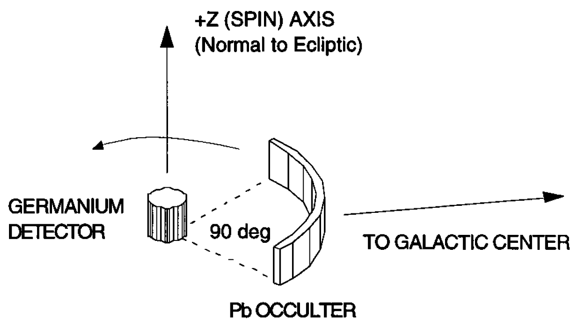

FIG. 1.—Schematic view of the TGRS detector/occulter. The spacecraft spin axis is coincident with the detector axis and normal to the ecliptic plane. The occulter subtends an angle of 90° × 16° (FWHM) with respect to the detector.

detector is coincident with the spin axis of the spacecraft, which is normal to the plane of the ecliptic. The $+Z$ axis of the spacecraft (and the TGRS main field of view) is oriented towards the south ecliptic pole. This orientation was chosen so that the Large Magellanic Cloud (presumed location of the 1978 March 5 gamma-ray burst) is in the TGRS field of view. The occulter is a 1 cm thick lead absorber located just outside of the radiative cooler in the plane of the detector, which subtends an angle of 90° with respect to the detector. Additional structure and shielding (not shown in Fig. 1) limit the low-energy threshold in the occultation mode to ~40 keV. The on-board processor accumulates data in four commandable energy windows (64 channels each) synchronized with the spin of the spacecraft. One of these is centered on the 511 keV annihilation line. Each spacecraft rotation (3 s) is divided into 128 sectors. One complete accumulation of all spin-synchronized data takes ~2 hr, which defines the minimum time resolution in this mode.

Figure 2 shows in Galactic coordinates the region of the sky that is occulted (FWHM = 16°) by TGRS. The occulter has been offset by an angle of 5°.5 with respect to the spin plane to make the center of the occultation band coincide with the Galactic center. The Crab also lies within the occultation region. Also shown in Figure 2 is a contour plot of the OSSE 511 keV flux distribution (Purcell et al. 1994). As can be seen, the TGRS occulter modulates most of the flux in the central bulge component of the OSSE distribution.

3. OBSERVATIONS

Preliminary data are presented here for the period 1995 January–October. The excellent stability of the instrument allows accumulations of long periods of data with no requirement for gain corrections. The 511 keV background line has

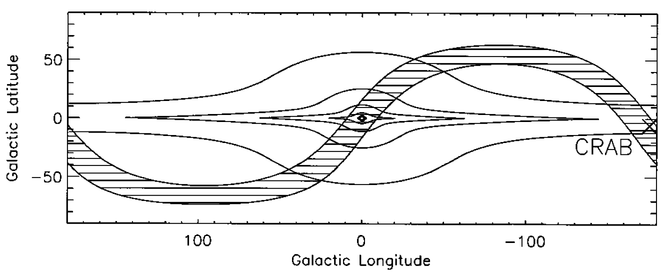

FIG. 2.—Band of the sky modulated by the TGRS occulter. Also shown is a contour plot of the 511 keV annihilation radiation as measured by OSSE. Contours are logarithmically spaced with a ratio between contours of 3.5. The location of the Crab, which lies within the occulation band, is also shown.

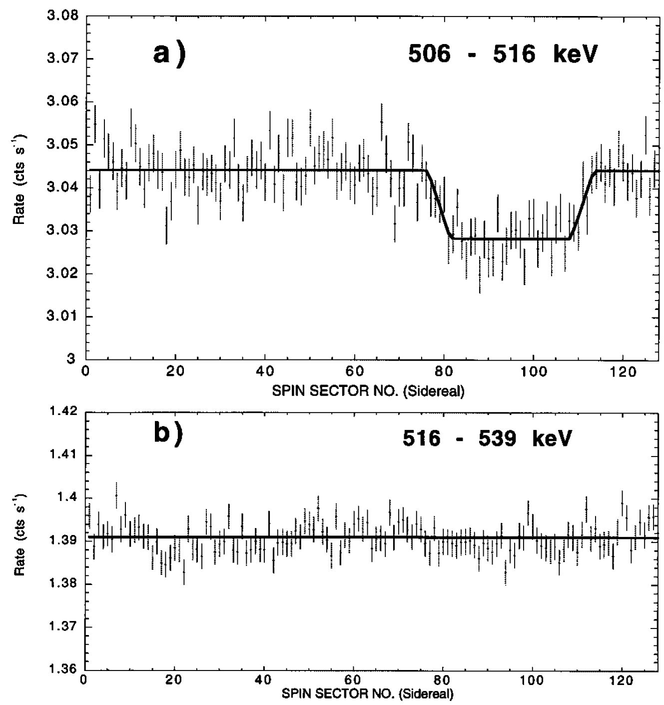

FIG. 3.—Counting rate as a function of spacecraft spin sector (128 sectors spin^{-1}). Data are accumulated between 1995 January 1 and 1995 October 27 (300 days). (*a*) Energy range 506–516 keV. Solid line is best-fit single point source model. The location is consistent with Galactic center. (*b*) Energy range 516–539 keV. No evidence for a significant source at the Galactic center is present.

been used for gain calibration. Figure 3*a* shows the counting rate in a window 10 keV wide centered on the 511 keV line versus the spin phase of the spacecraft, which is divided into 128 bins. The on-board accumulation is synchronized by a Sun sensor, and the data have been corrected for the sidereal variation of the phase. The solid line is the best fit to the data [χ^2 = 155, 125 degrees of freedom, $P(\chi^2, \nu) = 0.036$] for a single point source model in which the amplitude and position of the source are allowed to vary. The best-fit value for the source flux is $(1.64 \pm 0.09) \times 10^{-3}$ photons cm^{-2} s^{-1} and for the sector number of the source is 95.3 ± 0.4. The sector number corresponding to the Galactic center is 94.9. To check for systematic effects that could mimic the signal from the Galactic center, a control region (516–539 keV) adjacent to the 511 keV window was also examined. This is shown in Figure 3*b*. There is no evidence for any significant signal from the direction of the Galactic center. A small residual in the sector range 15–40 is present due to hard X-ray emission from the Crab.

The data have been tested for the possible presence of a broadened source. Two broadened models (rectangular and Gaussian profiles in ecliptic longitude) were fitted to the data. While the best-fit values for the widths were nonzero (21° in the rectangular case and 16° in the Gaussian case) the reduction in χ^2 was not significant (for both models $\Delta\chi^2$ = 2124 degrees of freedom). The 90% confidence upper limit on the width of the rectangular model is 34° and on the FWHM of the Gaussian model is 30°. *The TGRS data are therefore consistent with a point source at the Galactic center; however, an extended source distribution with width up to ~30° cannot be ruled out.*

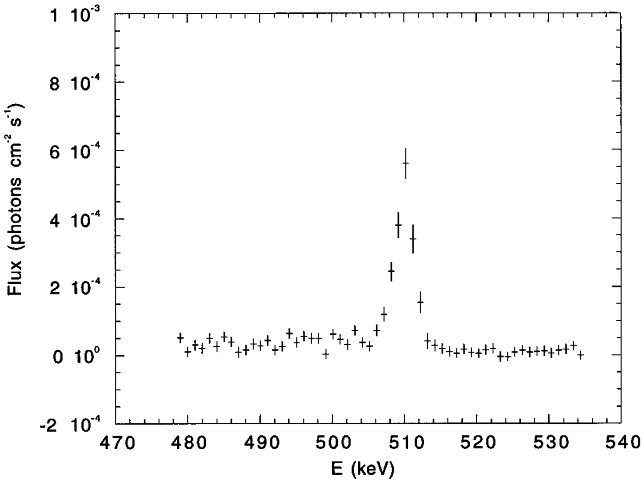

FIG. 4.—TGRS spectrum in vicinity of 511 keV line. Data accumulated from 1995 January 1 to 1995 October 27. Energy of line is consistent with 511 keV.

Figure 4 shows the channel-by-channel spectrum in the vicinity of 511 keV derived from the TGRS occultation data. The spectrum was calculated for an assumed point source at the Galactic center. The data over the 300 day period were accumulated as a function of energy and spin phase. The spectra were derived as follows. Let $C_i(E_j)$ = number of observed counts in the ith spin sector and the jth energy channel, M_i = transmission of occulter for the ith spin sector, $S(E_j)$ = source counts in the jth energy channel, and $B(E_j)$ = background counts in the jth energy channel. Over the limited band of energy in question (506–516 keV) M_i is taken to be independent of energy. The counts in each sector and energy bin are then given by

$$C_i(E_j) = M_i S(E_j) + B(E_j) . \quad (1)$$

The source spectrum is derived by linear regression on $C(E_j)$ of M, with a constant term. The coefficient of M gives the source flux and the constant B gives the background at E_j. This is equivalent to the previously discussed model fit with the source location held fixed (at the best-fit value) and the energy range restricted to a single energy channel.

The spectrum in Figure 4 displays a narrow line at 511 keV. A Gaussian fit to the line yields a flux of $(1.64 \pm 0.08) \times 10^{-3}$ photons cm^{-2} s^{-1} in excellent agreement with that derived from the data of Figure 3. There is a suggestion of line broadening. However, no gain shift corrections have been applied to the data, and there may as a result be some broadening beyond the normal instrumental resolution. Further careful analysis will be necessary to remove this effect (and possibly others) to obtain a reliable absolute value for the line width.

Figure 5 is a time history of the intensity of the Galactic center 511 keV line plotted on a monthly basis. The data points were derived by determining the best-fit values for the flux using the TGRS spin sector data such as shown in Figure 3. A single point source was assumed, and both the flux and position were allowed to vary. In all cases the best-fit position was consistent with Galactic center. The data are consistent with a constant flux with a χ^2 probability of ~17%.

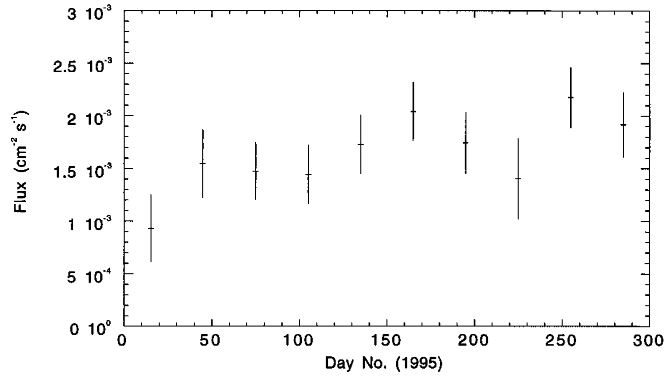

FIG. 5.—Time history of 511 keV line intensity during 1995

4. DISCUSSION

Through its occultation mode TGRS has detected a significant (~20 σ) flux of 511 keV emission from the direction of the Galactic center. The region observed corresponds to a band in the sky of FWHM 16° offset by −5.5° from the ecliptic plane, which passes through the Galactic center (see Fig. 2). Purcell et al. (1994) have fit the OSSE 511 keV data with a diffuse distribution consisting of a central bulge component and a disk component (see Fig. 2). The respective fluxes in these two components are 1.7×10^{-3} photons cm^{-2} s^{-1} and 0.5×10^{-3} photons cm^{-2} s^{-1}. If one convolves the OSSE model distribution with the TGRS occulter modulation function (for the occulter centered at the Galactic center), one obtains an occulted flux of 1.5×10^{-3} photons cm^{-2} s^{-1}. This is to be compared with the measured TGRS occulted flux of $(1.64 \pm 0.09) \times 10^{-3}$ photons cm^{-2} s^{-1}*. The TGRS and OSSE absolute flux measurements are therefore mutually consistent at approximately the 1 σ level.

The TGRS data can be well fit by a point source at an ecliptic longitude of 268.0 ± 1°.2 (J2000) which is 1.0 σ from the Galactic center (ecliptic longitude = 266°.8). The ecliptic longitude of the source 1E 1740.7−2942 is 266°.4 or within 1.3 σ of the best-fit TGRS position. The TGRS 511 keV source position is therefore consistent with both the Galactic center and the 1E 1740.7−2942 source. Because of the proximity of the TGRS occulter to the germanium detector, and the finite size of the detector itself, the effective TGRS point spread function is rather large (see Fig. 3). It is therefore not possible to make a definitive statement on the spatial extent of the source. The data were fitted with two different broadened source distributions, rectangular and Gaussian. While the best-fit values for the width were nonzero (21° for rectangular and 16° FWHM for the Gaussian distribution), the change in χ^2 was not significant ($\Delta\chi^2 \simeq 2$ in both cases). The 90% confidence upper limits on the widths were 34° for the rectangular model and 30° FWHM for the Gaussian model.

The historical evidence for variability in the Galactic center 511 keV flux comes primarily from a series of balloon flights from the late 1970s to the early 1990s. Two flights in 1981 (Leventhal et al. 1982; Paciesas et al. 1982) and one in 1985 (Leventhal et al. 1986) found no detectable narrow 511 keV line flux. These instruments had fields of view in the 15°–20° range and sufficient sensitivity to detect emission at the levels implied by the OSSE data. Teegarden (1994) showed that these data were inconsistent with a constant flux at the 1% level. However, the error estimates generally did not include systematic effects, which could reduce the significance of the time variation. Initial results from *HEAO 3* suggested a variation in the Galactic center 511 keV flux between the fall of 1979 and the spring of 1980 (Riegler et al. 1981). However, a subsequent re-analysis by Mahoney et al. (1993) reduced the variation to an insignificant value. None of the other satellite observations (*SMM*, *CGRO*/OSSE, *WIND*/TGRS) have found any evidence for temporal variability. The available body of evidence weighs most heavily in favor of a constant diffuse source for the narrow Galactic center annihilation radiation, although a variable point source at a level $<2 \times 10^{-4}$ photons cm^{-2} cannot be ruled out (Ramaty et al. 1994; Purcell et al. 1994).

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