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SMM OBSERVATIONS OF GAMMA-RAY TRANSIENTS. III. A SEARCH FOR A BROADENED, REDSHIFTED POSITRON ANNIHILATION LINE FROM THE DIRECTION OF THE GALACTIC CENTER

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ABSTRACT

We have searched the 1980–1988 *Solar Maximum Mission* gamma-ray spectrometer data for transient emission on timescales from hours to ~12 days of broad γ-ray lines at energies $\simeq$400 keV, which were reported by the *HEAO 1* and SIGMA experiments from two sources lying toward the Galactic center. The lines have been interpreted as the product of the annihilation of positrons in pair plasmas surrounding the black hole candidate 1E 1740.7−2942 and the X-ray binary 1H 1822−371. Our results from a combined exposure of $\sim 1.5 \times 10^7$ s provide no convincing evidence for transient emission of this line on any timescale between ~9 hr and ~1 yr. Our 3 σ upper limits on the line flux during ~12 day intervals are characteristically 4.8×10^{-3} photon cm^{-2} s^{-1}, while for ~1 day intervals our 3 σ upper limits are characteristically 4.9×10^{-3} photon cm^{-2} s^{-1}. These results imply a duty cycle of less than 1.3% for the transient line measured from 1H 1822−371 during a ~3 week interval in 1977 by *HEAO 1*, and a duty cycle of $\leq$0.8% for the transient line detected in 1990 and 1992 from 1E 1740.7−2942 on ~1 day timescales by SIGMA.

Subject headings: Galaxy: center — gamma rays: observations

1. INTRODUCTION

A strong transient broad γ-ray line at an energy around 400 keV has been reported from sources near the Galactic center (GC) on four separate occasions by two separate experiments. The A-4 instrument on the *HEAO 1* satellite detected a line of intensity $7.4 \pm 1.5 \times 10^{-3}$ photon cm^{-2} s^{-1} at 487 ± 30 keV, with a FWHM of 290 ± 64 keV, during an exposure of ~1 month to the GC region during 1977 September (Briggs 1991; Briggs et al. 1991, 1994); the source has been tentatively identified as the low-mass X-ray binary 1H 1822−371. Line emission from the other source, the black hole candidate 1E 1740.7−2942, has been reported no fewer than three times by the SIGMA experiment on the *Granat* spacecraft, as described below. These observations are of considerable interest in connection with the longstanding problem of whether or not the strong, narrow 511 keV positron (e^+) annihilation line from the direction of the GC is time-variable, implying the presence of one or more point sources. The broad line described above is most naturally interpreted as a broadened, redshifted 511 keV line, arising in a strong gravitational field at high temperatures. The sources of the broad line are therefore plausible contributors to the e^+ which annihilate to form the narrow line, accounting for its variability. For one of the two sources, 1E 1740.7−2942, a model has been proposed in which the e^+ are created episodically in a pair plasma in the very hot central region of an accretion disk around the black hole (Ramaty et al. 1992); the broad ~400 keV line may be the signature of such a plasma. A flux of e^+ may escape from the system to annihilate in the much colder molecule cloud which surrounds 1E 1740.7−2942 (Bally & Leventhal 1991), producing the narrow 511 keV line after a time lag of ~1 yr.

The reality of at least one of the measurements of the line has recently been called into question. The emission from 1E 1740.7−2942 was first detected by SIGMA during a 17 hr period on 1990 October 13, at a level of $6.2 \pm 1.6 \times 10^{-3}$ photon cm^{-2} s^{-1} (Bouchet et al. 1991; Sunyaev et al. 1991; Gilfanov et al. 1994); then as a steady feature present in the spectra during 1991 October 1–19 at a level of $3.4 \pm 1.1 \times 10^{-3}$ photon cm^{-2} s^{-1} (Churazov et al. 1993; Gilfanov et al. 1994); and, again, on a ~1 day timescale at a level $4.3^{+2.7}_{-1.5} \times 10^{-3}$ photon cm^{-2} s^{-1}, on 1992 September 19–20 (Cordier et al. 1993b; Gilfanov et al. 1994). However during the last of these periods the Oriented Scintillation Spectrometer Experiment (OSSE) on board the *Compton Observatory* made an observation of the GC which failed to show the broad-line feature (Jung et al. 1994).

An experiment to monitor the GC for long periods provides the capability of detecting or placing limits upon past outbursts of the source. We have used data taken by the Gamma Ray Spectrometer (GRS) on board the *Solar Maximum Mission* (*SMM*), whose characteristics—a long lifetime (almost 10 yr), exceptional gain stability, sensitivity to energies between 0.3 and 8.5 MeV, and a broad aperture—make it very suitable for this purpose. Since *SMM* was pointed at the Sun during the period 1980–1989, and since the FWHM of the GRS aperture at these energies is about 140°, the GC appeared to move slowly across the aperture during the ~140 day period centered on December 15 each year, as the Sun passed in front of it. A drawback of this wide field of view is that the GRS could not resolve sources within it. Thus we cannot distinguish between outbursts of 1E 1740.7−2942 and 1H 1822−371, or other nearby sources, and their exposures to the GRS were almost identical.[1]

The GRS was described fully by Forrest et al. (1980). Apart from the seven 7.6 × 7.6 cm NaI crystals forming the detector, it included CsI anticoincidence shields to the sides and rear, and plastic detectors at the front and back of the instrument to reject charged particles. The detector outputs were summed into 476 energy channels between 0.3 and 8.5 MeV; an extremely stable active gain control system operated during the entire mission. The GRS's energy resolution at 400 keV was about 35 keV FWHM, which is much less than the characteristic widths of the reported transient lines. Its effective area at 400 keV was approximately 160 cm^2. The data were obtained in 16.384 s accumulations, interrupted by passages of the South Atlantic Anomaly (SAA, during which time the detector was turned off), and by ~ 5 minute periods devoted to in-orbit calibrations performed typically once per orbit while the GRS was pointed towards Earth.

2. ANALYSIS

We searched for transient emission of lines at the several reported energies and over timescales comparable to those implied by the earlier reports. Our search for variability on time scales ~ 12 days used the analysis technique which we described in previous papers in this series (Harris et al. 1993, 1994, hereafter Papers I and II). It is therefore merely summarized here (§ 2.1). We used a rather different analysis in order to investigate variability on ~ 1 day timescales, which is described in § 2.2. The data analyzed were the 1 minute sums of GRS spectra taken during the periods 1980 February–1983 November and 1984 April–1989 February (the gap occurring prior to the in-orbit repair of *SMM*), from which data coinciding with known transient backgrounds such as solar flares and γ-ray bursts were removed. Data from orbits passing through the SAA, and from the $\sim 10^4$ s after such a passage, were also rejected.

2.1. *Variability on 12 Day Timescale*

Since no offset pointings for background subtraction were made by *SMM*, our analysis was based on the fact that, over the 10 year life of the mission, conditions of identical background recurred. Each 1 minute spectrum during 1980–1989 was considered in turn as a "source" spectrum, for which we identified a previous 1 minute spectrum which was both exposed to the same celestial source and subjected to the same backgrounds (as far as could be determined). We subtracted the background spectrum from the source spectrum to determine the *change* in the spectrum from the celestial source between the two widely separated minutes—clearly, any steady signal from the celestial source would be subtracted out using this method.

In the search for variability on 12 day timescales, the "background" 1 minute spectrum was obtained from ~ 1 yr earlier in the mission (in fact, eight *SMM* precession periods). Each 1 minute spectrum was labeled with the values of the parameters which determined the background, namely the geomagnetic field strength, the satellite's geographic position, the Sun-Earth-satellite angle, and the phase of that minute within the satellite's ~ 47 day period of precession with respect to the Sun (see Paper I). The "source" spectra were thus restricted to the interval 1981 February–1989 February. We then identified that "background" spectrum from 1 yr previously which had the closest values of the above parameters.[2] The background-subtracted 1 minute spectra were then summed over 12 day intervals into two bins, according to whether the GC was occulted by Earth or not. We then subtracted each 12 day Earth-occulted spectrum from the unocculted spectrum, to remove backgrounds due to the change since the previous year in the intensity of long-lived radioactivities in the spacecraft and detector. The residual spectrum (year-minus-year-before, unocculted-minus-occulted) contains the change in the spectrum of the GC since the previous year; an example is shown in Figure 1.

A model containing the expected transient line was fitted to these residual spectra in order to perform the search (§ 2.3). These spectra contain a residual background contribution from Earth's atmosphere, due to imperfect subtraction (Paper I), which was taken into account during the fitting.

2.2. *Variability on ≤ 1 Day Timescale*

It is clearly advantageous to obtain background spectra which are as close as possible in time to the source spectrum. In the case of transients lasting for less than 1 day, we made use of a background substraction method in which the background spectra were obtained from $\simeq 1$ day before and $\simeq 1$ day after the source spectrum (Share et al. 1993).

As noted previously, the background radiation in the GRS has been found to depend upon the geomagnetic field strength, the satellite's geographic position, the Sun-Earth-satellite angle, and the phase of the spectrum within *SMM*'s ~ 47 day Sun-oriented precession period. A shift of ± 1 day is sufficiently small that the discrepancy in precession period phase can be neglected. Furthermore, any combination of Sun-Earth-satellite angle and geographic and geomagnetic positions will approximately repeat after 24 hr, and the exposure of the GRS to the celestial source is virtually unchanged by the lapse of 1 day. We therefore sought background spectra from epochs which were behind and ahead of the source spectrum by 15 of *SMM*'s ~ 94 minute orbits, which are very close to 1 day before and after.

Spectra were summed to 3 minutes on the day containing the source spectrum and the days before and after. A search was made among the 3 minute spectra from 15 orbits before and after for those accumulated within 9° of the geographic latitude and longitude of the "source" spectrum. The search was restricted to intervals ± 6 minutes around the positions corresponding to the lapse of exactly 15 orbits. The two background spectra were summed; if only one background could be identified no selection was made and the source spectrum was rejected.

We accumulated only the source and background spectra over that part of each orbit during which the GC was not occulted by Earth (the Earth disk typically subtended $\sim 140°$ from *SMM*, so that the GC was visible for ~ 60 minutes out of each 94 minute orbit). The summed background spectra were

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[1] A search of the *SMM* data for similar transient lines from directions other than the GC, for example the line reported from Nova Muscae by Sunyaev et al. (1992) and Goldwurm et al. (1992), is in progress (Leising et al. 1994).

[2] For source spectra taken 1 yr after the 1983–1984 data gap, we used background spectra from 2 yr earlier (16 precession periods).

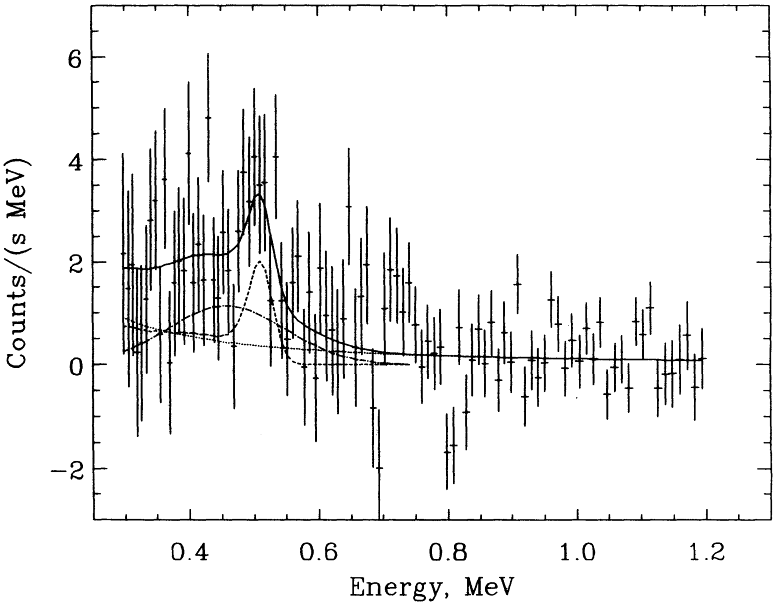

FIG. 1.—Residual spectrum of the GC for the 12 day period 1982 October 24–November 4. *Full line:* fitted model spectrum consisting of *dotted line:* power law continuum; *dashed line:* narrow line at 511 keV plus Compton-scattered continuum; *dot-dashed line:* broad 457 keV line. The inferred flux in the broad line is $1.6 \pm 1.0 \times 10^{-3}$ photon cm^{-2} s^{-1}.

subtracted from the summed source spectra to yield 60 minute "transient" spectra from the GC,[3] which were searched for evidence of the transient line by the spectrum-fitting method described in § 2.4. Examples of "transient" spectra on this 60 minute timescale are shown in Figure 2.

The satellite's passages through the SAA, and the choice to wait $\sim 10^4$ s afterward for the induced radioactivities to decay, reduced the number of orbits per day to which this technique could be applied. Characteristically, a group of four to eight orbits out of the 15 performed during a day were analyzed, followed by a gap of ~14 hr before the next day's group of orbits. In general, the "source" spectra in one orbital accumulation will appear among the "background" spectra for the corresponding orbits in the groups on the days before and after. It follows that, everything else being equal, a positive signal in the source spectrum (due either to a genuine transient from the celestial source, or to a background event) will be accompanied by two negative signals with 50% of the amplitude in the spectrum of the corresponding orbit on the previous and subsequent days.[4]

2.3. *Spectral Fits:* 12 *Day Timescale*

We searched for the reported transient redshifted e^+ annihilation lines by fitting the residual spectra obtained by the analyses of §§ 2.1, 2.2 with models including such lines. However, imperfect background subtraction leads to the presence of other features in the residual spectra which must also be included in the fits. The major residual feature in the 12 day spectra is due to albedo γ-rays from Earth's atmosphere (Paper I), whose spectrum has a well-known form (Letaw et al. 1989). In the spectral region 0.3–1 MeV, this spectrum may be approximated by a power law, on which are superposed a line at 511 keV and a rather flat continuum below 511 keV due to atmospheric Compton scattering of 511 keV line photons. We therefore fitted each 12 d residual spectrum by a model having four components, which closely resembled the spectrum models used in Paper II. The three components comprising the residual Earth-albedo spectrum were a narrow line at 511 keV, a Compton-scattering continuum, and an underlying power law. The fourth component was a broad Gaussian line corresponding to the reported transient. The published reports specify slightly different energies and widths for the feature, so we repeated the fits with slightly different parameters for the Gaussian line. The three combinations considered were line energy 380 keV, FWHM 235 keV (after Gilfanov et al. 1994), energy 457 keV and FWHM 214 keV (Briggs et al. 1991), and energy 487 keV, FWHM 282 keV (Briggs et al. 1994). Figure 1 shows an example of the four components of such a fit.

The fit was performed by folding the models through the GRS instrument response function and varying the parameters of the model components until the best agreement was obtained with the count spectrum according to the method of least squares. The amplitudes found for the transient line features during the periods when the GC was within the GRS FWHM field of view were arranged in time series at 12 day intervals.

As noted in Papers I and II, when the year-minus-year-before background subtraction was used, a weak systematic error was found in the measured transient line strengths due to the presence of the underlying Earth-albedo spectrum (from

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[3] By contrast with the analysis on 12 day timescales described in the previous section, spectra obtained when the celestial source is occulted by Earth were *not* accumulated to be used in a further subtraction to remove long-term(~1 yr) backgrounds. This makes the analysis described here relatively much more sensitive, since if occulted spectra are subtracted the difference contains the statistical error in those spectra. This statistical error is substantially larger than that in the unocculted spectra, which characteristically contain at least twice as much live time in each orbit.

[4] A similar argument was used in Appendix B of Paper I to show that, on ~12 day timescales, the signal from a transient event analyzed as described in § 2.1 would be followed ~1 yr later by an equal negative signal.

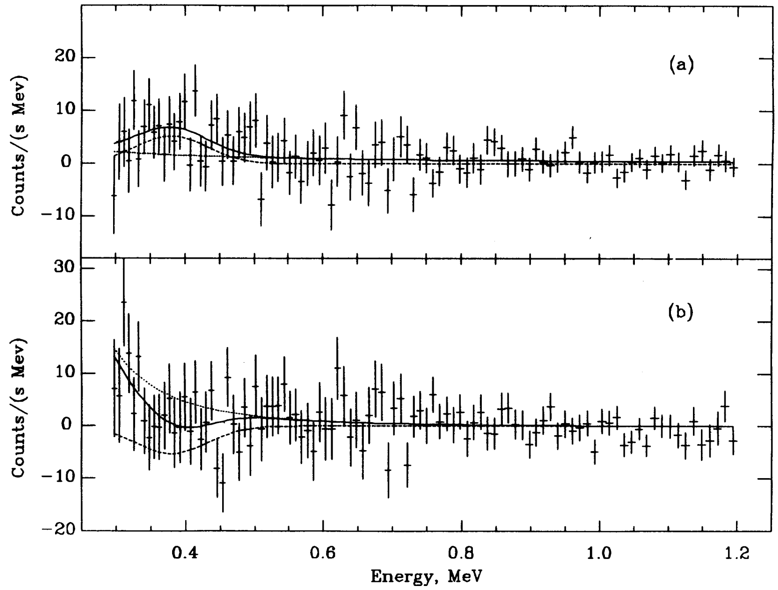

FIG. 2.—(*a*) Residual spectrum of the GC on orbital (~90 minute) timescale for 1988 April 18, $21^{\rm h}10^{\rm m}$–$22^{\rm h}09^{\rm m}$ UT. *Full line:* fitted model spectrum consisting of *dotted line:* power law continuum; *dashed line:* broad 380 keV line. The inferred flux in the line is $4.0 \pm 1.9 \times 10^{-3}$ photon cm^{-2} s^{-1}. (*b*) Residual spectrum of the GC on orbital (~90 minute) timescale for 1981 June 3, $16^{\rm h}39^{\rm m}$–$17^{\rm h}37^{\rm m}$ UT. *Full line:* fitted model spectrum consisting of *dotted line:* power-law continuum; *dashed line:* broad 380 keV line. The inferred flux in the line is $-4.5 \pm 2.5 \times 10^{-3}$ photon cm^{-2} s^{-1}.

which the line could not be sharply separated due to its width) in cases of imperfect background subtraction. The presence of this same systematic effect is shown by a correlation between the 12 day time series of broad line strengths and the count rates in the GRS back plastic charged-particle detector (see Paper I), which in turn are correlated with the intensity of Earth albedo radiation. We derived a correction factor for the measured transient line intensities from the back plastic detector count rates, on the basis of this correlation. The procedure is identical to that described in § 2.3.2 of Paper I.

2.4. *Spectral Fits: ≤1 Day Timescale*

In the case of the ≤1 day timescale analysis (§ 2.2), the background subtraction was very effective in eliminating the Earth albedo radiation, and the residual spectra were generally featureless and close to zero. We fitted these spectra by a power law on which was superposed the Gaussian line expected from the transient source on ~1 day timescales, at energy 380 keV with FWHM 118 keV (the weighted means of two measurements by Gilfanov et al. 1994). Note that this line is considerably narrower than the lines reported for the longer timescale transients, which greatly improves the GRS's sensitivity to it. Examples of fits using this model spectrum are shown in Figure 2.

The transient line amplitudes on ~60 minute timescales found by these fits during the periods when the GC was within the GRS field of view were arranged in a time series. Since they fell into well-defined daily groups (§ 2.2), we also co-added them on a daily basis to yield a time series of 1 day amplitudes for the relevant line (note, however, that the actual measurements typically cover only ~6–12 hr of each day).

Systematic effects in the time series of transient line strengths on orbital and 1 day timescales are small. The strengths of the weak continuum residuals are correlated with the level of solar activity, as monitored by radio flux at 2800 MHz measured daily at Ottawa, Canada, by the Herzberg Institute of Astrophysics;[5] the correlation is particularly marked during the 1980–1981 maximum of sunspot cycle 21. It is clear that the solar activity gives rise to magnetospheric disturbances on ≤1 d timescales, which have the effect of altering the geomagnetic field parameters at either of what should be two identical locations in orbits separated by ±1 day. In these cases our background method would not be reliable, but the effect does not appear to be strong (see § 3.2.2).

Figure 2*b* illustrates a spectral anomaly in the residual continua between 300 and 600 keV which arises from this cause—a departure from the general power-law shape in the direction of excess continuum at the lowest GRS energies, just above 300 keV. It can be seen from Figure 2*b* that this tends to generate a systematic error in the transient line flux which is opposite in sign to the power-law continuum. We emphasize, however, that such anomalies are rare, the event shown in Figure 2*b* being one of the worst cases.

3. RESULTS

3.1. *Results: Variability on 12 Day Timescale*

The 12 day time series of transient line intensities at 380 and 487 keV are shown in Figures 3 and 4. Neither time series shows compelling evidence of the occurrence of any celestial transient event; in particular, there are no good examples of a positive excursion followed ~1 yr later by a negative excursion (see footnote 4 to § 2.2). In Figure 5 we show the distributions of our measurements of the transient fluxes in all three lines, in terms of statistical significances. In general the measurements follow Gaussian distributions about zero flux, with a few outlying points of significance ≥3 σ. We again emphasize that we do not regard these outlying points as real transients, since the

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[5] For comparison with background-corrected *SMM* spectra, the 2800 MHz fluxes from the days before and after were subtracted in the way described in § 2.2

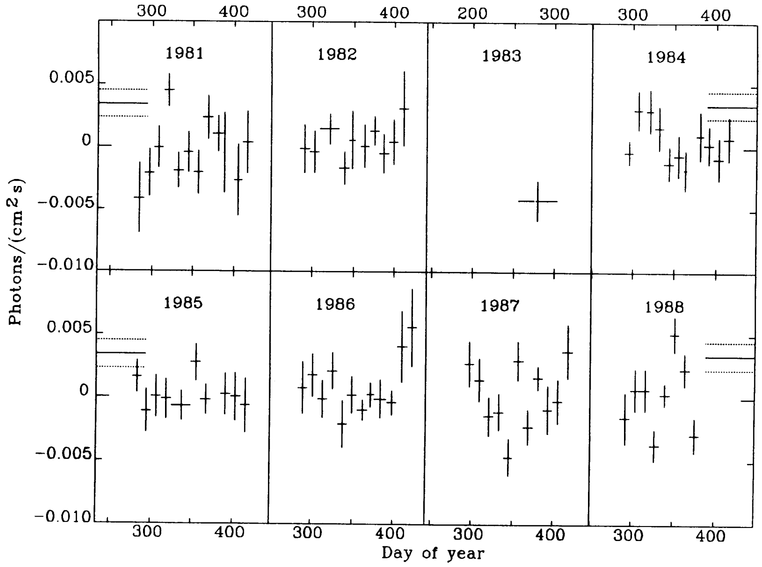

FIG. 3.—Inferred fluxes of transient emission from the GC of a line at 380 keV of FWHM 235 keV during 12 day intervals, 1981–1989 (data points and 1 σ errors). Also the flux observed from 1E 1740.7−2942 during 1991 October 1–19 by SIGMA (*full lines* at left and right edges), and 1 σ errors upon it (*dashed lines* at left and right edges).

negative points do not follow the expected pattern of occurrence ~1 year following the positive points.

Shown for comparison with our results are the fluxes reported by SIGMA in 1991 October (Fig. 3) and *HEAO 1* (Fig. 4). It is clear that our results in Figure 3, although negative, lack the sensitivity necessary to constrain significantly the occurrence of the type of transient observed by SIGMA. On the other hand, the results in Figure 4 clearly place strong constraints upon the transient reported by *HEAO 1* (Briggs et al. 1994). No single 12 day measurement in Figure 4 approaches the *HEAO 1* flux of 7.4 ± 1.5 × 10^{-3} photon cm^{-2} s^{-1}. We express this as a constraint on the duty cycle of the *HEAO 1* transient (the fraction of the time during which transient emission of this strength was detected), which must be less than 1/75 or 1.3%.

The *HEAO 1* data analyzed by Briggs (1991) were obtained from three exposures of the instrument to the GC during 1977 September, 1978 March, and 1978 September. The broad-line feature was seen only during the first exposure. The *HEAO 1* data, taken as a whole, therefore suggest a duty cycle $\sim\frac{1}{3}$ for the transient line. The disagreement between this duty cycle and the value less than 1.3% which we derive may be expressed quantitatively; this is done by applying the binomial formula in the simple case where the only possible outcomes of a measurement are that transient emission is either present or absent, and if present would have been detected by both instruments. A single random (Poisson) process, not modulated by any long-term processes, is thus assumed to underly the broad-line emission events. The probability that the ~33% duty cycle

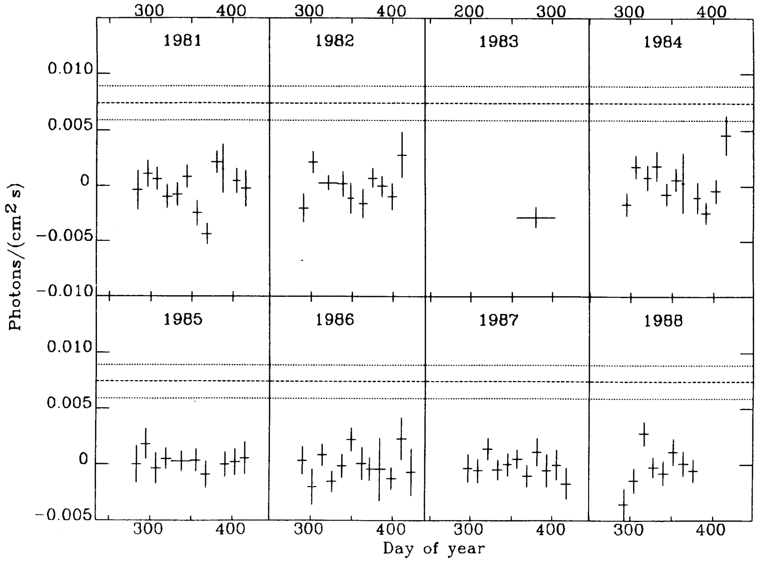

FIG. 4.—Inferred fluxes of transient emission from the GC of a line at 487 keV of FWHM 282 keV during 12 day intervals, 1981–1989 (data points and 1 σ errors). Also the flux observed from 1 H 1822−371 during 1977 September by *HEAO 1* (*dashed line*) and 1 σ errors (*dotted lines*).

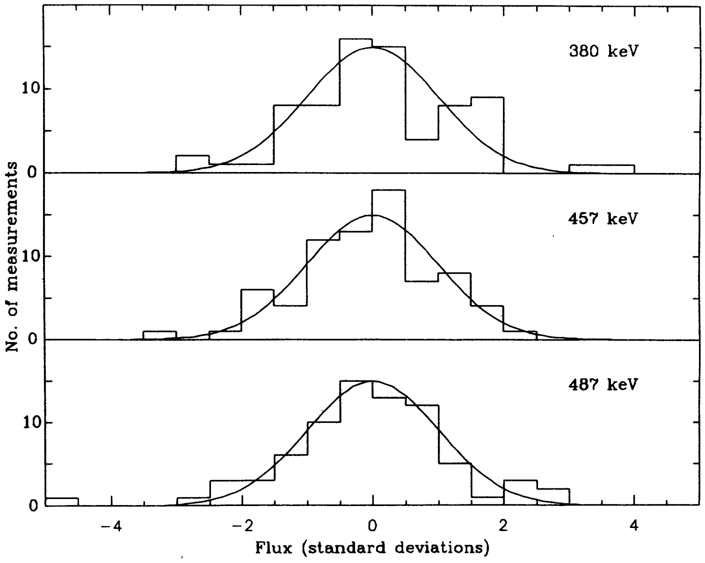

FIG. 5.—Number of *SMM* measurements of transient flux during 12 day intervals as a function of statistical significance, for lines at 380 keV (*top*), 457 keV (*middle*), and 487 keV (*bottom*). *Full lines:* normalized Gaussian distributions of unit variance.

found by *HEAO 1* was drawn from the same luminosity function as that measured by *SMM* is then less than $3!/(1!2!)(1/75)(1 - 1/75)^2 = 0.04$.

Although our transient flux measurements are nearly randomly distributed about zero (Fig. 5), weak systematic errors are apparent. The value of χ^2 per d.o.f. for the null hypothesis averages ~ 1.4, and increases with the width of the line. This effect is due mainly to imperfect separation of the systematic features in the background-corrected spectra which correlate with back plastic detector count rate (see § 2.3).[6] We therefore summarize our results in Table 1 in the form of mean 3 σ upper limits upon the transient flux for each line energy. These are conservatively defined as the average of the sum of 3 times the statistical uncertainty plus the absolute value of the measured flux (we treat this conservatively as a systematic error) in each 12 day interval. These mean upper limits range from 4.3×10^{-3} photon cm^{-2} s^{-1} for a relatively narrow line at 457 keV to 6.5×10^{-3} photon cm^{-2} s^{-1} for a broad line at 380 keV.

3.2. *Results: Variability on ≤1 Day Timescale*

3.2.1. *Comparison with SIGMA Measurements*

Samples of the transient behavior of the broad-line feature are shown in Figure 6 for ~ 90 minute timescales, and in Figure 7 for ~ 1 day timescales, for selected portions of the mission. No convincing evidence for celestial emission of a broad line at 380 keV was seen in 6632 measurements on 90 minute timescales, nor in 1102 measurements on 1 day timescales. The measurements on ~ 1 day timescales are of greater interest, since they may be compared with the 1990 and 1992 events observed by SIGMA (Bouchet et al. 1991; Sunyaev et al. 1991; Cordier et al. 1993b; Gilfanov et al. 1994), which are plotted in Figure 7 as the solid and dashed lines at the left and right edges.

Figure 7 shows that few of the *SMM* 1 day measurements attain the level of even the weaker (1992) of the two transients seen by SIGMA. We may use our results to obtain an upper limit on the duty cycle for emission of such lines from 1E 1740.7−2942. We assume that both the 1990 October 13 and 1992 September 21 events were manifestations of the same phenomenon; the weaker flux which SIGMA detected was 4.3×10^{-3} photon cm^{-2} s^{-1} on 1992 September 21. The

TABLE 1

SMM RESULTS FOR MEAN UPPER LIMITS ON TRANSIENT LINES DURING 12 DAY PERIODS

Line Energy (keV)	Line Width (keV)	Mean 3 σ Upper Limit [γ/(cm^2 s)]	Root Mean Square Systematic [γ/(cm^2 s)]
380	235	6.55×10^{-3}	2.07×10^{-3}
457	214	4.29×10^{-3}	1.17×10^{-3}
487	282	4.80×10^{-3}	1.47×10^{-3}

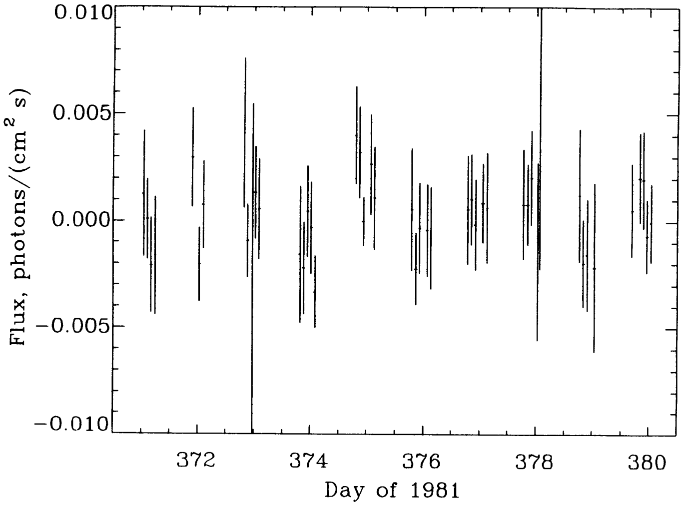

FIG. 6.—Inferred fluxes of transient emission from the GC of a line at 380 keV of FWHM 118 keV, orbit by orbit, during the period 1982 January 6–15.

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[6] During the spectrum fitting procedure described in § 2.3, the correlation between the shapes of the relatively smooth Earth albedo spectrum and the relatively peaked line feature increases as the latter is made broader; the correlation between the line amplitude and the back plastic detector count rate therefore also becomes more marked. A similar effect, caused by blending of a narrow line with the Earth albedo 511 keV line, was seen in the measurements of transient narrow lines from the Crab Nebula in Paper II.

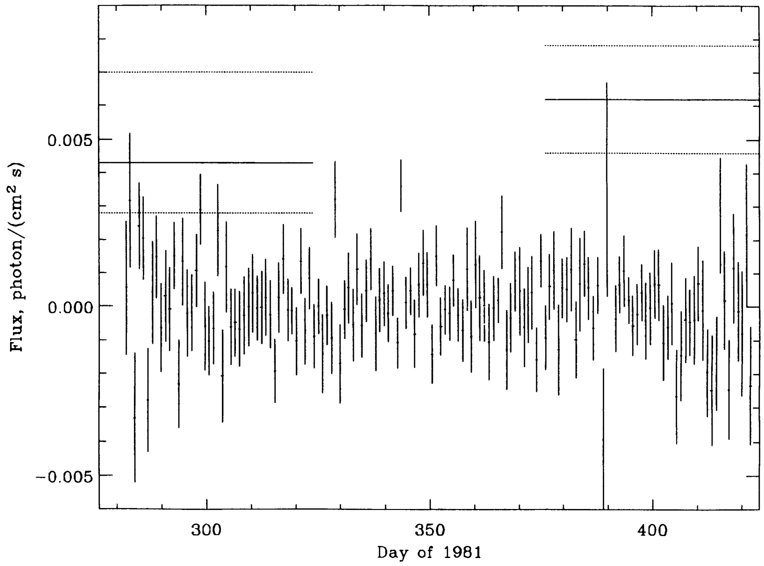

FIG. 7.—Inferred fluxes of transient emission on 1 day timescales of a line at 380 keV of FWHM 118 keV during the 1981 October–1982 February passage of the GC across the GRS aperture. Also the fluxes (*full lines*) and 1 σ errors (*dashed lines*) measured by SIGMA from 1E 1740.7−2942 on 1990 October 13 (*right edge*), and on 1992 September 19 (*left edge*).

SIGMA instrument followed a program of regular observations of the GC during the spring and fall of each year from 1990 to 1992; some 51 observations have been made during ~1 day intervals with spacings of one or a few days between them (Bouchet et al. 1991; Churazov et al. 1993; Cordier et al. 1993a, b). This record implies a duty cycle of $3.9^{+3.4}_{-2.2}$% for a transient line in excess of 4.3×10^{-3} photon $\mathrm{cm^{-2}\ s^{-1}}$. However, of the *SMM* measurements presented here, we have found only nine individual 1 d measurements where the absolute value of the transient line flux exceeded 4.3×10^{-3} photon $\mathrm{cm^{-2}\ s^{-1}}$, and, as discussed below, we believe that virtually all of these excursions are due to the presence of known systematic errors. The duty cycle implied by the *SMM* results is therefore $\le 0.8^{+0.3}_{-0.2}$%.

Due to the large number of measurements made by each instrument these duty cycles are quite well defined, and it is clear that they are incompatible at about the 1.5 σ level. We make a quantitative estimate of their mutual incompatibility using the binomial formula, as in § 3.1; the probability of the SIGMA measurements being drawn from the same distribution as the *SMM* measurements is only about 6%, i.e., $51!/(2!49!)(9/1102)^2(1 - 9/1102)^{49} = 0.057$.

3.2.2. *Upper Limits on Transient Line Flux*

In Table 2 we present the mean 3 σ upper limits on the intensity of a transient line at 380 keV on timescales of ~90 minutes and ~1 day. These limits include a measure of the systematic error, as described in § 3.1 and used in Table 1. Figure 7 suggests that the level of systematic errors resulting from our analysis is low. In Figure 8 we emphasize this by plotting the distribution of the measured transient fluxes on 1 day timescales; they are well approximated by a Gaussian centered at zero flux, with very few outlying points. Weak as they are, the transient line fluxes are significantly anticorrelated with the systematic residual continuum fluxes discussed in § 2.4, and we attribute the few outlying points to the influence of solar activity, as described there.[7]

We note that, comparing our upper limits in Table 2 with those in Table 1, the sensitivity attained by *SMM* on timescales ≤1 day is considerably better compared to that on ~12 day timescales than would be expected from the relative live times. Two effects mentioned in § 2 account for this increase in sensitivity. First, the low level of systematic errors in our analysis on 1 day timescales allowed us to dispense with the subtraction of an unocculted spectrum, whose larger statistical errors (see footnote 3, § 2.2) are not thereby propagated. Second, we searched on 1 day timescales for a much narrower line, on the basis of previous reports, than that sought on 12 day timescales (see § 2.3); both systematic and statistical errors are thus minimized. Each of these effects improves the sensitivity by about a

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[7] The anticorrelation between line and continuum fluxes is also explained in § 2.4: see Fig. 2*b*.

TABLE 2

SMM RESULTS FOR MEAN UPPER LIMITS ON TRANSIENT LINES DURING ≤1 DAY PERIODS

Line Energy (keV)	Line Width (keV)	Timescale	Mean 3 σ Upper Limit [γ/(cm^2 s)]	Root Mean Square Systematic [γ/(cm^2 s)]
380..............	118	90 minute	1.13×10^{-2}	4.54×10^{-3}
380..............	118	1 day	4.84×10^{-3}	1.49×10^{-3}

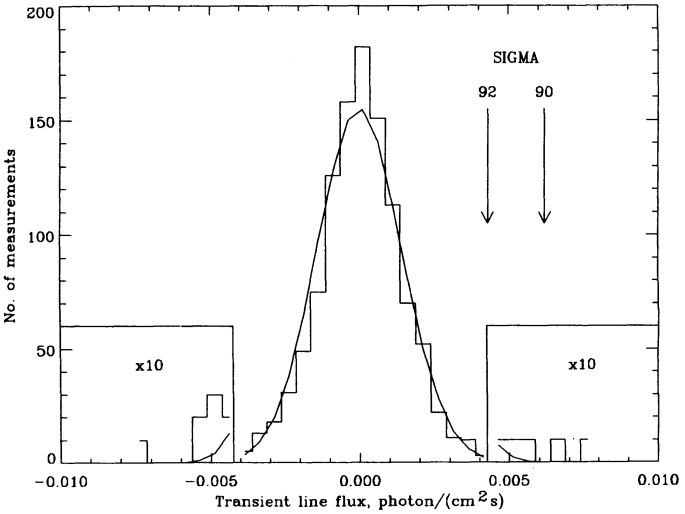

FIG. 8.—Distribution of 1102 *SMM* measurements of the transient flux from the GC on 1 day timescales in a line at 380 keV of FWHM 118 keV (*histogram*), and the best Gaussian approximation to this distribution centered at zero (FWHM 3.33×10^{-3} photon cm^{-2} s^{-1}). The wings of the distribution are shown in the two insets, magnified by a factor 10. The fluxes measured by SIGMA from 1E 1740.7−2942 on 1990 October 13 and on 1992 September 19 are shown by arrows.

factor of 2, which compensates for the degradation of a factor $\sim\sqrt{12}$ due to the reduction in live time.

4. DISCUSSION

The present work is the third in a series detailing the search in *SMM* GRS data for transient line features theoretically linked to e^+ annihilation in 1E 1740.7−2942 and other point sources. The other two studies (which also yielded negative results) focused on a narrow line at 0.511 MeV (Share et al. 1990), and a broad line at 1 MeV (Paper I). Given the previous reports of such a range of strong and relatively frequent transients from the GC, these consistently negative results are disappointing; we had anticipated that *SMM* would have confirmed at least some of them.

It now appears that the reality of the whole complex of reported line features must be questioned. The failure of OSSE to detect the reported broad ~400 keV line in an observation simultaneous with the 1992 September SIGMA measurement adds weight to this conclusion (Jung et al. 1994). Further monitoring of the GC by OSSE is clearly necessary to resolve the dilemma; the fate of the elegant theoretical structure which has been erected around the GC point sources of annihilation depends upon the resolution.

The reported variability of the narrow GC positron annihilation line at 511 keV (reviewed by, e.g., Lingenfelter & Ramaty 1989) requires a corresponding source of e^+, over and above the β^+-decays of nucleosynthesis products in the interstellar medium (which do not vary on such short time scales). The favored mechanism for producing e^+ is an instability to which the inner zones of accretion disks are vulnerable, by which an extremely hot two-temperature plasma arises with $T_e \sim 10^9$ K (Shapiro, Lightman, & Eardley 1976). The high T_e may lead, by coupling to the radiation field, to copious e^-e^+ pair production; in the resulting "pair-dominated plasma" the charge balance may be dominated by e^+ (Ramaty & Meszaros 1981; Liang & Dermer 1988). Annihilation of the resulting e^+ in various sites produces the suite of line features for which we have searched.[8] Annihilation within the pair plasma itself itself can produce a very broad line blueshifted from 511 keV (Ramaty & Meszaros 1981). At a plasma temperature of $T_e \simeq 5 \times 10^9$ K a broad line centered at ~1 MeV can be produced; such a feature was reported from the GC by *HEAO 3* in 1979 (Riegler et al. 1985). We found no evidence for such a feature in 10 yr of *SMM* observations in Paper I.

Gilfanov et al. (1994) attribute the lines seen from 1E 1740.7−2942 around 380 keV by SIGMA in 1990–1992 to the same mechanism operating at a much lower temperature ~1–5×10^8 K, with a gravitational redshift superposed on the much weaker thermal blueshift. The line reported from 1H 1822−371 by Briggs et al. (1994) might be due to the same mechanism, or to annihilation of the e^+ in the region of the accretion disk immediately outside the central pair plasma (Ramaty et al. 1992). Finally, in the case of 1E 1740.7−2942 a jet has been detected (Mirabel et al. 1992), by which Ramaty et al. (1992) postulate that the e^+ are ejected from the system on timescales of a few years, whereupon they slow down and annihilate in the surrounding molecular cloud (Bally & Leventhal 1991) on a ~1 yr timescale. However, Share et al. (1990) did not find the year-to-year variability in the narrow 511 keV line flux from the GC which would result from this mechanism, down to a level less than 8×10^{-4} photon cm^{-2} s^{-1}.

Our searches in Paper I and the present paper have probed directly the actual sources of e^+ in the pair plasmas. The lack of evidence for such plasmas during a 10 yr period is disturbing. It is however possible that episodes of pair plasma formation occurred during the gaps in *SMM*'s coverage of the GC,[9] or that they occur at a much lower level (i.e., producing γ-ray lines with fluxes below our upper limits) than previously reported.[10] These are obviously weak hypotheses. An alternative possibility is that the pair plasma generation process is modulated by some unknown process with a timescale ~10 yr, such that formation of pair plasmas was common before and after (but not during) the epoch 1980–1989 covered by *SMM* observations, allowing events to be detected in 1977 by *HEAO 1* (Briggs 1991) and in 1990–1992 by SIGMA (Gilfanov et al. 1994). Nevertheless, the continuing failure of OSSE to detect any of the members of the above-mentioned complex of annihilation features (Purcell et al. 1994) bodes ill for the theories—particularly when, as with the ~380 keV line reported on 1992 September 19, a simultaneous OSSE measurement fails to confirm one of the scenario's key observational supports (Cordier et al. 1993b; Jung et al. 1994).

5. SUMMARY

We have obtained 3 σ upper limits on the transient emission of a broad redshifted e^+ annihilation feature from any source in the GC region which range from 4.3 to 6.5×10^{-3} photon cm^{-2} s^{-1}, depending on the emission timescale and the exact energy and width of the line (see Tables 1 and 2). Upon comparing our results with previous observations of transient

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[8] The back-scattering of annihilation radiation from a cold accretion disk may produce an additional feature below the energy detectable by *SMM*, at 170 keV, which has been reported from the GC by Smith et al. (1993).

[9] These gaps amount to about 60% of a typical day, and two-thirds of a typical year: see Figs. 3, 4, and 6.

[10] Especially at low temperatures ~10^8 K on timescales ~12 days and longer, where our upper limits in the present work are weak: see Table 1.

emission, we find that one type of transient (a variable feature on a ~3 week timescale found by Briggs 1991 and Briggs et al. 1994 in *HEAO 1* data) must have a duty cycle less than 1.3%; a second type (seen during ~1 day intervals in 1990 October and 1992 September by SIGMA: Bouchet et al. 1991; Sunyaev et al. 1991; Cordier et al. 1993b) has a duty cycle ≤0.8%; while our analysis lacks the sensitivity to constrain the duty cycle of a third type, seen during ~3 weeks in 1991 October by SIGMA (Churazov et al. 1993). The probabilities of our result being consistent with the *HEAO 1* and the 1990 and 1992 SIGMA measurements are quite small, being in the range 4%–6% or less.

Taken in conjunction with upper limits reported previously by *SMM* upon other annihilation-related features (Share et al. 1990; Paper I), and with the conflict between OSSE and SIGMA measurements of the line reported in 1992 September (Jung et al. 1994), the reality of the reported features, and the validity of theories of e^+ production and annihilation in point sources near the GC, are open to question.

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