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SMM Observations of Gamma-Ray Transients. I. A Search for Variable Emission at MeV Energies from Five Galactic and Extragalactic Sources

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SMM OBSERVATIONS OF GAMMA-RAY TRANSIENTS. I. A SEARCH FOR VARIABLE EMISSION AT MeV ENERGIES FROM FIVE GALACTIC AND EXTRAGALACTIC SOURCES

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ABSTRACT

Transient emission at energies near 1 MeV has been reported by previous experiments on time scales of weeks to months from the Galactic center, the Crab Nebula, and Cyg X-1, and on shorter time-scales from NGC 4151 and Cen A. The spectra of these events fall into two broad classes: a broad line-like feature centered near 1 MeV, and continuum emission (or a very broad feature) extending from ~600 keV up to several MeV. These features have been interpreted theoretically in terms of emission from hot pair-dominated plasmas, which may be the necessary positron source implied by reports of narrow e^-e^+ annihilation lines from Cyg X-1 and the Galactic center. In this paper, data accumulated by the *Solar Maximum Mission* Gamma Ray Spectrometer (GRS) between 1980 and 1989 have been searched for evidence of these two types of features.

We find no compelling evidence for transient 1 MeV broad-line emission on time scales of order 12 d or longer when any of the sources are in the GRS field of view; upper limits on the transient line flux during any 12 d period are typically $\sim 4.5 \times 10^{-3} \gamma$ (cm^2 s)$^{-1}$. The same is true of variability of the continuum between 0.6–7 MeV, for which the upper limits are characteristically ~2 times the nominal flux from the Crab for any 12 d period. Our analysis was not sensitive enough either to confirm or to reject several reports from other experiments of transient emission in the 0.6–7 MeV continuum during 1980–1989. We withdraw the statement in Share et al. (1993) that our upper limit for one such event, a transient from the Crab Nebula in 1980 Spring, is inconsistent with the measurement of Ling & Dermer (1991). We did not detect any transient emission in the 1 MeV feature preceding or coinciding with reported emission of the 0.511 MeV annihilation line from the Galactic center in 1988–1989. We discuss briefly the implications of this result for models of the annihilation of positrons produced in the Galactic center source 1E 1740.7−2942.

Subject headings: galaxies: individual (NGC 4151, 5128) — Galaxy: center — gamma rays: observations — X-rays: stars

1. INTRODUCTION

A wide variety of transient spectral features has been reported at various times during the ~20 yr history of γ-ray astronomy from sources emitting at 100 keV to MeV energies. Confirmation of these reported observations is of the highest interest, because such transients bear witness both to the physical size of the sources and to the conditions under which the γ-ray emission originates. Earlier work on γ-ray source variability suffered from the sparsity of the observations and from conflicting results from different detectors; the time scale and even the existence of these variations are therefore in doubt.

The Gamma Ray Spectrometer (GRS) on the *Solar Maximum Mission* (*SMM*) during 1980–1989 was, in principle, well suited for monitoring transient γ-ray emission. This instrument detected photons of energies 0.3–8.5 MeV from a very broad field of view (FWHM ~150° at 1 MeV) over a period of nearly 10 yr. Its chief drawback—the poor localization of a source within this field of view—could be overcome to some extent by the use of Earth occultation of known sources (see, for example, Matz et al. 1988). Our purpose is to examine GRS data for evidence of the several kinds of transients which have been reported in the literature, on time scales varying from less than 1 d up to 1 yr or more.

In this paper we describe a search for two specific spectral features at ~MeV energies which have been described as varying on time scales of order tens of days in several sources. The first is a broad line (~1 MeV FWHM) centered at 1 MeV, which was detected by *HEAO 3* both from the Galactic center (hereafter GC; Riegler et al. 1985) and from Cyg X-1 (Ling et al. 1987; Ling & Wheaton 1989) in the fall of 1979. This feature, which in the case of Cyg X-1 is correlated with a distinct state of very low hard X-ray emission, has been interpreted by Liang & Dermer (1988) as a thermally blueshifted electron-positron annihilation line arising in a short-lived hot pair-dominated plasma in the inner region of the accretion disk around a black hole.

The second feature which we investigate here is an enhanced level of emission in a broad energy band from 0.6 MeV up to several MeV, which Ling & Dermer (1991) discovered in *HEAO 3* data from the Crab Nebula during the spring of 1980. Somewhat similar transients at MeV energies have been detected on short (< 1 d) time scales from several sources by balloon-borne experiments; from Cyg X-1, by Bassani et al. (1989) and by McConnell et al. (1989), from NGC 4151 by Perotti et al. (1981), and from Cen A by von Ballmoos, Diehl, & Schönfelder (1987). It is possible that the broad-band excess continuum from Cyg X-1 actually has the form of a very broad

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TABLE 1

REPORTED TRANSIENT SOURCES UNDER STUDY

SOURCE	GALACTIC COORDINATES		Transit Period[a] (day of year)	PREVIOUSLY REPORTED TRANSIENTS		
	l	b		Type	Strength	Units
Cyg X-1	71.3	3.2	330–103	Broad line[b]	1.4×10^{-2}	$\gamma\ (\mathrm{cm}^2\ \mathrm{s})^{-1}$
				Continuum[c]	2–4	Crab units
				Continuum[d]	2.6	Crab units
GC	0.0	0.0	274–64	Broad line[e]	1.5×10^{-2}	$\gamma\ (\mathrm{cm}^2\ \mathrm{s})^{-1}$
Crab Nebula	184.5	−5.8	89–244	Continuum[f]	4.7	Crab units
NGC 4151	155.1	75.1	173–324	Continuum[g]	2.3	Crab units
Cen A	309.5	19.4	228–11	Continuum[h]	1.6	Crab units
Pisces	97.7	−60.2	4–160			

[a] Owing to *SMM*'s permanent Sun pointing, sources moved slowly across the ~150° field of view during the months of each year when the Sun passed in front of them. We give the period each year in which the source's exposure to the GRS exceeded 50%.

[b] Ling et al. 1987; Ling & Wheaton 1989.

[c] Bassani et al. 1989.

[d] McConnell et al. 1989.

[e] Riegler et al. 1985.

[f] Ling & Dermer 1991.

[g] Perotti et al. 1981.

[h] von Ballmoos et al. 1987.

line (Owens & McConnell 1992), originating in an even hotter plasma of the kind from which the 1 MeV line arises, but the distinction is immaterial for the purpose of our analysis. These observations are summarized in Table 1.

A detailed study of the *SMM* GRS 0.3–8.5 MeV spectra showed no evidence of any steady long-term emission of such features from either the GC or the Crab Nebula, over a time scale of order several years (Harris et al. 1990). In the present paper we have searched for these two kinds of transient features from one year to the next during 12 d intervals, from six sources: the GC, the Crab, Cyg X-1, NGC 4151, Cen A (from which they have individually been reported), and from one "blank sky" direction, from which they are not expected. The blank field, in the direction of Pisces, is at the intersection of the ecliptic and the celestial equator, about 90° from the GC and the Crab Nebula; it was chosen to provide a control for our measurements of the five reported sources. Together, these six fields cover almost the whole of the sky accessible to *SMM* for which Earth occultation techniques may be used, given the broad GRS aperture.

The results of systematic searches for other reported transient spectral features, and for variability on shorter time scales ~1 d, will be presented in subsequent papers in the series. However, three of the reports of short-lived transients from our sources at MeV energies occurred during the lifetime of *SMM*. Therefore, in addition to our major aim of monitoring ~12 d variability over the long term, we also modified the analysis in order to examine the *SMM* data coinciding with these reports of individual short-term events. We describe the analysis used in the long-term monitoring in § 2 below, the results of which are given in § 3.1. The modifications introduced to deal with the individual events, and the results of these analyses, are described in §§ 3.4–3.6.

If the broad 1 MeV line is interpreted as the signature of a pair-dominated plasma, as described above, it is a possible source of the positrons whose annihilation in a small region near the GC has been debated for many years (see e.g., Phinney 1992). In § 4 we discuss how such a 1 MeV line may have been related to a possible episode in 1988–1989 of transient emission of the 0.511 MeV positron annihilation line from the GC.

2. ANALYSIS

The *SMM* GRS suffered in full measure from the high γ-ray background levels which are endemic to space platforms. However, we were able to identify characteristic time scales during the mission over which the backgrounds repeated themselves to some extent. By subtracting spectra obtained at such times to eliminate the backgrounds, we of course also canceled out any steady signal from the source. However, any *changes* in the source spectrum between the two epochs would remain in the subtracted spectra. As mentioned in § 1, we have reason to believe that the long-term (>1 yr) emission of the spectral features in question is zero, at least from the GC and the Crab Nebula (Harris et al. 1990).

2.1. *Data Acquisition*

The properties of the GRS were described in detail by Forrest et al. (1980). The essential features were seven 7.6 × 7.6 cm NaI crystals forming the detector, surrounded by a CsI anticoincidence shield to the sides and rear. Front and back plastic detectors were used to reject charged particle events. The GRS accumulated data continuously over 16.384 s intervals during the period 1980 February to 1989 December, except for a five month data gap between 1983 November and 1984 April. It was pointed at the Sun during this entire time except for the five month gap, during which time the spacecraft lost fine attitude control. Small gaps occurred in the data owing to an in-orbit calibration procedure, which was performed over ~5 minute periods while the GRS was pointed toward Earth; during most of the mission (1981 June–1987 September), these calibrations were performed once per orbit.

The data set used in this analysis comprised the 16 s spectra summed up to ~1 minute intervals, from which we excluded data contaminated by solar flares, γ-ray bursts, and other known transient backgrounds. We also rejected data taken during orbits which intersected the South Atlantic Anomaly (SAA), and up to ~10^4 s afterwards, which suffered from strong radioactive backgrounds induced by trapped particle bombardment. The 1 minute spectra were labeled by the time, the geographical longitude and latitude of the sub-spacecraft point, and the Sun-Earth-satellite angle.

The overall background experienced by the GRS was found to vary strongly as the satellite orbital plane precessed with a period ~47 d (see, for example, Share et al. 1988). We therefore also computed the value of the precession period from the satellite's known altitude, from which we assigned to each 1 minute spectrum its phase within the precession cycle.

2.2. *Background Subtraction*

Many sources of variable backgrounds in GRS data have been identified (Kurfess et al. 1989), including irradiation by solar and Galactic cosmic rays and by trapped SAA particles and Earth albedo radiation. In general, such backgrounds depend upon the strength of the geomagnetic field, the spacecraft's orientation relative to it and to Earth, the spacecraft's attitude as it traverses the SAA, and the phase of the precession cycle. For each 1 minute "source" spectrum taken during 1981–1989, we attempted to find 1 minute "background" spectra for which these quantities were as close as possible. Subtraction of the latter from the former then yielded a spectrum which ought to include the change in any cosmic source visible to the spacecraft on both occasions.

The way in which specific "background" spectra are selected depends on the time scale of the transient event which is being sought. For example, where any event such as a γ-ray burst is known to last <1 minute, the average of the two 1 min spectra on either side of the event should be used. For transients lasting for periods of hours, "background" spectra obtained 15 orbits (~1 d) earlier or later than the source spectrum would be used (as will be described in future papers in this series). In the present paper, where we are searching for transients lasting for periods of days or weeks, we have selected "background" spectra from periods 1 yr before or after the event. This method has the advantage that, owing to *SMM*'s solar pointing, the GRS's exposure to any cosmic source was repeated at intervals of 1 yr; the contribution of any source could then be distinguished by the Earth occultation method (§ 2.3). In general, we chose the "background" spectrum to be 1 yr before the "source" spectrum (hence, the transients occurring during 1980 could not be analyzed by this method).

Eight *SMM* precession periods of 47 d each were sufficiently close to 1 yr for us to be able to specify that the "source" and "background" spectra must have the same phase within the precession cycle to within 4%. We further restricted the choice of "background" spectra to those for which the satellite's geographic position was within 10° of that at the time of the "source" spectrum. Finally, we required that the Sun-Earth-satellite angle of the "background" spectrum be within 15° of its value for the "source" spectrum. Together, these conditions ensured that the spacecraft's position and orientation relative to the major sources of background—the cosmic-ray flux, Earth albedo, and the SAA—were as similar as possible during "source" and "background" minutes. Wherever more than one "background" spectrum was compatible with a given "source" spectrum, we chose that for which the discrepancies in geographical location and Sun-Earth-satellite angle were minimized.

In a few cases this background selection procedure required minor modifications. One problem arose because our assignment of phase within the *SMM* precession cycle was based on the assumption that the length of the cycle changed little from one year to the next. This condition did not hold during periods when the satellite's altitude was changing rapidly, which was the case at the very beginning and end of the mission (source spectra taken from 1989 February onward were not analyzed for this reason). The gap in the data between 1983 November and 1984 April gave rise to a second gap in the analyzable data between 1984 November and 1985 April, during which background spectra were not available from the previous year. However, since the altitude of the orbit had not changed appreciably during the 2 yr prior to this second gap, we were able to perform the analysis by using background spectra from the 16th preceding precession period (i.e., 2 yr previous to the source spectrum).[4] Finally, the analyses of the individual MeV transients reported by other experiments during 1980–1989 were handled on a case by case basis, as described in §§ 3.4–3.6.

2.3. *Transient Search*

The background-subtracted 1 minute spectra, constructed using the method described above, were summed over 12 d intervals. They were summed into 12 bins, according to whether one of the six sources listed in Table 1 was, or was not, occulted by Earth. By further subtracting the occulted background-corrected spectrum from the unocculted spectrum, we could detect changes in the spectrum of the designated source relative to the previous year. We henceforth use the term *residual spectra* for these 12 d unocculted-minus-occulted, year-minus-previous-year spectra. The subtraction of occulted from unocculted spectra accumulated on time scales of the order of days has been shown to remove background radiation due to long-lived radioisotopes in the spacecraft and detector (Letaw et al. 1989).

2.3.1. *Spectral Signatures of Two Types of Transients*

We searched the residual spectra from each of the six source locations for evidence of the specific transient spectral shapes detected by earlier experiments. This was straightforward in the case of "continuum-type" transients, since this spectral feature would have dominated the emission of the source over the entire GRS energy range above 0.6 MeV. We therefore simply added all the counts in each residual spectrum over the energy range of interest (which we took to be 0.6–7 MeV) and searched for significant excursions in the resulting time series of rates.

The search for a transient broad line at 1.0 MeV in the 12 d residual spectra (the "line-type" transient of § 1) required a more elaborate treatment. In these spectra, it is expected that the 1.0 MeV line, if present, will be superimposed on a continuum arising from imperfect background subtraction, and it is incumbent upon us to determine the likely shape of this residual continuum. We found that, in general, the residual continuum resembled the albedo spectrum of Earth's atmosphere (Letaw et al. 1989), either in positive or in negative. This can be understood as a result of imperfect subtraction in our background correction procedure. It is obvious that, in the

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[4] Systematic errors in the background subtraction were found to be about 10%–20% worse when using this modification of the method. During other periods in the mission, if this method of selecting the background from two years previously were used, the results would be considerably worse, since orbital changes over 2 yr periods were necessarily greater than over the normal 1 yr periods. We could not, therefore, use the results from this modification of the method as a check on the background subtraction. We did perform a check on the consistency of the normal method by repeating the background subtraction for parts of the mission, using background spectra selected in the normal way, but from the year *after* the source spectrum. We found that, as expected, the resulting measurements were approximately equal in amplitude to those obtained by the normal method, but opposite in sign.

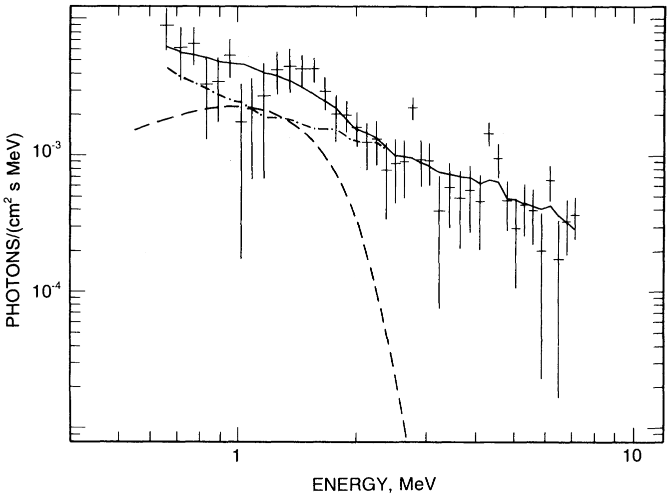

FIG. 1.—Representative residual spectrum for days 229–240 of 1985, obtained by subtracting Earth-occulted GC source spectra from unocculted GC spectra. The full line is a fit to the transient spectrum of a model containing the Letaw et al. (1989) Earth atmosphere albedo spectrum (*dash-dot line*) plus a broad line centered at 1 MeV (*dashed line*). The amplitude of the broad 1 MeV line is $2.8 \times 10^{-3} \gamma$ (cm² s)$^{-1}$; for comparison, the amplitude of the lines observed by *HEAO 3* was $1.5 \times 10^{-2} \gamma$ (cm² s)$^{-1}$.

absence of any other backgrounds, the subtraction of Earth-occulted spectra from unocculted spectra will yield a negative Earth-albedo spectrum. In principle, subtracting this Earth-albedo spectrum from one obtained the year before under identical conditions of Earth aspect ought to yield a null spectrum. However, a small difference in the two Earth-albedo spectra, 1 year apart, will cause the subtraction to be imperfect, yielding a residual which, to a first approximation, should itself have the same Earth-albedo shape (see, however, the discussion below, and in Appendix A).

As illustrated in Figure 1, we fitted the 12 d residual spectra between 0.6 and 7 MeV by a model consisting of the Earth-albedo spectrum at these energies (Letaw et al. 1989), plus a line centered at 1.0 MeV of FWHM 1.18 MeV. The fitted amplitude of this line in each spectrum represented the transient intensity of the line (relative to the year before) during the relevant 12 d period from the relevant source; we hereafter refer to them as line-type *transient strengths.* We arranged these 12 d transient strengths in a time series for each source, which we searched for significant excursions.

These measurements of the 1.0 MeV line features were subject to a subtle systematic error, because of their dependence on the shape of the underlying continuum. The residual continuum was approximated by the difference of two Earth-albedo spectra, which would have the shape of the standard Earth-albedo spectrum (Letaw et al. 1989). However, when the two Earth-albedo spectra have very similar amplitudes, small departures from the standard spectrum dominate the difference of the two. We show in Appendix A that when this is the case, a spectral shape proportional to $E^{-b} \ln E$ results, which may exhibit a peak at 1 MeV. Such cases are easily recognizable, since the residual spectrum changes sign at energies somewhat below 1 MeV, so that the fit using the Earth-albedo spectrum is obviously inappropriate. The few residual spectra which showed this behavior were fitted by a model consisting of the 1.0 MeV line plus the expected $\sim E^{-b} \ln E$ spectral shape, instead of the line-plus-Earth-albedo model normally used.

Finally, we note that our measurements of the "continuum-type" and "line-type" transients are not mutually independent; counts in any feature centered on 1 MeV will obviously be included in the sum over the range 0.6–7 MeV. This would be equally true of any fairly narrow line in the same energy range (although we have not searched for such lines at energies above 1 MeV). It is possible to invert this argument to obtain upper limits on the flux in such lines from our measurements of the 0.6–7 MeV continuum, as we will see in § 3.3.

2.3.2. *Time Series of Transient Strengths*

In Figure 2 we show the 1981–1989 time series of continuum-type transient strengths for the case of the Crab Nebula, in order to illustrate the temporal behavior expected from a valid transient outburst of the cosmic source. As discussed in Appendix B, any real transient outburst from the Crab on a ~12 d time scale will, in general, appear twice in our analysis: at first as a positive increase in rate at the time of the outburst, and then again as a negative signal 1 yr later. An example of this behavior is seen in Figure 2 around day 50 of 1986 and day 57 of 1987, where a strong positive excursion is followed exactly eight precession periods later by a corresponding negative excursion. Behavior of this kind is a necessary, but not sufficient, characteristic of a real transient event, since (as we will see in this particular case), a transient background event may be responsible.

We determined that, in general, the striking excursions and trends visible in the time series of Figure 2 (also present in the series for the other sources) are due to systematic effects in the residual spectra. The most important effect was due to imperfect subtraction of atmospheric γ-radiation penetrating the GRS NaI detector shielding, as would be expected from the discussion in § 2.3.1. The effect of this on the transient strength was found to be well-monitored by the rate of charged-particle events in the GRS back plastic detector. This is explicable in terms of the origin of the atmospheric radiation, which is a secondary (albedo) product of charged particle impacts in Earth's atmosphere. We illustrate the close correlation between the back plastic rate and the continuum-type transient strength for part of the mission in Figure 3. Over the whole mission, the correlation coefficient between the two rates was 0.7; the relationship is approximately linear.

A strong excursion in the back plastic detector rate will thus be associated with a positive transient strength, followed 1 yr later by a negative signal when it appears among the "background" spectra (see Appendix B). An example of this is visible around day 50 of 1986 in Figures 2 and 3. It is clear that such events can mimic a transient γ-ray source from any direction on the sky. We therefore corrected the transient strengths for atmospheric effects by subtracting the back plastic detector count rates (multiplied by a fitted constant). This correction procedure had to take account of the fact that, whereas the NaI detector gains were extremely stable throughout the mission (Share et al. 1988), the back plastic detector was not gain stabilized. The back plastic count rates were found to be subject to both abrupt and gradual trends due to changes in gain. We therefore divided the time series of both transient and back plastic count rates into 15 shorter periods of ~200 d each, during which the back plastic detector gain appeared to be stable or to vary sufficiently slowly. We then fitted the time series of line-type and continuum-type transient strengths during each ~200 d period by a model of the systematic

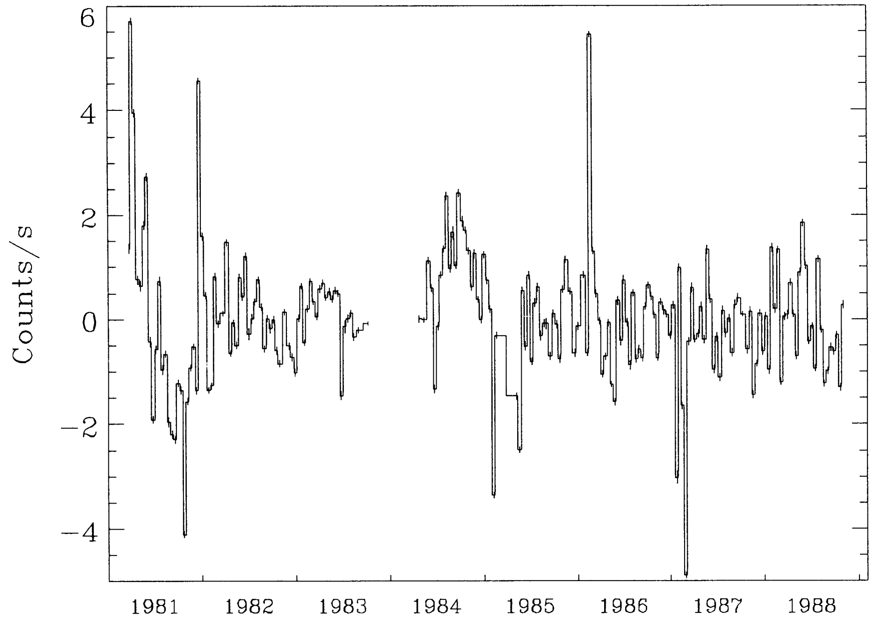

FIG. 2.—Time series of transient strengths (in 12 d intervals) for the 0.6–7 MeV continuum emission from the Crab Nebula, 1981–1989. The transient intensities were determined by using background measurements made 1 yr before (see text for explanation). The plotted errors are statistical (1 σ).

error—in other words, by the time series of back plastic count rates. As would be expected from Figure 3, the amplitudes of the model found by the fit were significant. The model, multiplied by this amplitude, was then subtracted from the transient time series, yielding a *corrected* time series of transient strengths.

3. RESULTS

3.1. *Long-Term Monitoring of Sources*

The corrected transient strengths obtained in § 2.3.2 were converted to transient fluxes from specific targets using the known orientation of the GRS aperture, and its angular response. This procedure has been described by Harris,

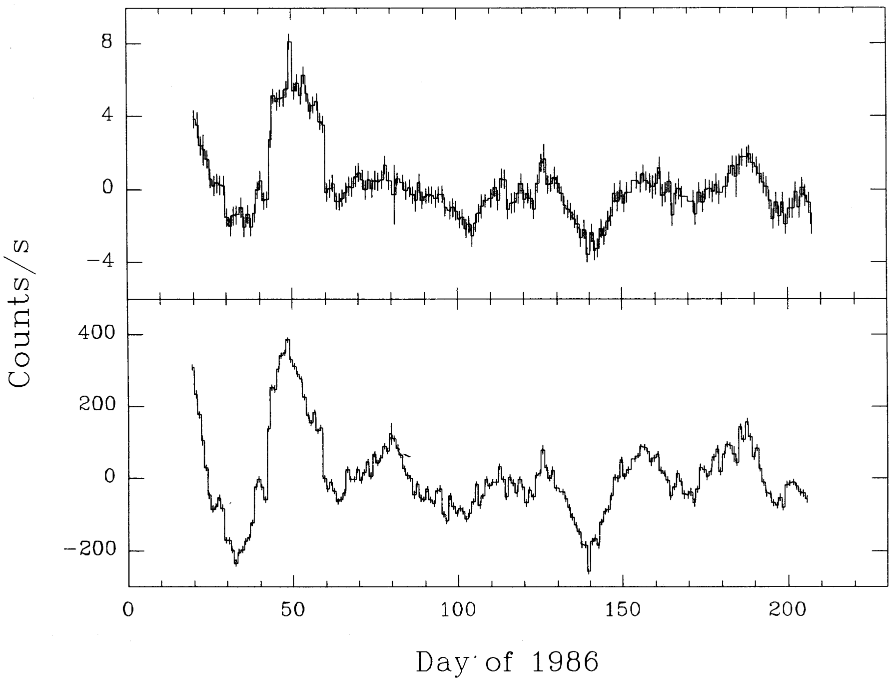

FIG. 3.—Time series of count rates of the 0.6–7 MeV continuum in the residual spectra for exposures to the Crab Nebula (*top*) and of the back plastic detector residual rates (*bottom*, using the same double subtraction), plotted at 1 d resolution.

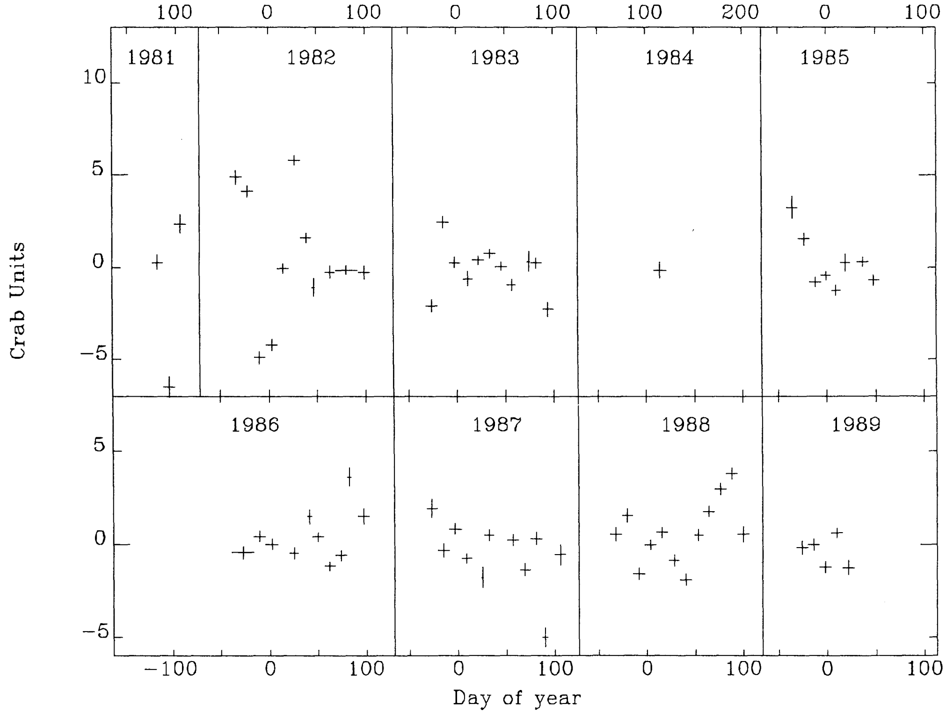

FIG. 4.—Inferred fluxes of transient 0.6–7 MeV continuum emission from Cyg X-1 (relative to the previous year) plotted at 12 d resolution (individual points and 1 σ errors.

Leising, & Share (1991; see their Fig. 1) and was performed for point sources at the Galactic coordinates listed in Table 1. The uncertainty introduced by knowledge of the GRS instrument response has been found to be small ($\sim$ 10%–20%; see §§ V and VI of Appendix B of Harris et al. 1990). We expressed the fluxes of the "continuum-type" transients in Crab units, defined as the flux in the energy range 0.6–7 MeV according to the extrapolated total Crab Nebula spectrum of Jung (1989). This Crab spectrum is a power law of the form $0.117(E/0.2\ \mathrm{MeV})^{-2.56}\gamma\ (\mathrm{cm}^{-2}\ \mathrm{s\ MeV})^{-1}$, and in these terms one Crab unit equals $2.64 \times 10^{-3}\gamma\ (\mathrm{cm}^2\ \mathrm{s})^{-1}$ in the 0.6–7 MeV band.

In Figures 4–9 we present the time series of continuum-type transient fluxes for each of the six targets for 12 d periods during 1981–1989. The results for the line-type transients are shown in Figures 10–15. Data are plotted in Figures 4–15 only for the periods of each year's transit when the GRS's exposure to the source exceeded 50% (see Table 1).

It is clear that the data in Figures 4–15 are not derived from a random source, i.e., that residual systematic errors are present in our results. The value of χ^2 per degree of freedom for the null hypothesis is typically $\sim$10 for the 0.6–7 MeV continuum transient (Figs. 4–9) and $\sim$4 for the 1 MeV line transient (Figs. 10–15). However, the origins of the excursions visible in these figures are generally well understood. For example, there is a tendency for large excursions to occur during 1981 for all sources. This is due to the fact that *SMM*'s orbit was changing relatively rapidly during the first $\sim$750 d of the mission (Kurfess et al. 1989), so that, as described in § 2.2, the synchronization of orbital precession periods between background (1980) and source (1981) spectra was imperfect. Occasional excursions are visible from some sources near days 50 of 1986 and 1987,[5] which are due to a strong charged particle event occurring around day 50 of 1986 (Fig. 3). In this case, the correction procedure described in § 2.3.2—subtraction of a linear function of the back plastic detector rate—was obviously inadequate due to the strength of the particle event.

We find no convincing evidence in any of the six sources for either of the two transient types for which we searched. In general, the significant excursions do *not* follow the pattern of a positive flux followed 1 yr later by a negative flux, which would be expected from a genuine outburst from a cosmic source. Even if the excursions conceal genuine transient events, we believe that their fluxes must be below our 3 σ upper limits (which we define conservatively as 3 times the statistical 1 σ error, plus the absolute value of the measurement). As we will discuss in § 3.2, these limits are generally smaller than the fluxes which have been reported from some of the objects.

An overview of our results is presented in brief form in Table 2. Since we do not regard the excursions in transient flux as real celestial transients, we present the mean values of our conservative 3 σ upper limits (which include systematic errors). We also give the rms spread in the flux for the two types of transient from each source, which provides an estimate of the characteristic level of these systematic errors. The fact that the rms spread in transient flux for the null direction (Pisces) is comparable with those from the supposed sources fortifies our conclusion that no genuine cosmic transient has been detected from any of the expected sources.

Due to the large *SMM* aperture, it remains possible, in principle, that other variable MeV γ-ray sources are included in each of the six fields of view, whose combined output is approximately constant. The rms flux values in Table 2 would then be interpreted as measurements of the variability in this output. We believe that this circumstance is unlikely, for two reasons. First, this kind of behavior of multiple variable sources would be expected particularly from the direction of

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[5] Equivalent to days 415 of 1985 and 1986 in Figs. 5 and 11.

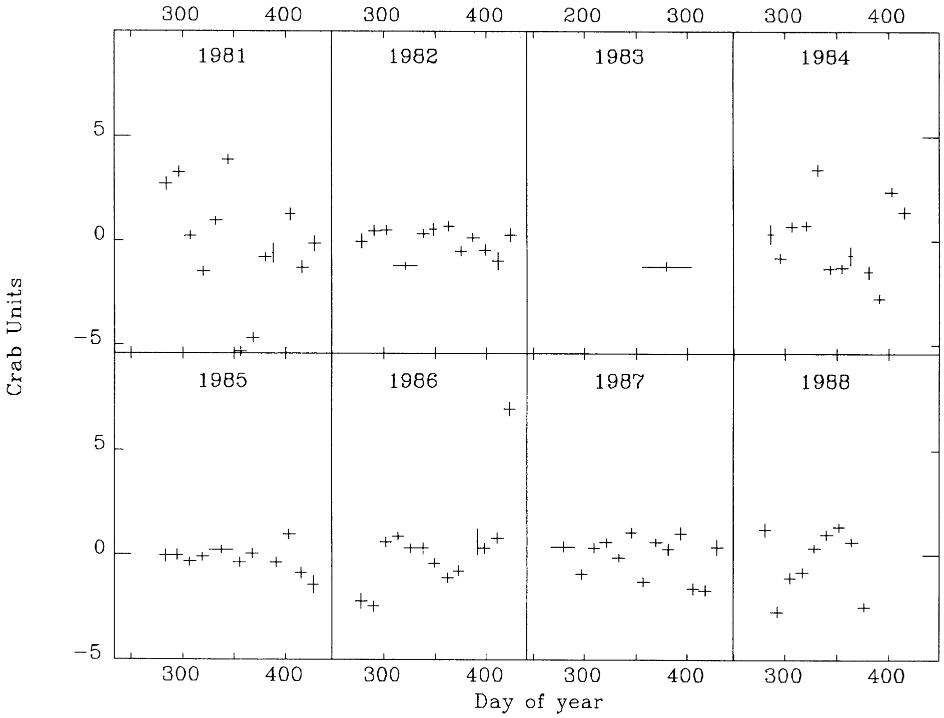

FIG. 5.—Inferred fluxes of transient 0.6–7 MeV continuum emission from the GC. Symbols as in Fig. 4.

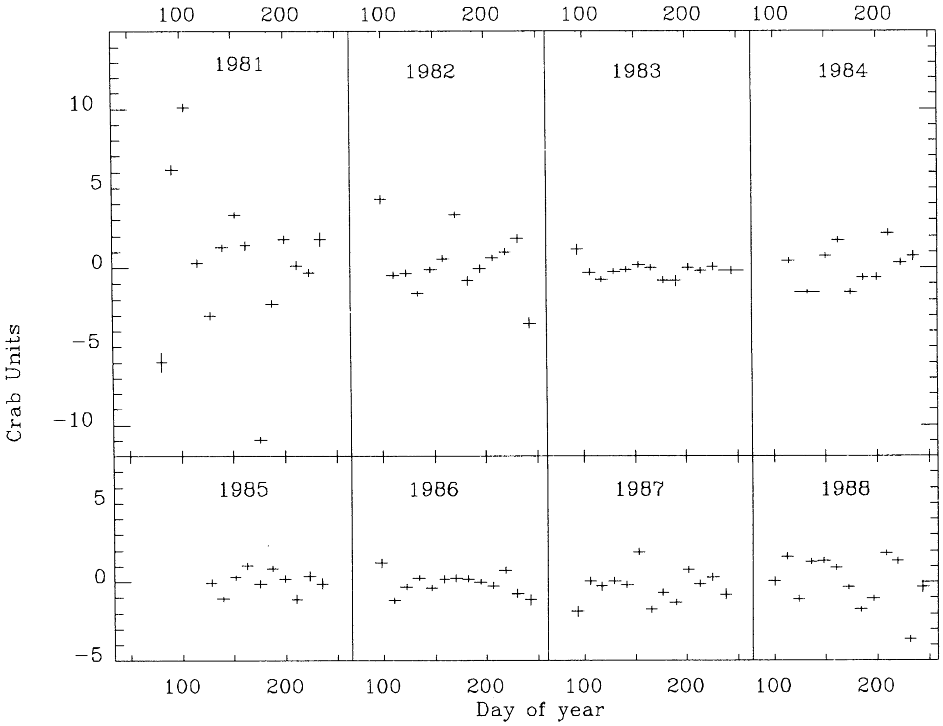

FIG. 6.—Inferred fluxes of transient 0.6–7 MeV line emission from the Crab Nebula. Symbols as in Fig. 4. On this scale, the flux reported during 1980 Spring by *HEAO 3* was 4.7 Crab units (Ling & Dermer 1991).

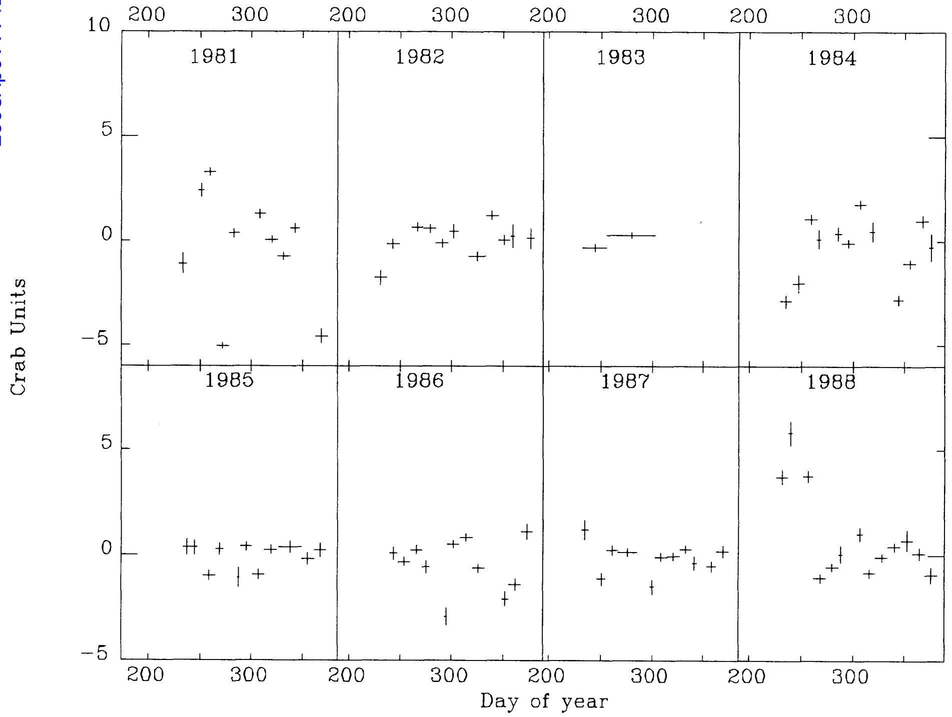

FIG. 7.—Inferred fluxes of transient 0.6–7 MeV continuum emission from Cen A. Symbols as in Fig. 4.

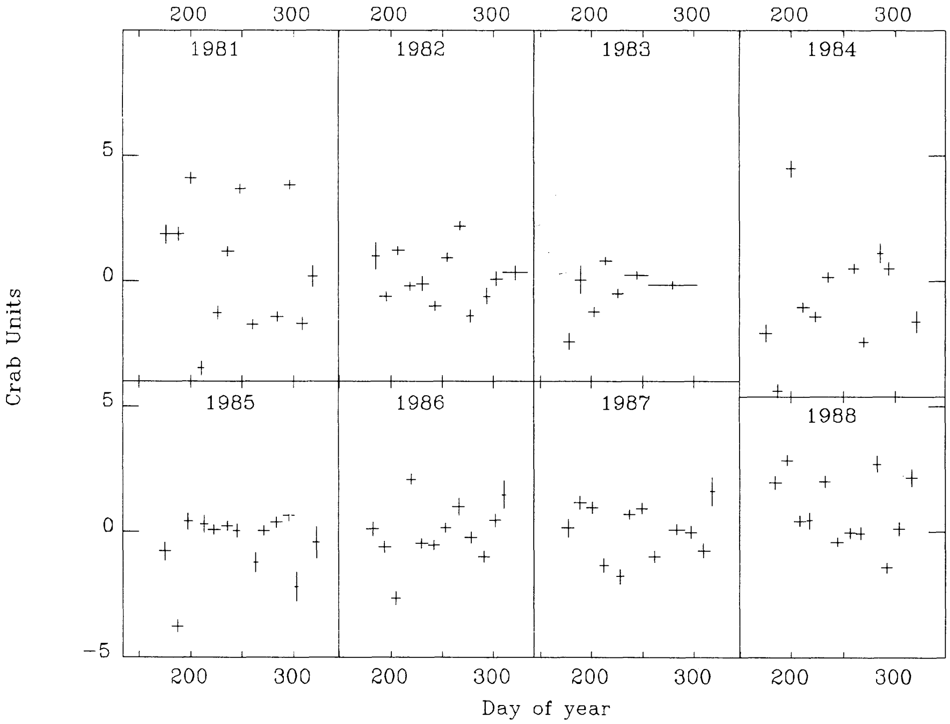

FIG. 8.—Inferred fluxes of transient 0.6–7 MeV continuum emission from NGC 4151. Symbols as in Fig. 4.

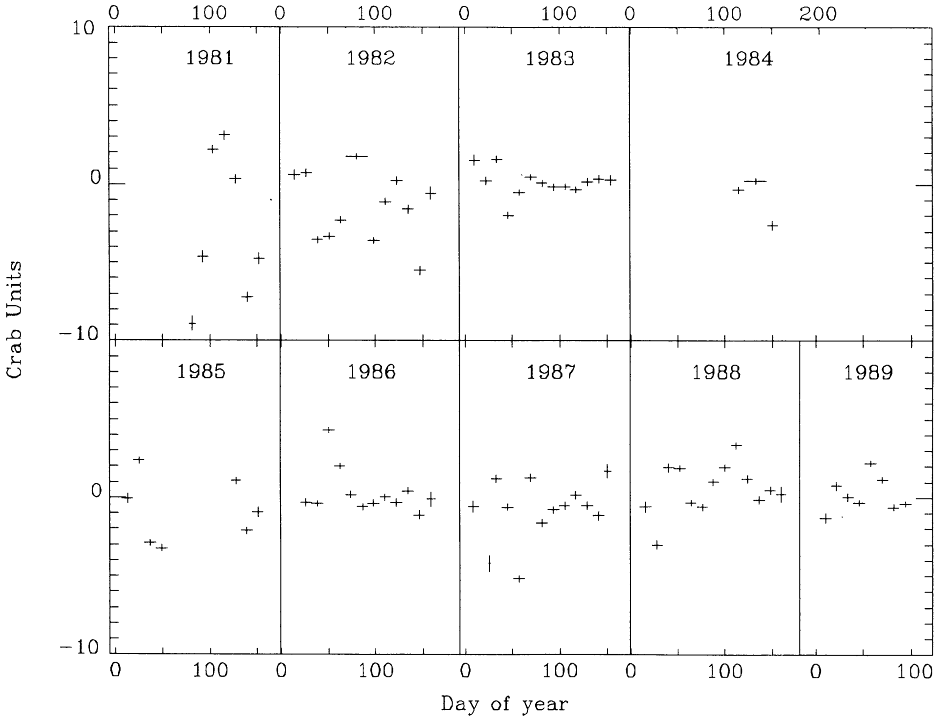

FIG. 9.—Inferred fluxes of transient 0.6–7 MeV continuum emission from the direction of Pisces. Symbols as in Fig. 4.

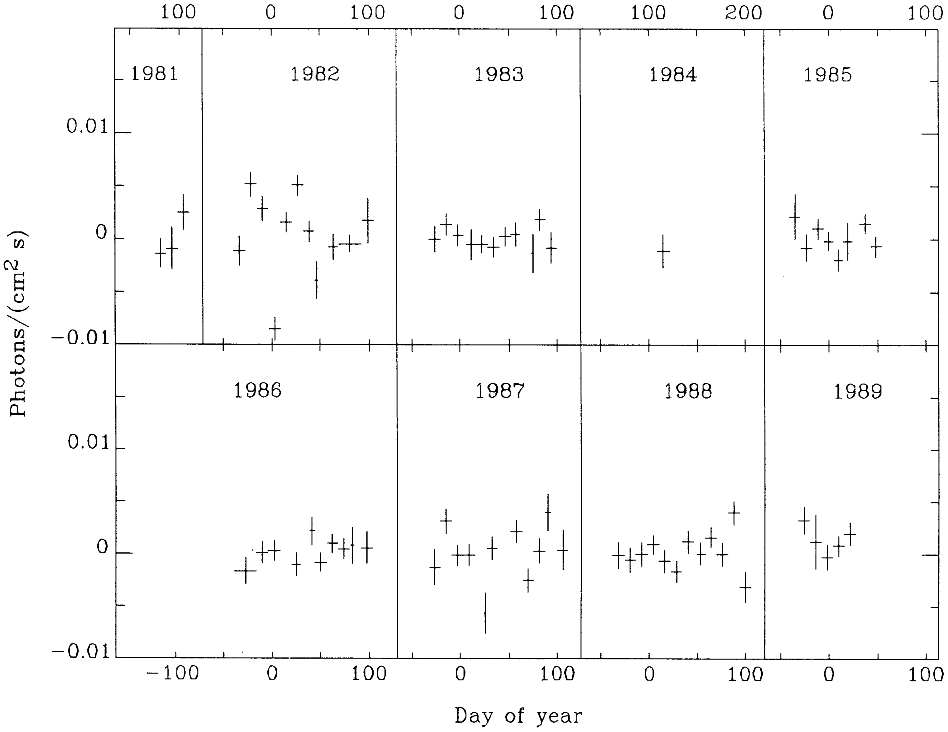

FIG. 10.—Inferred fluxes of transient 1 MeV line emission from Cyg X-1. Symbols as in Fig. 4. The flux reported during 1979 Fall by *HEAO 3* was 1.4 × $10^{-2}\gamma$ (cm^2 s)$^{-1}$ (Ling et al. 1987).

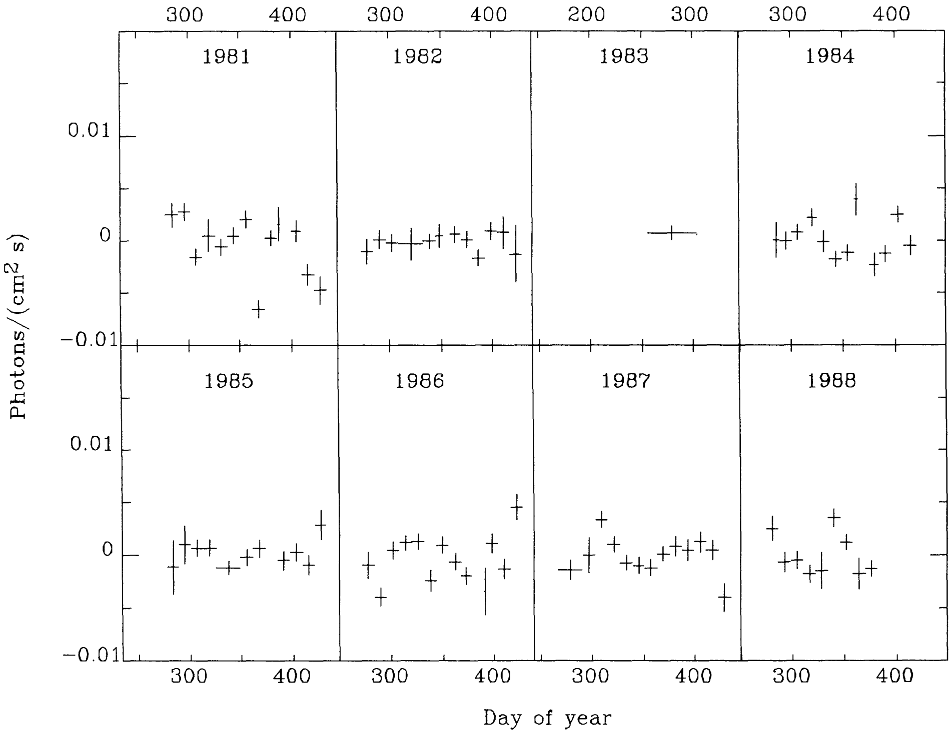

FIG. 11.—Inferred fluxes of transient 1 MeV emission from the GC. Symbols as in Fig. 4. The flux reported during 1979 Fall by *HEAO 3* was $1.5 \times 10^{-2}\gamma$ $(\text{cm}^{-2}\ \text{s})^{-1}$ (Riegler et al. 1985).

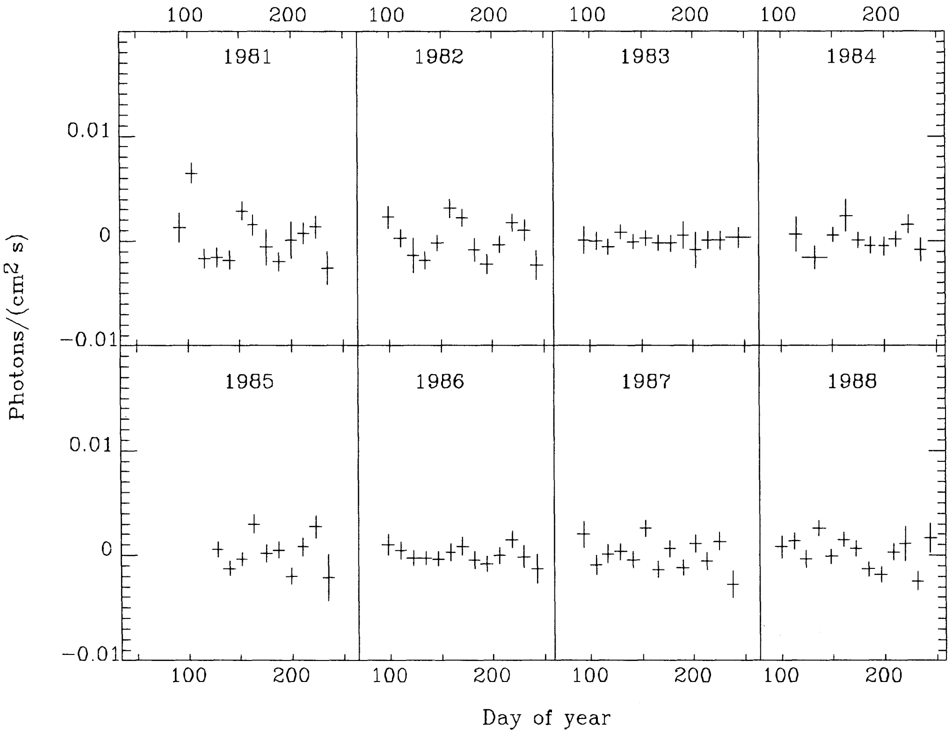

FIG. 12.—Inferred fluxes of transient 1 MeV line emission from the Crab Nebula. Symbols as in Fig. 4.

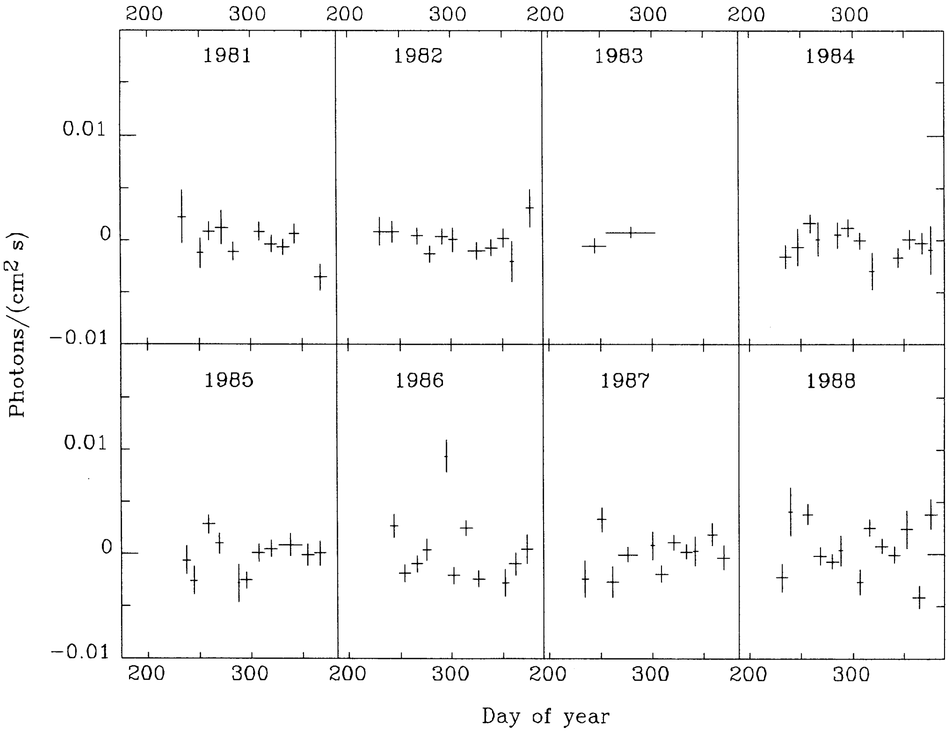

FIG. 13.—Inferred fluxes of transient 1 MeV line emission from Cen A. Symbols as in Fig. 4.

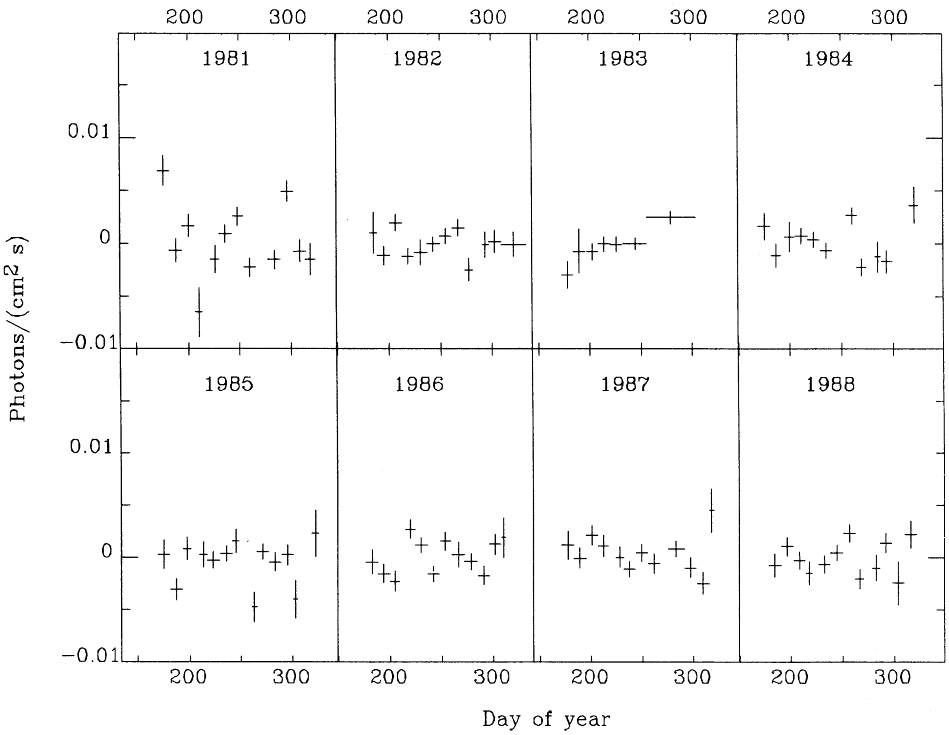

FIG. 14.—Inferred fluxes of transient 1 MeV line emission from NGC 4151. Symbols as in Fig. 4.

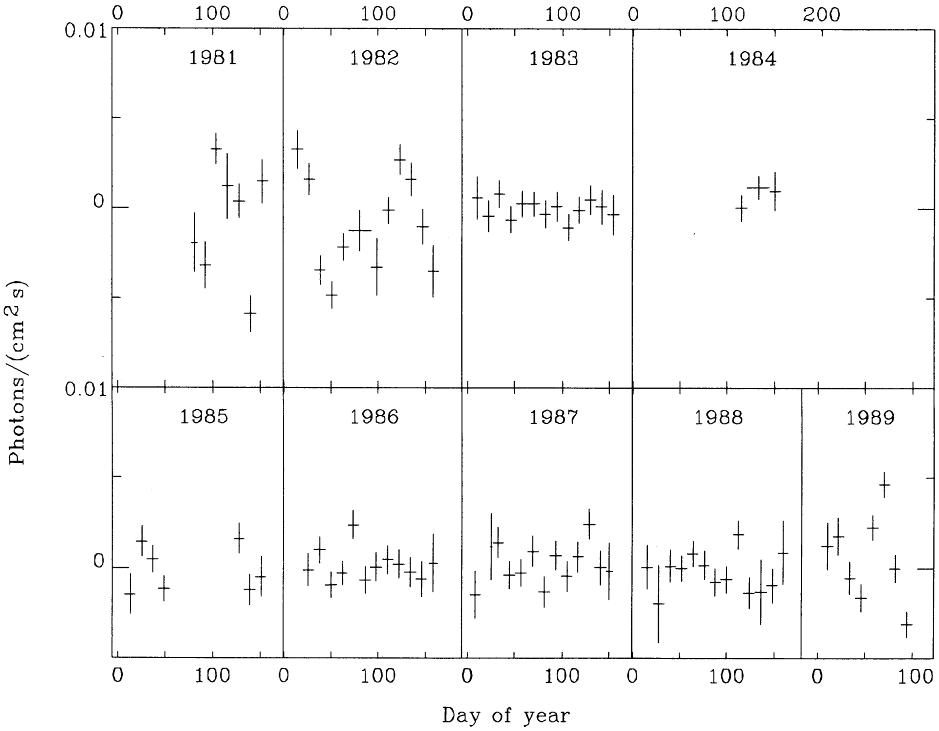

FIG. 15.—Inferred fluxes of transient 1 MeV line emission from the direction of Pisces. Symbols as in Fig. 4.

the GC (where it has been found to characterize the hard X-ray and soft γ-ray continuum). However, a long-term average spectrum obtained with the same broad *SMM* aperture would then be expected to show a consistent 1 MeV line or enhanced 0.6–7 MeV continuum, whereas no such features are observed in precisely such a spectrum obtained by Harris et al. (1990), down to a very low level (e.g., $2 \times 10^{-4} \gamma$ cm^2 s^{-1} for a line at 1 MeV). Second, this overlapping of multiple sources is least likely in the direction of Pisces; yet our results for this field of view in Table 2 do not differ materially from the others, as mentioned above.

3.2. *Activity of Reported Transients*

We see no convincing evidence of any 1.0 MeV line transient from the directions of Cyg X-1 or the GC during 1981–1989 at the level of the two *HEAO 3* measurements of 1979. We may express the results in terms of a "duty cycle," which is the fraction of time during which each object was a source of the 1 MeV line emission at the *HEAO 3* level $\sim 1.5 \times 10^{-2} \gamma$ (cm^2 s)$^{-1}$. Figures 10 and 11 show that the absolute value of no single 12 d measurement (out of a total of 72 from Cyg X-1 and 84 from the GC) approached the *HEAO 3* level, implying duty cycles less than 1.4% from Cyg X-1 and less than 1.2% from the GC.

We conclude that outbursts of 1 MeV line emission from the GC and Cyg X-1 at the levels reported by *HEAO 3* are very rare. This conclusion is fortified by comparing the results from the two known sources with the results from the other objects, from which no 1 MeV line is expected. In all cases, any "source" activity in the 1 MeV line is roughly the same and is consistent with the level of our systematic errors.

TABLE 2

MEAN UPPER LIMITS FOR TRANSIENTS DURING 12 d PERIODS

	TRANSIENT TYPE			
	1 MeV Line, γ (cm^2 s)$^{-1}$		Continuum, Crab Units	
SOURCE	Mean Upper Limit[a]	Root-Mean-Square Systematic	Mean Upper Limit[a]	Root-Mean-Square Systematic
Cyg X-1	5.2×10^{-3}	2.1×10^{-3}	2.4	2.0
GC	4.5×10^{-3}	1.9×10^{-3}	1.9	1.6
Crab Nebula	4.0×10^{-3}	1.5×10^{-3}	1.9	2.1
Cen A	4.8×10^{-3}	2.0×10^{-3}	1.8	1.5
NGC 4151	4.7×10^{-3}	2.0×10^{-3}	2.0	1.6
Pisces	4.1×10^{-3}	1.7×10^{-3}	2.3	2.2

[a] Conservative 3 σ upper limits as defined in text (§ 3.1).

Outbursts in the broad 0.6–7 MeV continuum at the level reported from the Crab Nebula by Ling & Dermer (1991; see Table 1) are also scarce in our data. There are four 12 d measurements from the Crab whose absolute values exceed the level of 4.7 Crab units reported by Ling & Dermer; this type of transient therefore has a duty cycle $\leq 4\%$ (Fig. 6).

The continuum-type transients reported from Cyg X-1, Cen A, and NGC 4151 (see Table 1) were all weaker and were detected on shorter (<1 d) time scales. Figure 4 shows that fifteen 12 d measurements are compatible with the level of 2–3 Crab units reported from Cyg X-1 by Bassani et al. (1989) and McConnell et al. (1989). The duty cycle for this type of transient from Cyg X-1, extending over intervals ~ 12 d, is therefore 20%. Likewise, from 14 measurements consistent with the von Ballmoos et al. (1987) measurement of Cen A, we find a duty cycle $\leq 17\%$ for this level of 0.6–7 MeV continuum emission from this source; and since the absolute values of 12 measurements exceed the level of the transient seen by Perotti et al. (1981) from NGC 4151, the duty cycle in this source is $\leq 13\%$. We conclude that transient emissions of 0.6–7 MeV continuum γ-radiation on ~ 12 d time scales from any of the reported sources are fairly rare.

3.3. *Implications for Lines above* 1 MeV

Given a measurement of the count rate in the 0.6–7 MeV continuum, we may estimate an upper limit on the flux in any transient celestial line in that range, at arbitrary energy E, by assuming that all the counts are concentrated in the GRS detector channels corresponding to energy E. The results for the Crab Nebula presented in Figure 2 may be taken as typical (note that, conservatively, they are *not* corrected by the back plastic count rate as described in § 2.3.2). The rms spread in the values in Figure 2 is 1.3 counts s^{-1}; given that for energies above 1 MeV the GRS detector photopeak effective area is about $100E^{-0.68}$ cm^2 averaged over the FWHM field of view, we thus estimate that for fairly narrow lines above 1 MeV, the flux in a transient line at energy E MeV might be $\sim 1.3 \times 10^{-2}E^{0.68}$ photons (cm^2 s)$^{-1}$. To this must be added the statistical error, which depends on the line FWHM ΔE MeV; in this procedure it ought to be approximately proportional to $[(7-0.6)/\Delta E]^{1/2}$, which, when applied to the typical 1 σ error ~ 0.07 counts s^{-1} on the data points in Figure 2, yields a typical 3 σ uncertainty of $\sim 5 \times 10^{-3}E^{0.68}$ photons (cm^2 s)$^{-1}$ for a line of FWHM 1 MeV at energy E MeV. Combining the statistical and systematic errors, we obtain an estimate of $\sim 1.7 \times 10^{-2}E^{0.68}$ photons (cm^2 s)$^{-1}$ for the conservative 3 σ upper limit on the transient flux in such a line on 12 d time scales.

3.4. *The Centaurus A Transient of 1982 October 31*

A balloon-borne Compton telescope experiment by the Max-Planck-Institute for Extraterrestrial Physics (MPE) detected emission at energies 0.7–8 MeV from Cen A during 3.5 hr on 1982 October 31 (von Ballmoos et al. 1987). Comparison between this measurement and upper limits obtained by O'Neill et al. (1989) suggests that this emission is variable on time scales less than 1 yr. In terms of the Crab unit used in this paper for measuring continuum-type transients, the transient flux found by the MPE group was $1.6^{+1.2}_{-1.0}$ units.

The *SMM* GRS was almost ideally placed to observe such a transient, since at the time Cen A was only $\sim 30°$ from the center of the field of view, and the GRS exposure to it was close to 100%. We therefore searched the data from which the results of Figure 7 were obtained for corroborating evidence. In order to constrain the duration of the event, the search was performed for two distinct time scales: the 12 d time scale used in the analysis hitherto (§ 3.4.1) and a time scale of ~ 1 d (§ 3.4.2).

TABLE 3

MEASUREMENTS OF 0.6–7 MeV TRANSIENT FROM CENTAURUS A ON 1982 OCTOBER 31

Day of 1982	Flux (Crab Units)	Experiment
304.56–304.71	$1.6^{+1.2}_{-1.0}$	MPI[a]
298.0–305.9	0.46 ± 0.34	*SMM*, 12 d time scale
303.57–303.96	-0.39 ± 0.8	*SMM*, ~ 1 d time scale
304.50–304.95	1.4 ± 0.9	*SMM*, ~ 1 d time scale
305.48–305.87	0.0 ± 1.0	*SMM*, ~ 1 d time scale

[a] von Ballmoos et al. 1987.

3.4.1. *Variation on 12 d Time Scale*

The time of the MPE measurement of the Cen A transient, 1982 day 304, was covered by our 12 d measurement for 1982 days 298–305. The result is presented in Figure 7 and Table 3. We measured a transient flux in the 0.6–7 MeV continuum of 0.46 ± 0.34 Crab units. This clearly indicates that the enhancement of the continuum on 1982 day 304, if present, did not endure on a time scale ~ 8 d. By combining the results for the adjacent 12 d periods given in Figure 7, it can also be shown that there is no evidence in the *SMM* data for longer-lasting transient emission (on time scales up to ~ 150 d).

The statistical uncertainties in our measurements during 1982 days ~ 300–320 are rather larger than would be expected for a typical ~ 12 d observation. This is due to the coincidence of two factors which severely reduced the acquisition of data during periods when Cen A was occulted by Earth. First, the phase of the ~ 47 d precession cycle (§ 2.1) was such that Cen A was occulted when *SMM* was in the southernmost part of its orbit (i.e., since Cen A is at a high southern declination, Earth's center was considerably to the north of the line connecting *SMM* and Cen A); the periods during which Cen A was occulted were therefore rather short. Second, the once-per-orbit calibration (§ 2.1) occurred precisely during this short period when Cen A was occulted. Therefore, subtraction of occulted from unocculted spectra, as described in § 2.2, involved propagation into the residual spectra of the large statistical uncertainty resulting from small live times in the occulted spectra. In fact, during 1982 days 306–315, there were insufficient occulted data for the subtraction to be performed at all.

3.4.2. *Variation on 1 d Time Scale*

For the purpose of corroborating a balloon observation, made on a time scale of a few hours, it is obviously desirable to examine the *SMM* data on the smallest possible temporal scale. We have therefore repeated the analysis described in § 2 around the time of the MPE observation of Cen A, the only change being that the background-subtracted 1 minute spectra were summed over 1 d periods (rather than 12 d). The results for the relevant day and one day on either side (Table 3) show that our analysis is not sensitive enough to have confirmed the transient observed by MPE even at the 2 σ level. We can only conclude, on the basis of our results from the longer time scale,

TABLE 4

MEASUREMENTS OF ~4 MeV TRANSIENT FROM CYGNUS X-1 AROUND 1984 OCTOBER 2

Day of 1984	Energy MeV	Flux (Crab Units)	Experiment
275.88–276.25	0.6–7	2.6 ± 0.8	UNH[a]
268.6–279.8	0.6–7	0.47 ± 0.43	*SMM*, 12 d time scale
273.0–278.9	0.6–7	0.761 ± 0.61	*SMM*, ~6 d time scale
275.88–276.25	4–8.5	3.6 ± 1.1 × 10^{-3} [b]	UNH[a]
275.88–276.25	4–8.5	−1.1 ± 2.1 × 10^{-3} [b]	*SMM*, 9 hr time scale

[a] McConnell et al. 1989; Owens & McConnell 1992.

[b] Units: $\gamma\,(\mathrm{cm}^2\,\mathrm{s})^{-1}$.

that the transient did not endure for a period longer than ~8 d.

3.5. *The Cygnus X-1 Transient of 1984 October 2*

The University of New Hampshire (UNH) directional γ-ray telescope detected strong transient emission from Cyg X-1 over a broad energy range between 0.4–9.3 MeV on 1984 October 2 (McConnell et al. 1989). Similar emission had been reported on previous occasions (the observations are reviewed by Owens & McConnell 1992). The flux measured by UNH is equivalent to 2.6 ± 0.8 Crab units in the 0.6–7 MeV energy band used in our analysis. Their experiment took place over a 5.5 hr period which was interrupted by a 3 hr gap; the same spectral feature was seen on either side of the gap.

The UNH event occurred about 60 d before the start of the 1984–1985 transit of Cyg X-1 across the GRS FWHM aperture (Table 1); at this time the GRS's exposure to Cyg X-1 was close to 40%. We were therefore able to search the relevant data for a 0.6–7 MeV continuum-type transient, with some loss in sensitivity. As in § 3.4, we performed the search on more than one time scale in order to investigate the duration of the transient. Here we examined the behavior of Cyg X-1 on the usual time scale of 12 d (§ 3.5.1), on an intermediate time scale ~1 d (§ 3.5.2), and during the actual 9 hr of the reported transient (§ 3.5.3, using a modification of the analysis performed hitherto).

3.5.1. *Variation on 12 d Time Scale*

Several days' worth of *SMM* data had been lost exactly 1 yr before the reported transient, owing to an early occurrence of the attitude control problem mentioned in § 2.1. Therefore, we used background spectra from the year after the event for subtraction from the source spectra taken during 1984 days 268–279. Otherwise, the analysis proceeded exactly as described in § 2. As shown in Table 4, we measured a corrected transient flux of 0.47 ± 0.43. Crab units. This result is inconsistent at about the 5 σ level with the UNH transient having persisted at the level measured by McConnell et al. (1989), over long time scales (~12 d) around the time of the balloon flight.

3.5.2. *Variation on 1 d Time Scale*

By summing the background-subtracted 1 minute spectra over intervals of 1 d, we were able to search for transient emission during the 1 d periods on either side of the event. As in the case of the Cen A transient described in § 3.4.2, we found that *SMM*'s sensitivity was insufficient to detect this UNH transient at a 2 σ level on a time scale ~1 d. By summing over a period of 6 d around the epoch of the UNH balloon flight, we measured a transient flux of 0.76 ± 0.61 Crab units (Table 4), demonstrating at the 3 σ level that the UNH transient did not last for this length of time.

3.5.3. *Variation on 9 hr Time Scale*

The balloon flight during which the UNH measurement was made actually took place mainly during a ~12 hr gap in the *SMM* data. This gap is due to the fact that on 1984 day 275.92 (about 1 hr after the start of the UNH observation) *SMM* began a series of orbits intersecting the SAA. Therefore, in contrast to our usual analysis procedure (§ 2.1), in order to achieve *SMM* coverage of the period of the UNH experiment (1984 day 275.88–day 276.25), we found it necessary to use data acquired during SAA orbits. No data at all were obtained during the actual SAA passages, lasting typically for about 0.5 hr out of each 1.5 hr orbit. Data from the remaining parts of the orbits exhibit very high background levels arising from the β-decays of the radioactive isotopes produced during the SAA passage. The background spectrum is dominated by an intense 0.511 MeV line due to the annihilation of positrons from β^+-emitting isotopes, superposed on two distinct exponential β-decay continua extending upwards in energy to ~2 MeV and ~5 MeV (Dunphy et al. 1989).

Bearing in mind that the spectrum of the reported transient extends above the energies at which these SAA-induced backgrounds cut off, we were able to avoid the backgrounds by using data from these orbits only above an energy of 4 MeV. Our source spectra therefore included 1 minute accumulations of data in the range 4–8.5 MeV, taken separately during times when Cygnus X-1 was and was not occulted by Earth as seen from *SMM*. In looking for transients on very short time scales, it has been shown that superior results are obtained by using background spectra much closer in time to the source spectrum. We therefore abandoned the method used hitherto of obtaining spectra from 1 yr before or after (§ 2.2). We chose background spectra using the same criteria of geographic position and Sun-Earth-satellite angle as in § 2.2, but from among those spectra taken on the previous and subsequent days (i.e., 15 orbits before and after the source spectrum). The average of the two closest day-before and day-after spectra was subtracted from the source spectrum. The method will be fully described in a companion paper (Leising et al. 1993).[6] We did

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[6] We note that this method requires sufficient data to have been taken on the days before and after for there to be a high probability that matching background spectra are available. In the case of the Cen A transient discussed in the preceding section, we were unable to use this method because this condition was not met for Earth-occulted spectra, for the reason discussed in § 3.4.1.

not find any evidence, using this method, for any transient emission from Cyg X-1 during the 1 d periods before and after the UNH measurement, which might cancel out in the subtraction.

The flux measured by the UNH experiment in the 4–8.5 MeV energy range was $3.6 \pm 1.1 \times 10^{-3} \gamma\ (\mathrm{cm}^2\ \mathrm{s})^{-1}$ (Owens & McConnell 1992). During the corresponding period (1984 day 275.88–day 276.25) we measured an average flux in this range of $-1.1 \pm 2.1 \times 10^{-3} \gamma\ (\mathrm{cm}^2\ \mathrm{s})^{-1}$ (see Table 4). We are unable to confirm the occurrence of this transient, and our result is inconsistent with a flux of $3.6 \times 10^{-3} \gamma\ (\mathrm{cm}^2\ \mathrm{s})^{-1}$ at the $\sim 2\ \sigma$ level.

3.6. *The Crab Nebula Transient of 1980 Spring*

Transient 0.6–4 MeV emission from the direction of the Crab Nebula was detected by Ling & Dermer (1991) in *HEAO 3* data from 1980 Spring. As with the Cyg X-1 transient discussed in § 3.5.1, no *SMM* data were available from the previous year for background subtraction. We therefore adopted the same strategy of using 1 minute spectra from the subsequent year (1981 Spring) for background subtraction. The spectrometer's exposure to the Crab Nebula at this time was rather small, rising from ~40% to ~60% during the period.

The *HEAO 3* transient was observed over a period of ~50 d between days 52 and 101 of 1980 and remained at a constant level during that time (Ling & Dermer 1991). Our measurements covered the four 12 d periods 1980 days 59–104; they were subject to considerable systematic errors due to the rapid change in the satellite's orbit during 1980–1981. When the results for the four periods are combined, they imply a transient 0.6–7 MeV continuum flux of -2.8 ± 0.3 Crab units; however in cases like this, where we believe the systematic error to be dominant, a better indicator of the true error is the rms spread in the transient flux measurements. By this criterion, the error in our measurement is 5.2 Crab units, compared with the *HEAO 3* measurement of 4.7 Crab units. We are thus unable either to confirm or to refute the occurrence of this transient. We retract a statement published earlier, based on preliminary results (Share et al. 1993), that our result is inconsistent with that of *HEAO 3*.

4. PRODUCTION AND ANNIHILATION OF POSITRONS AT THE GALACTIC CENTER

Although the 1 MeV line transient observed from Cyg X-1 and the suspected GC point source in late 1979 fell outside the period of *SMM* coverage, it is instructive to note that both observations also reported evidence of a transient narrow line at 0.511 MeV coinciding with the 1 MeV feature (Riegler et al. 1985; Ling & Wheaton 1989). Although the 1 MeV line has never been reported again from either source, the 0.511 MeV line was again reported from the GC by balloon-borne experiments at various times in the late 1980s, when *SMM* was in operation (Leventhal et al. 1989; Gehrels et al. 1991; Chapuis et al. 1992). *SMM*'s monitoring of the GC during the 1980s is not consistent at the 3 σ level with a *variable* source of the intensity $\sim 8 \times 10^{-4}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ reported by the balloon experiments; it has been suggested that these experiments, in fact, detected an unchanging level of 0.511 MeV emission corresponding to the fraction of the known diffuse interstellar annihilation radiation which fell within their apertures (Share et al. 1990).

In the following discussion, we assume for the purpose of argument that the balloon experiments detected a real transient 0.511 MeV line of intensity $\sim 8 \times 10^{-3} \gamma\ (\mathrm{cm}^2\ \mathrm{s})^{-1}$ lasting from approximately mid-1988 to mid-1989. It is presumed to be identified with the X-ray source 1E 1740.7−2942, on the basis of a broad redshifted annihilation line reported from that source by the *SIGMA* experiment in 1990 October, whose role is discussed below (Bouchet et al. 1991; Sunyaev et al. 1991). We propose to examine our measurements of the transient 1 MeV line from the GC (Fig. 11) for a possible correlation with these reported 0.511 MeV line detections.

Two theoretical models have been proposed which bear on the possible correlation between a narrow 0.511 MeV line and a broad 1 MeV line. In both models, the 0.511 MeV line is produced by annihilation in cold material of positrons (e^+) produced near a central black hole of mass ~10–100 $M_\odot$ undergoing accretion. The production of e^+ is attributed to the episodic development in the central part of the accretion disk of a hot ($\sim 5 \times 10^9$ K) pair-dominated plasma in which e^-e^+ pairs dominate the charge balance. Such plasmas have been investigated in detail by Liang and coworkers (Dermer & Liang 1988; Liang & Dermer 1988; Liang 1990; 1991), mainly in connection with Cyg X-1. A broad line at 1 MeV arises naturally from such a plasma; it is just the thermally broadened and blueshifted 0.511 MeV electron-positron annihilation line (Ramaty & Meszaros 1981). We assume for the purpose of argument that the e^+ which gave rise to the 1988–1989 transient 0.511 MeV line were produced solely by this mechanism, neglecting other possible sources of e^+, such as a pair cascade in a jet.

The first theoretical model, proposed by Ling & Wheaton (1989), has e^+ escaping from the pair-dominated plasma in Cyg X-1 and annihilating rapidly upon encountering either the companion star HDE 226868, its wind, or the accretion stream in the system. In this model the resulting narrow 0.511 MeV line is essentially *coincident in time* with the broad 1 MeV line; however, it is not clear whether the necessary ambient cold material is present around the hypothetical GC black hole 1E 1740.7−2942.

The other model, proposed by Ramaty et al. (1992), has the e^+ escaping from the central pair-dominated plasma and annihilating in two quite separate locations, on two different time scales; first, annihilation in the inner accretion disk (but outside the e^-e^+ pair cloud) produces immediately the broad, gravitationally redshifted annihilation line at ~0.480 MeV reported by *SIGMA* (Bouchet et al. 1991; Sunyaev et al. 1991); second, positrons escaping from the system annihilate in the molecular cloud which surrounds 1E 1740.7−2942 (Bally & Leventhal 1991), producing a narrow 0.511 MeV line whose appearance is delayed by anywhere from a few months to ~3 yr, depending mainly upon the energy of the e^+. Thus, in this model the narrow line appears *~1 yr later* than the broad 1 MeV line from the pair-dominated plasma.[7]

We therefore examined our results for the period coinciding with the reported 1988–1989 reappearance of the 0.511 MeV line from the GC (§ 4.1), and for a period ~1 yr earlier (§ 4.2).

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[7] Broad ~0.480 MeV lines of the kind seen by *SIGMA*, which are believed to arise in coincidence with the pair-dominated plasma and 1 MeV line, were not reported by other experiments during the lifetime of *SMM*. *SIGMA* did not itself report any simultaneous line feature around 1 MeV down to a level $\sim 3 \times 10^{-3} \gamma\ (\mathrm{cm}^2\ \mathrm{s})^{-1}$ (Sunyaev et al. 1991). A search for events exhibiting this feature in the *SMM* data will be the topic of a future paper in this series.

In principle, the broad 1 MeV line provides a very powerful test of the models of the 0.511 MeV line, since it is a direct probe of the actual source of the e^+. In a sufficiently compact source the e^+ abundance in the pair-dominated plasma is set by the balance between pair creation and annihilation, the fraction of e^+ escaping being small. Dermer & Liang (1988) pointed out that the flux from annihilating e^+ in the 1 MeV line therefore places a stringent upper limit upon the number of e^+ which may subsequently appear, through annihilation at rest, in a narrow 0.511 MeV line. We express this as a condition upon the fluences in the two lines:

$$\phi_{1.0}\tau_{1.0} \gg \phi_{0.511}\tau_{0.511} , \qquad (1)$$

where ϕ (with appropriate subscript) is the line flux in photons (cm^2 s)$^{-1}$ and τ is the duration of the emission of the line. If the two lines appear steadily together for a length of time (§ 4.1, below), a balance between e^+ escape and annihilation in cold matter may be assumed, in which case equation (1) becomes $\phi_{1.0} \gg \phi_{0.511}$ (Dermer & Liang 1988). In the delayed-annihilation model of Ramaty et al. (1992), however, the annihilation of the escaping e^+ in the molecular cloud is spread over a much longer period than the time scale of the pair-dominated plasma and 1 MeV line emission.

4.1. *Narrow Annihilation Line Coincident with* 1 MeV *Line*

Four balloon experiments during 1988–1989 reported a transient narrow 0.511 MeV line from the GC point source (Gehrels et al. 1991; Niel et al. 1990; Chapuis et al. 1991). Gehrels (1991) showed that the diffuse Galactic flux of narrow 0.511 MeV line radiation could be subtracted self-consistently from these measurements, if it had the value measured by Gehrels et al. (1991), leaving a point source flux $\simeq 8 \times 10^{-4}\gamma$ (cm^2 s)$^{-1}$ during the year 1988–1989. The measurements by Gehrels et al. (day 303 of 1988) and Niel et al. (day 330 of 1988) coincided with periods during which we obtained upper limits on the 1 MeV line flux from the *SMM* data. Inspection of Figure 11 reveals that our conservative 3 σ upper limits were 2.3×10^{-3} and $5.8 \times 10^{-3}\gamma$ (cm^2 s)$^{-1}$, respectively. These limits are consistent with our expectation that $\phi_{1.0} \gg \phi_{0.511}$, when compared with the narrow 0.511 MeV line fluxes $\sim 8 \times 10^{-4}\gamma$ (cm^2 s)$^{-1}$ measured simultaneously by the balloon experiments. Our results, therefore, do not constrain the model by which the narrow annihilation line arises almost immediately from e^+ escaping from the pair-dominated plasma.

4.2. *Narrow Annihilation Line Delayed Relative to* 1 MeV *Line*

In the model of Ramaty et al. (1992), a short-lived source of positrons (e.g., a pair-dominated plasma) injects relativistic positrons into the molecular cloud surrounding 1E 1740.7−2942, where they eventually slow down and undergo annihilation, producing the narrow 0.511 MeV line. The time delay between a single injection event and the annihilation of the e^+ is almost exactly fixed by the duration of the transient annihilation line, which for the 1988–1989 transient was $\sim$1 yr. The detailed results of Ramaty et al. indicate that the transient could have been caused by an "instantaneous" e^+ injection $\sim$2 yr previous to the transient. Some support is given to this model by the discovery at radio wavelengths of a jet emanating from 1E 1740.7−2942 (Mirabel et al. 1992). If the jet is composed of relativistic e^- and e^+ emitting synchrotron radiation, of which the e^+ slow down and annihilate at the end of the jet, then the length $\sim$1 pc of the jet implies a travel time of $\sim$3 yr between e^+ injection and annihilation.

We therefore anticipate the occurrence of a 1 MeV line transient, associated with the injection of e^+, about 2–3 yr prior to the 1988–1989 0.511 MeV transient, i.e., some time between mid-1985 and mid-1987. Out of our results for a 1 MeV line transient from the GC presented in Figure 11, those during the transit periods labeled "1985" and "1986" cover this interval. It can be seen that in no 12 d period did our 3 σ upper limit on the 1 MeV line flux exceed $1.1 \times 10^{-2}\gamma$ (cm^2 s)$^{-1}$, implying a fluence $\phi_{1.0}\tau_{1.0} \ll 1.1 \times 10^4\gamma$ cm^{-2} from any single transient lasting for $\sim$12 d. Since the fluence in the 0.511 MeV transient was approximately (8×10^{-4} γ cm^{-2} s^{-1}) × (1 yr) = $2.5 \times 10^4\gamma$ cm^{-2}, it is clear that equation (1) is not satisfied. We can therefore constrain the occurrence of any broad 1 MeV line associated with a e^+ source to the period 1986 March–September, which is not covered by our measurements. In this way, the time delay parameter in the Ramaty et al. (1992) model, which is directly related to the e^+ energy, may be constrained.

This test of the simplest version ("instantaneous" injection on a $\sim$12 d time scale) of the Ramaty et al. (1992) model may be extended to yield similar constraints on more complicated injection patterns over different time scales. For example, the case where a 1 MeV line is continuously present at a low level during the whole $\sim$2 yr period 1985–1987 can be shown to be excluded by combining our results from Figure 11 and using equation (1).

5. SUMMARY

We have measured the variation in flux (relative to the previous year) at MeV energies from five sources—the GC, Cyg X-1, the Crab Nebula, Cen A and NGC 4151—during the period 1981–1989. We searched for two types of transient from each source: a line-type transient centered at 1 MeV and an enhancement of the overall 0.6–7 MeV continuum. Our results for variability on 12 d time scales are summarized in Table 2, and are given in detail as a function of source and transient type for each 12 d period in Figures 4–15.

The several sources and transient types were chosen on the basis of positive results reported by previous experiments. Our conclusions may be summarized by the statement that we have observed no convincing example of either type of transient from any source. Our characteristic 3 σ upper limits for the transient flux on $\sim$12 d time scales from all sources are $\sim 4.5 \times 10^{-3}\gamma$ (cm^2 s)$^{-1}$ for line-type transients and $\sim$2 Crab units for continuum-type transients. These limits may be compared with previous reports of line-type transient fluxes of $\sim 1.5 \times 10^{-2}\gamma$ (cm^2 s)$^{-1}$ (Ling et al. 1987, from Cyg X-1; Riegler et al. 1985, from the GC) and of a continuum-type transient flux of 4.7 Crab units (Ling & Dermer 1991, from the Crab), on the same time scale. The duty cycles of the reported transients from the respective sources during 1981–1989 are estimated to be about 4% or less. Our analysis lacked the sensitivity to constrain strongly the occurrence on 12 d time-scales of other continuum-type transients reported from Cyg X-1 (Bassani et al. 1989; McConnell et al. 1989), Cen A (von Ballmoos et al. 1987), and NGC 4151 (Perotti et al. 1981), whose reported strengths were much weaker; our upper limits on the duty cycles of these outbursts on 12 d time scales are in the range 13%–20% (§ 3.2).

Three of the previously reported measurements occurred during the period 1981–1989 of *SMM* coverage. All were of the continuum type, from the sources Cen A (1982 October 31), Cyg X-1 (1984 October 2), and the Crab Nebula (1980 Spring). In no case can we confirm the occurrence of transient emission at MeV energies at the relevant times. In the cases of the first two events (Cen A and Cyg X-1), we cannot exclude the occurrence of the reported transients due to the reduced sensitivity of our analysis over the short (<1 d) time scales involved; we can, however, exclude the possibility that these events were prolonged over periods longer than 6–8 days (see Tables 3 and 4). In the case of the 1980 Crab transient, systematic errors prevent us from drawing any conclusion about the occurrence of the transient (§ 3.6). We withdraw our earlier preliminary conclusion (Share et al. 1993) that our result is in disagreement with that of *HEAO 3* (Ling & Dermer 1991).

We have not performed a general search for lines for arbitrary energy above 1 MeV; however, our upper limits on the "continuum-type" transient flux imply characteristic upper limits $\sim 1.7 \times 10^{-2} E^{0.68}$ photons $(\mathrm{cm}^2\ \mathrm{s})^{-1}$ on the flux in a line at energy E MeV from our sources during 12 d periods (§ 3.3). Our negative results are not, of course, relevant to reports of transient features at lower energies, such as lines around 400 keV from the Crab Nebula (Owens 1991) or around 500 keV from the GC (Tueller 1992), although in § 4 we discuss constraints on a model which relates the latter to our 1 MeV line. These features will be dealt with in future papers in this series.

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APPENDIX A

SUBTRACTION OF TWO EARTH-ALBEDO SPECTRA

As mentioned in § 2.2, we have generally assumed that the subtraction of background spectra from source spectra, both of which have the Earth-atmosphere albedo form studied by Letaw et al. (1989), will give rise to a residual continuum which will itself have the same Earth-albedo form. This expectation was found in general to be true; the amplitude of the Earth-albedo spectrum changes somewhat from one year to the next, while preserving roughly the same shape. However, cases occasionally arose where the amplitudes of the two Earth-albedo spectra were very similar. The difference of the two is then dominated by small departures from the standard atmospheric shape.

We found that this effect produced a systematic peak in the difference spectrum, which could be confused with a broad line at 1 MeV. To show this, we assume that the Earth atmosphere spectrum may be approximated by a power law in energy. Let two power laws of closely similar amplitudes and indices be subtracted. The difference spectrum is

$$y = (a + da)E^{-(b+db)} - aE^{-b} .$$

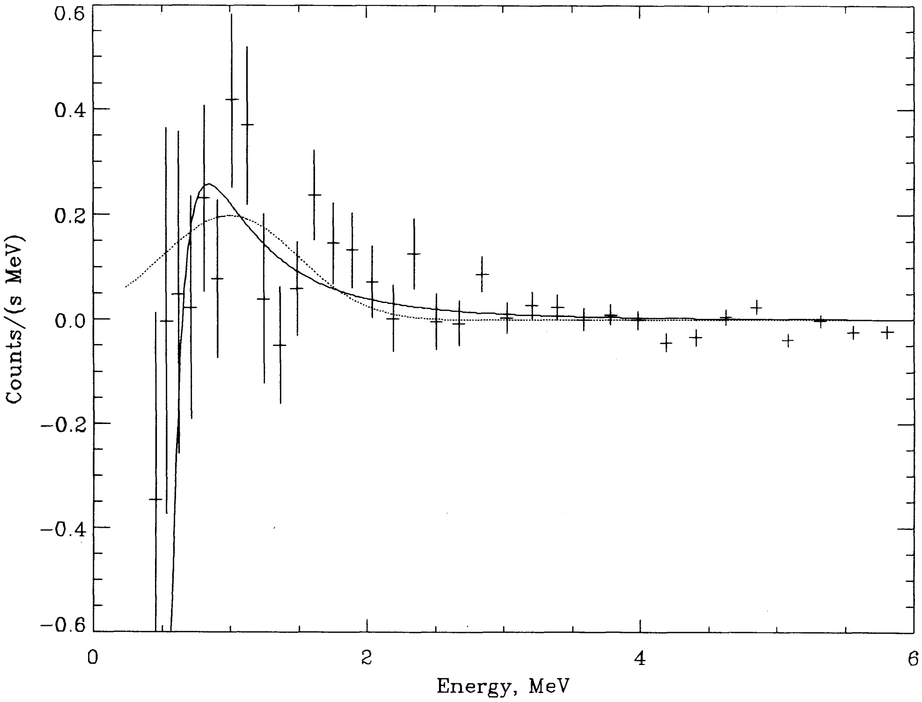

FIG. 16.—Spectrum of transient emission from the GC during days 188–199 of 1982. Background subtraction gives rise to spectrum which changes sign near 0.7 MeV (*data points*). *Solid line*: Spectrum fitted by equation (A1) without lines. *Dashed line*: Spectrum fitted by power law plus spurious broad line at 1.0 MeV.

The power laws must cross at some energy E_c. Let $x = E/E_c$. Therefore,

$$y = Ax^{-b}(x^{-db} - 1) ,$$

where $A = aE_c^{-b}$. Using $x^{-db} \simeq 1 - db \ln x$, from the Taylor series expansion for small db, therefore,

$$y = -A\,dbx^{-b} \ln x \tag{A1}$$

This function possesses a maximum at $x_{\max} = e^{1/b}$.

If the energy $E_{\max} = x_{\max} E_c$ is close to 1 MeV, then this maximum will appear as a spurious broad 1 MeV line in our transient spectrum. We therefore searched our 12 d transient spectra for such cases, and fitted them with a model spectrum in which the continuum had the form of equation (A1). These cases are very easy to recognize because the spectrum must change sign ($x = 1$) near or below 1 MeV; thus they will not be confused with any spectrum containing a celestial 1 MeV line transient. An example of such a spectrum is shown in Figure 16.

APPENDIX B

TEMPORAL SIGNATURE EXPECTED FROM COSMIC TRANSIENTS

Our background subtraction procedure (described in § 2.2) involves the subtraction from each 1 minute source spectrum of a background 1 minute spectrum taken one year previously. It is thus obviously possible for a transient event (either line-type or continuum-type) to appear *twice* in our residual spectra: first at the time of its occurrence in the source spectrum, and then again 1 yr later in a background spectrum. It might therefore naively be expected that the temporal signature of a genuine transient would consist of a positive flux measurement at the time of occurrence, followed by a negative flux of equal amplitude 1 yr later. In fact, the signature which will result from a genuine transient may be more complex, depending on the duration of the transient. In this Appendix we show that the naive expectation is fulfilled for transients whose duration is between ~4 d and ~150 d, which are the main subject of this paper.

In the first place, we note that a given 1 minute spectrum always appears once, and only once, among the source spectra. Therefore, if it contains a positive transient flux, the equal negative flux will only appear 1 yr later if that 1 minute spectrum is selected once, and only once, for use in background subtraction. In general, this will not be the case. In the procedure described in § 2.2, background spectra are selected from among all 1 minute spectra within a range of 8% of the *SMM* precession period, i.e., about 4 days. Any individual 1 minute background spectrum may be employed many times, or once, or not at all.

Consider now a steady transient of length t greater than 1 minute. A positive transient flux will always appear in t/(1 minute) source spectra. The equal negative flux will be measured 1 yr later only if the same number t/(1 minute) of spectra containing the transient are selected as background spectra. It is clear that this outcome becomes increasingly probable as t increases above 4 d. As t increases above this value, there is an increasing number of 1 minute source spectra (those 1 yr after the period of $t - 4$ days in the center of the transient) which *must* be accompanied by a background spectrum containing the transient.

It is also obvious that the temporal signature of a transient becomes more complex when t exceeds 1 yr. In this case, a positive flux is found during the first year of the transient; for the next $t - 1$ yr, the background subtraction cancels any signal; and for the year immediately after the end of the transient, a negative flux is found. It is virtually impossible to conduct an exhaustive search for this kind of behavior in our data, partly because t is unconstrained, and partly because *SMM*'s solar pointing yields only ~150 d of coverage of any source during a year (see the " transit periods " listed in Table 1).

In this paper, we therefore conclude that when results are presented in the form of a time series of transient fluxes:

(1) Positive signals in one 12 d period which are not accompanied by approximately equal negative signals 1 yr later are due to transient events on time scales ≤4 d;

(2) Positive signals in one or more 12 d periods (up to ~150 d) which are accompanied by negative signals 1 yr later are due to transient events on the appropriate time scale ~12–150 d;

(3) Positive signals lasting for 1 yr, followed by negative signals lasting for 1 yr at an indeterminate later time, are due to transient events on a greater than 1 yr time scale, but are not recoverable from our results.

More complex behavior due to the occurrence of multiple transients is not likely to affect the second conclusion above, relating to ~12 d time scales, which is most relevant for the purpose of this paper. The only exception would be if a second transient occurred exactly 1 yr after the first, causing cancellation of the negative signal. We regard this eventuality as very unlikely, in view of the rarity of transient events.

We also emphasize that, while these temporal signatures are characteristic of transients from cosmic sources, *they will also be true for the signal from any systematic error which occurs on the appropriate time scale.* An example is the background-subtraction error which correlates with the count rate in the GRS's back plastic detector, which is discussed in § 2.3.2 and illustrated in Figures 2 and 3. The appearance of the correct temporal signature in a time series of transient strengths is therefore *not* a guarantee that the emission arose from a cosmic source.

REFERENCES

Bally, J., & Leventhal, M. 1991, Nature, 353, 234

Bassani, L., Dean, A. J., di Cocco, G., Perotti, F., & Stephen, J. B. 1989, ApJ, 343, 313

Bouchet, L., et al. 1991, ApJ, 383, L45

Chapuis, C. G. L., et al. 1991, in Gamma-Ray Line Astrophysics, ed. P. Durouchoux & N. Prantzos (New York: AIP), 54

Dermer, C. D., & Liang, E. P. 1988, in Nuclear Spectroscopy of Astrophysical Sources, ed. N. Gehrels & G. H. Share (New York: AIP), 326

1993ApJ...416..601H

Dunphy, P. P., Forrest, D. J., Chupp, E. L., & Share, G. H. 1989, in High-Energy Radiation Background in Space, ed. A. C. Rester, Jr., & J. I. Trombka (New York: AIP), 259

Forrest, D. J., et al. 1980, Sol. Phys., 65, 15

Gehrels, N. 1991, in Gamma-Ray Line Astrophysics, ed. P. Durouchoux & N. Prantzos (New York: AIP), 3

Gehrels, N., Barthelmy, S. D., Teegarden, B. J., Tueller, J., Leventhal, M., & MacCallum, C. J. 1991, ApJ, 375, L13

Harris, M. J., Leising, M. D., & Share, G. H. 1991, ApJ, 375, 216

Harris, M. J., Share, G. H., Leising, M. D., Kinzer, R. L., & Messina, D. C. 1990, ApJ, 362, 135

Jung, G. V. 1989, ApJ, 338, 972

Kurfess, J. D., et al. 1989, in High-Energy Radiation Background in Space, ed. A. C. Rester, Jr., & J. I. Trombka (New York: AIP), 250

Leising, M. D., et al. 1993, in preparation

Letaw, J. R., Share, G. H., Kinzer, R. L., Silberberg, R., Chupp, E. L., Forrest, D. J., & Rieger, E. 1989, J. Geophys. Res., 94, 1211

Leventhal, M., MacCallum, C. J., Barthelmy, S. D., Gehrels, N., Teegarden, B. J., & Tueller, J. 1989, Nature, 339, 36

Liang, E. P. 1990, A&A, 227, 247

———. 1991, ApJ, 367, 470

Liang, E. P., & Dermer, C. D. 1988, ApJ, 325, L39

Ling, J. C., & Dermer, C. D. 1991, in Gamma-Ray Line Astrophysics, ed. P. Durouchoux & N. Prantzos (New York: AIP), 361

Ling, J. C., Mahoney, W. A., Wheaton, W. A., & Jacobson, A. S. 1987, ApJ, 321, L117

Ling, J. C., & Wheaton, W. A. 1989, ApJ, 343, L57

Matz, S. M., Share, G. H., Leising, M. D., Chupp, E. L., Vestrand, W. T., Purcell, W. R., Strickman, M. S., & Reppin, C. 1988, Nature, 331, 416

McConnell, M. L., Forrest, D. J., Owens, A., Dunphy, P. P., Vestrand, W. T., & Chupp, E. L. 1989, ApJ, 343, 317

Mirabel, I. F., Rodriguez, L. F., Cordier, B., Paul, J., & Lebrun, F. 1992, Nature, 358, 215

Niel, M., et al. 1990, ApJ, 356, L21

O'Neill, T., Tumer, O. T., Zych, A., & White, R. S. 1989, ApJ, 339, 78

Owens, A. 1991, in Gamma-Ray Line Astrophysics, ed. P. Durouchoux & N. Prantzos (New York: AIP), 341

Owens, A., & McConnell, M. L. 1992, Comm. Astrophys., 16, 205

Perotti, F., et al. 1981, ApJ, 247, L63

Phinney, E. S. 1992, Nature, 358, 189

Ramaty, R., Leventhal, M., Chan, K. W., & Lingenfelter, R. E. 1992, ApJ, 392, L63

Ramaty, R., & Meszaros, P. 1981, 250, 384

Riegler, G. R., Ling, J. C., Mahoney, W. A., Wheaton, W. A., & Jacobson, A. S. 1985, ApJ, 294, L13

Share, G. H., Harris, M. J., Leising, M. D., & Messina, D. C. 1993, A&AS, 97, 341

Share, G. H., Kinzer, R. L., Kurfess, J. D., Messina, D. C., Purcell, W. R., Chupp, E. L., Forrest, D. J., & Reppin, C. 1988, ApJ, 326, 717

Share, G. H., Leising, M. D., Messina, D. C., & Purcell, W. R. 1990, ApJ, 358, L45

Sunyaev, R., et al. 1991, ApJ, 383, L49

Tueller, J. 1992, Proc. Compton Obs. Symp., ed. N. Gehrels & M. Friedlander (New York: AIP), in press

von Ballmoos, P., Diehl, R., & Schönfelder, V. 1987, ApJ, 312, 134