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SMM OBSERVATIONS OF GAMMA-RAY TRANSIENTS. II. A SEARCH FOR GAMMA-RAY LINES BETWEEN 400 AND 600 keV FROM THE CRAB NEBULA

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ABSTRACT

We have searched spectra obtained by the *Solar Maximum Mission* Gamma-Ray Spectrometer during 1981–1988 for evidence of transient γ-ray lines from the Crab Nebula which have been reported by previous experiments at energies 400–460 keV and 539 keV. We find no evidence for significant emission in any of these lines on time scales between ~ 1 day and ~ 1 yr. Our 3 σ upper limits on the transient flux during 1 d intervals are $\simeq 2.2 \times 10^{-3}$ photons cm^{-2} s^{-1} for narrow lines at any energy, and $\simeq 2.9 \times 10^{-3}$ photons cm^{-2} s^{-1} for the 539 keV line if it is as broad as 42 keV FWHM. We also searched our data during the ~ 5 hr period on 1981 June 6 during which Owens, Myers, & Thompson (1985) reported a strong line at 405 keV. We detected no line down to a 3 σ upper limit of 3.3×10^{-3} photons cm^{-2} s^{-1}, in disagreement with the flux $7.2 \pm 2.1 \times 10^{-3}$ photons cm^{-2} s^{-1} measured by Owens et al.

Subject headings: gamma rays: observations — ISM: individual (Crab Nebula)

1. INTRODUCTION

The evidence for episodic emission, during the 1970s and 1980s, of narrow lines around 73–79 and 400–460 keV from the Crab Nebula was reviewed by Owens (1991). The detections of these features were made by balloon-borne instruments; taken individually, they were of very short duration (of the order of several hours) and of rather low statistical significance. More recently, a line of width ~ 42 keV (FWHM) and of short duration was reported at $\simeq 539$ keV by the SIGMA experiment on board the *GRANAT* spacecraft (Sunyaev et al. 1992; Gilfanov et al. 1993). We summarize these measurements in Table 1. Our purpose in this paper is to monitor the appearance of lines at these energies in the data acquired during 1981–1988 by the Gamma Ray Spectrometer (GRS) aboard the *Solar Maximum Mission* (*SMM*), whose capabilities (described below) were well suited to the function of monitoring rare events.

If the lines are real, their intensities must be highly variable, since many other observations (not given in Table 1) have not detected them. In particular, the *HEAO 3* experiment did not detect the ~ 400 keV line down to a level 1.8×10^{-4} γ cm^{-2} s^{-1} during two 50 d periods in Fall of 1979 and Spring of 1980 (Mahoney, Ling, & Jacobson 1984), nor did the OSSE instrument on board the *Compton Observatory* during a similar period in 1991 Spring down to a level 8×10^{-5} γ cm^{-2} s^{-1} (Johnson et al. 1993). The SIGMA instrument itself detected the 539 keV line on only one out of ~ 10 comparable observations; the 3 σ upper limits on the occasions when it was not detected were 3×10^{-3} γ cm^{-2} s^{-1} (Gilfanov et al. 1993). The SIGMA and balloon-borne experiments which did report lines all lasted for ~ 1 d or less, suggesting that they are not long-lived.

Owens (1991) tentatively concluded that the line emission was real, reaching intensities up to 7×10^{-3} γ cm^{-2} s^{-1}; that it occurred during the interpulse phase of the overall continuum emission; and that the line energies showed a secular increase (from 73 to at least 78, and from 400 to 455 keV) over a 20 yr period. He interpreted the $\simeq 75$ keV line as the product of cyclotron emission in the Crab's $\sim 10^{12}$ G magnetic field, and the ~ 400 keV feature as the familiar 511 keV positron annihilation line, redshifted by the gravitational field near the neutron star's surface; the secular increase in line energies might be due to an outward movement of the emitting region. He pointed out the relevance of these observations to the rather similar line features which have been reported from some γ-ray bursts (Mazets et al. 1980). A more detailed model explaining some of the observations was offered by Bednarek, Cremonesi, & Treves (1992), in which electrons accelerated toward the neutron star produce ~ 1 MeV photons by an electromagnetic cascade, which in turn produce positrons on impacting the surface. It is not clear whether the line detected in 1991 at $\simeq 539$ keV by SIGMA (Sunyaev et al. 1992) is compatible with these scenarios.

In this paper, we exploit the characteristics—a long lifetime (almost 10 yr), exceptional gain stability, and a broad aperture—which fit the GRS for the purpose of monitoring the occurrence of rare γ-ray transients. Since the GRS was sensitive to photon energies between 0.3 and 8.5 MeV, we restrict our search to the lines reported between 400 and 600 keV. The GRS aperture at these energies is $\sim 140°$; since *SMM* was pointed at the Sun continuously during 1980–1989, it follows that the Crab Nebula appeared to move slowly across the GRS aperture during the 150 days of April through August of each year.

Our method of analysis of the GRS data, described in § 2, closely resembles that of Harris et al. (1993, hereafter Paper I). It has been applied to each of the 150 d periods (referred to as "transits") during the years 1981–1988 when the Crab was

TABLE 1

PREVIOUSLY REPORTED LINE EMISSION FROM THE CRAB IN THE ENERGY RANGE 400–600 keV

Date	Duration (hr)	Line Energy (keV)	Line Flux [γ/(cm^2 s)]	Experiment
1976 May 10	4.5	400 ± 1	$2.2 \pm 0.9 \times 10^{-3}$	Bell-Sandia[a]
1977 Sep 30	6.4	400 ± 2	$7.4 \pm 5.4 \times 10^{-3}$	Rikkyo Univ.[b]
1981 Jun 6	4.8	405 ± 1	$7.2 \pm 2.1 \times 10^{-3}$	Durham Univ.[c]
1986 Jul 11	2.5	...	...	...[d]
1990 Jul 9	4.8	440 ± 10	$8.6 \pm 3.3 \times 10^{-5}$	FIGARO II[d]
1992 Mar 10–11	23	539^{+11}_{-14}	$5.2 \pm 1.9 \times 10^{-3}$	SIGMA[e]

[a] Leventhal, MacCallum, & Watts 1977.

[b] Yoshimori et al. 1979.

[c] Ayre et al. 1983, Owens, Myers & Thompson 1985.

[d] Two separate measurements by FIGARO II are combined here; no separate analysis of the 1986 flight has been published. The line flux is the average across the pulse profile. Agrinier et al. 1990; Massaro et al. 1991; Olive et al. 1993.

[e] Sunyaev et al. 1992; Gilfanov et al. 1993.

within the GRS field of view, so as to measure the *change* in line fluxes relative to the previous year, on a daily basis. The results are presented in § 3.1. Two of the reports of line detections around 400 keV occurred during this period (Table 1), both from balloon-borne experiments lasting less than 1 day—by Durham University on 1981 June 6 (Owens, Myers, & Thompson 1985) and by FIGARO II on 1986 July 11 (Agrinier et al. 1990; Massaro et al. 1991). We made a modification to our analysis procedure to search for the line reported by Owens et al. in the *SMM* data which were exactly contemporaneous with the Durham experiment (§ 3.2). The line reported by the FIGARO II experiments was much weaker than the sensitivity of *SMM* according to our analysis.

The lines detected during the two flights of FIGARO II (Massaro et al. 1991; Olive et al. 1993) were present only during a restricted portion of the pulsar light curve (the interpulse region and the second pulse; the transient 77 keV line reported by Strickman, Kurfess, & Johnson [1982] may have shared this behavior). The *SMM* GRS data are accumulated over 1 minute intervals, which precludes us from investigating this aspect of the lines' behavior.

2. ANALYSIS

2.1. *Background Subtraction*

The 1 minute GRS spectra are dominated by background radiation from a variety of sources, which must be eliminated in order to recover any signal from a celestial γ-ray source. Our analysis was based on the fact that, over the 10 year life of the mission, conditions of identical background recurred. For a given 1 minute spectrum, we were therefore able to identify a previous 1 minute spectrum wherein the background spectrum was the same, and to subtract the latter from the former. By this procedure the background was (in theory) eliminated,[1] as was any steady signal from the celestial source. However, the *change* in the source spectrum between the two widely separated minutes was preserved. Failure to detect the lines between 400 and 600 keV by *HEAO 3* (Mahoney, Ling, & Jacobson 1984) and by *OSSE* (Johnson et al. 1993) suggest that they are present only sporadically and are not likely to be subtracted out by this type of procedure.

Our method of analysis is described in detail in Paper I, where it was applied to a broad line at 1 MeV, and to an enhanced continuum over the broad region 0.6–7 MeV. The data to be analyzed were the 1 minute sums of GRS spectra taken during the periods 1980 February–1983 November and 1984 April–1989 February (the gap being due to a loss of fine attitude control, which was repaired in-orbit), from which data coinciding with known transient backgrounds such as solar flares and γ-ray bursts were removed. Data from orbits passing through the South Atlantic Anomaly (SAA), and from the $\sim 10^4$ s after such a passage, were also rejected. Measurements of the spacecraft's charged-particle environment, taken by the plastic charged-particle detector at the back of the GRS during the same 1 minute intervals, were also employed in the analysis.

Each 1 minute spectrum was labeled with the values of the parameters upon which the background was found to depend: the geomagnetic field strength, the satellite's geographic position, the Sun-Earth-satellite angle, and the phase of that minute within the satellite's $\sim$47 d precession period (see Paper I). Each spectrum taken between 1981 February and 1989 February was treated as a "source" spectrum, potentially containing a celestial transient. We then identified that "background" spectrum taken $\sim$1 yr earlier (in fact, eight *SMM* precession periods) which had the most similar values of the above parameters.[2] The background spectra were subtracted from the source spectra, and the subtracted 1 minute spectra were summed for each day into two bins, according to whether the Crab was occulted by Earth, or not.

By taking background spectra from $\simeq$1 yr prior to the source spectra, we ensure that the GRS's exposure to the Crab is essentially the same in both, in the unocculted spectra. We then subtracted the occulted spectrum for each day from the unocculted spectrum; this removes a contribution from 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 Crab Nebula since the previous year.

[1] Our method of identifying background spectra by the values of the parameters upon which the backgrounds depend is described below the (in detail) in §§ 2.1, 2.2 of Paper I. It is effective in rejecting over 95% of the typical level of background in the GRS.

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

2.2. *Spectrum Fitting*

The residual spectra obtained in the manner described above were searched for evidence of the kind of lines reported by the experiments in Table 1. It was shown in Paper I that imperfect background subtraction, in this analysis, left behind a spectrum of the form of the Earth atmosphere albedo spectrum (Letaw et al. 1989). In the spectral region 400–600 keV, this spectrum may be approximated by a power law, on which are superposed a line at 511 keV and a rather flat continuum extending below 511 keV, which is attributed to atmospheric Compton scattering of photons from the 511 keV line. Any transient lines from the Crab Nebula will in turn be superposed on a spectrum of this form. A typical example of such a residual spectrum is shown in Figure 1.

We fitted each 1 day residual spectrum by a series of four-component models. In each, the three components attributed to the residual Earth-albedo spectrum were a narrow line at 511 keV, a Compton-scattering continuum, and an underlying power law in energy, as in Figure 1. The fourth components were single lines at energies of 400–460 keV in steps of 10 keV, and at 539 keV, in the different models. The 10 keV step in energy was chosen to be less than the GRS energy resolution of 40 keV (FWHM). The intrinsic widths of the lines between 400–460 keV were set to be much narrower than this resolution (< 3 keV); the 539 keV line was fitted twice, having in one model the narrow FWHM 2.4 keV, and in the other a FWHM 42 keV (corresponding to the SIGMA measurement of the width, 42^{+52}_{-43} keV, which is also consistent with zero: Gilfanov et al. 1993). The fit was performed by folding the models through the GRS instrument response function and varying the parameters of the components until the best agreement was obtained (according to the method of least squares) with the count spectrum. The amplitudes of the transient lines were arranged in time series at 1 d intervals, excluding the periods when the Crab was outside the GRS FWHM aperture, totaling 1062 d. These time series were then searched for significant positive excursions.

The most important systematic error in the measured transient line strengths arose from the intensity of the underlying Earth-albedo spectrum which remained due to imperfect background subtraction. This error was particularly marked for the lines at 539 keV, which were in general partially blended with the atmospheric 511 keV line. In Paper I it was shown that this systematic effect was correlated with the count rate in the GRS back plastic charged-particle detector (§ 2.1), which provided us with a method of correcting for it.

We accumulated the 1 minute back plastic count rates in the same fashion as the 1 minute spectral rates (i.e., subtracting the background from the year before, and the occulted rate from the unocculted rate, and summing up to 1 d). The time series of transient line intensities was then fitted by the resulting time series of back plastic rates. A correction proportional to the fit amplitude was then subtracted from the line intensities; in effect, we corrected the line intensities according to the degree to which they were correlated with the back plastic count rate.

3. RESULTS

3.1. *Results from the Whole Mission*

No strong evidence of any positive transient line flux in the energy range ~400–600 keV was found at any of the line energies. Characteristic results for two line energies for one transit of the Crab are shown in Figures 2 and 3; the results for the other lines and the other years are very similar. In Table 2 we summarize the results, in terms of the characteristic 3 σ upper limits upon the transient flux for each line energy. These range from $\sim 2.2 \times 10^{-3}$ photons cm^{-2} s^{-1} for the narrow lines below 511 keV to 2.9×10^{-3} photons cm^{-2} s^{-1} for a broad line at 539 keV. The fluxes are more or less randomly distributed about the value zero, and the level of systematic errors is small (the value of χ^2 per d.o.f. for the null hypothesis is characteristically ~1.08).

An alternative way of expressing these results is in terms of the "duty cycle" of the specific reported transients of Table 1,

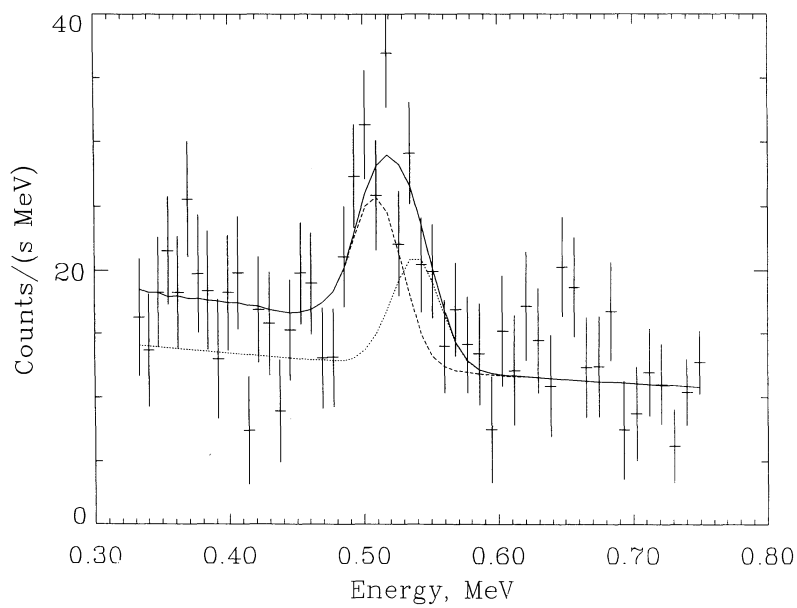

FIG. 1.—Characteristic residual spectrum for 1982 April 8 (1982 day 97.97–98.95), fitted by a model spectrum (*solid line*) consisting of a power-law continuum, narrow (< 3 keV) lines at 511 keV (*dashed line*) and 539 keV (*dotted line*), and a continuum below 511 keV formed by Compton scattering of that line. For this fit, the inferred line fluxes are 2.8×10^{-3} photons cm^{-2} s^{-1} at 511 keV, and 2.5×10^{-3} photons cm^{-2} s^{-1} at 539 keV.

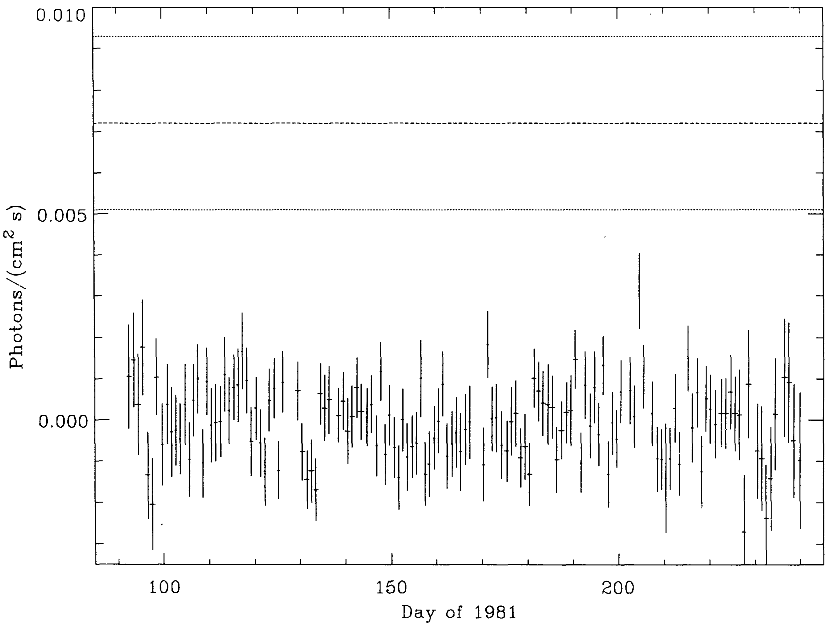

FIG. 2.—Inferred fluxes of transient 400 keV line emission during the 1981 transit of the Crab Nebula (data points and 1 σ errors). *Dashed line* represents the level of line emission observed by Owens, Myers, & Thompson (1985), and *dotted lines* the 1 σ error on that observation.

i.e., the fraction of the total time coverage (1062 days) during which a transient of the appropriate strength was detected; this approach focuses attention on the outlying points in our results, rather than on the statistical properties of the entire ensemble. In Table 3 we present the results in these terms; the duty cycle of all of the reported transients must have been less than 1% during 1981–1988.

The extent of our disagreement with the three balloon experiments which reported strong ($\geq 2.2 \times 10^{-3}$ photons cm^{-2} s^{-1}) transient lines close to 400 keV is expressed quantitatively using the binomial formula for the two possible outcomes of a measurement—either such a transient is measured on a given day, or it is not. Together with the three positive measurements at this energy (Tables 1 and 2), we also include the two balloon measurements during the pre-*SMM* period which did not detect the line down to this flux level during intervals ≤ 1 d (Ling et al. 1979; Hameury et al. 1983). The probability of this pattern of outcomes—three detections out of five attempts—is $P(3) = 5!/(2!3!)p^3(1 - p)^2$ where p is the probability of a line flux $\geq 2.2 \times 10^{-3}$ photons cm^{-2} s^{-1} being

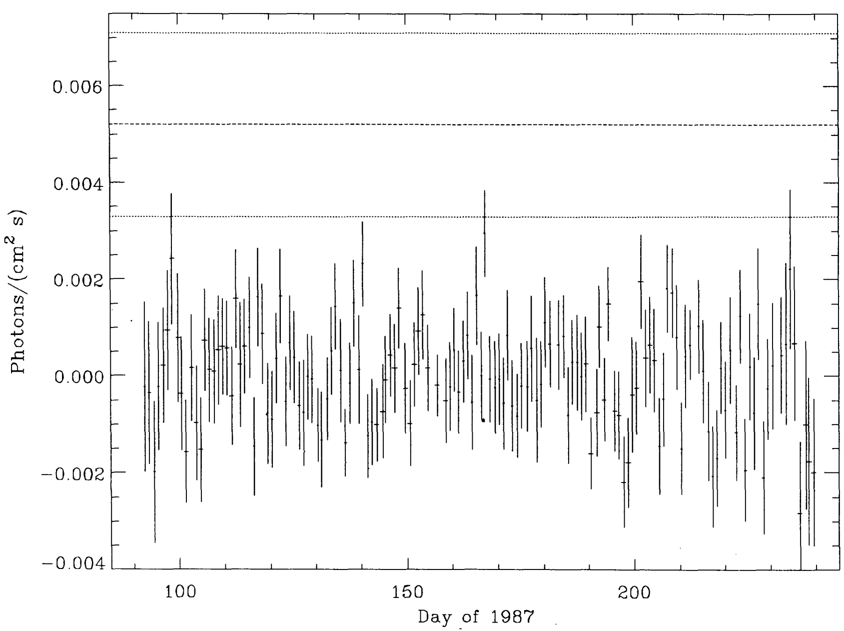

FIG. 3.—Inferred fluxes of transient 539 keV line emission during the 1987 transit of the Crab Nebula. Line width is assumed to be 42 keV FWHM. Symbols as in Fig. 2, except that the dashed and dotted lines refer to the line emission observed by SIGMA in 1991 (Gilfanov et al. 1993).

TABLE 2

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

Line Energy (keV)	Line Width (keV)	Flux 3 σ Upper Limit [γ/(cm² s)]
400	2.4	2.30×10^{-3}
410	2.4	2.33×10^{-3}
420	2.4	2.11×10^{-3}
430	2.4	2.21×10^{-3}
440	2.4	2.07×10^{-3}
450	2.4	2.16×10^{-3}
460	2.4	2.17×10^{-3}
539	2.4	2.32×10^{-3}
539	42	2.92×10^{-3}

measured on a given day. According to our results in Table 3, $p = 9/1062$, so that the probability of obtaining three detections in five balloon observations is $P(3) = 6 \times 10^{-6}$.

3.2. 405 keV *Line Transient of 1981 6 June*

The transient 404.7 keV line measured by the Durham University balloon experiment had an intensity $7.2 \pm 2.1 \times 10^{-3}$ photons cm^{-2} s^{-1} (Ayre et al. 1983; Owens, Myers, & Thompson 1985). The transient fluxes in a line at 400 keV measured by *SMM* on that day and the adjacent days did not exceed 1.0×10^{-3} photons cm^{-2} s^{-1} (Table 4 and Fig. 2). However, the *SMM* measurement overlapped only with part of the Durham observation, since at ∼19.18 UT the satellite began a series of orbits intersecting the SAA, and these data were not used in our general analysis (§ 2.1). We now examine them in more detail, so as to place tighter constraints on any transient line emission at that time.

The backgrounds arising in the GRS after SAA passages have been described by Dunphy et al. (1989). Such spectra contain linelike features, as yet unidentified, at energies around 400 keV. However, Dunphy et al. also showed that these features are removed (at least to a first approximation) by subtraction of a background spectrum obtained outside the period of SAA passages under the same conditions of spacecraft orientation, geographic position, and geomagnetic field parameters, after the lapse of ∼24 hr. Leising et al. (1994) have exploited this fact to search for transient lines on time scales of less than 1 d in the *SMM* data, and we have adopted the same technique to search for a transient line at 405 keV in the data from 1981 June 6–7.

The technique can be considered as a modification of that described in § 2.1, the difference being that the background spectrum is obtained, not from *1 year* before, but from *1 day* before and after the source spectrum. The 1 minute spectra during 1981 June 5–8 were summed into 3 minute accumulations. For every 3 minute "source" spectrum[3] during 1981 June 6–7 a "background" spectrum was obtained by averaging two 3 minute spectra obtained 15 orbits (≃1 d) before and 15 orbits after that minute, having the closest-matching values of the background parameters (Leising et al. 1994; see also Share et al. 1993 and § 3.5.3 of Paper I).

The 3 minute background-subtracted spectra were summed up over several 94 minute *SMM* orbital periods into separate bins according to whether the Crab was occulted by Earth or not, and the occulted bins were subtracted from the unocculted. The resulting transient spectra were fitted by a model spectrum containing a narrow line at 405 keV, as described in § 2.2 above. The results are given in Table 4. We see that during the period of the Durham University balloon observation there is no significant transient line at 405 keV measured by *SMM*; the Durham measurement lies ∼7 standard deviations above the *SMM* background level (line 6 of Table 4).[4]

4. CONCLUSIONS

The *SMM* results contain no evidence for lines from the Crab Nebula at any of the energies considered, between 400–460 keV and at 539 keV. In particular, these results do not support the existence of the strong transient line reported at ≃400 keV by three earlier balloon experiments (the Bell-Sandia, Rikkyo University, and Durham University experiments, Table 1). The duty cycle of this line must be less than 1%, according to the results of our eight years of monitoring (Tables 2 and 3), and the probability that three balloon experiments would have seen it, during very brief exposures, is estimated to be $\sim 6 \times 10^{-6}$ (§ 3.1). In addition, we find no trace of the line when we examine the *SMM* data which were obtained at exactly the same time as the Durham balloon measurement (§ 3.2).

This conclusion is fortified by several other reported nondetections of the line (only the actual detections are given in Table 1). Balloon experiments which could have detected it (at intensity $\geq 2.2 \times 10^{-3}$ photons cm^{-2} s^{-1}), but did not, were

[3] Selected as described in § 2, except for the restriction on time since SAA passage.

[4] We have not repeated this analysis for the *SMM* data contemporaneous with the 1986 July 11 FIGARO II experiment, which also reported the presence of a transient line, since the intensity was much weaker than the sensitivity which we could achieve. Our results during the ∼1 d intervals around this epoch did not differ materially from those presented in Fig. 2, and the upper limit from Table 2 on a 440 keV line may be taken as applying to them.

TABLE 3

RESULTS FOR UPPER LIMITS ON DUTY CYCLE OF PREVIOUSLY REPORTED TRANSIENT LINES

Transient	Model Line Energy (keV)	Model Line Width (keV)	Transient flux [γ/(cm² s)]	Number of Points ≥Flux	Duty Cycle (%)
Durham & Rikkyo	400	2.4	7.2×10^{-3}	0	<0.1
Bell-Sandia	400	2.4	2.2×10^{-3}	9	≤0.8
SIGMA	539	42	5.2×10^{-3}	1	≤0.1[a]

[a] The duty cycle implied by nondetections of this feature by *SIGMA* in other measurements during 1990–1992 is ∼0.1 (Gilfanov et al. 1993).

TABLE 4

MEASUREMENTS OF 405 keV LINE TRANSIENT ON 1981 JUNE 6

Day of 1981	Line Energy (keV)	Line Flux [γ/(cm^2 s)]	Experiment
157.71–157.91	404.7	$7.2 \pm 2.1 \times 10^{-3}$	Durham University[a]
156.42–156.72	400	$1.0 \pm 0.9 \times 10^{-3}$	*SMM*, 1 d timescale
157.39–157.80	400	$-1.3 \pm 0.8 \times 10^{-3}$	*SMM*, 1 d timescale
158.34–158.73	400	$-1.1 \pm 0.8 \times 10^{-3}$	*SMM*, 1 d timescale
157.39–157.68	405	$-1.3 \pm 0.9 \times 10^{-3}$	*SMM*, ~6 hr timescale
157.71–157.87	405	$-0.3 \pm 1.1 \times 10^{-3}$	*SMM*, ~6 hr timescale
157.91–158.34	405	$1.8 \pm 1.2 \times 10^{-3}$	*SMM*, ~6 hr timescale
158.37–158.73	405	$0.5 \pm 0.7 \times 10^{-3}$	*SMM*, ~6 hr timescale

[a] Ayre et al. 1983; Owens, Myers, & Thompson 1985.

conducted on 1974 June 10 by Ling et al. (1979), on 1980 September 25 by Hameury et al. (1983), and on 1990 May 31 by Bartlett et al. (1993). Much longer-lived satellite experiments have also failed to detect the line down to much lower levels $\sim 10^{-4}$ photons cm^{-2} s^{-1} (*HEAO 3*, Mahoney et al. 1984;[5] *OSSE*, Johnson et al. 1992).

Our results likewise show no evidence for the line reported by the SIGMA experiment at 539 keV (Table 1), though the disagreement is less conclusive; in the light of our results, the probability of the SIGMA detection is $\sim 10^{-2}$ (Table 3). Our measurements at $\simeq$440 keV are not sufficiently sensitive to confirm the transient line detected by two flights of the FIGARO II experiment during certain phases of the Crab pulse (Table 1).

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[5] A transient hard spectral component, at energies from 0.6–4 MeV, was discovered in *HEAO 3* data by Ling & Dermer (1991). The result of our search for this component, using the same method used in the present work, is described in Paper I.

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