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SEARCH FOR COMPTON-BACKSCATTERED ANNIHILATION RADIATION FROM THE GALACTIC CENTER WITH THE OSSE

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ABSTRACT

An emission feature near 170 keV, interpreted as Compton-backscattered 511 keV positron-annihilation radiation, has been reported twice by balloon-borne germanium spectrometers from within ~15° of the Galactic center (Leventhal, MacCallum, & Stang 1978; Smith et al. 1993). Upper limits on this feature set by *HEAO 3* (Mahoney, Ling, & Wheaton 1993) and other instruments indicate that it must be transient. We have searched data from the Oriented Scintillation Spectrometer Experiment (OSSE) on the *Compton Gamma Ray Observatory* (*CGRO*) for this feature, using daily spectral accumulations from all pointings near the Galactic center up to 1993 August, and covering most of the region viewed by the balloon instruments. We find no evidence for backscatter emission. Under the hypothesis that the source is 1E 1740.7−2942, the OSSE data set (186 days) disagrees with the balloon measurements with 99.3% confidence. The average daily 3 σ OSSE upper limit on backscatter flux from 1E 1740.7−2942 is 6.8×10^{-4} photons cm^{-2} s^{-1}, compared to the 1.3×10^{-3} photons cm^{-2} reported by the balloon observations. We also saw no evidence in 186 days for linelike emission from the point source EXS 1737.9−2952 recently discovered by Grindlay, Covault, & Manandhar (1993). This source exhibited bright emission from 83–111 keV, which has been interpreted as doubly backscattered 511 keV radiation. The average daily 3 σ upper limit from OSSE for this line is 9.8×10^{-4} photons cm^{-2} s^{-1}, or ~8% of the reported flux.

Subject headings: Galaxy: center — gamma-rays: observations

1. INTRODUCTION

Transient emission features near 170 keV have been reported twice from the Galactic center region. Both observations were made with balloon-borne germanium spectrometers; the spectra are shown in Figure 1. The Bell/Sandia instrument (Leventhal, MacCallum, & Stang 1978) had a circular field of view of 17° FWHM and a total observing time of 17.3 hr, and the High-Energy X-ray and Gamma-ray Observatory for Nuclear Emissions (HEXAGONE; Smith et al. 1993) had a circular field of view of 18° FWHM and observed for 6.3 hr. There may therefore be one or more sources of this feature within ~15° of the Galactic center, but no more positional information is available.

Figure 1 also shows a fit to both spectra, consisting of the sum of a power-law continuum, a Gaussian emission feature with an initial value of 170 keV for the centroid, and a positronium continuum (associated with the narrow Galactic 511 keV line, which is visible in both spectra but beyond the scope of this paper). The best-fit parameters for the 170 keV Gaussians are shown in Figure 1 and are nearly identical, despite the large difference in the amount of underlying continuum. The significance of the Bell/Sandia flux is 2.48 σ and that of the HEXAGONE flux is 2.76 σ.

A search of Galactic center data from the germanium spectrometer aboard the *HEAO 3* satellite found upper limits which strongly rule out the flux seen by the two balloon experiments, indicating that the source or sources must be variable (Mahoney, Ling, & Wheaton 1993). Other observations of the Galactic center region, which show statistically insignificant hints of 170 keV flux or show none at all, are tabulated in Smith et al. (1993).

The observations most directly comparable to those of Figure 1 are other Galactic center observations made with germanium spectrometers with fields of view from 15° to 20°. Since these are all from balloon flights, they are all on the order of a day long. In addition to the two spectra of Figure 1, this data set contains three null results: two from the Gamma-Ray Imaging Spectrometer (GRIS) in 1988 (Gehrels et al. 1991) which reject the Bell/Sandia and HEXAGONE fluxes with high significance, and one less significant result from the Low-Energy Gamma-ray Spectrometer (LEGS) in 1981 (Paciesas et al. 1982). The probability of finding at least two out of five

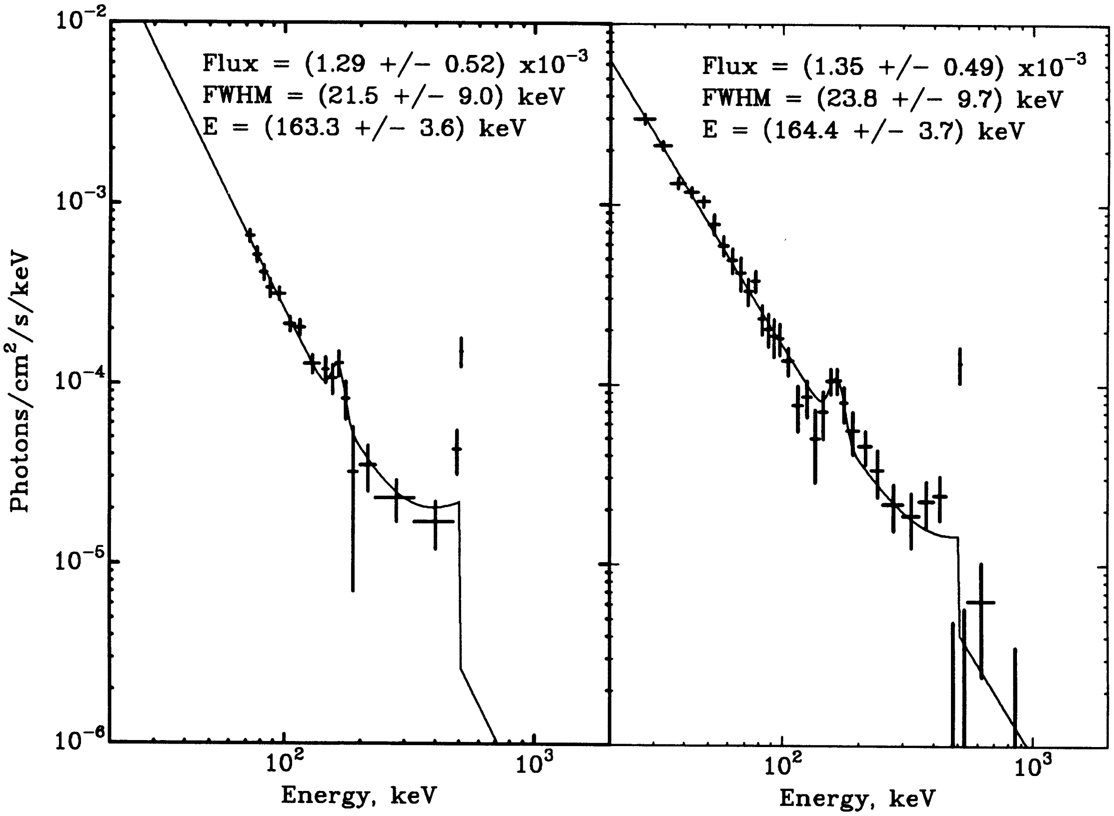

FIG. 1.—Balloon observations of the backscatter feature. *Left:* Bell/Sandia 1977 November; *right:* HEXAGONE 1989 May. Note that the fit Gaussian parameters for the feature are nearly identical.

observations to be greater than 2.48 σ in the absence of a real signal is 4.3×10^{-4}, assuming that the errors are purely statistical. This number does not take into account the information that the Bell/Sandia and HEXAGONE features have nearly identical fit parameters.

There are at least five other comparable balloon observations for which continuum spectra have not been published: two from the Bell/Sandia instrument and three recent observations, two from GRIS and one from HEXAGONE. If we assumed an additional five negative observations, the probability of having two above 2.48 σ would be 1.9×10^{-3}; in other words, we would have a 99.8% confidence that the reported 170 keV events are not statistical fluctuations.

The 170 keV emission has been interpreted as Compton-backscattered positron-annihilation radiation, originally at 511 keV (Lingenfelter & Hua 1991). In this model, positron production and annihilation occurs inside the inner edge of an accretion disk around a stellar-mass black hole; most of the unscattered annihilation flux is blocked by the near inner edge of the disk and is not seen by the observer. The backscatter feature is seen from the far side of the inner edge of the disk. They found that a positron annihilation rate of (2.5–5) $\times 10^{44} e^+ \text{ s}^{-1}$ best reproduced the observed backscatter flux. Smith et al. (1993) showed that, regardless of the exact geometry, an absolute minimum $10^{44} e^+ \text{ s}^{-1}$ of annihilation is required, or ~10 times the flux of the annihilation line seen in both spectra of Figure 1. This narrow annihilation line is thought to be mostly due to diffuse positron annihilation in the interstellar medium (see, e.g., Purcell et al. 1994).

A model for emission near 500 keV and/or 170 keV which does not require positrons at all has been proposed by Skibo, Dermer, & Ramaty (1994). The two lines are modeled as Compton-scattered features from an initial population of hard (power-law index > -1) continuum photons which are beamed parallel to two jets of cold, relativistically moving plasma. One jet provides the forward-scattered feature and the other the backscatter feature; the energies of the two features are fit by adjusting the viewing angle to the pair of jets and the velocity of the scattering plasma.

Recently observed flares of bright, transient emission near 511 keV from two black-hole candidates are compatible with both models and were, in fact, part of the inspiration for the model of Skibo et al. (1994). These observations were made by the SIGMA imaging gamma-ray instrument aboard the *Granat* spacecraft.

The first flare was on 1990 October 13, from 1E 1740.7−2942, ~1° from the Galactic center and therefore a candidate for the source of the backscatter (170 keV) events. This emission feature was broadened significantly, with FWHM 240^{+101}_{-94} keV, and had a statistically insignificant redshift if it was originally annihilation radiation, being centered at 480^{+96}_{-72} keV (Bouchet et al. 1991). Observations on the following day and three days earlier showed no such feature. This source is usually active in X-rays and hard X-rays and shows a core and two jets in the radio (Mirabel et al. 1992). It is coincident in position with a molecular cloud (Bally & Leventhal 1991; Mirabel et al. 1991). Ramaty et al. (1992) proposed that some of the positrons from flares in this object are propagated in the jets to the surrounding molecular cloud, where they annihilate over about a year, contributing a slowly varying component to the total Galactic narrow annihilation line. Further annihilation flaring reported by SIGMA in later years was less statistically significant (Churazov et al. 1993; Cordier et al. 1993).

The other SIGMA annihilation source is Nova Muscae, an X-ray transient of a sort believed to be caused by episodic accretion onto a stellar-mass black hole in a binary system. A transient line was detected in an observation on 1991 January 20–21, 11 days after outburst (Goldwurm et al. 1992). The line had a marginally significant redshift if due to positron annihilation (center energy 480 ± 22 keV) and was narrower than the 1E 1740.7−2942 flare (FWHM 23 ± 23 keV). In addition to the 480 keV line, there was a distinct emission feature near 200 keV. Hua & Lingenfelter (1993) demonstrated that backscatter of annihilation radiation could still explain a feature at this energy; the blueshift comes from infall of the inner edge of the accretion disk, the far side of which is the observed scattering site in their model. No repeat events were seen from Nova Muscae, and this source is too far from the Galactic center to be responsible for the balloon results.

A broad emission feature, similar in flux, energy, and width to the first 1E 1740.7−2942 outburst, was observed in *HEAO 1* A-4 data accumulated over ~2 weeks from a position ~12° below the Galactic plane (Briggs 1991). Because of a large uncertainty in its position, this source has not been identified.

A new transient point source near the Galactic center has been reported (Grindlay, Covault, & Manandhar 1993) by the imaging, balloon-borne Energetic X-ray Imaging Telescope Experiment (EXITE). This source, EXS 1737.9−2952, was observed to emit in only two of that instrument's energy bands: 20–30 keV and 83–111 keV out of a total range of ~20–250 keV. It was suggested by the authors that the 83–111 keV emission is double-backscattered annihilation radiation, which would have an energy of 102 keV. The flux in this band is ~10 times the 170 keV single-backscatter fluxes in Figure 1, yet a second backscatter would naturally *reduce* the flux by about an order of magnitude, so the implied annihilation rate would be greater than $10^{46} e^+ \ \mathrm{s}^{-1}$, or greater than 10^{40} ergs s^{-1} in annihilation photons. EXITE did not have the energy range to see unscattered annihilation photons.

A possible double-backscatter feature is also visible in some of the Nova Muscae data when the spectrum of Goldwurm et al. (1992) is subdivided into shorter time intervals (Goldwurm et al. 1993).

2. OBSERVATIONS

We have searched data from the Oriented Scintillation Spectrometer Experiment (OSSE) on the *Compton Gamma Ray Observatory* (*CGRO*) for backscatter features. OSSE's energy resolution at 170 keV (~24 keV FWHM) is comparable to the reported widths of the backscatter peak (12–24 keV). The OSSE field of view is rectangular, with FWHM 3°.8 and 11°.4, so it cannot simultaneously monitor the full fields of the germanium instruments. For a detailed discussion of OSSE and its operation, see Johnson et al. (1993).

From 1991 July through 1993 August, OSSE observed the Galactic center region for 215 days. We search daily spectral sums because that is the approximate duration of the HEXAGONE and Bell/Sandia balloon flights, the brightest SIGMA transient from 1E 1740.7−2942, and the SIGMA transient from Nova Muscae.

Each day, data are taken at several scan positions a few degrees apart, spaced along the axis perpendicular to the long axis of the collimator. During some viewing periods, these fields of view are chosen to overlap. The detectors switch rapidly between these positions and background fields further out (usually 10°) along the same axis which do not overlap the source fields. The background for each source pointing is a weighted sum of several observations of at least two background fields. The angle between the Galactic plane and the long axis of the collimator varies from day to day, but not within a day.

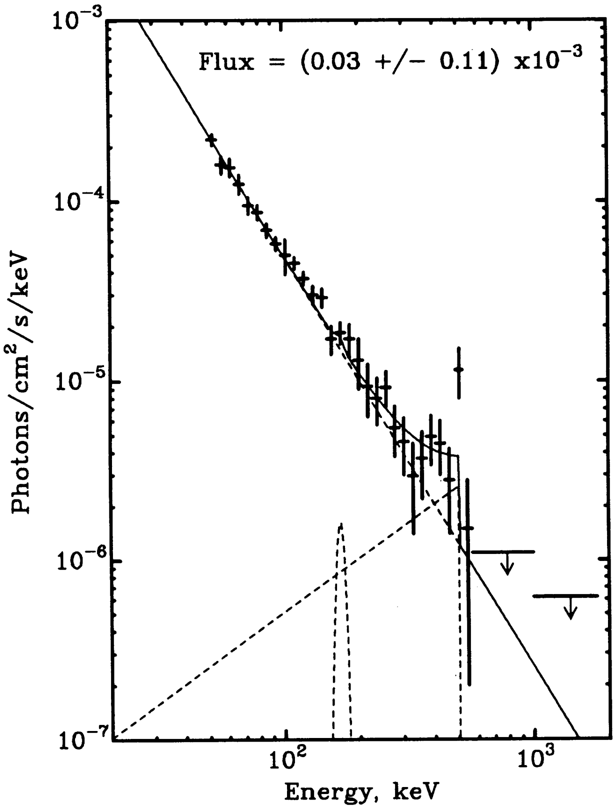

FIG. 2.—Typical daily OSSE photon spectrum with fit components (*dotted lines*) and total fit (*solid line*). The width and centroid of the Gaussian were constrained to lie within the HEXAGONE 1 σ limits.

Sometimes all four OSSE detectors follow the same pointing program; sometimes one or two detectors observe one pointing within the field of interest, while the others observe another pointing; and sometimes one or more detectors look at some other part of the sky entirely. When we refer to the data from a given pointing, we mean the summed spectrum from as many detectors as were pointing together at the time.

The total data from each pointing from each day were fitted with the same spectral form used for the balloon data above. Model spectra were folded through the OSSE instrument response and varied until the best fit to the count spectrum was obtained. The width and centroid of the backscatter peak were allowed to vary within the 1 σ errors on the fit to the HEXAGONE data. Figure 2 shows the result of a fit for one pointing on one day. Since all four detectors are pointing together on this day, the statistics are excellent.

3. RESULTS

Figure 3 shows the number of days of OSSE coverage available as a function of position in Galactic coordinates. A pixel is considered to have been observed on a given day if the OSSE sensitivity for that pointing is adequate to detect the mean of

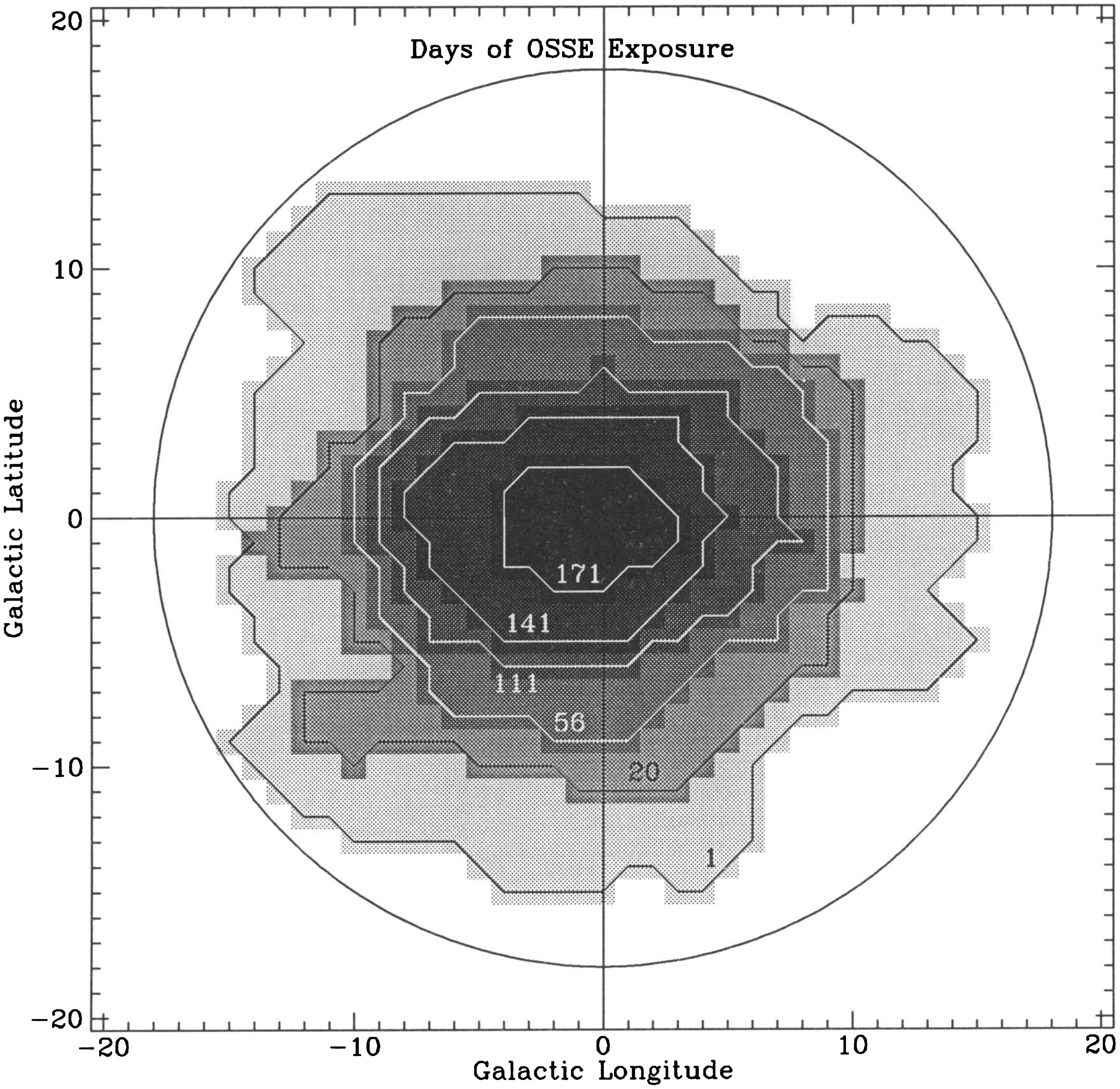

FIG. 3.—Map in Galactic coordinates of the number of days of useful OSSE exposure to each 1°-by-1° pixel. The circle of 18° radius is approximately the full field of view of both the Bell/Sandia and HEXAGONE balloon instruments.

the Bell/Sandia and HEXAGONE fluxes (1.32×10^{-3} photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ times a position-dependent correction for the balloon aperture response) at 2.0 σ. This criterion eliminates pixels on the very edge of the OSSE field of view.

The distribution of fitted backscatter fluxes from all the OSSE pointings is shown in Figure 4*a*, with the five balloon results shown for comparison. Figure 4*b* shows the distribution of statistical significances, which in the absence of a real source should be a Gaussian with a standard deviation of 1 (this is shown for comparison and has no fit parameters). In the following analysis we will assume the errors in the fit backscatter fluxes are normally distributed.

No pointing shows a flux as high as the two balloon observations, although one spectrum comes close, with 1.0×10^{-3} photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. The significance of this observation is 3.0 σ. To determine whether one such observation would be expected by chance, we examine the distribution of significances (the point with the highest flux is the point with the second-highest significance). Out of 742 observations, the expected number above 3.0 σ is 1.0 (compared to two in the data). The expected number above 3.5 σ is 0.17 (compared to one in the data). We conclude that there is no evidence for backscatter emission.

In order to quantify the compatibility of the balloon and OSSE data sets, the rest of the analysis varies depending on our hypothesis as to the origin of the emission.

3.1. *1E 1740.7−2942 Hypothesis*

Under this hypothesis, we assume the source is 1E 1740.7−2942 and that it produces backscatter flares in an uncorrelated fashion (as a Poisson process) with a constant brightness (the average of the two balloon detections). Since this source was almost precisely at the center of the balloon fields of view, there is no correction for the balloon collimators. Of the 215 days of OSSE data near the Galactic center, 186 contain pointings which include this source.

We account for the overlapping OSSE fields of view on some days by dividing the sky into a field of 1°-by-1° pixels (as in Fig. 3) and, for each day, taking a weighted sum of all pointings

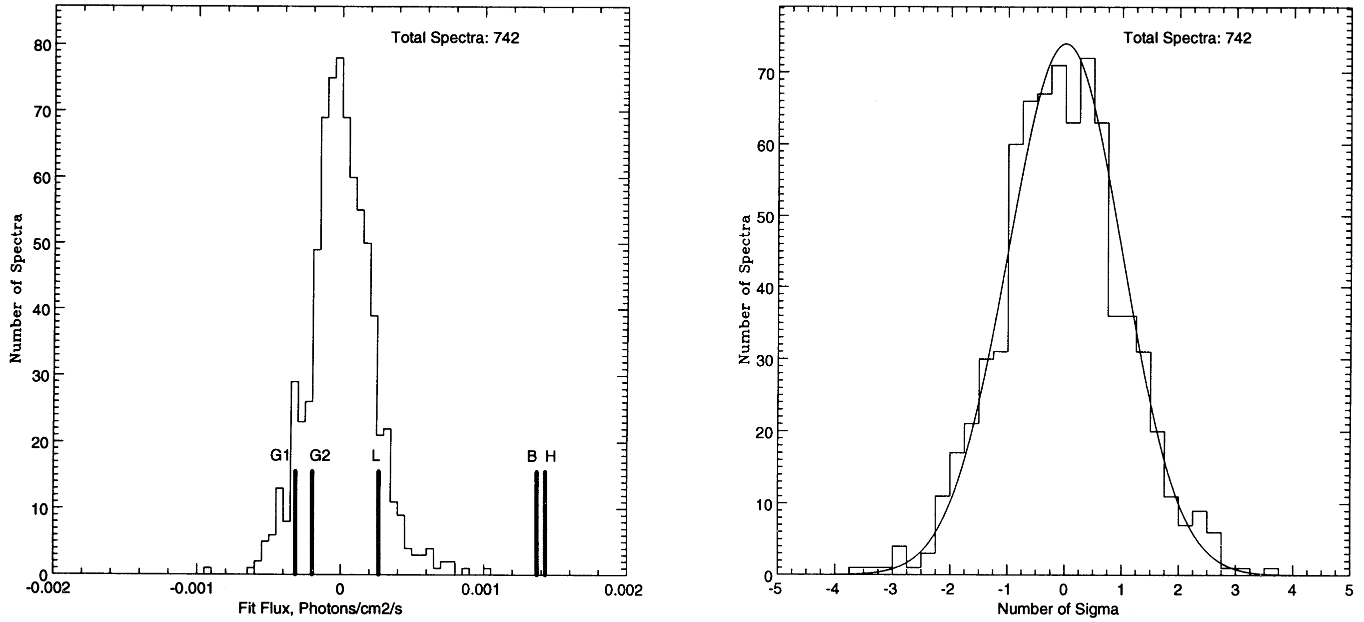

FIG. 4*a*

FIG. 4*b*

FIG. 4.—(*a*) Distribution of fit backscatter fluxes for all OSSE pointings (*histogram*) and for five balloon observations: B—Bell/Sandia 1977 (Leventhal et al. 1978); H—HEXAGONE 1989 (Smith et al. 1993); G1—GRIS 1988 spring (Gehrels et al. 1991); G2—GRIS 1988 fall (Gehrels et al. 1991); and L—LEGS 1981 (Paciesas et al. 1982). (*b*) Distribution of significances (number of σ) of OSSE backscatter fluxes (*histogram*) and a normal distribution.

which overlap the pixel containing 1E 1740.7−2942. The weighting is by the inverse square of the error of the fit backscatter flux, adjusted for the collimator response to the source.

The result is a distribution of daily measurements specifically for this source and is shown in Figure 5. There is no significant deviation from a normal distribution in the distribution of significances (Fig. 5*b*) and no flux values near the Bell/Sandia and HEXAGONE fluxes (Fig. 5*a*). The average daily 3 σ upper limit on the line flux is 6.8×10^{-4} photons cm^{-2} s^{-1}.

To estimate the compatibility of the OSSE and balloon data sets, we calculate the probability of having *this much disagreement or more* in the ratio of flaring to total days. The total number of OSSE days with adequate sensitivity is calculated by the 2.0 σ criterion mentioned above. When this criterion is applied to the balloon data, it eliminates the LEGS result entirely due to its poor statistics, leaving us with four balloon spectra for comparison. A day is considered to show flaring if the flux is within 1 σ of the mean flaring balloon flux, or higher. If $t_0 = 186$ is the total number of OSSE observations, $h_0 = 0$ the number of OSSE observations which are consistent with the high-flux balloon observations, and $t_b = 4$ and $h_b = 2$ the corresponding quantities for the balloon data, then the probability P of seeing the actual value of h_0 *or lower* along with the actual value of h_b *or higher* is

$$P = \left[\sum_{i=0}^{h_0} \frac{t_0!}{(t_0 - i)!\,i!}(1 - x_0)^{t_0 - i}x_0^i\right] \times \left[1 - \sum_{i=0}^{h_b - 1} \frac{t_b!}{(t_b - i)!\,i!}(1 - x_b)^{t_b - i}x_b^i\right], \quad (1)$$

where x_b is the probability of each balloon observation seeing a flaring result and x_0 is the probability of each OSSE day showing flaring. These probabilities must include both true and false positives. If y is the true duty cycle of flaring, then

$$x_0 = y\left(\frac{1}{2} + \frac{1}{\sqrt{\pi}}\int_0^{1/\sqrt{2}} e^{-t^2}\,dt\right) + (1 - y)\left(\frac{1}{2} - \frac{1}{\sqrt{\pi}}\int_0^{(F-\Delta)/\sqrt{2}\Delta} e^{-t^2}\,dt\right) \quad (2a)$$

$$= y(0.841345) + (1 - y)\left\{\frac{1}{2} - \frac{\operatorname{erf}[(F - \Delta)/\sqrt{2}\,\Delta]}{2}\right\}, \quad (2b)$$

where F is the (constant) flare brightness and Δ is the error on the fit backscatter flux. The first term represents true positives and the second false. The rate of true positives is independent of the quality of the data because our criterion for a positive detection takes the size of Δ into account. Since the errors Δ vary from day to day, we average x_0 over all 186 days before putting it into equation (1). The expected rate of positives in the balloon data, x_b, is calculated the same way.

Varying y until P is maximized, we find that the most probable duty cycle of flaring is exactly zero, with a probability of $P = 0.0073$ of at least this much disagreement occurring by chance. Therefore we can reject this hypothesis, that 1E 1740.7−2942 is a source of random flaring at 1.3×10^{-3} photons cm^{-2} s^{-1}, with 99.3% confidence.

3.2. *Other Point Source Hypothesis*

Here we assume the backscatter flaring comes from a single point source with unknown location, but still produces flares in a Poisson process. For all pixels with high coverage (defined as more than 30 useful days), we have repeated the analysis of § 3.1. There is no pixel which ever gives a flux with significance over 4 σ, and no pixel with more than 1 day over 3 σ. The

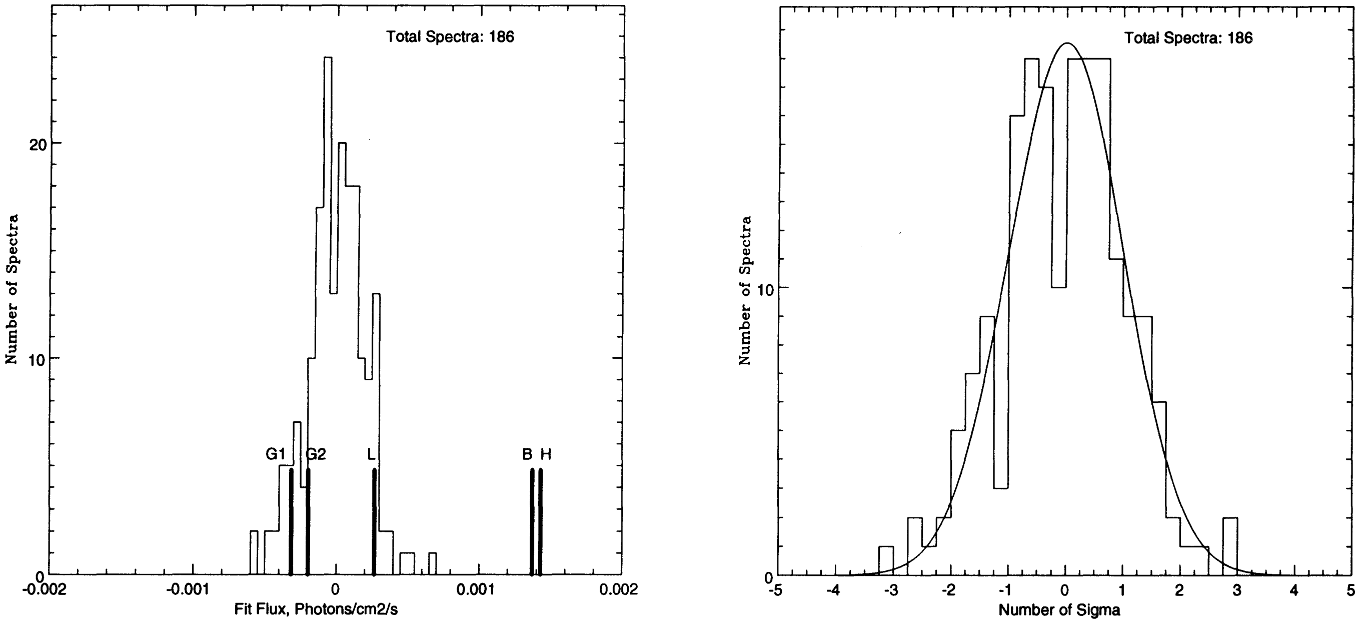

FIG. 5a FIG. 5b

FIG. 5.—Distributions of backscatter fluxes and their significances, for 1E 1740.7−2942 only

results for neighboring pixels are nearly identical, since the grid of pixels oversamples the collimator response.

The pixel which gives the highest compatibility with the balloon observations is at $b = 8°$ and $l = 3°$, and has six out of 40 days "positive." Since it is more toward the edges of the relevant OSSE fields of view than is 1E 1740.7−2942, both the fluxes and error bars tend to be larger than in Figure 5, and therefore the term in equation (2) for false positives is non-negligible. None of the six high fluxes is of greater than 3 σ significance. For this pixel the probability of compatibility between the OSSE and balloon observations is maximized when the duty cycle of flaring is $y = 11.4\%$, allowing us to reject with $1 - P = 94.4\%$ confidence the hypothesis of compatibility with this pixel as the source. For all the pixels in Figure 3 with more than 30 days exposure the confidence level is higher.

Each pixel with more than 140 days exposure implies a disagreement of greater than 99% with the balloon data. Obviously we can say nothing about a source near the outside of the balloon fields of view with little or no OSSE coverage.

3.3. *Many Point Source Hypothesis*

Finally, we consider the case in which backscatter flares are produced rarely by a large number of sources distributed randomly over the balloon fields of view, so that the probability of seeing one is independent of the exact OSSE pointing. With a large number of sources, the time dependence of flaring will approach being a Poisson process, whatever the time history from each individual source.

From this perspective, we consider each pointing a simultaneous observation of many pixels. Our collection of observations is then all 742 pointings of Figure 4; for now, we ignore the fact that some of these pointings overlap on the same day (we will discuss this further below). To begin with, we assume both balloon observations were of a flare near the center of the field of view, so that the nominal flux F is still 1.32×10^{-3} photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. The duty cycle of flaring y is then proportional to the number of pixels in each pointing: $y = Y\Omega$, where Ω is the solid angle in square degrees (pixels) to the 50% collimator response contour, and Y is the duty cycle of the sum of all Galactic bulge sources in probability $\mathrm{day}^{-1}\ \mathrm{deg}^{-2}$.

A positive result is declared for a given pointing if the observed flux is within 1 σ of the nominal flux with 50% collimator extinction, or higher. With these criteria we find $h_0 = 34$ high observations out of $t_0 = 742$ pointings in the OSSE data and $h_b = 2$ out of $t_b = 4$ in the balloon data, with the average expected rate of false positives 4.0% in the OSSE data and 48.3% in the balloon data. The latter percentage is high because the statistics in the balloon data are not good enough to detect the nominal flux if it were subject to 50% extinction. This is reflected in the poor confidence of the disagreement between the OSSE and balloon data sets, $1 - P = 64\%$, which is minimized when the duty cycle of flaring $Y = 0$.

We next take the nominal flux F to be twice as large, assuming the two balloon flares took place near the 50% collimator response contours rather than near the center of the fields of view. We then find only one out of 742 OSSE observations positive. The balloon data set is now two out of five observations positive, since with F twice as large the LEGS data become just barely good enough to include. The expected rates of false positives in OSSE and the balloon experiments are 0.10% and 10.9%, respectively, and the confidence of disagreement among the data sets, still minimized at $Y = 0$, is 92.2%.

Finally, we estimate the effect of the overlap of some OSSE fields of view within a given day. These OSSE pointings should not really be treated as completely independent of each other, but the correct treatment is complicated. Fortunately, we can estimate the most the effect could be, simply by throwing away half of the OSSE observations (dividing h_0 and t_0 by 2) and recalculating equation (1); we find that in no case does the final result, P, change by more than ~10% of its value. This is because most of the uncertainty is in the balloon data set.

We conclude that the balloon data are not of sufficient quality to allow us to make any confident statements about a set of sources with multiple locations. We note again, however, that under this hypothesis as under the others, the OSSE data, which are of superior sensitivity, show no evidence of backscatter emission beyond the expected statistical rate of false positives.

3.4. *The EXS 1737.9−2952 Transient*

Since the EXITE instrument is an imager with a source location accuracy of a few arcminutes, we have only one position to examine in looking at the OSSE data for a repeat of the flare of EXS 1737.9−2952. We fit to each spectrum the sum of a power law, a positronium continuum, and a Gaussian with centroid allowed to vary from 82–111 keV and FWHM allowed to vary from 5–25 keV. No flux near that seen by EXITE was observed in 186 days of data, with an average daily 3 σ upper limit of 9.8×10^{-4} photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, or $\sim$8% of the EXITE flux. We conclude that the EXITE transient either is rare if it occurs as a Poisson process (with a duty cycle less than $\sim$1%), or else has some other sort of time dependence.

4. CONCLUSIONS

Galactic center data from the first 3 yr of *CGRO*/OSSE show no evidence for the 170 keV backscatter feature reported by balloon observations. Specifically, we have concluded the following:

1. The hypothesis that 1E 1740.7−2942 produces backscatter flares in a Poisson process on a 1 day timescale is rejected with 99.3% confidence (§ 3.1).
2. The hypothesis that any source visible to OSSE for more than 140 days (i.e., in approximately a 5° radius around the Galactic center, as shown in Fig. 3) does the same is rejected with 99% confidence or greater (§ 3.2).
3. We cannot with high confidence reject the hypothesis of many sources flaring rarely, but it is the balloon data whose sensitivity is inadequate (§ 3.3).
4. Considering only the balloon data, the probability that the two reported 170 keV features are statistical fluctuations is no more than 1.9×10^{-3} if there are no unknown systematic errors in the spectra (§ 1).
5. The 100 keV feature from EXS 1737.9−2952 was not observed in 186 days of OSSE data (§ 3.4).

The OSSE and balloon results at 170 keV can still be reconciled in a number of ways which are not testable with this data set. There might be a source in a position not well sampled by OSSE. There may be flares which are not produced in a simple Poisson process; for instance, events from 1E 1740.7−2942 might be restricted to times when it is in a particular hard X-ray state, which would reduce the amount of OSSE data which are relevant. Alternatively, flares may be produced in a Poisson process, but not on a day-long timescale. If there are backscatter flares which last for a month (which is not contradicted by the balloon data), the proper way to search for them would be to combine much longer stretches of data, resulting in far fewer independent OSSE measurements, and therefore insufficient coverage to contradict the balloon results.

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