# A Search for Hard X-ray Emission from Active Stars Using CGRO/BATSE

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**Abstract.**
We report the results of a search for $> 20$ keV photons from active stars using CGRO/BATSE Earth-occultation observations. Twelve of the "usual suspects" together with 12 "placebo" locations have been analyzed using the BATSE software for occultation analysis developed at NASA/MSFC. There are four detections at the nominal $5\sigma$ level, and eight at the $3\sigma$ level. However the strongest detection (that of AB Dor) shows clear evidence for contamination from the nearby strong source LMC X–4. 18 of the 24 fields yield positive fluxes, indicating a clear bias in the results, and possibly indicating the presence of weak background hard X–ray sources detectable by BATSE in long–term studies.

## 1. Active Stars as $\gamma$-ray Sources

So far, no star showing solar–like activity has been detected to emit photons at energies above 20 keV, i.e., in the hard X–ray and $\gamma$-ray range. Yet there is no question that such active stars must be sources of nonthermal >20 keV photons at some level, since they are strong soft X-ray sources, they show large flares in which we believe (by the solar analogy) that energetic nonthermal electrons are produced, and they exhibit nonthermal MeV-energy electrons in the form of steady nonthermal radio fluxes.

The high–energy fluxes of active stars are potentially important for a number of branches of astrophysics:
(i) in order to understand the nature and properties of the high–energy emission. In particular, is it largely confined to flares, as on the Sun? Or does it occur in a

steady fashion, as suggested by the presence of nonthermal radio magnetospheres in stellar coronae (e.g., White 1996).
(ii) in order to determine whether stellar flares obey the solar analogy, in that much of the soft X–ray emission is due to heating of chromospheric plasma by nonthermal electrons accelerated in the corona which emit hard X–rays on entering the chromosphere. In this model, the hard X–ray peak will precede the soft X–ray peak.
(iii) in order to understand whether active stars are a significant contributor to the diffuse galactic hard X–ray background. Recent observations by GRO instruments have confirmed that the spectrum of the diffuse background steepens below 100 keV (e.g., Strong et al. 1996; Purcell et al. 1996;Skibo, Ramaty & Purcell 1996), and this is a problem for the energy budget of the continuum since it increases the energy required by a large factor, above what seems plausible for the injection of cosmic rays into the galaxy by supernovae (Skibo & Ramaty 1993). But this is the photon energy range where active stars might be expected to contribute, by analogy with the Sun, because solar flares have a spectrum which is typically steeper than those of many other classes of source. Active stars are believed to be significant contributors to the soft X–ray background (Schmitt & Snowden 1990; Caillault 1990; Kashyap et al. 1992; Favata et al. 1992; Ottmann & Schmitt 1992), because there are so many of them: of order $10^{10}$ active K and M dwarf stars, and $10^{8}$ active evolved binaries such as RS CVns.
(iv) Gamma–ray burst time profiles are largely indistinguishable in morphology from those of solar flares at hard X–rays (although the timescales are often much shorter than those of solar flares), and although it now seems an increasingly unlikely prospect, several groups have pursued the possibility that active stars may be responsible for some fraction of $\gamma$–ray bursts (Liang & Li 1993; Rao & Vahia 1994; Li et al. 1995).

Several methods for detecting $> 20$ keV photons from active stars are being pursued, but the distance of even the nearest stars makes this a difficult task: $(distance)^2$ reduces the fluxes by a factor of order $10^{12}$ (at 5 pc) compared to the Sun. The largest solar flares (e.g., the famous events in the first half of June, 1991: see Ramaty et al. 1994) produce count rates of up to $10^7$ counts $s^{-1}$ per detector above 20 keV in the CGRO/BATSE 2000 $cm^2$ detectors. Such a flare at the distance of AD Leo (5.5 pc) would produce a count rate of only $10^{-5}$ counts $s^{-1}$, compared to typical background rates of $10^3$ $s^{-1}$ per detector and typical occultation measurement noise levels of order 25 $s^{-1}$. Fortunately, stellar soft X-ray flares and stellar nonthermal radio fluxes are 3-5 orders of magnitude larger than their solar counterparts: if all the energy radiated as soft X-rays is initially present as accelerated nonthermal electrons (the solar analogy which we wish to test), rates as high as 1 count $s^{-1}$ might be seen in individual occultations. During periods when the nonthermal corona is bright, the fluxes could reach 10 counts $s^{-1}$ if the energy spectrum is very steep and the decay time is short enough.

These numbers emphasize the difficulty of detecting hard X–rays from active stars. It is clear that large collecting areas are essential, and a small field of view will help in reducing the background count levels. One approach is to use satellites such as GINGA and XTE, which have large effective areas above 20 keV, for long pointed observations of likely targets. However, limitations on the amount of time available for observing active stars on these projects means that they are of limited statistical value, although their potential for individual studies is powerful (e.g., Tsuru et al. 1989; Stern et al. 1992). Here we report the results of an alternative approach: studying the occultations of a number of likely candidates by the Earth's limb as seen from the large BATSE detectors on the CGRO satellite. This method is less sensitive than, e.g., XTE observations, because of the higher background count rates in the BATSE detectors and the short effective integration times offered by occultations, but the large amount of data offers some compensations for statistical studies.

Table 1. Results of BATSE occultation analysis for 12 sources and 12 nearby blank fields. The unit of flux is $10^{-3}$ counts cm$^{-2}$ s$^{-1}$.

| Source | Type | Mean flux | Median flux | Std. error | S/N of mean | Confusing sources |
|---|---|---|---|---|---|---|
| **AB Dor** | dK0 | 3.21 | 3.39 | 0.37 | **9$\sigma$** | LMC X-4: 1°<br>A0535-668: 2° |
| Blank | | 0.12 | 0.57 | 0.37 | $<1\sigma$ | AB Dor: 3°<br>LMC X-4: 4°<br>A0535-668: 9° |
| **AD Leo** | dMe | 1.95 | 1.80 | 0.25 | **8$\sigma$** | |
| Blank | | 0.14 | 0.18 | 0.26 | $<1\sigma$ | AD Leo: 4° |
| Algol | Algol | 0.11 | 0.30 | 0.24 | $<1\sigma$ | NGC 1275: 2° |
| Blank | | 1.31 | 0.88 | 0.30 | 4$\sigma$ | NGC 1275: 2°<br>Algol: 4° |
| AR Lac | RS CVn | -0.13 | 0.01 | 0.32 | | Cyg X-2: 9° |
| Blank | | 0.89 | 0.62 | 0.32 | 3$\sigma$ | AR Lac: 3° |
| AU Mic | dMe | 0.95 | 0.83 | 0.27 | 3$\sigma$ | |
| Blank | | -0.54 | -0.59 | 0.28 | | AU Mic: 3° |
| EQ Peg | dMe | 0.50 | 0.38 | 0.22 | 2$\sigma$ | |
| Blank | | -0.24 | -0.18 | 0.23 | | EQ Peg: 8° |
| HD 283447 | WTT | 0.38 | 0.28 | 0.23 | 2$\sigma$ | X Per: 5°<br>J0422+32: 5° |
| Blank | | -0.42 | -0.49 | 0.24 | | HD 283447: 4°<br>J0422+32: 7°<br>X Per: 9° |
| HD 32918 | FK Com | 0.77 | 1.15 | 0.38 | 2$\sigma$ | LMC X-4: 9°<br>A0535-668: 9°<br>SMC X-1: 14° |
| Blank | | -0.28 | -0.09 | 0.36 | | HD 32918: 4°<br>SMC X-1: 11°<br>LMC X-4: 11°<br>A0535-668: 11° |
| **HR 1099** | RS CVn | 1.02 | 0.78 | 0.21 | **5$\sigma$** | |
| Blank | | 1.04 | 0.72 | 0.23 | 4$\sigma$ | HR 1099: 3° |
| HR 5110 | Algol | 0.29 | 0.54 | 0.25 | 1$\sigma$ | |
| **Blank** | | 1.47 | 1.50 | 0.28 | **5$\sigma$** | HR 5110: 4° |
| UV Cet | dMe | 0.37 | 0.48 | 0.22 | 2$\sigma$ | |
| Blank | | 0.78 | 0.64 | 0.24 | 3$\sigma$ | UV Cet: 3° |
| UX Ari | RS CVn | -0.10 | -0.10 | 0.22 | | X Per: 6° |
| Blank | | 0.67 | 0.39 | 0.23 | 3$\sigma$ | UX Ari: 3°<br>X Per: 9° |

## 2. Analysis of BATSE Data

CGRO is in a low–Earth orbit with approximately 16 orbits per day. The BATSE telescope consist of eight 2000 cm$^2$ detectors at each corner of the satellite, guaranteeing complete coverage of the sky at all times. On each orbit, a source can potentially be occulted twice: it may be occluded by the rising Earth limb and exposed by the setting Earth limb. In principle, a source may be occulted up to 32 times per day, but in practice the number is smaller than this, depending on the location of the source relative to the ecliptic and on factors leading to missing data, such as SAA passages and data recovery. Thus BATSE acquires occultations of a given source typically 15 – 30 times per day, and this large number of occultations compensates for the intrinsic difficulty of individual occultation measurement. The BATSE occultations provide a uniformly sampled dataset which is better able to address such questions as the mean contribution of stars to the galactic background. We have analyzed data from the start of the mission to May, 1997, covering over 1700 days and 50000 occultations for each target location. The typical "background" count rate noise for a single occultation is 25, which after 50000 occultations translates to a flux noise level of roughly $5 \times 10^{-5}$ cm $^{-2}$ s$^{-1}$.

The occultation technique is discussed further by Harmon et al. (1993), Zhang et al. (1993), McNamara et al. (1995), Zhang et al. (1996) and Ling et al. (1996). Data analysis for this project was carried out using standard routines developed by the BATSE group at the Marshall Space Flight Center, running on MSFC computers. The basic technique is simply to compare the fluxes in the BATSE detectors closest to the source before and after an occultation. The dataset used for occultation analysis is the CONT dataset from the Large Area Detectors, which consists of 16 energy channels covering energies from as low as 20 keV up to 1800 keV (the actual channel energy limits may be different at different times depending on the setting of discriminator levels: at various times during the mission discriminators have been set so that, e.g., sensitivity to very soft sources is emphasized). CONT data have a basic time resolution of 2 s, and an occultation lasts $8/\cos\beta$ seconds, where $\beta$ is the angle of the source with respect to the orbital plane. The effective spatial resolution of the occultation technique is of order $0.5°$.

Since each BATSE detector sees a large fraction of the sky at any given time, any sources which happen to be occulted elsewhere on the Earth's limb at the same time will affect any steps seen in the data, and this effect needs to be included. In practice this is carried out by referring to a catalog of known or likely sources, and solving for their fluxes as well when relevant. Naturally, this catalog is incomplete: the catalog used for this program contained some 60 sources in addition to the targets of interest here, but, as we shall see, uncataloged weak sources present a major source of confusion for a search such as this.

We produced two data products in the course of the analysis, but they produce effectively the same results. One is a set of count rates for individual occultations for each source. The second is a set of daily averages of source photon fluxes (photons cm$^{-2}$ s$^{-1}$) in the energy range 20 – 600 keV, achieved by taking all valid occultations in a day and fitting them to a power–law energy spectrum over the energy range 20 – 200 keV. Since all of our sources are too

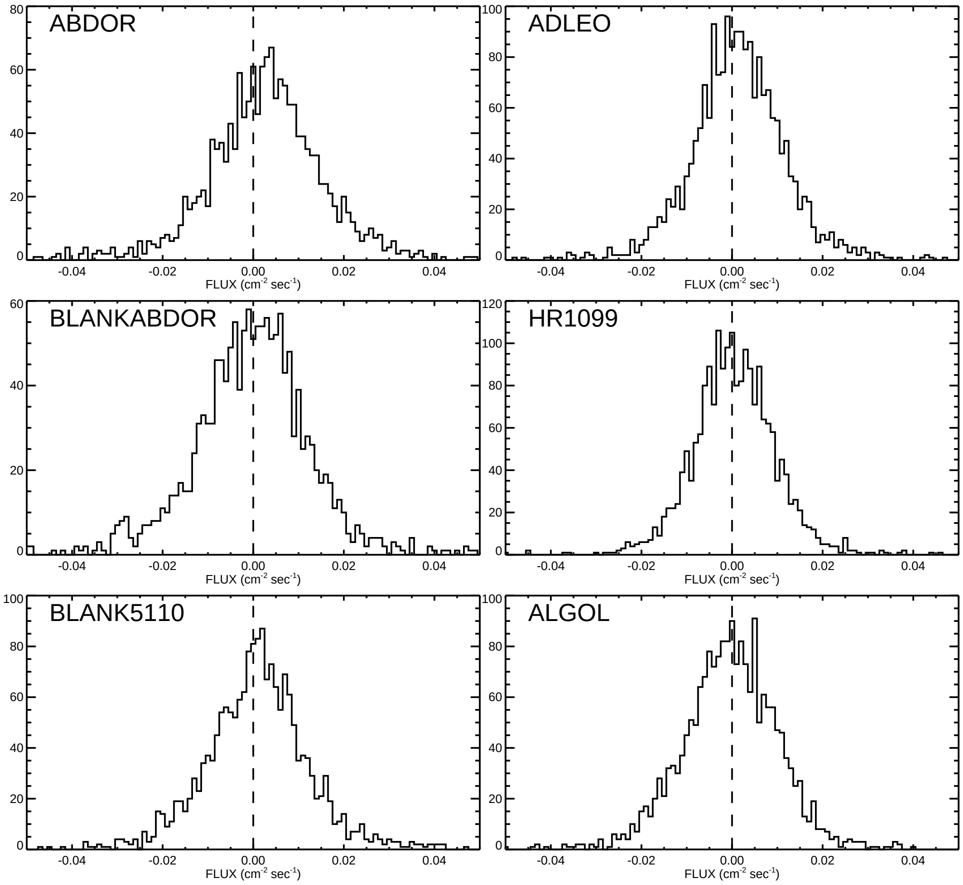


Figure 1. Distributions of daily photon flux averages for 6 targets in the survey: the "detected" sources AB Dor, AD Leo, HR 1099 and the "blank" field near HR 5110; and the "undetected" fields at Algol and near AB Dor.

weak to determine the photon spectral index, we fixed the photon power–law index at -3.0: unfortunately, data analysis for the full BATSE dataset was so time consuming that we could not repeat the analysis for other values of the index, but for the purpose of determining whether sources have been detected, it should not matter. Data which were flagged as bad by the on–line system were excluded from the fits, as were periods of high background (large uncertainty), and data were not available for the TJD period 8700 - 8900. Rapidly time-varying sources also present a major source of error for the occultation technique, and we therefore also excluded the 1994 Jan-March period of the A0535+262 outburst (which reached over 100 counts s$^{-1}$ in the BATSE detectors: Finger, Wilson & Harmon 1996) from the final averages.

## 3. What Might We Expect?

If the stellar hard X-rays are due to flares, we expect that some fraction of occultations will take place while the stars are flaring and therefore in elevated states. There may also be a steady non-flaring level due to precipitation of energetic electrons from the nonthermal coronae responsible for the quiescent radio emission. We might expect that any steady emission will displace the noise distribution of the count rates, while the flares will lead to a distribution with a large positive wing. The former effect would show up statistically as a shift in the median flux, while the latter will show up as a higher–order effect such as the skewness (although such high–order moments are often unreliable). As noted above, the effect we might expect based on the solar analogy is very small.

## 4. Target Selection and Results

We have processed data for 12 stars chosen as a representative sample of the likely classes of active stars (dwarf flare stars, RS CVn and Algol binaries, one FK Comae star, one young K0 star, and one pre-main-sequence object). Since radio is the only domain in which we are certain of the presence of electrons with energies $> 20$ keV, the targets are chosen to be those in each stellar class with large radio fluxes, but (with the exception of the peculiar and relatively unknown southern FK Comae star HD 32918) they are all candidates likely to be selected on the grounds of any other activity indicator.

There has been relatively little work done to characterize the properties of blank fields of sky when studied with the occultation technique. Since we are expecting our sources to be relatively weak, after some experience with the data we decided to add a nearby (4° away) blank field for each of the 12 target sources to act as control regions. If there are statistically significant detections amongst the candidate targets, then the properties of the target fields should show significantly more flux than the blank fields. We ensured that none of the sources in the BATSE occultation catalog lay in the blank fields.

Mean, median and rms fluxes for the 24 fields based on the daily average photon spectrum fits are given in Table 1, together with the locations of possible contaminating sources from the BATSE occultation catalog. Note that the rms values are derived from the distribution of fluxes, not from *a priori* estimates of the likely errors. The rms values differ significantly, depending largely on the presence of nearby strong sources: thus the highest rms values occur for AB Dor and HD 32918, which are both close to the LMC. There are 4 "detections" at the $5\sigma$ level. The two strongest detections, AB Dor and AD Leo, show clear evidence for asymmetry (about zero flux) in the flux distributions just based on visual inspection (Figure 1). The mean fluxes for all fields are plotted in Figure 2, together with $\pm\ 3\sigma$ error bars.

## 5. Individual Sources

*AB Doradus* is a favorite target for X–ray satellites, having flared in every single X–ray observation of it so far. It is a rapidly–rotating K dwarf just 15 pc

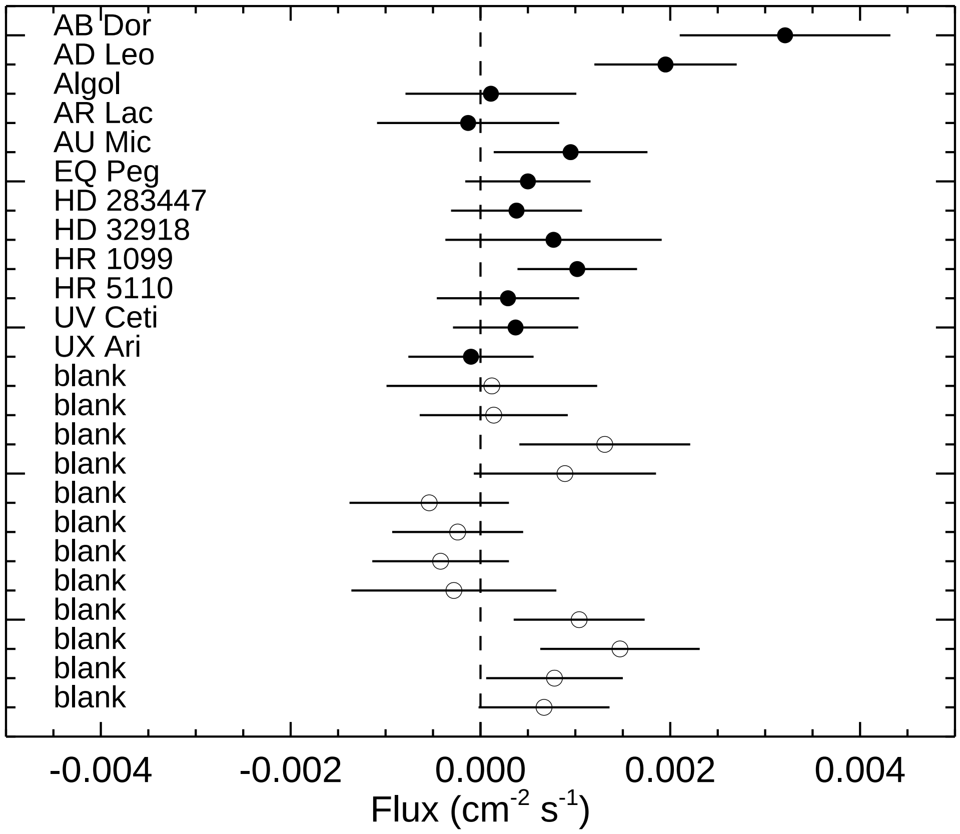


Figure 2. The statistical flux values based on the daily averages for the 24 fields studied in this paper. Filled circles are used for active star targets, while open circles represent the corresponding nearby blank–sky fields.

away with a strong Lithium line suggesting youth (Pleiades age). By virtue of its proximity and activity level, AB Dor would be high on everyone's list of likely hard X–ray detection candidates. Unfortunately for this study, AB Dor is very close to the LMC, and to LMC X-4 and the transient source 0535-668 in particular. 0535-668 has not been active recently and has not been detected by BATSE (it is at best a marginal detection in the XTE All Sky Monitor data, being weaker than HR 1099 and UX Ari). However, LMC X-4 is detected by BATSE (Zhang, Harmon & Paciesas 1996) at a mean flux level of order $10^{-2}$ photons $cm^{-2}$ $s^{-1}$, or of order 4 times the flux we determine for the position of AB Dor.

Fortunately, there is a test for contamination of AB Dor's flux by LMC X–4 since the latter has a pronounced 30.5 day orbital period which is clearly seen in the BATSE data with 100% modulation. A periodogram analysis of the daily photon flux averages does indeed yield a highly significant (at the $10^{-10}$ level) peak at a period of 30.4 days, from which we conclude that there is indeed significant contamination of the AB Dor position from LMC X–4. This result indicates the difficulty of using the occultation technique to identify sources: a confusing source as close as $1^\circ$ away will leak into the field being analyzed.

The only other peak in the periodogram for AB Dor with a significance of more than 0.5 is at a period of 51.1 days with a significance of 0.1. In a periodogram for data from the blank field $3^\circ$ away (at 05 36 00, -63 00 00 in J2000 coordinates), this same period shows up with a significance of $5 \times 10^{-4}$, while the 30.4–day period of LMC X–4 is missing. This period shows up in several of the other fields, such as the blank field near HD 32918. AB Dor and HD 32918 are at high ecliptic latitude and therefore are occulted less often than lower–latitude fields: we suspect that this period actually represents the 53 day period of precession of GRO's orbit about the Earth.

*AD Leonis* is one of the most active nearby dMe flare stars, and so is also a likely candidate for detection. The detection remains significant when the data is broken down into smaller periods, indicating a source present over a timescale of years. Unlike AB Dor, there are no no obvious confusing high–energy sources known to lie in the vicinity, and the periodogram shows only a mildly significant peak at 53 days which we again attribute to satellite precession.

We note that AD Leonis does have a nearby source which may potentially be of interest. Radio astronomers have long been aware that the double–lobed extragalactic source 1017+201 is just $2'$ from AD Leo and is a source of difficulty in analyzing the radio emission from the star. However, it is not a particularly strong extragalactic source (just 0.7 Jy at 408 MHz), and if this is the source of high–energy photons from the direction of AD Leo then we would expect many such high–energy sources to be present: based on radio surveys, roughly 0.5 such sources as bright or brighter per square degree of sky. Based on the resolution estimate of $0.5^\circ$ (e.g., Zhang et al. 1993) for occultation data, we expect 0.5 sources (sq. deg.)$^{-1}$ $\times$ 0.2 (sq. deg. per field) $\times$ 24 fields $\sim$ 2 such sources to be detected in our survey, which is not inconsistent with Table 1.

*HR 1099* is another target which is among the most active nearby RS CVn systems, and one of the brightest active–star X–ray sources in the sky, so its detection would not be surprising. Inspection of the daily flux values shows a single suspiciously high point, which results from a day on which 5 occultations occurred at a high and uniform flux level while the remaining 27 occultations were at the usual noise level: since this occurs on a day (TJD 9265 = 1993 October 5) immediately following a satellite reboost, we believe that the high values are likely to be instrumental. However, if this point is removed, the mean flux drops only slightly, to 0.0097 photons cm$^{-2}$ s$^{-1}$, with the median and rms remaining essentially unchanged. Thus this detection appears to be significant.

The blank field $4^\circ$ from *HR 5110* (at 13:48:00.0, +40:00:00) produced the third highest flux measured in this survey, at 0.0015 photons cm$^{-2}$ s$^{-1}$. There are no cataloged bright radio sources (similar to that near AD Leo) within $30'$ of this field.

Two other sources which we might have expected to be detected are Algol and UX Ari, but neither shows any sign of flux. These two, plus HR 1099, are also being monitored by the All Sky Monitor (ASM) on XTE. Algol is easily the brightest of the active stellar sources monitored by XTE/ASM in the 2–10 keV range at 0.6 counts s$^{-1}$, while HR 1099 and UX Ari are both at 0.2 counts s$^{-1}$. ASM data for the last 400 days exist for Algol, HR 1099 and UX Ari, but

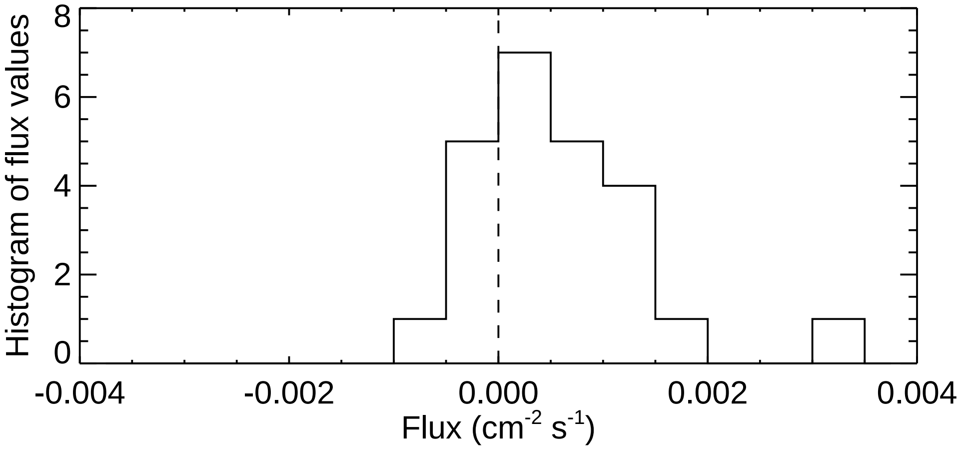


Figure 3. A histogram of the flux values from Table 1.

a cross-correlation analysis failed to find any correlation between the ASM 2-10 keV and BATSE $>$ 20 keV datasets for these three stars.

## 6. Discussion

Clearly active stars are on average weak $>$ 20 keV sources, and thus are difficult to study. Stars need to be very much brighter than the Sun above 20 keV to be detected, but these data suggest that BATSE can indeed detect these sources over long time periods at plausible levels.

Little is actually known about the properties of weak sources in the BATSE data: our data show a clear preference for positive detections (18 out of 24 positions), even among the "blank" fields (8 out of 12). The positive bias in the results is interesting, but the number of sources is small. Figure 3 plots a histogram of the flux values, showing a clear bias to positive fluxes. For a random position on the sky, there is no reason why the occultation technique itself should produce a positive bias since it is a differencing technique and positive and negative outcomes should be equally likely. Eight of the fields show positive detections above the $3\sigma$ level, whereas none of the fields show negative fluxes at the -$3\sigma$ level. This result could indicate a background population of weak hard X–ray sources, or indicate detections of the target stars: since there are four $3\sigma$ detections in both the 12 stellar targets and the 12 blank fields, the former interpretation seems more plausible.

**Acknowledgments.** This work was supported by NASA GRO GI grant NAG 5 2885. SW thanks the Gerry Fishman and the BATSE team at MSFC for their help during his visit and their tolerance of his subsequent occupation of their batch queues. SW also thanks Craig Robinson and Mike McCollough for helpful discussions.

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