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# A SEARCH FOR STELLAR FLARES IN GAMMA-RAY BURSTS OBSERVED BY BATSE AND *ULYSSES*

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## ABSTRACT

We have searched for gamma-ray bursts during stellar flares using *Ulysses* and BATSE/*CGRO* data and for a correlation between flare star positions and burst positions. More than 3000 stellar flares have been identified optically, but neither BATSE nor *Ulysses* observed any gamma-ray bursts which could be attributed to them. Using the BATSE trigger threshold, and the known distances to these flare stars, upper limits to the gamma-ray luminosity were obtained. We have also studied the conditions under which stellar flares could be detected by BATSE as weak GRBs. We found that if some weak events ($10^{-7}$ ergs cm$^{-2}$ s$^{-1}$) are to be explained by flares as recently suggested, the X-ray emission (>25 keV) must be comparable to the stellar optical emission, and the ratio of $L_x/L_{\rm opt}$ must be higher than that for solar flares by at least four orders of magnitude. The stellar flare log *N*–log *S* and spatial distributions are studied and their implications for gamma-ray bursts are discussed.

*Subject headings:* gamma rays: bursts — stars: flare

## 1. INTRODUCTION

Recent observations from *BATSE* show that the gamma-ray burst spatial distribution is isotropic, with no concentration toward the Galactic plane or center, and that the number of weak events is smaller than that expected from a homogeneous source distribution in a static Euclidean space (Fishman et al. 1991; Meegan et al. 1992). These results suggest that we are at the center of the gamma-ray burst distribution. Therefore the observed distribution does not appear to support a Galactic disk origin (however, see Quashnock & Lamb 1993), but a halo origin for at least some GRBs may not be excluded (Hakkila et al. 1994a). While Paczyński (1991a) showed that the "ordinary" dark matter halo does not satisfy the observational constraints, the possibility of an extended halo was considered by several groups (Eichler & Silk 1992; Li & Dermer 1992; Hartmann 1992; Hartmann et al. 1994; Hakkila et al. 1994b), but with the addition of ~1 burst per day the observational constraints have become so severe that even the extended halo origin no longer appears feasible (Hartmann 1994). It seems that the most natural explanation for BATSE angular and intensity distribution is cosmological (Paczyński 1991b; Mao & Paczyński 1992; Piran 1992). Although multiple component models are still possible, disk sources cannot contribute more than 20% to the total sample, with the majority of sources being considerably more distant (Lingenfelter & Higdon 1992; Smith & Lamb 1993; Hakkila et al. 1994b; and Katz 1994). The source distance scale is unknown and a contentious issue at the present time.

Although we do not know what kind of objects cosmic gamma-ray bursts are associated with, we do know that the nearest star to us—the Sun—sometimes produces gamma-ray emission when it flares. This impulsive solar flare gamma-ray emission lasts from $10^{-2}$ to $10^{3}$ s (Hurley et al. 1983; Kiplinger et al. 1983) and clearly has nonthermal spectra above 30 keV (Vestrand 1988; Dennis 1988). The maximum total energy released during a flare reaches ~$10^{32}$ ergs (Dennis 1988; Wu et al. 1986). The energy released in the form of nonthermal X- and gamma rays is insignificant in the total energy budget, with luminosity ratios of $L_x/L_{\rm tot} \sim 10^{-6}$, and $L_x/L_{\rm opt} \sim L_x/L_{\rm EUV} \sim 10^{-5}$ (Hudson 1991). Since some temporal and spectral properties of cosmic gamma-ray bursts are similar to those of solar gamma-ray flares (see, e.g., Hurley 1989a, b, 1993 for reviews of the former, and Dennis 1988; Vestrand 1988 for the latter), it is natural to inquire whether some cosmic gamma-ray bursts originate from flares on stars other than the Sun.

The association between cosmic gamma-ray bursts and stellar flares has been studied on and off since the discovery of gamma-ray bursts (Ruderman 1975; Higdon & Lingenfelter 1990). It has been proposed that cosmic gamma-ray bursts might be flares on main-sequence stars (Stecker & Frost 1973), white dwarfs (Chanmugam 1974; Mullan 1976), or neutron stars (Pacini & Ruderman 1974; Tsygan 1980). More recently, based on observations of flares on dK/M stars, it has been proposed that some weak gamma-ray bursts observed by BATSE could be stellar flares (Liang & Li 1993; Rao & Vahia 1994). However, these studies contained several ad hoc assumptions and postulated the total gamma-ray (>25 keV) output for stellar flares. Although stellar flares have been observed in the radio, optical, EUV, and soft X-ray ranges, they have not been observed above 25 keV. Most of the observations have been in the optical, and, to date, only a few low sensitivity searches for time- and/or position-coincident events have been made (Hudson & Tsikoudi 1973; Pye & McHardy 1983).

TABLE 1

STELLAR FLARE OBSERVATIONS

| Date | Start Time | Duration | Star | Spectral Type | $D$ (pc) | Wavelength | Instrument | Total energy (ergs) | $L$ (ergs $s^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| 1991 Sep 3 ...... | 4:56:10 | 3 s | AU Mic | dM1e | 9.3 | UV | *HST* | $10^{30}$ | $3.3 \times 10^{29}$ |
| 1992 Jul 15 ...... | 12:38:00 | 2 hr | AU Mic | dM1e | 9.3 | EUV | *EUVE* | $3 \times 10^{34}$ | $4.2 \times 10^{30}$ |
| 1992 Sep 9 ...... | 12:46 | 1 hr | AU Mic | dM1e | 9.3 | OPT | AAT | $10^{34}$ | $2.5 \times 10^{30}$ |
| 1993 Mar 2...... | ~09:00 | 4 hr | AD Leo | dM3.5e | 4.9 | OPT/EUV | Lick/*EUVE* | $6 \times 10^{32}$ | $4 \times 10^{28}$ |
| 1993 Mar 3...... | ~10:00 | 3 hr | AD Leo | dM3.5e | 4.9 | EUV | *EUVE* | $10^{32}$ | $9 \times 10^{27}$ |

About 10% of the stars in the Galaxy are flare stars, and most flare stars in the vicinity of the Sun are M or K dwarf stars; the farthest observed dM flare star is only 22 pc away (Haisch, Strong, & Rodonò 1991). Their spatial distribution is essentially uniform to a sampling distance of ~300 pc, so that a population of stellar flares should be characterized by an isotropic angular distribution with a log $N$–log $S$ curve of slope of $-3/2$. For dK/M stellar flares, the highest optical energies and luminosities observed are $10^{35}$ ergs and $10^{32}$ ergs $s^{-1}$ respectively; this implies that few stellar flares are capable of generating energies comparable to those of bright bursts. The $-3/2$ slope of the flare log $N$–log $S$ curve indicates that flares might be a large fraction of the dataset for GRBs at low fluences, where the BATSE log $N$–log $S$ curve deviates the most from a $-3/2$ power law. However, flares can comprise a moderate fraction of low fluence bursts only by requiring that the log $N$–log $S$ curve of the nonflare GRBs turns over even more rapidly than observed. Thus a stellar flare is likely to be present only as a contaminant, if at all.

The objectives of this study were twofold; first, to confirm or disprove the possible contamination by stellar flares of the BATSE catalog so that an unambiguous interpretation can be made for the classical cosmic gamma-ray bursts; second, to obtain constraints on stellar flare energetic emission using BATSE and Ulysses cosmic gamma-ray observations, as well as observations at other wavelengths.

## 2. INSTRUMENTATION AND OBSERVATIONS

A search for stellar flares which occurred between the launch of *Ulysses* (1990 November and 1993 July) has turned up more than three thousand events, all from late-type dM/K stars in the vicinity of the Sun. The search is continuing and more are expected. Among these flares, five have known properties, such as total energy, flux, and duration, and are listed in Table 1. The first three stellar flares are in the literature (Woodgate et al. 1992; Cully et al. 1993; Robinson et al. 1993), while the last two were kindly provided by S. Hawley and her team of *EUVE* Guest Observers (Hawley et al. 1993). Other observations were kindly provided by the American Association of Variable Star Observation (AAVSO) simply as a flare time and direction and are not listed here (Mattei 1993). They come from the following stars: UV Cet (2.7 pc), V317 Ori (15.6 pc), YZ Cmi (6.2 pc), AD Leo (4.9 pc), AU Mic (9.3 pc), and EV Lac (5.0 pc).

We have examined the *Ulysses* data from launch (1990 November to 1991 April); we found no triggered GRBs at the times around the stellar flares (i.e., within 60 minutes before and after the flare time). We then examined the BATSE data, starting at *CGRO* launch in 1991 April; no triggered GRBs were observed by BATSE within ±60 minutes of the times of these flares and from their directions (within the ~5° BATSE error circle). As a result, we found no association between stellar flares and GRBs, and the gamma-ray emission from all these stellar flares must be below the trigger threshold for BATSE ($10^{-7}$ ergs $cm^{-2}$ $s^{-1}$, see, e.g., Fishman et al. 1989) or for *Ulysses* (nominally $10^{-6}$ ergs $cm^{-2}$ $s^{-1}$, see Hurley et al. 1992). Using the BATSE trigger threshold, the upper limits to the X-ray luminosities $L_x$ for these stars can be calculated, assuming isotropic emission. We list the results in Table 2. Since the flare duration at lower energies (<10 keV) can be longer than that at high energies (>25 keV), they may last for many *Compton Observatory* orbits, and the BATSE duty cycle for observing a burst from them is ~50%. Therefore we still used the *Ulysses* data, with its 4$\pi$ sr, >95% time coverage, to complement the BATSE data after the launch of *CGRO*.

The optical flares observed on dK/M stars, such as those mentioned previously, have many properties similar to those of solar flares (Pettersen 1989; Shakhovskaya 1989; Tandberg-Hanssen & Emslie 1988). In addition to some temporal and spectral similarities, most stellar flare size distributions can be best fitted by power laws with indices around 0.8, much like the Sun. The total optical energy is consistent with the magnetic field energy on the surface of the flare star, a result expected if the conversion of magnetic energy operates as it does in solar flares. But the dK/M stellar flare area and volume may be bigger than those for solar flares. If we assume the same luminosity ratio $L_x/L_{\rm EUV} \sim 10^{-5}$ as for a solar flare, then the intrinsic gamma-ray luminosity, estimated from EUV observations, is $\sim 4 \times 10^{25}$ ergs $s^{-1}$ (or $4 \times 10^{-15}$ ergs $cm^{-2}$ $s^{-1}$ at Earth) for the very large AU Mic event of 1992 July 15. This value is far below the critical luminosity $L_x$ required for that flare to be observed by BATSE or *Ulysses*. Therefore we should not expect BATSE to observe these stellar flares if we believe that

TABLE 2

GAMMA-RAY LUMINOSITY UPPER LIMITS

| Luminosity | UV Cet | V371 Ori | YZ Cmi | AD Leo | AU Mic | EV Lac |
|---|---|---|---|---|---|---|
| $L_x$ (ergs $s^{-1}$) | $8.7 \times 10^{31}$ | $2.9 \times 10^{33}$ | $4.6 \times 10^{32}$ | $2.9 \times 10^{32}$ | $1.0 \times 10^{33}$ | $3.0 \times 10^{32}$ |

the properties of dK/M stellar flares are similar to those of solar flares. In other words, solar-type flares on dK/M stars scaled up to the maximum observed less than 25 keV luminosity cannot be observed by BATSE or *Ulysses*.

### 3. CONDITIONS REQUIRED TO TRIGGER BATSE

The results of the previous section indicate that the stellar flares identified were not powerful enough at gamma-ray energies to be observed by BATSE or *Ulysses*. However, we may still be limited by the available observations. There are about $10^6$ flare stars within 300 pc (Haisch et al. 1991). The actual number of stellar flares which occurred over the period of this study was probably much larger than the number recorded, due to lack of coverage. The most extensively observed and studied stellar flares are dK/M flares in the vicinity of the Sun. The maximum optical luminosity may vary considerably, from $\sim 10^{32}$ ergs $\mathrm{s}^{-1}$ for late-type dK/M stellar flares ($<25$ pc), to $\sim 10^{33}$ ergs $\mathrm{s}^{-1}$ for pre–main-sequence T Tauri and FU Orionis stellar flares, to $\sim 10^{34}$ ergs $\mathrm{s}^{-1}$ for subgiant RS CVn systems (Haisch et al. 1991; Shakhovskaya 1989).

If $\eta = L_x/L_{\mathrm{opt}}$ is the gamma-ray to optical luminosity ratio for stellar flares, then for isotropic stellar flare emission to be powerful enough to be observed by BATSE, we need

$$\frac{\eta L_{\mathrm{opt}}}{4\pi d^2} > F_c \,, \tag{1}$$

where $F_c$ is the trigger threshold. Thus $\eta$ therefore needs to satisfy

$$\eta > \left(\frac{F_c}{L_{\mathrm{opt}}}\right) 4\pi d^2 \,. \tag{2}$$

The assumption of isotropy may be justified by the analogy that greater than 25 keV solar flare emission is istropic (see, e.g., Kane 1974; Datlowe et al. 1977; Kane et al. 1988; Li 1994; Li et al. 1994). Theoretically, there is no anisotropy at energies above $>25$ keV if the photons are produced by bremsstrahlung under solar flare conditions (McTiernan & Petrosian 1990, 1991). The nearest dK/M flare stars are at $\sim 1$ pc. Using the lowest distance and highest optical luminosity, we derive a lower-limit $\eta_{\min} \sim 0.1$, which is significantly higher than that of solar flares. Subgiant stars such as RS CVn do not flare as often as dK/M late-type stars. Most observed RS CVn stellar flares are at larger than 20 pc (Pye & McHardy 1983), although there may be some in the vicinity of the Sun. If we take a moderate $d_{\min} = 10$ pc for them, then again $\eta_{\min} \sim 0.1$. If we take an extreme case, $d_{\min} = 1$ pc, and assume that there are some RS CVn systems in the solar neighborhood, the best value we can obtain is $\eta_{\min} \sim 10^{-3}$, which is still two orders of magnitude higher than that for solar flares.

Observations of flares on RS CVn systems are too infrequent to establish their size distribution. For the relatively frequent late-type dK/M stellar flares, the maximum luminosity in the gamma-ray range is $(L_x)_{\max} = 10^{32}$ ergs $\mathrm{s}^{-1}$, if we take $\eta = 1$. Their size distribution can be represented by

$$N(>L_x) = N_0\left(\frac{L_x}{L_{x0}}\right)^{-\alpha} \quad (L_x)_{\min} \le L_x \le (L_x)_{\max} \,, \tag{3}$$

where $\alpha \sim 0.8$, and $N$ is the number of flares per year per star with luminosity greater that $L_x$. It has been found (Shakhovskaya 1989), from studies of larger than $10^4$ dK/M flares, that $N_0 \sim 20$ $\mathrm{star}^{-1}$ $\mathrm{yr}^{-1}$ for $L_{x0} = 10^{31}$ ergs $\mathrm{s}^{-1}$ (equivalent to $L_{\mathrm{opt}} = 10^{31}$ ergs $\mathrm{s}^{-1}$ assuming $\eta = 1$). The all-sky flare rate with flux larger than $F_c$ can be calculated as

$$N(>F_c) = \int_{(L_x)_{\min}}^{(L_x)_{\max}} \frac{4}{3}\pi\left(\frac{L_x}{4\pi F_c}\right)^{3/2} n \left|\frac{dN}{dL_x}\right| dL_x \,, \tag{4}$$

where $n$ is the spatial density of flare stars. Equation (4) can be integrated using equation (3), yielding

$$N(>F_c) = \frac{4}{3}\pi N_0\left(\frac{L_{x0}}{4\pi F_c}\right)^{3/2} n \frac{\alpha}{1.5-\alpha} \times \left(\left[\frac{(L_x)_{\max}}{L_{x0}}\right]^{1.5-\alpha} - \left[\frac{(L_x)_{\min}}{L_{x0}}\right]^{1.5-\alpha}\right) . \tag{5}$$

Since $(L_x)_{\max}/(L_x)_{\min} > 10^6 \gg 1$ (Shakhovskaya 1989), we can drop the last term in equation (5), giving rise to:

$$N(>F_c) = \frac{4}{3}\pi N_0\left(\frac{L_{x0}}{4\pi F_c}\right)^{3/2} n \frac{\alpha}{1.5-\alpha}\left[\frac{(L_x)_{\max}}{L_{x0}}\right]^{1.5-\alpha} , \tag{6}$$

which simplifies to

$$N(>F_c) \sim 400(\mathrm{yr}^{-1})\left(\frac{n}{1\ \mathrm{pc}^{-3}}\right) . \tag{7}$$

The estimated flare star density $n$ is 0.01–0.1 $\mathrm{pc}^{-3}$ (Haisch et al. 1991). Using an upper limit $n = 0.1$ $\mathrm{pc}^{-3}$, equation (7) gives $N(>F_c) = 40$ $\mathrm{yr}^{-1}$, which is 5% of the total gamma-ray burst rate inferred from BATSE ($\sim 800$ $\mathrm{yr}^{-1}$; see Fishman et al. 1994). These flares must be within 3 pc to be observable with BATSE. As there are only a few known flare stars within 3 pc, identifying a gamma-ray burst from one of them would be relatively simple; however, these results are based on the uncertain assumption that $\eta = 1$.

Equation (7) used the size distribution of dK/M late-type stars. For early-type and subgiant stars, the flaring rates are lower by at least one order of magnitude (Pettersen 1989; Shakhovskaya 1989). Even though their luminosity can be two orders of magnitude higher than those of late-type stars, their contribution to weak BATSE events cannot exceed that of dK/M stellar flares, assuming $\eta = 1$. Taking the highest $L_{\max} = 10^{34}$ ergs $\mathrm{s}^{-1}$ for RS CVn and assuming $\eta = 1$, the flare stars observable by BATSE must be within 30 pc. As discussed in the previous section, there are few early and subgiant flare stars within this distance, their flaring rate is very low, and their contribution to BATSE triggers is even less significant.

### 4. NONSIMULTANEOUS SEARCH FOR BURSTS FROM FLARE STARS

Despite the large number of flares from the six flare stars considered in § 2, it is still possible that a search for simultaneous bursts could fail, either because none of the flares was energetic enough, or because those that were energetic enough were rare and were missed due, for example, to Earth occultation. For this reason, we have conducted a non-simultaneous search for bursts from the positions of 78 flare stars at distances between $\sim 1$ and 40 pc, provided by S. Hawley (1993, private communication); this list includes the six stars in § 2. For each star, we searched a list of 1033 gamma-ray bursts for positional coincidences. Most of these bursts were detected by

BATSE; they include the events in the 2B catalog, as well as many events from the 3B catalog. Some of the 1033 have been localized by triangulation to either small error boxes or narrow annuli. The sum of the area of the BATSE error circles occupies about 55 sr, or about $4.4 \times 4\pi$, so any given flare star should be included in an average of 4.4 error circles (sky coverage effects are relatively unimportant in this analysis and have not been included). We found that 367 bursts had positions coincident with the 78 flare stars, or an average of 4.7 bursts star$^{-1}$, versus an expected 343 bursts based on random coincidences. This suggests that these flare stars, as a group, did not contribute significantly to the sample of 1033 bursts. Had more than 424 bursts (an excess of 8% over the expected 343) of the bursts originated at the positions of this sample, the number of coincidences would have exceeded that expected by 3 $\sigma$.

In the above study, too, it is possible that a search for coincidences could fail, because not all of the stars, in our sample may produce observable bursts. Thus we have examined the number of bursts whose positions were coincident with each of the stars in the sample to see whether any flare stars had a significant number of bursts associated with their positions. In one case a total of 10 bursts were coincident with a position (HU Del). The probability of finding 10 or more bursts when the average is 4.4 is 0.015, which is not significant, particularly considering that the number of trials is 78. Finally, we note that in no case was a flare star position consistent with a small IPN annulus or error box.

## 5. CONCLUSION AND DISCUSSION

We have searched for gamma-ray emission in stellar flares and its possible association with the gamma-ray bursts observed by BATSE and *Ulysses*, using a large sample of events. We have found no association between them.

More than 3000 stellar flares (from six flare stars) and 1033 GRBs have been observed during the ~3 year search period. The chance of a random coincidence in both time and space is ~0.2%, so the fact that we found no association is not surprising. These calculations were based on the assumption that stellar flare gamma-ray emission is isotropic. Although in the solar case above 25 keV gamma-ray emission is almost isotropic as we discussed, we cannot completely rule out beaming in the stellar flare case. The chance of coincidence would be reduced if this were the case.

No stellar flares have yet been observed in gamma-rays above 25 keV. Apart from this, however, observations at other wavelengths show that most dK/M stellar flares have properties similar to those of solar flares and solar flare models have been successfully applied to them, producing results in agreement with observations (Haisch et al. 1991; Pettersen 1989). The physical conditions and characteristics of RS CVn systems are more extreme and have the largest energy output of all, but they do not flare very often and are more distant.

Previous searches for associations between gamma-ray bursts and optical stellar flares (all from dK/M flare stars) using the low-sensitivity gamma-ray burst detector on *OSO 3* did not reveal any time and/or position coincidences (Hudson & Tsikoudi 1973). The *Ariel V* 2–18 keV all-sky survey of fast transients revealed 27 sources, two of which were observed to repeat (Pye & McHardy 1983). Most of the sources were flares on RS CVn systems. Of particular interest is that one soft X-ray transient was found to be associated with a cosmic gamma-ray burst in time and position, although the soft X-ray source itself was unidentified. Due to the relatively large location uncertainties, we cannot conclude that they came from the same source. We studied the possibility that some gamma-ray bursts may be stellar flares on RS CVn systems. Although the flare rate of RS CVn systems is low, repetitions should be observable if the coverage is long enough. Thus continuing searches for fast transient counterparts (including stellar flares) of cosmic gamma-rays bursts is worthwhile.

In order to be observed by BATSE or *Ulysses*, stellar flares must reach their maximum luminosities and satisfy $L_x/L_{\rm opt} > 0.1$. Such a constraint on $\eta$ is very extreme, since it is more than four orders of magnitude higher than that for solar flares. This condition implies that a simple scaling-up of solar flares to dK/M stellar flares cannot account for BATSE or *Ulysses* events. Moreover, if we take $\eta = 1$, $L_x = (L_x = (L_x)_{\rm max} = 10^{32}$ ergs s$^{-1}$, and assume that larger than 25 keV energetic photons are produced by energetic electrons through nonthermal bremsstrahlung, generally believed to be the production mechanism for the solar case (Tandberg-Hanssen & Emslie 1988), then the power in energetic electrons reaches $10^{37}$ ergs s$^{-1}$. Taking this number as input to well-developed stellar flare models (Fisher & Hawley 1990; Cheng & Pallavicini 1991; Pallavicini 1992), the expected soft X-ray, EUV, and optical flares would be several orders of magnitude higher than those observed, contradicting the existing observations. However, since $\eta$ is unknown, we cannot completely rule out the possibility of $L_x/L_{\rm opt} = 1$ for some unusual stellar flares. If, on the other hand, $L_x/L_{\rm opt}$ for AD Leo is similar to that of solar flares, then to detect the flares in gamma rays would require an instrument with effective area $10^{11}$ times larger than that of BATSE, assuming a sensitivity proportional to the square root of the detector area.

Flare energy is generally agreed to be derived from the magnetic field at the stellar surface through magnetic annihilation. The dK/M star surface magnetic fields are generated by the dynamo of the convective zone of the star. Photospheric kinetic motions cause stressing, shearing, and reconnection of magnetic fields which give rise to flares. The magnetic field strength of spots on dK/M stars is ~$10^3$–$10^4$ G and the total energy contained in the field within a typical flare volume (~$10^{27}$ cm$^3$) is $10^{32}$–$10^{34}$ ergs. The constraint $\eta > 0.1$ implies that most of the flare energy goes into photons above 25 keV. It is not clear what kind of physical mechanism can accomplish this. To relax the constraint on $\eta$, one possible alternative would be flares from magnetic white dwarfs. A magnetic white dwarf has a field up to ~$10^9$ G and a typical radius of ~$10^9$ cm. Assuming a flare dimension approximately equal to the radius of the star, the total magnetic energy available will be ~$4 \times 10^{43}$ ergs for magnetic white dwarfs, 7–8 orders of magnitude higher that the total flare energy on dK/M stars. Synchrotron radiation is the most likely mechanism to produce the greater than 25 keV gamma rays. Even if we assume low energetic efficiency (i.e., $10^{-6}$ of the total energy goes to the larger than 25 keV photons as in the case of solar flares) and a duration of $10^2$ s, flares from magnetic white dwarfs within ~180 pc should be observed by BATSE. These flares have been studied theoretically, but no detailed mechanism has been proposed to convert magnetic energy into relativistic particle kinetic energy in a short time. White dwarfs are not convective and solar-type flare magnetic fields and active regions may not form. It is not clear whether magnetic annihilation mechanisms based on solar conditions (e.g., reconnection) apply to these objects. More theoretical investigations need to be carried out. To date, no flares have been unambiguously observed from white dwarfs. To account for some cosmic gamma-ray bursts, their hard to soft X-ray luminosity ratio must be high, unlike the case for solar flares.

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