THE ASTROPHYSICAL JOURNAL, 288:L37–L40, 1985 January 15

HIGH-ENERGY EMISSION IN GAMMA-RAY BURSTS

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Received 1984 September 17; accepted 1984 October 24

ABSTRACT

Between 1980 February and 1983 August the Gamma-Ray Spectrometer (GRS) on the *Solar Maximum Mission Satellite* (*SMM*) detected 72 events identified as being of cosmic origin. These events are an essentially unbiased subset of all γ-ray bursts. The measured spectra of these events show that high-energy (> 1 MeV) emission is a common and energetically important feature. There is no evidence for a general high-energy cut-off or a distribution of cut-offs below ~ 6 MeV. These observations imply a limit on the preferential beaming of high-energy emission. This constraint, combined with the assumption of isotropic low-energy emission, implies that the typical magnetic field strength at burst radiation sites is less than 1×10^{12} gauss.

Subject heading: gamma rays: bursts

I. INTRODUCTION

The generally accepted characterization of γ-ray burst spectral shape from ~ 30 keV to ~ 1 MeV is $dN/dE \propto E^{-1} \exp(-E/E_0)$, with a typical E_0 being 300 keV. This description is consistent with a large number of observations from different experiments. Based on these observations, at least three distinct continuum models have been developed which give approximately the same spectral shape over this energy range: optically thin thermal bremsstrahlung (e.g., Mazets *et al.* 1981); thermal synchrotron (e.g., Liang, Jernigan, and Rodrigues 1983); and inverse Compton (e.g., Fenimore *et al.* 1982).

Because of the soft nature of these model spectra and the pair-production attenuation processes thought to be important in burst sites, little or no significant emission was expected at high energies. Isolated measurements of > 1 MeV emission have been made in some strong bursts, notably by the *Apollo 16* experiment (Gilman *et al.* 1980). But for most events the spectral shape above 1 MeV could not be determined because of the limited high-energy sensitivity of the burst detectors.

The main detector of the Gamma-Ray Spectrometer (GRS) on the *Solar Maximum Mission Satellite* (*SMM*) (Forrest *et al.* 1980) consists of seven 3″ × 3″ NaI crystals, actively shielded and continuously gain stabilized. While the anisotropic response and long spectral accumulation time (16.384 s) of the instrument make some burst studies difficult, the large sensitive area and energy range (0.3–9 MeV) allow us to study, for the first time, the high-energy component of a large number of γ-ray burst spectra.

II. *SMM* GRS GAMMA-RAY BURSTS

The *SMM* GRS data have been searched for bursts of γ-ray emission at ~ 300–400 keV. In the data for the period 1980 February to 1983 August we have found 72 such events which have been identified as of cosmic origin based on spectral and temporal characteristics as well as coincident observations by other spacecraft instruments. Particular care has been taken to avoid the inclusion of solar events in this data set. None of these events is coincident with a strong solar flare. In addition, the two types of events have markedly different X-ray spectra and time scales. Comparison of our event list with that of the Hard X-Ray Burst Spectrometer (HXRBS), which is also on *SMM*, indicates that only 14 of our 72 events are also detected by the smaller field-of-view (FOV) HXRBS. This implies that 58 of our events are from sources outside this Sun-centered FOV, and thus they are not solar. Finally, during a period of good coverage by other burst detectors (1981 November–1983 February) 29 of our 30 events have been at least preliminarily identified as being of cosmic origin (Hurley 1984).

While the GRS covers an energy range which is different from other burst detectors, all of our events have strong emission below 1 MeV. Thus they should, in principle, be detectable by conventional instruments. In fact, ~ 70% of GRS–observed γ-ray bursts have been detected by other experiments. It is clear then that we are detecting some subset of the ordinary class of bursts and not some new phenomenon. It is possible, however, that the instrumental characteristics of the GRS cause an unacceptable detection bias in favor of events with "hard" spectra.

We argue that this is not the case. The GRS event rate is ~ 20 per year. For a part of spacecraft night and during satellite passage through the South Atlantic Anomaly, no data are transmitted. In addition, part of the sky is blocked by Earth, and there is a lower sensitivity to events from sources outside our forward field of view. The result is that, assuming an isotropic source distribution, the probability of a burst occurring from an observable direction while the instrument is operating is less than 45%. This implies a rate of "GRS type" events of > 46 per year. Our absolute detection threshold (based on the smallest observed burst) is roughly $S(> 30 \text{ keV}) = 1 \times 10^{-5}$ ergs cm^{-2}. The effective average threshold, which depends on background, burst duration, and observation angle, is certainly higher. Based on log N–log S measurements (summarized in Jennings 1982), we expect ~ 50 bursts per year above our threshold. The rate of GRS type events is thus consistent with the rate of *all* γ-ray bursts. We can conclude then that our data set is not strongly biased but is representative of the entire class of γ-ray bursts.

III. HIGH-ENERGY EMISSION IN GAMMA-RAY BURSTS

GRS data showing the existence of high-energy emission in γ-ray bursts have already been published for a few events (Share *et al.* 1982; Rieger *et al.* 1982; Nolan *et al.* 1984). In fact, based on all GRS observations, we conclude that high-energy emission is a common feature of burst spectra. Figure 1 is a histogram showing the number of events with significant emission above photon energy E versus E, based on our main detector data. The criterion for significance was a greater than $3\ \sigma$ excess above the measured background in the energy range from E to 9 MeV. Over 60% of all bursts show significant flux above 1.03 MeV, 44% above 2 MeV, 29% above 4 MeV, and 24% above 5 MeV.

We have also calculated the *expected* maximum observable energies, using the known instrument response, the measured backgrounds, and the measured low-energy spectral shapes. For each of three spectral models (optically thin thermal bremsstrahlung, thermal synchrotron, and power-law), the best fit is found to each individual spectrum below 1 MeV. The predicted maximum energy is then the energy at which the instrument counts from the extrapolated best fit spectrum fall to $3\ \sigma$ above the background. The results for all events are tabulated and plotted with the observations in Figure 1. At high energies the number of detectable events predicted by the two thermal models falls significantly below the number observed, indicating that, in general, burst spectra are harder than either of these models.

These calculations can also be used to make an indirect test for spectral cut-offs. If the observed spectra are as hard as the fitted model but contain cut-offs, the number of events detected at high energies will be less than the number predicted. This is obviously a model-dependent procedure; however, even assuming a power-law spectral shape, the decline in the number of observed events is consistent with instrumental effects *alone*, at least out to ~ 6 MeV. Thus no spectral cut-off or distribution of cut-offs is required at lower energies. This is consistent with the fact that we have found no individual burst spectrum with a sharp, clearly defined cut-off.

Note that not all our observed spectra are power laws (Nolan *et al.* 1984), but since the power law is the hardest generally used continuum model, it provides a conservative test for cut-offs. No particular importance should be attached to the excess events above 6 MeV predicted by the power-law fits; since some spectra are softer than power laws, they will cut off at a lower energy than that predicted by a power-law fit.

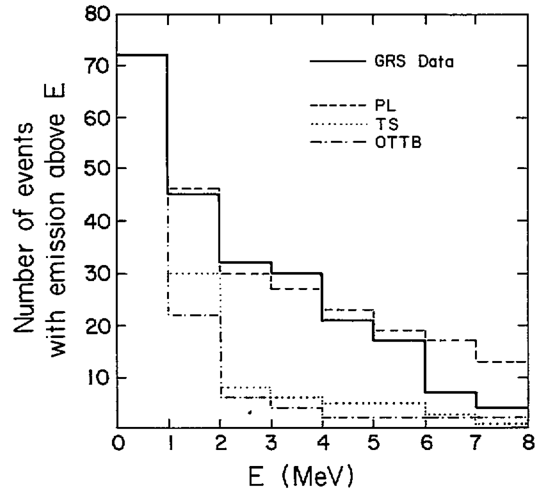

FIG. 1.—The solid line indicates the number of events observed by GRS above photon energy E vs. E. The three broken lines show the number of events we would expect to observe assuming power-law (PL), thermal synchrotron (TS), and optically thin thermal bremsstrahlung (OTTB) model spectra.

IV. HIGH-ENERGY EMISSION AND MAGNETIC FIELDS

Theoretical arguments have been made that strong magnetic fields ($> 10^{12}$ gauss) are required at γ-ray burst sites, based on the need to confine high-temperature (> 200 keV) plasmas on the time scales of bursts (Colgate and Petschek 1981; Lamb 1982). The assumption is that bursts are truly thermal phenomena with temperatures derived from optically thin thermal bremsstrahlung fits. The fields required were consistent with those expected on neutron stars.

The presence of high magnetic fields received some experimental support from the Konus experiments on the *Venera* spacecraft which measured spectral features in the energy range 30–70 keV. These were interpreted as cyclotron absorption lines, implying magnetic fields of $(2–6) \times 10^{12}$ gauss at the burst site (Mazets *et al.* 1981). Similar values were obtained using the thermal synchrotron model to analyze the same data set (Liang, Jernigan, and Rodrigues 1983). Both analyses find an average field for bursts with features of 4.6×10^{12} gauss. Bursts with measurable features are a fairly small fraction ($\sim 20\%$) of the total data set.

At magnetic fields of this strength it is possible for a high-energy photon to produce an electron-positron pair. These secondary particles then radiate photons as they move in the magnetic field; if these photons are of high enough energy, they will again pair produce. This process continues until the photon energies are below the pair-production threshold or the photons escape from the high-field region. The effect of this is that strong magnetic fields can act as efficient attenuators of high-energy photons. This process was first discussed in an astrophysical situation in connection with pulsars (Sturrock 1971).

Calculations have shown that the resulting spectrum has a sharp cut-off at a critical energy which depends on the field strength B and the sine of the angle (θ) between the photon direction and the direction of the magnetic field (Ögelman, Ayasli, and Hacinliyan 1977). This cut-off can fall within the spectral range of the GRS; therefore, for each burst the maximum observed energy results in an upper limit for $B \sin\theta$. We can also derive an upper limit on the "typical" magnetic field by using our complete data set and the following argument: The emission < 1.022 MeV is not attenuated by the field and may be isotropic. If the low-energy emission *is* isotropic and the source is near the stellar surface, these photons will be observable over a solid angle of approximately 2π sr. For a fixed field there is a maximum angle for which a photon above 1.022 MeV can escape and this angle decreases with increasing photon energy. Thus, at higher photon energies the burst is observable over a smaller solid angle. At any given field strength, then, the fraction of all bursts which are observable above any photon energy should be less than or equal to the solid angle of escape for that energy, divided by 2π sr. Because our burst list is based on the detection of photons below the threshold for this process, our data set presumably represents a random sample of observation angles. In that case the actual fraction of events observed at high energies gives an upper limit on the typical field strength at the radiation site.

Figure 2 shows such a comparison for two magnetic field strengths. The solid line indicates the percentage of events actually observed at or above photon energy E. The dashed and dotted lines indicate the fraction of events we would expect to observe, assuming a power-law spectrum up to the cut-off, for fields of 1×10^{12} gauss and 2×10^{12} gauss, respectively. If the actual spectrum is softer, we would expect even fewer events. Above 5 MeV, the deviations of the observed from the predicted have binomial probabilities corresponding to 3.7 σ significance for 1×10^{12} gauss and 9.0 σ for 2×10^{12} gauss. Even if we exclude the effects of declining instrument sensitivity the prediction for a 2×10^{12} gauss field differs by 4.0 σ from the observations.

For these calculations we have estimated the spectral cut-off to be at the photon energy for which the attenuation length equals 10 cm, using the approximate form of the attenuation coefficient given by Daugherty and Harding (1983). This length is much less than the expected physical scale size of the magnetic field, so this assumption produces a conservative limit on the field. The results are not sensitive to the chosen attenuation length. Under the less general assumption of a dipole field, we can set a slightly lower limit on the typical field strength, 8×10^{11} gauss at 3.8 σ significance.

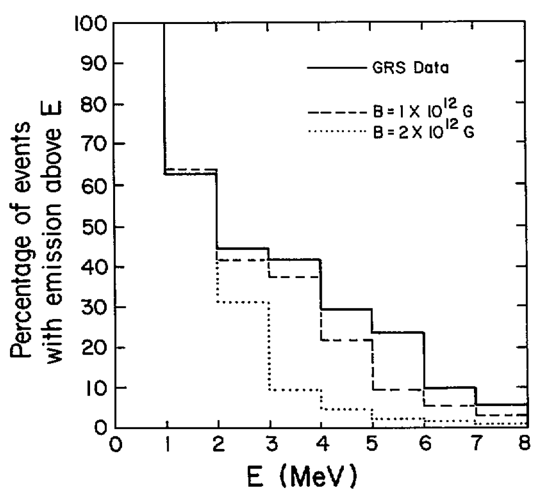

FIG. 2.—The solid line is the data from Fig. 1 converted to percentages of all observed events. The dashed line indicates the power-law spectra and percentage of burst spectra with observable photon emission $> E$ assuming a field of 1×10^{12} gauss at the source. The dotted line shows the result for a field of 2×10^{12} gauss.

These observations do not exclude the possibility that some burst sources have fields of $> 2 \times 10^{12}$ gauss, but most must be weaker and, indeed, the typical field strength must be $< 1 \times 10^{12}$ gauss. This indicates that the magnetic fields inferred from the Konus data cannot be representative of the entire source population. This is not surprising since fields of lesser strength would produce features outside the effective energy range of the Konus instruments.

It is possible to conceive of models which avoid this constraint on the field. The difficulty is in constructing a realistic model which avoids this limit and is not inconsistent with the data supporting strong fields. For example, both low- and high-energy emission could be beamed due to bulk motion along the field lines. It is not clear, though, that the observed narrow features could be produced in such an environment. Alternatively, the high-energy emission might be a separate component, originating in a low-field region away from the strong fields in which the < 1 MeV photons are produced. While this may be implausible, we cannot rule it out based on our data alone. However, we have found no strong evidence that the observed spectra are composed of separate high- and low-energy components. In neither of these cases would the plasma be confined, so the original argument for high fields would be invalid.

The arguments in this section do not depend on the GRS data set being strictly unbiased. All that is required is that we not be biased in favor of events without observable cut-offs. Since our search for events covered $E \sim 300$–400 keV and the pair-production process increases flux < 1 MeV and decreases flux > 1 MeV, we are actually *more* likely to detect events with cut-offs due to this process. Thus removal of bias from our sample would strengthen, not weaken, our conclusions.

V. CONCLUSIONS

The most important result reported here is that GRS data indicate that high-energy (> 1 MeV) emission is a common, indeed characteristic, feature of γ-ray burst spectra. It is not confined to some small subset of bursts. Thus, accounting for this emission must be a primary goal of any burst theory.

These observations are in conflict with the usual thermal models of burst spectra, which are generally too soft to predict the observed high-energy emission based on fits below 1 MeV. Since the spectrum is often harder than expected above 1 MeV, energy content calculations will be affected. In at least one burst observed by GRS (GB 800419), emission above 1 MeV accounted for half the total energy content above 30 keV.

Based on the pair-production attenuation of high-energy photons and assuming isotropic low-energy emission, we have placed an independent limit on the typical field strength at burst sites that is below the level deduced from the Konus data. It is important to note that the geometrical argument used to place a limit on the magnetic field applies equally well to any model which requires high-energy emission to be selectively beamed. The observations argue against any scheme of isotropic low-energy emission and highly beamed high-energy emission. Low- and high-energy emission must, in general, have roughly similar angular distributions. If both high- and low-energy radiation are beamed, many more sources would be required.

The authors acknowledge pertinent discussions with Dr. Patrick Nolan. We also thank Robert Hoffman for his help in typing this paper. This work was supported in part by contract NAS5-23761 and grant NGL 30-002-021 at the University of New Hampshire, NASA contract S.70926A at the Naval Research Laboratory, and contract 010K017-ZA/WS/WK at the Max-Planck Institute.

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