Observations of High-energy Gamma-ray Bursts with EGRET

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1 Introduction

Gamma Ray Bursts (GRBs) have puzzled astronomers since their discovery more than 20 years ago. As no counterparts at wavelengths other than X- and γ-rays have yet been found the identification of the sources is still missing. Theoretical explanations range from colliding comets (1993) and merging neutron stars (1982) to more exotic objects, such as superconducting cosmic strings (1988). Data accumulated until now still do not discriminate between these models, although results from the *BATSE* (Burst and Transient Source Experiment) instrument aboard the Compton Gamma Ray Observatory (*CGRO*) strongly favor extragalactic models.

The Energetic Gamma Ray Experiment Telescope (*EGRET*) aboard *CGRO* has s ofar detected photons from 5 GRBs with its spark chamber. These are the highest energy γ-rays associated with GRBs to date. In this work we review previously published data and summarize the properties of these events. Elsewhere we present possible constraints from the data on the models proposed to explain GRBs.

2 EGRET as a burst detector

The *EGRET* instrument consists of a large area particle tracker, a spark chamber with interspaced tantalum foils to convert the γ-rays into electron positron pairs, a trigger telescope used to detect the presence of an event and to remove upward going particles by time of flight discrimination, and an energy calorimeter dubbed TASC (Total Absorption Shower Calorimeter) using a NaI (Tl) crystal read out with photomultipliers. An anticoincidence dome (A-dome) of plastic scintillator material encloses most of the instrument to discriminate

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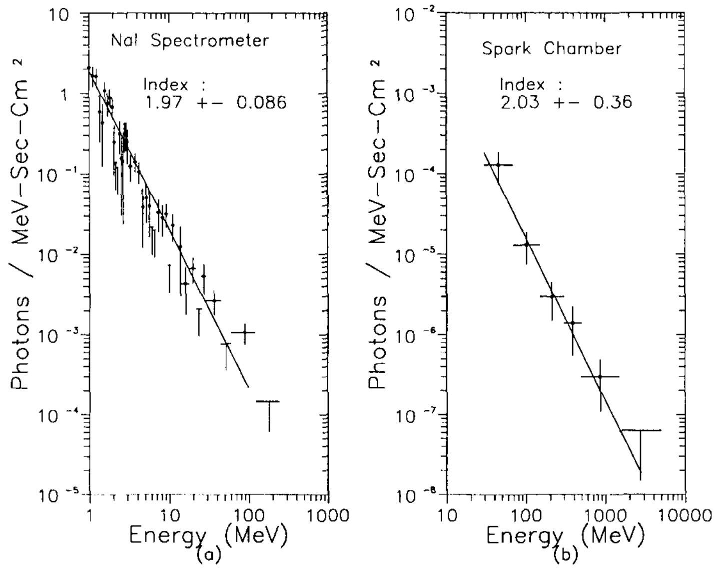

Fig. 1. Energy spectra of GRB 930131. (a) Energy spectrum from the TASC for the 1 second time interval beginning at 18:57:11.708 UT of 1993 January 31. A power law fit given by $(1.90 \pm 0.26)(E\,/\,1MeV)^{-1.97\pm0.09}$ photons/(cm^2 s MeV) is also shown. (b) Energy spectrum for the 16 γ-rays detected with the spark chamber within 25 s after the burst started. The power law fit is given by $(7.4 \pm 1.8)\cdot 10^{-6}(E\,/\,147MeV)^{-2.03\pm0.36}$ photons/(cm^2 s MeV).

against charged particles. A detailed description of *EGRET* can be found in Kanbach et al. (1988) and a discussion of the calibration and performance of the instrument was given by Thompson et al. (1993).

For the detection of GRBs, the A-dome, the TASC calorimeter, and the spark chamber can be used. The time profile of a burst can be obtained from the observed count rate in the A-dome. The plastic scintillator is sensitive to low energy γ-rays with energies higher than 50 keV. This rate is sampled with a time resolution of 0.256 seconds. The background rate in this detector is quite high and depends on the orbital position of the spacecraft. A careful treatment of the data is therefore needed to obtain the net burst time profile.

Spectra of bursts in the energy range between 1 and 100 MeV can be measured with the TASC crystal. During normal operations pulse-height spectra of 32.78 s duration are accumulated continuously and transmitted to Earth. After a BATSE trigger a special burst mode aquires four sequential spectra of 1, 2, 4 and 16 seconds duration. After background subtraction and correction with the response function of the calorimeter, derived from a detailed spacecraft mass model (for details see Schneid et al. 1993), energy spectra are derived. As an example we show in Fig. 1a the spectrum obtained during the first second after the *BATSE* trigger of GRB 930131 (Sommer et al. 1994). Although in general only a few photons are detected in the spark chamber, it is possible to derive an energy spectrum from them. In Fig. 1b we show the spectrum of GRB 930131

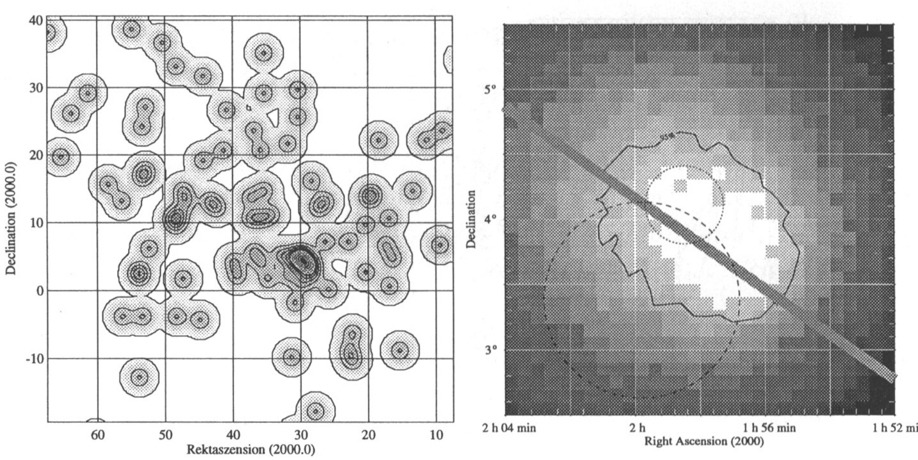

Fig. 2. Position of GRB 940217. (a) Raw image of photon arrival directions. (b) Image of likelihood analysis. The solid line corresponds to the 95% confidence contour; the small dotted circle is the error radius of the 18 GeV photon detected 4733 s after the *BATSE* trigger; the dashed circle is the $2\,\sigma$ *COMPTEL* burst location. The arc results from triangulation of *Ulysses* and *BATSE* arrival times. (Hurley et al. 1994)

derived from the imaged photons.

A burst location can be derived from the imaged photons detected in the spark chamber. The effective area of this detector increases from the threshold energy of 30 MeV to a maximum value of 1500 cm^2 at a few hundred MeV. As an example we show in Fig. 2a a raw image of GRB 940217 with single photon directions smoothed with a mean point spread function that was derived from calibration measurements. A few single photons are scattered over the full FoV. The GRB is clearly visible although only a few photons were detected. In Fig. 2b we show for the same burst the likelihood image after correcting for exposure. The 95% C.L. countour derived from this analysis is shown as a solid line (Hurley et al. 1994). We refer to the Figure caption for a detailed describtion of the other circles.

3 The 5 GRBs detected with EGRET

EGRET detected spark chamber photons from GRBs on May 3, 1991, June 1, 1991, January 31, 1993, Febraury 17, 1994 and March 1, 1994. Details on these detections can be found in Schneid et al. (1992) (GRB 910503), Kwok et al. (1993) (GRB 910601), Sommer et al. (1994) (GRB 930131), Hurley et al. (1994) (GRB 940217) and Schneid et al. (1995) (GRB 940301). We summarize some features of these bursts in Table 1. For the first time it was possible with *EGRET* to measure the very high energy tail of GRB spectra. Emission up to several GeV was detected. All spectra can be fit with a power law above 1 MeV. Strikingly, the spectral index derived from these fits is different for each GRB.

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Table 1. Properties of the 5 GRBs detected with the *EGRET* spark chamber

GRB	Position (J2000.0) RA	Dec	Max. Energy	Specrtal Index	Duration	Delayed Emission
GRB 910503	$05^h51.2^m$	38.6°	10000 MeV	-2.2 ± 0.1	3 s	10 GeV γ 84s after burst
GRB 910601	$20^h39.6^m$	32.3°	314 MeV	-3.7 ± 0.2	33 s	10 delayed γs in 400 s
GRB 930131	$12^h15.1^m$	10.2°	1200 MeV	-2.0 ± 0.4	25 s	2 γs in next 70 s
GRB 940217	$01^h58.1^m$	4.0°	18000 MeV	-2.5 ± 0.1	180 s	18 γs up to 5400 s after burst
GRB 940301	$07^h12.0^m$	65.1°	160 MeV	-2.5 ± 0.1	21 s	no

The most surprising result was the detection of delayed emission of $\geq$30 MeV to GeV photons long after some bursts, when all lower energy activity had ceased. The most prominent example of this is GRB 940217 from which 10 photons were detected in the spark chamber during the burst duration of 180s. Another 8 γ-rays were registered from the same direction during a 600s interval following the burst, while one expects only 1.8 events from the background rate. Past this time the spacecraft entered earth occultation and data could not be taken; after emerging from the earth shadow (4700 s after the burst trigger) another 10 photons whose directions were consistent with the burst location were detected, while only 2.9 are expected from the background. During this period of delayed emission a photon with 18 GeV energy was observed. During the whole period of 5400 s of delayed high energy emission following the burst no low energy activity (25-150 keV) could be detected by the *Ulysses* γ-ray detector. More details on this extraordinary burst are given in Hurley et al. (1994). Although emission of delayed high-energy photons was most significant during this peculiar burst, there is some indication of delayed emission on several other bursts, as summarized in Table 1 (see also Dingus et al. 1994).

The typical fluence above 20 keV of the GRBs detected with *EGRET* is 10^{-5} erg cm^{-2}. These events are the most intense GRBs detected by *BATSE*, and which are also in the FoV of *EGRET*. This suggests that bursts with much lower fluences may also have spectra that extend to high energies, but perhaps at flux levels that require next generation instruments for detection.

4 Discussion

Although only 5 GRBs were detected with *EGRET* so far, some interesting physical constraints can be set. The power law spectra found up to several hundred MeV rule out all models predicting blackbody or optically thin thermal spectra. The small size of the emission region implied by the observed short temporal variations and the high photon densities derived from the observed fluxes should lead to a significant attenuation of high energy photons due to photon-photon

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absorption in an isotropically emitting source. The fact, that no attenuation was detected up to several GeV (e.g. in the MeV range) can only be explained if the emission comes from highly collimated beams or ultra-relativistically expanding shells. For a typical source distance of 50 kpc (e.g. locations in the Galactic halo) the observation of GeV photons during the main burst interval requires bulk Lorentz factors of $\gamma \geq 25$ whereas for cosmological sources at distances around 1 Gpc $\gamma \geq 1000$ is necessary. One should remember that the highest bulk Lorentz factors observed so far are from jets in AGN with typical values of only ~ 10. Thus the very high Lorentz factors needed in GRBs are a challenge for most of the extragalactic models which on the other hand are favored by the isotropic and homogeneous distribution of GRBs. Only models that explain GRBs with cusps on superconducting cosmic strings as discussed by Paczynski (1988), although very speculative, provide a natural way to obtain very high bulk Lorentz factors.

The observation of photons up to 18 GeV also sets an upper limit on the distance of the sources due to the lack of absorption of these photons by the microwave and infrared/optical photon fields. A maximum redshift of $z \leq 100$ is still compatible with all proposed models and only detection of TeV photons by ground based detectors could possibly constrain this distance sufficiently to rule out some cosmological interpretations.

The delayed emission observed in some GRBs has been discussed by Katz (1994) and Mészáros & Rees (1993). In their models GRBs are due to merging neutron star binaries, which leads to shock acceleration and interaction of accelerated particles with some surrounding material. These models still need some tuning to explain the widely different spectral indices found in the burst spectra and the very high bulk Lorentz factors needed. More experimental data at high photon energies would certainly advance our understanding of the GRB puzzle.

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