ABSTRACT

On January 6th 2004, the IBAS burst alert system triggered the 8th gamma–ray burst (GRB) to be detected by the INTEGRAL satellite. The position was determined and publicly distributed within 12 s, enabling ESA’s XMM–Newton to take advantage of a ToO observation just 5 hours later during which the X–ray afterglow was detected. Observations at optical wavelengths also revealed the existence of a fading optical source. The GRB is $\sim 52$ s long with 2 distinct peaks separated by $\sim 24$ s. At gamma–ray energies the burst was the weakest detected by INTEGRAL up to that time with a flux in the 20–200 keV band of 0.57 photons cm$^{-2}$ s$^{-1}$. Nevertheless, it was possible to determine its position and extract spectra and fluxes. Here we present light curves and the results of imaging, spectral and temporal analyses of the prompt emission and the onset of the afterglow from INTEGRAL data.

1. INTRODUCTION

Gamma–ray bursts are an amazingly energetic phenomenon, capable of an isotropic output of order $10^{52}$–$10^{54}$ erg in a few seconds. Although first detected in the late 1960s, significant progress has mostly been achieved in the last dozen years. That GRBs are extra–galactic in origin was suggested by the isotropic distribution of GRBs observed by BATSE on board the Compton Gamma–Ray Observatory (Meegan et al. 1992; Fishman et al. 1994). The discovery by BeppoSAX of afterglows in the X–ray (Costa et al. 1997) and subsequent discoveries at optical (van Paradijs et al. 1997) and radio (Frail et al. 1997) wavelengths have led to redshift measurements (Metzger 1997) for $\sim 40$ bursts ranging from $z = 0.168$ – 4.5. A theory of gamma–ray bursts must provide a mechanism capable of releasing enormous quantities of non–thermal energy by compact sources at cosmological distances.

Although not built as a GRB oriented mission, INTEGRAL has a burst alert system (IBAS) and the two main instruments on board have coded masks, a wide field of view (FoV), cover a wide energy range (15 keV–8 MeV) and offer high resolution capabilities in imaging (IBIS) and spectroscopy (SPI). IBAS carries out rapid localisations for GRBs incident on the IBIS detector with precision of a few arcminutes (von Kienlin et al. 2003). The public distribution of these co–ordinates enables multi–wavelength searches for afterglows at lower energies. INTEGRAL data of the prompt emission in combination with the early multi–wavelength studies offers the best currently available probe of the origin of these transient phenomena.

In §2 observations and imaging analysis of GRB 040106 are presented. §3 describes the spectral analysis methods utilised and the results obtained from analysis of SPI data. A brief account of the temporal analysis is presented in §4.

2. DETECTION AND LOCALISATION

GRB 040106 was detected at 17:55:11 UTC on January 6th 2004. Lying at an off–axis angle of 10.5$^\circ$, the GRB was visible in the partially coded FoV of IBIS and of SPI, but was outside the FoV of the two monitoring instruments, JEM–X and the OMC. This GRB falls into the class of long GRBs, lasting approximately 52 s with two prominent peaks separated

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by a quiescent period of ~24 s. The ISGRI detector of IBIS, which is most sensitive between 15–300 keV, is used to produce the light curves of GRB 040106 shown in Fig. 1. The imaging capabilities of SPI are due to a coded mask comprising of 127 tungsten elements, with a thickness of 30 mm, placed at a distance of ~1.7 m from the detection plane, providing an angular resolution of 2.5′ (Vedrenne et al. 2003). Due to the weak nature of this burst, data from the two time intervals around the prominent peaks of emission (Fig. 1) were combined to enable SPI to determine a position for the GRB in the range 20–60 keV. The position for GRB 040106 extracted from the SPI data is $\alpha_{J2000} = 11^h 52^m 51.12''$, $\delta_{J2000} = -46^\circ 47' 13.2''$, which is 5.7′ off the position determined from the ISGRI data.

The IBAS alert (Mereghetti et al. 2004) was automatically distributed approximately 12 s after the burst start time with a positional uncertainty of only 3′. An XMM–Newton ToO observations began a 45000 s exposure at 23:05 UT. A bright source was visible in the 30 ks Quick–Look–Analysis (Ehle et al. 2004), 0.9′ from the IBAS position (Tedds & Watson 2004). At optical wavelengths the REM Telescope at the European Southern Observatory reported no new sources (Palazzi & Masetti 2004) detected during an observation at 04:45 on January 7th. The Swope Telescope at Las Campanas Observatory identified two faint sources as candidate optical afterglows of GRB 040106 (Price et al. 2004), but these were later observed to have retained the same flux to ±0.1 magnitude and hence are not candidate optical counterparts to GRB 040106 (Fox et al. 2004). Observations with ESO’s New Technology Telescope on two consecutive nights immediately after the GRB found one source demonstrating fading behaviour from 22.4 mag to 23.7 mag (Masetti et al. 2004), consistent the IBIS error circle and hence identifying a likely optical afterglow. Radio observations on January 10th with the Australia Telescope Compact Array (ATCA) at a frequency of 8.6 GHz detected a $160 \mu$Jy source with a 5σ significance 1.8′ from the centre of the XMM–Newton error circle (Wieringa & Frail 2004). However this source is not consistent with any of the optical sources reported and was not observed on January 21st with the Very Large Array (Frail et al. 2004).

### 3. Spectral Analysis with SPI

We have investigated the spectral evolution of GRB 040106 with SPI. The two bright peaks indicated in Fig. 1 were selected for analysis. The first interval is 7 s long starting at the very beginning of the burst 17:55:11 UTC, and the second begins 34 s later and lasts for 12 s. Spectra for each of these intervals were extracted at the XMM–Newton afterglow position.

Several background handling approaches were considered. The ‘CONSTANT’ background applies the same background to each detector. The default value of $10^{-7}$ counts/det/sec/keV was chosen for this analysis. The ‘ACS’ method assumes that the background follows the time variation of the total number of Anti–Coincidence Shield counts, scaled appropriately per detector in the spectral extraction. There is good agreement between the results obtained with ACS and CONSTANT backgrounds, when the GRB is in SPI’s FoV it is not detectable by the ACS. The ‘DFEE’ background utilises the count rates of the individual detectors to create a time variable model background. The ‘SPIOFFBACK’ program calculates the relative intensity of the background in each detector by examining the counts for a period in the same pointing, but excluding the time around GRB and scaling to the GRB duration thus all sources in the FoV, except the GRB, are subtracted as background. The DFEE results yield harder indices for both peaks than the other three methods and produces a hard excess above a few hundred keV. Therefore, unsurprisingly, since it assumes all sources are constant, this is not a suitable background choice for GRB analysis. The SPIOFFBACK results are consistent with the other methods and because its purpose is to remove all other sources in the FoV, it is the most suitable method for GRB studies. In this case a 40 minute period in the same science window as the GRB but before the trigger, is used to generate the background.

The single events detected by SPI, corrected for intrinsic deadtimes and telemetry gaps, are binned into 5 equally spaced logarithmic energy bins in the
Table 1. Spectral analysis of GRB 040106 with SPI for two intervals around the prominent peaks of emission

| Interval | Parameter       | SPI         |
|----------|-----------------|-------------|
| 1st peak | Photon Index    | 1.47$^{+0.59}_{-0.52}$ |
|          | Normalisation   | 1.67        |
|          | *Flux (erg cm$^{-2}$ s$^{-1}$) | 5.9$\times10^{-8}$ |
| 2nd peak | Photon Index    | 1.32$^{+0.34}_{-0.31}$ |
|          | Normalisation   | 0.90        |
|          | *Flux (erg cm$^{-2}$ s$^{-1}$) | 6.1$\times10^{-8}$ |

*Flux is measured in the energy range 20 - 200 keV

Table 2. Timing analysis of GRB 040106

| Parameters | $t_r$ (s) | $t_f$ (s) | FWHM |
|------------|-----------|-----------|------|
| 1st Pulse  | 2.4       | 2.8       | 4.5  |
| 2nd Pulse  | 4.1       | 5.8       | 10.1 |

20 keV to 200 keV range for each of the chosen intervals. The SPIROS (SPI Iterative Removal of Sources, [Shipman & Connell 2003]) software package is used for spectral extraction, while XSPEC 11.2 is used for model fitting. The spectrum for each of the two intervals is best fit by a single power law model (Fig. 2). The photon indices, normalisation values and fluxes obtained are presented in Table 1. Inspection of the IBIS/ISGRI light curves in low and high energy bands (Fig. 1) suggests that the second peak is harder than the first. Errors quoted are 1 parameter of interest at 67% confidence level. Spectral analysis yields a photon index of 1.47$^{+0.59}_{-0.52}$ for the first peak, but 1.32$^{+0.34}_{-0.31}$ for the second peak confirming that the second peak is harder, while the flux remains approximately constant $\sim 6.1 \times 10^{-8} \text{erg cm}^{-2} \text{s}^{-1}$ for both peaks. The same analysis was conducted for multiple events incident on the SPI detectors, but yielded no significant improvement to the fit.

4. TEMPORAL ANALYSIS

Table 2 summarises the results of denoising GRB 040106 using a wavelet analysis and the temporal properties of the two significant pulses. The duration (T90) of the burst is 52 s and there is a time interval, $\Delta T$, of 42 s between the peaks. The pulse properties of pulses in short and long GRBs are consistent with lognormal distributions ([Oulligan et al. 2002]). Furthermore the pulse properties and time intervals between pulses are related to T90 ([McBreen et al. 2002]) and presented in the form of a set of timing diagrams. The time interval and properties of the two pulses, $\Delta T$, the rise time ($t_r$), fall time ($t_f$) and FWHM of this GRB are are proportional to T90 and fit well on the timing diagrams. A long, weak GRB generally has slow pulses well separated from each other, rather than fast pulses close together. There is no satisfactory explanation of this phenomenon but it is probably related to a low value of the bulk Lorentz factor $\Gamma$ and a viscous accretion disk surrounding a black hole ([Fryer et al. 1994]).

5. DISCUSSION & CONCLUSIONS

On December 19th 2003, SPI’s detector #2 was confirmed dead after several attempts to revive it met with no success. As yet a new redistribution matrix has not been released to take account of this change in SPI’s response. GRB 040106 was incident on detector #2 and the surrounding detectors, so an improvement in the fit is expected when the new matrix is issued.

The results of spectral analysis of GRB 040106 confirm that the second peak is harder than the first and that it is well fit by a single power–law model of photon index $\alpha \sim -1.3$. It is unlikely that this is an X–ray rich GRB with a peak energy at or below the low end of the SPI detector sensitivity (i.e. $\sim 20 \text{keV}$) since the spectral index would correspond to an unusually hard value for the high–energy index above the spectral turnover ([Preece et al. 2000]). It is more likely that the weakness of this GRB washes out evidence for a spectral break at more typical en-
ergies of a few hundred keV. There is no evidence in the IBIS/ISGRI light curve for soft extended or delayed emission such as that observed by, for example, SIGMA/GRANAT in GRB 920723 (Burenin et al. 1999) or by HETE–II in GRB 021211 (Crew et al. 2003). The temporal decay of the 2nd peak is consistent with a power–law of slope \( \beta = -0.3 \pm 0.7 \) which may indicate the presence of a high–energy afterglow, due to external shocks, during the burst itself. However, the data are not sufficiently constrained to indicate fast or slow, or radiative or adiabatic, cooling in the synchrotron shock model (Giblin et al. 2002; Piro 2004). Further analysis and comparison with XMM–Newton results are on–going (Moran et al. 2004).

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