Discovery of the short γ-ray burst GRB 050709

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Gamma-Ray Bursts (GRBs) are the most brilliant events in the universe. They fall into two classes: short-hard and long-soft bursts[1,2,3]. The latter are now known to have X-ray[4] and optical afterglows[5], to occur at cosmological distances[6] in star-forming galaxies[7], and to be associated with the explosion of massive stars[8,9]. In contrast, the distance scale, the energy scale, and the progenitors of short bursts have remained a mystery. Here we report the discovery of a short-hard burst whose accurate localization has led to follow-up observations that have identified the X-ray afterglow[10] and (for the first time) the optical afterglow[10−12] of a short-hard burst. These, in turn, have led to identification of the host galaxy of the burst as a late-type galaxy at $z = 0.16$,[10] showing that at least some short-hard bursts occur at cosmological distances in the outskirts of galaxies, and are likely to be due to the merging of compact binaries.

On 9 July 2005, at 22:36:37 UT (81397 SOD), the Soft X-Ray Camera (SXC), Wide-Field X-Ray Monitor (WXM) and French Gamma Telescope (FREGATE) instruments on board the High Energy Transient Explorer 2 satellite (hereafter HETE[13]) detected GRB 050709, a short-hard pulse followed by a long-soft bump from the same location. Figure 1 shows the WXM and SXC localizations for the burst, and the location of the X-ray and optical afterglows. Figures 2 and 3 show the time history of the entire burst and of the short-hard pulse in several energy bands.

Figure 4 compares the best-fit spectral model and the spectral data for the short-hard pulse. Table 1 gives the best-fit spectral parameters for different time intervals during the burst. The spectrum of the short pulse is hard and that of the intense first peak of the pulse (corresponding to the first 0.2 s of the burst) is even harder.

The duration and the peak energy $E_{\rm peak}^{\rm obs}$ of the spectrum of the short-hard pulse are consistent with those of short-hard GRBs.[14,15] We note that its duration is much shorter and its spectrum is much harder than these were for GRB 020531, the other short-hard burst localized by HETE.[16] We also note that the time history and the spectral properties of GRB 050709 are similar to those of several Burst and Transient Source Experiment (BATSE) bursts, including GRBs 921022, 990516, and 990712[17,18] (see Table 1). Table 2 gives the emission properties of the burst. The gamma-ray to X-ray fluence ratio of the short-hard pulse is 3.1, which is also consistent with those of BATSE short-hard bursts.

The isotropic-equivalent energy $E_{\rm iso}$ of the short-hard pulse is a factor ~ 1000 smaller than is typical of long GRBs and implies that the energy E_γ radiated by the short-hard pulse in γ rays is at least 40 times less than is typical for long GRBs.[19] The very small value of $E_{\rm iso}$ also places the short-hard pulse off of the $E_{\rm iso} - E_{\rm peak}$ relation found by Refs. 20 and 21 for long GRBs by a factor of ~ 1000 in $E_{\rm iso}$. The luminosity $L_{\rm iso}$ of the short-hard pulse is also very small, and places it off of the $L_{\rm iso} - E_{\rm peak}$ correlation found by Refs. 21 and 22 for long GRBs by a factor of ~ 100 in $L_{\rm iso}$. These three results strengthen the conclusion that GRB 050709 is a short-hard burst.

There is evidence that many BATSE short-hard bursts exhibit a similar long-soft bump following the initial hard pulse.[23,24] We have already mentioned the similarity of the time history and spectral properties of GRB 050709 and those of GRBs 921022, 990516, and 990712. Ref. 23 reported evidence that BATSE short-hard bursts are followed by a 30-200 s period of long-soft emission having a spectrum consistent with what we find for the long-soft bump in GRB 050709, while Ref. 24 reported evidence that BATSE short-hard bursts show an excess of soft emission from 20 s to 100-300 s after the burst.

We have analyzed the time history of the long-soft bump and find no evidence for brightness oscillations of the kind that characterize the long-soft bump of SGR giant flares[25,26] (see Figure 2). We have also searched for any evidence of stochastic variability of the long-soft bump and find none (also see Figure 2). Finally, we have searched for evidence of spectral evolution during the long-soft bump and find none (see Table 1).

The most natural interpretation of the long-soft bump is that it is the beginning of the afterglow. Its time history and spectrum are consistent with those expected for an afterglow, as is the lack of any time variability or spectral evolution. The ratio of the fluence in the short-hard pulse to that in the short-hard pulse plus the long-soft bump implies an radiative efficiency of $< 25\%$ for the prompt phase. If the peak of the long-soft bump at ≈ 100 s corresponds to the time at which the fireball decelerates, a consistent solution exists in which $z = 0.16$, the GRB jet has an isotropic-equivalent kinetic energy $E_{\rm KE} \sim 5 \times 10^{49}$ erg, a relativistic bulk $\Gamma \approx 100$, and expands into a low-density medium having a number density $n \sim 10^{-2}$ cm^{-3} (see Figure 2).

The accurate location of GRB 050709 by the WXM and SXC on board HETE has led to the identification of the X-ray afterglow,[11] and for the first time, the identification in ground-based[11–13] and HST[11] images of the optical afterglow of a short-hard burst. These have led to the first secure identification of a host galaxy: a late-type spiral galaxy lying at a redshift $z = 0.16$.[11] The X-ray and optical afterglows lie at a projected distance of ≈ 3 kpc from the center of the host galaxy and are therefore not coincident with the brightest optical emission from the host galaxy (in contrast to long bursts[28]).

These results constrain the nature of the central engine for GRB 0500709, and by implication all short-hard bursts. The absence of any large-amplitude oscillations with a period in the range 1-10 s in the long-soft bump and the offset of GRB 050709 from the center of the host galaxy argue against an association between this short-hard burst and SGR giant flares.[25,26] Models based upon core collapse in massive stars[9] explain the association of some long-soft bursts with supernovae. However, given the time it takes for the GRB-producing jet to emerge from a collapsing massive star, it is difficult for such models to produce bursts shorter than a few seconds. Merging neutron stars, on the other hand, can produce very short bursts.[29] Given the smaller mass of the accretion disk that forms, it is not unreasonable to expect a lower average $E_{\rm iso}$ for short-hard bursts, and hence a smaller average redshift. Moreover, since binary neutron stars are imparted with a "kick" at birth and travel large distances before merging, one expects an offset of order several kpc between the star-forming regions of the host galaxy and the burst.[30] GRB 050709 exhibits all of these properties. The roughly 100 s lag between the short-hard pulse of GRB 050709 and the peak of the much softer afterglow is consistent with the low-density interstellar medium expected in the vicinity of a merging compact binary.[23] If short-hard GRBs are due to merging neutron stars, they produce powerful bursts of gravitational radiation that should be detectable by the second-generation Laser Interferometry Gravitational-Wave Observatory.

The HETE localization of the short-hard burst GRB 050709 has led to follow-up observations that have identified the X-ray afterglow and (for the first time) the optical afterglow of a short, hard burst. These, in turn, have led to identification of the host galaxy of the burst as a late-type galaxy at $z = 0.16$, showing that at least some short-hard bursts occur at cosmological distances in the outskirts of galaxies, and are likely to be due to the merging of compact binaries.

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Table 1. Spectral Model Parameters for GRB 050709.

Parameter	t = 0–0.20 s	t = 0.20–0.50 s	t = 0–0.50 s	t = 20–180 s
Spectral Model:	PLE	PLE	PLE	PL
Photon index α	$0.53^{+0.12}_{-0.13}$	$0.55^{+1.0}_{-1.3}$	$0.82^{+0.13}_{-0.14}$	$1.98^{+0.18}_{-0.15}$
Peak energy ($E^{\rm obs}_{\rm peak}$)	$83.9^{+11}_{-8.3}$	$10.6^{+4.5}_{-3.5}$	86.5^{+16}_{-11}	—
Normalization (at 15 keV)	$0.79^{+0.07}_{-0.08}$	$0.650^{+3.24}_{-0.48}$	$0.377^{+0.04}_{-0.04}$	0.0075 ± 0.0013
Chi-squared (DOF)	439 (366)	374 (366)	467 (366)	336 (367)

Note. — The spectral models are power-law times exponential (PLE) and power-law (PL). Errors are for 90% confidence. The normalization units are photons cm^{-2} s^{-1} keV^{-1}. DOF is the number of degrees of freedom in the fit. We have also fit PL and Band models to the first three time intervals and find χ^2 (DOF) values of 550 (367), 383 (367), and 538 (367) for the PL model and 439 (365), 374 (365), and 467 (365) for the Band model, demonstrating that the data request the PLE model but not the Band model. Similarly, we have also fit a PLE model to the fourth time interval and find χ^2 (DOF) values of 336 (366), demonstrating that the data request the PL model but not the PLE model. The large values of χ^2 per DOF that we find for the PLE model for the 0-0.2 s and 0-0.5 s time intervals are due to the rapid spectral evolution during the short-hard pulse. We have calculated the hardness ratio H = counts(5-10 keV)/counts(2-5 keV) for 10, 20, 30, and 40 s time intervals and find no evidence of spectral evolution during the long-soft bump. The time history and spectral parameters of GRB 050709 are similar to those of the BATSE bursts GRBs 921022, 990516, and 990712.[18,19] In particular, the short-hard pulse of GRB 921022 had a duration $\approx$ 256 ms and spectral parameters $\alpha = -1.1 \pm 0.3$, $\beta = -2.15 \pm 0.12$, and $E^{\rm obs}_{\rm peak} = 123 \pm 28$ keV, while the long-soft bump of that burst had a PL spectrum with index $\alpha \approx$ -2.[18]

Table 2. Emission Properties of GRB 050709.

Energy (keV)	Peak Photon Flux (ph cm^{-2} s^{-1})	Photon Fluence (ph cm^{-2})	Peak Energy Flux (10^{-8} erg cm^{-2} s^{-1})	Energy Fluence (10^{-8} erg cm^{-2})
Short, hard pulse:				
2-10	29.0 ± 5.2	3.47 ± 0.59	24.9 ± 3.9	2.81 ± 0.42
2-25	53.6 ± 6.1	5.55 ± 0.69	88.7 ± 7.7	8.31 ± 0.70
2-30	58.1 ± 6.9	5.94 ± 0.70	111 ± 8.6	10.1 ± 0.76
7-30	37.1 ± 2.8	3.31 ± 0.25	96.8 ± 6.8	8.35 ± 0.59
30-400	34.1 ± 2.7	2.51 ± 0.22	400 ± 46	30.3 ± 3.8
50-100	13.9 ± 1.1	0.986 ± 0.087	156 ± 13	11.0 ± 1.0
100-300	6.62 ± 1.1	0.515 ± 0.092	155 ± 29	12.4 ± 2.5
2-400	92.1 ± 7.6	8.43 ± 0.752	511 ± 49	40.3 ± 4.1
Long, soft bump:				
2-10	2.36 ± 0.43	107 ± 18	1.53 ± 0.27	69.1 ± 10
2-25	2.72 ± 0.47	123 ± 18	2.41 ± 0.37	109 ± 14

Note. — The quantities in this table are derived assuming the best-fit PLE model for the spectrum of the short-hard pulse and the best-fit PL model for the spectrum of the long-soft bump. Errors are 90% confidence level. The photon number and photon energy peak fluxes for the short-hard pulse are in 70 ms, corresponding to T90 for the short-hard pulse; those for the long-soft bump are in 1 s. Using the redshift $z = 0.16$ measured for the host galaxy,[11] the isotropic-equivalent energy of the short-hard pulse in the 1-10,000 keV energy band in the rest frame of the source is $E_{\rm iso} = (2.8^{+0.4}_{-0.2}) \times 10^{49}$ erg, taking $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $h = 0.65$. Using a time interval 0.060 s in the rest frame of the source (corresponding to a duration of 0.07 s in the observer frame) and assuming the same cosmology and energy band, the luminosity of the short-hard pulse in the 1-10,000 keV energy band in the rest frame of the source is $L_{\rm iso} = (5.2 \pm 0.7) \times 10^{50}$ erg s^{-1}.

FIGURE CAPTIONS

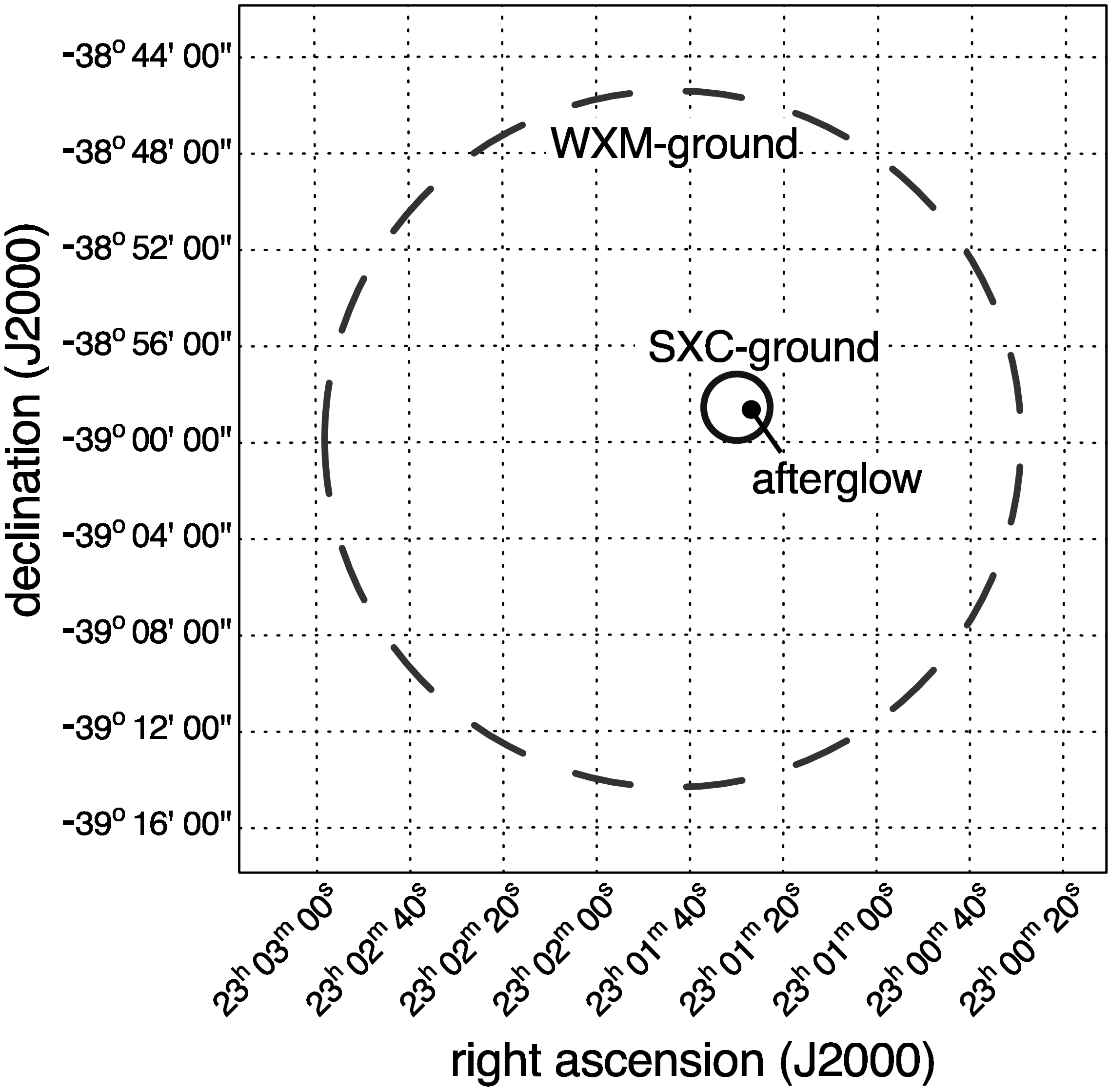
Fig. 1.–**Sky map showing the HETE localization error circles for GRB 050709 and the location of the X-ray and optical afterglow.** The WXM obtained a localization in flight. However, the spacecraft attitude-control system was not locked at the time of the trigger, resulting in a drift of the satellite pointing direction, and real-time aspect was not available. Consequently, the location was not distributed in real time. Ground analysis of the data from the optical cameras provided reliable spacecraft aspect information, despite the spacecraft drift rate. A GCN Notice was sent out at 22:00:09 UT on 10 July 2005, after ground determination of the spacecraft aspect[12]. Ground analysis of the WXM data produced a location with a 90% confidence region that is a circle centered at R.A. = +23h 01m 44s ; Dec. = -38° $59^{'}$ $52^{''}$ (J2000) with a radius of $14.5^{'}$ (large circle labelled "WXM-ground"). Ground analysis of the SXC data yielded a refined location with a 90% confidence region that is a circle centered at R.A. = +23h 01m 30s ; Dec. = -38° $58^{'}$ $33^{''}$ (J2000) with a radius of $1.34^{'}$ (small circle labelled "SXC-ground"). The location of the X-ray and optical afterglow is labelled "afterglow."

Fig. 2.–**Time history of GRB 050709.** From top to bottom: Time history observed by WXM in the 2-10 keV energy band (a) and in the 2-25 keV energy band (b); time history observed by FREGATE in the 6-40 keV energy band (c) and in the 30-400 keV energy band (d). The event is a short-hard spike of duration T90 = 220 ± 50 ms in the 2-25 keV energy band and 70 ± 10 ms in the 30-400 keV energy band, followed $\sim$ 25 seconds later by a long-soft bump of duration T90 = 130 ± 7 s in the 2-25 keV energy band – where T90 is the time interval containing 90% of the photons. We have performed an FFT on the time history of the long-soft bump for the time interval 5-175 s after the trigger. We find no evidence for any coherent brightness oscillations in the period range 1-10 s, and derive 3σ upper limits on the amplitude of any such oscillations of 77% and 89% at periods of 1 and 5 s, respectively.

We have also computed the variability measure V,[27] for the long-soft bump, using smoothing time scales of 10, 20, 30, and 40s. We find $V = 0.005 \pm 0.013, 0.003 \pm 0.026, 0.007 \pm 0.031$, and 0.025 ± 0.036, respectively. We therefore find no evidence for a non-zero value of V. If the long-soft bump is the afterglow and its peak at $t_{\rm peak} \approx 100$ s corresponds to the time at which the fireball decelerates, a consistent solution exists in which $z = 0.16$; the GRB jet has an isotropic-equivalent kinetic energy $E_{\rm KE} = (1 - \cos\theta_{\rm jet}) {E_{\rm iso}}^{\rm total}/\eta \sim 5 \times 10^{49}$ erg – where ${E_{\rm iso}}^{\rm total} = E_{\rm iso}({\rm pulse}) + E_{\rm iso}({\rm bump}) \sim 1 \times 10^{50}$ erg, $\theta_{\rm jet} \sim 0.3$ is the jet opening angle,[19] and $\eta = 0.2$ is the radiative efficiency; a relativistic bulk $\Gamma \approx 100$; and expands into a low-density medium having a number density $n \sim 10^{-2}$ cm^{-3}.[23]

Fig. 3.–**Time history of the short-hard pulse of GRB 050709.** From top to bottom: Time histories observed by the WXM in 2–10 kev energy band (a) and 10–25 keV band (b); and by FREGATE in 6–30 keV energy band (c), 30–85 keV energy band (d), and 85–400 keV energy band (e), plotted in 5 ms time bins. The pulse has a duration T90 = 220 ± 50 ms in the 2-25 keV energy band and 70 ± 10 ms in the 30-400 keV energy band, and exhibits no detectable emission before $T = 0$ or after $T = 400$ ms, confirming the short, hard nature of the pulse.

Fig. 4.–**Comparison of the observed count spectrum and the best-fit PLE model for the short-hard pulse.** Upper panel: comparison of the counts in the WXM energy loss channels (lower energies) and the FREGATE energy loss channels (higher energies) and those predicted by the best-fit PLE model (smooth curves). Lower panel: residuals to the fit. The short-hard pulse exhibits emission at all energies, confirming that its spectrum is hard.


WXM-ground
SXC-ground
afterglow
declination (J2000)
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-38° 48' 00"
-38° 52' 00"
-38° 56' 00"
-39° 00' 00"
-39° 04' 00"
-39° 08' 00"
-39° 12' 00"
-39° 16' 00"
23h 03m 00s
23h 02m 40s
23h 02m 20s
23h 02m 00s
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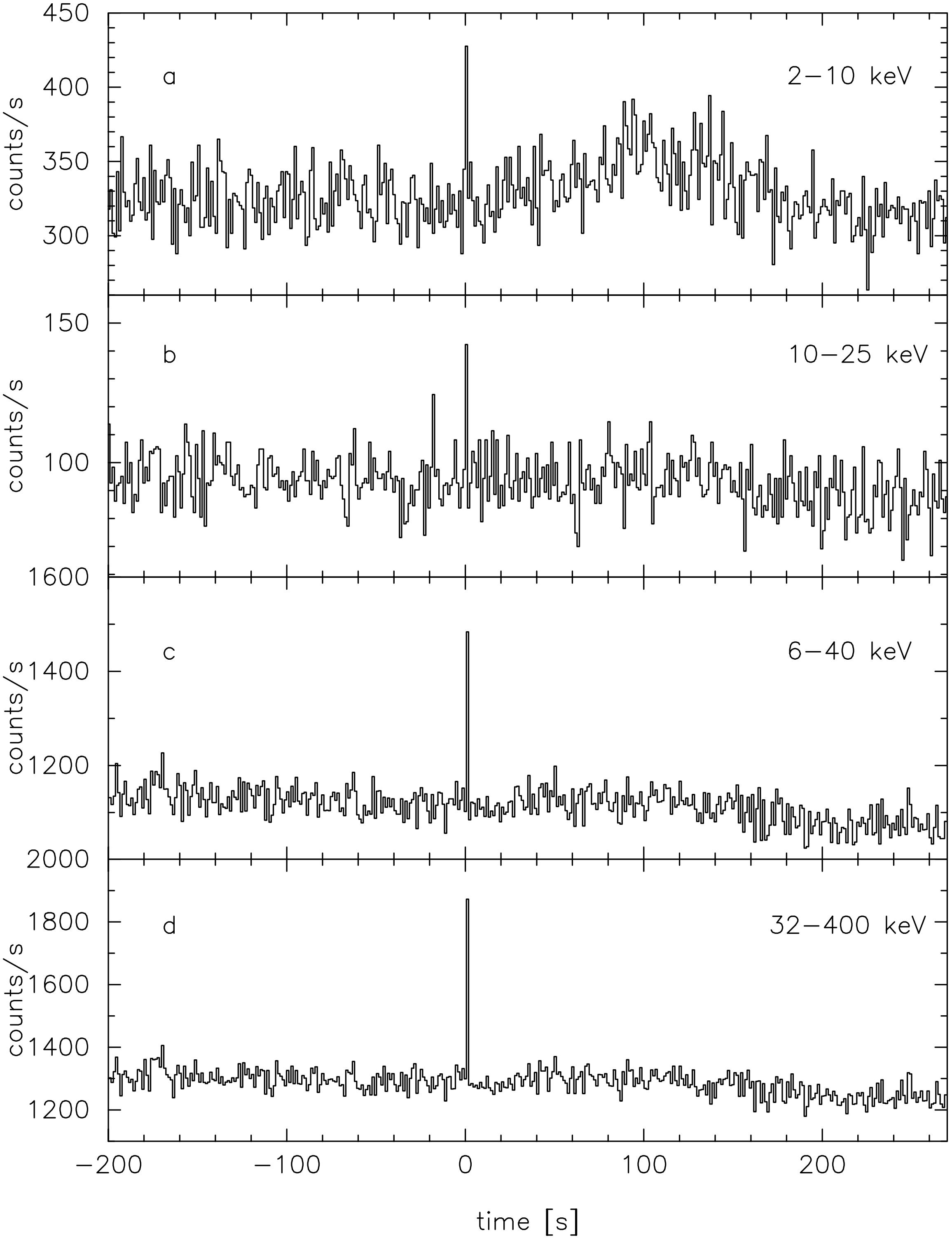
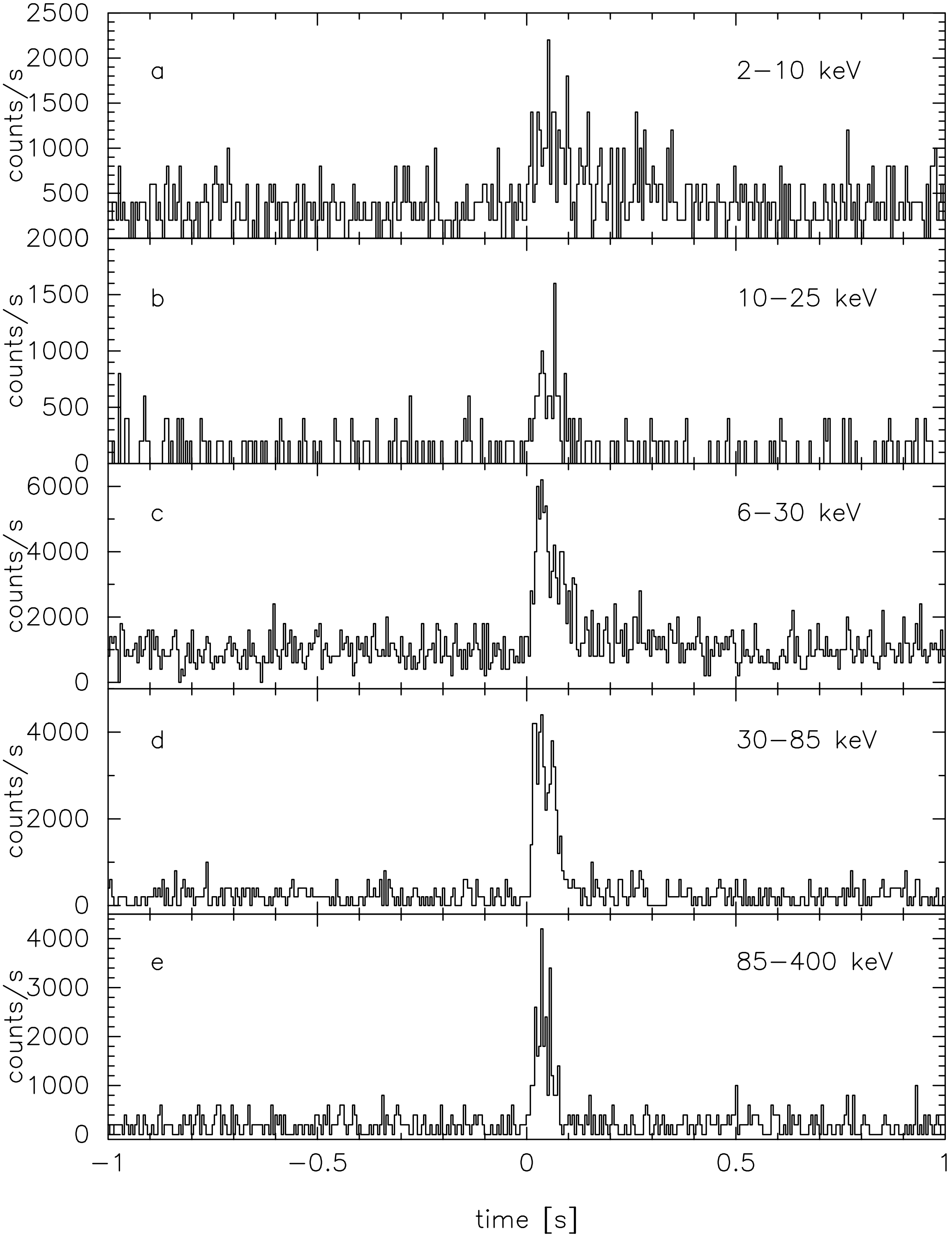
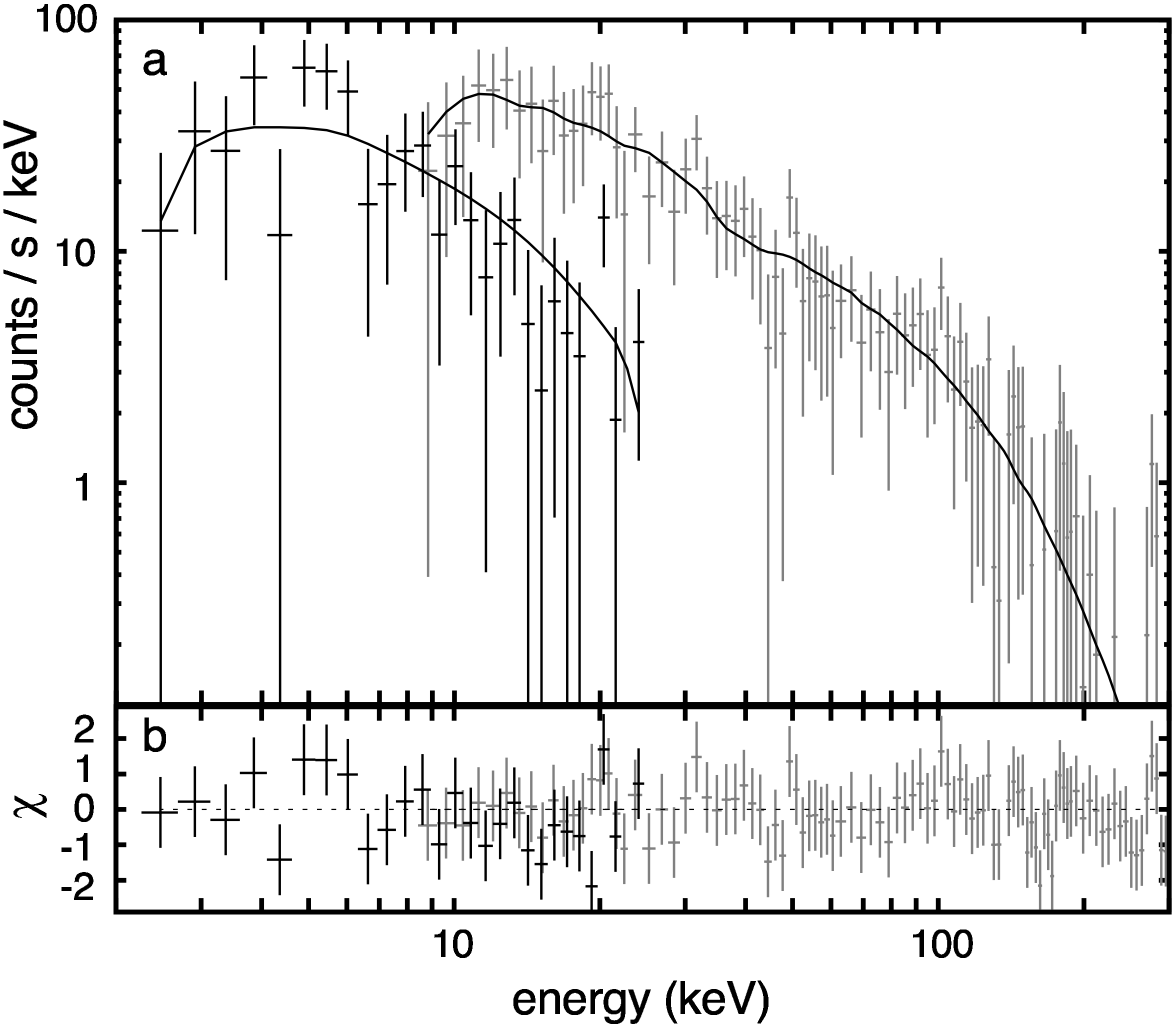
23h 00m 20s
right ascension (J2000)


a
2–10 keV
b
10–25 keV
c
6–40 keV
d
32–400 keV
counts/s
450
400
350
300
150
100
1600
1400
1200
2000
1800
1600
1400
1200
−200
−100
0
100
200
time [s]



2500
2000
1500
1000
500
2000
counts/s
a
2–10 keV
1500
1000
500
0
counts/s
b
10–25 keV
6000
4000
2000
0
counts/s
c
6–30 keV
4000
2000
0
counts/s
d
30–85 keV
4000
3000
2000
1000
0
counts/s
e
85–400 keV
−1
−0.5
0
0.5
1
time [s]


a
b
100
10
1
counts / s / keV
2
1
0
-1
-2
χ
10
100
energy (keV)