Chandra and XMM-Newton observations of the extraordinary GRB 060729

Dirk Grupe (PSU), Dave Burrows (PSU), Xue-Feng Wu (UNLV, Nanjing University), Bing Zhang (UNLV), & Gordon Garmire (PSU)

Abstract. We summarize the results of the late-time Chandra observations of the X-ray afterglow of the Swift-discovered GRB 060729. These Chandra observations have been the latest X-ray detections of an afterglow even, up to 21 month after the trigger. The last two Chandra observations in December 2007 and May 2008 suggest a break at about a year after the burst, implying a jet half-opening angle of about 14 degrees, if interpreted as a jet break. As an alternative this break may have a spectral origin. In that case no jet break was observed and the half-opening angle is larger than 15 degrees for a wind medium. Comparing the X-ray afterglow of GRB 060729 with other bright X-ray afterglows we discuss why the afterglow of GRB 060729 was such an exceptionally long-lasting event. The detection by Chandra in May 2008 was the latest detection of an X-ray afterglow at cosmological distance ever. WE also re-analyzed the X-ray spectra taken by XMM about a day after the trigger and probably found a weak H-like Fe XXVI Kα line at rest-frame 7.0 keV.

I. Introduction: one of the predictions of the "Fireball" model is that the GRB afterglow decay rate increases when the relativistic beaming angle equals or exceeds the physical jet opening angle as the jet decelerates in the surrounding medium. This can be seen as an achromatic jet break in the light curve. Since its launch, Swift has detected roughly 550 bursts (Oct. 2010). For the majority of these bursts, jet breaks have not been detected (e.g. Racusin et al. 2009, Evans et al. 2009). However, one reason could be that jet breaks occur at times after Swift stopped observing the afterglow. Typically Swift follows an afterglow roughly a week or two after the detection. One exception was the X-ray afterglow of GRB 060729 which Swift was able to detect even 125 days after the trigger (Grupe et al. 2007). However, by December 2007 the afterglow had faded below the Swift XRT detection limit. In order to extend the light curve of this exceptional X-ray afterglow, we observed it 5 times with Chandra in 2007 and 2008 (Grupe et al. 2010).

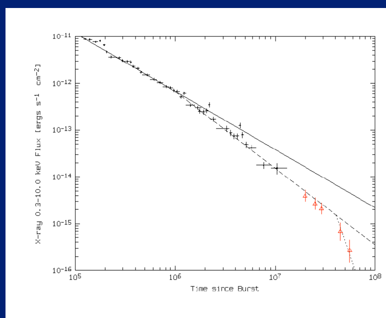

Figure1: Swift XRT (black crosses) and Chandra ACIS-S (red triangles) light curve of the X-ray afterglow of GRB 060729. The solid line displays an initial decay slope of 1.32 (Grupe et al. 2007), the dashed line the decay slope of 1.61 post-break at 1 Ms after the burst and the doted line the steep decay slope of 4.65 after the break at 41 Ms after the burst (Grupe et al. 2010).

II. X-ray Observations of the afterglow of GRB 060729

While Swift could detect the X-ray afterglow of GRB 060729 until the end of November 2006 it became to faint to be detected by the Swift XRT in December 2006. All further observations of the X-ray afterglow needed to be performed by Chandra. Therefore we had 3 Chandra ACIS-S observations in March, May and June 2007 for 30 ks, 40 ks, and 60 ks respectively as part of the Penn State GTO time. These were followed by an 80 ks observation in December 2007 and an 120 ks observation in May 2008 as GO observations (see Grupe et al. 2010 for details).

III. Temporal Breaks in the light curve of GRB 060729

Figure 1 displays the Swift XRT and Chandra ACIS light curve of the X-ray afterglow of GRB 060729. The first day is not shown here because we focus on the late-time light curve. This light curve was fitted with multiple broken power laws. Fitting the light curve with just a single power law model with a decay slope of 1.32 as reported by Grupe et al. (2007) shows a significant deviation of the data after about 1 Ms after the burst. A closer look at the light curve shows that there is also a spectral break at about 1 Ms after the trigger. The spectrum significantly hardens after this break. On the flux light curve the decay slope becomes steeper with a slope of 1.61 (shown as the dashed line in Figure 1). While the first three Chandra points (red triangles) agree perfectly with that slope, the last two point from Dec. 2007 and May 2008 seem to deviate from this line. They suggest a break at about 41 Ms after the trigger. This break is followed by a very steep decay slope of 4.6. Note, however, that this break is not well constrained.

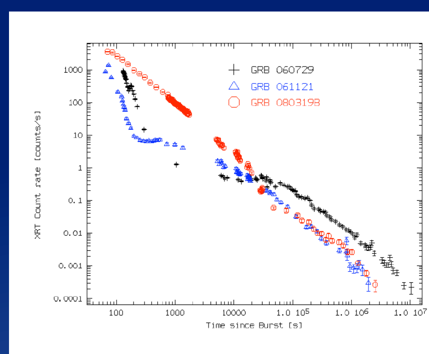

Figure 2: Comparison of the observed Swift XRT count rate light curves of GRB s060729, 061121, and 080319B.

IV: GRB Luminosity light curves:

Figure 3 displays the observed Swift XRT count rate light curves of GRBs 060729, 061121, and 080319B. The figure clearly shows why 060729 could be observed by Swift alone about 4 times longer than 061121 and 080319B.

Figure 4 displays the rest-frame isotropic luminosity of several bright Swift and pre-Swift bursts. The figures shows that up to about about a day after the burst the X-ray afterglow of 060729 was not exceptionally luminous. However, after a few days after the trigger 060729 becomes the most luminous X-ray afterglow seen so far. The total energy output in the 2-10 keV band of 7×10^{52} ergs makes GRB 060729 one of the most energetic X-ray afterglows ever detected. Only 061121 and 080319B appear to be more energetic. However, when correcting for beaming, with its 14 degree half opening angle, the beaming-corrected energy of 060729 is still 2×10^{51} ergs, while the energies of 061121 and 080319B is significantly lower due to their much smaller jet half opening angles.

VII: XMM-Newton Observation of GRB 060729

GRB 060729 was also observed by XMM-Newton which started the observation 45 ks after the trigger for a total of 61 ks (Grupe et al. 2007). The spectrum can be fitted by a single power law model with β_X=1.12 and a column density of 8.58 x 1 0^{211} cm^{-2}. We re-examined the XMM spectra again and found some residuals at about 4.67 keV. These residuals can be fitted with a Gaussian line at a rest frame energy of 7.05 keV. The line (if present at all) is weak with an equivalent width of 30 eV. Most likely this line can be associated with the H-like Fe XXVI Kα line (6.97 keV). Detections of emission lines in X-rays in GRB spectra are extremely rare and have been reported in the past only for a few cases (e.g. Reeves et al. 2003). X-ray lines, however, have never been detected in Swift XRT spectra. This is because emission lines are additive features. So when the continuum is bright at early phases of the burst, the lines are not detectable, because their equivalent widths are too small. At later phases however, the burst becomes dimmer and the count statistics is not sufficient for a line detection. One basically has to observe a burst at a sweet-spot so the line can be detected.

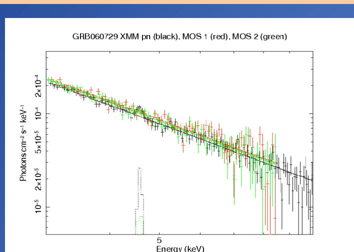

Figure 4: XMM-Newton spectra of GRB 060729 observed about a day after the trigger. The Spectrum may suggest the presence of a weak (30 eV equivalent width) Fe Kα 6.97 keV line.

VI Discussion: The exceptional light curve of GRB 060729:

What makes the X-ray afterglow of GRB 060729 so remarkable is the fact that it was still detected even almost two years after the burst. This exceptional late-time detectability is related to three things: a) with an initial 0.3 - 10.0 keV flux of almost 10^{-7} ergs s^{-1} cm^{-2} it was one of the brightest afterglows ever detected by Swift, b) its flat decay phase (Nousek et al. 2006, Zhang et al. 2006) extended out to about 60 ks after the burst, and c) the decay slope after that break is about 1.3. Bursts like GRBs 060614, 061121, or even 080319B (Mangano et al. 2007, Page et al. 2007, Racusin et al. 2008, respectively) were even brighter in X-rays at about 100 s after the burst than GRB 060729, but their plateau phases are significantly shorter than that of GRB 060729. They therefore faded more rapidly than GRB 060729 at late times.

VI: Discussion: Theoretical Explanation:

Analysis and modeling of the X-ray afterglow of GRB 060729 show that this burst happened in a tenuous wind. During the early plateau phase, the energy in the external shock increased by two orders of magnitude. At ~ 1.3 Ms after the burst. The decay slope steepened from 1.32 to 1.61 and the X-ray spectrum hardened, indicating a cooling break (the cooling frequency of synchrotron radiation crosses the X-ray band). The break at 1.3 years after the trigger tentatively indicated by the last two Chandra points coincides with a possible softening, suggesting that the break may be of spectral origin, though a hydrodynamic origin (jet break) is also possible. If due to a jet break, the implied half-opening angle 14 degrees. If due to a spectral break, such a spectral softening could be the result of a very steep power-law distribution of shock-accelerated electrons responsible for the synchrotron radiation. In this case, with no evidence for a jet break up to 642 days after the burst by Chandra, the jet half-opening angle must be 15 degrees and the jet energy 3×10^{52} ergs. Such a large jet energy implies that the central engine must be a fast-rotating massive black hole, not a magnetar. **Our Chandra observations presented here have shown again how important Chandra is for the late-time detections of GRB X-ray afterglows. XMM on the other hand is needed to obtain high-quality spectra of X-ray afterglows.**

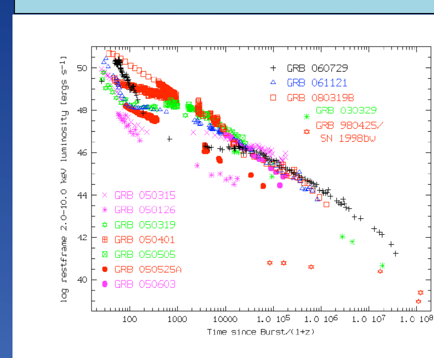

Figure 3: Combined rest-frame isotropic equivalent luminosity of several Swift and pre-Swift bursts taken from Nousek et al. (2006), including GRBs 060729, 061121, and 080319B

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