GRB 130831A: Rise and demise of a magnetar at z = 0.5

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Gamma-ray bursts (GRBs) are the brightest explosions in the universe, yet the properties of their energy sources are far from understood. Very important clues, however, can be deduced by studying the afterglows of these events. We present observations of GRB 130831A and its afterglow obtained with *Swift*, *Chandra*, and multiple ground-based observatories. This burst shows an uncommon drop in the X-ray light curve at about 100 ks after the trigger, with a decay slope of $\alpha \simeq 7$. The standard Forward Shock (FS) model offers no explanation for such a behaviour. Instead, a model in which a newly born magnetar outflow powers the early X-ray emission is found to be viable. After the drop, the X-ray afterglow resumes its decay with a slope typical of FS emission. The optical emission, on the other hand, displays no clear break across the X-ray drop and its decay is consistent with that of the late X-rays. Using both the X-ray and optical data, we show that the FS model can explain the emission after $\simeq 100$ ks. We model our data to infer the kinetic energy of the ejecta and thus estimate the efficiency of a magnetar "central engine" of a GRB. Furthermore, we break down the energy budget of this GRB into prompt emission, late internal dissipation, kinetic energy of the relativistic ejecta, and compare it with the energy of the accompanying supernova, SN 2013fu.

Keywords: Magnetar.

1. Introduction

Basic questions about the Physics of Gamma-ray Bursts (GRBs; for a review see Kumar & Zhang 2015) are still open, for example i) the nature the central engine (black hole, magnetar, something exotic) and how it works; ii) the process(es) that produce the high-energy radiation and how long this emission can last. The consensus is that the prompt γ-ray and X-ray emission is produced by dissipation process(es) (e.g. synchrotron, photosphere) within the ultrarelativistic ejecta. As a consequence, such an emission presents very rapid variations, and it can die off very quickly. Instead, the afterglow emission is attributed to electrons of the circumburst medium. When the ultra-relativistic ejecta plunge into this medium, they drive a forward shock (FS) into it. The FS energizes the medium electrons, which produce synchrotron emission. The afterglow emission can be modeled as power-laws in both time and frequency: $F_\nu \propto t^{-\alpha}\nu^{-\beta}$, where t is time from trigger and ν the frequency. The indices α and β are linked in mathematical relations predicted by the FS model itself. The FS emission fades away with time but it lasts indefinitely. Moreover, it will also show a much less rapid variability.

Most X-ray and optical afterglows follow the "canonical model" (Nousek et al. 2006; Oates et al. 2009). Canonical light-curves show a plateau, i.e. a phase of slow decline of the flux. This phase usually has a temporal index $\alpha \simeq 0.5$ and lasts a few ks. Following the plateau, there are phases of slightly steeper decays. The canonical light-curves can be explained by the FS model. However, in a small subsample of GRBs, the X-ray afterglow plateaux give way to very fast decays. These are steeper than 3 and can approach $\simeq 10$ in extreme cases. This behaviour cannot be interpreted as FS emission. The early X-ray emission is instead regarded as a form of "internal emission" (similar to prompt), produced inside the relativistic shells and able to vary rapidly. This interpretation has testable predictions. The FS emission cannot be "switched off". Once the high-energy internal emission turns off, the X-ray flux will drop until the FS emission becomes dominant. We therefore expect the steep drop to end and give way to a more slowly decay flux decay, due to the FS emission. Since the FS emission is already the dominating component in the optical, we expect the decay slopes of the optical and the late X-ray to be similar. In this work, we shall briefly discus the *Swift* GRB 130831A. This event presents a steep break in the X-ray light-curve, which successively resumes a slower decay. This GRB has well-sampled optical observations as well. For a more in-depth study of this GRB, we refer the reader to De Pasquale et al. (2016).

2. Observations and results of data analysis

The prompt emission of GRB 130831A was detected by *Swift* BAT and *Konus − Wind*; the fluence (20-10000 keV) is 7.6×10^{-6} erg cm^{-2} which, at redshift z=0.48 (Cucchiara et al. 2013), corresponds to an emitted energy of 1.1×10^{52} erg. *Swift* X-ray and UV/optical Telescopes (XRT, UVOT), SKYNET, RATIR, ISON, NOT, LT, and GTC observed GRB 130831A up to $\simeq 10^7$ s after the trigger, covering the emission of SN 2013fu associated with this burst (Cano et al. 2014). These UVOIR data span the range 160-1800 nm. In this proceedings, we focus on the afterglow emission. After a relatively shallow decay, the X-ray light-curve begins a much quicker decay at 10^5 s after the trigger. To catch the late X-ray behaviour, *Chandra* DDT observations (PI: De Pasquale) were carried out at +17 and +33 days, yielding 8 counts (5.4σ detection) and 1 count, respectively. Finally, tight upper limits on radio emission were provided by Laskar et al. (2013). Fig 1 shows the X-ray and UVOIR light-curves (LCs).

2.1. *X-ray and UVOIR light-curves and spectral energy distribution (SED)*

We fit the X-ray LC with a power-law + broken power-law + power-law model, which gives an acceptable $\chi^2/dof = 51/48$. The steep break occurs at $98.3^{+3.0}_{-3.3}$ ks, and the slope of the precedent slow decay is $\alpha_2 = 0.80^{+0.01}_{-0.02}$. The 0.3–10 keV luminosity at 10 ks in the cosmological rest frame is $\simeq 10^{46}$ erg s^{-1}. The latest power-law slope is artificially shallow, to avoid an initial excessive flux. Thus, we fit the LC from 100 ks only, first with a simple power-law, then with a power-law + power-law model, obtaining $\chi^2/dof = 17.8/5$ and $\chi^2/dof = 2.4/3$ respectively. The addition of a late, slowly decaying segment is not statistically required. However, the fit with a single power-law decay would lead to a very low flux ($\sim 10^{-17}$ cgs) at the first *Chandra* observation, which in turn would lead to a non-detection. Thus, we conclude that the fit with the sum of two power-laws is correct. In this model, the best-fit slopes are $\alpha_3 = 6.8^{+2.0}_{-1.5}$ (3σ lower limit: 3.9), $\alpha_4 = 1.11^{+0.22}_{-0.29}$.

The early optical afterglow presents a flare followed by a plateau. At $\simeq 5$ ks, a steeper decay starts. Optical light-curves before 15 ks cannot be fitted by power-law decay model, given the presence of "whiggles" that cause a very high χ^2, and were not used in the following. We fit the r', i' and R_C-band LCs from 15 to 230 ks, since we have measurements of the host galaxy flux in these filters, and we exclude the optical data between $\simeq 230$ ks and 6 Ms to avoid the contribution from SN 2013fu. The weighted average of the decay indices in these three bands is $\alpha_{opt} = 1.59 \pm 0.03$. The LCs in the other filters are consistent with a simple power-law decay with this slope. No break of the power-law optical decay is found at the time of the X-ray flux drop.

We build a spectral energy distribution (SED) at 173 ks (Fig. 2 bottom), after the end of the steep X-ray decay, and we fit it by a simple power-law with spectral index $\beta_{OX} = 1.03^{+0.05}_{-0.04}$. We extrapolate this fit model to 80 ks (Fig 2 top), i.e. prior to the steep X-ray break, by multiplying the normalization factor by $(173/80)^{1.59}$ and find that this extrapolation severely underestimates the X-ray flux. This outcome points to a different origin for the X-ray flux before the steep break.

3. Discussion

3.1. *Internal dissipation and forward shock components*

In the FS model, the steepest decay index is $\alpha \simeq p$, where p is the index of the power-law energy distribution of the radiating electrons. However, $p \simeq 7$ is neither predicted on theoretical grounds or found in modelling. Instead, after the 100 ks drop, the X-ray flux decay slope $\alpha_2 = 1.11^{+0.23}_{-0.29}$ is consistent with the optical one, $\alpha_{opt} = 1.59$, at 2σ level. In addition, the 173 SED, which encompasses the two bands, is adequately fitted by a single power-law. All of this points to a common origin for the late emission in the X-ray and optical bands. The FS model predicts that, in a constant density medium and below the synchrotron cooling frequency ν_c, the flux decay rate is $\alpha = 3/2\beta$; this is consistent with the best-fit values within 1σ. We find that other cases are excluded. Overall, we conclude that the early X-ray emission is produced by some dissipation mechanism(s) in the ejecta, i.e. it is internal emission, which stops at $\sim$ 100 ks causing a steep flux drop. The optical is basically FS emission at all times. Once the internal emission is over, the FS produces the X-ray late power-law decay, whose slope is consistent to that of the optical band. In the following, we shall briefly discuss the magnetar model for the central engine of GRB 130831A. If stellar progenitor of GRB 130831A collapsed into a magnetar, this object might powers a collimated wind (or "jets") via dipole spin-down. These jets may in turn produce the early X-ray emission of GRB 130831A (Zhang & Mészáros 2001). In the basic scenario, the magnetar magnetic field and the X-ray luminosity are mostly constant; when the magnetar collapses into a black hole (BH) or uses up all its rotational energy, the flux drops. This model explains other bursts with a flat internal emission plateau and successive very steep decay, such as GRB 070110 and 060607A. However, it fails with GRB 130831A because the flux before the drop is not constant. In a more evolved model, we consider that the magnetar wind modified the spin down law, so that the wind luminosity decreases with time. We find that for an initial period $P_0 \sim 1-2$ ms and $B \simeq 10^{15}$ G, the jet luminosity, decay slope and duration can explain the slow decline phase of GRB 130831A (Metzger et al. 2011). The expected collapse of the magnetar into a BH, for the P and B above, should take $\simeq$ 60 ks (cosmological frame), again quite similar to the case of GRB 130831A.

We considered other alternatives for the central engine of GRB 130831A: i) a black hole with fall-back accretion disk (Kumar et al. 2008); ii) a binary origin (Barkov & Komissarov 2010). However, we find that they are unlikely to explain the X-ray behaviour observed. A detailed discussion is given in De Pasquale et al. (2016).

3.2. *Derivation of the kinetic energy of the ejecta*

Knowing the FS flux, we can calculate the relativistic kinetic energy $E_{\rm K}$ of the ejecta. To this aim, we use the formalism of Zhang et al. (2007), and we derive $E_{\rm K} = 11.8 \times 10^{52}$ erg. To calculate this value, we assume that the fraction of the energy given to radiating electrons $\epsilon_{\rm e}$, to the the magnetic field $\epsilon_{\rm B}$ and the density of the environment n are 0.27, 2×10^{-3} and 10^{-3} respectively. We shall show that these estimates are robust (and, consequently, our evaluation of $E_{\rm K}$ is reliable). The values of $\epsilon_{\rm B}$ and n are low compared to other modeling of GRBs emission; such low parameters are however required to keep $\nu_{\rm c}$ above the X-ray band for the duration of observations (see previous subsection). At the same time, $n < 10^{-3}$ is not expected for long GRBs such as 130831A, because these events occur in the dense star forming regions of their host galaxies. If $\epsilon_{\rm B} < 10^{-3}$, one may expect to detect Inverse Compton emission in the afterglow, for which there is not evidence. The synchrotron peak frequency $\nu_{\rm m} \propto \epsilon_{\rm e}$. If $\epsilon_{\rm e} < 0.25$, the synchrotron peak would be close to the radio band, for which we have tight upper limits (see Sect. 2.1).

3.3. *Energy partition of GRB 130831A and the associated SN*

The non-relativistic ejecta of SN 2013fu, the supernova associated with GRB 130831A, have kinetic energy $E_{SN} = 1.9 \times 10^{52}$ erg (Cano et al. 2014). Integrating the 0.3-10 keV luminosity of 130831A from the end of the prompt emission up to the steep drop, we find an X-ray energy release of $E_X = 2.8 \times 10^{50}$ erg. The energy emitted in prompt γ-rays is $E_\gamma = 1.1 \times 10^{52}$ erg. Including all these contributions and the kinetic energy of the relativistic ejecta $E_{\rm K}$, the total energy budget of the GRB 130831A and SN 2013fu event is $E_{\rm tot} \simeq 1.5 \times 10^{53}$ erg. This value is much larger than the energy resorvoir a magnetar can tap, which is $\simeq 3 \times 10^{52}$ erg (magnetar limit). One may then argue that the magnetar model is then ruled out. However, E_γ, E_K and E_X estimated above are upper limits, that hold only if the GRB emission is isotropic. If the outflow is collimated, they decrease. The solid *Chandra* detection at 1.4×10^6 s enables us to set a minimum value on the opening angle of the outflow (Zhang et al. 2009) $\theta \gtrsim 0.12$ rad. This lower limit on the beaming angle in turn implies a lower limit of the energy budget, corrected for beaming, of $\simeq 2 \times 10^{52}$ erg. If $\theta > 0.44$ rad, then the budget is $> 3 \times 10^{52}$ erg. In De Pasquale et al. (2016), we show a detailed breakdown of the energetics into the three different cases above. Here, we summarize three important results: i) the energy emitted in X-ray of internal origin is always small, less than 0.2% of the total; ii) much more energy is released during the prompt γ-ray emission, 20-40 times more than in the previous channel; iii) at least 4.5% of the energy explosion is coupled with relativistic ejecta (but less than 40% if the central engine is a magnetar).

4. Conclusions

The X-ray afterglow of the *Swift* GRB 130831A has an initial shallow slope, that breaks to an unexpectedly steep decay with index $\alpha \simeq 7$ at 100 ks. The well-sampled optical afterglow shows no simultaneous break. The X-ray emission up to 100 ks cannot be produced by a typical FS and instead must be of "internal origin". A newly born magnetar with $P \simeq 1$ ms, $B \simeq 10^{15}$ G may explain this X-ray emission, if the fraction of magnetar magnetic field that produces the wind decays with time. The optical and the *late* X-ray emission (detected by *Chandra*) can be interpreted as FS emission, which enables us to derive the kinetic energy of the ejecta. We thus obtain the breakdown of the global energetics of GRB 130831A and its associated SN 2013fu and we show that, regardless of the unknown collimation of the explosion, at least 4.5% of the total energy is coupled with the relativistic ejecta, and less (probably much less) than 0.2% goes into X-ray emission of internal origin.

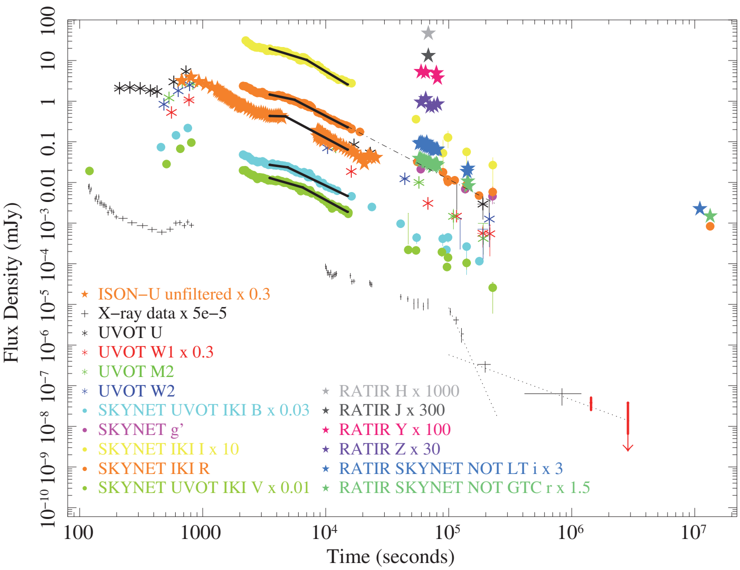

Fig. 1. GRB 130831A UVOIR and X-ray light-curves. XRT and *Chandra* data points are black and red respectively. Data between 230 ks and 6000 ks are not shown because they are contaminated by SN 2013fu, associated with this GRB. The reader is referred to Cano et al. (2014) for a complete study of the supernova. Data points at $\simeq 10^7$ s are due to the host galaxy. On the optical light-curves, we show the best fit model between 3.5 and 15 ks (see De Pasquale et al. 2016 for more details). On the *R* band and X-ray light-curves, we plot the best-fit power-law model (dashed and dotted lines) between 15 and 230 ks. More specifically, the X-ray band model shows two power-laws that contribute to the flux.

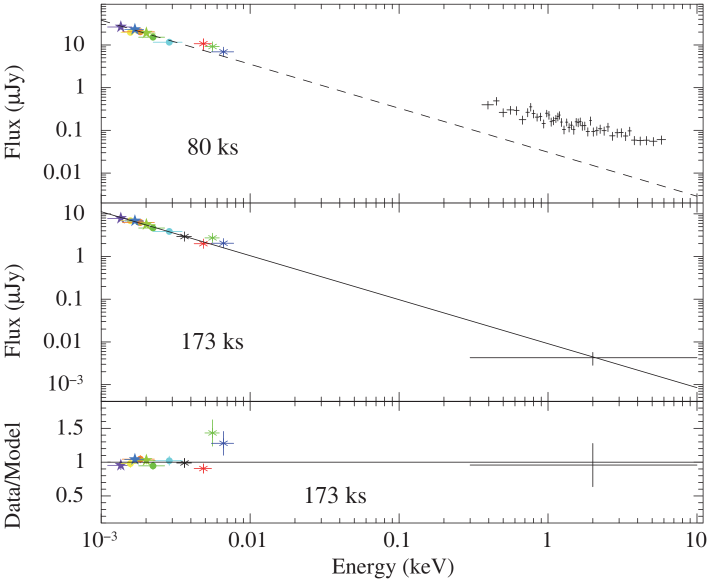

Fig. 2. Spectral Energy Distributions (SEDs) of GRB 130831A at 80 ks (top) and 173 ks (2 days) after the trigger (bottom). We plot on the 173 ks SED the best-fit model, a power-law of index $\beta_{OX} = 1.03$. We rescale this model by $(173/80)^{1.59}$, where 1.59 is the temporal decay slope, and draw it on the 80 ks SED (dashed line). Such an extrapolation predicts the optical, but clearly underestimates the X-ray emission, which must be due to a component absent at 173 ks.

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