The central engine of GRB 130831A and the energy breakdown of a relativistic explosion.

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ABSTRACT

Gamma-ray bursts (GRBs) are the most luminous explosions in the universe, yet the nature and physical properties of their energy sources are far from understood. Very important clues, however, can be inferred by studying the afterglows of these events. We present optical and X-ray observations of GRB 130831A obtained by Swift, Chandra, Skynet, RATIR, Maidanak, JSON, NOT, LT and GTC. This burst shows a steep drop in the X-ray light-curve at $\simeq 10^3$ s after the trigger, with a power-law decay index of $\alpha \simeq 6$. Such a rare behaviour cannot be explained by the standard forward shock (FS) model and indicates that the emission, up to the fast decay at $10^2$ s, must be of “internal origin”, produced by a dissipation process within an ultrarelativistic outflow. We propose that the source of such an outflow, which must produce the X-ray flux for $\simeq 1$ day in the cosmological rest frame, is a newly born magnetar or black hole. After the drop, the faint X-ray afterglow continues with a much shallower decay. The optical emission, on the other hand, shows no break across the X-ray steep decrease, and the late-time decays of both the X-ray and optical are consistent. Using both the X-ray and optical data, we show that the emission after $\simeq 10^3$ s can be explained well by the FS model. We model our data to derive the kinetic energy of the ejecta and thus measure the efficiency of the central engine of a GRB with emission of internal origin visible for a long time. Furthermore, we break down the energy budget of this GRB into the prompt emission, the late internal dissipation, the kinetic energy of the relativistic ejecta, and compare it with the energy of the associated supernova, SN 2013fu.

Key words: Gamma-Ray Burst, general – Gamma-Ray Burst, individual (GRB 130831A) - magnetar

1 INTRODUCTION

The study of gamma-ray bursts (GRBs) has received an exceptional boost thanks to the Swift mission (Gehrels et al. 2004), which has enabled rapid follow-up radio to X-ray observations of GRBs. However, despite a very large number of such fast follow-up observations performed by this spacecraft and by ground observatories, the characteristics of the “central engine” that produces the GRB are still unclear. The prevailing model (Woosley 1993; MacFadyen 1999, 2001; Thompson 2007) predicts the formation of a compact object, either a black hole or a magnetar, surrounded by an accretion disk. The compact object is the result of the core collapse of a very massive star or the final merger of two neutron stars (NS-NS) or NS - black hole binary. Under the correct conditions of angular momentum and magnetic field, such a system may launch a collimated, ultra-relativistic jet (e.g. via the Blanford-Znajek mechanism; Blanford & Znajek 1977). Within these jets, one or more “internal dissipation” processes take place (for a review, see Zhang 2011), converting part of the kinetic and/or magnetic energy into radiation. A burst of gamma-rays will then be visible if the observer is placed within the opening angle of the outflow.

Following the prompt gamma-ray emission, long-lived afterglow emission is detected in several energy bands (radio, optical, X-ray and probably high-energy gamma-rays). The consensus is that the afterglow radiation is emitted when ultra-relativistic ejecta interact with the circumburst medium, driving a forward shock (FS), which moves into the medium, and a reverse shock (RS), which propagates backwards through the ejecta. In particular, the emission due to the FS can in principle last indefinitely. A hallmark of RS and FS afterglow emission is that the flux density $F_\nu$ behaves as a power-law both in time and frequency, being described as $F_\nu \propto t^{-\alpha} \nu^{-\beta}$, where $t$ is the time from the GRB trigger (Kobayashi & Zhang 2007) and $\nu$ is the frequency. However, Swift observations have produced evidence of more complex phenomena during the afterglow phase, such as X-ray and optical flares (Falcone et al. 2006; Margutti et al. 2011; Swenson et al. 2013), that cannot be attributed to the FS due to their fast temporal variability. For a few kiloseconds (ks) after the trigger, the afterglow flux often decays in a slow fashion (phase II of the canonical XRT light-curve, also known as “plateau”; O’Brien et al. 2006, Nousek et al. 2006; Racusin et al. 2009; Margutti et al. 2010) which cannot be understood if the fireball follows an adiabatic evolution; a process of energy injection (Zhang et al. 2006) into the fireball is usually invoked to explain such a feature. These observations strongly suggest that the GRB central engine is still active, and produces energy and/or a relativistic outflow.

In a small subset of Swift GRB afterglows, observations have shown slow decline phases of the X-ray flux which terminate with an abrupt fall in the emission, with slopes $\alpha \gtrsim 3 - 4$, sometimes approaching $\alpha \simeq 9 - 10$ (Troja et al. 2007, Liang et al. 2007, Lyons et al. 2010, Rowlinson et al. 2013; Liu & Zhang 2014). Again, the FS model does not predict such behaviour. Instead, such steep decay can be expected when the central engine is a newly born magnetar, which emits a very high luminosity outflow due to the spin-down process (Usov 1992, Zhang & Meszaros 2001, Zhang & Meszaros 2002, Dall’Osso et al. 2011), which in turn produces emission we can directly observe in the X-ray. A very energetic outflow could also be produced by a newly formed stellar mass black hole surrounded by an accretion disk. The electromagnetic luminosity is expected to fall rapidly after the time-scale $T_{em}$ of the spin-down process, if the magnetar...
collapses into a black hole, or accretion onto the black hole stops.

The outflow produced by the spin-down process should generate emission via the synchrotron process. This kind of emission seems to be produced mostly in the X-ray band, while it is not usually detected at lower frequencies such as the optical (see Troja et al. 2007, Zhang et al. 2009, Rowlinson et al. 2013; however see Cano et al. 2014 for GRB130215A), perhaps because the optical band is at or below the synchrotron self-absorption frequency (Zhang 2009; see also Shen & Zhang 2009). At low frequencies, the dominant emission mechanism seems to be the standard FS, with its power-law decays and slow flux variations. FS emission, however, is still expected to be present even in the X-ray band, and it should emerge once the X-ray emission from the outflow produced by the magnetar or the black hole drops. So far, this has been seen clearly in the case of the long GRB 070110 (Troja et al. 2007). In this event, the X-ray light-curve showed a plateau lasting for 20 ks, after which the flux fell quickly with a slope of $\alpha \sim 9$, and then resumed a power-law decay with a much shallower slope of $\alpha \sim 1$. Such a late slope appears in most GRB afterglows and is likely produced by the FS.

In this paper, we present the well-sampled X-ray, UV/Optical and NIR observations of the afterglow of GRB 130831A, and show that its behaviour can be interpreted as a superposition of FS emission and “internal emission”, the latter of which suddenly ceases at $\approx 100$ ks. This article is organized as follows. In Sect. 2, we present the observations taken by different instruments and observing facilities, and show how the data were reduced and analyzed. We recall the results of the observations taken by other groups on GRB130831A as well. In Sect. 3, we show and fit the resulting light-curves and spectral energy distributions of this GRB. In Sect. 4, we model the afterglow of GRB 130831A in the context of FS and internal emission models, we discuss the possible origins of the observed emission and the properties of the object that produced the explosion. Finally, we present our conclusions in Sect. 5. Throughout the paper, errors are expressed at the $1\sigma$ confidence level (CL) unless stated otherwise, and we assume a $\Lambda$CDM Cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27$ and $\Omega_\Lambda = 0.73$ (Jarosik et al. 2011).

2 OBSERVATIONS AND ANALYSIS

2.1 X-ray data

2.1.1 Swift-BAT

The Swift Burst Alert Telescope (BAT; Barthelmy et al. 2005) triggered on GRB 130831A at $T_0 =$13:04:16.54 UT, 2013 August 31. The mass-weighted light-curve in the 15-350 keV energy range (see Fig. 1) shows a main pulse with a fast-rise-and-exponential-decay (FRED) shape. It starts at $T_0-2$ s and peaks at $T_0+3$ s. The major pulse structure ends at $T_0+12$ s. However, there is some extended emission that lasts until $T_0+41$ s, with two additional peaks at $T_0+20$ s and $T_0+32$ s ($15-350$ keV), the interval during which from 5% to 95% of the total emission is recorded, is $30.2 \pm 1.4$ s (error includes systematics).

The time-averaged spectrum between $T_0-1.9$ s to $T_0+41.4$ s can be fitted by a simple power-law model with a spectral index $\beta = 0.93 \pm 0.03$ ($\chi^2 = 56.7$ for 57 degrees of freedom, $dof$) in the energy band 15-150 keV. This model gives a fluence of $(6.49 \pm 0.09) \times 10^{-6}$ erg cm$^{-2}$ in the same energy range. The 1-s peak spectrum can also be fitted by a simple power-law model with $\beta = 0.70 \pm 0.05$ ($\chi^2/dof = 56.4/57$) in the energy band 15-150 keV, which gives a peak flux of $0.44 \pm 0.25 \times 10^{-7}$ erg cm$^{-2}$ s$^{-1}$ in the same band. The BAT analysis uses the event data from $T_0-240$ s to $T_0+963$ s.

2.1.2 Swift-XRT Observations

After the BAT trigger, the Swift satellite promptly slewed to point the narrow field instruments at the source. The X-ray Telescope (XRT; Burrows et al. 2005) began observations of GRB 130831A 125.8 s after the trigger in the 0.3–10 keV energy band. The XRT monitored the source until 2013 September 14, collecting 84.9 s of data in Window Timing (WT) mode (11.6 s were taken while the spacecraft was setting and the remaining 73.3 s pointing mode) and 59.7 ks in Photon Counting (PC) mode.

XRT data were processed using the HEASoft software packages\footnote{1 http://heasarc.nasa.gov/heasoft/} version 6.15 and version 20130313 of the XRT Calibration DataBase\footnote{2 www.swift.ac.uk/analysis/xrt/files/SWIFT-XRT-CALDB-09_v17.pdf} applying calibrations and standard filtering and screening criteria (for more details, see Evans et al. 2009). WT data were extracted in an interval centred on the source, 20 pixels on each side, and the background estimated using intervals between 40 and 60 pixels from the source. The PC data were initially affected by pile-up, and corrected by excluding the central core of 6 pixel radius. The remaining PC data were extracted using a circular region with 30-pixel radius, and when the count rate dropped below $10^{-2}$ counts s$^{-1}$, within a 10 pixel radius. During the extraction of the light-curve, a minimum signal-to-noise ratio (S/N) criterion was applied for the re-binning, such that we required a S/N greater than 3 for all data points, with the

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.pdf}
\caption{Swift BAT light-curve of the prompt emission from GRB 130831A.}
\end{figure}
exception of the last data point. The 90% confidence level intervals were estimated following the Kraft et al. (1991) technique for low count rate sources. The X-ray light-curve (Fig. 2), which shows the temporal evolution of the flux, was constructed once the spectral information was obtained (see Sect.s 3.3 and 3.4 Tables 1 and 2).

2.1.3 Chandra observations

After the very steep break, we requested and obtained two Chandra Director’s Discretionary Time (DDT) observations (PI: De Pasquale). Meanwhile, Swift continued observing for several more days detecting a dim X-ray afterglow, which suggested that the steep decay had broken to a gentler slope. The Chandra observations of GRB 130831A took place on 2013 September 17 (T$_0$ +16.6 days, or 1430 ks) and 2013 October 3 (T$_0$ +33.1 days, or 2860 ks) with an exposure of 15 ks each. The location of GRB 130831A was imaged on the ACIS S3 chip in both observations. The ACIS data were processed using ciao version 4.6 and version 4.5.9 of the Calibration Database (Fruscione et al. 2006) using standard tools. We filtered the events for grades 0, 2, 3, 4, and 6 and energy from 0.5–8 keV. We extracted the source counts within a 1.5′′ radius region centered on the best known position of the GRB, yielding 8 and 1 counts in the two observations, respectively. The first epoch yielded a detection with a significance of 5.4σ determined using the method described in Kraft et al. (1991). The second epoch was only ∼1σ above background, thus it should not be regarded as a real detection.

2.2 Optical observations

Here we describe how we collected, reduced and calibrated the ultraviolet, optical and infrared photometry of GRB 130831A. All magnitudes have been calibrated to the Vega system. The full set of photometric measurements is provided in an on-line table; a sample is shown in Table 3.

2.2.1 UVOT

Swift/UVOT (Roming et al. 2005) began observing the field of GRB 130831A 114 s after the trigger (Hagen et al., GCN Circular 15139) and started settled observations 191 s after the trigger, with a finding chart exposure in the ultraviolet, optical and infrared photometry of the GRB field, yielding 8 and 1 counts in the two observations, respectively. The first epoch yielded a detection with a significance of 5.4σ determined using the method described in Kraft et al. (1991). The second epoch was only ∼1σ above background, thus it should not be regarded as a real detection.

photometric zero points (Breeveld et al., 2011). The analysis pipeline used version 20130118 of the UVOT Calibration Database.

2.2.2 RATIR

The Reionization And Transients Infra-Red camera (RATIR; Butler et al. 2012) observed GRB 130831A over a period of seven hours, beginning 15.8 hours after the Swift trigger, with follow-up observations on six nights over the next month. RATIR is mounted on the 1.5-meter Harold L. Johnson telescope of the Observatorio Astronomico Nacional on Sierra San Pedro Martir in Baja California (Mexico). This facility, which became fully operational in December 2012, conducts autonomous observations (Watson et al. 2012; Klein et al. 2012) of its targets in the six photometric bands r, i, z, Y, J and H simultaneously. RATIR captured 80 s exposure frames in r and 67 s exposure frames in z′YJH due to additional overhead. We applied their standard image reduction pipeline with twilight flat division and bias subtraction routines written in Python and using astrometry.net (Lang et al. 2010) for image alignment and SWARP (Bertin 2010) for image co-addition. Aperture photometry was calculated using SEXTRACTOR (Bertin & Arnouts 1996).

2.2.3 NOT and LT

The 2.5 m Nordic Optical Telescope (NOT) and the 2 m Liverpool Telescope (LT), located at Roque de los Muchachos Observatory, La Palma in the Canary Islands (Spain), obtained three epochs of photometry presented in this paper: 2013 September (r and i), 2013 September 3 (i), 2014 January 5 (i). Several additional epochs of griz NOT and LT photometry were obtained as part of a campaign to observe SN 2013fu, which are presented in Cano et al. (2014). Image reduction of the r and i photometric data was performed using standard techniques in IRAF, bias combine, bias-subtract, flat-field co-add, flat-field normalise, flat-field divide, align and co-add (Tody 1986, 1993). The optical data were calibrated using Sloan Digital Sky Survey (SDSS; Ahn et al. 2012) stars in the GRB field, and converted into Vega magnitudes.

2.2.4 Skynet

Skynet (Reichart et al. 2005) obtained images of the field of GRB 130831A on 2013 August 31 with four 17′′ telescopes of the Panchromatic Robotic Optical Monitoring and Polarimetry Telescope (PROMPT) array at Siding Spring Observatory, New South Wales, Australia. Further observations were taken on September 1, this time observing also with the four 16′′ telescopes of the PROMPT array at the Cerro Tololo Inter-American Observatory, Chile and the 41′′ telescope at Yerkes Observatory, Wisconsin, USA. Beginning at 13:39 UT (T-T$_0$ = 35.5 min), exposures ranging from

3 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
60 to 180 s were obtained in the BVRI (PROMPT), and $g'r'i'$ (Yerkes) bands. Bias subtraction and flat-fielding were performed by SkyNet’s automated pipeline. Post-processing occurred in SkyNet’s guided analysis pipeline, using both custom algorithms and ones based on IRAF. Differential aperture photometry was performed on single and stacked images, with effective exposure times from 60 s to 2.7 h. Photometry was calibrated against the catalogued BV $g'r'i'$ magnitudes of six APAS-DR7 stars in the field (Henden & Munari 2014). The calibrations for RI magnitudes were derived using transformations obtained from prior observations of Landolt stars (A. Henden, private communication).

2.2.5 IKI Network for Transients

The field of GRB 130831A was observed by several facilities of the follow-up network organized by the Space Research Institute (IKI) of Moscow, where observations of GRBs are planned and data reduction is carried out. We detail the observations of GRB 130831A of the individual observatories below.

The International Scientific Optical-Observation Network (ISON; Molotov et al. 2008, Pozanenko et al. 2013c) started observing on 2013 August 31 at 13:14:32 UT, i.e. ~10 minutes after the trigger, with the 0.65-m telescope SANTEL-650 of ION-Usuriiyk observatory. Thirty unfiltered images, each with 120 seconds exposure, were taken. The 50-cm telescope VT-50 of ISON-Usuriiyk observatory started to observe at 13:26:10 UT, 22 min after the trigger, taking 384 unfiltered images with exposures of 30 seconds in two epochs with a gap of about 1.8 h ($\text{Volnova et al.} [2013]a$). Starting at 19:12:30 UT during the first day, the 40-cm SANkovich-TELescope (SANTEL) - 400AN of ISON-Kislovodsk observatory took 34 frames with exposures between 60 and 120 s ($\text{Volnova et al.} [2013]d$).

The Astronomicheskii Zerkalnyi Telescope - 8 (AZT-8) 0.7-m telescope of Gissar (Tajikistan) observatory took 57 frames in $R$ band with 60 s exposure time each starting at 17:47:54 UT.

The AZT-8 0.7-m telescope of the Chuguev Observational Station (Institute of Astronomy, Kharkiv National University) observed the afterglow in $R$ filter starting on September 1 at 19:37:49 UT ($\text{Volnova et al.} [2013]c$).

The optical afterglow was also observed by the 1.5-m telescope AZT-22 of Maidanak observatory (Uzbekistan) on 2013 September 1, 2, 4, 5, 7–11, 15, 16, 22, 27, and 29. Every observational night, frames were taken in the $R$ filter with an exposure time of 600 s each. On September 1 we also took several frames in the $B$, $V$ and $I$ bands with the same exposure, and on September 2 we obtained additional observations in the $B$ filter.

Most of the data obtained by Maidanak are presented in Cano et al. (2014) and used to study SN2013fu; in this article we use the early data which were not contaminated by the SN emission (see Sect. 3.3).

Observations were also taken with the 1.6-m telescope AZT-33IK of Sayan observatory (Mondy, Russia) on September 3, 4, and October 10, 11 and 14, taking several frames in the $R$-band with an exposure of 60 seconds each. The optical afterglow was also imaged with the 2.6-m Shajn telescope of the Crimean Astrophysical Observatory on September 5, taking several frames in the $R$ band with an exposure of 120 seconds each.

All data obtained by the facilities indicated above were processed with the same initial reduction including dark frame subtraction and flat-fielding, and using the IRAF packages APHOT and DAOPHOT. For the photometric calibrations we used four stars from the SDSS, indicated in Table 4. The $ugriz$ magnitudes of the reference stars were transformed to the BVRI photometric system using the transformation equations attributed to Robert Lupton in the SDSS online documentation.$^5$

2.2.6 GTC

The 10.4m Gran Telescopio Canarias (GTC; Canary Island, Spain), equipped with the Optical System for Imaging and Low-Intermediate Resolution Imaging Spectroscopy (OSIRIS) instrument (Cepa et al. 2000), performed deep $r'$-band imaging of the GRB field 13330 ks after the trigger (2014 February 1), in order to obtain photometry for the host galaxy. Nine 60 s images were acquired in $2 \times 2$ binning, providing a pixel scale of 0.25 arcsec pixel$^{-1}$. The images were dark-subtracted and flat-fielded using custom IRAF routines. Aperture photometry was performed using DAOPHOT tasks as implemented in IRAF. Photometric calibration was based on SDSS standard stars present in the OSIRIS un-vignetted field of view (7.8 arcmin $\times$ 7.8 arcmin).

2.2.7 Results from other facilities

In this subsection, we describe results obtained by other teams, not involved in our work. Nonetheless, we will use their results in the next sections.

Konus-Wind Observations. GRB 130831A was observed by Konus-Wind onboard the WIND spacecraft. Golenetskii et al. (2013) found that this burst had a duration of 35 seconds; it was detected up to ~6 MeV. In addition, the spectrum is relatively soft; it can be fitted between 20 keV and 15 MeV with the Band model (Band et al. 1993), yielding a low-energy spectral index $\beta_1 = -0.61 \pm 0.06$, a high-energy spectral index $\beta_2 = -2.3 \pm 0.3$ and peak energy $E_p = 55 \pm 4$keV. The fluence between 20 keV-10 MeV is $(7.6 \pm 0.4) \times 10^{-6}$ erg cm$^{-2}$ (90% CL). We use the results of the Konus-Wind data analysis presented in Golenetskii et al. (2013), which spans a much wider spectral range than the BAT data, to derive the energetics of this burst. Thus, they are better suited to assess the energy emitted by the burst without using extrapolation. Using a cosmological k-correction (Bloom et al. 2001) and the redshift $z = 0.479$ of this burst (Cucchiara et al. 2013), we derive 1–10000 keV rest-frame energetics of $E_{\gamma} = 1.06 \times 10^{52}$ erg. This burst follows the Amati relation (Amati et al. 2006; Amati et al. 2009; see also Cano et al. 2014, their Fig. 12).

Radio. GRB 130831A field was also observed by the Jansky Very Large Array (EVLA) and Combined Array for

$^4$ http://www.aavso.org/apass

$^5$ www.sdss.org/DR7/algorithms/sdssUBVRITransform.html/Lupton2005
Research in Millimeter Astronomy (CARMA), Zauderer et al. 2013. According to the analysis reported by Laskar et al. (2013), no significant radio emission was detected: the $3\sigma$ upper limits are 38 $\mu$Jy and 71 $\mu$Jy at 5.8 and 21.8 GHz, respectively, at 0.64 days after the trigger. Similarly, CARMA obtained a $3\sigma$ upper limit of 780 $\mu$Jy 0.76 days after the trigger (Zauderer et al. 2013).

2.2.8 Building the UVOIR light-curves

In the subsections above we summarized the observations of the optical instruments and how the data produced by each one were reduced. We shall now describe how we combined these different datasets into a homogeneous set of flux light-curves. Magnitudes were translated to fluxes using the zero-magnitude flux densities listed in Table 5. Our overall approach has been that when data have been obtained from multiple observatories in the same (or almost the same) band, we scale all the data to match the dataset which provided the largest number of measurements in that band. The largest set of measurements in $r'$ and $i'$ come from RATIR. We normalized the NOT and LT $r'$ and $i'$ data points to RATIR using the calibration stars common to the two datasets (see Table 4). The comparison of the calibration stars led us to scale the flux from the NOT $r'$ band data point by a factor of 0.99 and, based on the scatter between the NOT and RATIR measurements of the calibration stars, we added a systematic error of 2 per cent to the errors on the NOT fluxes. The NOT and LT $i'$ band flux was scaled by a factor of 1.01 and a systematic error of 1 per cent was added. The Skynet Yerkes $r'$ and $i'$ data were matched to RATIR using the common reference stars listed in Table 4.

The $r'$ and $i'$ fluxes from Skynet were scaled by factors of 0.94 and 0.91 respectively and systematics of 3 per cent ($r'$) and 2 per cent ($i'$) were added to the uncertainties on the Skynet fluxes.

The largest set of measurements in $B$, $V$, $R$ and $I$ came from the Skynet PROMPT observations. To incorporate the UVOT $v$ and $b$ data into the $V$ and $B$ light-curves, we first transformed the UVOT magnitudes of the GRB afterglow and the Skynet calibration stars into Johnson magnitudes using the appropriate colour transformations in Poole et al. (2008), before translating to flux densities. The UVOT and Skynet photometry of the Skynet calibration stars (see Table 3) were then compared to determine the appropriate scaling factors and systematic errors for UVOT. The UVOT $V$ and $B$ fluxes were scaled by factors of 1.13 and 1.07 respectively, and systematic errors of 9 per cent and 6 per cent were added respectively to their flux uncertainties.

Based on the photometry of the calibration stars in common between the Maidanak and Skynet PROMPT observations (see Table 3) in the $B$, $V$ and $I$ bands, we scaled the Maidanak $B$, $V$ and $I$ fluxes by factors of 1.01, 1.01 and 1.06 respectively and added systematic errors of 10, 5 and 7 per cent. For the $R$-band data from the IKI Gissar, Maidanak, Chuguev and Sayan observatories, the calibration stars in common with Skynet suggested a scaling factor of 1.01 for these data and a 6 per cent systematic error, but the resulting GRB $R$-band light-curve from these observatories appeared to be systematically lower than that obtained from Skynet. A power-law fit to the $R$-band flux light-curve derived from IKI observations between 15 and 100 ks, performed simultaneously with a power law fit to the Skynet $R$ band data in the same time interval, and with the power-law slope tied between the two datasets, gives a best-fitting normalisation for the IKI data which is 0.79 times that of the Skynet data. Therefore the IKI $R$ fluxes were scaled by this factor before combining them with the Skynet PROMPT data.

3 RESULTS

3.1 Spectral analysis of X-ray data

The XRT spectral data (0.3–10 keV) were extracted in nine different temporal segments, with boundaries selected according to the different observing modes and breaks in the light-curve (see Table 2). Ancillary response files and exposure maps were created using the HEASOFT software for each segment, as well as appropriate response matrices from calibration database. All the spectra were fitted using XSPEC v12.8.1 (Arnaud et al. 1996) with an absorbed power-law model. Some indication of spectral evolution was found, with the spectral index trending from soft, during the first orbit, to hard from the second orbit onwards. Details results are shown in Table II.

The X-ray spectrum between 9 ks and 132 ks, i.e., the end of the unusual late steep decay, can be modeled with power-law with Galactic absorption and intrinsic absorption at the redshift of the burst, $z = 0.479$. The Galactic absorption has been fixed to $N_H = 4.8 \times 10^{20}$ cm$^{-2}$ (Kalberla et al. 2005). The best fit parameters are: spectral index $\beta_N = 0.77 \pm 0.07$, intrinsic $N_H (z = 0.479) = 6.8^{+3.3}_{-3.1} \times 10^{20}$ cm$^{-2}$ which is consistent with 0 at 2.1$\sigma$ CL.

To infer the late X-ray flux from Chandra measurements, we applied the following procedure. First, we corrected for the portion of the PSF excluded from the 1.5 arcsec radius aperture. Using the PC mode XRT spectral fit parameters (spectral index $\beta_N = 0.77$, intrinsic $N_H = 6.8 \times 10^{20}$ cm$^{-2}$), we derived 0.3–10 keV fluxes for the two epochs of $7.4 \pm 2.5 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ and $7.8^{+1.5}_{-0.9} \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$ respectively. To derive the latter, we used the estimates on confidence limits for small numbers of events in astrophysical data (Gehrels 1986). The 3$\sigma$ upper limit corresponding to the second Chandra observation is $7.4 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$. Both XRT and Chandra fluxes are corrected for absorption. The results of the spectral analysis were used to compute the rate to flux conversion factors employed to build the X-ray light-curve.

3.2 The X-ray light-curve of GRB 130831A.

The X-ray light-curve is shown in Fig. 2. After an initial fast decay with slope $\alpha \simeq 6$ ending at $T_0 + 200$ s, there is an X-ray flare starting at about 500 s after the trigger and lasting at least up to the end of the first orbit at 900 s. The highest flux recorded was about $10^{-9}$ erg cm$^{-2}$ s$^{-1}$ at the beginning of XRT observations. When GRB observations resumed, $\simeq 9$ ks after the trigger, the decay slope was slower than that at the very beginning of observations. This decay terminated at about $\simeq 100$ ks after the trigger, when the flux showed a surprisingly steep drop.
We fit the X-ray data (see Table 2) from the very beginning with the sum of an early power-law, a broken power-law decay, a Gaussian flare superimposed on the second segment, and another, final power-law. The first power-law basically represents the tail of the prompt emission, probably due to the curvature effect, which then gives way to a shallower decay usually attributed to a different emission mechanism (Zhang et al. 2006). When this second process ends as well, the flux falls quickly again. The late power-law may represent emission powered by the FS mechanism, which can emerge once the emission from the previous process is over. The fit is acceptable, yielding $\chi^2/dof = 50.7/48$. We find a decay slope $\alpha_{X,2} = 0.8$ between 0.3 and 98 ks. Such a slope is intermediate between the typical shallow decay phase $\sim 0.3$ and the “normal” decay phase $\sim 1.2$ seen in a wide sample of GRB afterglows (see Evans et al. 2009). We can still find a value of 0.8, however, in the distributions of decay indices of both phases. After the break at 98 ks, the best fitting temporal slope is $\alpha_{X,3} = 5.9^{+1.0}_{-1.4}$, much faster than is usually observed in late X-ray afterglows, even in the case of a jet break, when $\alpha \sim 2 - 3$ (Sari et al. 1999; Racusin et al. 2009). This steep drop suggests that the X-ray afterglow might have been, until then, produced by some internal dissipation mechanism rather than the typical FS emission. We can still find a value of 0.8, however, in the distributions of decay indices of both phases. After the break at 98 ks, the best fitting temporal slope is $\alpha_{X,3} = 5.9^{+1.0}_{-1.4}$, much faster than is usually observed in late X-ray afterglows, even in the case of a jet break, when $\alpha \sim 2 - 3$ (Sari et al. 1999; Racusin et al. 2009). This steep drop suggests that the X-ray afterglow might have been, until then, produced by some internal dissipation mechanism rather than the typical FS emission. With this fit model, the late power-law component has a decay slope $\alpha_{X,3} = 0.90^{+0.11}_{-0.05}$. We note that this decay slope of the X-ray flux after $\sim 200$ ks is steeper than the decay slope during the shallow decay phase. If the late X-ray flux were FS emission, it might have begun hundreds or even thousands of seconds after the trigger. However, the fitted model above does not include this possibility, and it may yield late power-law component slopes flatter than the real ones in order not to over-predict the flux at very early epochs. To better investigate the late emission, we use a different time interval. If we fit the X-ray data points from 100 ks onwards with a simple power-law model, we obtain a poor fit, $\chi^2/dof = 17.8/5$. The best fit decay slope is $\alpha_{X,3} = 4.6^{+0.5}_{-0.4}$. However, if we fit the same data points with a power-law + power-law model, we obtain a much better fit, with $\chi^2/dof = 2.4/3$. This model yields a decay slope for the
first power-law of $\alpha_{X,3} = 6.8^{+2.0}_{-1.5}$ with a 3$\sigma$ lower limit (with $\Delta \chi^2 = 9$) of $\alpha_{X,3} = 3.9$. Such a value, though, is still too steep for the PS model, see above. The best fit value for the late power-law component is $\alpha_{X,4} = 1.11^{+0.29}_{-0.22}$ while its flux at 2 days (173 ks) after the trigger is $6.08^{+2.31}_{-2.77} \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$.

An analysis with the F-test suggests that the two-power-law model is not necessary, because the probability of an improvement by chance is 4%, which is not negligible. However, if we adopted the simple power-law model with the steep decay slope $\alpha = 4.6$ after 100 ks, then the flux at the time of the first Chandra observation would be $\simeq 5 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$. Such extremely low flux corresponds to less than 0.1 counts with a ACIS-S 15 ks observation; thus our first Chandra observation would most likely yield 0 counts. We can place a 99.5% CL upper limit of 5.3 counts, according to Gehrels (1986). This prediction, however, is in disagreement with the fact that the observation actually produced 8 counts. According to Kraft et al. (1991), these 8 counts represent a 5$\sigma$ detection. We therefore conclude that the X-ray afterglow decay has become much shallower at late epochs, and we will adopt the results of the fit of the two-power-law model after 100 ks.

### 3.3 Optical light-curve of GRB 130831A

The combined optical light-curves in Fig. 2 show an initial short plateau, which lasts until $\sim 500$ s, followed by a steep rise and a peak at $\simeq 800$ s. This optical flare is basically concurrent with the X-ray flare. Following the flare, there is another plateau that in turn gives way to a steeper decay at $\simeq 5000$ s. In this phase, fitting the optical light-curves with simple models such as a broken power-law does not provide a statistically acceptable fit. For example, the best fit of $B$ band data between 3.5 and 15 ks with a broken power-law yields an early decay slope of $\alpha_1 = 0.42 \pm 0.08$, break time $t_{\text{break}} = 4.90 \pm 0.08$ ks, and post-break slope $\alpha_2 = 1.45 \pm 0.03$ with $\chi^2/dof = 81.49/49$. Fitting the other light-curves in this interval yields similar results. We nonetheless plot the best-fit curves in Fig. 2, as an indication for the behaviour of the optical afterglow, and report the results of fitting the light-curves in the interval between 3.5 and 15 ks in Table 4. Such high $\chi^2$ are due to some “wiggles” of the densely sampled light-curves in this phase, which has been seen in other GRBs (e.g. Swenson et al. 2013; Matheson et al. 2003). The post-plateau decay is moderately steep and does not seem to change its slope at the epoch of the X-ray drop. However, about $\sim 5$ days after the trigger, the optical emission starts to rise due to the time coming from SN 2013fu, the supernova associated with GRB 130831A (Klose et al. 2013; Cano et al. 2014). Given the complication of considering the SN flux, we have excluded all data points that had a $> 10\%$ contribution from the SN, basically those after $\sim 230$ ks and before $\sim 6000$ ks. The SN contribution at these epochs have been estimated using the SN 1998bw template program presented in Cano (2013).

In addition, we have observations at $T - T_0 > 100$ days in $r'$ and $i'$ filters, taken with Gran Telescopio Canarias (GTC) and LT (see Sect. 2.2.3 and 2.2.6). These late time data do not suffer significant contamination from the SN and the afterglow, which have faded away. They correspond to the magnitude of the host galaxy, and have been used to determine the optical afterglow behaviour (see below). Vega magnitudes of the host galaxy are $r' = 23.75 \pm 0.11$, $i' = 23.83 \pm 0.10$. Assuming the conversions from Jordi et al. 2006 (their Table 1), we find a Vega magnitude $R = 23.84 \pm 0.15$. Spectral observation taken at the Gemini North Observatory revealed that GRB 130831A occurred at redshift of $z = 0.479$ (Cucchiara et al. 2013). For such a redshift, the magnitude of the host corresponds to a luminosity $L \simeq 0.04L_\odot$ in the B band (Hjorth et al. 2012).

We know the host contribution in $R$, $r'$ and $i'$ only, from our late-time GTC and LT images. We fitted the light-curves in these filters with the same model, namely a power-law $F \propto t^{-\alpha}$ plus constant, from 15 ks up to 100 days after the trigger. We ignored the data before 15 ks because they would lead to a very bad fit, as we previously noted (see above). The best fit decay slopes and $\chi^2$ are $\alpha_R = 1.60 \pm 0.03$, $\chi^2/dof = 9.4/10$; $\alpha_i = 1.49 \pm 0.06$, $\chi^2/dof = 30.7/14$; and $\alpha_r = 1.64 \pm 0.07$, $\chi^2/dof = 29.2/15$ (see Table 4). These fits are statistically acceptable and consistent within 2$\sigma$. We find that the weighted mean is $\alpha_{\text{opt}} = 1.59 \pm 0.03$. The decay slopes of the flux in other filters are consistent with this value within 3$\sigma$ as well. We note that Cano et al. (2014), in their analysis of the afterglow light-curves, find that the optical decay slope is $\alpha = 1.63 \pm 0.02$, consistent with our analysis. We remark upon the fact that we can fit the optical light-curves with an uninterrupted power-law, even across the X-ray break. This feature strongly suggests that optical and X-ray emission (at least part of it) have different origins.

### 3.4 Spectral Energy Distributions

To test the hypothesis that the late emission is entirely due to FS, we built a spectral energy distribution (SED) with the available UVOIR + X-ray data at 2 days after the trigger (173 ks).

First, we calculated the count rates at 2 days. We used the data between 15 ks and 100 ks, since no colour evolution was detected in the UV to the near IR, and the count rate in all light-curves could be fitted as a power-law with a common decay index $\alpha = 1.59$ between these two epochs. The UVOT data were translated to XSPEC-compatible files using the standard ftool uvot2pha. Then, we adjusted the count rates of these files to the values determined by fitting the light-curves. Each of the ground based optical and near IR photometric data points were imported into XSPEC using bespoke software, as follows. Each photometric data point was recorded as a single-channel spectral file containing a count rate and count-rate uncertainty, with a corresponding response file. To produce the response files, the responsivity of the filter/telescope combination as a function of wavelength was converted to a normalised effective area as a function of energy. As for the X-ray, we first determined the light-curve count rate at 2 days, $f_{\text{CR}}$. We then determined a new exposure time $t_{\text{newexp}}$ for which $\text{spec}_{\text{CR}}t_{\text{newexp}} = f_{\text{CR}}$, where $\text{spec}_{\text{CR}}$ is the count rate of the source after background subtraction. Then we imported the source and background XRT spectral files with the changed exposure times into XSPEC. To build the SED, we used the XRT data after the steep decay slope, but did not use the Chandra data because XRT and Chandra fluxes would have to be renormalized to the same value and XRT has more counts.
We fitted the optical and X-ray data with XSPEC (Arnaud et al. 1996). We adopted a simple power-law model with two absorbers and two 
\textit{z} dust extinction components, one at \( z = 0 \) and another one at \( z = 0.479 \), i.e. the redshift of the burst (Cucchiara et al. 2013). The values of the absorbers are the same given in the X-ray data analysis section 3.1. The Galactic reddening was fixed at \( E(B - V) = 0.04 \) mag according to the map of Schlegel et al. (1998). As for the extinction at the redshift of the burst, we tried the Milky Way, Large and Small Magellanic Clouds (MW, LMC and SMC) extinction laws as in Pei (1992). We found that all of them yield acceptable and similar fitting results. However, the MW extinction law provides the best fit, so we have adopted the results of the fit with this law. The SED of GRB 130831A at 2 days is shown in Fig. 3. The best fit parameters are an index \( \beta_{\text{OX}} = 1.03^{+0.05}_{-0.04} \) and a small or absent amount of extragalactic reddening \( E(B - V) = 0.02 \pm 0.01 \) mag (Cano et al. 2014 find a negligible rest-frame extinction as well); this fit yields \( \chi^2/dof = 12.7/9 \). A broken power-law model does not significantly improve the fit, since it yields \( \chi^2 = 12.4/8 \) and the break energy is unconstrained. Moreover, fits with LMC and SMC extinction law result in a break energy above the X-ray band. All in all, we believe that a simple power-law model is adequate to describe the SED at this late epoch. Results of the fit of the 173 ks SED are shown in Table 2. There are only \( \simeq 15 \) counts collected by XRT after the fast drop, and to build the SED and obtain the quoted results we constructed a single X-ray data bin spanning from 0.3 to 10 keV. We were concerned that the use of such a wide bin might be not the optimum in the SED fitting process. Therefore, we repeated the fit using standard \( \chi^2 \) statistics with optical data and Cash statistics for the X-ray data, where the bins were constituted of single counts. We obtained very similar results. The fit with a simple power-law model yielded \( \beta_{\text{OX}} = 1.03^{+0.05}_{-0.04} \), \( E(B - V) = (1.9 \pm 1.3) \times 10^{-2} \) mag with total statistics of 23.4 and 26 dof. A fit with a broken power-law model was marginally better, yielding statistics of 22.2 with 25 dof, but the F-test indicates that the probability of an improvement by chance was high, with a probability of 25%.

We also show that the same model does not apply to earlier data. Following the same procedure outlined above, we built a SED with UV/OIR and X-ray data at 80 ks (Fig. 4), before the steep X-ray drop. Then, we changed the normalization of the 173 ks power-law fit, following a decay slope of \( \alpha = 1.59 \). We then plotted such a re-normalized power-law model with \( \beta_{\text{OX}} = 1.03 \) onto the 80 ks SED. We see that, while the optical emission is easily matched, the observed X-ray flux lies well above the model prediction. This finding is confirmed by the fact that if we fit the 80 ks SED with the same power-law model used for the 173 ks SED, we obtain a best-fit spectral slope \( \beta_{\text{OX}} = 0.76 \pm 0.01 \). This is harder than the slope found at 2 days and inconsistent with it. This result confirms that the spectrum at 80 ks across the X-ray and optical bands is not consistent with the spectrum at 173 ks and lends credence to the idea that there is an additional component in the X-ray band at early epochs.

4 DISCUSSION

4.1 Modeling of GRB 130831A and the Efficiency of its “Central Engine”.

We found that the X-ray light-curve, after the steep drop at 100 ks, resumes a slower decay slope of \( \alpha_{\text{OX}} = 1.11^{+0.22}_{-0.07} \), such a decay slope is statistically consistent with the optical decay slope from 15 ks onwards, \( \alpha_{\text{OPT}} = 1.59 \pm 0.03 \), at 2.1\( \sigma \) CL. The SED at 2 days (173 ks) after the trigger is adequately fit with a simple power-law model, in which the X-ray and the optical band lie on the same spectral segment. Values of the spectral and temporal indices seem to be typical of GRB late afterglow emission, and are easily explainable by the FS model.

The FS model predicts basic relations between spectral and decay indices (for a review, see Zhang et al. 2006), which depend on the type of expansion (spherical or jet) and the spectral regime, i.e. where the observing bands are located relative to the synchrotron peak frequency and cooling frequency, \( \nu_m \) and \( \nu_c \), respectively, and the density profile of the circumburst medium. We can use these closure relations to find the conditions that apply to the case at hand. We adopted \( \alpha_{\text{OPT}} \) as decay slope, since it is better constrained than the late X-ray decay index, and \( \beta_{\text{OX}} \) as the spectral slope. If the observing bands (both the X-ray and optical) were below \( \nu_c \) and the medium had a constant density profile, we would have \( \alpha - \frac{2}{3} \beta = 0 \); this is in agreement with observations at 1\( \sigma \). If the medium had a stellar wind profile, with density \( \rho \) decreasing with radius \( r \) as \( \rho \propto r^{-2} \), then \( \alpha - \frac{2}{3} \beta - 1/2 = 0 \); this is ruled out at \( \simeq 10 \sigma \). If the observing frequency is above the cooling frequency, for both the constant medium and stellar wind profile cases the relation \( \alpha - \frac{2}{3} \beta + 1/2 = 0 \) should be satisfied; but this is rejected at \( \simeq 10 \sigma \). Finally, if the outflow is collimated and has decelerated enough so that the observer detects emission from the edges, the decay should become steeper (“jet break”). After the jet break, the relations to satisfy are \( \alpha - 2 \beta - 1 = 0 \) and \( \alpha - 2 \beta = 0 \) if the observing frequency is below or above \( \nu_c \). These relations are ruled out at 16\( \sigma \) and 5\( \sigma \) respectively. The only relation of those above fulfilled within 1\( \sigma \) is that for the observing frequency below \( \nu_c \), constant density medium, and pre-jet break expansion.

In the context of the FS model, the flux produced by the afterglow depends on several factors, such as the kinetic energy \( E_K \) of the outflow, the fraction of energy given to radiating electrons \( \epsilon_e \) and to the magnetic field \( \epsilon_B \), the density of the environment \( n \), the slope of the power-law energy distribution of electrons \( p \), the type of expansion and where the observing bands are located. It is possible to derive the kinetic energy through simple relations once the flux is known, but one has to make assumptions of the values of the other parameters.

Following Zhang et al. (2007), the flux density \( F_\nu \) of the FS emission is given by

\[
F_\nu(\nu_m < \nu < \nu_c) = 1600D_\text{L}^2(1 + z)^{3 + p} \epsilon_B^{p - 1} \epsilon_e^{p + 1} \times \frac{\nu_3}{\nu} \times \frac{J_{\text{opt}}^{\nu_3}}{J_{\text{opt}}^{\nu}} \times \mu \text{Jy}
\]

Where \( f_p \) is a parameter depending on \( p \), and \( D \) is the luminosity distance in cm. Subindices indicate normalized quan-
Figure 3. Spectral Energy Distributions of GRB 130831A at 80 ks (top) and 173 ks (2 days) after the trigger (bottom). At 173 ks, we plot on the SED the best-fit model, a simple power-law model with $\beta_{OX} = 1.03$. We rescaled this best-fit model, multiplying the normalization constant by $(173/80)^{1.59}$, where 1.59 is the temporal decay slope, and we plot such an “extrapolated model” with a dashed line on the 80 ks SED. Such an extrapolation predicts the optical but clearly under-estimates the X-ray emission, which must be produced by a component not present at 173 ks. Each filter has the same colour in the plot.

tities, $Q_\nu = Q/10^4$ in cgs units. A spectral index $\beta_{OX} = 1.03$ for an observing frequency $\nu$ between $\nu_m$ and $\nu_c$ implies $p = 3.06$. Such a large value of $p$ is not very common; typically $p = 2.1 - 2.5$. However, $p = 3.06$ is still within two standard deviations from the centre of the distribution of this parameter, as implied from the analysis of more than 300 Swift GRBs (Curran et al. 2010), and we will adopt this value. As for the observing frequency, we take $\nu = 2.42 \times 10^{17}$ Hz, i.e. 1 keV. We convert the X-ray flux between 0.3 and 10 keV into a flux density of $\approx 7 \times 10^{-3}$ µJy at this frequency.

From the equation above, we obtain

$$\epsilon_{B, -2}^{1.02} \epsilon_{e, -4}^{2.06} E_{K, 52}^{1.52} n^{1/2} \approx 2.0$$  \hspace{1cm} (2)

We infer $E_{K, 52} = 11.8$ if we assume $\epsilon_{e, -1} = 2.7, \epsilon_{B, -2} = 0.2$, and $n = 10^{-3}$. These low values of $\epsilon_{B}$ and $n$ are required to have $\nu_c$ well above the X-ray band 2 days after the trigger. A lower value of $\epsilon_{B}$ may imply significant Inverse Compton flux, which is usually not detected in GRBs. The low density is not totally unprecedented in GRB afterglow modeling, since it has already been found for events in constant density media (Panaitescu & Kumar 2002, Cenko et al. 2011; with radio observations) and stellar wind media (Cenko et al. 2011, Perley et al 2014). On the other hand, a density lower than $\sim 10^{-3}$ is not usually expected in long GRBs, which occur next to, or within, dense star forming regions. We also note that $E_K$ has a weak dependance on $n$, so our inferred $E_K$ would not be dramatically different if the value of this parameter were within one order of magnitude from what we use. As for $\epsilon_{e, -1}$, the value we have chosen is close to that of equipartition, and is obtained by modeling GRB afterglows (see aforementioned references). However, we now show that in our modeling we cannot have $\epsilon_{e, -1} > 2.5$. From Eq. 2 we have $E_K \propto \epsilon_{e, -1}^{4/3}$ roughly. FS theory predicts that $\nu_m \propto E_K^{1/2} \epsilon_e$ and $F_\nu(\nu_m) \propto E_K$, where $F_\nu(\nu_m)$ is the peak synchrotron flux reached at $\nu_m$. For $\nu < \nu_m, F_\nu \propto \nu^{1/3}$; the flux below $\nu_m$ will therefore be $F(\nu) \propto \epsilon_{e, -1/3}$. For the values of the parameters quoted above, the radio flux at 22 and 5.8 GHz predicted 0.67 days after the trigger would be 56 µJy and 36 µJy respectively, below the upper limits determined by the VLA (Laskar et al. 2013). However, if $\epsilon_{e, -1}$ were less than 2.5 the predicted radio flux would instead be larger than the above limits. We note, though, that interstellar scintillation could suppress the observed radio flux as well. For the values of parameters we’ve constrained, the FS peak flux will be $\approx 550$ µJy. Such a flux is quite typical for GRB FS peak; see Chandra et al. (2012) and De Ugarte-Postigo (2012). We can assume that our estimate on $E_K$ is robust at least to an order of magnitude.

The modeling above enables us to determine the efficiency $\eta$ of the conversion of the energy of the outflow into energy $E_\gamma$ emitted in high energy photons during the prompt
emission. The efficiency is defined as $\eta = E_e/(E_K + E_e)$. Given $E_e = 1.06 \times 10^{52}$ erg and the value of $E_K$ constrained above, we find $\eta \approx 0.07$. By means of both optical and X-ray data, we have thus measured the efficiency of the central engine of a GRB with a prolonged internal emission episode. The optical light-curves were well sampled, and late Chandra observations constrained the X-ray flux light-curve after the steep drop. Thus, we could establish with little doubt that the late emission was entirely consistent with the FS model. Zhang et al (2007) and, more recently, Lü & Zhang (2014) carried out a similar task by using XRT light-curves; such a study with X-ray data alone, especially without precise late measurements, may be even more ambiguous.

An efficiency of $\eta \approx 0.07$ is lower than that of those few GRBs that unambiguously show a plateau of “internal origin” (see figure 12 of Lü & Zhang 2014). The efficiency of GRB 130831A is more characteristic of those GRBs that have their afterglow emission entirely explained by the FS mechanism, but with the presence of energy injection into the ejecta perhaps powered by a magnetar. Typically, GRBs with a plateau of internal origin have $\eta \approx 0.5 - 1$, while those explained by FS have a range of $\eta \approx 0.001 - 0.1$ with most clustering around $\eta = a \times 0.01$.

4.2 Origins of the X-ray radiation between the end of the prompt emission and up to the 100 ks drop.

4.2.1 Observations

The sudden drop in the X-ray flux at $\simeq 100$ ks, with a decay index $\alpha_{X,3} \simeq 7$, cannot be interpreted as FS emission. The steepest decay in this model is $\alpha = p$, where $p$ is the index of the power-law energy distribution of radiating electrons, which occurs during a jet-break expansion phase. However, $p \simeq 7$ is not predicted at all on theoretical grounds (e.g. see Rieger et al. 2007); thus it is very difficult to explain such a steep decay index at late times. Theoretically, an index as steep as $\alpha \sim 3$ can be achieved by taking into account relativistic effects in simulations (e.g. Granot 2006, van Eerten et al. 2010) even if $p < 3$, but the value of the decay index reached in the case of GRB 130831A is greater than this prediction. Duffell & MacFadyen (2014) explored the possibility that the plateau we see in GRB afterglows are produced by a jetted outflow before deceleration, followed by a steeper decay, which flags the Blandford & McKee deceleration of the ejecta. However, such a decay in their model does not reach a value as steep as $\alpha \sim 7$ detected in GRB 130831A between 100 and 200 ks.

By assuming that the steep decay is due to the curvature effect (Kumar & Panaitescu 2000; see also Uhm & Zhang 2014), we followed Liang et al. (2006) to test the internal origin of X-ray emission up to the steep break. We found that to satisfy the $\alpha \simeq \beta + 2$ condition of the curvature effect, the zero time $T$ of this emission needs to be $\simeq 75$ ks after the trigger, slightly before the beginning of the flux drop. The very steep decay component therefore strongly suggests that the X-ray emission up to 100 ks is of internal origin, since $T$ is allowed to occur at large time intervals from the initial prompt emission in this case (Zhang et al. 2006; Liang et al. 2006).

In a more general study of the curvature effect emission (Uhm & Zhang 2014), the emitting ejecta are assumed to accelerate or decelerate while producing the radiation. If the ejecta are accelerating, which may be the case for the magnetically dominated jet of the IC318 (Zhang & Yan 2011), the decay index may temporarily reach a value of $\alpha \sim 7$ we observe even assuming $T$ as the trigger of the prompt emission and $\beta \sim 1$. A magnetically dominated jet thus appears to be a reasonable solution for the GRB at hand.

However, whichever solution applies, one would always have to assume that the emission is produced inside the ejecta and not in the medium surrounding the explosion as in the case of the FS scenario. Finally, in the previous section we made it clear that the final part of the X-ray light-curve, after the end of the steep decay, appears to be FS emission.

We conclude that the X-ray emission up to the 100 ks break is not produced by the external, circumburst medium energized by the FS, but it is instead of “internal origin”, generated directly within the explosion outflow. This component stops abruptly and the X-ray flux drops rapidly, until the FS emission in the X-ray band prevails. The optical emission is basically dominated by the FS mechanism (with the possible exception of the early flare; see Sect. 4.3). In the next sections, we shall discuss the possible origins of the high-energy emission between the end of the prompt emission and the fall of the X-ray flux at 100 ks.

4.2.2 A Magnetar Central Engine

The nature of the X-ray afterglow and the nature of the central engine are two of the many open questions in the contemporary field of GRBs (see Zhang 2011 for a review), even more so because this GRB shows that we may be mis-interpreting the behaviour of other X-ray light-curves solely or primarily attributed to FS. For example, if we had not observed the steep drop at 100 ks for 130831A, we might have easily mistaken the relatively ordinary decay and spectral slopes as being produced by the standard FS-emission.

The core of the stellar progenitor of GRB 130831A may have collapsed into a magnetar (see for example Thompson et al. 2010). The rotational kinetic energy $E_{rot}$ of such objects is

$$E_{rot} = 3 \times 10^{52} \left( \frac{M}{1.4M_\odot} \right) \left( \frac{R}{12\text{ km}} \right)^2 P_{\text{ms}}^2 \text{ erg} \tag{3}$$

where $M$, $R$, and $P$ are the mass, radius, and period in ms of the object, respectively. Assuming unitary values for the parameters above, $E_{rot} \simeq 3 \times 10^{52}$ erg, which is enough to power the supernova explosion and ultra-relativistic outflow. If the mass $M$ is closer to the Tolman - Oppenheimer - Volkoff limit, which is thought to be slightly larger than $2M_\odot$ (Antoniadis et al. 2013), the parameter $E_{rot}$ might be slightly different (Metzger et al. 2015).

In a simple scenario, the magnetar would initially tap into rotational energy and produce a very energetic outflow, likely roughly collimated into bi-polar jets. Such a wind would be produced through the process of dipole spin-down. The energy of the outflow is initially imparted to the stellar envelope, causing, or at least contributing to, the supernova explosion. Moreover, the magnetar outflow may be long-lived, and produce radiation that we observe.
(see below). In this scenario, the luminosity \( L_0 \) of the magnetar could be roughly constant, even for a relatively long timescale \( T_{\text{em}} \) (Zhang & Mészáros 2002), depending on physical parameters. After \( T_{\text{em}} \), or if the magnetar collapses into a black hole, the light-curve would show a flux drop. This magnetar model is relevant for a few GRBs that show a plateau with approximately constant flux, with \( \alpha \approx 0 \), followed by the steep slope segment (see cases studied by Liang et al. 2007, Lü & Zhang 2014, Cano et al. 2014, Bernardini et al. 2014, Lü et al. 2015). However, the early decay slope of 130831A is \( \alpha_X \approx 0.8 \), which is in contrast to the aforementioned cases, and requires a more complicated model to explain our observations.

### 4.2.3 A Magnetar with decaying magnetic field

In the simple spin-down calculation above, one assumes that the magnetic field \( B \) is constant and independent of the period of the magnetar \( P \). Metzger et al. (2011), however, assume that \( B \) is linked to \( P \), taking into account that the magnetic field is generated from the energy available in differential rotation. They thus estimate

\[
B = 10^{16} R_0^{-1/2} P^{-1}_3 \, \text{G}
\]

(4)

Under this assumption, \( B \) decreases with increasing \( P \), i.e., with increasing time since the explosion. In such conditions, the jet luminosity \( L \) is not constant. As shown in Figures 2 and 5 of Metzger et al. (2011), \( L \) decreases with time, scaling approximately as \( L \propto t^{-1} \) from 100–1000 s to tens of ks after the collapse for reasonable values of parameters at the beginning of the spin-down, such as \( B_0 \approx 10^{15} \) G and \( P_0 = 1–2 \) ms. The predicted luminosity of the jet seems to be in the right range to explain the X-ray emission of GRB 130831A during the slow decay phase, too. For the values quoted above, Metzger et al. (2011) predict a few \( \times 10^{46} \) erg s\(^{-1} \) at 10 ks; at the same epoch, GRB 130831A had a luminosity of \( \sim 10^{46} \) erg s\(^{-1} \).

We note that a jet luminosity \( L_{\text{jet}} \) does not convert immediately into X-ray luminosity \( L_X \); one has to take into account that the radiation mechanism will have a certain efficiency. Moreover, we have not yet considered that GRB emission is beamed. We can write

\[
L_X = \eta_X f_{b,x}^{-1} L_{\text{jet}}
\]

(5)

where \( \eta_X \) and \( f_{b,x} \) are the efficiency in converting the jet luminosity into X-ray radiation and the correction for the beaming, respectively.

According to Metzger et al. (2011), at late epochs (> 100 – 1000 s after the collapse), the magnetar outflow is highly relativistic and Poynting-flux dominated; in such conditions, internal shocks and reconnections within the jet itself are not possible. Forced reconnection, however, can occur at large radii, when the outflow collides with the circum-burst medium and/or the previous ejecta, and convert the jet energy into X-ray emission. Assuming that the efficiency of this process is similar to the one which generates the prompt emission, and the correction for beaming is 10 times lower than that during the prompt emission, Metzger et al. (2011) find that they can explain the observed \( L_X \) and plateau durations of several GRBs similar to GRB 130831A.

The newly born magnetar may also provide a large energy input in the exploding progenitor, powering an energetic and luminous supernova explosion. This is in agreement with observations of Cano et al. (2014), who find a kinetic energy for the (non-relativistic) ejecta of SN 2013fu of \( E_{\text{SN}} = 1.9 \times 10^{52} \) erg and a peak absolute magnitude \( M_V = -19.3 \). We note that Greiner et al. 2015 found \( E_{\text{SN}} \approx 10^{52} \) erg for SN2011kl, a very bright supernova associated with GRB 111209A, whose properties can be explained by the energy injection of a newly born magnetar. In addition, the energetics of SN2013fu is quite typical of other SNe associated with GRBs (Cano et al. 2015).

As for the abrupt end of the X-ray emission of “internal origin”, with a very steep slope, we may attribute it to the delayed collapse of the magnetar into a black hole (Vietri & Stella 1998, Lyons et al. 2010, Rowlinson et al. 2013). Once the magnetar has lost much of its rotational energy to power the jet, the weakened centrifugal forces may not be able to avoid the collapse. The timescale of such an event, for a neutron star mass of \( \sim 2M_\odot \), initial period of \( \sim 2 \times 10^{-3} \) s and magnetic field of \( 10^{15} \) Gauss would be \( \sim 6 \times 10^4 \) s (Vietri & Stella 1998, their Eq. 1), comparable to the epoch of the steep drop in the X-ray light curve of GRB 130831A. Such a collapse should be relatively quick, and rapidly stop energy emission from the central object. If a magnetar collapsing into a black-hole is the right model, GRB 130831A might be a candidate for the production of Fast-Radio Bursts (FRBs), as described in Zhang (2014), as thus a target for observational campaigns in radio aimed at understanding the origin of FRBs.

### 4.2.4 A black hole with a fall-back accretion disk

Another possibility we consider is that the central engine of this GRB could be a stellar black hole with a fall-back accretion disk (Kumar et al. 2008). Basically, in the supernova explosion associated with the GRB, the innermost part of the star collapses into a black hole. A continued fall-back of matter - directly from the progenitor envelope or from supernova ejecta that failed to reach escape velocity - occurs at the centre. Some of this material does not accrete directly onto the black hole, but creates an accretion disk around it. Depending on the fall-back rate and the accretion time \( t_{\text{acc}} \) onto the black hole, the material of this disk can power relativistic ejecta from the black hole for a long time, which may produce both the prompt emission and a long-lived, slowly decaying X-ray flux.

For the latter, Kumar et al. (2008) envisage a few possibilities. One is that the accreting disk has a low viscosity. It will thus take a long time, of the order of \( \sim 10^4 – 10^5 \) s, for the whole disk material to accrete onto the black hole and power the jet. This model explains a long-lived plateau, but it predicts a flux decay with slope \( \alpha \approx 1.3 \) at the end of this phase, which is not observed in GRB 130831A and other GRBs with similar features.

Another possibility is that the disk has high viscosity. Then \( t_{\text{acc}} \) is much less than the fall-back time, and the emission basically traces the rate of the matter falling back onto the accretion disk. However, such a scenario cannot explain why the fall-back rate is less steep than expected: on theoretical grounds, we expect a fall-back rate to vary as \( t^{-5/3} \) (Chevalier 1989). Secondly, the plateau slope and the sud-
den cut-off can be explained only by a particular density and angular momentum profile of the matter of the progenitor. A luminosity that evolves close to $t^{-1}$, as in the case of GRB 130831A, might be explained if the density profile of the stellar envelope has a profile of approximately $r^{-3}$, where $r$ is the radius from the centre of the star. A steep drop at the end of the plateau might be achieved if the material of the stellar envelope, which is the last to be accreted, has a relatively small angular momentum: this will cause the matter to fall rapidly onto the black hole and shut off the emission. Such a peculiar configuration, however, seems somewhat contrived and at odds with models of stellar progenitors (e.g. Woosley et al. 2011). Moreover, to support accretion for $\sim 10^5$ s, the disk should be unusually large and massive, leaving little mass for ejecta. Cano et al. (2014) find instead that the SN 2013fu, associated with GRB 130831A, has an ejecta mass of $M_{ej} \approx 4.7 \ M_\odot$, which is typical of other GRB-SNe (e.g. Cano 2013).

For the model discussed, the jet luminosity is expected to be in the range of $10^{52}$ erg s$^{-1}$ at the end of the plateau, which is similar to the X-ray luminosity of the GRB 130831A afterglow at the end of the shallow decline phase.

4.2.5 A Binary Origin

Barkov & Komissarov (2010) conceive another scenario in which a black hole might power a GRB and long-lived outflow (see also Komissarov & Barkov, 2009). If a compact object and a Wolf-Rayet (WR) star form a very close binary, such a system can go through a common envelope phase in which the compact object spirals in and can accrete the matter of the companion. The common envelope matter will have very high angular momentum and can take a long time to accrete. According to Barkov & Komissarov, the accretion timescale of such a system is:

$$t_d \approx 8000 \left( \frac{\alpha}{0.01} \right)^{-1} \left( \frac{R_c}{R_\odot} \right)^{3/2} \left( \frac{M_e}{2M_\odot} \right)^2 \left( \frac{M_*}{10M_\odot} \right)^{-7/2} \text{s} \quad (6)$$

where $\alpha$ represents the viscosity, $R_c$ and $M_e$ the radius and mass of the WR star, and $M_*$ is the mass of the compact object. For massive compact objects, an accretion timescale of several tens of ks is not impossible. According to Barkov & Komissarov (2010), during accretion the compact object will produce jets via the Blandford-Znajek mechanism, and the jet luminosity will be in the range of $10^{50}$ erg s$^{-1}$, more than enough to explain the luminosity during the slow decline phase. Nonetheless, this scenario might suffer from the same problems as the previous one. If the viscosity of the accretion disc is low, which is required to keep the material around the black hole for $\sim 1$ day, then the flux should not decrease quickly at the end of the plateau. The binary origin scenario could not reproduce the steep X-ray flux drop and/or it would require a peculiar structure of the WR star to explain the temporal dependence of the luminosity. We note, however, that in their papers, Barkov and Komissarov do not discuss what happens at the end of the plateau, so we can only postulate.

Finally, we remark that this binary origin model can predict a supernova, like the one associated with GRB 130831A.

4.2.6 Concluding remarks on the origin of the X-ray emission

We have shown that the FS scenario (or any refreshed shock scenario) cannot explain the X-ray emission of GRB 130831A between the end of prompt emission and $\sim 100$ ks, since such a model cannot entail the steep decay of the flux at that epoch.

We have investigated whether such early X-ray emission can be attributed to dissipation processes occurring in the outflow of a newly born magnetar, produced via spin-down energy extraction of the compact object. We have found that the simplest model cannot explain the observations, because it predicts a flat X-ray light-curve followed by a steep drop. In the case of GRB 130831A, the decay slope before the break is $\alpha \approx 0.8$, which is much steeper than what we expect in this model. However, a more elaborate model of the magnetar spin-down, in which the magnetic field is expected to decay as the rotation time increases, predicts a luminosity decay more consistent with observations and a duration that can extend up to tens of ks. Moreover, the anticipated X-ray luminosity is in the right range. The assumed initial parameters - initial period $P$ and magnetic field $B$ - for the newly born magnetar that would produce such a X-ray light-curve are $P = 1 - 2$ ms and $B \approx 10^{15}$ G, which are expected on theoretical grounds for such an object.

We have also discussed whether the compact object could be a black hole rather than a magnetar. In order to power emission for such a long time, the black hole should be surrounded by an extended disk, perhaps produced by fallback material of the supernova associated with the GRB. While this model still may predict the right luminosity and duration for the “internal” X-ray emission, it would require an anomalous distribution of angular momentum in the progenitor star, and peculiar fallback rates. Similar advantages and disadvantages may be present in a model in which the compact object forms a binary with a WR star and spirals in, blowing up the star into a massive disk. All in all, we deem the magnetar model with a decaying magnetic field the most plausible of those presented so far to explain the properties of GRB 130831A.

4.3 Energy budget of the X-ray radiation between the end of the prompt emission and the 100 ks drop.

In the cosmological rest frame, the X-ray internal emission begins no later than $200 \times (1 + 0.479) = 135$ s and lasts until $\approx 98.2 \times 10^3 / (1 + 0.479) \approx 66.4 \times 10^4$ s. Taking into account cosmological corrections, the $0.3-10$ keV luminosity at 135 s is $2.1 \times 10^{57}$ erg s$^{-1}$; we assume that from this epoch the luminosity decreases as $t^{-0.8}$ up to 66.4 ks. We subtract the amount of X-ray emission produced by the FS (see section 4.3), and we obtain a total energy $E_X \approx 2.8 \times 10^{56}$ erg. Such
a value represents \( \simeq 2.5\% \) of the energy emitted during the prompt phase, and only \( \simeq 0.25\% \) of the kinetic energy of the relativistic ejecta producing the FS emission. We note, however, that the internal emission may extend below 0.3 keV and above 10 keV. Thus, \( E_x \) and the percentage we have determined represent a lower limit.

4.4 Energy breakdown of GRB 130831A and the associated supernova

We know that the kinetic energy of the ejecta of SN 2013fu, the supernova associated with GRB 130831A, is \( \simeq 1.9 \times 10^{52} \) erg (Cano et al. 2014). This is a factor \( \sim 6 \) lower than the kinetic energy of the relativistic ejecta and comparable to the energy emitted during the prompt emission, and \( \sim 60 \) times higher than the energy associated with the X-ray emission of “internal origin”. We do caution, however, that the estimated SN kinetic energy is isotropic, while the energy of the relativistic ejecta, the prompt and the early X-ray energetics must be corrected for an unknown beaming factor. GRB 130831A does not show the signature of a jet break (Sari, Piran & Halpern 1999) within our observations, so we cannot derive the beaming angle \( \theta_j \) of the ejecta and thus the beaming factor. However, we can set limits. The detection of the X-ray afterglow by Chandra at 1430 ks after the trigger indicates that the FS X-ray afterglow had a decay slope of \( \simeq 1 \) up to that epoch and no jet break had yet occurred. Following Zhang et al. 2009, the beaming angle of the ejecta in a medium with constant density can be estimated as

\[
\theta_{jet} = 0.12 \frac{t_{jet,d}}{1 + z}^{3/8} \left( \frac{E_{K,53}}{n} \right)^{-1/8} \text{ rad} \tag{7}
\]

where \( t_{jet,d} \) is the jet break time in days. Our first Chandra observation took place 16.6 days after the trigger and we adopt the values \( E_K \) and \( n \) determined from our modeling; we note that the exact value of \( \theta_j \) depends only weakly on the value of these parameters anyway. We infer that \( \theta_j \simeq 0.123 \) rad; thus the lower limit on the beaming factor is \( f_b \simeq \theta_j^2/2 \simeq 7.56 \times 10^{-3} \). By definition, the maximum value for the beaming factor is \( f_b = 1 \) when the source is isotropic.

If the beaming factor of GRB 130831A emission were \( f_b = 7.56 \times 10^{-3} \), the total energy budget of this event and its supernova would be \( \simeq 2.0 \times 10^{52} \) erg. The prompt energy \( E_{\gamma} \), the energy emitted in X-rays up to 100 ks \( E_x \), and the kinetic energy \( E_K \) of the relativistic ejecta would be \( \simeq 0.4\% \), \( \simeq 0.01\% \), and \( \simeq 4.3\% \) of the total energy budget. If, as an extreme and unlikely case, GRB 130831A were isotropic, its total energy budget would be \( 1.5 \times 10^{53} \) erg; the above percentages would become \( \simeq 7\% \), \( \simeq 0.2\% \), and \( \simeq 80\% \). The kinetic energy of the relativistic ejecta is at least \( \simeq 4.3\% \) of the total energy produced by the GRB and the SN. Moreover, the fraction of energy going into the “internal emission” X-rays is always rather small, being substantially less than 1% in both cases.

If GRB 130831A and its SN are powered by a magnetar, the total energy budget cannot be \( \gtrsim 3 \times 10^{52} \) erg (see section 4.2). To not exceed this limit, the beaming factor of the GRB must be \( f_b \lesssim 0.1 \). If \( f_b = 0.1 \), \( E_{\gamma} \), \( E_x \), and \( E_K \) represent \( \simeq 3.3\% \), \( \simeq 0.1\% \), and 37% of the total energy. In reality, we should expect these percentages to be between those of the \( f_b = 0.1 \) and \( f_b = 7.56 \times 10^{-3} \) cases if GRB 130831A is actually powered by a magnetar. The breakdown is presented again in Table 5.

4.5 Early Afterglow

In our analysis, we have focused on the afterglow emission between 15 and 230 ks. It is worth exploring whether our model can explain the interesting features of the early afterglow, especially the optical band.

The initial flare peaks at 730 s. It takes place both in the X-ray and optical bands, but it is very pronounced in the latter. Its rapid temporal evolution (the optical flux increased by a factor of \( \sim 5 \) between 400 and 800 s after the trigger) suggests that it could be explained in the context of internal dissipation processes which occurred in the outflow, when the Lorentz factor is very high and relativistic effects cause rapid variations of the observed flux. Thus, GRB 130831A may show a clear example of internal dissipation that produces strong emission in the optical other than in the X-ray. Alternatively, the optical flare might flag the onset of FS emission. However, if this were the case, the decay slope after the flare peak would be consistent with the decay slope of the late optical afterglow \( \alpha_{opt} \). Instead, the decay rate after the flare peak is \( \alpha = 1.79 \pm 0.02 \), which is inconsistent with \( \alpha_{opt} = 1.59 \pm 0.03 \) found later. After the flare, the early optical emission shows a plateau up to a few ks (see Section 3). Typically, an early slow optical decay is interpreted as energy injection, which ends at the time of the break. However, this interpretation might be difficult in our scenario, because the energy injection would have to stop at \( \sim 5 \) ks while, according to our analysis, the GRB outflow is still active at \( \sim 100 \) ks.

A possibility is that the optical plateau basically results from the combination of the decaying optical flare and the rising of the FS peak, which has been shown for a number of Swift bursts for which early optical light-curves are available (Oates et al. 2009). The peak Lorentz factor \( \Gamma' \) of the ejecta then can be calculated (Molnari et al. 2007 and references therein) as

\[
\Gamma = 160 \left( \frac{E_{\gamma,53} (1+z)^{3/2}}{\eta_{0.2} \times t_{dec,2}} \right)^{1/8} \tag{8}
\]

For a deceleration time \( t_{dec} = 4000 \) s and adopting the values of energy and density we have determined above, the resulting peak Lorentz factor would be \( \Gamma \simeq 100 \), which is within the overall distribution of Lorentz factors for GRB afterglows (Oates et al. 2009). The reason for such a late deceleration, in our model, comes naturally given the low density of the circumburst medium.

The late emission, which we attribute to FS in our modeling, seems to have a relatively steep decay slope. So one may wonder whether it could give some important contribution to the X-ray flux as well at an earlier epoch. If we extrapolate the late X-ray flux to earlier epochs using a decay slope of \( \simeq 1.6 \), it would become comparable to or even higher than the observed X-ray flux at the end of the first orbit (at \( \sim 800 \) s) and the shape of the X-ray light-curve would differ from what we see. However, if the FS onset occurs at \( \sim 4000 \) s, this problem is avoided. As for the observations
from $\simeq 9$ ks (i.e. the beginning of the second orbit) onwards, at 10 ks the flux by FS emission is $\simeq 6 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1} \times (\frac{\text{erg}}{\text{Hz}}) = 5.5 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$, which is $\sim 3$ times weaker than the observed X-ray flux. Afterwards, the FS flux decreases faster than that of “internal origin” that times weaker than the observed X-ray flux. Afterwards, the at 10 ks the flux by FS emission is $\simeq 6 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1} \times (\frac{\text{erg}}{\text{Hz}}) = 5.5 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$, which is $\sim 3$ times weaker than the observed X-ray flux. Afterwards, the FS flux decreases faster than that of “internal origin” that times weaker than the observed X-ray flux. Afterwards, the

5 CONCLUSIONS

We have discussed the case of the long Swift GRB 130831A. The X-ray afterglow of this burst initially shows a shallow decay. However, at $\sim 100$ ks the X-ray light-curve breaks to an unusually steep decay slope $\sim 6$, which cannot be explained by the standard FS model. Late XRT and especially Chandra observations show that the X-ray afterglow has a successive break to a more sedate decay with a slope $\sim 1.1$.

The well-sampled optical afterglow shows no change of slope concurrent with the steep break in the X-ray band, which we interpret as arising from a different mechanism. By means of data taken by Swift, Chandra and several ground-based observatories, we have shown that both the optical and late X-ray emissions, after $\sim 200$ ks after the trigger, have the typical decay and spectral slopes of GRB afterglows explained by the FS model.

We have interpreted the X-ray and optical afterglow as the superposition of two emission components. One component is of “internal” origin, generated within a relativistic outflow and responsible for the early X-ray emission up to $\simeq 100$ ks; the outflow is produced by either the spin-down of a newly formed magnetar or a black hole feeding on fallback material. A second component, responsible for the late X-ray and optical from a few ks after the trigger, is the typical FS emission. When the magnetar has lost much of its rotational energy or the black hole does not accrete and does not power the outflow any longer, the first component dies off and we see the steep X-ray decay that lasts until the standard FS emission emerges. We believe that the magnetar model is favoured, since the other scenario would require a rather peculiar stellar progenitor structure and fall-back process.

Modeling the late optical and X-ray afterglow, we have inferred the kinetic energy of the relativistic ejecta and thus an efficiency $\eta \simeq 0.07$ of the “central engine” of this GRB to produce $\gamma$-ray emission. This efficiency is smaller than that of other bursts that show emission of internal origin (Lü & Zhang 2014; although these were examined in the X-ray band only), and more typical of those GRBs in which no internal emission is clearly visible. Thus, GRB 130831A may represent a “trait d’union” between GRBs with different dominant emission processes.

More importantly, gathering the information on the kinetic energy of the supernova associated with 130831A, we have provided a breakdown of the energetics of the GRB and its associated supernova. We have found that, regardless of the nature of the central engine and unknown collimation of the ejecta, at least $\simeq 4.3\%$ of the total energy of the event is coupled with relativistic ejecta; and less (probably significantly less) than $\simeq 0.2\%$ of the energy goes into X-ray emission of “internal origin” lasting up to 100 ks in our case; this component produces a factor $\sim 30$ less energy than that released in $\gamma$-ray during the prompt emission.

Showing several emission processes at work, GRB 130831A has offered us the opportunity to investigate the complete phenomenon of a supernova with a central engine that produces the explosion and drives an energetic relativistic outflow, where dissipation processes take place for a long time.

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Table 5. Flux densities corresponding to zero magnitudes used in the conversion of magnitudes to flux densities for the light-curves shown in Fig. 2.

| Filter        | Flux (Jy) |
|---------------|-----------|
| ISON unfiltered | 2786      |
| UVOT $u$      | 1445      |
| UVOT $UVW1$   | 888       |
| UVOT $UVW2$   | 769       |
| Skynet $B$    | 4127      |
| Skynet $V$    | 3690      |
| Skynet $R$    | 3103      |
| Skynet $I$    | 2431      |
| Skynet $g'$   | 363       |
| RATIR $r'$    | 3147      |
| RATIR $i'$    | 2590      |
| RATIR $Z$     | 2211      |
| RATIR $Y$     | 2040      |
| RATIR $J$     | 1564      |
| RATIR $H$     | 1007      |
Table 1. Time resolved spectral analysis. ST = settling exposure, WT = Window Timing Exposure, PC = Photon Counting exposure. Note: errors are at 90% C.L.

| Name | Start time (s) | End Time (s) | excess N_H (10^{20} cm^{-2}) | β | Observed flux (× erg cm^{-2} s^{-1}) | Unabsorbed flux (× erg cm^{-2} s^{-1}) | Cstat | dof |
|------|---------------|--------------|-------------------------------|----|------------------------------------|----------------------------------------|-------|-----|
| ST   | 115.8         | 125.2        | < 700                         | 1.7±0.2 | 7.93×10^{-10}          | 1.06×10^{-9}                          | 125.4 | 146 |
| WT1  | 132.0         | 157.9        | < 400                         | 1.7±0.1 | 6.91×10^{-10}          | 9.21×10^{-10}                         | 163.3 | 159 |
| WT2  | 157.9         | 205.6        | < 500                         | 1.3±0.1 | 3.34×10^{-10}          | 4.06×10^{-10}                         | 182.2 | 184 |
| PC1  | 207.2         | 287.2        | < 500                         | 1.2±0.3 | 1.70×10^{-10}          | 2.03×10^{-10}                         | 82.5  | 76  |
| PC2  | 287.2         | 307.2        | < 100                         | 0.7±0.3 | 1.47×10^{-10}          | 1.61×10^{-10}                         | 60.3  | 60  |
| PC3  | 367.2         | 437.2        | < 20                          | 1.1±0.4 | 9.69×10^{-11}          | 1.14×10^{-10}                         | 37.1  | 41  |
| PC4  | 437.2         | 847.2        | < 500                         | 0.8±0.1 | 1.47×10^{-10}          | 1.63×10^{-10}                         | 199.4 | 216 |
| PC5  | 9891.6        | 113785.0     | < 700                         | 1.0±0.9 | 1.52×10^{-14}          | 1.80×10^{-14}                         | 10.3  | 17  |
| PC6  | 171385.0      | 1193789.0    | < 700                         | 1.1±0.4 | 9.69×10^{-11}          | 1.14×10^{-10}                         | 37.1  | 41  |

Table 2. Results of the temporal analysis of the X-ray emission of GRB 130831A, which includes XRT and Chandra data. We show the results of fitting the data with two models. The first model, BPLs + flare, consists of power-law plus broken power-law plus power-law plus gaussian flare and it fits the whole X-ray dataset. The second model, 2powls, includes 2 power-law components and it fits the data after 100 ks. We show the decay indices, break time and the centre (GC), width (GW) and flux normalisation (GN) of the gaussian flare, of the first model. The latter model has \( \alpha_{X,3} \) and \( \alpha_{X,4} \) only.

| Model      | \( \alpha_{X,1} \) | \( \alpha_{X,2} \) | \( t_b \) (ks) | \( \alpha_{X,3} \) | GC (ks) | GW (ks) | GN (×10^{-13} erg cm^{-2} s^{-1}) | \( \alpha_{X,4} \) | \( \chi^2/dof \) |
|------------|-------------------|-------------------|----------------|-------------------|---------|---------|-------------------------------|-------------------|----------------|
| BPLs + flare | 5.97 ± 0.01       | 0.80^{+0.03}_{-0.02} | 98.26^{+2.94}_{-3.30} | 5.9^{+1.0}_{-0.4} | 0.73 ± 0.03 | 0.11 ± 0.02 | 11.2 ± 1.6 | 0.90^{+0.11}_{-0.05} | 50.7/48 |
| 2powls     | 6.8^{+1.5}_{-1.5} |                   |                   |                   |         |         |                               | 1.11^{+0.22}_{-0.29} | 2.4/3 |

Table 3. Photometry of the Afterglow of GRB 130831A. All magnitudes are in the Vega system. The full table is available online.

| \( t - t_0 \) (s) | Exposure time | mag | Filter | Telescope |
|-------------------|---------------|-----|--------|-----------|
| 484               | 10            | 14.86^{+0.09}_{-0.08} | uvw2 | UVOT     |
| 633               | 10            | 14.03^{+0.06}_{-0.05} | uvw2 | UVOT     |
| 783               | 10            | 13.67 ± 0.05          | uvw2 | UVOT     |
| 10346             | 450           | 17.53^{+0.05}_{-0.04} | uvw2 | UVOT     |
| 43951             | 2844          | 19.44^{+0.15}_{-0.13} | uvw2 | UVOT     |
| 123835            | 3414          | > 21.27               | uvw2 | UVOT     |
Table 4. Calibration stars which were used for the optical telescopes. RATIR used a much longer list of calibration stars, but we list only those in common with other instruments.

| Catalogue | RA      | Dec     | Telescopes       |
|-----------|---------|---------|------------------|
| APASS     | 358.594169 | +29.341196 | Skynet RATIR    |
| APASS     | 358.660796 | +29.429860 | Skynet RATIR    |
| APASS     | 358.548308 | +29.427729 | Skynet RATIR    |
| SDSS      | 358.682125 | +29.427583 | IKI RATIR      |
| SDSS      | 358.660833 | +29.429806 | IKI            |
| SDSS      | 358.598500 | +29.414667 | IKI RATIR      |
| SDSS      | 358.643042 | +29.454639 | IKI RATIR      |
| SDSS      | 358.63521  | +29.42802  | NOT, LT, RATIR |
| SDSS      | 358.63296  | +29.42655  | NOT, LT, RATIR |
| SDSS      | 358.62188  | +29.42342  | NOT, LT, RATIR |
| SDSS      | 358.63986  | +29.41882  | NOT, LT, RATIR |
| SDSS      | 358.64747  | +29.41695  | NOT, LT, RATIR |

Table 6. Results of the temporal analysis of the optical emission of GRB 130831A between 3.5 ks and 15 ks (upper part) and 15 ks and 13 Ms (lower part). Time is expressed in ks, while the constant flux is in $\mu$Jy. Since the host galaxy constant flux is not important during the first fit, which does not extend up to late times anyway, we have omitted it.

| Filter | $\alpha_1$ | $t_{b,1}$ (ks) | $\alpha_2$ | Const ($\mu$Jy) | $\chi^2$/dof |
|--------|------------|----------------|------------|-----------------|-------------|
| No Filter | 0.06$^{+0.19}_{-0.20}$ | 4.79$^{+0.16}_{-0.17}$ | 1.62 $\pm$ 0.07 | - | 86/53 |
| B      | 0.42 $\pm$ 0.08 | 4.90 $\pm$ 0.08 | 1.45 $\pm$ 0.03 | - | 81/49 |
| V      | 0.86 $\pm$ 0.03 | 6.47 $\pm$ 0.10 | 1.65 $\pm$ 0.03 | - | 160/57 |
| R      | 0.64$^{+0.04}_{-0.06}$ | 5.56$^{+0.11}_{-0.16}$ | 1.56 $\pm$ 0.02 | - | 232/57 |
| I      | 0.92 $\pm$ 0.03 | 6.99$^{+0.17}_{-0.19}$ | 1.82$^{+0.05}_{-0.06}$ | - | 119/50 |

| R | 1.60 $\pm$ 0.03 | – | – | 0.81 $\pm$ 0.14 | 9.4/10 |
| r' | 1.49 $\pm$ 0.06 | – | – | 0.96 $\pm$ 0.11 | 30.7/14 |
| i' | 1.64 $\pm$ 0.07 | – | – | 0.73 $\pm$ 0.08 | 29.2/15 |

Table 7. Best fit parameters obtained when fitting the 173 ks (2 days) SED with a single broken power-law and Milky Way extinction law. We indicate the reddening in our Galaxy and that in the host at $z = 0.479$ separately. The absorption in our Galaxy ($z=0$) and in the host of the GRB ($z=0.479$) has been fixed to the best fit value of the X-ray data.

| $N_H$ at $z=0$ | $N_H$ at $z=0.479$ $\times 10^{22}$ | $E(B-V)$ at $z=0$ (mag) | $E(B-V)$ at $z=0.479$ (mag) | $\beta_{OX}$ | $\chi^2$/dof |
|----------------|--------------------------------------|------------------------|---------------------------|-------------|-------------|
| $4.8 \times 10^{20}$ | 0.068 | $4.0 \times 10^{-2}$ | $1.8 \pm 1.3 \times 10^{-2}$ | $1.03^{+0.05}_{-0.04}$ | $12.7/9$ |

Table 8. Breakdown of energetics of GRB 130831A and its associated SN 2013fu into energy emitted in $\gamma$-rays $E_\gamma$, energy produced in X-rays of internal origin $E_X$, and kinetic energy associated with the relativistic GRB ejecta $E_K$. These values are corrected for beaming corresponding to the beaming factor $f_b$. The kinetic energy of the SN is $E_{SN} = 1.9 \times 10^{52}$ erg (Cano et al. 2014), and the total energy is $E_{tot} = E_{SN} + E_\gamma + E_X + E_K$.

| Beaming factor $f_b$ | $E_{tot,f_b}$ | $E_{\gamma,f_b}$ | $E_X$ | $E_K$ |
|----------------------|---------------|-----------------|-------|-------|
| 1 (isotropic)        | 14.8          | 7.2%            | 0.19% | 80%   |
| 0.1 (magnetar limit) | 3.2           | 3.3%            | 0.09% | 37%   |
| 7.56 $\times 10^{-3}$ (lower limit) | 2.0 | 0.39% | 0.01% | 4.3% |