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GRB 101225A - an unusual stellar death on Christmas Day

C. C. Thöne[1,2], A. de Ugarte Postigo[3], C. Fryer[4], K. L. Page[5], J. Gorosabel[1], M. A. Aloy[6], D. A. Perley[7], C. Kouveliotou[8], H. T. Janka[9], P. Mimica[6], J. L. Racusin[10], and the Christmas burst collaboration

[1] IAA-CSIC, Glorieta de la Astronomía s/n, 18008 Granada, E e-mail: cthoene@iaa.es
[2] Niels Bohr International Academy, Blegdamsvej 17, 2100 Copenhagen, DK
[3] DARK, NBI, Univ. of Copenhagen, Juliane Maries Vej 30, 2100 Copenhagen, DK
[4] LANL, MS D409, CCS-2, Los Alamos, NM 87545, USA
[5] Dept. of Physics & Astronomy, Univ. of Leicester, Univ. Road, Leicester LE1 7RH, UK
[6] Dept. de Astronomia y Astrofisica, Univ. de Valencia, 46100 Burjassot, E
[7] UC Berkeley, Astronomy Dep., 601 Campbell Hall, Berkeley CA 94720, USA
[8] Space Science Office, VP62, NASA/MSFC, Huntsville, AL 35812, USA
[9] MPA, Karl-Schwarzschild-Str. 1, 85748 Garching, D
[10] NASA, GSFC, Greenbelt, MD 20771, USA

Abstract. GRB 101225A, the "Christmas burst", was an extremely long γ-ray burst (T_{90} >2000s) followed by a bright X-ray afterglow and a very unusual optical counterpart. The X-ray spectrum shows an additional black-body component as observed for a few other nearby GRBs. The UV-optical-IR SED does not show any sign of the usual powerlaw behaviour, but evolves as a cooling, expanding black-body until 10 days, after which a faint supernova emerges. We detect a faint host galaxy 6 months after the burst, the faintest host so far associated to a GRB. Our preferred model is a helium-neutron star merger where the post main-sequence star, in the common-envelope phase during inspiral, ejects most of its envelope in the form of a torus. At the final merger creating a GRB-like event, the jet interacts with the material surrounding the progenitor where it gets fully thermalized. GRB 101225A might be a member of a new class of GRB which can only rarely be observed due to the faintness of the non-relativistic counterpart.

Key words. Gamma-ray burst: individual: GRB 101225A; supernovae: individual

1. Introduction

In the widely accepted fireball model, afterglows of GRBs are produced by synchrotron emission. The ultra-relativistic jet originating from the central engine interacts with the surrounding interstellar medium leading to the so-called "external shocks" where the highly relativistic electrons produce the synchrotron emission which we observe as afterglow from X-rays to radio wavelengths. The spectral-energy distribution and the lightcurve therefore

Send offprint requests to: C. Thöne

follow broken powerlaws (2000). This model has been confirmed by numerous observations.

GRBs are usually divided into two classes according to their duration (2000). Long GRBs ($T_{90} > 2s$) have been associated to the death of massive stars and broadline SN Type Ic (2000). Short bursts ($T_{90} > 2s$) have not been connected to SNe and are suggested to be the result of a merger between two compact objects. Exceptions of long GRBs have been found that did not shown any SN signature, probably related to a different progenitor (2000). Nearby, long GRB-SNe often have a relatively low γ-rays energy release compared to the average long GRBs. For some GRB-SNe, an additional thermal component in the X-ray afterglow had been found and attributed to the shock breakout of the star or the circumstellar wind (2000,?,?).

2. Observations

2.1. Prompt emission and afterglow

GRB 101225A was detected by *Swift* on Dec. 25, 2010, 18:37:45 UT in an image trigger (2000). It had a $T_{90} > 2000$s and a very soft spectrum putting it at the extreme end of the hardness–duration distribution of *Swift* GRBs (2000). At $z = 0.33$ (see below), its total energy release was $E_{\gamma,iso} > 1.4 \times 10^{51}$ erg, higher than most nearby GRB-SNe. XRT detected a bright counterpart in X-rays showing a very shallow decay for the first ~ 0.2 days before decaying rapidly with $t^{-5/3}$. An optical counterpart was discovered by AlFOSC/NOT 1.54h after the burst (2000).

An extensive follow-up with several telescopes around the world and UVOT onboard *Swift* enabled us to follow up the UV-optical-IR (UVOIR) lightcurve in several different bands until 2 months after the event. Spectroscopy of the event at 2 and 41 days post burst with OSIRIS/GTC and LRIS/Keck respectively did not reveal any absorption or emission lines. Using SED modeling, we determined the redshift to $z = 0.33$ (see below).

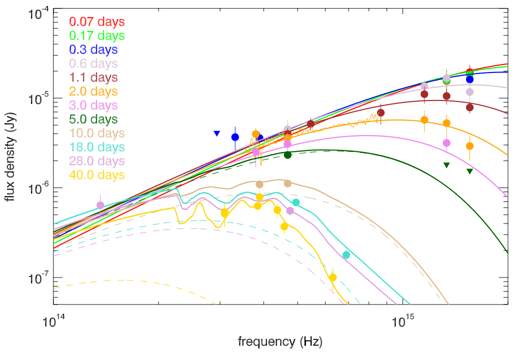

Fig. 1. UVOIR SED evolution from 0.07 to 40 days. Until 10 days, the BB emission is the main component, at later times, the contribution from the SN increases until the SN dominates the optical emission.

2.2. Afterglow SED and SN modeling

The bright X-ray afterglow showed another component in addition to the power-law fit, best modeled with a blackbody (BB) of T~ 1 keV and a radius of ~ $1R_\odot$ (assuming a redshift of $z = 0.33$). The BB component can be detected until 8 ks, contributing around 20% to the total flux and shows no significant temporal evolution. At later times, the S/N becomes too low to determine different components in the X-ray SED.

The UVOIR multi band observations allow us to derive an SED at 7 epochs from 0.07 to 40 days after the burst (see Fig. 1). In contrast to other GRBs, the SED does not show any powerlaw shape but instead is well modeled with an expanding, cooling blackbody for the first ~10 days. The radius of the UVOIR BB increases from ~13 to 45 AU while the temperature drops from 43,000 to 5,000 K from 0.07 to 18 days. Temperature and radius evolution of X-ray and UVOIR BB are inconsistent with each other and the two emissions much therefore come from different processes (see Fig. 2).

At around 10 days, a component in addition to the pure BB starts to appear, coincident with a flattening in the lightcurve. The lightcurve reaches a faint maximum at 30 days after which it continues to decay. The behaviour is well modeled with a supernova associated to GRB 101225A taking as template the "generic" GRB-SN GRB 980425/SN 1998bw

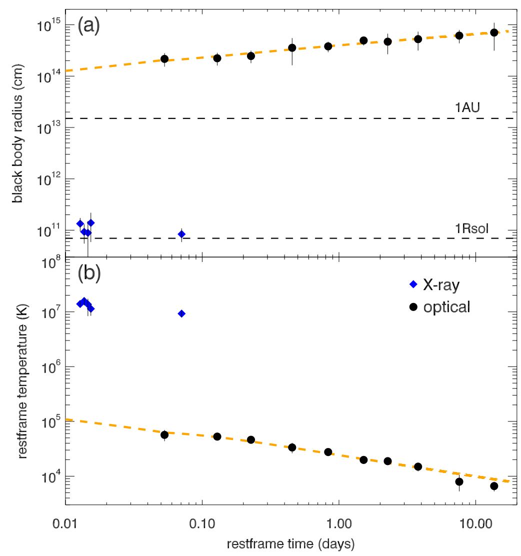

Fig. 2. Evolution of radius and temperature of the X-ray BB component and the UVOIR BB emission. The radius is determined assuming a redshift of z = 0.33 as described in the text.

(2000), although stretched with a factor of 1.25 in time and only 1/10th of its luminosity. For this, we use the SED at 40 days which also allows us an accurate determination of the redshift due to observations in two different r-bands that happen to fall on one of the broad SN emission lines and we obtain $z = 0.33^{+0.07}_{-0.04}$.

2.3. Host galaxy

Due to its proximity to the Andromeda galaxy, the field of GRB 101225A was covered in the PAnDAs survey (2000) carried out with the 3.5m CFHT/Hawaii. From this survey, we obtained a limit on an underlying host galaxy of i' >25.5 and g' >26.9. At 6 month after the burst, we reobserved the field with OSIRIS/GTC on 3 nights in g' and r' under good conditions with a total observing time of 4.1 h. An unextended object is detected in both bands with g' =27.21±0.27 and r' =26.90±0.14 (see Fig. 3). The object shows a blue color, consistent with a star-forming galaxy and lies well above the extrapolation of the lightcurve, we therefore propose this to be the host galaxy of GRB 101225A, confirming its extragalactic nature, in contrast to the model presented in (2000).

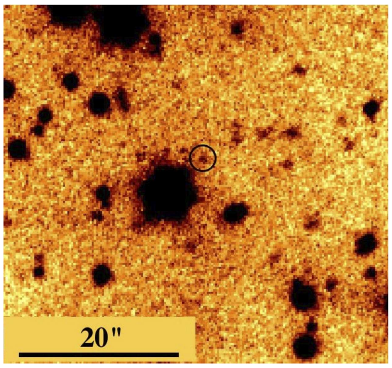

Fig. 3. Image of the host galaxy candidate in r'. The host is indicated with a circle.

3. Model

Our preferred model to explain all the observed features described above is a He-star - neutron-star binary merger which had been suggested as GRB progenitor in the past (2000). When the He-star leaves the main sequence, it expands and incorporates the NS, leading to a common envelope (CE) phase during which the He-star ejects most of its envelope in form of a thick shell. In our model, this shell forms a torus with a narrow opening (funnel) at the rotation axis.

When the two stars finally merge, an accretion disk and jet formation causes a GRB-like event, possibly with a magnetar as remnant explaining the prolonged emission. Only a small part of the jet escapes through the opening in the shell while most of it interacts with the previously ejected material. Backwards scattered material from the inner boundary of the envelope lead to a hot spot causing the X-ray emission. Most of the jet gets thermalized when interacting with the material in the wall of the funnels, creating the observed UVOIR BB emission when it breaks out of the shell. In the end, the weak SN produced by this progenitor (the progenitor naturally implies a small Ni production) overtakes the other emission components (see Fig. 4).

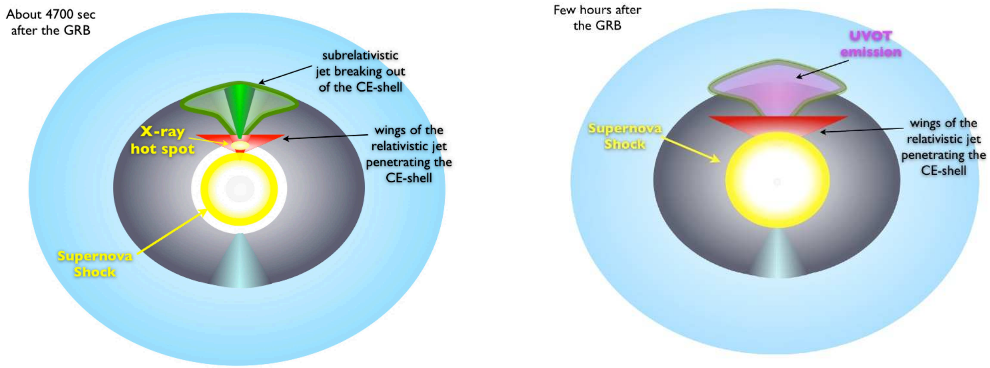

Fig. 4. Evolution of the different emission components from the GRB itself to the emerging of the supernova.

4. Conclusions

Our suggested progenitor model manages to explain all the observed features: 1. The prompt, very long γ-ray emission. 2. The X-ray BB with a small radius of $\sim$ 1 $R_\odot$. 3. The "afterglow", an expanding, cooling BB with an initial radius of $\sim$ 13 AU, starting while the X-ray BB component is still observed. 4. A late, faint SN emerging at around 10 d.

An X-ray BB component has been observed in 3 other bursts: XRF 060218 (2000), XRF 100316D (2000) and GRB 090618 (2000) with similar temperatures but somewhat larger radii, usually explained as shock breakout from the star or its wind. We reanalyzed the early optical data of XRF 060218 and SN 2008D (a Type Ib SN showing high-energy emission (2000)) and find a similar UVOIR BB component. GRB 090618 had a generic powerlaw afterglow (2000), for GRB 100316D, we do not have enough early optical data due to contamination from the host. GRB 101225A might not be the first observed of its kind, but shows some similarities with XRF 060218. The differences between these two events might be explained by a different progenitor. Due to its nonrelativistic nature, the observation of GRBs from this class would be rather difficult at higher redshifts.

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