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Supernovae and gamma-ray burst connection

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I review the status of the Supernova/Gamma-Ray Burst connection. Two decades of observations have established that long-duration Gamma-ray Bursts are associated with very energetic SNe-Ib/c. These SN explosions are produced by the gravitational collapse of Wolf–Rayet progenitors, with masses on the main sequence, between 30–50 $M_{\odot}$. Current measurements provide a GRB/SNe-Ibc ratio in the range ∼0.02–1.5%, so GRBs are very rare events, even when compared with the SN frequency. There is a minority fraction of long-duration GRBs with no accompanying SN that are likely produced during the merging of neutron star or white dwarf neutron star merger.

Keywords: Supernovae; gamma-ray bursts

1 Introduction

Supernovae (SNe) are historically classified into two spectroscopic types: Type I (hydrogen-poor) and Type II (hydrogen-rich). Although this pattern is 80 years old [42], it still reproduces the modern view of the SN phenomenon, which identifies two classes of objects. The distinction is based on the properties of their respective progenitors and on the explosion mechanisms. The first class is formed by the so-called thermonuclear SNe, nicknamed SNe-Ia. They are extensively used in cosmological studies. They are the result of the breakup of the white dwarf progenitor hosted in a binary system. Standard SNe-Ia are characterized by the strong Si II 6355 Å line observed in peak luminosity spectra at ∼6150 Å [14] and form a relatively homogeneous object class [2]. The second class is formed by the core-collapse SNe, originating from the gravitational collapse of the core of massive progenitor stars. These are further divided into types which exhibit spectra rich of H (SNe-II) or poor or without H, but with intense lines of He (SNe-Ib) or even without H and He (SNe-Ic). They formed the so-called "stripped" core-collapse SNe. A small fraction of these objects $<$ or $\ll$ 5% [24] has been found to be associated with long-duration GRBs.

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2 The pillars of SNe–GRB connection

The SN–GRB connection has been solidly established over the past 20 years using an impressive "plethora" of space- and ground-based telescopes. This conclusion is based on the following observational evidence:

(i) The discovery of about 60 SNe associated with GRBs [7, 32].

(ii) A few of them have occurred relatively close (within $z \sim 0.3$), therefore their spectroscopic and photometric follow-ups have been extensively studied [3, 5, 13, 20, 26, 35, 40, 41, 52, 67].

(iii) Observations of the SNe associated with GRBs show that their spectra are characterized by the lack of H and He and by "broad lines". The first characteristic allows us to classify the associated SNe as type Ic. The latter is interpreted in terms of Doppler effect, thus indicating very high ejecta expansion velocities, of the order of 30,000 km/s, i.e. three times larger than those observed in "standard" SNe-II. This fact has a very obvious implication: these objects are very energetic events, and this explains why they have been termed as Hypernovae (HNe).

(iv) Spectroscopic observations of the rebrightenings observed during the late stages of the afterglows of distant GRBs (up to $z \sim 1$) show the presence of SN features [9, 10, 28, 64].

(v) The host galaxies of long GRBs are star forming galaxies, mostly Irregulars or late Spirals, often characterised by disturbed morphology [12, 17].

(vi) GRB and SNe-Ic SNe occur in similar environments [31], i.e. in the HII regions, where star formation is very active. In other words, the progenitors of GRBs are born and die in the same places. This observation has an important consequence: these stars do not have time to significantly depart from their places of birth. Hence, their main sequence life must be on the order of a few 10^6 years. In turn, this fact implies that the mass of the progenitors should be in the range $\sim$30–50 $M_\odot$ [57].

(vii) The spectroscopic and photometric follow-up of the nearby events, complemented with the stellar evolution theory, have allowed us to provide direct measurements of the masses of the progenitors for a handful of objects, which are consistent with the masses estimated above [33, 37, 72].

Based on these pieces of evidence, there are several theoretical scenarios that have been conceived and refined over the past 20 years. These scenarios can be broadly divided into two families:

a) Long-duration GRBs are the product of the collapse of Wolf–Rayet stars (e.g. [74]) into a magnetar or a black hole (e.g. [39] and references therein). If the star rotates fast enough it avoids the red supergiant phase and directly becomes a WR, then it maintains a high angular momentum in the core because the huge envelope H does not form [73, 75]. Conservation of angular momentum is a necessary ingredient to produce a GRB because of the high energy emission, up to 10^{54} erg, which are expected to be powered by the rotational energy of the residual compact objects.

b) Long-duration GRBs are the products of the explosion of massive stars in binary systems, the so-called *binary driven Hypernovae* (BDHNe) scenario. This is a binary system consisting of a W–R star and a neutron star [59, 60, 61, 16]. In this case the ejecta produced by the explosion of the Wolf–Rayet progenitor (as SNe-Ic) triggers a hypercritical accretion process onto the NS companion which may collapse

into a black hole or a more massive neutron star and then emits a GRB. This second scenario is based on the fact that most massive stars live in binary systems [49].

3 The prototype: GRB 980425/SN 1998bw

GRB 980425 was discovered in ESO 184-G82 ($z = 0.085$) and was fainter by 4 orders of magnitude with reference to the "standard" reservoir of 10^{51} erg typical of cosmological GRBs [1, 15, 48]. The associated SN was classified as Ibc [51] and characterized by unusually high expansion velocity of the ejecta, of about 30,000 km/s. It has long been assumed that GRB 980425 was an outlier of the Amati relationship [1] and initially this observation was used to question the existence of a physical association between this SN and GRB 980425. However, in recent years [36] convincingly demonstrated that GRB 980425's apparent discrepancy with the Amati relationship was only the result of observational biases. Today GRB 980425/SN 1998bw is considered the prototype of the GRB–SN associations. Theoretical modeling of the light curve and spectra indicates that SN 1998bw is the product of the explosion of a star stripped of its H envelope, of about 40 $M_{\odot}$ on the main sequence (e.g. [46, 72]). Other authors [33] modeled the bolometric light curve of SN 1998bw with a smaller amount of ^{56}Ni ($\sim$0.4 $M_{\odot}$) by assuming that the SN explosion was highly asymmetric.

4 The size of the progenitor: GRB 060218/SN 2006aj

GRB 060218 was discovered by Swift at $z = 0.033$. This burst was unusually long, with $T_{90} \sim 2100$ s. Early observations carried out by the UVOT telescope revealed an emission peak first at the UV wavelengths and later in the optics [5]. Low resolution spectra obtained at VLT at the same epochs indicated the presence of an emerging SN (2006aj) characterized by broad emission lines similar to those observed in other GRB–SNe [52]. One of the most important features of this event is represented by the presence of a black body component observed in the XRT data, up to 10 ks, and in the UVOT data, up to about 100 ks. This thermal component shows a decreasing temperature and a quick increasing in brightness, which implies an increase in the apparent emission radius up to $\sim 3 \times 10^{14}$ cm in about 100 ks, corresponding to an expansion speed of the order of 30,000 km/s, which is similar to that observed in SN 1998bw and in other SNe associated with GRB. From the fit of the data, extrapolating backwards up to about 100 s from the gamma event, it can be inferred that the initial radius of the progenitor star was no more than 4×10^{11} cm, which is comparable to the size of a Wolf–Rayet star. For comparison, this size is about 100 times smaller than the size of the progenitor star of a typical SN-II (H-rich).

5 The link between SNe and hypernova

In January 2008 at 9.57 UT the X-ray telescope (XRT) aboard Swift detected GRB 080109 in the galaxy NGC2770. A rapid optical follow-up showed the presence of an

associated supernova, SN 2008D. The first spectra [70] showed broad absorption lines superimposed on a blue continuum. The lack of hydrogen or helium lines indicated an Ic-type classification, typical for GRB–SNe. The spectrum initially similar to that of SN 2006aj/GRB060218 showed an unusual development, it underwent a spectral metamorphosis: unlike other GRB–SNe the broad spectral features do not persist and soon disappeared, while the He I lines develop [38, 43]. Several authors [38, 68] have reproduced the spectral evolution and the light curve of SN 2008D through the explosion of a ∼25–30 $M_{\odot}$ main sequence star and $KE \sim 6{\times}10^{51}$ erg, only 8% of which related to material moving at $v > 0.1$ c. Its quick disappearance implies that the mass moving at high velocities was small, possibly of the order of 0.03 $M_{\odot}$. The kinetic energy of this event, computed assuming spherical symmetry, although smaller than the "canonical" $KE \sim 10^{52}$ erg associated with HNe, is definitely larger than that measured in "standard" core-collapse SNe.

The X-ray spectrum of SN 2008D can be fitted with either a simple power-law indicating a non-thermal emission mechanism or a combination of a black body ($T = 3.8 \times 10^6$ K) and a power law. In the latter case, the black-body contribution is a small fraction of the total X-ray luminosity (about 14%). The angular size of the emitting area (about 6° and radius $R \sim 10^{10}$ cm) is typical of GRB jets. GRB 080109 might be the breakout of a failed relativistic jet powered by a central engine. The jet failed because its energy was initially low or because it was damped by the He layer, which is normally absent in GRB–HNe [38]. This interpretation, in terms of a failed jet, is an alternative to the shock break-out scenario proposed by [66]. However, recent observations may have resolved this annoying ambiguity. In low-energy GRB–SN events such as GRB 080109/SN 2008D or even Hypernovae that are not associated with GRBs, the detection of an excess of high velocity material may be interpreted as a signature of "choked" jet [47, 54] which failed to emerge from the progenitor star because it has deposited most of its energy in a thermal "cocoon". This idea becomes much more than a simple hypothesis after the observation of an emerging "cocoon" in GRB 171205A/SN 2017iuk [27]. These authors showed spectra displaying features characterized by extremely high expansion velocities, ∼115,000 km/s within the first day after the GRB. Such 0.3 c velocities cannot be produced by the SN ejecta. In fact [27] using spectral synthesis models developed for SN 2017iuk, were able to demonstrate that these features are characterized by chemical abundances different from those observed in the ejecta of SN 2017iuk at a later time, indicating that the high-speed features were due to material coming from the innermost parts of the progenitor star [77].

6 Supernova and GRB rates

The rates of SNe-Ibc as determined by Asiago [8] and Lick [30] surveys converge towards $\sim 2.6{\times}10^4$ SNe Gpc^{-3} yr^{-1}. For long GRBs [25] found an average rate of 0.7 GRB Gpc^{-3} yr^{-1}. After combining these values together we find a ratio GRB/SNe-Ibc in the range 1.5–0.02% according to different values of the beaming factors: 500 [15] and 7 [55], corresponding to $\theta_{\rm jet} = 4°$ and $\lesssim 30°$, respectively. Radio surveys result in similar constraints: GRB/SNe-Ibc < 10% [65]. Several authors have noted that the volume sampled by sub-energetic GRBs is smaller, by a factor $\sim 10^6$, than

that probed by cosmological GRBs, therefore the number of sub-energetic GRBs may well be higher, even by orders of magnitude, than that of the more powerful "cosmological" GRBs. Finally, we note that the beaming factor range is only marginally due to uncertainties in the measurements, but rather reproduces a real range of values, probably related to the energetics of the GRBs. For example, [23] propose that the most energetic GRBs are characterized by the smallest values of $\theta_{\rm jet}$ and vice versa.

7 Long-duration GRBs without supernova

Observations of the long-duration GRB 060614 [11, 18, 19, 4] question the simple idea that all long-duration GRBs are produced by SNe-Ibc explosions. VLT and HST observations of this GRB indicated that the magnitude of any possible SN associated with it was at least 200 times fainter than that observed in other GRB–SN events. This result may suggest different scenarios, such as:

i) Most of the ^{56}Ni produced during the later stages of stellar evolution of the progenitor star is not ejected with envelopes, as observed in other SNe-Ibc associated with GRBs, but falls back into the newborn black hole. If this is the case, the only nickel that can escape from the exploding star is that which is confined in the jets, likely of the order of $\sim 10^{-4}\ M_{\odot}$. This fact would explain the extreme faintness of a possible SN associated with GRB 060614. This scenario received indirect support through the detection of some unusually faint core collapse SN [50, 71].

ii) The progenitor fails to explode as Supernova, and it collapses directly into Black Hole [22].

iii) Merging event [21, 4].

We note that there is growing evidence in favor of this latter scenario. After reviewing the optical afterglow data of GRB 060614 [29] found an excess of F814W bandwidth two weeks after the burst, which was interpreted, by these authors, as evidence for the existence of a kilonova associated with this GRB (see [63, 53] for an accurate description of the spectroscopic and photometric follow-up of the kilonova associated with GW170817 event). Very recently several teams (e.g. [76]) came to the same conclusion by observing the long-duration GRB211211A without accompanying SN.

Conclusions

Observations of GRBs over the past two decades have led to significant advances in our understanding of the GRB–SN phenomenon. Below I have reported the summary of the most prominent results:

i) Long-duration GRBs are linked to death of massive stars. This fact is demonstrated by: a) direct observations of a handful of nearby SNe-GRBs for which it was possible to extensively study their spectroscopic and photometric evolution; b) several dozen of rebrightenings were discovered during the final stages of the GRB afterglows. The luminosities of these "bumps" were well reproduced by adding a SN light curve component to the extrapolated afterglow light curves. In some cases, SN features were

observed in the spectra obtained during the rebrightenings; c) most host galaxies of long GRBs exhibit an intense star forming activity; d) GRB and SNe-Ic appear to be located in similar environments, i.e. in the star-forming regions of the hosts. This fact implies very short lifetimes, on the main sequence, for the GRB progenitors, of the order of $\sim$ a few 10^6 years, which in turn implies high values for their masses, on average in the range of 30–50 $M_\odot$.

ii) Observations of GRB 060218 indicate that the progenitor star of the associated SN (2006aj) had a radius of $\sim 4\times10^{11}$ cm. This is similar to the size of a Wolf–Rayet star and fully consistent with the fact that all GRB–SNe, so far observed, belong to Ic types, i.e., they are derived from the collapse of H/He stripped-off massive single stars in single or binary systems.

iii) Only 0.02–1.5% of SNe-Ibc (corresponding to $\ll$1% of all core-collapse SNe) are capable of producing GRBs. Therefore, there are some special circumstances which are required for a massive star to become a GRB progenitor. Several studies indicate that asymmetry in the SN explosions [33, 34, 44], rotation [73, 75], metallicity [17, 45], binarity [56, 62] may all play an important role [6].

iv) The discovery of GRB 060218 at $z = 0.03$ raised the interesting hypothesis that this type of "local" and low-luminosity GRBs ($<10^{49}$ erg s^{-1}) could be predominant over high luminosity "cosmological" GRBs ($>10^{51}$ erg s^{-1}). Since the volume sampled by low-luminosity GRBs is approximately 10^6 times smaller than that probed by cosmological GRBs, the number of the former could be far larger: they are probably the most common long-duration GRBs in the Universe.

v) GRB 060614 challenges the idea that all long-duration GRBs are produced in Supernova explosions: any possible SN associated with this GRB was at least 200 times fainter than other GRB–SNe. This fact may suggest that GRB 060614 was either the prototype of a new class of long-duration GRB which are produced in a new kind of massive star death ("dark" Supernovae), different from those producing bright SNe-Ibc. Oservations of GRB 060614 coupled with new observations on GRB 211211A and with the kilonova associated with GW170817 ([53, 63,78]) strongly support a more likely scenario, that is that GRB 060614 is in fact the product of the coalescence of compact stellar remnants (e.g. two neutron stars or a white dwarf Neutron star binary).

vi) Quite bafflingly, a short GRB with an associated core-collapse SN has been observed very recently [58]. The authors suggest that this could be a collapsar event that falls into the low tail of the duration distribution of long-duration GRBs.

At this point I wouldn't be surprised if more surprises were on the way ...

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