Swift, VLT and Gamma–Ray Bursts: The Richness and Beauty of the Global View

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In this paper we emphasise the role of ESO in the optical follow-up of gamma-ray burst light curves and the importance of early observations via rapid response mode. We describe some of the best short gamma-ray burst observations ever and illustrate the need for spectroscopic data. Specifically, we show how the exceptional dataset collected for the naked-eye burst GRB 080319B, the brightest burst ever, has proved very challenging for current theoretical models. The final aim is the understanding of the physical processes that make such phenomena the true beacons at the edge of the Universe.

How it happened

Heritage, know-how, creativity and organisation. Our previous experience with BeppoSAX and the related optical follow-up from the ground, taught us that we needed a very fast re-pointing of the spacecraft, multi-wavelength coverage and high sensitivity instruments. These goals were achieved in the design of the Swift satellite (Gehrels et al., 2004), where on-board decision-making successfully substituted for human intervention. But all of this would be completely useless without a fast and efficient communication system, able to deliver data and information all over the world. A gamma-ray burst (GRB) explodes: in a few seconds the Swift team has provided the astronomical community with the accurate position of the event, allowing ground-based telescopes to collect photons coming from the remote corner of the Universe where a giant explosion has just occurred. From the very first Swift meetings we realised that to achieve very fast Very Large Telescope (VLT) pointing, we needed not only a letter of intent from the ESO Director General (DG), but also a strategy. The Rapid Response Mode (RRM) was born: in this mode a VLT instrument is able to set on the target and start acquiring data less than seven minutes after an alert. This is a fantastic technical and organisational achievement by ESO. Essential for obtaining early data of objects characterised by a rapidly declining luminosity, the RRM gives the community the potential to understand the early physics of these events, with the final aim of using GRBs as beacons at the edge of the Universe. The primary need was to secure GRB redshifts, a task that has been fulfilled effectively by the various European teams with ESO as lead player on the scene (45–50 % of GRB redshifts have been obtained with ESO observations, see, e.g., Fynbo et al., 2007).

Figure 1. Organisation of GRB follow-up: ASI Science Data Center (ASDC) staff are involved in GRB science while the Malindi ground station is responsible for satellite duties and for the Swift-XRT (X-Ray Telescope) data analysis software. MISTICI (Multiwavelength Italian Swift Team with International Co-Investigators) and CIBO (Consorzio Italiano Burst Ottici) are the optical follow-up groups. Economic support comes mainly from ASI (Agenzia Spaziale Italiana) and MIUR (Ministero dell'Istruzione Università e Ricerca). The unique architecture of the ESO follow-up related to the Swift Mission was organised also thanks to the collaboration of the Directors General Riccardo Giacconi and Catherine Cesarsky and the unique technical contribution of Roberto Gilmozzi and Jason Spyromillio.

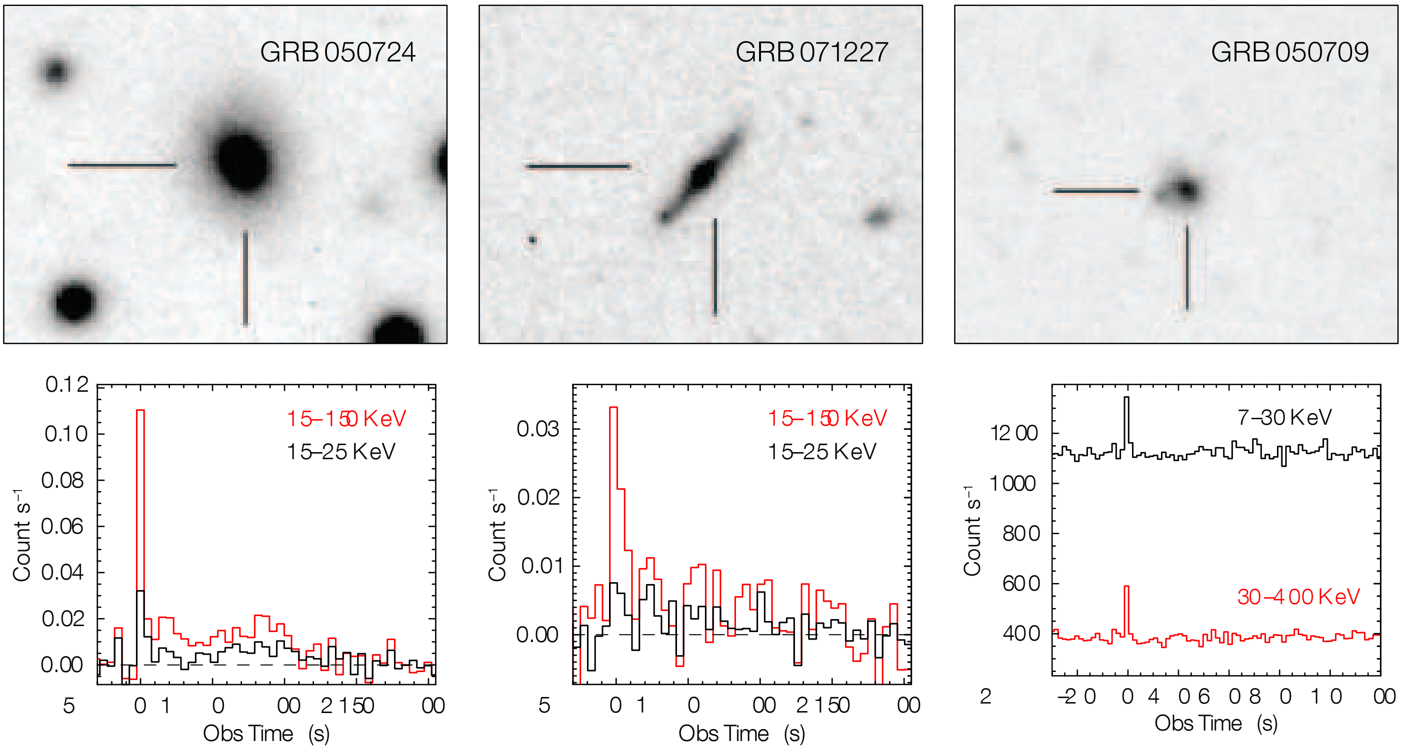

Figure 2. Top panels, from left to right: VLT observations of the host galaxies of the short GRBs, GRB 050724, GRB 071227, and GRB 050709. Bottom panels: prompt high energy emission coming from the same bursts; note the broad soft bump following the early short spike. GRB 050709 is a HETE (High Energy Transient Explorer) burst, the other two come from Swift.

But there was another requirement: the Swift UVOT (Ultra-Violet/Optical Telescope) instrument is not sensitive to wavelengths longer than 650 nm, and we considered it crucial to have observations reaching out to the near-infrared. Following some in-house discussions and early interactions with Catherine Cesarsky, the then ESO DG, we decided on a new concept for a robotic telescope in Chile on the ESO territory: the REM (Rapid Eye Mount) was born. Funded by the Italian MIUR, this telescope provided the opportunity to collect unprecedentedly early information on GRBs. Later a symbiotic telescope, the TORTORA (Telescopio Ottimizzato per la Ricerca di Transienti Ottici Rapidi) was added to this unit. This telescope — the result of a Russian–Italian collaboration — may be limited in sensitivity, but has the advantage of a very large field-of-view and of spectacular time resolution. The latter was of great advantage for the “naked eye burst”, GRB 080319B.

This short account gives a feel for how organised and synchronised the Swift and the Italian teams are. For a full appreciation of what we believe is a unique model of working collaboration and management, we show the follow-up organisation in Figure 1. This organisation, and the will to make it work, is what made and currently makes the research successful. In the following we will only discuss a few open issues and concentrate on a few results among many.

Morphology and progenitors

Morphology in any species, class of objects or natural phenomena is the result of heritage and of the mechanisms generating them. As in other cosmic objects, GRB morphology (GRBs are classified into long [LGRB] and short [SGRB] types according to the duration of the high energy initial event) is a consequence of the different progenitors, host galaxies and various physical mechanisms at work. LGRBs are likely due to the collapse of very massive stars ($M > 20M_{\odot}$), as testified by their association with core collapse supernovae (SN). No SN explosion has ever been observed in connection with SGRBs, which are believed to originate from the merging of compact objects (neutron stars or black holes, see, e.g., Nakar, 2007). LGRBs occur in late-type galaxies, but never in early-type galaxies. The prototype host of an LGRB is a young, blue, metal-poor and subluminous (about 0.1 L*) galaxy, with high specific star formation rate, but low mass. In contrast, SGRBs seem to span galaxies of various morphologies (see Figure 2); the model in this case is that of a hot and dense torus of 0.01–0.3 $M_{\odot}$ that is accreted onto a stellar mass black hole (BH). The high energy involved, (10^{46}–10^{50} erg after correcting for the jet opening angle) implies rather large accretion rates that call for an equally efficient cooling mechanism: neutrino cooling is the first candidate. While the occurrence of the jet is likely related to the asymmetry of the model, it still remains unclear how and if the late engine activity, testified by the presence of flares, might be related to the duration of the primary burst and to the viscous and gravitational instabilities of the disc.

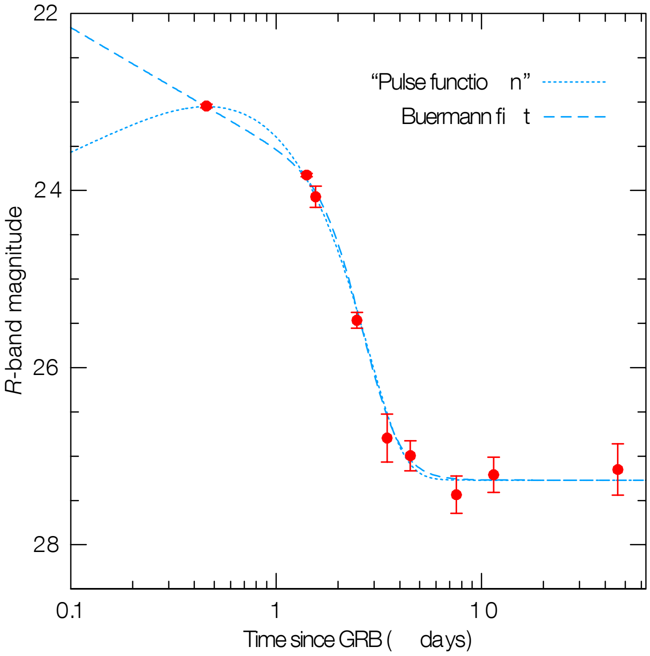

Figure 3. *R*-band light curve of the short GRB 070707 afterglow. Either a smoothly joined broken power law (dashed line) or a pulse function (dotted line) gives an equally acceptable fit. After ten days the flux levels off at the host galaxy contribution.

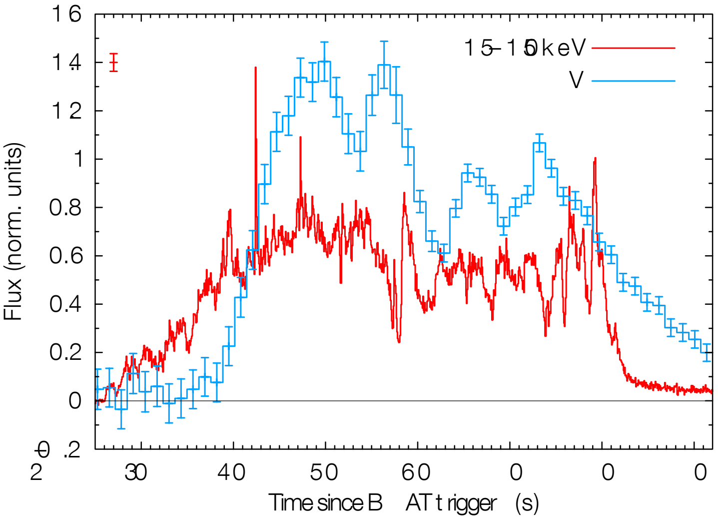

Figure 4. The GRB 080319B prompt emission is shown. In blue, the optical data collected by TORTORA; in red, the gamma-ray component (15–150 KeV) detected by Swift BAT (Burst Alert Telescope).

Nature does not fit into any particular classification scheme. In particular, the simple long–short dichotomy hides a more complex reality: how do we account for the broad and soft emission following, in some cases (see, e.g., Figure 2), the primary short pulse? This pattern requires a rather long-lasting activity of the central engine, a different progenitor model and perhaps a new classification scheme. What we do know is that in all these cases — and for SGRBs in particular — optical observations are fundamental. Such observations enable direct information to be gained on the host galaxy (HG) morphology, on the interstellar medium properties and the progenitor parent population; then indirectly we constrain the jet structure and the physical mechanisms at work, with the final aim of understanding the nature of the central source that powers these explosions. This raises the question of whether we really need the VLT and the RRM?

The answer is unequivocally, yes, since we have no optical spectrum of an SGRB to date. Moreover, we need high resolution spectroscopy, fast photometry and polarisation information: fast reaction from an 8–10 m telescope is therefore crucial. The best-sampled SGRB afterglow optical light curve comes from GRB 070707, from ESO–VLT observations (Piranomonte et al., 2008): the light curve displays an initial slow decay that becomes significantly steeper, beginning one to two days after the explosion, and later levelling off at $R = 27.3$ (see Figure 3). This is most likely the HG emission level, the faintest yet detected for an SGRB. Unfortunately, due to the low signal-to-noise ratio, spectroscopic observations did not reveal any line feature or edge able to constrain the redshift, so that only an upper limit ($z < 3.6$) can be inferred from the lack of Lyman limit suppression down to 420 nm.

As with a number of other SGRBs, the nearly unconstrained redshift of GRB 070707 remains an important handicap. These strong limitations bias and constrain our knowledge: not only do we not know clearly the nature of the progenitors and of the physical processes at work, but we are still unable to say whether these merging events originate in galaxies or in extragalactic globular clusters. The SGRB research field is currently one of the most intriguing; progress can only come by setting on the target with large optical telescopes as soon as possible after the burst, and then following the light curve evolution with multicolour observations down to the limits of the telescope sensitivity.

The naked eye burst GRB 080319B

"The simplicity offers us the possibility to enter a rich field of physical processes and to challenge our understanding, leading us to a beautiful variety of observable effects." R. Sunyaev

The extremely bright GRB 080319B is a showcase for the role of follow-up observations. The data from the ESO facilities provide an example of the key observations of this burst, while the international collaboration demonstrated how sharing data, ideas and expertise often leads to unique and rapid results. The Italian robotic telescope REM was pointing at GRB 080319A at the time it received the alert for GRB 080319B. It automatically started slewing to the new target, but TORTORA with its wide field of view and high time resolution, happened to be imaging the burst location from before the time of explosion. This observation, the first of this quality since GRBs were discovered, revealed that the optical flux was too bright to be the extrapolation of the high energy (0.3 keV–1.16 MeV) tail.

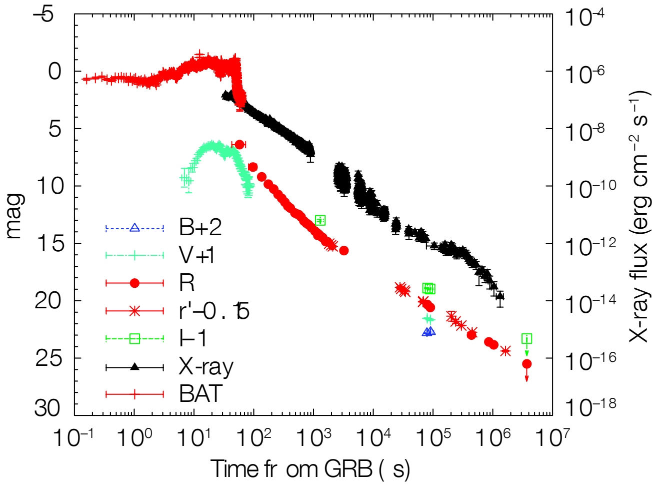

Figure 5. Broadband light curve of GRB 080319B, including radio, NIR, optical, UV, X-ray and gamma-ray flux densities. Data have been renormalised for graphical purposes.

The observations also showed some temporal coincidence of the bright optical flash and the gamma-ray emission. The prompt optical flux profile is broadly correlated with the gamma rays, sharing a comparable duration, rise and decay times, with the first half brighter than the second. A visual inspection of Figure 4 suggests a delay of a few seconds in the arrival times of the optical photons with respect to the gamma rays. A possible interpretation invokes the former being produced by synchrotron radiation, which is initially self-absorbed (thus explaining the later rise of the optical flux), while the latter are up-scattered photons via synchrotron self-Compton (SSC). But there is an aspect missing: relativistic electrons up-scatter the low energy photons turning them into gamma-ray photons (first inverse-Compton, IC) while the same electrons will further scatter these high energy photons, kicking them into the TeV range (second IC). This emission could be detected by Cherenkov ground-based telescopes (e.g. MAGIC) or, at lower energies, by the Fermi satellite.

Following the first phases, REM and TORTORA had to hand the baton on to larger telescopes and in particular to the VLT, which then allowed the community to follow the event down to very faint magnitudes. The Swift X-ray telescope (XRT) was gathering data at the same time. As is apparent from Figure 5, this burst shows a completely different behaviour in the optical and the X-ray ranges, suggesting that they must stem from different emitting regions. A possible explanation requires the action of a two-component jet: a, highly relativistic jet with a very narrow opening angle (0.2 degrees) pointing to the observer that is responsible for the prompt gamma emission via internal shocks, and coaxial with a wider jet (opening angle 4 degrees). In this picture the afterglow is the result of the forward and reverse shocks from both the narrow and wide components. While this model is not unique and has a few caveats, it is the most likely interpretation — a product of the joint efforts of a worldwide collaboration (Racusin et al., 2008).

The power of the VLT/UVES (Ultraviolet and Visual Echelle Spectrograph) rapid response mode has also been fully exploited for the observation of this GRB (D’Elia et al., 2008). We were able to observe the spectrum just 8 minutes 30 seconds after the trigger, at a time when the magnitude was R ~ 12, obtaining the best ever signal-to-noise, high resolution spectrum of a GRB afterglow. We caught the absorbing gas in a highly excited state producing the strongest Fe II absorption line ever observed. More to the point, we witnessed the local effects caused by the GRB explosion, enabling the study of the evolution of the interstellar medium (ISM) parameters.
A few hours later the optical depth of the lines was reduced by factors of 4–20 and the optical UV flux by a factor of ~ 60.

GRB 080319B does not show any kind of plateau or flares in either the X-ray or the optical light-curves. While affecting about half of the GRB X-ray light-curves, flares seem to be sporadic events at optical wavelengths, a spectral range where statistics are currently lacking, especially at later times. The power of multi-wavelength observations is testified by GRB 060418 and GRB 060607A for which we have contemporary REM near-infrared (NIR) and XRT X-ray data.
The early X-ray light curves of both events show several, intense flares superimposed on a smooth power-law decaying continuum. On the other hand, the flaring activity, if any, is much weaker at NIR frequencies: the NIR curve is very smooth with peaks at 153 s and 180 s for GRB 060418 and GRB 060607A respectively. This implies an initial bulk Lorentz factor of 400, confirming the highly relativistic nature of GRB fireballs. From our multicolour observations we were able to firmly establish that late engine activity, as exemplified by the X-ray flares, does not affect the optical light curve in the same way: at 800 s after GRB, when both the NIR and X-ray light curves are decaying regularly, the spectral energy distribution is described by a synchrotron spectrum, so no SSC need be invoked.

Multi-wavelength follow-up is therefore crucial both at early and late times.

Towards new challenges

Wavelength coverage and spectral resolution are key ingredients for understanding the different aspects of an astrophysical process. At the same time, an accurate temporal analysis of the GRB light curves represents a powerful tool for obtaining a deeper insight into the physics underlying these explosions. The fireball model is able to account for the vast majority of the observations, but other models are not ruled out. In particular, we would like to stress that the magnetar model, where the jet is Poynting flux dominated and the small baryon loading is naturally explained, has not yet been fully investigated (Lyutikov & Blandford, 2004). The determination of the relevant time scales in different wavelength ranges could help in distinguishing between competitive models, while the accurate study of the time variability could reveal particularly interesting information on the source that powers this

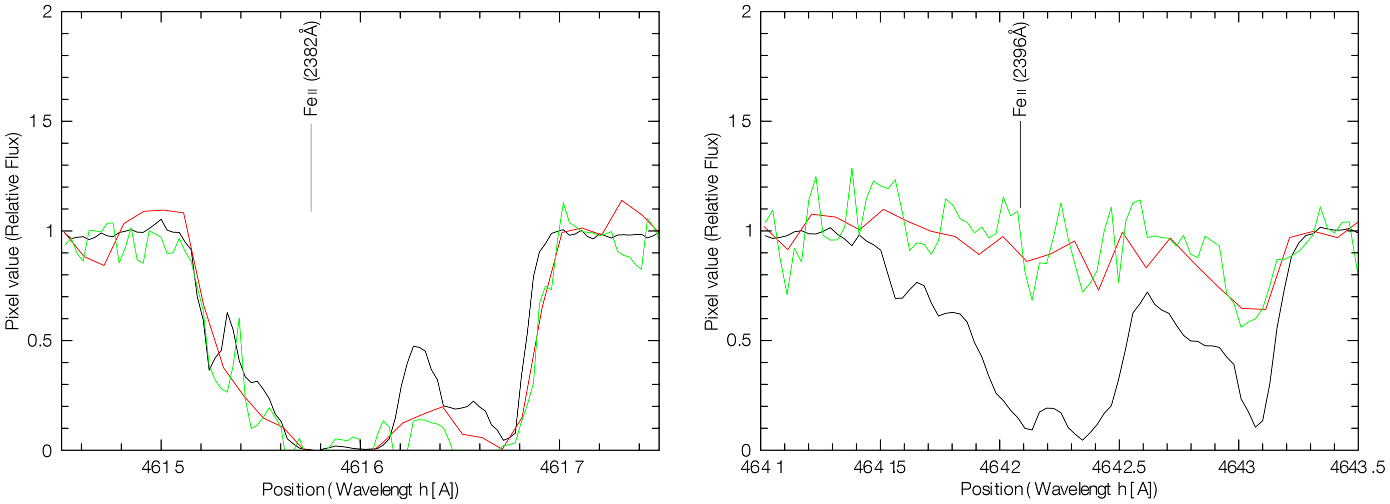

Figure 6. UVES spectra of GRB 080319B around the Fe II 2374 Å (left panel), and Fe II 2396 Å (right panel) transitions. Black lines refer to the first epoch spectrum (8 minutes 30 seconds after the Swift trigger); red lines refer to the second epoch spectrum (1.9 hours after the GRB event); green lines refer to the third epoch spectrum (2.9 hours after the GRB onset).

kind of explosion. More specifically, the details of the time structure are invaluable footprints of the original mechanism at work, being determined by a combination of intrinsic properties (cooling mechanism, jet profile, energisation, etc.) and of extrinsic properties (viewing angle effects, intervening absorption). Investigation of these details calls for high time resolution, multi-wavelength observations.

GRBs are aperiodic short-term events, with a temporal structure that represents a challenge for standard temporal analysis techniques: while a fraction (about 15 %) of the gamma-ray prompt emission consists of a single smooth pulse, the vast majority appear to be the result of the random superposition of a number of emission episodes. A pulse decomposition of the entire light curve is often difficult and in bright bursts the pulses are often blended, while in most dimmer bursts the low signal-to-noise prevents any kind of pulse-by-pulse study. For this reason we decided to develop a completely different kind of analysis.

A modified version of power spectrum analysis in the time domain, formerly developed by Li (2001), has been applied to the prompt and afterglow emission of GRBs: unlike the Fourier transform, this technique is suitable for studying the root-mean-squared (rms) variations of a completely aperiodic signal at different time scales. This method has the advantage of being completely model-independent. GRB 080319B is a showcase for the application of this technique to the prompt gamma-ray emission and the study of GRB 080319B high energy data shows the evolution of the characteristic time scale of variability from 0.1 s at the beginning of the emission up to 1 s at the end of the prompt event. Moreover, an energy-resolved analysis reveals that the variability time is strongly energy dependent. The same kind of analysis could be applied to high time resolution optical data. GRB 080319B showed the extraordinary importance of high time resolution multi-wavelength observations: it was the simultaneity of high time resolution optical and gamma-ray observations that gave us the unprecedented opportunity to study the underlying emission mechanism in detail. High time resolution optical observations, able to record the flickering behaviour of the light curve, are therefore of primary importance. This was understood even at the time of the REM design; however, contrary to earlier expectations, most afterglows are already faint a few minutes after the explosion, so that we soon realised that it would be very difficult to collect good quality data (except of course for GRB 080319B-like events, where brightness and luck played a major role). The implications are that large area robotic telescopes are fundamental.

Prospects

We have described a few of the many interesting results obtained for GRBs. The final goal — the real source that powers the bursts — is still elusive. The new Fermi mission will certainly add a wealth of information, owing to the spectacular high energy coverage. The coupling with Swift will provide unique broadband spectroscopic information, settling the long-lasting question about the mechanism for the prompt radiation (synchrotron or SSC). Furthermore, within a few years, LIGO (Laser Interferometer Gravitational Wave Observatory), Virgo and other facilities will open up the new observational window of gravitational waves. Their detection will constitute the real proof of the collapse of massive stars, SNe and the merging of relativistic objects. In the meanwhile VLT and the other extremely large telescopes will drive human knowledge on towards new challenges.

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