The future of GRB investigation from ground and space

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I will describe the prospects for future investigations of gamma-ray bursts (GRBs) in the ‘electromagnetic’ domain, by giving a brief overview of some near future facilities. I will discuss in some detail one of the most (if not the most) exciting perspective in the field, the use of GRBs as cosmological beacons.

Keywords: gamma-ray bursts; gamma-ray burst afterglows; cosmology

1. Introduction

The study of gamma-ray bursts (GRBs) has largely expanded from its original niche and it is now encompassing several other fields of astrophysics, fundamental physics and cosmology. It includes and has implications on stellar evolution and collapse, UHE and cosmic ray acceleration, interstellar medium, quantum gravity, gravitational radiation and several topics related to cosmology such as the history of metals and star formation, the dark early Universe and reionization, the cosmic network of baryon accretion onto dark matter structures and dark energy. These different ramifications of the GRB research are at different stages of development, ranging from a well-established research track to very promising perspectives. In the first part of the paper, I will give a brief overview on future experiments and facilities relevant to the GRB science. I will focus mostly on the classical electromagnetic domain, given that neutrino, VHE, GW have been summarized in this colloquium by Waxman (2007), Chadwick (2007) and Hough (2007), respectively. Throughout the paper, main emphasis is given to the future perspectives of GRB in cosmology that will be the explicit subject of the second part of the paper. In this context, I will present a mission under study, explorer of diffuse emission and GRB explosions (EDGE), explorer of the diffuse emission and GRB explosions (formerly ESTREMO/WFXRT).

2. An overview of near future facilities

In the radio range the LOFAR array is being constructed in The Netherlands, with a projected goal of starting first operations with a reduced set of antennas in 2007. The experiment will operate in two modes. At low frequencies (30 MHz), a central...
concentration of dipoles (‘virtual core’) and multiple beams provide LOFAR with the potential to monitor two-thirds of the sky daily. In this all sky mode, it reaches a sensitivity of approximately 10 mJy. This is probably too shallow to detect GRB radio afterglows. Nonetheless, there exist interesting prospects to detect radio emission connected with the earlier phases of the GRB phenomenon. For example, Hansen & Lyutikov (2001) have examined the possibility of radio emission from NS–NS coalescence. They model the system as a conducting sphere (one neutron star) moving through an external magnetic field (due to the other neutron star). They compute induced currents and the acceleration of charged particles drawn off from the neutron star, and by assuming the energy of the charged particles is converted to radio waves with the same efficiency as in pulsars, they predict detectable radio emission at LOFAR frequencies at the level of a few mJy.

At higher frequencies (200 MHz), the sensitivity is approximately 100 uJ, thus good enough to detect radio afterglows or to set significant upper limits. In this case, the sky coverage is more limited but the beam can be rapidly reoriented on the sky (through software phase change) towards the direction of the GRB. So far, most radio measurements of afterglows have been carried out above 1 GHz. The extension of broadband spectral information below this frequency is particularly important because it should allow measurement of the synchrotron self-absorption frequency and its evolution with time. This provides, in turn, a constraint on the density of the environment and its profile.

Indeed, progenitors of long GRBs are expected to have undergone vigorous wind ejection. However, the broadband afterglow modelling has not shown a strong preference for this case (Painatescu & Kumar 2002). Chevalier & Li (1999) have proposed one solution to this problem, where the wind profile extends up to a maximum radius (termination shock) beyond which a constant density profile takes over. In this scenario, one would expect that the afterglow evolution tracks a wind profile first, and then an ISM profile. Evidence of such a case has been recently proposed for GRB050904 (Gendre et al. in press), but more cases are needed to consolidate the scenario. The other puzzling issue is the very large dispersion of the density values derived from the broadband modelling (Painatescu & Kumar 2002) and the typical values which are much lower than expected from star forming regions. In this respect, the measurement of the synchrotron self-absorption frequency is once more particularly important.

In fact, the synchrotron absorption frequency is primarily dependent on the density of the environment, expressed by $n$ for the ISM and $A_*$ for the wind case, and on the efficiency $\epsilon_e$ in producing non-thermal electrons. Neglecting the mild dependence on $E_{53}^{1/5}$ (taken equal to 1) for the ISM and $E_{53}^{1/5}$ (taken equal to 0.01) for both density profiles, it is obtained that (Painatescu & Kumar 2000)

$$v_a \approx 3n^{3/5} \epsilon_e^{-1} \text{GHz}, \quad (2.1)$$

for the ISM case and

$$v_a \approx 4E_{53}^{-2/5} A_*^{6/5} \epsilon_e^{-1} t_d^{-3/5} \text{GHz}, \quad (2.2)$$

for the wind case. The two equations above show that, for typical parameters, $v_a$ is expected to be in the GHz region and that it is almost linearly dependent upon the density. Furthermore, the two profiles can be easily disentangled, owing to the different evolution with time. In the ISM case, $v_a$ remains constant while for the wind, it should decrease with time.
In the context of broadband afterglow modelling, measurements in the millimetre and submillimetre range are particularly important, because the peak of the spectrum is expected to be located in that frequency region over a time-scale of days. First of all, a measurement in this range constrains the overall shape of the spectrum below the peak frequency, hence improving the determination of $n_a$. Furthermore, the peak flux is directly related to the density of the environment, being $F_m \propto A_t t_d^{3/2}$ for the wind (e.g. Chevalier & Li 1999) and $F_m \propto n^{1/2}$ for ISM (Sari et al. 1998).

Present measurements (e.g. Smith et al. 2005; Tanvir & Jakobsson 2007) are sparse, with just a few detections and several upper limits at a sensitivity level around a mJy. Submillimetre observations (of the host galaxy) also are of key importance because they provide estimates of the (obscured) star formation rate. The spectra of luminous star forming galaxies detected by SCUBA are dominated by a peak close to 100 um. This feature is produced by reprocessing of the optical and UV radiation emitted by hot young stars that is absorbed by dust and re-radiated at longer wavelengths.

SCUBA has discovered submillimetre bright galaxies out to high redshift (Blain et al. 2002). The relatively small population of extremely luminous dusty galaxies (with luminosities of several $10^{12} L_\odot$) may dominate the total star formation in the Universe at early epochs. If GRBs strongly trace star formation, many of them should be located in such galaxies. The present submillimetre sample of GRB host galaxies, however, shows a deficit of bright sources when compared with the expectation (Tanvir & Jakobsson 2007). More generally, GRB hosts do not appear to be consistent with being typical submillimetre bright galaxies. However, there could be selection or systematic effects in both samples. For example, a substantial contribution to the energy output of the SCUBA-bright galaxies from active galactic nuclei. Furthermore, the GRB present sample (Tanvir et al. 2004)—mostly derived from optically detected afterglows—may be biased against dusty hosts and against high-redshift galaxies.

A dramatic improvement in this range is foreseen with the deployment of ALMA (Europe, USA) in 2011. The array will cover the range from 30 to 950 GHz, with a sensitivity of 60 uJy at 230 GHz (Bachiller et al. 2001). This should allow the detection and flux monitoring of essentially all GRB afterglows and a good characterization of the submillimetre properties of GRB host galaxies (given that the sensitivity limit corresponds to a ‘normal’ galaxy with a luminosity of $10^{11} L_\odot$). The detection of dusty star forming galaxies (whether connected with GRBs or not) can be extended up to very high redshift, $z=20$, in the dark Universe. In fact, the large negative K-correction induced as the wavelength of the observation is redshifted up the Rayleigh–Jeans slope of the thermal dust emission peak overcomes the effect of the inverse square law and cosmological dimming. In practice, the flux density measured in the submillimetre range is almost independent of redshift in the range $z\approx 0.5$–20. Furthermore, the redshift can be measured directly by ALMA using molecular transition lines available (e.g. CO, CII), without resorting to optical spectroscopy (not possible anyway at $z\gtrsim 6$).

The James Webb Space Telescope (JSWT) will provide another milestone in the study of the early Universe and the formation of the first assembly of galaxies. The JSTW is an infrared-optimized (0.6–29 um) 6.6 m space telescope by NASA with major contributions by ESA and CSA, with a launch in 2014. The science case is described by Gardner et al. (2006). To find the first galaxies,
the JWST will make ultra-deep near-infrared surveys of the Universe, and follow-up with low-resolution spectroscopy and mid-infrared photometry. The direct detection of an individual pop III star is not feasible, as even a 1000 $M_\odot$ star at $z=30$ would have an AB mag of 36. However, the JWST could detect the Super Nova associated with the explosion of a massive primordial star or dwarf galaxies made of pop III stars. The prospects for using GRBs as cosmological beacons for the study of the early Universe and its evolution will be discussed in §3.

Next in the list of approved ground or space based facilities to be deployed in the near future are two high energy missions. AGILE is an Italian small satellite to be launched in 2007 (Tavani et al. 2006). The two main instruments are a silicon-tungsten tracker, covering the range 30 MeV–50 GeV and an X-ray coded-mask imager, SuperAGILE, working in the 15–45 keV range with a FOV of 1sr and 1–2 arcmin location accuracy. In addition, a minicalorimeter provides an independent trigger in the range 0.5–100 MeV. The main asset of AGILE is the capability to measure and localize (in X-rays) GRBs detected in the GeV range. Approximately 10–20 GRBs per year are expected. Some of these, depending on the observability, will be followed up with Swift.

GLAST (Michelson 2001) is a US (NASA, DoE) mission, with contributions by Italy, France, Japan, Sweden and Germany. The LAT instrument is a silicon/tungsten tracker covering the 20 MeV–300 GeV range with arcmin location capability. The GBM is a scintillator (10 kev–30 Mev). Approximately 60 GRBs per year are expected to be simultaneously present in the FOVs of LAT and GBM, thus allowing very broadband spectral measurements. Approximately 20–30 GLAST GRBs per year are expected to be followed up with Swift. We note, in particular, that a simultaneous coverage in the GeV range by GLAST or AGILE and in X-ray by Swift can be crucial in assessing the origin of the GeV delayed emission (Hurley et al. 1994) and its possible connection with X-ray flares (Galli et al. 2006; Wang et al. 2006).

(a) GRB-related projects under study

Here, we briefly mention projects in different stages of maturity but not yet approved, aimed to study primarily GRBs in X-rays or gamma-rays.

SVOM/ECLAIR is a France–China small satellite under study based on a combination of instruments covering the keV–MeV range with the addition of an optical telescope (Schanne et al. 2005). The main goals are the broadband spectrum of the prompt emission, including the study of XRF, and their localization to the arcmin level.

Lobster (Fraser et al. 2002) is an experiment, originally proposed for the ISS by the UK, which is now under study in the context of the ‘new’ Spectrum X-gamma mission in collaboration with Russia and Germany. The payload will include a GRB monitor. The instrument is aimed to perform a sensitive soft X-ray all-sky survey, based on Lobster-type optics. This should provide, in particular, important clues on the existence of (X-ray) orphan afterglows, i.e. GRBs seen off axis.

PHAROS (Elvis et al. 2004), studied in the context of MIDEX US future calls, is aimed to use GRBs as cosmological beacons by performing high spectral resolution of X-ray afterglows with gratings.

In §3, we will describe in more detail a mission under study in the context of the future call by ESA for Cosmic Vision 2015–2025.
3. Cosmology with GRBs

(a) High-z GRBs

The possibility that GRBs are present at very high redshift gained much attention with the recognition of a population of dark events from the early BeppoSAX sample, and now by SWIFT, that accounts for 20–40% of the total. The argument is that an event at $z \gtrsim 5$ is optically dark due to the Ly$_\alpha$ forest absorption. Other explanations that have been proved in some cases, include dust obscuration, optical underluminous afterglows or simply observational bias. However, the SWIFT discovery GRB050904 at $z \approx 6.3$ is definitively supporting the view that some of the dark GRBs are at high $z$. Indeed, it has been estimated (Bromm & Loeb 2002) that ca 10–20% GRBs should lie at $z \gtrsim 5$. Hence, it is likely that we have already observed and localized some GRBs at $z \gtrsim 10$, but we simply do not recognize it because we do not know the redshift. In this respect, it is important to note that both BeppoSAX and SWIFT have shown that more than 90% of GRBs have an X-ray afterglow. Thus, the only way to measure a redshift at $z \gtrsim 5$ is through X-ray or infrared observations.

Here, we will briefly discuss the perspectives in the long wavelength domain, and turn to X-rays in §4. A photometric or spectroscopy redshift (through absorption measurements) requires a high ‘fluence’. This can be achieved in the infrared either by a fast (minute) observation with relatively small telescopes (of the 1 m class) or with large telescopes (e.g. VLT) on a somewhat longer time-scale (10 min, as already implemented). It looks more effective (time-wise and budget-wise) to concentrate efforts on ground-based IR capabilities (and committing more time of large telescopes with relatively fast reaction) rather than aiming to a fast reaction IR telescope in space. In addition, as mentioned before, important prospects will be opened by ALMA by measuring the (submillimetre) redshift of (GRBs) host galaxies and by the JWST in the infrared.

(b) Explorer of diffuse emission and GRB explosions

Tracing cosmic history, from present ages back to the time when the first objects ignited ending the dark era of the Universe, is one of the major goals of Cosmology and Astrophysics. The interplay (feedback) between star-size sources and the largest structures in the Universe is an important element that influences their evolution. X-ray observations by the mission described below can provide privileged and unique information in this respect, by relying on two cosmological probes: large scale X-ray structures (cosmic web and clusters) and GRBs.

The explorer of diffuse structures and GRB explosions (EDGE, a joint mission concept stemming from ESTREMO/WFXRT (Piro et al. 2006), NEW (Den Herder et al. 2006) and DIOS (Ohashi et al. 2006) with contributions from UK, France, Denmark and USA) is being studied in the context of the ESA Cosmic Vision 2015–2025 call. The mission profile is based on two complementary capabilities.

— Observing and surveying through an X-ray telescope with a wide field of view and with high sensitivity extended sources, i.e. cluster of galaxies and the warm hot intragalactic medium.
— Observing with fast reaction GRBs at their brightest levels, thus allowing high resolution spectroscopy. For example, a mid-bright afterglow observed within a minute from the trigger (and for approx. 50 ks) would yield millions of counts with a 1000 cm\(^2\) telescope and, in particular, thousands of counts in 1 eV resolution bin.

Here, we will discuss in more detail the use of GRB as cosmological probes. In this respect, the main goals of the mission are the following.

— The filamentary network of baryons. The formation of cosmic structures is one of the most important topics in current research. Theoretical models based on hydrodynamical numerical simulations (e.g. Cen & Ostriker 1999) predict that the majority of baryons in the local Universe resides in large-scale structures, the so-called warm hot intergalactic medium (WHIM). Since baryons make up only 5% of the total mass/energy of the Universe, the evolution of large-scale structures is mostly determined by dark matter, which constitutes 25% of the total mass/energy of the Universe. Baryons that fall in the dark matter potential wells are heated up to X-ray emitting temperature \(10^5\)–\(10^7\) K. Thus, X-ray observations play a fundamental role in characterizing the formation and evolution of large-scale structures. In the current framework of WHIM mission concepts, three alternative observational approaches can be considered: (i) spectroscopy of WHIM absorption features against a bright background source, in particular GRB afterglows with microcalorimeter detectors (or gratings), (ii) spectroscopy of WHIM emission features with an array of microcalorimeters, and (iii) mapping of WHIM emission with a low background wide field detector (at CCD-like spectral resolutions). Clearly, a mission able to exploit simultaneously all three observational strategies would allow a major step forward. This is the case of EDGE.

For what regards specifically absorption studies with GRBs, EDGE is expected to detect OVII absorption lines in hundreds of filaments (figure 1) and to measure two or more different lines in a substantial fraction of them, thus allowing a physical and chemical characterization of the WHIM (figure 2).

— History of metal enrichment in star-formation sites and galaxies. GRBs (in their long flavour) are associated with the explosion of massive stars in star-formation sites. A large fraction of GRBs shows intrinsic (i.e. \textit{in situ}) absorption, of the order of a few \(10^{22}\) cm\(^{-2}\) (Stratta et al. 2004; Campana et al. 2006). By exploiting the large area of EDGE, its fast reaction capability and the spectral resolution, it will be possible to measure metal edges in a large sample of GRBs (figure 3). This will allow the achievement of two major results. First, a direct measure of the redshift, including events in the dark region of the Universe \((z=7\,\text{--}\,20)\), at least for those with a metallicity larger than approximately one-tenth of the solar one (figure 4). Second, the measurement of metal abundances as a function of redshift for a numerous sample of sites (approx. 150) from the local Universe up to a redshift of six (the highest \(z\) determined so far for a GRB \(z=6.3\)), possibly beyond (see next point). It is worth noting that this information can be compared with the metal abundance derived by EDGE in large-scale structures, i.e. WHIM and clusters of galaxies, providing an important element in understanding the processes leading to the metal enrichment on different cosmological scales.

\textit{Phil. Trans. R. Soc. A} (2007)
The dark Universe at $z \geq 7$. According to the theory the very first stars (pop III) formed approximately 180 million years after the Big Bang. They were very massive ($\gtrsim 100$ solar masses) objects so that in a few millions years collapsed and exploded, probably producing a GRB (Woosley & Zhang 2007). The explosion enriched with metals their environs for the subsequent generation of stars, and led to the formation of primordial black holes, seeds of the huge black holes now found at the centre of nearly all galaxies. The only mean to detect the early populations of stars in the foreseeable future is through their explosive end. Indeed, it is expected that a substantial fraction of GRBs lies at redshift greater than 7 (e.g. Bromm & Loeb 2002) so, as mentioned above, we should have already seen some of them, but we miss the redshift information. The measurement strategy employed by EDGE should allow the direct measurement of the redshift of those early explosions (subsequent to the zero metal first stars) if the metallicity in their environs is approximately one-tenth the solar value (figure 4) or larger. In this respect, it is worth noticing that the strong intrinsic X-ray absorption (which is due to metals) in the spectrum of the highest redshift GRB050904 (Gendre et al. in press; Cusumano et al. in press) sets a lower limit of approximately one-tenth to the metallicity of this burst at $z = 6.3$.

Dark energy. The prospect of using GRBs as standard candles (i.e. deriving their luminosity through observables) to measure cosmological parameters, in particular dark energy, is consolidating (Ghirlanda 2007). Essentially, the
Figure 2. Simulation of an absorption spectrum observed by EDGE towards an afterglow with a fluence of $4 \times 10^{-6}$ erg cm$^{-2}$ (i.e. a mid-bright afterglow observed from 1 min to approx. 60 ks). The spectrum corresponds to one random line of sight through a WHIM derived from hydrodynamical simulations (M. Viel et al. 2006, private communication) and extends to a maximum redshift of 0.5. In this case, different lines from two filaments at $z = 0.26$ and 0.46 are detected. Note that the small equivalent width requires a high spectral resolution (2 eV).

Figure 3. Simulation of X-ray edges produced by metals (Si, S, Ar, Fe) by a medium with column density $NH = 5 \times 10^{22}$ cm$^{-2}$ with solar-like abundances in the environs of a bright GRB at $z = 5$, as observed by EDGE (1 min to 60 ks).
same sample of GRB available from studies mentioned above and with a good determination of $E_{\text{peak}}$ will provide the information needed to test and implement the study.

In addition to the cosmological use of the GRB, the capabilities of the mission will provide new insights into the physics of GRBs and akin explosions. In this respect, the low energy (X-ray) extension of the Wide Field Monitor will allow the localization (and thus follow up with the X-ray telescopes) of not only GRBs but also XRFs. Furthermore, the high energy extension will allow a precise measurement of $E_{\text{peak}}$ also for the hardest GRBs. It is expected to obtain a sample of approximately 200 events (from XRFs to GRBs) fully characterized in terms of their prompt properties ($E_{\text{peak}}$, Energy), afterglow and redshift.

The mission and payload configuration is summarized below.

— Wide field monitor in the X/hard-X range with $\approx 2$ arcmin localization accuracy, a field of view of 3 sr with extension to MeV for spectral measurements.

— A spacecraft equipped with fast (min) and autonomous slewing to carry out the follow-up observations of GRBs with narrow field instruments.

— An X-ray telescope (1000 cm$^2$) with transition edge sensor (TES) microcalorimeters, devoted to high resolution spectroscopy (0.1–3 keV range, 2 eV resolution).

— A wide field X-ray telescope with a similar area with a polynomial mirror profile, assuring a constant point spread function (HEW = 15") over the entire 1° field of view and with a CCD on the focal plane. This telescope is tailored to observations of extended faint structures (most of the diffuse XRB is resolved) and cluster survey.

— Low background: 600 km equatorial orbit.

— VEGA launcher (2 tons in equatorial orbit).

Figure 4. Capability of measuring the redshift (X-axis) and metallicity (Y-axis) for two bright afterglows with a column density NH = 5 × 10$^{22}$ cm$^{-2}$, GRBF = 1 × 10$^{-5}$, $Z$ = 0.1, NHGal = 2 × 10$^{20}$ and a metallicity one-tenth of the solar value. (a) $z$ = 5, min = 1.747 × 10$^3$, levels = 1.750 × 10$^3$, 1.752 × 10$^3$, 1.756 × 10$^3$. (b) $z$ = 10, min = 1.815 × 10$^3$, levels = 1.817 × 10$^3$, 1.820 × 10$^3$, 1.824 × 10$^3$. The figures show the error contour plots at 68, 90 and 99% levels.
4. Conclusions

One of the most important open issues in the GRB field is the energy source of the explosion (the central engine) and of the progenitor. In this regard, it is important to recall that our view to the central source is not direct. The information carried by photons in the GRB and afterglow phases is, according to the fireball model, produced on a scale that is much larger than the central source. Inferring the origin of the central source is thus to be derived by gathering and analysing indirect information, such as the environment, the density profile, the host galaxy types, the location on GRBs in their host galaxies, the connection with SN and the X-ray flares as a possible indication of a long duration engine. In this respect, the new observing facilities mentioned above will assure a substantial, yet progressive, improvement in the field.

Conversely, observation of gravitational waves can open the perspective of a detection of unambiguous and direct signatures of the formation of the central engine. There are two caveats though. First, present estimates assume an efficiency that—at least for the merger and ring down phase—may be optimistic. Furthermore, no events in our own Galaxy have been detected so far, although this may be due to the short time LIGO and VIRGO have started operations.

GRBs are very powerful cosmological probes. Present investigation is already bringing important results in this respect. The prospects for the future are very bright. We expect a big step forward in the study of the high redshift Universe and the reionization epoch, the evolution of star formation and history of metal production, the baryon cosmic web shaped by the dark matter and the dark energy. To achieve these goals would require a significant step in space experiments, as outlined here. However, the information provided by GRBs will be, in several respects, unique, while in others will be complementary and synergical with that provided, e.g. by ALMA and the JWST.

References


Phil. Trans. R. Soc. A (2007)


