Gamma-ray bursts with SKA

Alberto J. Castro-Tirado[1,2], Javier Gorosabel[1,3,4,†] Bin-Bin Zhang[1], Samantha R. Oates[1], Soomin Jeong[1], You-Dong Hu[1], Rubén Sánchez-Ramírez[1,3,4] and Juan Carlos Tello[1]

[1] Instituto de Astrofísica de Andalucía (IAA-CSIC), P.O. Box 03004, 18080 Granada
[2] Unidad Asociada Ingeniería de Sistemas y Automática (ISA-UMA), Universidad de Málaga, C/. Doctor Ortiz Ramos s/n (Campus de Teatinos) 29071 Málaga
[3] Unidad Asociada Grupo Ciencias Planetarias (UPV/EHU, IAA-CSIC), Departamento de Física Aplicada I, E.T.S. Ingeniería, Universidad del País Vasco (UPV/EHU), Alameda de Urquijo s/n, E-48013 Bilbao
[4] Ikerbasque, Basque Foundation for Science, Alameda de Urquijo 36-5, E-48008 Bilbao
[†] Deceased on April 21, 2015

Abstract

The unique capabilities of SKA will allow us to study the different phases of the GRB afterglow emission with unprecedent sensitivity to determine the afterglow properties and the radiation mechanisms.

1 Introduction

Gamma-ray Bursts (GRBs) are transient events with the bulk of the emission arriving as high energy photons lasting 0.1-100 s that originate at cosmological distances with energy releases of 10^{49}–10^{51} ergs considering that the emission is collimated.

The multi-wavelength emission (from radio to X-ray wavelengths; i.e., the “afterglow”), that follows the gamma-ray emission satisfies the predictions of the ”standard” relativistic fireball model [3], which generally decays rapidly as $t^{-2\sim-1}$. These detections have recently been possible for more afterglows due to the rapid and precise localization capabilities of the *Swift* satellite [1].

There is a bimodality in the burst duration distribution [2], with short bursts (lasting < 2s) and long bursts (lasting > 2s). As a matter of fact, long-duration GRBs, those usually lasting more than 2s, have been found at redshifts in the range of z = 0.1-9. The central engines that power most of these extraordinary events are linked to the explosion of massive stars [4] related to highly energetic type Ibc supernovae and can be used as tracers of star formation and as beacons to point to the location of these high-z galaxies, thanks to their extreme luminosities (with energy releases of 10^{51}–10^{53} ergs). On the contrary, short-duration GRBs have been found in galaxies with different morphology and with no underlying supernova. The merger of two compact objects is the preferred model.

The aforementioned "standard" relativistic fireball model considers a black hole as the end product of either the collapse of a massive star or the merger of two compact objects.

The collimated ejecta, which are launched by the black hole central engine, expand outward relativistically with Lorentz factors Γ of several hundred initially. Internally, the ejecta release their energy through internal shocks [7, 6, 5], magnetic dissipation (e.g, ICMART model; [8]) or photospheric dissipation (e.g., [9, 10, 11, 15, 12, 13, 14]) and produce the prompt γ-ray emission of GRBs. Externally, the ejecta are further decelerated by an ambient medium (e.g., a constant density interstellar medium, ISM; or a stellar wind environment with density inversely proportional to distance squared) and produce long term broadband afterglows through external shocks (see e.g., [16], for a review). The accelerated non-thermal electrons give rise to the typical synchrotron spectrum [20, 19], which is theoretically expected to be accompanied by an SSC (synchrotron self-Compton, [18, 17]) component.

Early observations of the afterglows allow to provide redshifts and additional spectral information about the host galaxies. This is most essential as some of these galaxies (the ones a $z > 6$) are responsible of a significant proportion of ionizing radiation during the reionization era.

2 GRB observations at radio wavelengths

Since the detection of the first afterglow at radio wavelengths in 1997 [21], more than 100 afterglows have been detected so far at these frequencies. Most of them have been achieved for long-duration GRBs (with a success detection rate of 1/3) whereas only very few radio afterglows for short GRBs have been detected.

Observations are normally performed within 0.1-100 days after the trigger with a predominant frequency of 8.4 GHz, but other frequencies (4.8 GHz, 1.4 GHz) have been also used to constrain the spectrum. Radio observations do not need to be performed as fast as those at shorter wavelengths because the peak of the synchrotron spectrum moves to the radio wavelengths in timescales of few days. The low detection rate (compared to optical/nIR afterglows) is due to the lack of sensitivity of most facilities as μJy is required to detect most radio afterglows.

Amongst the most important results obtained so far, we highlight the following: i) radio scintillation (GRB 970508, [21]) which showed that the outflow is relativistic; ii) the late time ($\sim$100 days) flattening of the light curve (GRB 980703, [22]) has been interpreted as the jet becoming nonrelativistic; iii) late time (100 – 450 days after the burst) radio calorimetry for several events (GRB 030329, [23] amongst others) sets some constraints on the total kinetic power of the jet; iv) the observation of a ultra-high redshift event (GRB 090423A, [24]) was interpreted as the reverse shock emission; v) radio monitoring of local SN Ibc has put some constraints on the GRB/SN association ([25]); and vi) the detection of a few GRB hosts [26] in the radio band has provided an estimate of the host unobscured star formation rate.

3 Expected results from the SKA study of GRBs

3.1 Early time (1-30 days) observations

- The reverse shock. Reverse shock and self-absorption effects are important in the early phase of GRB afterglow in the radio and sub-mm regime. For ultra-high redshift (z > 5) events, observations within ~ 1 day might reveal the rapidly decaying reverse shock emission, as was attributed to GRB 090423A. This will help to constrain some of the unknown parameters such as the fraction of the shock energy in electrons and post-shock magnetic field (ϵ_B/ϵ_e).

- The forward shock. At early times (few days post burst), the radio afterglow emission is suppressed by synchrotron selfabsorption until (due to expansion) the emitting region becomes optically thin and the flux peaks (typically around 10 days with a flux density of $\sim$100 μJy). After the peak, the flux decreases as t^{-2} until the outflow becomes non-relativistic (at $\sim$ 100 days with a flux density - e.g. at 8.5GHz - of few μJy). According to the expected MeerKAT and full SKA (SKA phase 2) continuum sensitivities, $\sim$ 70% and $\sim$95% of the long-duration burst population can be detected by MeerKAT and SKA2. In the case of short-duration events, the number of radio afterglows to be detected by MeerKAT and SKA2 should significantly increase on the basis of the improved continuum sensitivities, with respect to the low detection number currently.

3.2 Late time (30-300 days) observations

According to the standard afterglow model, the outflow should become nonrelativistic (NR) at $t_{NR} = 275(1 + z){E_{53}}^{1/3}n^{1/3}$ and a flattening of the radio emission is predicted following a temporal decay index variation $\Delta\alpha = (21 - 5p)/10$ where p is the slope of the electron energy distribution at the shock front. This can vary if there is a steep electron energy distribution differing than the canonical value $p = 2.2$ or if the surrounding medium is not a constant density one such as a wind-profile medium (resulting of the late stages evolution of Wolf-Rayet massive star progenitor). According to the expected sensitivities, MeerKAT will be able to monitor $\sim$10-15% of the events whereas SKA2 will be able to monitor the trans-relativistic transition up to $\sim$50% of the events detected at earlier times.

3.3 Very late time ($>$300 days) observations

Several hundred days after the initial explosion, the host galaxy flux will dominate the overall *radio emission* and the properties of the GRB host population and of the burst environment will allow us to use GRBs to trace the cosmic star formation history up to very high redshifts. Assuming a typical SFR and a typical spectrum we expect that the host galaxies should have typical fluxes between 0.01 and 0.5 μJy. Whereas MeerKAT sensitivity is likely too low, we estimate that SKA will be able to detect $\sim$ 50% of the host galaxies.

Thus, in conjunction with other multi-wavelength observations, MeerKAT and SKA observations of GRB will allow us to address fundamental physics questions such as:

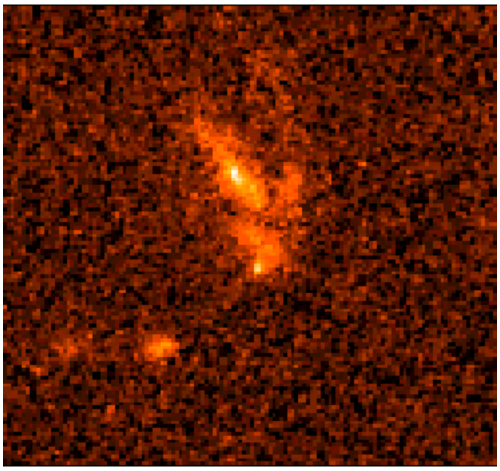

Figure 1: The host galaxy of GRB 990123 as imaged by *HST* on 23 March 1999. The optical afterglow (the faint point source close to the centre of the image), which reached V = 8.9 simultaneously to the burst, faded to V=27.7 by that time [30]. A break observed in the light curve $\sim$ 1.5 days after the high energy event suggested for the first time the presence of a beamed outflow in a GRB [29, 30, 31].

- What is the range of GRB explosion energies? For every GRB, the following six observables can be measured: the synchrotron peak, break and self-absorption frequencies, the maximum flux and the power-law decay exponent (all from the multi-wavelength spectrum) and z (from optical or X-ray spectroscopy). The properties of the blast wave can be derived from the classical synchrotron spectrum produced by a population of electrons with the addition of self absorption and a cooling break. This will allow us to obtain the total energy per solid angle, the fraction of the shock energy in electrons and post-shock magnetic field, and the density of the ambient medium (e.g., [28, 27]).
- What is the environment of the circumburst medium? This can be addressed by performing a detailed study of the time evolution of the multi-wavelength afterglow emission over the first 2-4 weeks after the event. This will enable us to trace the evolution of the characteristic synchrotron self-absorption frequency, the peak frequency and the peak flux density. Taken together, this can constrain the different theoretical models (eg. homogeneous or wind-generated ambient media with a spherically symmetric outflow; a relativistic collimated outflow, etc).
- What is the nature of "dark" GRBs? These are a fraction of long-duration events ($\sim$20-30%) that remain undetected at optical wavelengths. A radio detection will determine the position of the optically obscured GRBs with better accuracy than high-energy (X-ray telescopes and gamma-ray detectors) can provide, thus pinpointing the host galaxies of a fraction of dark events even if no afterglow is found at optical wavelengths. In principle one should expect that bright X-ray afterglows to be accompanied by strong radio afterglows, according to the canonical model, but the recent claim of significant absorption in the X-ray spectra of GRB afterglows makes this statement inconclusive.

- Are high-z events a different population? The nature of the GRB explosions at z > 5 may trace the first generation of massive stars and their host galaxies, may show distinct properties.

4 Conclusions

The fundamental topics mentioned above will be addressed by MeerKAT and SKA thanks to their broad-band coverage and unprecedented sensitivity. This will be complemented with all other available data regarding both the prompt gamma-ray emission and and the afterglow emission from X-rays to optical/nIR and mm wavelengths. The Spanish community should should take the advantage of having access to the largest optical telescope in the world (GTC) as well as additional Spanish ground-based facilities (optical/nIR: Calar Alto, mm: 30 m PV) and other resources worldwide (optical: BOOTES robotic telescope network; optical/nIR/mm: ESO; mm: PdBI). The expertise we have gathered over the last 20 yr will allow to better understand the most energetic phenomena in the Universe (after the Big Bang), taking advantage of the unique capabilities of the SKA.

Acknowledgments

We acknowledge the support of the Spanish Ministry grant AYA2012-39727-C03-01.

References

[1] Gehrels, N., Chincarini, G., Giommi, P., et al. 2004, ApJ, 611, 1005

[2] Kouveliotou, C. et al., ApJ, 413, 101

[3] Meszaros, P. and Rees, M.., 1993, ApJ, 405, 278

[4] Woosley, S. E. 1993, ApJ, 405, 273

[5] Daigne, F., & Mochkovitch, R. 1998, MNRAS, 296, 275

[6] Kobayashi, S., Piran, T., & Sari, R. 1997, ApJ, 490, 92

[7] Rees, M. J., & Meszaros, P. 1994, ApJ, 430, L93

[8] Zhang, B., & Yan, H. 2011, ApJ, 726, 90

[9] Lazzati, D., & Begelman, M. C. 2010, ApJ, 725, 1137

[10] Ryde, F., et al. 2010, ApJ, 709, L172

[11] Ryde, F., et al. 2011, MNRAS, 415, 3693

[12] Guiriec, S., et al. 2010, ApJ, 725, 225

[13] Guiriec, S., et al. 2011, ApJ, 727, LL33

[14] Guiriec, S., et al. 2015, arXiv:1501.07028

[15] Pe'er, A., & Ryde, F. 2011, ApJ, 732, 49

[16] Gao, H., Lei, W.-H., Zou, Y.-C., Wu, X.-F., & Zhang, B. 2013, New Astronomy Review, 57, 141

[17] Kumar, P., & McMahon, E. 2008, MNRAS, 384, 33

[18] Panaitescu, A., & Mészáros, P. 2000, ApJ, 544, L17

[19] Medvedev, M. V. 2000, ApJ, 540, 704

[20] Meszaros, P., Rees, M. J., & Papathanassiou, H. 1994, ApJ, 432, 181

[21] Frail, D. A., Kulkarni, S. R., Nicastro, L., Feroci, M., & Taylor, G. B. 1997, Nature, 389, 261

[22] Frail, D. A., Yost, S. A., Berger, E., et al. 2003, ApJ, 590, 992

[23] van der Horst, A. J., Kamble, A., Resmi, L., et al. 2008, A&A, 480, 35

[24] Chandra, P., Frail, D. A., Fox, D., et al. 2010, ApJ, 712, L31

[25] Soderberg, A. M. 2006, Gamma-Ray Bursts in the Swift Era, 836, 380

[26] Berger, E., Cowie, L. L., Kulkarni, S. R., et al. 2003, ApJ, 588, 99

[27] Ryan, G., van Eerten, H., MacFadyen, A., & Zhang, B.-B. 2015, ApJ, 799, 3

[28] Zhang, B.-B., van Eerten, H., Burrows, D. N., et al. 2014, arXiv:1405.4867

[29] Castro-Tirado, A. J. et al. 1999, Science, 283, 2069

[30] Fruchter, A. et al. 1999, ApJ, 519, L13

[31] Kulkarni, S. et al. 1999, Nature, 398, 389