Gamma-ray bursts and afterglows

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Gamma-Ray Bursts (GRBs) are brief, intense flashes of gamma rays, going off at a rate of about one per day all over the sky. For thirty years after their discovery in 1967, the origin of these events has remained a mystery. Hundreds of events were observed by several experiments, but all the information was essentially limited to the few seconds of intense gamma-ray activity, after which the GRB vanished in the background, with no measurable sign of activity at other wavelengths. The lack of any measurement of the distance has left the field open for about a hundred different models as to their origin. The isotropic distribution of these events in the sky measured by the BATSE experiment on board of the Compton Gamma-Ray Observatory was suggesting an extragalactic origin, but a direct determination of the distance of even a single event was lacking.

Establishing the cosmic distances to gamma-ray bursts

A *fast and precise* position of GRB was needed, where the *Holy Grail* of GRB scientists, i.e. *the counterpart*, could have been searched for at all wavelengths. This became possible within a year after the launch on April 30, 1996, of the Italian-Dutch satellite BeppoSAX, named after Giuseppe (Beppo) Occhialini, one of the fathers of high energy astrophysics in Italy. The poor positional accuracy of Gamma-ray instrumentation is circumvented by associating to a monitor of gamma-ray bursts (GRBM, which provides the temporal signature of a GRB), two wide-field X-ray cameras (WFC), able to locate the GRB within 3', in a field of view of 40° × 40°. A deep search of the afterglow emission of the GRB is then carried out with a set of more sensitive, narrow-field (~ 1°) X-ray telescopes (NFI), by re-orienting the satellite towards the location provided by the wide field instruments. On February 28, 1997, the gamma-ray burst GRB970228 was detected by the BeppoSAX GRBM and localized by the WFC. The NFI were pointed to the GRB location 8 hours after burst, leading to the discovery of a previously unknown X-ray source. The new source appeared to be fading away during the observation. On March 3, another observation confirmed that the source was quickly decaying: at that time its flux was a factor of about 20 lower than at the time of the first observation. This was the first detection of an "afterglow" of a GRB (Fig.1). While the X-ray monitoring of GRB970228 was going on, numerous observatories probed the location of the GRB, which had been provided by the BeppoSAX team, at all wavelengths. This campaign led to the discovery of an optical transient associated with the X-ray afterglow by a group led by Jan van Paradijs. Yet, the crucial information on the distance of the GRB was still missing. On 8 May 1997 the second breakthrough came with another BeppoSAX GRB: GRB970508, which was observed by the BeppoSAX NFI 5.7 hours after the burst, and by optical telescopes starting 4 hours after the burst. The early detection of the optical transient, and its relatively bright magnitude permitted a spectroscopic measurement of its optical spectrum with the Keck telescope by a team led by S. Kulkarni. The spectrum revealed the presence of absorption lines at a redshift of $z = 0.835$, produced by the gas of the galaxy hosting the GRB, and therefore demonstrated that GRB970508 was at a cosmological distance. As of today, we have measured the distance of 20 GRB, and all of them are in distant galaxies.

The BeppoSAX observation of GRB970228 and GRB970508 have also changed the old concept of a brief - sudden release of luminosity concentrated in few seconds by a GRB. The energy produced in the afterglow phase turns out to be comparable to that of the GRB. The afterglow emission is found when the GRB signal disappears, and lasts for days or even months, decreasing in time according to a power law (Fig.2). These properties are nicely accounted for by the fireball model, proposed by M. Rees, P. Meszaros and others. At cosmological distances the observed fluxes correspond to a luminosity in gamma-rays of $\sim 10^{53}$ erg/s concentrated in a region of the order of a few light seconds. Under such conditions a *fireball* of gamma-rays and electron-positron pairs develops. The initial radiative energy released by the central source is converted to kinetic energy of a shell which expands with relativistic motion (Lorentz factor $\gamma \sim 100$) up to a size of $\sim 10^{16\text{-}17}$ cm, where it converts its energy back into electromagnetic radiation (i.e. the GRB and its afterglow).

GRB970508 was the first GRB in which a radio afterglow was discovered by D. Frail and collaborators. But, even more importantly, this measurement yielded direct evidence of a relativistically expanding source, in nice agreement with the fireball scenario. The GRB of December 14, 1997 localized by BeppoSAX introduced a new issue. At a redshift $z = 3.42$ (that corresponds to a look-back time of about 85% of the present age of the Universe), its luminosity would have been about 3×10^{53} erg/s, if the emission were isotropic. Currently, we have other examples of even more luminous GRB. The most extreme is GRB990123. With an isotropic luminosity of $\sim 10^{54}$ erg/s, this explosion would have produced an energy in gamma-rays equivalent to the mass-energy of the Sun. No other known phenomenon in the Universe can compare with this luminosity, but the Big Bang. Indeed, assuming isotropic emission, the energy required, is so high that another possibility needs to be considered. A jet, i.e. a

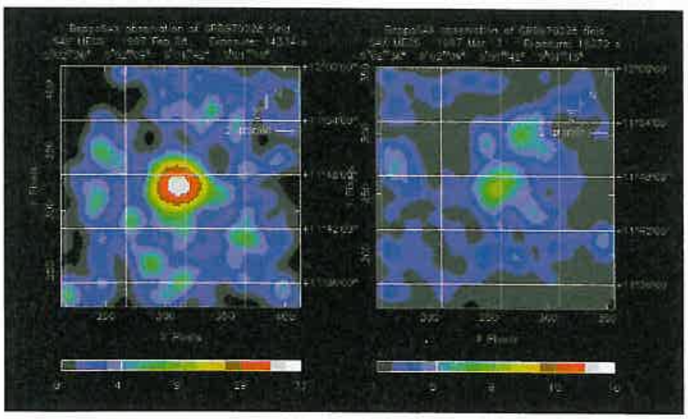

Fig. 1: The discovery of the first X-ray afterglow of a Gamma-Ray Burst: the event of Feb. 28, 1997. The figure shows the image in the 2-10 keV range obtained by the X-ray telescopes of BeppoSAX. A previously unknown bright X-ray source was visible 8 hours after the GRB (left panel). Three days after (March 3. Right panel), the source had faded by a factor of about 20.

collimated outflow of material producing radiation beamed towards us within a narrow cone, would decrease the energy requirement by a factor proportional to the solid angle of the jet. Some observational evidence suggests a presence of a jet in some, but not all GRBs.

The nature of gamma-ray-burst progenitors

Whether a jet is present or not, the energies required are still compatible with bursts arising from stellar progenitors, which undergo a catastrophic explosion at the end of their evolution. One family consists of very massive stars, usually referred to as *hypernovae* or *collapsars* after B. Paczinsky and S. Woosley. Another consists of a binary system formed by neutron stars or a neutron star- black hole. The end-product of the evolution of both families of *progenitors* is a black-hole surrounded by a disk of very high density. The energy that can be tapped out of this system by extracting either the gravitational energy of the torus or the energy of e.g. a rotating black hole, is comparable to that implied by observations. The radiation physics and energy of all mergers and hypernovae are then, to order of magnitude, the same, so other elements are needed to disentangle the nature of GRB progenitors.

This information can be derived from the study of the GRB environment. In the case of a hypernova, the massive star evolves very rapidly (~ 10^6 years) and therefore GRB should go off in the same site where the progenitor was born, i.e., in a star-forming region. On the contrary, neutron star-neutron star coalescence happens on much longer time scales (billions of years) and the kick velocity given to the binary system by two consecutive supernova explosions should bring a substantial fraction of these systems away from their formation site. In the case of massive progenitors, the large radiation field of hard X-ray photons produced by the GRB, would ionise the surrounding medium, leading to the production of lines, the most prominent being the iron K_α line in X-rays. On the contrary, GRB produced by mergers should go off in a clean environment, and no line is expected. Evidence of iron features in the X-ray spectra of GRB has grown in the last years. Early marginal detections in two GRB by BeppoSAX and the Japanese X-ray satellite ASCA in 1997-1998, have been followed more recently by measurements in other events, like that observed by BeppoSAX in GRB000214 and by the American X-ray satellite Chandra in GRB991216. These measurements are consistent with the line being produced by a material predominantly made up by iron lying within a light day or two of the GRB and with a mass approximately equivalent to one-hundredth that of the Sun. The line width observed by Chandra also indicates that the material is moving very quickly (at approximately 10 percent the speed of light) and that it was probably pre-ejected by the GRB. There is further evidence in agreement with these findings. At early times, during the GRB itself, the photons having an energy near to that needed to ionise the iron atoms, are absorbed by the gas, until the atoms are fully stripped of their electrons. If the gas lies in the line of sight, we then expect to see an iron absorption edge appearing for only a few seconds during the burst, as found in GRB990705 by BeppoSAX. These observations are strongly suggesting that the progenitor of the GRB was very a massive star, but the details of the process require more data and theoretical computations. The large content of iron and the velocity of the ejecta also suggest that the ejection of the material was similar to a supernova explosion.

The extraordinary advances in the GRB field over the last years have also opened new areas of investigations. What is the origin of *GHOSTs* (GRB Hiding Optical Source Transient), a.k.a. *dark GRB*, i.e., events without optical afterglows? If GRBs are indeed associated with massive progenitors and therefore lie in regions of star formation, it is likely that the optical emission is heavily absorbed by dust in a large fraction of events, while the more penetrating X-rays escape the region and are therefore observed. It is also possible that the optical emission is completely absorbed by the intragalactic gas between us and the GRB, that would set the distance of dark GRB at a redshift $z > 5$. BeppoSAX has also revealed the existence of another new class of events, the so-called *X-ray rich GRB*, characterized by a very faint gamma-ray flux. An intriguing possibility is that these events are located at such large distances ($z > 10$) that the Hubble expansion shifts the peak of the spectrum from gamma-rays into the X-ray range. Finally, very little is known on *short GRB*, i.e. events lasting less than 1 sec., since no counterpart has been so far identified.

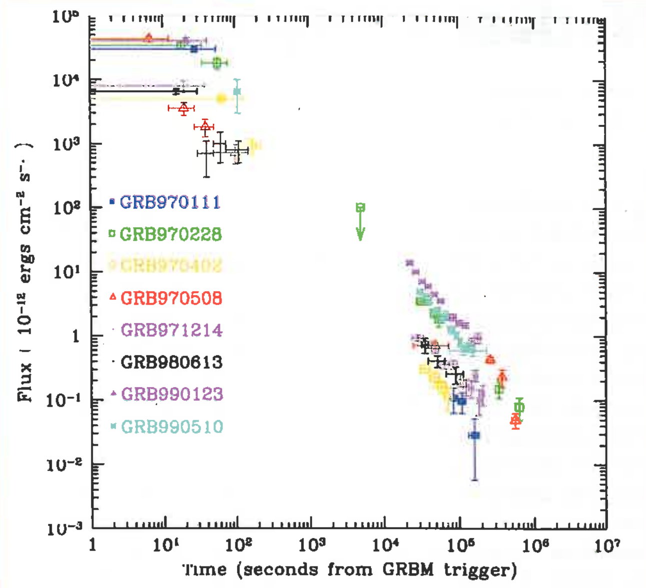

Fig. 2: The X-ray light curves of a sample of afterglows by BeppoSAX. The data points at t<100 sec are gathered by the Wide Field Cameras, that catch the GRB in action. The position derived from these instruments is then followed up by the more sensitive X-ray telescopes, few hours after the GRB (data points in the lower-right part of the image). Note that the light curves follow a power law curve over a range of 6 orders of magnitude in flux and time.

Using gamma-ray-bursts to probe the early Universe

The luminosity of GRBs is so high that they can be detectable out to distances much larger than those of the most luminous quasars or galaxies observed so far. We expect thus, in the near future, to use GRB as beacons to probe star and galaxy formation at much earlier epochs of the Universe evolution, by studying the features imprinted over their spectrum by the gas through which they shine. The future of the GRB field is indeed rich in expectations. The satellite HETE2, launched in Oct. 2000, will transmit the position few seconds after the event for about 20-30 GRB per year. The satellite SWIFT, to be launched in 2003, will provide multi-wavelength data within a minute of the GRB for hundreds of events.

Updated information can be obtained at:
www.ias.rm.cnr.it/sax/grb1.html