The Discovery of Gamma-Ray Bursts

The serendipitous discovery of Gamma-Ray Bursts (GRBs) in the late sixties puzzled astronomers for several decades: GRBs are pulses of gamma-ray radiation (typically lasting for a few seconds), with a non-thermal (broken power-law) spectrum peaking at $\sim$10–300 keV, and can be seen a few times a day **from** random directions (eg. Band et al. 1993; Kouveliotou et al. 1993; Meegan et al. 1992). Their spectacular nature, the more recently-established origin in the distant Universe, and their connection with supernovae explosions and black-holes formation, have placed the study of GRBs at the forefront of astrophysical research (eg. Piran, 1999; Mészáros, 2002; Zhang, 2007; Woosley & Bloom, 2006; Fox & Mészáros, 2006).

The launch of Compton Gamma-Ray Observatory (CGRO) in 1991 was the first major step toward a better understanding of the GRB phenomenon. The Burst and Transient Source Experiment (BATSE) onboard CGRO established the isotropic distribution of these explosions at a very high statistical significance and also showed the deviation of their brightness (defined by the burst peak flux) distribution from Euclidean at the faint end (Meegan et al. 1992). These were strong evidence that the bursts are at cosmological distances (eg. Mao & Paczyński 1992, Piran 1992).

The firm confirmation of the cosmological distance to GRBs was obtained in 1997, when the BeppoSAX satellite provided angular position of bursts to within 5 arc-minutes – more than a factor 10 improvement compared with the Compton Gamma-ray Observatory – which enabled optical and radio astronomers to search for counterparts for these explosions. A rapidly fading X-ray, optical and radio emission (the "afterglow") accompanying a GRB was found in February 1997, about a day after the detection of a burst, and led to the determination of burst redshift (Figure 1). It launched a new era in the study of GRBs which has led to wealth of new information and a much deeper understanding of these enigmatic explosions (eg. Frail et al. 1997; Kulkarni et al. 1998; Bloom et al. 1999).

It was expected from theoretical considerations that GRB outflows are highly relativistic e.g. Fenimore et al. (1996), Piran (1999). We now have direct observational confirmation of this provided by the measurement of "superluminal" motion of the radio afterglow of a relatively nearby burst GRB 030329 (Taylor et al. 2004).

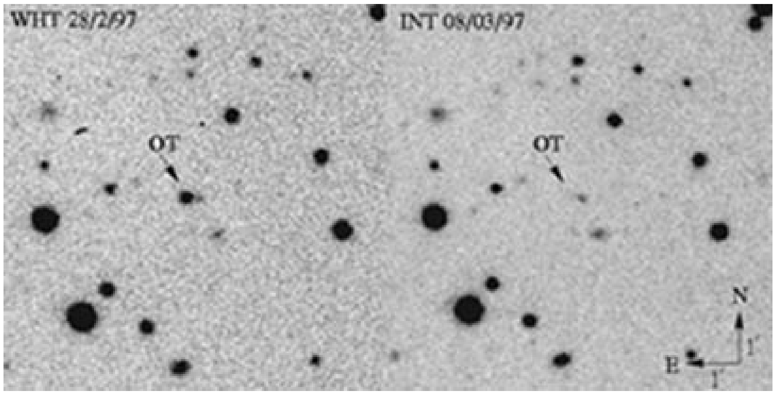

Figure 1: Images of the optical afterglow of GRB 970228. The first optical afterglow ever detected (van Paradijs et al. 1997).

The redshifts and burst fluences showed that GRBs radiate between 10^{51} and 10^{54} ergs, if isotropic. This means that GRBs are the most energetic explosions in the Universe; the luminosity of the brightest bursts rivaling that of the entire Universe at all wavelengths, albeit for only a few seconds (Kulkarni et al. 1999). We now know from breaks in optical afterglow lightcurves that GRBs are highly beamed and the true amount of energy release in these explosions is $10^{50} - 10^{51}$ergs (Frail et al. 2001; Panaitescu & Kumar, 2001; Berger et al. 2003).

Our understanding of GRBs has improved enormously in the last 10 years due to the observations made by several dedicated γ-ray/X-ray satellites (BeppoSAX, HETE-2, Swift) and the follow-up observations carried out by ground-based optical and radio observatories. Much of this progress has been made possible by the monitoring and theoretical modeling of the long-lived afterglow emission following the burst.

Recent Progress in the Study of GRBs

The follow-up of GRBs at longer wavelengths (X-ray, optical, and radio) has established that the afterglow light-curve decays as a power-law with time ($F_\nu \propto t^{-1.0\pm0.3}$) and has a power-law continuum ($F_\nu \propto \nu^{-0.9\pm0.3}$). The *forward-shock* caused by the ejecta interaction with the circumburst

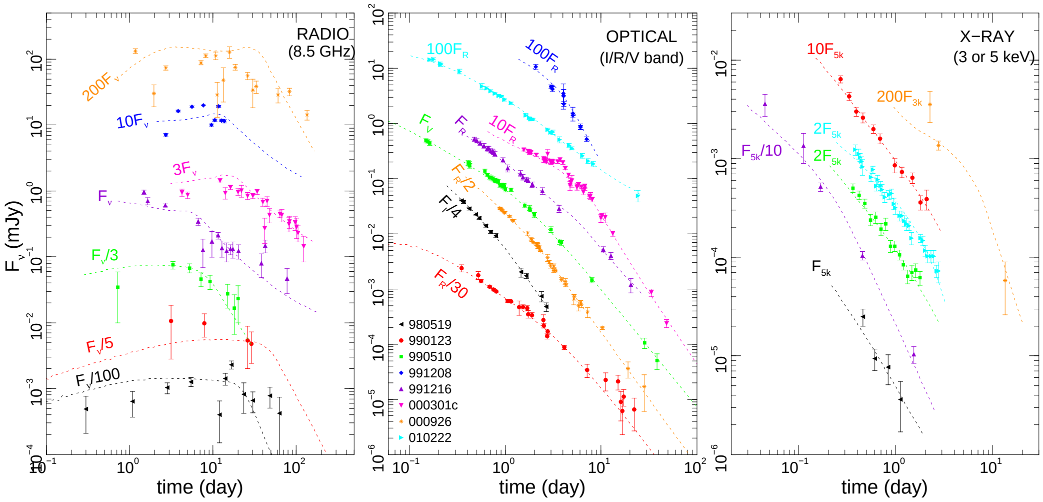

Figure 2: Radio, optical, X-ray emission and model light-curves for eight GRB afterglows (legend of middle graph applies to all panels). The model light-curves were obtained by χ^2-minimization using radio, millimeter, sub-millimeter, near infrared, optical, and X-ray data. The radio fluctuations are due to scatterings by inhomogeneities in the Galactic interstellar medium (Goodman 1997). Fluxes have been multiplied by the indicated factors, for clarity (Panaitescu & Kumar 2001).

medium (Mészáros & Rees 1997) provides a natural explanation for these observations. The synchrotron radiation in the forward shock provides very good fit to the mutiwavelength afterglow data for GRBs as shown in Figure 2.

In many cases, the decay of the optical or X-ray afterglow light-curve steepens to $F_\nu \propto t^{-2.2\pm0.5}$ at ~ 1 day after the burst. The most natural explanation for this steepening (foreseen by Rhoads 1999) is that GRB outflows are not spherical but collimated into narrow jets. As the ejecta are decelerated and the strength of the relativistic beaming diminishes, the edge of the jetted ejecta becomes visible to the observer. The finite angular extent of the ejecta leads to a faster decay of the jet synchrotron emission (a so-called "jet-break").

The jet initial angular opening and kinetic energy can be obtained by modeling the broadband emission (radio to X-ray) of those GRB afterglows whose light-curve fall-off exhibited a steepening. Figure 2 shows the best fits obtained for eight such GRB afterglows. From these fits we found that the opening angle of GRB jets is in the range of 2–5 degrees, thus the ejecta collimation reduces the required energy budget by a factor $10^2 - 10^3$ relative to the isotropic case; the true amount of energy release for most long duration GRB is found to be $\sim 10^{51}$erg (Frail et al. 2001; Berger et al. 2003). The medium within ~ 0.1 pc of the burst is found to have uniform density in most cases, and the density is of order a few protons per cc (Panaitescu & Kumar 2002). This is a surprising result in the light of the evidence that long duration GRBs are produced in the collapse of a massive star – as suggested by Woosley (1993), MacFadyen & Woosley (1999) – where we expect the density to decrease as r^{-2} due to the wind from the progenitor star (eg. Chevalier & Li, 2000; Ramirez-Ruiz et al. 2001).

The evidence for association of long-duration GRBs (those lasting for more than 2s) with core collapse SNa comes from two different kinds of observations: (i) GRBs are typically found to be in star forming regions of their host galaxies (e.g., Bloom et al. 2002, Fruchter et al. 2006, Christensen et al. 2004, Castro Cerón et al. 2006) (ii) for five GRBs SNa spectrum was detected: GRB 980425 (Galama et al. 1998), 021211 (Della Valle et al. 2003), 030329 (Hjorth et al. 2003, Stanek et al. 2003), 031203 (Malesani et al., 2004), and 060218 (Modjaz et al. 2006; Campana et al. 2006, Pian et al. 2006). Additionally, a subset of about 10 GRBs show at late-times ($\sim$ 10 days) SNa-like "bump" in the optical afterglows and simultaneously a change in color that is inconsistent with synchrotron emission (Bloom et al. 1999; Woosley & Bloom 2006).

The long standing question regarding the nature of short duration GRBs (those lasting for less than 2s) was resolved when a fraction of these bursts was shown to be associated with older stellar population, on average located at a lower redshift, and less energetic (Fox et al. 2005; Panaitescu 2006; Bloom et al. 2006; Nakar 2007). These observations are consistent with the old idea that these bursts originate from neutron star mergers Eichler et al., 1989. However, there is no conclusive support for this model as yet.

The Swift satellite has provided a wealth of puzzling observations (Tagliaferri et al 2005, Chincarini et al 2005, Nousek et al 2006). Its X-Ray Telescope (XRT) has evidenced the existence of a sharp flux decay ($F_x \propto t^{-3}$)

after the burst, followed by a plateau during which the X-ray afterglow flux decrease is much slower ($F_x \propto t^{-1/2}$) than expected in the standard forward-shock model (Figure 3). The former feature indicates that the GRBs and the afterglows are produced by two different mechanisms or arise from different outflows while the latter suggests that the forward shock that powers the afterglow is not fully developed at the end of the burst phase.

Swift has also discovered episodes of a sharp increase in the X-ray flux (flares) minutes to hours after the end of the gamma-ray burst (Burrows et al. 2005, 2007; Chincarini et al. 2007). The rapid rise time for the X-ray flux, with $\delta t/t \sim 0.1$, rules out the possibility that flares are produced as a result of inhomogeneity in the circumstellar medium where the curvature of the relativistic shock front limits $\delta t \sim R/2c\Gamma^2 \sim t$ or $\delta t/t \sim 1$ (Nakar & Piran, 2002; Lazzati & Perna, 2007; Nakar & Granot, 2007). This suggests that the central engine in these explosions is active for a time period much longer than the burst duration.

The wealth of afterglow data provided by Swift has led to a number of new puzzles. While the x-ray and optical data after 10^4s are consistent with forward shock emission, the features seen in the x-ray data prior to $\sim 10^4$s are not well understood. Similarly the expected achromatic breaks in the lightcurves (associated with finite jet angle) are seen in some bursts but not others (Fan and Piran, 2006; Panaitescu et al. 2006; Curran et al. 2008).