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GAMMA RAY BURSTS - OBSERVATIONS

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We are in an exciting period of discovery for gamma-ray bursts. The *Swift* observatory is detecting 100 bursts per year, providing arcsecond localizations and sensitive observations of the prompt and afterglow emission. The *Fermi* observatory is observing 250 bursts per year with its medium-energy GRB instrument and about 10 bursts per year with its high-energy LAT instrument. In addition, rapid-response telescopes on the ground are providing new capabilities to study optical emission during the prompt phase and spectral signatures of the host galaxies. The combined data set is enabling great advances in our understanding of GRBs including afterglow physics, short burst origin, and high energy emission.

1. Introduction

GRBs are the most luminous explosions in the Universe and are thought to be the birth cries of black holes. They are a product of the space age, discovered [1] by *Vela* and observed by satellites for 40 years. Despite impressive advances over the past three decades, the study of bursts remains highly dependent on the capabilities of the observatories which carried out the measurements. The era of the *Compton Gamma Ray Observatory (CGRO)* led to the discovery of more than 2600 bursts in just 9 yr. Analyses of these data produced the key result that GRBs are isotropic on the sky and occur at a frequency of roughly two per day all sky [2]. The hint from earlier instruments was confirmed that GRBs come in two distinct classes of short and long bursts, with distributions crossing at ~ 2 s duration [3]. The *BeppoSAX* mission made the critical discovery of X-ray afterglows of long bursts [4]. With the accompanying discoveries by ground-based telescopes of optical [5] and radio [6] afterglows, long GRBs were found to emanate from star forming regions in host galaxies at typical distance of $z = 1$. *BeppoSAX* and the following *HETE-2* mission also found evidence of associations of GRBs with Type Ic SNe. This supported the growing evidence that long GRBs are caused by "collapsars" where the central core of a massive star collapses to a black hole [7].

2. *Swift* GRBs

Swift [8] is a dedicated GRB observatory that is now measuring many properties of the prompt and afterglow radiation. It carries a wide-field Burst Alert Telescope (BAT) [9] that detects GRBs and positions them to arcmin accuracy, and the narrow-field X-Ray Telescope (XRT) [10] and UV-Optical Telescope (UVOT) [11] that observe their afterglows and determine positions to arcsec accuracy, all within ~ 100 seconds. The BAT detects the bursts in the $15 - 150$ keV band and determines a few-arcmin position onboard within 12 s. The position is provided to the spacecraft which is then re-pointed to the burst location in less than 2 minutes to allow XRT and UVOT observations of the afterglow. Alert data from all three instruments is sent to the ground via NASA's TDRSS relay satellite. The full data set is stored and dumped to the Italian Space Agency's equatorial Malindi Ground Station.

The *Swift* mission was built by an international team from the US, UK, and Italy. After five years of development it was launched form Kennedy Space Center on 20 November 2004. Full normal operations commenced on 5 April 2005.

As of October 2009, BAT has detected 475 GRBs. Approximately 90% of the BAT-detected GRBs have repointings within 5 minutes (the remaining 10% have spacecraft constraints that prevent rapid slewing). Of those, virtually all bursts observed promptly have detected X-ray afterglow. Already, 80% of the known X-ray afterglows are from Swift. The fraction of rapid-pointing GRBs that have UVOT detection is $\sim 30\%$. Combined with ground-based optical observations, about 60% of *Swift* GRBs have optical afterglow detection. To date there are a total of about 155 redshift determinations, of which 41 are pre-*Swift* bursts.

3. GRB Properties

Figure 1 shows spectra for several representative GRBs, and two other high-energy sources, the Crab nebula and Cyg X-1. Due to beaming, the actual GRB luminosities may be over-estimated by their apparent, isotropic-equivalent fluxes. Figure 2 presents a broad-band GRB spectrum.

Swift is detecting GRBs at higher redshift than previous missions due to its higher sensitivity and rapid afterglow observations. The average redshift for the *Swift* GRBs is 2.3 compared to 1.2 for previous observations. Although statistics are poor, the highest redshift GRBs are seen to have high luminosity, well above the detection threshold. Such bursts are also strong at other wavelengths. Table 1 presents optical data for the highest redshift GRBs observed to date. GRBs are incredibly bright. A typical galaxy at a redshift of only $z = 3$ is much fainter at $m \sim 27$. Multiwavelength observations of the current record holder, GRB 090432 (at $z \gtrsim 8$), are beginning to provide us with information about the intergalactic medium at a time when the Universe was only about 4% of its current age, and shed light on the process of reionization in the early Universe[12,13].

GRBs come in two kinds, long and short, where the dividing line between the two is about 2 seconds[3]. A further division can be made spectrally according to

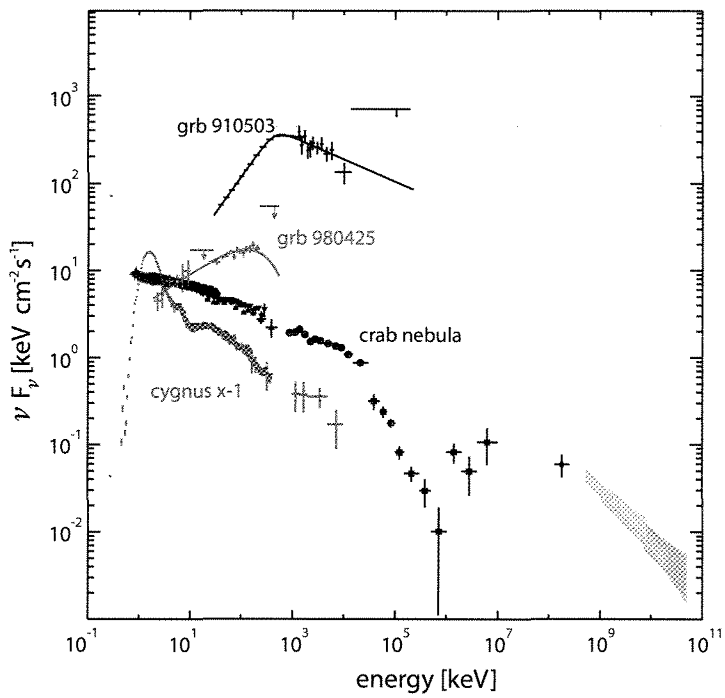

Fig. 1. Representative broad-band νF_ν spectra [14] of GRBs [15,16], along with the Crab pulsar nebula [17] and Cyg X-1 [18].

Table 1. High z GRBs.

z	Look-Back Time (Gyr)	GRB	Optical Brightness		
8.3	13.0	090423	$K = 20$	@	20 min
6.7	12.8	080813	$K = 19$	@	10 min
6.29	12.8	050904	$J = 18$	@	3 hr
5.6	12.6	060927	$I = 16$	@	2 min
5.3	12.6	050814	$K = 18$	@	23 hr
5.11	12.5	060522	$R = 21$	@	1.5 hr

their hardness ratio (i.e., ratio of high to low energies). The redshift range is from about 0.2 to 2 for short GRBs (sGRBs), with a mean of about 0.4. For long GRBs (lGRBs) the range is between about 0.009 and 8.2, with a mean of about 2.3. The typical energy release is $\sim 10^{49} - 10^{50}$ erg for sGRBs and $\sim 10^{50} - 10^{51}$ erg for lGRBs. These ranges are based on observed isotropic-equivalent energies of $\sim 10^{51}$ erg for sGRBs and $\sim 10^{53}$ erg for lGRBs, and estimates for jet beaming

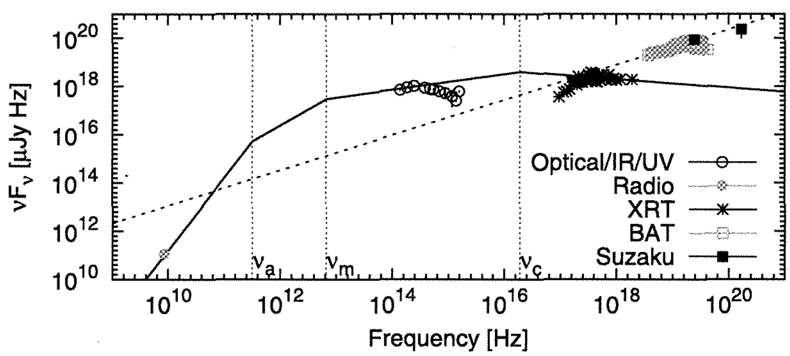

Fig. 2. Broadband spectrum of GRB 051111 from radio to gamma-ray energies[20]. The line segments indicate a synchrotron fit. It is assumed that electrons are distributed as a power law in Lorentz factor γ above a minimum value $\gamma_{\rm m}$ according to $N(\gamma_{\rm e}) \propto \gamma_{\rm e}^{-p}$, for $\gamma_{\rm e} > \gamma_{\rm m}$. For $\nu < \nu_{\rm a}$, the self-absorption frequency, the spectrum drops off steeply (ν^2). For $\nu_{\rm a} < \nu < \nu_{\rm m}$, the spectrum varies as $\nu^{1/3}$. The higher energy electrons cool first, hence one expects a time-dependent cooling frequency $\nu_{\rm c}$ which decreases with time as $t^{-1/2}$. For $v_{\rm m} < v < v_{\rm c}$, the spectrum varies as $\nu^{-(p-1)/2}$, while for $\nu > \nu_{\rm c}$, it varies as $\nu^{-p/2}$.

for each class, $\theta_{\rm j} \sim 15°$ for sGRBs and $\theta_{\rm j} \sim 5°$ for lGRBs. The corresponding beaming factors $f_b = 1 - \cos\theta_{\rm j} \simeq \theta_{\rm j}^2/2$ are roughly 1/300 for lGRBs and 1/30 for sGRBs. Figure 3 shows a comparison of the X-ray afterglow fluxes at 11 hr post-GRB with the isotropic-equivalent gamma-ray energies. The $L_{\rm X}/E_{\gamma-{\rm iso}}$ values are similar between lGRBs and sGRBs. The sGRBs have weaker X-ray afterglows, a mean value of $\sim 7\times10^{-10}$ erg cm^{-2} s^{-1} versus $\sim 3\times10^{-9}$ erg cm^{-2} s^{-1} for lGRBs.

4. Short GRBs

At *Swift*'s launch, the greatest mystery of GRB astronomy was the nature of short-duration, hard-spectrum bursts. Although more than 50 long GRBs had afterglow detections, no afterglow had been found for any short burst. In May 2005 (GRB 050509B), *Swift* provided the first short GRB X-ray afterglow localization [21]. This burst plus the *HETE-2* GRB 050709 and *Swift* GRB 050724 led to a breakthrough in our understanding [21,22,23,24,25,26,27] of short bursts. BAT has now detected 46 short GRBs, most of which have XRT detections, and about one third of which have host identifications or redshifts (an additional two have been detected by *HETE-2*, one by *INTEGRAL*, and one by *Fermi*/LAT). We now have nearly 50 sGRB

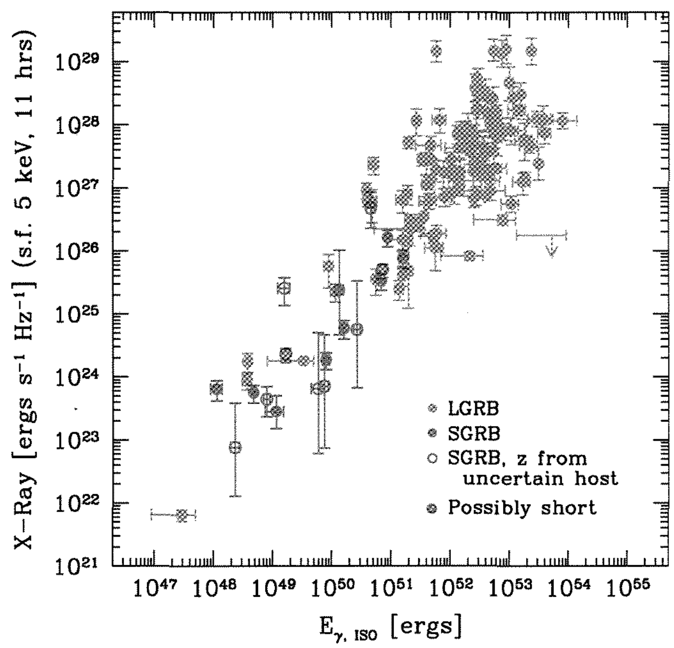

Fig. 3. A comparison of the afterglows of sGRBs and lGRBs[19]. The y−axis shows the 5 keV flux values at $T0 + 11$ hr, where $T0$ indicates the BAT GRB trigger time, while the x−axis indicates the isotropic-equivalent gamma-ray energies determined from the prompt emission.

localizations.

In stark contrast to long bursts, the evidence to date on short bursts is that they can originate from regions with low star formation rate. GRB 050509B and 050724 were from elliptical galaxies with low current star formation rates while GRB 050709 was from a region of a star forming galaxy with no nebulosity or evidence of recent star formation activity in that location. Taken together, these results support the interpretation that short bursts are associated with an old stellar population, and may arise from mergers of compact binaries [i.e., double neutron star or neutron star - black hole (NS-BH) binaries].

5. GRB 060218/SN 2006aj

On 18 February 2006 *Swift* detected the remarkable burst GRB 060218 that provided considerable new information on the connection between SNe and GRBs. It lasted longer than and was softer than any previous burst, and was associated with SN 2006aj at only $z = 0.033$. The BAT trigger enabled XRT and UVOT observations during the prompt phase of the GRB and initiated multiwavelength observations of the supernova from the time of the initial core collapse.

The spectral peak in prompt emission at $\sim$ 5 keV places GRB 060218 in the X-ray flash category of GRBs [28], the first such association for a GRB-SN event. Combined BAT-XRT-UVOT observations provided the first direct observation of shock-breakout in a SN [28]. This is inferred from the evolution of a soft thermal component in the X-ray and UV spectra, and early-time luminosity variations. Concerning the supernova, SN 2006aj was dimmer by a factor $\sim$ 2 than the previous SNe associated with GRBs, but still $\sim 2-3$ times brighter than normal SN Ic not associated with GRBs [29,30].

GRB 060218 was an underluminous burst, as were 2 of the other 3 previous cases. Because of the low luminosity, these events are only detected when nearby and are therefore rare occurrences. However, they are actually $5-10$ times more common in the Universe than normal GRBs [31].

6. *Fermi* GRBs

Table 2. *Fermi* LAT GRBs.

GRB	t-T0	z	comments
080825C	22 s		extended emission
080916C	66 s	4.35	extended emission
081024B (sGRB)	0.8 s		
081215A	7.7 s		
090217	33 s		
090323	150 s	3.57	
090328	100 s	0.736	
090510 (sGRB)	2.1 s	0.903	extended emission
090626	70 s		
090902B	21 s	1.822	34 GeV photon
090926A	20 s	2.1062	
091003	21 s		

Fermi was launched into low-Earth orbit in June 2008 and has two primary high-energy detectors: the Large Area Telescope (LAT) which operates between 20 MeV and $\gtrsim$ 300 GeV, and the Gamma-Ray Burst Monitor (GBM) which operates between 10 keV and 25 MeV. Table 2 indicates the GRBs that have been detected in the LAT. One of the most luminous to date has been GRB 080916C[32] at a redshift of 4.35. It had extended emission (18 min) and exhibited a lag in LAT energies with respect to GBM (see Figure 4). Recent theoretical work[33] on the *Fermi*/LAT detected GRBs suggests that these may represent unusually powerful explosions with Lorentz factors $\gtrsim 10^3$ in which the entire progenitor is obliterated. The simplest model, namely an external shock with synchrotron emission, can be used to take the early values (at $\sim 10-10^2$ s) of the observed high-energy emission and successfully predict the much later values of the optical and X-ray afterglow (at $\sim 10^5-10^6$ s).

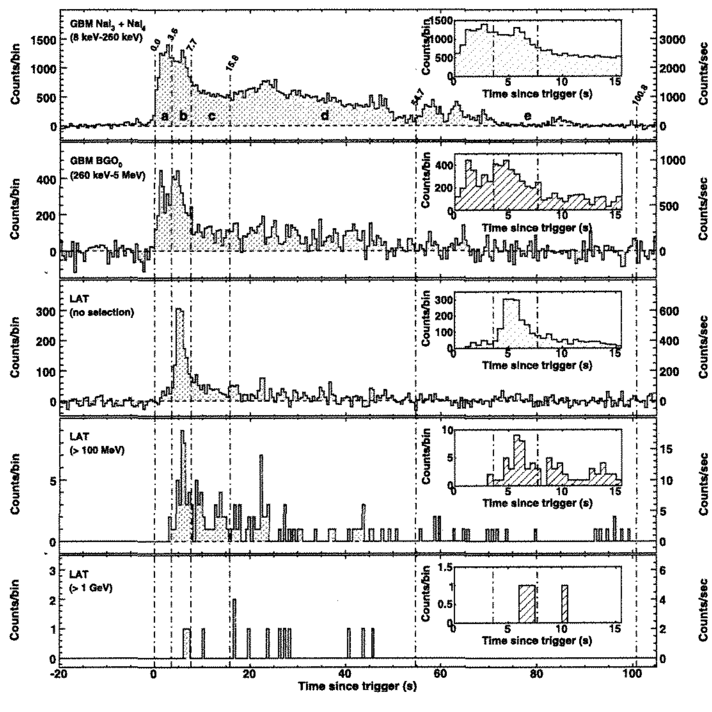

Fig. 4. *Fermi* view[32] of extended high-energy emission from GRB 090816C.

7. Conclusions

The future is bright for GRB astronomy. *Swift* and *Fermi* have good prospects for operating together for the next five years and possibly ten. The ground-based GRB follow-up capabilities have advanced greatly over the past decade and now feature about a dozen special-purpose telescopes for GRB follow-up and improving instrumentation on larger telescopes. These telescopes have a wide range of specialties including rapid follow-up (even faster than *Swift*), IR coverage, and wide-field imaging for self-triggering transient detection. One example is the X-Shooter on the VLT, which has simultaneous coverage from 300 to 2500nm at medium spectral resolution. Ground-based gamma-ray TeV telescopes are now on-line with high sensitivity and rapid GRB follow-up. There are exciting prospects for more sensitive radio GRB observations with EVLA and, expanding to lower and higher frequencies, LOFAR and ALMA. An opportunity for future breakthroughs in GRB understanding will come from non-photonic experiments such as ICECUBE and ANTARES for neutrinos and LIGO/GEO/VIRGO for gravitational waves. For future GRB missions, the Chinese-French mission *SVOM* is under development.

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