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Short duration gamma ray bursts

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Abstract. After a short review of gamma ray bursts (GRBs), we discuss the physical implications of strong statistical correlations seen among some of the parameters of short duration bursts ($T_{90} < 2$ s). Finally, we conclude with a brief sketch of a new unified model for long and short GRBs.

Keywords. Short gamma ray bursts; statistical correlations; spectral lag.

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1. Introduction

Gamma ray bursts (GRBs) are transient extragalactic events appearing randomly in the sky as localized flashes of electromagnetic radiation, consisting predominantly of photons with energy in the range of ~0.1–1 MeV. These sporadic bursts, occurring at the rate of ~600 per year, are isotropically distributed in the sky, as expected of sources located at cosmological distances. Durations as well as time profiles of GRB prompt emission (of soft gamma rays) vary widely from event to event, with the former lying in the range of $\sim 10^{-2}$ s to about 10^3 s [1]. The burst time profiles usually exhibit rapid variability and often can be broken up into individual pulses. Pulse width varies from ~ millisecond to ~ seconds (even sub-millisecond structure has been reported [2]). Majority of these pulses are manifestly asymmetric, displaying a fast rise followed by a gradual decay.

The prompt gamma ray emission spectrum is non-thermal in nature, and can be fitted very well with a four parameter 'band' function F_ν, over a broad range of gamma ray frequency ν [3]. The energy at which νF_ν attains maximum value is termed as the spectral peak energy E_{p}. A narrow lognormal function peaked around ~250 keV provides a good fit to the distribution of E_{p} for various bursts.

Observed variability of gamma ray flux on short time-scales (typically $\sim 10^{-2}$ s) implies a causally connected emission region of size smaller than ~3000 km. For a region that compact, the density of ~ MeV scale photons is very high, leading to a large optical depth for such photons (because of $\gamma\gamma \to e^+e^-$ interactions). In that case, the emerging prompt emission should have a thermal spectrum, contrary to what is really observed!

This paradox can be resolved by invoking ultra-relativistic motion for the emitting region (see [4]). If photons are detected from a source that moves towards the observer with a Lorentz factor Γ, the observed time-scale of variability is $\Delta t \sim \Delta t_0/\Gamma^2$ while the observed frequency ν of photons is Doppler boosted to $\sim \nu_0 \Gamma$ (the subscript '0' refers to the quantities measured in the rest frame of the source). With the rest frame variability time-scale being actually larger, the region of emission from causality argument is bigger, making the estimated photon density drop. Also, now the rest frame frequencies of majority of photons are too low to produce $e^{\pm}$ pairs. Hence, the region of emission is indeed optically thin as necessary. The required bulk Lorentz factor for the burst ejecta responsible for prompt emission is in excess of $\sim$100.

The brightest GRBs detected by burst and transient source experiment (BATSE) on board Compton Gamma Ray Observatory (CGRO) have γ-ray fluence (i.e. time integrated flux) as high as $\sim 10^{-4}$ erg cm^{-2}. A simple characterization of the distribution of photon energy in a GRB is that of burst hardness ratio (HR) which may be defined typically as the ratio of fluence corresponding to photons with energy above 100 keV to that of photons of energy less than 100 keV for that burst. Most GRBs exhibit hard-to-soft spectral evolution as a function of burst time. This feature can be studied using a parameter called spectral lag that basically measures the difference in the arrival times of hard and soft photons from a burst.

Emission from some of the GRBs also show intriguing features. EGRET on board CGRO had detected hard gamma rays from some GRBs. For example, GRB 940217 was found to be radiating GeV photons for $\sim$1.5 h, well after the prompt emission. Also, it has been reported recently that prompt emission from GRB 021206 is polarized, with a degree of polarization as high as $\sim$80%. Thus, GRBs are as colourful as a peacock feather!

2. Afterglow from long bursts

It has been known for about a decade that GRBs are of at least two distinct varieties [5]. Long bursts, with duration more than $\sim$2 s, form a bigger class of GRBs ($\sim$75% of the total population), while the rest of the GRBs that last for less than $\sim$2 s are classified as short duration bursts. Afterglows from many long GRBs have been detected in X-ray, optical and radio band. The spectra of afterglows are non-thermal in character. All afterglow flux decay with time (typically, as $\sim t^{-1}$, in the early phase).

Observations have revealed that long bursts, with recorded afterglow, tend to reside in the star forming regions of normal galaxies. Moreover, GRB 980425 and GRB 030329 are known to be associated with SN1998bw and SN2003dh, respectively, both of which are peculiar supernovae of type 1b/c, hydrogen and helium being absent in the ejecta. There are strong evidences for such supernovae resulting from explosions of massive stars ($M > 20 M_0$).

Optical afterglow from some bursts show steepening after a certain time, with flux decaying typically as $\propto t^{-2}$. This can happen if the burst outflow is in the form of a jet with an initial opening angle $\theta_{\rm j}$ and bulk Lorentz factor Γ that steadily decreases with time due to interactions between the ejecta and the ambient gas.

Then, as the jet moves outward, the opening angle increases as $\sim \theta_{\rm j} + (\sqrt{3}\,\Gamma)^{-1}$ [6]. The second term represents the expansion of the jet fluid with local sound speed $\sim c/\sqrt{3}$ due to the internal pressure, transformed from the comoving frame to the observer's frame, leading to a reduction by a factor of $\sim\Gamma$. In the early times, when Γ is much larger than $\theta_{\rm j}^{-1}$, lateral expansion of the jet as seen by an observer is negligible due to the special relativistic time dilation. However, because of deceleration, eventually $\Gamma^{-1} > \theta_{\rm j}$ and thereafter, sideways expansion becomes significant, leading to a steeper fall of the afterglow flux. The steepening observed in some of the optical afterglows suggest $\theta_{\rm j}$ to be $\sim 6^\circ$ or less.

Although the GRB central engine, hidden from the view, is still an enigma, the above considerations reinforce one's confidence in the 'collapsar' type models for (at least long) GRB progenitors in which core collapse of a rapidly rotating massive star leads to jets of relativistic matter ejected from the central remnant (possibly an accreting black-hole (BH) with a torus of gas around it) along the spin axis (see [7]). It is believed that after the jets break out of the star, their energy is dissipated by means of internal shocks leading to a variable GRB prompt emission. These shocks eventually merge with one another, forming an external shock ploughing through the ISM that leads to afterglows at lower frequencies. Total energy released in such catastrophic events is typically $\sim 10^{53}$ erg ($\sim$99% of this energy is likely to be carried away by neutrinos). Like supernovae, GRBs are expected to be potential sources of gravitational waves (see ref. [8]).

Red-shifts of $\sim$33 long GRBs are already available from their optical afterglow studies. The closest burst is GRB 980425 with $z = 0.0085$, while GRB 000131 is the most distant burst, so far, with $z = 4.5$. Because of such large distances and high luminosities, multi-wavelength studies of photon arrival times from GRBs may be employed to look for wavelength-dependent light speed (in vacuum), predicted by some quantum gravity theories (see ref. [9]). High red-shift GRBs are also important for the study of reionization as well as star formation history, particularly after the WMAP discovery of large electron scattering optical depth (refer [10]).

No short duration burst has been detected till date in the optical or radio band. Little is known about their progenitors and host galaxies. In the next section, we discuss some of the characterstics of the short bursts.

3. 'Short' story

Our knowledge of the short GRBs pertain to their prompt emission in the soft gamma ray regime. Spectra of the short bursts tend to be harder than those of the long ones [5]. Fluences of the short bursts are on an average $\sim$20 times weaker than those of their longer counterparts [11,12]. However, the average spectral peak energy for the short bursts is larger than that of the long ones by a factor of $\sim$2. This suggests either larger bulk Lorentz factors or spatially closer locations for the short GRBs [13]. From luminosity function studies, the local space density of the short GRBs is likely to be lower than that of the long ones by a factor of $\sim$3 [14].

While analysing time tagged event (TTE) data for 156 category A type bursts with $T_{90} \leq 2$ s, drawn from the BATSE 4B catalog, we found some interesting statistical correlations among burst parameters [15,16]. After identifying individual pulses, we measured burst complexity index (CI) which is defined as the total number of pulses in a given burst [17]. Lognormal functions are found to provide very good fits to the individual pulses [18]. Of the 156 short bursts, 45 are single pulse GRBs, while only ∼12% of them have CI ranging from 5 to a maximum value of 8. In contrast, long GRBs are more complex with CI typically exceeding 10 [19,20].

The spectral lag τ_1 for a burst was estimated by taking the difference between time centroids obtained using arrival instants (from TTE data) corresponding to photon energies larger than 100 keV, and to energies less than 100 keV so that

$$\tau_1 \equiv \tau_{\,>\,100\ \mathrm{keV}} - \tau_{\,<\,100\ \mathrm{keV}}. \tag{1}$$

The time centroid for an energy channel is given by

$$\tau = \frac{1}{N}\sum_{j}^{k} t_i, \tag{2}$$

where t_i and N represent the arrival time of the ith photon and the total number of photons, respectively, detected in that energy channel between the starting instant (t_j) and the end (t_k) instant of the burst. From TTE data, t_i s are known with an accuracy of $\sim 2\ \mu$s and therefore, statistical error $\Delta\tau_1$ in measuring spectral lag is $\sim 2N^{-1/2}\ \mu$s (photon number N is typically ∼100 or more, implying $\Delta\tau_1 \leq 0.1\ \mu$s).

We found negative (positive) τ_1 for 116 (40) short GRBs indicating that a substantial fraction (∼ 26%) of them undergo soft-to-hard spectral evolution. Negative spectral lags range from $(-5 \times 10^{-2} \pm 4 \times 10^{-8})$ s to $(-7.27 \times 10^{-5} \pm 1 \times 10^{-7})$ s while the positive values range from $(9 \times 10^{-5} \pm 6 \times 10^{-8})$ s to $(3 \times 10^{-2} \pm 4 \times 10^{-8})$ s. The difference between the least positive and least negative τ_1 is more than two orders of magnitude larger than the corresponding error. Hence, the possibility of confusion between positive and negative spectral lags is unlikely.

A negative τ_1 reflects harder photons arriving earlier than those with energy <100 keV, implying a hard-to-soft spectral evolution. To study statistical correlations between various burst parameters we used weighted linear correlation analysis. For both negative as well as positive τ_1 bursts, CI was observed to be strongly correlated with T_{90}, fluence and HR. Similarly, the pairs HR and fluence as well as T_{90} and $|\tau_1|$ display strong correlations for the full sample of 156 bursts. These statistical correlations have been observed at more than 99% confidence level. What do these correlations tell us?

GRB prompt emission is likely to be due to internal 'shockings' of relativistic matter squeezed out of a central engine [21,22]. The T_{90}-CI and T_{90}-$|\tau_1|$ correlations suggest that when the central engine is ON for a longer duration, (a) instead of a broad single peak, emission tends to be in the form of several pulses, favouring 'multiple collision of shells' scenario and (b) effective Γ decreases on longer timescales. Also, if the total energy released is larger, one expects higher values of Γ, leading to a correlation between fluence and HR.

For bursts with positive (negative) τ_1, pulse hardness ratio and pulse brightness show strong correlations (anti-correlation) with peak position at more than 94% (> 99%) confidence level. The magnitude of τ_1 is strongly correlated with fluence, CI as well as HR in the case of bursts that display hard-to-soft evolution (i.e. $\tau_1 < 0$)

at more than 97% confidence level, while bursts with positive τ_1 do not display any such correlation. These observations suggest that for bursts with $\tau_1 > 0$, the central engine possibly gets rejuvenated towards the end because of which there is not only soft-to-hard spectral evolution but also individual pulses tend to become stronger with time. Enhanced accretion of matter (just before the engine is finally switched OFF) may lead to such behaviour.

4. Discussions

Several long GRBs have been located in the star forming regions of external galaxies. Some of them are directly associated with SN Ib/c type supernovae. These observations support the 'collapsar' paradigm for the progenitors of the long bursts. In contrast, the absence of afterglow data for the short bursts heighten their mystery.

A unified picture for both the short and the long GRBs involving collapsars can possibly be developed. The core of a collapsing star is likely to receive a 'kick' due to asymmetric neutrino emission, causing the central remnant to move with a velocity $\vec{V}$. If the 'kick' is sufficiently large, jets squirted out of the remnant along the rotation axis in opposite directions will encounter different physical environments. The jet (J1) along $\vec{V}$, drilling through a denser medium and working against a larger ram pressure, is likely to be narrower (with only higher Γ components of the ejecta surviving) and short-lived. When J1 happens to point towards an observer, the burst will be seen as a harder and shorter event. Even the occurrence of a larger fraction of soft-to-hard short bursts may be explained by later infall of stellar gas on to the approaching remnant. On the other hand, J2 (the jet in the reverse direction) would be subjected to less ram pressure, and would break out of the star without undergoing much dissipation. If the observer's line of sight passes through J2, the resulting burst would appear as a long GRB.

If the average solid angle into which J1 is released is about one-third of the mean solid angle of J2 then approximately one out of every four GRB detected is likely to be short, as observed by BATSE. Lack of observed afterglow from the short bursts may be due to the following reasons. First of all, estimated energy budget is proportional to the fluence as well as the jet solid angle. Hence, energy of J1 is likely to be lower than that of J2 by a factor of $\sim 10^{-2}$. Secondly, with a narrower and short-lived J1, the amount of shocked ambient gas piled up near its head is likely to be less than that in the case of the long GRBs. These factors can bring down the equipartition values of electron energy density and magnetic field, resulting in a fainter synchrotron emission. More work on these lines is under progress.

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