Cosmological Implications of Compton Tails in Long Duration GRB

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The recent suggestion of the possible presence of a significant amount of material (Thomson optical depth ~ 1) at rest and at a typical distance of $\sim 10^{15}$ cm with respect to the GRB is presented. The relevance of such interpretation for GRB energetics and its cosmological implications is outlined.

1. Introduction

The detection of GRB optical counterparts has allowed to measure (since 1997) their redshifts, showing that they are cosmological sources. The broad redshift interval (presently extending out to z$\sim$4.5) and the huge power emitted in the prompt γ-ray phase, make these sources excellent candidates to probe the distant universe. The continous progress on the determination of the main GRB phenomenological (temporal and spectral) properties is providing new clues on their nature: in particular intrinsic correlations have been recently revealed between the GRB spectral characteristics and their global energetics, which can potentially allow to use GRB as rulers to measure the cosmological parameters.

It is stressed the relevance both for the GRB understanding and for their cosmological use of assessing the role of the material present in the GRB environment. In fact, the statistical analysis of a large sample (400) of GRB light curves has revealed the presence of late time structures (about 300 s and 800 s after the burst) which might be indeed interpreted as the effect of the interaction of the burst photons with a relatively dense ambient medium[1].

2. GRB Properties and Cosmology

The large sample of GRB recorded by BATSE[2] showed an isotropic sky distribution (in galactic coordinates) which already supported a likely cosmological origin of these sources (contrary to the most accredited interpretations which, still in the middle of the 90s, were associating these events with galactic phenomena)[3].

The definite settling of the galactic vs extragalactic debate was reached in 1997 when the Italian-Dutch satellite *Beppo*SAX localized with arcmin accuracy the afterglow of GRB 970508, allowing the spectroscpic measure of its redshift (z=0.835)[4]. Currently a redshift has been estimated for about 42 events, and ranges from z=0.0085 (the nearest GRB 980425)[5] to z=4.5 (for GRB 000131)[6]. These comprise bursts detected also by instruments other than BATSE, i.e. *Beppo*SAX, RXTE, INTEGRAL and Hete-II. The z distribution and the position of GRB within their host galaxies suggest a possible relation between GRB and star forming regions, providing support for models which associate GRB events with the death of massive stars.

Among the many results obtained on GRB with known redshift, three key aspects are relevant here.

(1) Signatures of a nearly simoultaneous supernova event have been detected for 3 GRB at $z < 0.3$ (e.g. ref.[7] for a recent review). On one side they clearly strengthen the possible association of GRB and SN events as predicted by a large category of theoretical models, and on the other side they suggest that GRB are located in a rather "polluted" environments.

(2) The afterglow light curve often presents a steepening between a few hours and several days after the γ-ray event. This "break" in the light curve has been interpreted within the GRB standard model[8] as the evidence that the GRB relativistic outflow is anisotropic and collimated in a jetted structure. According to this model the measure of this break time allows to infer the jet opening angle: the estimates give (so far) values ranging between 3 and 25 degrees[9]. Such a strong anisotropy clearly affects any estimate of the GRB energetics (with respect to the isotropic hypothesis).

(3) The investigation of the GRB (rest frame) emission properties revealed a strong correlation between the burst emitted energy (inferred assuming isotropic emission) $E_{\rm iso}$ and its characteristic spectral energy, i.e. the energy at which most of the radiation is emitted, $E_{\rm peak}$[10]. Intriguingly, if the GRB energetics is corrected for the collimation angle θ, the resulting correlation between "true" energetics $E_\gamma = E_{\rm iso}(1-\cos\theta)$ and $E_{\rm peak}$ is even tighter[11]. Clearly such finding has the potential of allowing the use of GRB as standard candles to constrain the cosmological parameters[12]. These correlations between the energetics of GRB and the peak energy of their prompt emission are recently found to account for the observed fluence distribution of all 'bright' BATSE GRB. Furthermore for an intrinsic GRB peak energy distribution extending toward lower energies with respect to that characterizing

bright GRB, such correlations allow to reproduce the fluence distribution of the whole BATSE long GRB population[13].

3. GRB Progenitors and Circumburst Material

The standard model of long duration GRBs suggests that the progenitor of these cosmic explosion might well be massive stars at the end of their lives[14, 15]. In this scenario the history of the burst progenitor (e.g. intense stellar wind phases) should modify the circum–burst ambient medium (e.g. by deposition of large amount of material)[16]. The photons emitted by the GRB afterglow should interact with this thick environment. It has been proposed ([17, 18]) that the X–ray emission properties of the GRB afterglow might give quantitative indications of the physical properties of this material (e.g. composition, density and distribution). Nevertheless, also the prompt γ ray photons might interact with such material and produce observable effects still in the prompt phase[19].

The possible association of GRB with massive stars suggests the possible presence of a significant amount of material in the circumburst region. In such a scenario the delayed emission could naturally correspond to the GRB prompt radiation reprocessed by such intervening material[1]. In the late time ($\sim 10^2 - 10^3$ sec) GRB light curve a (low luminosity) residual emission due to Compton scattered photons by the external material might be revealed. A systematic search in the light curves of a statistically relevant set of 400 BATSE GRB for possible evidence of afterglow emission has revealed a significant excess of photons (with respect to average background) after ~ 300 and ~ 800 s since the burst trigger[20]. If this experimental result is indeed due to Compton scattering by the external medium, we can constrain the material distance R_0 and its column density. Moreover, in this scenario, the magnitude and time-of-appearance (with respect to the peak) of the Compton tail may be correlated with the burst intensity.

4. Compton Scattering by Circumburst Material

The material distributed around the burst interacts with the prompt emission photons produced, according to the standard scenario, by synchrotron emission in the internal shocks (e.g. [21]). These photons have typical energies between few keV and few MeV. The Compton scattering is thus regulated by the material cross section σ. We consider a simple configuration (see fig. 1) in which the material is distributed in a (geometrically) thick shell between R_0 and $R_0 + \Delta R$ (where ΔR is $\sim R_0$). The material in this shell is uniformly distributed with average density $\langle n \rangle$. The optical depth of this region can be expressed as $\tau \sim \langle n \rangle \, \Delta R \, \sigma$. The burst is collimated into a cone of semi–aperture θ_j (~ 0.1 e.g. [9]).

The prompt γ–ray photons (of total number n_p) produced in the internal shocks are attenuated by the external material by a factor $e^{-\tau}$. The average photon flux at the surface $R_0 + \Delta R$ per unit solid angle and unit time is

$$\langle L_s \rangle = \langle \frac{dn_s}{d\Omega \; dt} \rangle \simeq \frac{n_p \; e^{-\tau}}{\pi \theta_s^2 \; \tau_{grb}} \cdot \frac{\theta_s^2}{\theta_j^2}$$

where θ_s is the beaming angle of synchrotron emission ($\sim 1/\langle \gamma_e \rangle$, where $\langle \gamma_e \rangle$ is the average electron energy in the post shock region) and τ_{grb} is the burst duration. This photon flux corresponds to the typical prompt emission detected in the gamma ray band.

Similarly the photons n_p are Compton scattered by the circum–burst material and appear at the surface $R_0 + \Delta R$ attenuated by a factor $1 - e^{-\tau}$. Compton scattering is nearly isotropic (i.e. scattered photons are distributed over $\sim 2\pi$) and the average flux is:

$$\langle L_c \rangle = \frac{n_p \; (1 - e^{-\tau})}{2\pi \; \tau_{geom}}$$

Compton scattering of the prompt photons introduces a time delay in the observation of these photons. The typical timescale is regulated by the diffusion of the photons within the shell and results $\tau_{geom} \simeq \frac{(R_0 + \Delta R)\theta_j^2}{c}$. (this value of τ_{geom} is obtained assuming the line of sight at the border of the jet cone).

Moreover, also the incident spectrum of the photons will be modified due to the energy dependence of the scattering cross section. The observed Compton tail, however, should be very similar to the prompt burst spectrum above some tenths of keV. We also notice that, in this scenario, the prompt emission that is not scattered by the circum burst material preserves its intrinsic time variability whereas the Compton emission, with a broad peak at $\sim \tau_{geom}/2$, should be characterized by a lower variability than the prompt burst.

The ratio between the attenuated synchrotron component and the scattered Compton component is:

$$Q = \frac{\langle L_c \rangle}{\langle L_s \rangle} = (e^{\tau} - 1) \cdot \frac{c \; \tau_{grb}}{(R_0 + \Delta R)}$$

Assuming a typical radius $R_0 \sim 10^{15}$ cm (see Sec.3), i.e. $(R_0 + \Delta R) \sim 2 \cdot 10^{15}$ cm, and an aperture angle $\theta_j = 4°$ (e.g. [9]), the maximum of the emission of Compton scattered photons, with respect to the prompt burst photons results at $\tau_{geom}/2 \sim 150$ **s**.

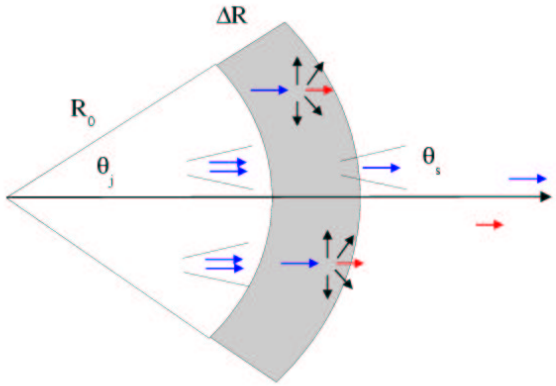

Figure 1: Attenuation of the the burst prompt photon number by the interaction with the circum–burst material.

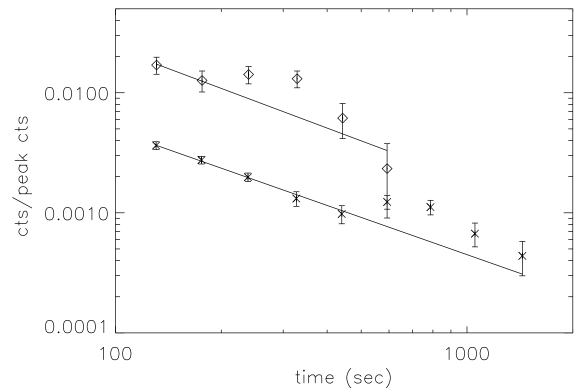

Figure 2: Average ratio of the flux with respect to the peak flux as a function of time for the sample of 400 GRB studied by ref. Bright (asterisks) and dim (diamonds) GRB are represented. The solid lines show the best power–law fits to the decay. The excesses with respect to these fits in both luminosity classes are significant at $>3\sigma$.

Then for a typical bursts of average duration ~ 20 s the ratio of the Compton to synchrotron luminosity results $Q \simeq 3 \cdot 10^{-4}(e^{\tau} - 1)\ \tau_{grb,20}\ R_{0,15}^{-1}$.

Note that the Q ratio is independent from the jet opening angle θ_j while the geometric time delay τ_{geom} depends from θ_j^2. If an independent measure of τ were available (e.g. from the X-ray features), R_0 and θ_j might be estimated from this Compton tail effect.

The search for this effect is difficult and possibly complicated by the large dispersion of the (observed) prompt emission luminosity observed in GRBs (e.g. [22]). Nonetheless, the above picture predicts, for reasonable assumptions on R_0 and θ_j, that the typical delay between the prompt and the scattered emission should be of the order of some hundred seconds since the burst trigger. Moreover, a critical point for the detection of signals in the late burst light curve of the order of few 10^{-4} of the burst prompt emission is the presence of a variable and not uniform background. Although very small, the ratio Q might still be detected if accurate background subtraction, from the burst light curve, is performed. Indeed, the detection of a such a signal in the light curve, if interpreted within this scenario, might further constrain the parameters of the external medium. In fact, in order to observe both the attenuated and the Compton scattered photons, the external material should have an optical depth $\tau \simeq 1$. If Q is measured from the burst light curve it can be used to derive an estimate of the external medium column density $\langle n \rangle \Delta R = \tau/\sigma$.

5. Experimental Evidences

The analysis reported in ref.[20] compared the light curves (in the 20-100 keV energy range) of ~ 400 BATSE bursts in search of late γ ray emission which could be possibly interpreted as the signature of the early afterglow. A particular effort has been done by the author to properly subtract the background from the bursts' light curves in order to detect even the faintest late time GRB tails. We re-considered the results searching for any evidence of a possible tail which instead might be due to the Compton scattering of the prompt GRB radiation by the circum–burst material.

It is very unlikely that the matter around GRB source has a constant column density and it is located at a fixed distance. Under the hypothesis that the GRB energetic is indeed more standard than the absorbing material amount and position, it is interesting to investigate the possible dependence of the Compton tail on different observed GRB intensities.

In the late light curves of the 400 GRB analysed in the ref.[20], it is possible to identify two different bumps in the count rate for bright and dim GRB classes. The GRBs were divided into three classes: bright GRBs with peak flux ≥ 1.5 phot/cm^2 sec, dim bursts with peak flux ≤ 0.65 phot/cm^2 sec and medium burst with intermediate flux. We could find a clear evidence of a possible Compton tail (see fig.2) only in the class of bright (*asterisks*) and dim (*diamonds*) bursts. The time of the peak of the Compton tail in bright and dim bursts is ~ 300 s and ~ 800 s, respectively. The average residuals of the Compton tail with respect to the fits (*solid lines* in fig.2) are $Q_{bright} = (4.0\pm0.8)\cdot10^{-4}$ and $Q_{\rm dim} = (5.6\pm1.4)\cdot10^{-3}$ with a considerable statistical significance (around 5 σ and 4 σ for the bright and dim class).

If we apply the formulae obtained in Sec. 4, taking a mean value of $\tau_{grb} \sim 50$s for long GRB and a mean jet opening angle $\theta_j \sim 4°$(e.g. [9]), it is possible to derive a different value of the optical depth

$\tau = \ln\left[\frac{Q\tau_{geom}}{\theta_j^2\tau_{grb}} + 1\right]$ for the two classes. This might indicate that the circum–burst material has different properties in dim and bright bursts: under the hypothesis that their intrinsic emitted energy is standard, the observed different intensity might be due to a largely distributed (for similar $\langle n\rangle$) absorbing material or equivalently to a larger average density (for similar ΔR) in dim bursts with respect to bright bursts. Indeed the excesses of signal appearing at ~ 800 and ~ 300 s for the "B" and "D" GRB, respectively, require corresponding Thomson optical depths of the material responsible for the scattering, of $\tau_{\rm B} = 1.33$ and $\tau_{\rm D} = 2.75$ at average distances from the progenitor of $R_{\rm B} \sim 10^{16}$ cm and $R_{\rm D} \sim 4.6 \cdot 10^{15}$ cm, respectively (assuming the same average value of the jet opening angle ∼4 deg for both classes). Assuming an isotropic distribution of the absorbing material (and equal number of protons and neutrons) these values imply total masses for the material of $M_{\rm B} \sim 5M_\odot$ and $M_{\rm D} \sim 2M_\odot$.

Since the observed prompt GRB intensity is proportional to $e^{-\tau}$, the GRB engine should correspondingly emit a total energy $E = e^{\tau}E_{obs}$. The absorbed energy is transferred to the Compton component:

$$E_{Compt} = E_{obs}\frac{Q}{\theta_j^2}\frac{\tau_{geom}}{\tau_{grb}}$$

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6. The Absorption Material and the Ep-E_γ Correlation

The empirical E_γ–$E_{\rm peak}$, as inferred by ref.[11] on the basis of 15 GRB, is given by:

$$E_{\rm peak} \propto E_\gamma^{(0.70\pm0.04)}$$

If indeed the scenario described above proved to be correct and to occur in all GRB, this rest frame correlation should be corrected for the effect of the scattering material, which would modify both the observed flux and the GRB spectrum. The global qualitative effect would be to produce a steeper correlation.

A more quantitative estimate of the predicted intrinsic relation between E_γ and $E_{\rm peak}$ at this stage can be only tentative. As the GRB considered by ref.[11] would mostly correspond to bright GRB (according to the above definition) their average optical depth would be $\tau \sim 1.33$, in turn causing a steepening the correlation to approximately $E_{\rm peak} \propto E_\gamma^{0.8}$. However, such a simple assumption leads to a worsening of the scatter in the correlation, indicating that one would need to estimate τ for individual GRB to correct the corresponding E_γ and $E_{\rm peak}$. Despite this is not currently feasible, the point we wish to stress is that a significant amount of material in the circumburst region could lead to incorrect estimates of the E_γ and $E_{\rm peak}$ correlation, with implications both on the understanding of the physical origin of the relation and its use for cosmology.

7. Conclusions

The recently found correlations between the spectral properties and the total energy emitted by GRB open the possibility of probing the Universe expansion in the region of high z using them as distance indicators. If there is a variable amount of material between the emitting engine and the detector, in order to understand its role in the observed empirical correlations when the number of GRB will be a few hundred (Swift), the amount of material associated to each GRB has to be measured. A Compton tail following the prompt signal with a typical delay of a few hundred seconds from the trigger would be the signature and the solution to this problem.

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