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Cosmological implications of Compton tails in long duration GRB(*)

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Summary. — 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.

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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.

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2. – GRB properties and cosmology

The large sample of GRB recorded by BATSE [1] 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) [2].

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 ($z = 0.835$) [3]. Currently a redshift has been estimated for about 42 events, and ranges from $z = 0.0085$ (the nearest GRB 980425) [4] to $z = 4.5$ (for GRB 000131) [5]. 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 very 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 $z < 0.2$ (*e.g.,* ref. [6] 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 rather "polluted" environments. The latter implication also suggests that if a significant amount of material is present it might intercept and affect the observed emission [7].

2) The afterglow flux decrease with time (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 (and under some other assumptions) 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, 14].

3. – The Compton tail and the circumburst material

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 few hundreds of seconds since the

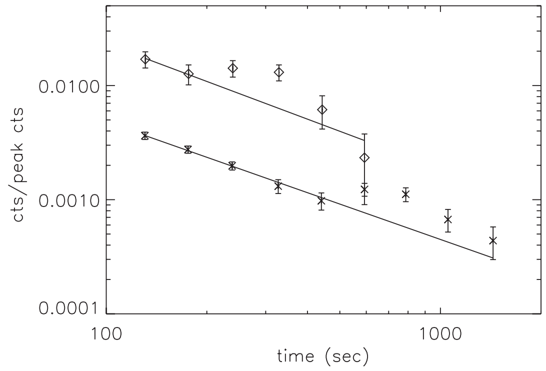

Fig. 1. – Average ratio of the flux with respect to the peak flux as a function of time since the GRB peak for the sample of 400 GRB studied by ref. [15]. Bright (asterisks) and dim (diamonds) GRB are represented. The solid lines show the best power–law fits to the decay. The excesses with respect to these fits in both luminosity classes are significant at $> 3\sigma$.

burst peak [15]. In this analysis the photon energy range has been restricted to the interval 20–100 keV to get the optimal BATSE detector energy response. The ratio of counts with respect to the counts at the peak of the burst, is plotted in fig. 1 as a function of time since the GRB peak (from ref. [15]). In this analysis the 400 GRB have been divided into 3 classes (of equal number of GRB) according their peak luminosity: in the figure the two extreme classes of bright "B" and dim "D" bursts are shown (peak fluxes > 1.5 and $< 0.65\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ for "B" and "D" GRB, respectively). One possible interpretation of the excess of photons at ~ 300 s and ~ 800 s after the GRB, is that it might represent the beginning of the afterglow emission. However (see the discussion in ref. [15]) a spectral analysis of these excesses did not prove to be conclusive.

On the other hand 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 [7]. In fact, a late time residual emission such as that observed in the representative sample of 400 BATSE bursts can be simply due to the different light travel times of photons scattered by the circumburst material [7].

Indeed the excesses of signal (fig. 1) appearing at 850 and 360 s for the "B" and "D" GRB, respectively, would require corresponding Thomson optical depths of the material responsible for the scattering, of $\tau_{\mathrm{B}} = 1.33$ and $\tau_{\mathrm{D}} = 2.8$ at average distances from the progenitor of $R_{\mathrm{B}} \sim 10^{16}$ cm and $R_{\mathrm{D}} \sim 4.6 \cdot 10^{15}$ 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 $M_{\mathrm{B}} \sim 5M_{\odot}$ and $M_{\mathrm{D}} \sim 2M_{\odot}$.

4. – The absorption material and the Ep-E_γ correlation

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

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

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), assuming that the observed spectrum has passed an absorber material with average optical depth of $\tau \sim 1.33$, we back-corrected the observed spectrum for the differential absorption and derived the peak energy and the collimation corrected energy. We then fitted this corrected correlation finding a steepening of the relation to approximately $E_{\rm peak} \propto E_\gamma^{0.8}$ although with a poorly significative fit. In fact the assumption of a unique value of tau in making this correction, increases the scatter of the resulting correlation. However, the worsening of the scatter in the correlation indicates that the only way forward would be to actually 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.

5. – 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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