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A review of the redshift influence on GRBs observed properties

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Abstract. Jointly with the cosmological time dilation, spectral lags obtained from Cross Correlation Function (CCF) or peak analysis of GRB's profiles at different energy bands need to be corrected from the influence of the energy redshift by a procedure named k-correction. Even the growing number of papers devoted to spectral lags, there is only a minority of them dedicated to k-correction. Conscious that some more accurate values of the lags at the source frame are important to provide us with the information about the correctness of the Lag-Luminosity Relation (the relation between the spectral lag and the isotropic peak luminosity), we ask a new way to take into account the energy redshift influence in lags. After using a linear analysis of the pulse shape around the maximum and finding a new estimate of the k-correction effect, we apply it to a group of Swift GRBs studied recently. We find that this term improves sensibly the correlation in the Lag-Luminosity Relation.

Key words. gamma rays: bursts; radiation mechanisms: non thermal

1. Introduction

Spectral lag, the time interval between the arrival of high-energy and low-energy photons, is a common property of GRBs. Based on six GRBs with known redshifts, Norris et al. (2000) found a relation between the spectral lag and the isotropic peak luminosity (Lag-Luminosity Relation or LLR). Further evidence for this correlation was provided by other works, based on observations with Swift (Gehrels et al. 2006) and BATSE channels (Hakkila et al. 2008).

The spectral lag between different channels seems to become a key for understanding the properties of GRBs (Donaghy et al. 2006). Combining spectral and temporal features, it can potentially constrain GRB models; it can also be useful in distinguishing between long and short GRBs (Norris & Bonnel 2006). The LLR is used sometimes as a redshift indicator (Band et al. 2004) and a cosmological tool (Bloom 2003).

If one wants to use LLR as a probe into the physics of GRBs (so in the source frame), the lags need to be corrected from the influence of the cosmological redshift (z-correction). The first effect is the cosmological time dilation, directly given by the factor of correction $(1+z)^{-1}$.

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The second effect comes from the redshift of the energy spectrum, from the source to the observer; it takes into account the fact that for GRBs with various redshifts, observed energy bands correspond to different energy bands at the GRB's rest frame. In analogy to the first effect, this second one has roughly been written $(1 + z)^k$ and the corresponding correction is named k-correction, a name originated at the similarity with the photometric technique employed in observational astronomy.

Even the growing number of papers devoted to spectral lags, there is only a minority of them dedicated to k-correction. Often this effect is not considered, sometimes it is taken $(1 + z)^{1/3}$ for small z and $(1 + z)$ for big ones. These estimations are based on the analysis of some hundreds of GRBs (Norris 2002) or are simply based on the empiric relation $t_p \sim E^{-0.33}$ between pulse width and energy (Norris et al. 1996).

2. A different estimate for the k-correction

Conscious that some more accurate values of the lags at the source frame are important to provide us with the information about the correctness of the LLR, Hafizi et al. (2009) considered a different approach to estimate the k-correction, using a linear analysis of the pulse shape around its maximum (following Hafizi & Mochkovitch (2007)). They found analytically the lag Δt_{AB} between two energy bands $A = [E_1, E_2]$ and $B = [E_3, E_4]$ for one-pulse burst:

$$\frac{\Delta t_{AB}}{t_p} = \frac{f_{AB,E_p}\dot{e} + f_{AB,\alpha}\dot{a} + f_{AB,\beta}\dot{b}}{C}, \qquad (1)$$

where t_p is the pulse width (pulse duration), C - a "curvature parameter" characterizing the pulse shape, whereas other factors on the right hand side represent spectral evolutions (dotted values) or derivatives of a cumulative spectral function F_{AB}:

$$F_{AB} = \frac{\int_{E_3/E_p}^{E_4/E_p} B_{\alpha\beta}(x)dx}{\int_{E_1/E_p}^{E_2/E_p} B_{\alpha\beta}(x)dx}. \qquad (2)$$

The instantaneous spectrum $B_{\alpha\beta}$ consists of two smoothly connected power laws of slopes α and β, respectively at low and high energy and $E_p(t)$-the peak energy (Band 1993), whereas $\dot{e}_p = \frac{\dot{E}_p}{E_p}t_p$, $\dot{a} = \frac{\dot{\alpha}}{\alpha}t_p$, $\dot{b} = \frac{\dot{\beta}}{\beta}t_p$, $f_{AB,X} = \frac{\partial \log F_{AB}}{\partial \log X}$.
In the source frame we have

$$F^s_{AB} = \frac{\int_{E_3/E_p(1+z)}^{E_4/E_p(1+z)} B_{\alpha\beta}(x)dx}{\int_{E_1/E_p(1+z)}^{E_2/E_p(1+z)} B_{\alpha\beta}(x)dx}. \qquad (3)$$

Knowing that t_p contains the time dilation, the relation (1) provides us with the analytical dependence of the spectral lag on energy shift (the k-correction effect). Calculated on the source frame, it is clear that the dependence on z is through the term $E_p(1 + z)$. For generally accepted values $\alpha = -1$ and $\beta = -2.33$ (Kaneko et al. 2006) and for $C = -8$ (based on Kocevski et al. (2003)) we obtained some common curves for BATSE bands 1 and 3, shown in the Fig. 1a (see Hafizi et al. (2009) for more details).

The shape of curves in Fig. 1a allows us to conclude that

- The k-correction term cannot generally be a mere function of the form $(1+z)^k$, except of cases with high z or peak energies (zone III).
- For high z and peak energies, there is a clear log-linear dependence.
- Some cases, situated around the maximum of the Fig. 1a (zone II), need not to be k-corrected.
- Evolutions of the spectrum slopes change sensibly the value of the k-correction.

The way to apply the energy correction depends basically on the value of the peak energy relative to the channels of observation, measured at the observer's frame.

3. Consequences on LLR

In a recent work, Ukwatta et al. (2010) considered LLR for 31 Swift Bursts with known redshifts. The spectral lags are extracted for all Swift bands: 15-25 keV (band 1), 25-50

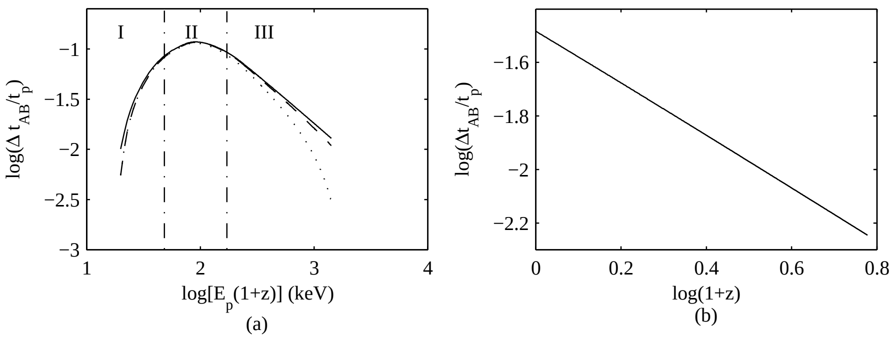

Fig. 1. a) The logarithmic dependence of the k-correction term $\frac{\Delta t_{AB}}{t_p}$ on $E_p(1+z)$ for BATSE bands 1 and 3. We considered three cases: the full line taken for α and β not evolving in time; the dashed line for $\dot{a} = \dot{b} = -0.01$ and dotted line for $\dot{a} = -0.05$ and $\dot{b} = -0.01$. Remark that around the maximum (zone II) the term is nearly independent ($k \sim 0$). For arguments above the maximum (zone III), the full line is roughly a straight line. b) The logarithmic dependence on $(1+z)$ of the k-correction term $\frac{\Delta t_{AB}}{t_p}$ in the theoretical case with $Ep = 60KeV$; $\alpha = -1$ and $\beta = -2.33$ not evolving in time; $\dot{e} = -1$. This case corresponds to lags between two first Swift bands of detection and is similar to the straight line of the zone III in 1a. The k-correction effect for such a case is therefore of the form $(1+z)^k$, with $k = -0.99$. We verified that the slope of the straight line is not affected by the values of α and β; by β time evolutions; by the curvature C. At the same time, we verified that the straight line keeps the slope for any value of the peak energy situated above the two channels of observation.

keV (band 2), 50-100 keV (band 3), 100-200 keV (band 4) and in each case are plotted the isotropic peak luminosities as functions of spectral lags. The authors considered four possibilities: not z-corrected lags; time dilation corrected lags; k-corrected lags through the dependence $(1+z)^{0.33}$; both ways corrected lags. They regained the LLR, whereas their best mean value of the correlation coefficient for various channel combinations is -0.68, attained in the case of time dilation corrected lags. The correlation becames weaker by applying k-correction of the form $(1+z)^{0.33}$.

In the present work we make use of the Ukwatta et al. (2010) analysis, applying to their spectral lags the energy corrections demonstrated above, instead of $(1+z)^{0.33}$ term. Here we show the results of our corrections on the lags between the first two channels of detection. Examining Ukwatta et al. (2010) data, we remark that the peak energies of all 31 GRBs are situated above these two channels, so we are in the simple case of the zone III of the Fig. 1a. Based on the relation (1), with similar calculations as in Fig. 1a, we obtain a theoretical k-correction dependence on redshift for these lags, shown in the Fig. 1b.

We find that the k-correction term has the dependence $(1+z)^k$, with $k = -0.99$. We verified also that

- The k-value is independent on α, β, or pulse curvature.
- Only the evolution on time of α influences the k-value. We would be able to find this influence, if we need to take it into account in a specific case.

For each of the Swift GRBs analyzed by Ukwatta et al. (2010), we apply a time dilation correction $(1+z)^{-1}$ and a k-correction $(1+z)^{-0.99}$. We plot the representative points in the lag-isotropic luminosity diagram, shown in Fig. 2.

We regain the LLR with visibly a better correlation (compare Fig. 2a and Fig. 2b). We find that the correlation coefficient in that case reaches the value −0.8 instead of −0.63.

4. Conclusions

We conclude that

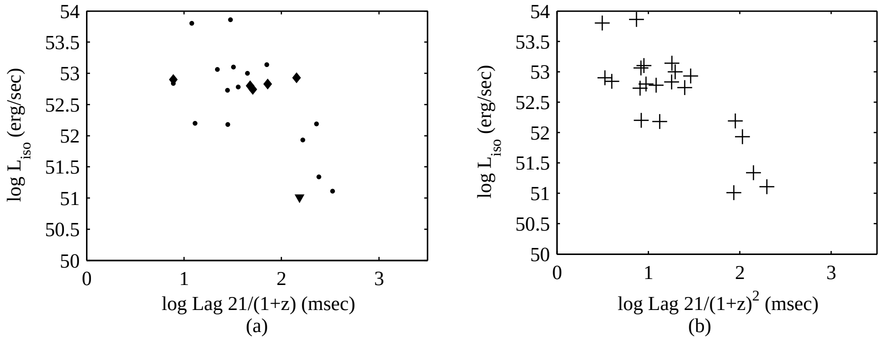

Fig. 2. a) Isotropic luminosity as a function of the spectral lag between BAT channel 2 (25-50 keV) and 1 (15-25keV) for 21 GRBs examined by Ukwatta et al. (2010). b) The same representative points for GRBs as in 2a, but with a spectral lag corrected not only for the cosmological time dilation, but also k-corrected by the term $(1 + z)^{-0.99}$. Remark that the distribution of points shows visibly a better correlation.

1. The k-correction term of the form $(1 + z)^{-0.99}$ for GRBs with peak energies above the channels of observation gives tighter correlation between the peak isotropic luminosity and the lag in LLR.
2. For peak energies situated below or between these channels, the k-correction term would not be the same, but it can be found directly from the calculations in the formula 1.
3. If the time variations of spectral slopes could be taken into account, we believe that the correlation in LLR would be tighter.
4. The other parameters do not affect the k-correction.

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