INTERNAL PHYSICAL PROCESSES IN GAMMA-RAY BURSTS LEADING TO AMATI-LIKE RELATIONS

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Abstract

Gamma-ray bursts (GRBs) are the most energetic events in the Universe. Despite the great number of works carried out during more than three decades, there is not yet a general consensus on their physical origin. The direct way of studying is to find the correlation between different properties, from the analysis of signals captured from the detectors installed on board of satellites. One kind of these relations is Amati one, which links up the energy of the signal with its spectral properties. In this work we make use of a numerical code which simulates GRBs and look for the constraints on internal physical processes, for having respected the above mentioned empirical relations. We find that Amati relation is compatible with the generally discussed model of internal shocks in GRBs.

Keywords: Gamma-ray bursts; Distances, Redshifts; Astrophysical Plasmas; Special Relativity.

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Përmbledhje

Shpërthimet gama janë ngjarjet më energjike në Univers. Megjithë numrin e madh të punimeve shkencore përgjatë më se dy dekadave, ende nuk ka një konsensus të përgjithshëm mbi origjinën e tyre fizike. Mënyra direkte e studimit është gjetja e korrelacionit mes vetive të ndryshme, nëpërmjet analizës së sinjaleve të kapura nga detektorët e instaluar në bordet e satelitëve. Një lloj i këtyre relacioneve është edhe relacioni Amati, që lidh energjinë e sinjalit me vetitë spektrale. Në këtë punim ne përdorim një kod numerik që simulon shpërthime gama dhe kërkojmë për ato procese të brendshme fizike që kënaqin relacionet empirike të sipërpërmendura. Ne gjejmë që relacioni Amati përputhet me modelin e shumëdiskutuar të goditjeve të brendshme në këto shpërthime.

1. Introduction

GRBs are very powerful electromagnetic signals, coming from sources in cosmological distances. Their duration varies from fractions of a second to hundreds of them. Each photon holds energy varying in the interval between some keVs to tens of MeVs. Most of GRBs are followed by the afterglow, a kind of emission which is longer in time, but lower in energy.

The temporal profiles of bursts, meaning the count rate as a function of time, are sometimes monopulse, but generally have a complicated behavior. Energy spectra are nonthermal; essentially they are well fitted by two different power laws, with parameters α and β, smoothly connected at peak energy E_p [4]:

$$n(E) = A\left(\frac{E}{100keV}\right)^{\alpha} \exp\left(-\frac{E}{E_0}\right)$$
$$E \leq E_0(\alpha - \beta) \qquad (1)$$

$$n(E) = A\left(\frac{(\alpha - \beta)E_0}{100keV}\right)^{\alpha - \beta}\left(\frac{E}{100keV}\right)^{\beta} \exp(\beta - \alpha)$$
$$E \geq E_0(\alpha - \beta) \qquad (2)$$

where E_0 $(\alpha - \beta)$ is the break energy. For most observed values of α and β, $E^2n(E)$ peaks at $E_p = (2 + \alpha)\, E_0$.

Such a spectral shape is close to the prediction of the synchrotron radiation from a power law distribution of electrons [8]. Spectral parameters E_p, α and β usually evolve in time.

Amati [1], making use of data from BeppoSAX and HETE for 12 long GRBs with known redshifts, discovered a relation between peak energy E_p and the total radiated energy E_{iso} (assuming isotropic emission):

$$E_p = KE_{iso}^{m} \qquad (3)$$

E_p given in keV and E_{iso} in 10^{52} erg. The total radiated energy comprises photons in the large energy band 1 – 10000keV, in the source frame of reference.

Later, Amati [2] reconfirms his relation making use of 22 GRBs with known redshifts and goes on by reconfirming in 2006 [3], bringing into play 41 GRBs with known redshifts.

Amati finds $K \sim 100keV$ and $m \approx 0.5$, which is a value situated between 0.4 and 0.6, well-matched with previous findings by Lloyd, Petrosian & Mallozi (2000), Ghirlanda, Ghisellini & Lazzati (2004), Friedman & Bloom (2005), Nava et al. (2006) (see [3]).

This empirical relation, $E_p = KE_{iso}^{m}$, is known as Amati relation.

There are several other empirical relations between E_p and other intensity indicators, which are known as Amati-type relations. One of them is Ghirlanda relationship [6]:

$$E_{peak}^{p} = 380\left(\frac{L_{iso}^{p}}{1.6 \times 10^{52}}\right)^{0.43} \qquad (4)$$

linking up the peak energy of the spectrum E_{peak}^{p} and the luminosity L_{iso}^{p}, both in the particular instant of the pulse maximum. These quantities are obtained by analyzing the spectrum of the signal in a time interval of about two seconds around the maximum of the time profile.

Because of the time evolution of spectral parameters, instantaneous values are generally different from integrated ones. Ghirlanda relation is found by the analysis of 22 long bursts with known redshifts and is confirmed for 424 other bursts, whose redshift is estimated indirectly.

Correlations like the Amati relation can be used to understand the physical mechanism responsible for the prompt GRB emission. The present study investigates this question in the framework of the 'internal shock model'.

2. Theoretical model and numerical simulation

The most discussed model for the prompt emission, which explains the high variability in GRB light curves, is the internal shock model in a relativistic wind. Here we don't take into consideration the physical nature of the source; we suppose that it is able to provide the sufficient amount of energy, transported by a non uniform relativistic flow of baryons, with low density. The fact of being non uniform in velocity leads to internal shocks between layers of matter. GRBs are thought as electromagnetic radiation emitted by relativistic electrons accelerated by these internal shocks. The non thermal spectrum suggests an optically thin medium, with no thermal equilibrium between photons and matter.

A numerical code, based on this theoretic model, has been developed for the first time at the L'Institute d'Astrophysique de Paris by F. Daigne and R. Mochkovitch [5]. We adopted it for our specific problem.

In this code, the relativistic wind is considered to be made of different layers, with a reasonable distribution in relativistic velocities, emitted during equal time intervals. This plasma possesses a high magnetic field. The Lorentz factor of layers is of the order of ~100. After a collision between two layers, a fraction of kinetic energy is converted into internal energy, which on its turn provides electron and proton acceleration, as well as the magnetic field amplification. The fraction of dissipated energy, injected in electrons, can be transformed into electromagnetic energy.

Final efficiency is the product of several factors: i) efficiency of the conversion of kinetic energy into internal one by internal shocks, which depends on the variability of the Lorentz factors Γ(*t*); ii) fraction of the dissipated energy, which is injected in electrons; iii) fraction of the electron energy, which is radiated (usually it is assumed to be close to 100%, for electrons in fast cooling regime); iv) fraction of the radiated energy in gamma photons.

We have assumed that the observed emission is due to the synchrotron radiation of shock-accelerated electrons in the amplified magnetic field. The spectrum of synchrotron emission is composed by two different (α and β) power law curves, joined at peak energy E_{CAR}; this last one named also characteristic energy of synchrotron radiation, is found to be [8]:

$$E_{car} = (h\nu_{syn}) = \frac{heB}{m_0}\Gamma_e^2\Gamma_r \qquad (5)$$

where Γ_e and Γ_r are respectively Lorentz factors of the electrons in the commoving frame and of the merged layers in the source frame, m_0 is the rest electron mass.

The total burst spectrum is obtained by adding all elementary shocks. For the integrated spectrum we can find the peak energy E_p, assuming generally accepted values for $\alpha = -1.5$ and $\beta = -2.5$.

3. Results and discussion

We consider two different assumptions for the peak energy of the emission, the synchrotron one with constant equipartition as described above (eq. 5) and the synchrotron radiation with varying microphysical parameters. In the second case, the fraction of the dissipated energy injected in electrons or in magnetic field are not constant, but function of the shocked layer's conditions. Its characteristic energy is described by the following phenomenological expression:

$$E_{car} \sim n_*^{0.25}\varepsilon^{0.25}\Gamma_r \qquad (6)$$

where n_* is the electrons density in the shocked layer, ε is the dissipated energy per unit mass in the commoving frame, Γ_r is the Lorentz factor of the merged layer in the source frame. Even if formulas (5) and (6) look very distinctive, they can obtain a similar form after some changes, differing only on exponents of energy.

We have considered several long bursts, objects of our study as obeying to the Amati relations, by varying the energy, emitted by the central engine. Lorentz factors are chosen in the interval 100-200, found to be more appropriate for long type bursts [9].

We choose the following distribution of Lorentz factors:

$$\Gamma(t) = 130 + 100\frac{t}{0.5T} \quad \text{for } t < 0.5T \qquad (7)$$

$$\Gamma(t) = 230 \quad \text{for } t \geq 0.5T, \qquad (8)$$

where T is the total emission time of the relativistic wind.

After the collision between layers, about 3% of kinetic energy is converted into thermal one. The fraction injected into electrons can be transformed into electromagnetic energy in the form of high energy gamma photons. We have assumed that 25% of the thermal energy is converted into gamma radiation and as a final result, the radiated energy is around 0.8%, in agreement with the previous findings [7] that about 1% of the energy of explosion is converted into radiation in long bursts (more than 10 s).

We have changed the injected power given to the baryonic layers, to get some GRBs with different isotropic total radiated energy and different luminosity.

Our code computes E_p, E_{iso}, E^p_{peak} and L^p_{iso}.

In fig. 1,a we show the log E_p -log E_{iso} dependence, which is clearly linear (as we expected, based on the Amati relation):

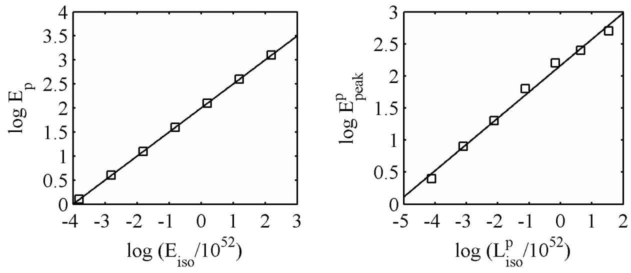
$$E_p = 100 \times (E_{iso} / 10^{52})^{0.5} \qquad (9)$$

very well-matched with the empirical Amati relation.

In fig. 1b, we show the log E^p_{peak} -log L^p_{iso} dependence, which is also linear, as required by the Ghirlanda relation. The formula fitting this dependence would be

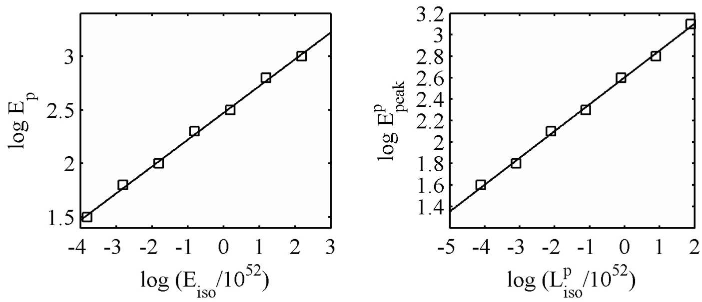
$$E^p_{peak} = 192 \times \left(\frac{L^p_{iso}}{1.6\times10^{52}}\right)^{0.41} \qquad (10)$$

whose exponent is very well-matched with the



a) b)

Figura 1. $\log E_p - \log E_{iso}$ **(a) and** $\log E^p_{peak} - \log L^p_{iso}$ **(b) plots in the case of the synchrotron radiation model with equipartition distribution. Gamma factors are distributed according to formula 7 and 8.** E_p **and** E^p_{peak} **are given in keV,** E_{iso} **(ergs) is divided by** 10^{52} **ergs,** L^p_{iso} **(ergs/s) is divided by** 10^{52} **ergs/s.**



a) *b)*

Figura 2. Same as Fig. 1 for the formula with microphysical assumptions.

Ghirlanda relation, but not the same thing for the constant of proportionality.

We repeated our calculations for other kinds of Lorentz factor's distribution between layers. We obtain the same exponent as before, but the constant of proportionality varies.

The same calculations are carried out making use of the phenomenological formula for the distribution of Lorentz factors given in eqn. (7, 8). The obtained results are given in fig. 2a, b, and can be best fitted, respectively, by the relations:

$$E_p = 316 \times (E_{iso} / 10^{52})^{0.25} \qquad (11)$$

and

$$E^p_{peak} = 398 \times (L^p_{iso} / 10^{52})^{0.25} \qquad (12)$$

In both cases, the numerical relations above cannot fit the experimental results, since the exponents found are too much different from those in the Amati and Ghirlanda relations.

From this analysis, we can conclude:

1) It is possible to reproduce Amati relations with the internal shock model. This result would be considered as a good indicator to confirm the theoretical model of internal shocks.

2) The exponent is well reproduced in the case of the equipartition distribution. This value is affected by the assumptions on microphysics, so gives an interesting constraint on internal physical processes and favors the equipartition distribution.

3) The constant of proportionality depends strongly on the assumptions about the distribution of Lorentz factors, mostly because the efficiency of the conversion of the kinetic energy into internal one depends on the variability of $\Gamma(t)$. This conclusion can help to predict a large dispersion in the observed Amati relation when more bursts are included in the sample, except of some expression for $\Gamma(t)$ favored in nature.

4) We find that the two relationships, those of Amati and Ghirlanda, follow each other, rein-

forcing the general consensus that they share the common physical origin.

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