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Structure of gamma ray burst jets(*)

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Summary. — Since 2002 a growing number of works have been addressing a major and still open issue: the GRB outflow geometry and the luminosity distribution across the jet surface. This issue is not only linked to the nature of the GRB engine and to the jet formation but also to the main energy content of the outflow. Here, I will review my contribution in opening up the possibility that a non-uniform luminosity structure can be hidden behind observations: the Universal Structure Jet (USJ). This is, in fact, the only jet structure significantly different from the constant energy homogeneous jet model (HJ) that mimics its lightcurves. The USJ can, thus, account for all the main afterglow observations. Moreover, unlike the HJ, the USJ can explain the observed constant linear polarization angle. Finally, the USJ is a highly testable model since it predicts a luminosity function, which will be soon compared with SWIFT data.

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1. – Introduction

If it is widely accepted that GRBs are produced by a relativistic moving source, the geometrical configuration and how energy and momentum are distributed within the source are highly debated issues. One of the implications of the source relativistic motion is that information come only from a portion of the fireball of angular size $\sim 1/\Gamma$. Thus, we are limited to measure the luminosity per unit solid angle, and in some cases alarmingly large values of the isotropic equivalent energy are inferred (*e.g.* $\sim 10^{54}$ erg for GRB 990123). This was the first fact that led astronomers to consider the possibility that GRBs arise from jetted and not spherical outflows, analogously to other astrophysical sources (*e.g.* AGNs and galactic superluminal sources). In 1997 it has been predicted [1] that a signature of a jet with a homogeneous luminosity distribution within the cone

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would be an achromatic break in the afterglow lightcurve when the observer eventually sees the whole emitting surface of the jet ($1/\Gamma \sim \theta_j$). Indeed, this has been observed in more than 20 bursts now. By collecting the break time and the luminosity for a dozen bursts, Frail *et al.* [2] and Panaitescu and Kumar [3], showed the existence of a correlation between the isotropic equivalent energy and the time of the break in the afterglow lightcurve: $E_{iso} \propto t_b^{-1}$. If t_b is related to the typical angular size of the emitting region, one gets $E_{iso}\theta_j^2 \simeq$ constant, implying a constant total emitted energy. This result motivated what is now considered the standard homogeneous jet scenario: all GRB jets carry the same total energy, but spread over a large variety of aperture angles (Frail *et al.* 2001). Different observation are related to intrinsic source dissimilarities (*i.e.* the opening angle; see fig. 1)

2. – Universal Structure Jet idea

Rossi, Lazzati and Rees [4] realized that the relation $E_{\rm iso}\,\theta_j^2 =$ constant may reflect a universal angular distribution of jet energy rather than a distribution of opening angles among different jets (see also [5]). In this case, assuming *an angle-independent radiation efficiency*, one would write

$$\frac{\mathrm{d}E(\theta)}{\mathrm{d}\Omega} \equiv \epsilon \propto \theta^{-2}, \tag{1}$$

where ϵ is the *kinetic* energy per unit solid angle. Rossi *et al.* also showed that such an energy pattern (and no other power law configurations) would produce an afterglow that reproduces the Frail *et al.* correlation and does not violate other observations (see sect. **3**). Different observed properties would reflect different observing geometries rather than different intrinsic jet properties (see fig. 1). Later, Berger *et al.* [6] extended to the X-ray afterglow the existence of a correlation between the emitted energy per unit solid angle and the break time: again this can be interpreted alike within the HJ or the USJ scenario. Since then, different jet morphologies have been proposed and studied, specifically general power law profiles and Gaussian profiles [7-10]. A discussion and comparison between the lightcurves given by these different models is the topic of the next section (see [9] for more detail).

3. – Afterglow lightcurve

If one *assumes* that the lightcurve from a USJ is dominated by the line-of-sight emission, it is very easy to demonstrate that a USJ satisfies the Frail correlation [11]. However, it is necessary to prove it, and therefore to calculate the lightcurve arising from such a jet (see fig. 3). Our semi-analytical and numerical results were fully confirmed later by more sophisticated calculations, *e.g.* [7]. Indeed, the lightcurve is determined before the break by the local energy per unit angle $\epsilon(\theta_o) \equiv \epsilon_o$ and after, by the "total energy" $\epsilon_o\theta_o^2$ of the cone with semi-aperture θ_o(where θ_o is the viewing angle). Finally, there is a break in the lightcurve even in the absence of sharp jet edges and the value of the break time t_b is related to the value of the observer angle; the algebraic relation is the same that links t_b with the jet angle θ_{jet} in the HJ model. This implies that the observed quantity $\epsilon_o\theta_o^2$ is constant, which is the Frail correlation. It should also be noticed that the USJ luminosity distribution (eq. (1)) is not only consistent with observational results, but it is the *only* configuration (substantially different from the HJ) that can reproduce the lightcurves given by a HJ. This is illustrated in fig. 2, where other power law relations

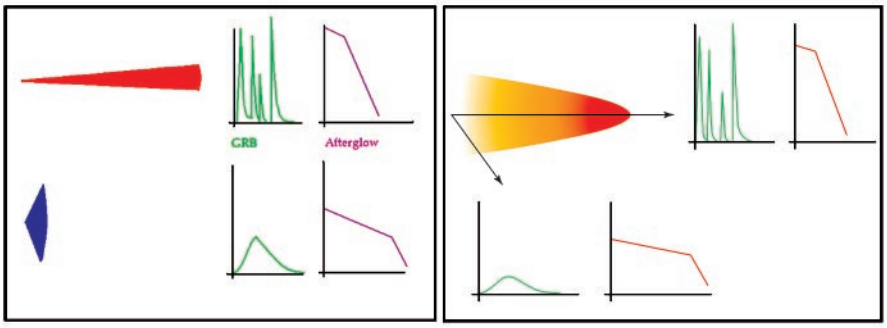

Fig. 1. – A cartoon of the models that explain the F01 and possibly the variability-luminosity correlation with HJs (left panel) and USJs (right panel). *Left panel*: the same total energy is injected into very different opening angles: wide jets are dimmer and the afterglow lightcurve breaks at later times comparing to narrow jets. The variability-luminosity correlation is also satisfied if wide jets have lower Lorentz factors (thus typical timescales are observed to be longer) than jets with smaller apertures. *Right panel*: the different observed characteristics of the prompt and the afterglow emission do not mirror intrinsic differences of the emitting source but they are due to a standard source viewed under different angles.

$\epsilon \propto \theta^{-\alpha_\epsilon}$ are shown. A decay flatter than 2 would cause two breaks in the lightcurve: the first due to the cone pointing towards the observer when $\Gamma(\theta_o) \sim \theta_o^{-1}$ and the second, at later times, when the observer sees the edge of the jet and $\Gamma(\theta_{jet}) \sim \theta_{jet}^{-1}$. The power law index after the first break is flatter than t^{-p} because the cones with $\theta_o < \theta \leq \theta_{jet}$ enter the line of sight with $\epsilon \geq \epsilon_o$ and substantially modify the lightcurve shape. With a steeper decay in the distribution of ϵ the time break and the emission after that break would be dominated by the jet along the axis. The jet break would then be preceded by a prominent flattening in the lightcurve, especially for $\alpha_\epsilon > 3$, difficult to reconcile with observations.

In fig. 3 the USJ lightcurve is compared with the HJ and the GJ lightcurves seen respectively within the jet aperture and within the nearly constant core. (Notice that a GJ seen off-axis shows very peculiar lightcuirves, hardly compatible with data.) The close comparison emphasizes the fact that a USJ is indistinguishable from a HJ (or a Gaussian Jet) from the observed total flux. This motivated us to investigate different tools that could, in principle, reveal the underlining jet structure: these are discussed in sects. **4** and **5**.

4. – Polarization curves

The previous section concludes that from the lightcurve properties, it is extremely hard to infer the structure of the jet. Polarization curves, on the other hand, are extremely different (fig. 3). Since the brightest part of the jet is always on the same side for structured (SJ and GJ) outflows, the position angle of polarization remains constant throughout the whole evolution. In addition, for a USJ the polarization peak is coincident in time with the jet break in the light curve, which instead corresponds to the time of minimum polarization in homogeneous jets. The exponential wings in a GJ, however, shift the position of the peak after the break in the lightcurve, a feature that marks the difference between the GJ and the USJ predicted polarization. I should however stress

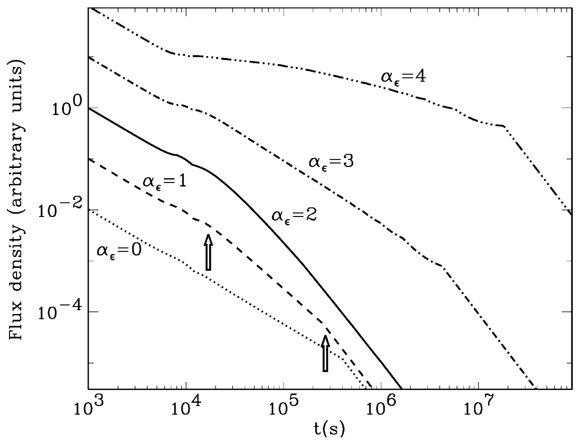

Fig. 2. – The lightcurve of SJs with different indices α_ϵ ($\epsilon \propto \theta^{-\alpha_\epsilon}$). The lightcurves have the same ϵ_o but they are plotted shifted by factors of 10 for clarity (they would be indistinguishable at small time). The arrows mark the location of the two breaks for $0 < \alpha < 2$.

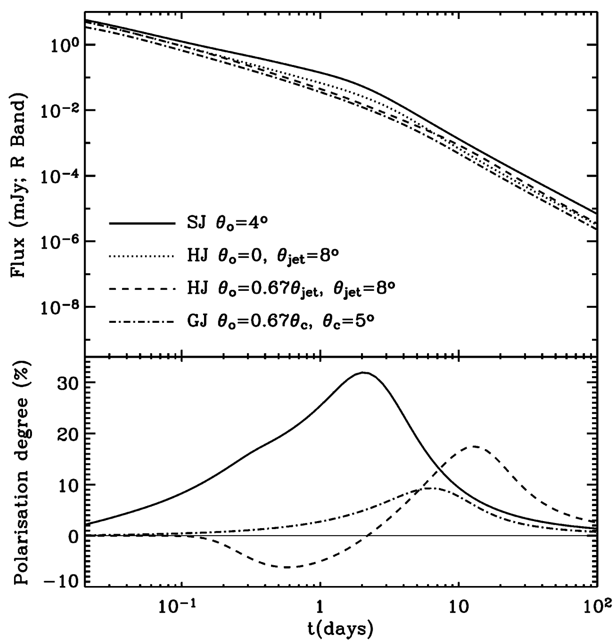

Fig. 3. – Lightcurves (upper panel) and polarization curves (lower panel) comparison between a SJ seen at $\theta_o = 4°$, a homogeneous jet with $\theta_{jet} \simeq 2\,\theta_o$, $E_{iso} \simeq E_{iso}(\theta_o)$ and $\Gamma_0 \simeq \Gamma_0(\theta_o)$ and a GJ with the same E_{iso} and Γ_0 but characteristic size $\theta_c \simeq 0.6\theta_{jet}$; the HJ is seen on-axis and at $\theta_o = 0.67\theta_{jet}$, while the GJ is seen at $\theta_o = 0.67\theta_c$. The other parameters are: $z = 1$, $E_c = 2 \times 10^{54}$ erg, $\alpha_\epsilon = 2$, $\beta_\epsilon = 1$, $\beta_\Gamma = 0$, $\Gamma_c = 2 \times 10^4$, $\theta_c = 1°$, $\theta_{jet} = 90°$, $\epsilon_e = 0.01$, $\epsilon_B = 0.005$ and $n = 1$ cm^{-3}. All jets do not undertake lateral expansion.

that due to the many uncertainties inherent in the derivation of polarization curves, it is hardly possible to use them to measure in a fine way the energy distribution of the jet (*e.g.* tell a $\epsilon \propto \theta^{-2}$ structured jet from a $\epsilon \propto \theta^{-2.5}$ one). What polarization can robustly determine is whether the energy distribution in the jet is uniform or centrally concentrated. Finally, a chromatic study of polarization curves both for a HJ and for a USJ [9] find a spectral dependence of the degree of polarization and predict changes in the temporal behavior of the polarized fluxes (in all bands but in particular in the radio band) associated with spectral breaks in the lightcurve.

Alternative approaches, such as the observed luminosity function [4] are also important to further constrain the jet profile, even though the data seem not to be accurate enough at this stage [12, 13]. This is the topic of the next section.

5. – Luminosity function

Under the USJ assumptions, each γ-ray luminosity corresponds to a particular viewing angle. This feature makes the USJ a more testable model than the HJ. A specific prediction of the USJ is the luminosity function that in principle can be tested against data.

The probability to see a jet between θ and $\theta + \mathrm{d}\theta$ is given by

$$P(\theta)\mathrm{d}\theta \propto \sin\theta \mathrm{d}\theta \qquad 0 \le \theta \le \theta_j, \tag{2}$$

$\langle\theta\rangle \simeq 0.7$ and the highest probability is for $\theta = \theta_j$. Therefore it is highly improbable to see a jet on axis. Consequently, more faint GRBs than very luminous ones are expected, according to a luminosity function

$$N(L) \propto L^{-2}, \tag{3}$$

where again a constant radiation efficiency is assumed. Since there are only a small number of GRBs with observed redshift, the direct comparison of our predicted luminosity function with data is currently not possible. A histogram of the bolometric k-corrected prompt energies for 17 GRBs has been published by [14]. The distribution is roughly flat from 6×10^{51} to 2×10^{54} erg but as the authors emphasize this analysis applies only to observed GRBs with redshifts and several observational biases obscure the true underlying energy distribution. The main bias that overcasts faint GRBs is the detection threshold of the instruments: this sample is thus flux and not volume limited. Moreover redshift determination encounters more problem for faint GRBs.

Recently many papers testing the predictions of the USJ have appeared. A calculation of the expected distribution of inferred viewing angles has been performed, assuming that GRBs follows the star forming history and taking into account instrumental flux limits [12]. Integrating over the redshift, a good agreement with observations has been found. On the other hand it has been noticed that, if at all angles the prompt emission peaks in γ-rays, the USJ predicts too many small angles (bright bursts) at high redshift and too many large angles (faint bursts) at low redshift compared to what is observed [13]. However, the authors are aware that selection effects strongly affect these results. Finally, it has been shown that if the emission at large angles peaks in X-ray, data are still consistent with the predictions of the USJ model [15].

Given the somewhat contradictory results discussed above, it is evident that more accurate spectral and fluence measures and a larger sample of bursts are needed for a proper comparison.

6. – Discussion

The Structure Jet was at first a phenomenological answer. However, it seems to be the natural outcome of two models for the jet formation. In the purely electromagnetic model by Lutikov and Blandford [16], where the magnetic energy alone drives the expansion, the USJ is the asymptotic kinetic energy distribution across the jet. More recently, Lazzati and Begelman [17] showed that the USJ seem to be the natural result of the jet-cocoon interaction, while the jet makes is way out from the collapsed core to the surface of a massive star progenitor. These models bring theoretical support to the idea of a $\epsilon \propto \theta^{-2}$ jet profile.

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