EXTRAGALACTIC GAMMA–RAYS: GAMMA RAY BURSTS AND BLAZARS

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The extragalactic gamma–ray sky is dominated by two classes of sources: Gamma–Ray Bursts (GRBs) and radio loud active galactic nuclei whose jets are pointing at us (blazars). We believe that the radiation we receive from them originates from the transformation of bulk relativistic energy into random energy. Although the mechanisms to produce, collimate and accelerate the jets in these sources are uncertain, it is fruitful to compare the characteristics of both classes of sources in search of enlightening similarities. I will review some general characteristics of radio loud AGNs and GRBs and I will discuss the possibility that both classes of sources can work in the same way. Finally, I will discuss some recent exciting prospects to use blazars to put constraints on the cosmic IR-Optical-UV backgrounds, and to use GRBs as standard candles to measure the Universe.

Keywords: Gamma–rays; Gamma–ray bursts; blazars; cosmology.

1. Introduction

The golden ’60s, together with the Cosmic Microwave Background and the pulsars, witnessed the discovery of other two important classes of sources: Gamma–Ray Bursts (GRBs) and radio loud active galactic nuclei whose jets are pointing at us (blazars). We believe that the radiation we receive from them originates from the transformation of bulk relativistic energy into random energy. Although the mechanisms to produce, collimate and accelerate the jets in these sources are uncertain, it is fruitful to compare the characteristics of both classes of sources in search of enlightening similarities. I will review some general characteristics of radio loud AGNs and GRBs and I will discuss the possibility that both classes of sources can work in the same way. Finally, I will discuss some recent exciting prospects to use blazars to put constraints on the cosmic IR-Optical-UV backgrounds, and to use GRBs as standard candles to measure the Universe.

Keywords: Gamma–rays; Gamma–ray bursts; blazars; cosmology.
In both classes of sources we see non-thermal radiation and it is therefore likely that magnetic field and non-thermal particles are the key ingredients to produce the radiation we see. This radiation, being produced by plasma in relativistic motion, is strongly beamed in the velocity direction, and we have evidences that also in GRBs the emitting fireball is collimated in a cone, i.e. a “jet”. For these reasons it is instructive to compare them looking for similarities and differences, to see if their physics is similar. In the following I will briefly discuss some of the basic facts of blazars and GRBs, and discuss the possibility that, at the origin of their phenomenology, there is a common engine. Being so powerful, blazars and GRBs are well visible even at redshifts greater than 6, and we can use them as probes of the far universe. In the case of GRBs, we can even measure the universe, thanks to a recently found correlation between their properties which enable us to use them as standard candles.

2. Blazars vs GRBs

2.1. Speeds: blazars

Soon after the achievement of the VLBI technology, in the early ‘70s, 3C 279 and 3C 273 were discovered to have spots of radio emission moving away from the nucleus at the apparent speed of $\beta_{\text{app}} \sim 10$. This was one of the few dramatic features in astronomy which were anticipated by theory (Rees 1966), and it is the result of real motion at velocities close to $c$, observed at small, albeit not vanishingly small, viewing angles. The corresponding bulk Lorentz factors $\Gamma$ are greater or equal than $\beta_{\text{app}}$, and today superluminal speeds are routinely measured in almost all (and the exception are important) blazars. It is difficult to assign an upper limit to the inferred distribution of $\Gamma$, but it is believed that in powerful blazars (showing relatively strong broad emission lines, as in radio–quiet AGNs), the range is $3 < \Gamma < 20$, with some remaining uncertainty associated with the phenomenon of intraday variability in radio, leading to huge brightness temperatures (see Wagner & Witzel 1995 for a review). This is now explained by the effect interstellar scintillation, but a source scintillates if its angular size is small, suggesting in any case very high brightness temperatures, even if not so extreme, requiring large $\Gamma$ in any case (e.g. Kedziora–Chudczer et al. 2001). Furthermore, at the other hand of the power scale, models of TeV BL Lacs seem to require $\Gamma$ up to $\sim 50$ or so, to explain their TeV emission, especially when their $\gamma$–ray spectrum is “de–absorbed”, i.e. when the depletion of TeV photons interacting with the IR cosmic background is taken into account (e.g. Krawczynski, Coppi & Aharonian 2002; Konopelko et al. 2003). Interestingly, VLBI and space VLBI observations of these TeV BL Lacs have revealed that their apparent speed at the submas scale ($\sim 1$ pc) is only moderately superluminal or even subluminal (Piner & Edwards 2004; Giroletti et al. 2004). This of course opens the issue of strong deceleration from TeV emitting region ($\sim 10^{17}$ cm from the center) to 1 pc (Kazanas & Georganopoulos 2003, Ghisellini, Tavecchio & Chiaberge 2004).
From the beginning, the plasma moving inside the jets was assumed to have a monodirectional velocity, despite the conical geometry of the jet itself. There have been sporadic attempts to see what happens if the velocity vectors are distributed in a fan-like geometry ("sprayed", Celotti et al. 1993), but this possibility has not been followed in any detail. Instead, there is some suggestions that the jet may have a velocity structure (but still monodirectional), with a fast spine and a slow layer (e.g. Laing 1993; Chiaberge et al. 2000 and references therein; Ghisellini, Tavecchio & Chiaberge 2004), at least in low power (and TeV emitting) BL Lacs and in their misaligned counterpart, i.e. FR I radiogalaxies.

2.2. Speeds: GRBs

We do not see "jets" in GRBs, but we nevertheless believe that their emission originates from plasma moving with $\Gamma > 100$, making them the speed record holders among all known sources. There are essentially three arguments suggesting such large speeds:

1. Compactness. We see variability on timescales 1–100 ms, powers $\sim 10^{50}$ erg s$^{-1}$ and spectra extending above 511 keV, the threshold for $\gamma-\gamma \rightarrow e^+e^-$. If the source is not moving the optical depth for the photon–photon process is of the order of $10^{11}$–$10^{12}$. Relativistic bulk motion comes to the rescue by allowing much larger sizes of the emitting region than inferred from variability, much smaller intrinsic powers, and much less photons above threshold.

2. Variability. To produce the radiation we see, the source cannot be as small as inferred from the observed variability, since the required leptons would make the source Compton or Thomson thick for scattering. Again, a large $\Gamma$ is required.

3. Theory. A huge amount of energy put in a small volume in a short time generates a small Big–Bang: $e^+e^-$ pairs are immediately created, the source becomes instantaneously thick and expands, pushed by its internal pressure, to become relativistic. This is the fireball (Cavallo & Rees 1978).

At first, fireballs were thought to be spherically symmetric, with radial velocities. Now there are strong indications that they are collimated into cones (or flying pancakes) of some aperture angle $\theta_j$. These angles are of the same order of blazar’s jets, but in GRBs studies the ‘sprayed’ nature of the velocities has been maintained in almost all models of GRBs (with the exception of the cannonball model; e.g. Dar & De Rújula, 2003).

2.3. Power: blazars

The spectra (SED) of blazars are characterized by two broad emission peaks, believed to be produced in the same zone of the jet (at some hundreds of Schwarzchild radii from the base) by the synchrotron and inverse Compton processes (but there are alternative views, see e.g. Mucke et al. 2003 and references therein).
Fossati et al. (1998) found that the SED is controlled by the bolometric observed luminosity, with both peaks shifting at smaller frequencies when the luminosity increases (see Fig. 1 left). Furthermore, the dominance of the high energy peak increases when increasing the bolometric luminosity (but this latter inference was based on the few low power BL Lacs detected by EGRET). This blazar sequence can be explained by a different degree of radiative cooling: in powerful blazars electrons cool faster, producing a break in the electron distribution function at smaller and smaller energies when increasing the total (radiation plus magnetic) energy density in the comoving frame (Ghisellini et al. 1998).

Fig. 1. **Left:** the blazar sequence. From Fossati et al 1998, Donato et al. 2002. **Right:** The GRB sequence (i.e. the “Ghirlanda correlation”). From Ghirlanda et al. 2004b, with the addition of the recent GRB 041006; which nicely fits the correlation. The filled black squares correspond to the energy emitted during the prompt phase of the bursts $E_{\text{iso}, \gamma}$ assuming isotropy (Amati et al. 2002). The circles (red and blue) are the collimation corrected energy $E_{\gamma} = E_{\text{iso}, \gamma}(1 - \cos \theta)$, where $\theta$ is the aperture angle of the jet (assumed to be conical). For both blazars and GRBs the SED is a function of the observed bolometric energy output, but the two behaviors are opposite: blazars are bluer when dimmer, GRBs are bluer when brighter. Note the extremely small scatter of the Ghirlanda correlation.

In the most powerful blazars, we believe that most of the energy carried by the jet is not radiated away, but it is kept to power the large scale radio–lobes. Equipartition and minimum energy arguments are used to infer the energy contained in these structures, and by dividing it with the estimated lifetime of the source the average power of the jet can be estimated. Rawling & Saunders (1991) find average powers ranging from $10^{43}–10^{44}$ erg s$^{-1}$ for FR I radio galaxies to $10^{46}–10^{47}$ erg s$^{-1}$ for FR II radio galaxies and radio–loud quasars.
One can also calculate the power carried by the jet by inferring its density through modeling the observed SED and requiring that the jet carries at least the particles and the magnetic field necessary to make the radiation we see. This has been done on the pc scale by Celotti & Fabian (1993), on sub–pc scale (the γ–ray emitting zone) by Celotti & Ghisellini (2004, see also Ghisellini 2003), and on the hundreds of kpc scale (the X–ray jets seen by Chandra) by Celotti, Ghisellini & Chiaberge (2001) and Tavecchio et al. (2000). These studies find consistent values of the power transported by the jet and require the presence of a dynamically dominating proton component (see also the arguments by Sikora & Madejski 2000).

2.4. Power: GRBs

Assuming isotropic emission, GRBs emit $E_{\gamma, \text{iso}} = 10^{51}–10^{54}$ erg in the γ–ray and hard X–ray band in a few seconds, and a factor 10 or so less during the much longer lasting afterglow. The prompt spectra are characterized by a single component, peaking (in $\nu F_\nu$) at an energy $E_{\text{peak}}$. Early results from BATSE led to believe that $E_{\text{peak}}$ was clustered around $\sim 300$ keV, but now (mainly thanks to HETE II, see e.g. Lamb et al. 2004, Sakamoto et al. 2004) we think that the $E_{\text{peak}}$ distribution is broader, ranging from a few keV and a few MeV. Both the prompt and the early afterglow emissions are very likely collimated into cones of semiaperture angles $\theta_j$, decreasing the energy budget by the factor $(1 - \cos \theta_j)$ (two jets are assumed; e.g. Frail et al. 2001). The cone angle can be measured by measuring the time $t_j$ at which the afterglow lightcurve steepens. Being the result of a geometric effect, this break must be achromatic. Recently, Ghirlanda, Ghisellini & Lazzati (2004) found a remarkably tight correlation between the collimation corrected energy $E_\gamma = (1 - \cos \theta_j)E_{\gamma, \text{iso}}$ and $E_{\text{peak}}$ (Fig. 11 right): $E_{\text{peak}} \propto E_\gamma^{0.7}$: then GRBs are bluer when brighter, just the opposite of blazars. The fact that the scatter around this correlation is so small has a profound cosmological implication, since it allows to use GRBs as standard candles (see below).

3. The central engine

Despite the efforts of the last 30 years, the acceleration, launching and collimation of jets are still open issues. Even the primary energy reservoir is debated, since it may be in the spin of the black hole, or in the rotational energy of the accretion disk. For GRBs the early suggestions of neutrino–neutrino interactions resulting from the merging of two neutron stars seems now disfavored by energetic arguments and by the fact that GBRs preferentially occur well within galaxies. For blazars, the large ratio between the γ–ray and the X–ray fluxes suggests that the reprocessing due to $\gamma - \gamma \rightarrow e^\pm$ is not important, requiring that the jet dissipation region is not very compact. This in turn requires that most of the dissipation takes place at some distance from the black hole (hundreds of Schwarzschild radii, Ghisellini & Madau 1996), and energy has to be transported there in a low entropy fashion, favoring a Poynting flux origin of the jet power. On the other hand, the dominance
of the \( \gamma \)-ray emission with respect to the synchrotron radiation emitted at lower frequencies requires a magnetic field which is not dominant, at least in the emission region. Therefore pure Poynting flux jet models face some difficulties, even if the role of the magnetic field at the start of the jet is probably crucial. For GRBs, the “standard” model (e.g. Rees & Mészáros 1992; Rees & Mészáros 1994; Sari & Piran 1997) assumes that dissipation takes places right at the start, with a little “contamination” of barions, and that it is the internal pressure that accelerates the fireball to ultrarelativistic speeds. However, also for GRBs a low entropy pure Poynting flux has been proposed (Blandford 2003, Lyutikov & Blandford 2003). A possible observational diagnostics for this alternative model is a high level of polarization of the prompt and the early (minutes from the trigger) afterglow (Lyutikov, Pariev & Blandford 2003) which could flag the presence of a well ordered and dominant magnetic field.

The most accepted scenario for the production of the prompt radiation in GRBs proposes that the energy, initially in high entropy form, is transformed into bulk motion. To produce radiation, this ordered kinetic energy has to be re-converted in random energy and then into radiation. In this scenario this job is done by inhomogeneities and different velocities in the ultrarelativistic fireball wind which cause internal shocks. Generally, these shocks can convert only a modest fraction of the total energy in radiation, unless the relative bulk Lorentz factors of the different parts of the fireball are extremely large (Beloborodov 2000, but note that this may cause other difficulties, see e.g. Ghisellini 2003). On the contrary, the interaction of the fireball with the circumburst medium, which is thought to produce the afterglow radiation, should be more efficient, since the circumburst medium is at rest, and a larger fraction of the initial kinetic energy of the fireball can be dissipated. As a result, we naively expect that the total energy radiated during the afterglow phase is greater than the one radiated during the prompt phase, contrary to what is observed.

The low efficiency of internal shocks, which is a problem for GRBs, is instead required for blazars, where the very same idea of internal shocks has been successfully applied (Ghisellini 1999; Spada et al. 2001; Guetta et al. 2004). Powerful blazars, in fact, radiate a minor fraction of their jet power, and keep the rest up to the end of the jet, where it is used to energize the radio lobes. In addition, internal shocks in blazars explain why most of the dissipation takes place at some distance from the black hole: it takes time for a faster part of the flow to catch up with a slower one: if the two parts have bulk Lorentz factors \( \Gamma \) and \( 2\Gamma \) and are initially separated by a distance \( R_0 \), the collision will take place at \( R_{\text{diss}} \sim \Gamma^2 R_0 \); with \( R_0 \) of the order of the Schwarzschild radius and \( \Gamma \sim 10 \), \( R_{\text{diss}} \) is just right. After the first collisions, the range of bulk Lorentz factors is reduced, and therefore subsequent collisions will take place with a reduced efficiency: in other words, internal shocks select a preferred distance where most of the energy is dissipated, in agreement with what we observe.
EXTRAGALACTIC GAMMA-RAYS

Fig. 2. The Spectral Energy Distribution of the most distant blazar Q0906+6930 (Romani et al. 2004). For this and alike blazars, a high energy cutoff is expected in the spectrum due to the $\gamma-\gamma \rightarrow e^+e^-$ process between $\gamma$-rays and optical–UV photons, both produced in the vicinity of the source and belonging to the optical–UV cosmic background photons. The solid line is a synchrotron inverse Compton model which takes into account $\gamma-\gamma$ absorption, pair creation and the associated pair reprocessing (along the lines discussed in Ghisellini et al. 1998).

4. Distant blazars and the IR–UV background

Romani et al. (2004) have recently associated a previously unidentified EGRET source to the more distant blazar known, 0906+6930, at $z = 5.47$. Its SED is shown in Fig. 2 together with a possible spectral model. If confirmed, this would be the most distant $\gamma$–ray emitter. Besides flagging the presence of really supermassive (although young) black holes (of masses exceeding $10^{10} M_\odot$), these sources will be crucial for studying the cosmic background radiation at UV–Optical frequencies, which will imprint a sharp cutoff at high (tens of GeV) $\gamma$–ray energies. Similarly, but at much lower redshifts, one can study the IR background through the absorption it produces at TeV energies. One should be careful to disantangle the local absorption due to photons produced within the source (which, incidentally, must also act as seed photons for the scattering process) from the absorption due to the cosmic backgrounds, but this is possible by studying sources of similar luminosities at different redshifts. In this respect, one can judge the potential of GLAST by looking its detection limit in Fig. 2.

5. Measuring the Universe with GRBs

The “Ghirlanda correlation” shown in the right panel of Fig. 1 opens up the possibility to use GRBs as rulers to measure the universe. This is more than a wishful thinking, and already now the 15 GRBs of the sample of Ghirlanda et al. (2004b) put interesting constraints on the cosmological parameters. Fig. 3 shows the clas-
Fig. 3. Classical Hubble diagram in the form of luminosity–distance $D_L$ vs redshift $z$ for Supernova Ia and GRBs (filled red circles: the 15 bursts in Ghirlanda et al. 2004b). In the top panel no correction was applied for the SN Ia and all GRBs are assumed to emit $E_\gamma = 10^{51}$ erg. In the bottom panel we have applied the stretching-luminosity and the $E_\gamma$–$E_{\text{peak}}$ relations to SN Ia and GRBs, respectively. Both panels also show curves for different $D_L(z)$, as labelled. From Ghirlanda et al. (2004a).

Classical Hubble diagram for both SN Ia and GRBs. In the top panel we can see the data points before correcting the luminosity of SN Ia for the Phyllips relation (i.e. a relation connecting the rate of decay of the lightcurve with the luminosity of the event; Phyllips 1993), and assuming that all GRBs emit $10^{51}$ erg. In the bottom panel, both the luminosity of SN Ia and the energetics of GRBs have been corrected, assuming, for GRBs, the Ghirlanda relation between $E_\gamma$ and $E_{\text{peak}}$. The left panel of Fig. 4 shows the constraints in the $\Omega_M$–$\Omega_\Lambda$ plane, considering GRBs alone, SN Ia alone, and a combined fit. One can see that despite the huge difference in number (15 GRBs vs 156 SN Ia), GRBs can affect the constrained derived by SN Ia, to make the combined fit more in agreement with the “concordance” cosmological model, which suggests $\Omega_M \sim 0.3$ and $\Omega_\Lambda \sim 0.7$. But the huge potential of GRBs for cosmology is not much in finding more accurate values of $\Omega_M$ and $\Omega_\Lambda$; i.e. in saying how the universe is now. The real potential lies in the ability of GRBs to find out in which way the universe became what it is, i.e. how the dark energy evolves. To do that we must have sources of known luminosity or power embracing the maximum possible range of redshifts, to find out, for instance, if the equation of state of the dark energy was described by a constant or a time dependent relation between pressure and energy density.
Fig. 4. **Left:** Constraints in the $\Omega_M-\Omega_\Lambda$ plane derived for the GRB sample (15 objects, red contours); the “Gold” Supernova Ia sample of Riess et al. (2004) (156 objects, blue contours). The WMAP satellite constraints (black contours, Spergel et al. 2003) are also shown. The three colored ellipsoids are the confidence regions (dark green: 68%; green: 90%; light green: 99%) for the combined fit of SN Ia and our GRB sample. **Right:** Constraints in the $w'-w_0$ plane, where the equation of state of the dark energy is assumed to be described by $P = (w_0 + w'z)\rho c^2$. The combined GRB+SN Ia contours are more consistent with $w_0 = -1$, $w' = 0$ than SN Ia alone. From Ghirlanda et al. 2004a.

For illustration, the right panel of Fig. 4 shows the constraints in the $w'-w_0$ plane, when assuming a time dependent equation of state of the dark energy, of the form $P = (w_0 + w'z)\rho c^2$, where $P$ and $\rho$ are the pressure and the energy density of the dark energy. If the dark energy is described by the classical Λ cosmological term, then we must have $w_0 = -1$ and $w' = 0$. Again, note that although GRBs alone are not very constraining, the combined fit of GRB+SN Ia moves the 68% confidence region to embrace the $w_0 = -1$, $w' = 0$ point.

An obvious advantage from using GRBs for cosmology is that we can detect them up to redshift 10 or 20, contrary to SN Ia, detectable up to $z \sim 1.7$. The other point in favor is that GRBs are virtually unaffected by dust or Lyman α absorption. Finally, if the Ghirlanda correlation is obeyed by GRBs of any luminosity, it is evolution-independent.

The SWIFT satellite is expected to localize 100–150 bursts per year. For the majority of them we foresee to have redshifts and well sampled afterglow lightcurves, allowing the most optimistic expectations for doing cosmology with GRBs.

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