A jet-disk symbiosis model for Gamma Ray Bursts: fluence distribution, CRs and ν's

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Abstract.
We consider a jet-disk symbiosis model to explain Gamma Ray Bursts and their afterglows. It is proposed that GRBs are created inside a pre-existing jet from a neutron star in a binary system which collapses to a black hole due to accretion. In our model we assume that a fraction of the initial energy due to this transition is deposited in the jet by magnetic fields. The observed emission is then due to an ultrarelativistic shock wave propagating along the jet. Good agreement with observational data can be obtained for systems such as the Galactic jet source SS433. Specifically, we are able to reproduce the typical observed afterglow emission flux, its spectrum as a function of time, and the fluence distribution of the corrected data for the 4B BATSE catalogue. We also studied the relation between the cosmological evolution of our model and the cosmic ray energy distribution. We used the Star Formation Rate (SFR) as a function of redshift to obtain the distribution in fluences of GRBs in our model. The fluence in the gamma ray band has been used to calculate the energy in cosmic rays both in our Galaxy and at extragalactic distances. This energy input has been compared with the Galactic and extragalactic spectrum of cosmic rays and neutrinos. We found that in the context of our model it is not possible to have any contribution from GRBs to either the extragalactic or the Galactic cosmic ray spectra.

INTRODUCTION

Gamma-Ray Bursts are short bursts that peak in the soft γ-ray band, between 100 KeV and a few MeV. The duration of their emission goes from 10×10^{-3} s to 10^3 s, and they show variability of the order of ms. They also show persistent emissions in the X, optical, infrared and radio bands (afterglow), a spatially isotropic distribution, and a nonthermal spectrum. It is believed that GRBs are associated with relativistic shocks caused by a relativistic fireball in a pre-existing gas, such as the interstellar medium or a stellar wind/jet, producing and accelerating electrons/positrons to very high energies, which produce the gamma-emission and the various afterglows observed [1,2]. More than 30 years after their discovery, thanks to the Burst and Transient Source Experiment (BATSE) and the Italian-Dutch satellite BeppoSax, the scientific community knows that Gamma Ray Bursts (GRBs) are isotropically distributed in the sky and that at least some of them are at cosmological distances. But the present data available for redshift position and host galaxy localization are still too few to give us good statistics to study the evolution of GRBs and their redshift distribution. Because of this lack of information, it is still necessary to assume that GRBs follow the statistical distribution of some other well known objets to obtain the GRBs fluence or flux distribution itself [3,4].

GRB JET MODEL: KEY POINTS

In our model [5], GRBs develop in a pre-existing jet. We consider a binary system formed by a neutron star and an O/B/WR companion in which the energy of the GRB is due to the accretion-induced collapse of the neutron star to a black hole. To fix the jet parameters we use the basic ideas of the jet-disk symbiosis model by Falcke & Biermann [6]. In this model, accretion disk, jet, and compact object are considered as an entire system. Mass and energy conservation are applied and the total jet power $Q_{\rm jet}$ is found to be a substantial fraction of disk luminosity $L_{\rm disk}$. We assume that the collapse of a neutron star to a black hole in a binary system induces a highly anisotropic energy release along the existing jet: a violent twist and jerk of the magnetic field. It initiates a relativistic shock wave, with an initial bulk Lorentz factor of about 10^4. Baryonic mass is known to be low in jets. The bulk Lorentz factor evolution derives from the sweep up of the jet material. Magnetic field and particle number density evolution are obtained from the jump conditions in the ultrarelativistic shock. We consider a power law electron energy distribution with a low energy cut-off. Pre-existing energetic electrons/positrons are further accelerated in the shock. The afterglow emission is due to synchrotron and Inverse Compton processes from the shock region. The fluence of the initial burst is determined by shock, dissipation, and γ-γ optical depth effects. The emission region is optically thin very early on and always in the fast cooling regime. There are only two parameters for the explosion: the energy in bulk flow along the jet, $E_{51} \cdot 10^{51}$erg, and the fraction δ of shock energy in relativistic particles. The parameters from the binary system jet are: the mass flow $\dot{M} \cdot 10^{-5} M_{\odot}/\mathrm{yr}$, the speed of the unperturbed jet $0.3 \cdot v_{0.3}$, as well as the minimum electron Lorentz factor $100 \cdot \gamma_{\rm m,2}$. With these parameters and a distance $D_{28.5} \cdot 10^{28.5}$cm, a time $t_5 \cdot 10^5$s, and a frequency $\nu_{14} \cdot 10^{14}$Hz, we obtain the correct flux level of the afterglow:

$$F_{\nu}^{(\rm ob)}(t) \simeq 7.45 \times 10^{-28} \delta (E_{51}^{5/4} \dot{M}_{-5\rm j}^{-1/4} v_{0.3}^{1/4}) \gamma_{\rm m,2} D_{28.5}^{-2} t_5^{-5/4} \nu_{14}^{-1} \ \mathrm{erg\ cm^{-2} s^{-1} Hz^{-1}} \quad (1)$$

CONTRIBUTION TO COSMIC RAY AND NEUTRINO FLUX

We calculated the GRB rate and compared the corresponding cumulative distribution in fluence with the data. We used the SFR as a function of the redshift presented by Madau [7] with a flatter SFR at high redshift to obtain the corresponding fluence distribution of GRBs with the redshift and to use their rate to study the eventual contribution of GRBs to the cosmic ray distribution, both in our Galaxy and in the extragalactic region. We checked if in our jet model GRBs were standard candles. The corrected data for the 4B BATSE catalogue fluence distribution [8] require the adoption of a luminosity function with a power $\phi(f) \propto f^{-1.55}$. The result of our calculations is shown in Fig. 1(left), in which the theoretical fluence distribution curve is compared with the 4B corrected data. Considering the total number of GRBs in BATSE catalogue, an observing time of 8 years, a volume scale of $h^{-3}10^{10.8}\mathrm{Mpc}^3$, with $H_0 = h\,(100 \text{ km s}^{-1} \text{ Mpc}^{-1})$ the Hubble constant, a

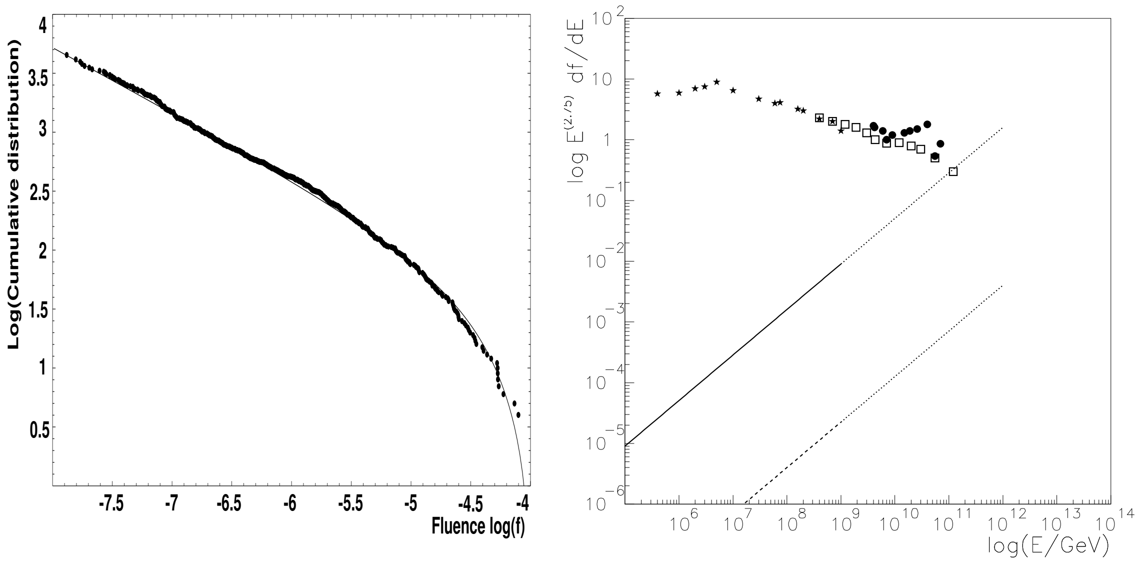

FIGURE 1. Left: comparison between the cumulative fluence distribution obtained with our model (solid line) and the corrected data of catalogue BATSE 4B (full circles), kindly provided by V. Petrosian. The fit we obtained requires a power law luminosity function distribution for GRBs $\phi(f)\,df = f^{-1.55}\,df$. Right: comparison between the extragalactic GRB contribution and the all particle cosmic ray spectrum, expressed in $[\mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}]$. The solid line corresponds to the assumption that each GRB gives the same contribution to the CR spectrum; this model is excluded by observations. The dashed line corresponds to the model in which each GRB gives a contribution proportional to its own fluence. Any contribution beyond 10^{18} eV is ruled out (dotted lines) considering the attenuation due to the interaction with the microwave background. The stars represent the cosmic ray data from the Akeno experiment, the open squares are the Fly's Eye data and the full circles are the AGASA data.

beaming factor $\frac{4\pi}{2\pi\theta^2} = 200\,\theta_{-1\mathrm{j}}^{-2}$, with θ the jet opening angle, the rate of GRBs is:

$$10^{-5.4}(h^3\theta_{-1\mathrm{j}}^{-2}) \text{ GRBs per year per } 100 \text{ Mpc}^3 \qquad (2)$$

We used the GRB rate obtained with the SFR from Madau and two different approaches to calculate the contribution from GRBs to the cosmic rays and the neutrino spectra. First we considered that each GRB gives the same contribution equal to 10% of the initial energy, here 10^{51}ergs. Secondly we assume that each GRB contributes proportionally to its own fluence; the fluence distribution adopted has a power law. In Fig. 1(right) we compared the all particle energy spectrum as measured by different ground-based experiment with the spectrum from GRBs in the case that each of them gives the same contribution (dashed line) and with the one in which the contribution is proportional to the fluence (solid line) for the extragalactic case. In the jet-disk symbiosis model for GRBs any extragalactic origin at high energies for cosmic rays is ruled out considering that for energies greater than 10^{18} eV (dotted line), the interactions with the microwave background are relevant and decrease the curve substantially. A corresponding analysis for the cosmic ray contribution from GRBs inside our Galaxy leads to the same result: Near 10^{18} eV the arrival directions of CRs are observed to be ispotropic to an excellent approximation, and yet their diffusion time out of the Galaxy is much shorter than the time scale between GRBs in our Galaxy. Therefore the time for isotropization is not available, ruling out any contribution from GRBs.

CONCLUSIONS

To summarize, our model can explain the initial gamma ray burst, the spectrum and temporal behaviour of the afterglows, the low baryon load, an optical rise, and do all this with a modest energy budget. Moreover, this GRB model is developed within an existing framework for galactic jet sources, using a set of observationally well determined parameters. Using a relatively small set of parameters, the jet-disk symbiosis model applied to GRBs, a tested SFR, and the fundamental physics of the photohadronic interactions we arrive at the conclusion that GRBs are unlikely to give any contribution to the high energy cosmic ray spectrum both inside and outside our Galaxy and to the neutrino spectrum as well.

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