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LETTER

Letter to the Editor

On the possible origin of gamma ray bursts as a result of interaction of relativistic jets with the soft photon field in dense stellar regions

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Abstract. We examine and develop the model of gamma ray bursts origin proposed by Shaviv and Dar (1996), according to which the strong gamma ray emission is produced by the interaction of the baryonic relativistic jet with the soft photon field in a dense stellar region. By the simulations of the burst profiles we show that these profiles are sensitive to the jet geometry. Also we derive and discuss the model restrictions based on the event rate.

Key words: Gamma ray bursts – jets – neutron stars

1. Introduction

The idea of cosmological origin of gamma ray bursts (Prilutski & Usov 1975; Usov & Chibisov 1975) is well supported by their observed isotropy on the sky and non-uniform spatial distribution Meegan et al. 1992). The enormous luminosity needed for explanation of gamma ray bursts if their origin is cosmological imply that the best candidates for their sources are the mergers of binary neutron stars and/or neutron stars with black holes at redshifts ($z \simeq 1-2$), (Blinnikov, et al. 1984; Paczyński 1991, 1992). Lipunov et al (1995) showed that the cosmological origin of gamma ray bursts is consistent with the observed BATSE gamma ray bursts log N–log S distribution, but the beaming of the radiation is required for the balancing of the observed and predicted event rates.

The cosmological models for gamma ray bursts have not yet been proven; moreover, they come across severe problems, one of them being the problem of the efficiency of transforming the gravitational binding energy into gamma-rays. The explanation of the observed profiles of the bursts remain another unsolved problem.

Recently Shaviv and Dar (1995,1996a,b) proposed a model of the gamma ray bursts origin which was the first one to reproduce the observed burst profiles, and also solved the problem of energy transformation into gamma rays. In this model, a gamma ray burst is produced by reemission of the soft field photon ($E \sim 1$ eV) by the atoms of a relativistic jet (or expanding shell) (with $\Gamma \sim 1000$), which transforms these photons to those of the energies $\sim \Gamma^2 E \sim 1$ MeV.

It is suggested that such a jet or shell can be generated during a binary neutron star merger. In a dense stellar region such as a globular cluster core or a galaxy center, the particles of the jet would pass close to several stars. The light photons filling the vicinity of the stars in the comoving frame of the jet would have energy $\sim \Gamma E \sim 1$ keV. Shaviv and Dar show that these photons could be absorbed by photoionization or photoexcitation of heavy atoms (like iron) that may be present in the jet, the cross section of such absorption being much higher than that of Compton scattering. When reemitted, in the rest frame of the observer the photons will have energy of the order of $\Gamma^2 E \sim 1$ Mev and will be beamed into the $1/\Gamma$ angle. Thus, when passing by a star, the jet would produce a burst of γ radiation.

These γ photons generated closer to the jet source should come to the observer earlier than those generated far from it because the jet expansion velocity $v = c\sqrt{1-1/\Gamma^2}$ is smaller than the velocity of light. Therefore, each of the stars on the way of the jet would produce a peak in the burst profile. Below we will determine the shape of this peak. In general, the observed burst profile would map the distribution of the soft photon density on the way of the jet: $u(R) \rightarrow F(t)$, where R is the distance from the source to the current point, t is the total time taken the signal to pass from the jet source to the observer: $t = R/v + (D-R)/c$, where D is the distance from the source to the observer.

The above model explains many of the observed features of gamma ray bursts, including the profiles.

2. The geometry of the emitting region

Let us now discuss the formation of the burst profile with taking into account the γ emission generated out of the line of sight.

If the jet particles moving with the relativistic velocity emit isotropically, then in the observer frame their emission will be concentrated into a narrow beam of the width $\theta_0 \sim 1/\Gamma$ centered with the particle motion direction. For $\Gamma \gg 1$ the angular distribution of the emission in the observer frame is approximated by

$$A(\theta) = 1/\left(1 + \Gamma^2 \cos^2 \theta\right) \quad (1)$$

In the most general case we can determine the burst flux profile by computing the following integral:

$$F(t) = \int \rho(\boldsymbol{R}, t - \frac{|\boldsymbol{R} - \boldsymbol{D}|}{c}) u(\boldsymbol{R}) A(\theta) d\boldsymbol{R}, \quad (2)$$

where $\rho(\boldsymbol{R}, t)$ is the density of rate of the soft to hard photon conversion by the jet atoms in space and time, $u(\boldsymbol{R})$ is the density of soft photons and $A(\theta(\boldsymbol{R}, t))$ is the angular distribution of the emitted light in the observer frame, the integral being taken over the whole space. $\theta(\boldsymbol{R}, t)$ here is the angle between the particle velocity direction and the direction to the observer.

If we assume that the jet is optically thick (for the photons of the energy ΓE in its rest frame), then the we would see the emission from a geometrically thin region (the jet "front"). Then we can approximate $\rho(\boldsymbol{R}, t)$ as

$$\rho(\boldsymbol{R}, t) = \delta(\boldsymbol{R} - \boldsymbol{R}(t)), \quad (3)$$

where $\boldsymbol{R}(t)$ defines expansion of the jet front. Shaviv and Dar assumed that the jet has a plane front moving in the direction of the observer. Then in Eq. (2) $\theta = 0$ anywhere and

$$\boldsymbol{R}(t) = \boldsymbol{v}t + \boldsymbol{R}_\perp, \qquad \boldsymbol{v} = const. \quad (4)$$

Then the observed flux would be

$$F(t) \sim u((\frac{D}{c} - t)\frac{v}{1 - B}), \quad (5)$$

where $B = v/c$, i.e. the burst profile reflects the soft photon density in the vicinity of the jet.

Let us now study another case, when the jet front expands spherically and then discuss the difference between these two geometries of the jet expansion. In our case

$$\boldsymbol{R}(t) = \boldsymbol{v}t, \qquad \boldsymbol{v} = v\boldsymbol{n}. \quad (6)$$

The main difference between the spherical and plane front is that for the spherical one the emission from different parts of the front arrive to the observer at different time. This effect is well known as the rings around supernovae. The γ photon arrival time from the point with the coordinates (R, θ) for the spherical front geometry is

$$\Delta t = \frac{R}{v} + \frac{(D - R\cos\theta)}{c}. \quad (7)$$

We detect the γ photons from the surface with $\Delta t = const$ simultaneously. For the plane jet front, this surface coincides with the front while for the case of the spherical front this surface is an ellipsoid with the jet expansion source in a focus:

$$R = \frac{vt - DB}{1 - B\cos\theta}. \quad (8)$$

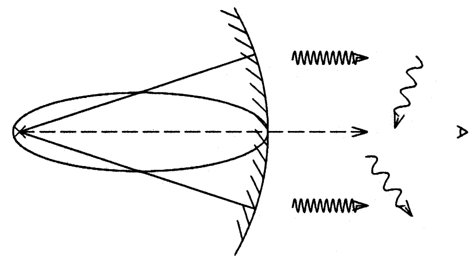

Fig. 1. A sketch of the model: We see simultaneously the γ photons coming from the ellipsoid expanding after the spherical jet front.

This ellipsoid is strongly elongated in the direction of the observer – its eccentricity is as close to unity as $B \approx 0.999995$. Due to the fact that the jet γ-emission is concentrated in a narrow beam with width $\theta_0 \approx 1/\Gamma$, we will see the emission only from the part of the ellipsoid located inside the $1/\Gamma$ cone with the vertex at the jet source. It is easy to show that the ellipsoid and the cone intersect at $R_{min} \approx 0.5R_{max}$, where R_{max} is the apocenter distance of the ellipsoid (Fig. 1).

Thus we detect simultaneously the emission coming from rather big region of space, which definitely leads to a kind of averaging of the photon distribution $u(\boldsymbol{R})$ details. So the details are not so sharp as in the plane front case. Their characteristic width should be determined by $0.5R$, and not by the distance of the star from the line of sight. Calculations show that only the stars located inside or close to the $1/\Gamma$ cone can produce sharp narrow peaks (Fig. 2).

It is important that in the case of spherical jet geometry the peak is asymmetric – its tail is much longer that the front – which hardly corresponds to the observer profiles of gamma ray bursts.

In order to make the computed profiles consistent with the observed ones, the average distance between stars in the vicinity of the jet should be

$$\Delta R \sim \frac{c}{1 - B}\Delta t \quad (9)$$

where Δt is the average time between the peaks in the burst. For $\Gamma = 1000$ $\Delta R \sim 0.02\Delta t$ pc/sec. It means that for realistic gamma ray burst profiles the star density should exceed

$$\rho_\star \sim \Delta R^{-3} \sim 10^5 \quad \text{pc}^{-3} \quad (10)$$

Such high density can occur only in globular clusters and in the galactic nuclei. The size of the region where the burst is formed should be of the order 1 pc which is similar to that of the globular cluster core.

After the above the gamma ray burst profiles can be simulated from the integrating of the contributions of all the stars in the vicinity of the jet. We assumed that in the globular cluster core 10^6 stars are located within 1 pc^3.

3. The event rate

In order to bind the gamma ray bursts to any events at cosmological distances the rate density of such events should be

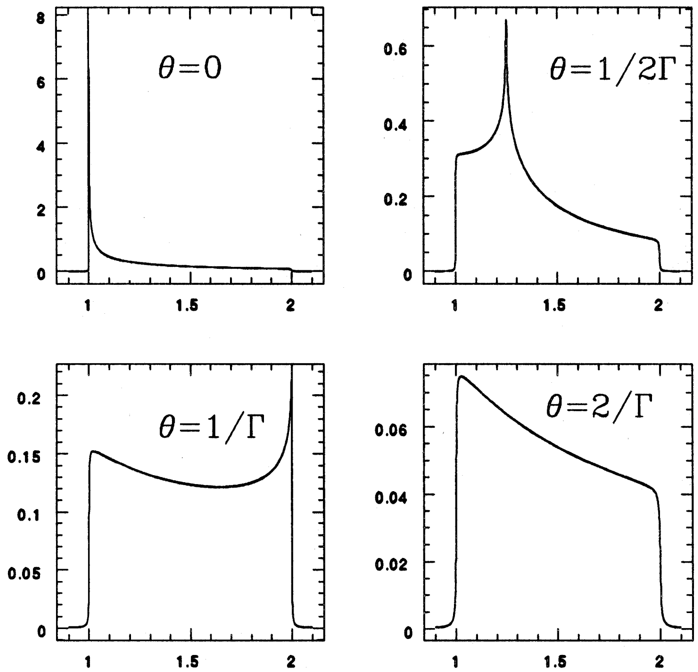

Fig. 2. The sample burst profile produced by a single star at different angular distances from the explosion-observer line: $\theta = 0, 0.5/\Gamma, 1/\Gamma, 2/\Gamma$. The flux is shown in arbitrary units; time is in the units of $R(1-B)/c$.

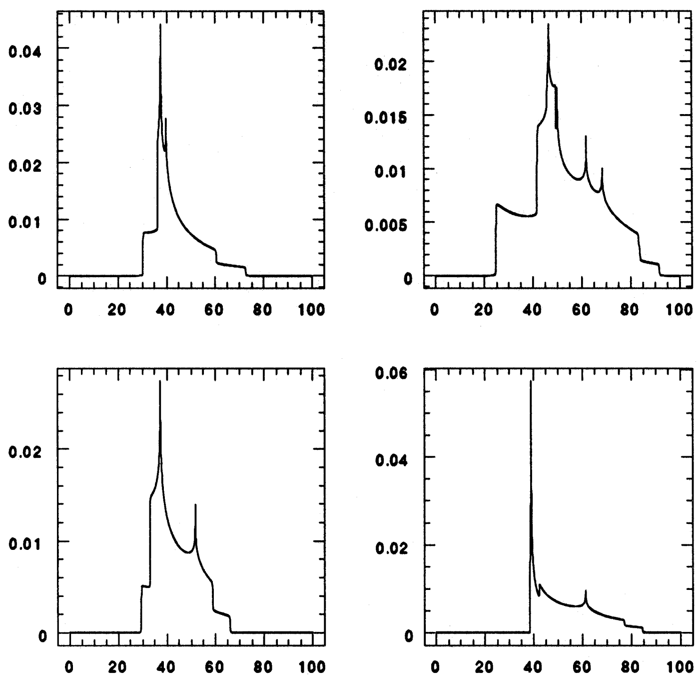

Fig. 3. The example simulated gamma ray bursts profiles computed with a real distribution of stars in a globular cluster.

$\mathscr{R} \sim 10^{-8}$ Mpc^{-3} yr^{-1}. If we allow for a beamed radiation, then $\mathscr{R} \sim 2 \cdot 10^{-3} \beta_\circ^2$ Mpc^{-3} yr^{-1}, where $\beta_\circ$ is the beam width in degrees.

The rate of neutron star mergers in the dense stellar regions – globular clusters and galactic nuclei – is still not clear.

Numerical simulations of the evolution of close binaries (Lipunov et al, 1996) show that the neutron stars merger rate is strongly dependent on the stellar population age. For the old stars of the globular clusters it should not exceed 10^{-5} yr^{-1} per $10^{11} M_\odot$; for the relatively young stars in the galactic nuclei it should be of the order of 10^{-4} yr^{-1} per $10^{11} M_\odot$. After taking into account the fact that the mass fraction of these dense star configurations in the galaxies is not more than 10^{-2} we obtain the optimistic upper limit of about $r = 10^{-6}$ yr^{-1} per $10^{11} M_\odot$ galaxy.

For the flat Universe with $\Omega_{stars} = 0.005$ and $H_0 = 75$ km/c/Mpc it corresponds to the rate density $\mathscr{R} = 10^{-8}$ yr -1. So, there is no place for the beaming, and, thus, for the jets. At least, the jets should be very wide (which supports the spherical geometry case described in the previous section, in fact, if the jet front is plane, all emission should be in very narrow $1/\Gamma$ beam).

If only the neutron star merger rate in globular clusters or galactic nuclei is essentially higher than 10^{-4} yr^{-1} per $10^{11} M_{\odot}$ the above model can be used for explanation of the gamma ray bursts origin.

4. Conclusions

We have studied some of the conditions necessary for the explanation of gamma ray bursts as the interaction of the baryonic relativistic jet with the soft photon field in the dense star regions (Shaviv, Dar 1996). The main attractiveness of this model is that it is the only one that predicts the observable gamma ray burst profiles. We have found out two difficulties of these model, none of them being fatal but each of them putting strong restrictions on it. First of all, the main achievement of the model – the reproduction of the observational burst profiles – has seemed to be strongly sensitive to the jet front geometry. The shape of the peaks in the spherical case becomes more wide and asymmetric, and the number of the peaks becomes smaller.

The second is that it is hard to agree the theoretical event rate with the observed one. The neutron star merger rate in globular clusters and/or galactic nuclei should be high and the beaming of the jet should be small.

The spherical geometry is more consistent with the event rate than the plane one because it allows for beaming wider than $1/\Gamma$, but is in worse agreement with the observed bursts profiles. The detailed investigation of the jet expansion geometry would allow now for the further treatment of this model of gamma ray bursts origin.

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