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A fireworks model for GRB structured jets

G.Barbiellini[1], A. Celotti[2] and F.Longo[1]

[1] Dipartimento di Fisica, Universitá di Trieste, via Valerio 2, 34100 Trieste and INFN, Sezione di Trieste, Italy
[2] SISSA, via Beirut 4, 34014 Trieste, Italy

Abstract. The energetics of the long duration Gamma Ray Burst (GRB) phenomenon is compared with models of a rotating Black Hole (BH) in a strong magnetic field generated by an accreting torus. The GRB energy emission is attributed to a high magnetic field that breaks down the vacuum around the BH and gives origin to an $e^{\pm}$ fireball. Its subsequent evolution is hypothesised, in analogy with the in-flight decay of an elementary particle, to evolve in two distinct phases. The first one occurs close to the engine and is responsible of energising and collimating the fireball. The second one consists of a radiation dominated expansion, which correspondingly accelerates the relativistic photon–particle fluid and ends at the transparency time. An anisotropy in the fireball propagation is thus naturally produced, whose degree depends on the bulk Lorentz factor at the end of the collimation phase.

Key words. Gamma-ray: bursts

1. Introduction

At cosmological distances the observed GRB fluxes imply energies up to a solar rest-mass ($\sim 10^{54}$ erg), and as they vary on timescales of the order of milliseconds from causality arguments these must arise in regions whose size is of the order of kilometers. This implies that an $e^{\pm}, \gamma$ fireball must form, which would expand relativistically. The fireball is energised and possibly collimated, mechanically or magnetically, close to the engine (for a review see e.g. Piran (1999)). Subsequently it adiabatically expands and accelerates, until the Thomson transparency is reached. The GRB phenomenology gives compelling reasons for the bulk motion of the emitting plasma to be highly relativistic with Lorentz factors of the order $\Gamma \sim 10^2 - 10^3$. The degree of isotropy/collimation of the ejected fireball is however still unclear. In fact, as the observer only detects γ–ray flux from an angle $\sim \Gamma^{-1}$, it is not possible to simply discriminate between an isotropic and a jet-like structure from the observed GRB event. Nevertheless this is in principle possible via the determination of the behaviour of the light curves during the afterglow phase: following the deceleration/sideway expansion of the fireball more and more of the emitting plasma can be seen and a break (and steepening) in the

Send offprint requests to: F.Longo
Correspondence to: Dipartimento di Fisica, via Valerio 2, 34100 Trieste

light curve would appear when the whole of the volume becomes observable. Indeed, recently a few GRB afterglows were observed at many wavelengths and suggest an axisymmetric jet-like structure for the fireball, thus strongly reducing the estimate of the energetics with respect to the isotropic case. The temporal decays of the emission at different frequencies, interpreted according to the fireball model, suggest jet beaming with opening angles $\theta \sim 3^{\circ}$ (Frail et al. 2001). The anisotropy of a collimated fireball alternatively can account for the observed phenomenology (Zhang & Meszaros (2002),Rossi et al. (2002)). In our work (Barbiellini et al. 2003) we focus on two aspects of the 'standard' scenario for the GRB event. The first, developed in Section 2, concerns the extraction of energy from a rotating compact object and its conversion into a certain number of photon-e$^{\pm}$ fireball shells. Subsequently, in Section 3 we suggest that the acceleration and collimation could occur in two phases: the first one consists in energising and collimating the shells, the second one of a radiation dominated expansion. This mechanism predicts that the observed Lorentz factor is determined by the product of the Lorentz factor of the shell close to the engine and the Lorentz factor achieved through the expansion, thus naturally giving rise to an anisotropic fireball (Barbiellini et al. 2003).

2. Gamma-Ray Burst Progenitor

In 1977 Blandford and Znajek proposed the interaction via magnetic fields between a rotating BH and an accretion disk to explain the energetics of Active Galactic Nuclei (Blandford & Znajek 1977). The same mechanism could be a good candidate for GRB engines as already pointed out (e.g. Paczynski (1998), Lee et al. (2000)). In the BZ mechanism the magnetic field of the accretion disk acts as a break on the BH and the energy output is mainly due to the loss of rotational energy. The rotational energy for a maximally rotating BH of mass $M_{\rm bh}$, with the rotation parameter $\tilde{a} = Jc/M_{\rm bh}^2 G = 1$, is $0.29\ M_{\rm bh}c^2$. Even with the optimal efficiency the available extractable energy for the BZ mechanism is (Lee et al. 2000) $E_{\rm BZ} = 0.3 \times 10^{54} \left(\frac{M_{\rm bh}}{M_{\odot}}\right)$ erg. In the following considerations it will be assumed that a dissipative interaction is at work between the BH and the torus surrounding it, due to an internal torque. If the short interaction is treated as an inelastic shock it is possible to apply the angular momentum conservation law. In this approximation and considering the torus approximately at the last stable orbit, the loss of rotational ($\Delta E_{\rm rot}$) and gravitational energy ($\Delta E_{\rm g}$) can be derived as $\Delta E_{\rm rot} + \Delta E_{\rm g} \simeq 0.7 M_{\rm t} c^2$, ranging between $10^{53} - 10^{54}$ erg for a torus mass $M_{\rm t} = 0.1 - 1 M_{\odot}$.

A model for the generation of the GRB fireball is the vacuum breakdown in the volume close to the polar cap of the BH (Heyl 2001), where a value of $B_c \sim 4.5 \times 10^{13}$ G for the vacuum breakdown in the ergosphere is found. In the proximity of the BH is thus possible to generate e$^{\pm}$ pairs which could give origin to the GRB fireball, provided a sufficiently clean environment in order to avoid previous electric field discharge. This condition can be verified if the residual density close to the rotational axis is less than 10^9 cm^{-3} (Schatskiy & Kardashev 2002). Considering a typical electromagnetic field configuration around a Kerr BH it is possible that initially the E field generated by the rotation of the BH in the magnetic field of the torus Schatskiy (2001) can actually contribute to clear the environment of electron-proton plasma.

A magnetic field of the order of B_c breaks the vacuum in a volume $V \sim R_s^3$ (cf Heyl (2001)). For a pair density of the order of 8×10^{29} cm^{-3}, typical of a high density fermion plasma (e.g. Fermi (1966)), the available magnetic energy density for a field of order of B_c implies that each outgoing particle gets an energy $\epsilon_0 \sim 10^{-4}\eta_{\rm acc}$ erg, where $\eta_{\rm acc}$ is the acceleration efficiency. Its relativistic Lorentz factor is then $\gamma_0 = \epsilon_0/m_{\rm e}c^2 \sim 10^2\eta_{\rm acc}$. After their creation by vacuum breakdown, the particles undergo three important processes, particle acceleration by an electric field of the order of 2×10^{15} V/cm, momenta randomisation by collision with the ambient photon density and single particle collimation in the direction of the magnetic field by synchrotron radiation. The momentum components perpendicular to field line for all the particles are damped. The result is the formation of a plasmoid made of a stream of particles with velocity parallel to the external field lines with $\gamma \sim \gamma_0/3$. The plasmoid thus travels as a parallel stream with bulk Lorentz factor $\Gamma_1 = \gamma \sim 30\,\eta_{\rm acc}$.

The energy of the particles in the plasmoid before the cooling by synchrotron emission is $E_{\rm plasmoid} = V\frac{B^2}{8\pi} \sim 10^{45}$erg. The available energy in the overall inelastic collision is $\Delta E \sim 10^{53}$ erg, so that the emission of plasmoids could happen $N_{\rm plasmoid} \sim \eta_{\rm B}\frac{\Delta E}{E_{\rm plasmoid}} = 10^8\,\eta_{\rm B}$, times, where we have taken into account also an efficiency, $\eta_{\rm B}$, for conversion of mechanical energy into the electro-magnetically generated $e^{\pm}$ fireball. The model therefore predicts for long duration GRB a pulsed emission from $\sim 10^7\,\eta_{\rm B,0.1}$ emitted plasmoids. This large number of shells are likely to merge, thus producing a significantly smaller number of well defined spikes in the light curve with superposed a low amplitude flickering due to individual shells.

3. Collimation and acceleration: Two phase expansion

The subsequent jet evolution is composed by two distinct phases, the first one (phase-1), occurring close to the engine responsible of energising and collimating the burst. Phase-1 ends (at R_1) when the pre–existent collimating mechanism (by magnetic field) cannot balance the jet pressure any further. We could give a rough estimate of R_1 considering the distance when the collimation time scale becomes equal to the randomisation time scale. Assuming a dependence R^{-3} of the magnetic field, R_1 could be estimated to correspond to a distance $\sim 10^8$ cm.

It then follows the second phase (phase-2), which consists of adiabatic expansion and corresponding acceleration of the relativistic particle fluid. This phase lasts for the radiation dominated phase and ends at the radius $R_{\rm pair}$ where the fireball becomes radiation dominated (e.g. Piran (1999)). Assuming that the total mass of the shell is dominated by the electrons, which is justified by the very low environment density assumed in our model, this radius could be estimated as $\sim 100 R_0$, where R_0 is the initial dimension of the fireball. Therefore, for a radiation dominated expansion (Paczynski 1986): $\frac{\Gamma_2'}{\Gamma_1'} \sim \frac{R_{\rm pair}}{R_0} \sim 100$, where $\Gamma_1' \sim 1$ is derived from the mean energy after the collimation phase measured in the comoving frame of a shell, Γ_2' is the Lorentz factor at the end of phase 2 measured in the same reference frame.

At the moment of transparency the ejecta are thus moving in such a way that a particle accelerated during the radiation dominated expansion in the collimation direction will have $\Gamma_{\parallel} = 2\Gamma_1\Gamma_2'$ where $\Gamma_{\parallel}$ is the bulk Lorentz factor in the axis direction being Γ_1 the Lorentz factor of the moving shell in the observer frame. The opening angle of the conical jet structure generated at the end of the two phases is determined by the particles accelerated perpendicularly to the collimation direction moving with Lorentz factor $\Gamma_{\perp} = \Gamma_2'$. The collimation angle $\theta_{\rm c}$ is then: $\theta_{\rm c} \sim \tan\theta_{\rm c} = \frac{\Gamma_{\perp}}{\Gamma_1\Gamma_2'} = \frac{1}{\Gamma_1}$. Assuming $\Gamma_{\parallel} \sim 10^3$ (e.g. Lithwick & Sari (2001)) and estimating $\Gamma_2' \sim 100$ from the previous considerations, the value Γ_1 at the end of the collimation phase has to be of the order of $\Gamma_1 \sim 5$ and consequently $\theta_{\rm c} \sim \frac{1}{\Gamma_1} \sim 2 \times 10^{-1}$.

Furthermore, in the above scenario, the observed angular distribution of the expanding fireball is expected to be anisotropic, with a behaviour qualitatively similar to that postulated by Zhang & Meszaros (2002) and Rossi et al. (2002) to account for the phenomenological findings by Frail et al. (2001). (See Barbiellini et al. (2003) for further details).

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