Afterglow jet breaks, GeV photons and the electromagnetic model of short GRBs

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We discuss three topics: (i) the dynamics of afterglow jet breaks; (ii) origin of Fermi-LAT photons; (iii) the electromagnetic model of short GRBs

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1 Jet breaks

The concept of the light curve breaks is an important part of the theoretical studies of GRBs [Rhoads (1999); Frail et al. (2001)]. We point out that the “standard” view point - the jet starts to expand laterally when the Lorentz factor becomes of the order of the opening angle - is flawed. At the afterglow stage, when the outflow launched by the central engine has transferred most of its energy to the forward shock, there is no “jet”, but a non-spherical shock. Evolution of strong non-spherical shocks is a well studies problems in fluid dynamics, in particular the evolution of non-spherical shock produced by nuclear explosions in the Earth atmosphere [Kompaneets (1960); Laumbach & Probstein (1969); Zeldovich & Raizer (2003); Bisnovatyi-Kogan & Silich (1995)]. For example, in the Kompaneets approximation the internal pressure of the gas is assumed to be constant. Then the Rankin-Hugonio conditions determine the normal velocity of the shock in the external inhomogeneous medium. A modification of the Kompaneets approximation - a thin or snowplow shell approximation - has also been used extensively (e.g. Wiita 1978; Mac Low & McCray 1988; Bisnovatyi-Kogan et al. 1989). In a complimentary Laumbach-Probstein approach (Laumbach & Probstein 1969) the streamlines of the shocked material are assumed to be radial, thus neglecting the lateral pressure forces.

These works, especially that of Kompaneets (1960), bear an important lesson: post-shock pressure equilibration does not mean spherical shock. In the Kompaneets approximation the post-shock pressure is constant, yet the shock is non-spherical.

The relativistic generalization of the Kompaneets and the Laumbach-Probstein methods have been discussed by Shapiro (1979); Lyutikov (2012). Relativistic dynamics provide extra support for the thin shell method, since in the relativistic blast waves the shocked material is concentrated in even narrower region $R/\Gamma^2$ than in the non-relativistic Sedov solution. In addition, the limited causal connection (over the angle $\sim 1/\Gamma$) provides a justification for the Laumbach-Probstein method on the angle scale comparable to $1/\Gamma$. As has been pointed out by Shapiro (1979), the two methods - Kompaneets and Laumbach-Probstein - become very similar in the relativistic regime.

Lyutikov (2012) has re-derive the relativistic Kompaneets equation Kompaneets (1960); Shapiro (1979), allowing for the arbitrary velocity of the shock and arbitrary (angle-dependent) luminosity and/or external density. It was found that the relativistic motion effectively “freezes out” the lateral dynamics of the shock front: only extremely strongly collimated shocks, with the opening angles $\Delta\theta \leq 1/\Gamma^2$, show appreciable modification of profiles due to sideways expansion. For less collimated profiles the propagation is nearly ballistic; the sideways expansion of relativistic shock becomes important only when they become mildly relativistic.

The origin of the $\Delta\theta \sim 1/\Gamma^2$ scaling for fast lateral shock evolution is easy to understand: the shock spreading relates to the rate of change of the direction of the
shock normal. For a typical collimated shock with angle $\theta \sim 1/\Gamma$ this rate of change of the direction is of the order of the dynamic time scale in the shock frame: thus, it is $\Gamma$ times longer in the observer frame. In order to have a change in the direction of the order of unity on the dynamical time in the observer frame one need very fast, $t'_{\text{dyn}} \sim 1/\Gamma$, change in the shock frame - this then gives the scaling $\theta \sim 1/\Gamma^2$ for quick sideways expansion in the observer frame.

These theoretical results are in general agreement with the detailed numerical simulations [van Eerten & MacFadyen 2013], which demonstrate very slow, logarithmic with time, sideways expansion. The results discussed above are all related to shock structure, while the observational implications are affected by other effects, like limb brightening and subtle edge effects.

Thus, contrary to the commonly assumed fast lateral expansion, the lateral evolution of the GRB shocks is effectively frozen out by the highly relativistic motion of the shock. Only when the shock becomes weakly relativistic ti starts to evolve laterally on the dynamical time in the observer frame. This has important implications for the calculated spectra of GRB afterglows.

2 GRBs and Fermi LAT photons: not synchrotron

The detection of GRBs by the Fermi satellite [Abdo et al. 2009] is an important probe of the GRB physics. The recent observation of the 95 GeV photon (125 GeV in rest frame) at $\sim 250$ seconds and 30 GeV (40 GeV in rest frame) at $\sim 35$ ksec from GRB130427A can be used to exclude the synchrotron origin of LAT photons. There is an acceleration theory-independent upper limit on the frequency of synchrotron emission by radiation reaction-limited acceleration of electrons [Lyutikov 2010]. In astrophysics the effective accelerating electric field is a fraction $\eta \leq 1$ of the magnetic field (this is equivalent to acceleration on time scale of inverse cyclotron frequency $1/(\eta \omega_{B, r})$, where $\omega_{B, r} = \gamma / \omega_B$ is relativistic cyclotron frequency of a particle). Equating the acceleration rate and synchrotron energy losses,

$$\eta eBc \sim \frac{e^2}{c} \gamma^2 \omega_B^2$$

the peak energy of synchrotron emission is then

$$\epsilon'_{\text{max}} \sim \hbar \frac{me^3}{e^2} \approx 100 \text{ MeV}.$$  

Note, the upper limit [2] assumes the most efficient, non-stochastic, DC-type acceleration.

If the emitting plasma moves with a Lorentz factor $\Gamma$ towards the observer, the observed maximal frequency is $\sim 2\Gamma \epsilon_{\text{max}}$. The Fermi photons come over times much
longer than the duration of the prompt emission. Assuming the Blandford & McKee [1976] scaling of the Lorentz factor, we find

$$\Gamma \sim \left( \frac{E_{iso}(1 + z)}{c^5 t_{ob}^3 m_p n_{ISM}} \right)^{1/8}, \quad \epsilon_{\text{max}} = 2\Gamma \epsilon'_{\text{max}}/(1 + z)$$

(3)

where we introduced the cosmological factor $(1 + z)$. The relation (3) put a constraint on the maximal synchrotron energy emitted at the observer time $t_{ob}$. The burst GRB130427A put particular tight constraints, see Fig. 1. (We assumed $E_{iso} = 10^{54}$ erg and $n_{ISM} = 1$.) Note that $\epsilon_{\text{max}}$ is very insensitive to the precise values of $E_{iso}$ and $n_{ISM} = 1$, $\epsilon_{\text{max}} \propto (E_{iso}/n_{ISM})^{1/8}$.

Figure 1: Upper limit of synchrotron emission from the forward shock and two LAT photons from GRB130427A. The very late high energy photon, $\sim 35\text{GeV}$ at $\sim 35$ ksec violates the upper limit on the synchrotron emission.
3 The electromagnetic model of short GRBs

Many short GRBs show long prompt tails that last up to hundreds of seconds and may be energetically dominant over the initial spike (by a factor of 30 as in GRB080503 [Perley 2009]). Such a long activity is problematic in the model of neutron star-neutron star mergers. Numerical simulations indicate that the active stage of NS-NS coalescence typically takes a very short time, 10 msec (e.g., [Kiuchi et al., 2010]). Highly spinning neutron stars with hard equation of state may form a transient object which collapses on 100 msec time scale (Hotokezaka et al., 2011), but not on hundred seconds time scale. A small amount of material, $\leq 10^{-3} M_\odot$, may be ejected during the merger and accretes on time-scales of 1-10 secs, depending on the assumed $\alpha$ parameter of the disk (e.g., Kiuchi et al., 2010 [Liu et al., 2008; Faber, 2009]).

We developed an electromagnetic model of short GRBs (?) that explains the two stages of the energy release, the prompt spike and the prompt tail. The key point is the recent discovery that an isolated black hole formed from the collapse of a rotating neutron star can keep its open magnetic field lines for times much longer than the collapse time and, thus, can spin-down electromagnetically. The “no hair” theorem (Misner et al., 1973), a key result in General Relativity, states that an isolated black hole is defined by only three parameters: mass, angular momentum, and electric charge. We have recently demonstrate that the “no hair” theorem is not applicable for black holes formed from collapse of a rotating neutron star (Lyutikov, 2011; Lyutikov & McKinney, 2011). The key point in the classical proof is that the outside medium is a vacuum. In contrast, the surroundings of astrophysical high energy sources like pulsars and black holes can rarely be treated as vacuum (Goldreich & Julian, 1969; Blandford & Znajek, 1977; Muslimov & Tsygan, 1992).

Merger of two neutron stars produces a transient supermassive fast spinning sheared neutron star in which magnetic field may be amplified to $\sim 5 \times 10^{15}$ Gauss, typical of magnetars. This magnetic field extracts the rotational energy and drives an electromagnetic wind that may carry of the order of $10^{50}$ ergs, limited by the collapse time of a neutron star in the black hole. We identify the prompt spike in shorts GRBs as emission from highly relativistic Poynting flux-dominated wind produced by the transient supermassive neutron stars.

The black hole resulting from the collapse of the supermassive neutron star releases its rotational energy on a time scale of hundreds to thousands of seconds. We identify the prompt tails with the emission from the electromagnetic wind generated by the isolated highly spinning black hole. The corresponding powers and times scales are sensitive functions of the neutron star masses, equation of state of the supermassive neutron stars, and the level of magnetic field amplification. The proposed model for short GRBs implies a different type of collimation of the outflow than the conventionally envisioned jet-like structure: short GRBs produce equatorially, not axially, collimated relativistic outflow.
Figure 2: The electromagnetic model of short GRBs. At the prompt stage the surrounding torus collimates the BH-driven outflow along the rotational axis, producing a short GRB. After the torus is accreted, the isolated BH spins down electromagnetically, producing equatorially-collimated outflow - the extended emission in short GRBs. Equatorial observer may miss the prompt spike, mis-identifying the extended emission in short GRBs for a long, supernova-less GRB.

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