Electromagnetic (versus fireball) model of GRBs

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Abstract. We briefly review the electromagnetic model of Gamma Ray Bursts and then discuss how various models account for high prompt polarization. We argue that if polarization is confirmed at a level $\Pi \geq 10\%$ the internal shock model is excluded.

ELECTROMAGNETIC MODEL

Electromagnetic model interprets Gamma Ray Bursts (GRBs) as relativistic, electromagnetic explosions [5], (also Lyutikov & Blandford, in preparation), see Fig. 1. It is assumed that rotating, relativistic, stellar-mass progenitor loses much of its rotational energy in the form of a Poynting flux during the active period lasting $\sim 100$ sec. The energy to power the GRBs comes eventually from the rotational energy of the progenitor, converted into magnetic energy by the dynamo action of the unipolar inductor, so that the central source acts as a power-supply generating a current flow (along the axis, the surface of the bubble and the equator). Initially non-spherically symmetric, electromagnetically dominated bubble expands non-relativistically inside the star, most rapidly along the rotational axis of the progenitor. The velocity of expansion of the bubble is determined by the pressure balance on the contact between magnetic pressure in the bubble and the ram pressure of the stellar material. After the bubble break out from the stellar surface and most of the electron-positron pairs necessarily present in the initial outflow quickly annihilate the bubble expansion becomes highly relativistic. After the end of the source activity most of the magnetic energy is concentrated in a thin shell inside the contact discontinuity between the ejecta and the shocked circumstellar material. The electromagnetic shell pushes ahead of it a relativistic blast wave into the circumstellar medium. Current-driven instabilities develop in this shell at a radius $\sim 3 \times 10^{16}$ cm and lead to acceleration of pairs which are responsible for the $\gamma$-ray burst. At larger radii the energy contained in the electromagnetic shell is mostly transferred to the preceding blast wave. Particles accelerated at the fluid shock may combine with electromagnetic field from the electromagnetic shell to produce the afterglow emission.

Electromagnetic model produces “structured jet” with energy $E_{\Omega} \propto \sin^{-2} \theta$ in a natural way (in fact, there is no proper “jet”, but non-spherical outflow and non-spherical shock wave); there is no problem with “orphan afterglow” since GRBs are produced over large solid angle; X-ray flashes are interpreted as GRBs seen “from the side”, but their total energetics should be comparable to proper GRBs; the model can qualitatively reproduce hard-to-soft spectral evolution as a synchrotron emission in ever decreasing magnetic field $B \propto \sqrt{L/r}$ ($L$ is luminosity, $r$ is emission radius), akin to “radius-to-frequency mapping” in radio pulsars; similarly, the correlation $E_{\text{peak}} \sim \sqrt{L}$ is also a natural con-
sequence. Finally, high polarization of prompt emission may also be produced \[7\] (it should correlate with the spectral index; if there is a mixing between circumstellar material and ejecta, \textit{e.g.} due to Richtmyer-Meshkov instability, and if optical polarization is seen, then the position angles of the prompt emission and afterglow should coincide and be constant over time; fractional polarization should be independent of the “jet break” time, but may show variations due to turbulent mixing).

**POLARIZATION OF PROMPT EMISSION**

A very high linear polarization (nominally 80\%) has been reported in RHESSI observations of GRB021206 \[2\]. Although the uncertainty in the measured polarization is large and a degree of reservation about the very result is necessary, the observation, \textbf{if correct}, puts strong constraints on the GRB models. In particular, it is inconsistent with the internal shock model, as we argue below.

High polarization fraction cannot be naturally produced in a fireball model, since magnetic fields expected in this model are produced on small microscopic scales. In order to account for high polarization fraction of the prompt emission the fireball model needs to make four limiting assumptions three of which are made specifically in order to explain polarization (some, but not all are listed in \[9\]).

First, the turbulent magnetic fields, generated presumably by the Weibel instability, are assumed to be exactly two-dimensional in the whole shocked region. Weibel instability \[8\] indeed produces one-dimensional current filaments oriented normally to the surface of the shock front but the typical coherence size of magnetic field is ion skin depth

\[
\delta_i = c / \omega_{pi} = (m_i c^2 / e) \Gamma r \sqrt{c / L} \sim 5 \text{ cm} L_{50}^{1 / 2} \Gamma_{12} \sim \text{10}^{10} \text{ cm, nine orders larger.}
\]

Two dimensional inverse cascade that sets in after the field generation does increase field coherence to tens or hundreds of ion skin depths, but it still remains microscopically small. Numerical simulations of the Weibel turbulence cannot run for long enough times to describe the late evolution of currents, still we consider it unreasonable to expect that current will support alignment on such large scales. One of the reasons is that the postshock material is expected to be strongly MHD turbulent. In fact, in the fireball model MHD turbulence is \textit{needed} in order to accelerate particle by the Fermi mechanism. This turbulence will easily randomize subtle current structures. Thus, the finely-aligned, one-dimensional currents and the presence of turbulence necessary to accelerate particles are in contradiction in the fireball model. In addition, one may expect that oppositely directed currents created by the Weibel instability will eventually close-up creating three-dimensional magnetic structures.

Secondly, in order to produce high polarization in the fireball model the two-dimensional turbulent magnetic field should be viewed "from the side", so that the line of sight lies in the plane of the field. This imposes a constraint on the position of the observer: the viewing angle with respect to the jet axis should be \( \theta_{ob} \sim 1 / \Gamma \). Thirdly, in order to see the emitting layer quasiplanar, the jet opening angle should be very small \( \Delta \theta \lesssim 1 / \Gamma \). Both these assumptions are not generic to the fireball model and are made exclusively in order to maximize polarization. (Generally, if one needs to assume \( \Delta \theta , \theta_{ob} \lesssim 1 / \Gamma \) then the emission mechanism better be inverse Compton.)
Fourthly, since the observed burst was multi-peaked, many emitting shells are required. In order to reproduce high polarization is assumed that all shells move with the same Lorentz factor [9]. This assumption runs contrary to the very basic postulate of the fireball model that the emitting shells are due to collision of material moving with different Lorentz factor, so that the velocity of the resulting shocks must be different.

Thus, the fireball model needs to fine-tune several parameters to explain polarization. An argument of exclusivity has been invoked: the burst was not like any other burst, so it tells nothing about the other bursts. This is virtually equivalent to neglecting the results altogether.

Though one can possibly argue in favor of chance coincidence of $\Delta \theta$ and $\theta_{ob}$ (but the GRB rate also goes up by $\Gamma^2 \sim 10^4$) one cannot bypass the problem with the spread in Lorentz factors and turbulent randomization of fields. In order to maximize polarization the spread in the Lorentz factors of the emitting shells must be small. This, in principle, can be achieved by a carefully arrangement of shells so that collisions occur only between the two blobs that are moving with the same Lorentz factors (if the source emits shells with $\Gamma_1, \Gamma_2, \Gamma_1$ etc). This is an extremely contrived situation. A more generic case is that the blobs’ Lorentz factors are randomly distributed. In this case the fireball model needs to thread a thin line: larger polarization would require smaller spread in Lorentz factors, but then the energy available for dissipation is small, so that the total energy of the burst will be very large (and the burst GRB 021206 was unusually luminous to start with), aggravating even further the efficiency problem of internal shocks.

In addition to the problems specific to the fireball model, there is a kinematic depolarization of synchrotron radiation due to inhomogeneous expansion velocity [7] (it was taken into account by [9]). Electrical vectors of waves emitted by different parts of the flow are rotated by different amount during a boost into observer’s frame, so that the observed electric fields are generally not orthogonal to the observed magnetic field. Averaging over emitting volume reduces total polarization.

Thus, even if turbulence downstream and current closure are completely neglected, the effects of relativistic kinematics, randomness of magnetic field, spread in Lorentz factors and (presumably) not a perfect fine-tuning of $\Delta \theta$ and $\theta_{ob}$ will all contribute to reduction in polarization. Generically, each of these effects will contribute a factor of two, so that the resulting polarization will not exceed $\sim 10\%$. (Mathematically, when all depolarization effects are minimized at once, polarization may be somewhat higher, but still $\leq 20\%$).

In the case of electromagnetic model the magnetic field has a large coherence scale, $\sim r$, so that within a visible patch of linear size $r/\Gamma$ the field is quasihomogeneous. There are also depolarization effect. First, there is kinematic depolarization discussed above [7]. Secondly, possible presence of random component of magnetic field would lead to further decrease of polarization. But generically random component is not needed in the electromagnetic models. What is needed is presence of currents, so that the magnetic field is inhomogeneous, but it still can be ordered. The field structure of the Sweet-Parker reconnection layer gives an excellent example (see Fig 2.a). Random component of the magnetic field is naturally expected and one should account for it. In fact, the very amount of the dissipated magnetic energy may be related to the random component of the field (e.g. MacFadyen, these proceedings). For efficient accelerations of electrons one then would need $\delta B/B \sim 1$. In this case the total polarization decreases (Fig. 2.b),
remaining reasonably high for $\delta B/B \leq 1$.

The three competing models of GRBs are compared in Fig 3. Electromagnetic model is the best contender. It does not require fine tuning of parameters, all observers should see large polarization regardless of the viewing angle, Lorentz factor etc. The only constraint is that the random component of the field is not dominant.

The cannonball model [3] (and other models invoking inverse Compton scattering [1, 4]) can in principle produce very high polarization. It does make an unphysical (in our opinion) assumptions $\Delta \theta, \theta_{ob} \leq 1/\Gamma$, but this was inherent to the model before polarization results came out. There is a large degree of fine-tuning: it is assumed that all ”cannonballs” are flying within an extremely narrow cone. If their directions were to have a scatter $\Delta \theta > 1/\Gamma \sim 10^{-3}$ polarization would drop to zero. Still, it has an advantage that in the best case it can produce up to 100% polarization.

Internal shocks model is the weakest player in the field. It needs to make very contrived and contradictory assumptions to reproduce observations.

**Is RHESSI polarization real?**

High polarization of prompt emission, if confirmed, would put strong constraint on the emission mechanisms and GRB models. Only inverse Compton may produce polarization as high as 80%. Electromagnetic models can get to $\sim 50\%$, but with a random component a comfortable range is $\leq 30 - 40\%$. For internal shock anything above $\sim 10\%$ is unreasonable. Obviously, the RHESSI polarization result is highly doubtful, so that an independent confirmation or refutal is a must. If the results are not confirmed, i.e. polarization is $\Pi \leq 20\%$, that won’t exclude any model since a multitude of depolarization effects may intervene.

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FIGURE 2. (a) An example of ordered inhomogeneous magnetic field (relativistic Sweet-Parker model of reconnection, after [6]). (b) Polarization fraction in the electromagnetic model as a function of \( q \), the ratio of the rms fluctuations to the total field \( q = \sqrt{\langle B^2_{\text{rms}} \rangle} / B \) for different values of the particle power-law index \( p \). Solid lines are for two-dimensional random magnetic field confined to the \( e_\theta - e_\phi \) plane, dashed lines - for the three-dimensional random magnetic field. The large scale magnetic field is \( B_\phi \). For details see [7].

FIGURE 3. Comparison of different models for prompt polarization. For the fireball and cannonball models the maximum polarization given is for a single emitting shell (or ball).

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