Electromagnetic Outflows and GRBs

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Abstract

We study the dynamics of relativistic electromagnetic explosions as a possible mechanism for the production of Gamma-Ray Bursts. We propose that a rotating relativistic stellar-mass progenitor loses much of its spin energy in the form of an electromagnetically-dominated outflow. After the flow becomes optically thin, it forms a relativistically expanding, non-spherically symmetric magnetic bubble - a "cold fireball". We analyze the structure and dynamics of such a cavity in the force-free approximation. During relativistic expansion, most of the magnetic energy in the bubble is concentrated in a thin shell near its surface (contact discontinuity). We suggest that either the polar current or the shell currents become unstable to electromagnetic instabilities at a radius \( \sim 10^{16} \) cm. This leads to acceleration of pairs and causes the \( \gamma \)-ray emission. At a radius \( \sim 10^{17} \) cm, the momentum contained in the electromagnetic shell will have been largely transferred to the surrounding blast wave propagating into the circumstellar medium. Particles accelerated at the fluid shock may combine with electromagnetic field from the electromagnetic shell to produce the afterglow emission.

1 Introduction

Most contemporary explanations of Gamma Ray Bursts (GRBs) attribute them to high entropy "fireballs" which convert their energy into a matter-dominated (baryonic) jet within which relativistic electrons and electromagnetic field are subsequently re-created (e.g. Piran 1999). In our opinion, there are a number of problems with this scenario. Besides the commonly recognized problems of low efficiency and baryon mass and magnetic-field fine-tuning, the creation of the plasma-dominated flows is
problematic. It is usually envisaged that the energy is released electromagnetically
(e.g., MacFadyen & Woosley 1999; Kim et al. 2002; Wheeler et al. 2000) and is
dissipated right away into “lepto-photonic” plasma. Yet, there is no clear mechanism
for transforming magnetic energy into a hot plasma on an outflow time-scale. Also,
the baryonic jets are inferred to have Mach numbers $\sim 300$ and to maintain a ratio
of bulk to internal energy $> 10^5$, (or equivalently to maintain a flow that deviates locally
by angles of less than $\sim 10'$), while dissipating heavily through internal shocks.

We explore an alternative model for GRBs in which the energy remains in electromagnetic form all the way from the its origin to the sites of $\gamma$-ray and afterglow emission.

1.1 The case for electromagnetic energy transport

Several arguments point to the importance of electromagnetic field in producing GRBs: (i) Magnetic fields naturally collimate outflows and have been invoked in all other jet outflows. (ii) Magnetic outflows are “clean” – instead of requiring a finely tuned baryon fraction, baryons are may be absent completely. (iii) There is no need to convert Poynting flux into fluid energy flux and then back again. (iv) Electromagnetic energy is “high quality” – it is in a low entropy form and can be efficiently dissipated through current instabilities during particle acceleration. (v) Electromagnetic dissipation is intrinsically intermittent (c.f. solar flares); the observed GRB variability need not be tied to the source and can consequently arise at much larger radii than in internal shock models, thereby relaxing the $\gamma$-ray opacity constraint. (vi) “Standard candle” – simple electromagnetic models offer an explanation for the surprisingly narrow reported burst energy distribution – approximately the same burst energy will be inferred independent of the viewing angle (c.f. Frail et al. 2001; Panaitescu et al. 2002; Lazzati et al. 2002). (vii) Ultrarelativistic electromagnetic outflows are formally subsonic which implies that they are more naturally established than hypersonic, fluid jets. (viii) There are astrophysical examples of collimated Poynting flux dominated outflows (pulsars, AGNs, black hole candidates).

1.2 Sources of Electromagnetic Outflow

We assume that the GRB source (sometimes referred to as “millisecond magnetar”,
Usov 1992) is a strongly magnetized neutron star (e.g., Kouveliotou et al., 1998) or
a stellar mass black hole-accretion torus with mass $M \sim 1 - 10 M_\odot$, size given by
the effective light cylinder radius $r_0 \sim 10 \text{ km}$, angular velocity $\Omega \sim r_0/c \sim 10^4 \text{ rad s}^{-1}$ and magnetic field strength $B_0 \sim 10^{15} \text{ G}$. Such super-strong magnetic fields
may be generated by $\alpha - \omega$ dynamos (e.g., Thompson & Murray, 2001), or just
by differential rotation (e.g., Kluźniak & Ruderman, 1998). A rotational energy,
$E \sim 0.1 M r_0^2 \Omega^2 \sim 10^{52} \text{ erg}$ – a one parameter quantity, is available to power GRB
bursts (intermediate mass black holes can supply more energy.) The field is chosen to
produce a characteristic electromagnetic power $L \equiv \Delta \Omega L_\Omega \sim B_0^2 r_0^6 \Omega^4 / c^3 \sim 10^{50} \text{ erg}$
s\(^{-1}\), comfortably larger than that inferred for GRBs and giving a source lifetime \(\sim 100\) s matched to long bursts.

### 1.3 The Electrical Circuit

Independent of the source, we suppose that the combination of magnetic flux \(\Phi \sim B_0 r_0^2 \sim 10^{27}\) G cm\(^2\) and angular velocity combine to create a unipolar inductor with EMF \(\mathcal{E} \sim 0.1\Omega \Phi/c \sim 10^{22}\) V and that the axisymmetric part of the electromagnetic field dominates at large radius. An equivalent and useful way to think about this is to say that there is a strong, quadrupolar current distribution outward along the axes and inward along the equator (or vice versa). Under electromagnetic conditions, the effective impedance is roughly that of free space – \(\sim 100\) \(\Omega\) is fine for estimates – so the current flowing around the circuit is \(I \sim 10^{20}\) A and the power that is delivered to the “load” is \(L \sim \mathcal{E} I \sim 10^{49}\) erg s\(^{-1}\). (This interpretation of the load resistance is valid even if there is no dissipation and the electromagnetic Poynting flux just propagates away from the source with little reflection.) Our proposal differs from the conventional interpretation principally through the assumption that the current flows all the way out to the expanding blast wave, rather than completes close to the source (c.f. Fig. 2). In addition, we make the conjecture that the complex magnetic field geometry, that must be present within \(r_0\), sorts itself out and becomes axisymmetric and primarily toroidal for \(r \gg r_0\), by analogy to what is observed in the quiet solar wind. This can occur completely without (e.g. Blandford 2002) or with partial (e.g. Lyutikov 2002b) dissipation of magnetic field.

### 1.4 Lepton Loading

The sources that are envisaged generally release energy though baryonic, leptonic and electromagnetic channels. The first is usually parameterized by the initial baryon rest mass fraction of the total energy density \(\eta\), which we shall assume to be quite small. It is also useful to define a quantity \(\sigma\) which is the ratio of the electromagnetic to the total matter energy density.

Somewhat paradoxically, it gets harder to convert electromagnetic energy directly to pair plasma the stronger the field becomes. The reason is that plasma tries to short out any electric field along magnetic field on a very short time scale, a few Langmuir periods. Even if there is not enough plasma to enforce \(\mathbf{E} \cdot \mathbf{B} = 0\) conditions the required amount of pairs will be created through vacuum breakdown. However, pair creation is not likely to drain all the potential EMF since the potential differences required to create pairs through a vacuum breakdown are typically \(\sim 1\) GV and never more than \(\sim 1\) TV, which is orders of magnitude smaller than the EMF required to account for ultra-relativistic outflows \(\sim 10\) ZV in GRBs. When the field strength is as high as \(\sim 10^{15}\) G, the minimum density of plasma needed to short out the electric field – the Goldreich-Julian density \(n_{GJ}\) – is tiny in comparison with the equipartition density \(n_{eq}\). Put another way, \(\sigma_0 < \sigma_{\text{max}} \sim n_{eq}/n_{GJ} \sim \mathcal{E}/\Delta V_{\text{vac}} \sim \omega_G/\Omega \sim 10^{16}\).
The actual value of \( \sigma_0 \) is model-dependent. At one extreme, if there is an evacuated neutron star or black hole magnetosphere, only enough pairs need be created to supply the necessary space charge and current so that \( \sigma_0 \sim \sigma_{\text{max}} \). At the other, there might be a weakly magnetized hot torus radiating neutrinos with energy above \( \sim 5 \text{ MeV} \) so that \( \sigma \ll 1 \) and the standard fireball model would apply. All intermediate values are possible (e.g., dissipation of large scale magnetic field through pair creation is likely to give \( \sigma_0 \sim E \mathcal{M} \mathcal{F} / \Delta V_{\text{breakdown}} \sim 10^{10} \)). If we suppose that the flow is initially electromagnetically dominated, with \( \sigma \gg 1 \), then about the only way that it seems possible to create entropy directly and reduce \( \sigma \) appreciably is for an electromagnetic turbulence cascade to develop, operating down to wavelengths, \( \lambda_{\text{min}} \), so small that electromagnetic energy can be dissipated in accelerating pairs, somewhat analogous to the viscous dissipation that terminates a fluid turbulence spectrum. If this really can operate then it is hard to see how more than a few percent of the electromagnetic energy will be dissipated on a source dynamical time scale, more specifically, \( \sigma \sim \ln(r_0/\lambda_{\text{min}}) \sim 100 \), and the flow will remain electromagnetically dominated.

In fact, even if there is an appreciable pair content close to the source (but still \( \sigma \gg 1 \)), this will quickly become irrelevant because the pairs will annihilate when their temperature falls to \( \sim 20 \text{ keV} \), just like in the early universe. The Thomson optical depth of the plasma will then drop to a low enough value that the photons can escape and decouple from the flow. If this happens in GRBs then a weak \( \gamma \)-ray precursor is predicted (Lyutikov & Usov 2000; Fig. 1) and this may have been observed (Preece 2002).

### 1.5 Outflow Phases

Before discussing a few of the details, we should distinguish the principal stages through which the outflow passes in our GRB model.

1. **Flow formation** (\( r < r_0 \)) There must be a quasi-steady source of electromagnetic power within \( r_0 \sim 10 \text{ km} \). For a long burst, this should last for \( \sim 10^6 \) dynamical times. The initial temperature of the pair plasma is \( T_0 \sim 3(\sigma_0/100)^{-1/4} \text{ MeV} \) and the associated optical depth \( \tau_T \sim (B/B_L)(n/n_{\text{GJ}}) \), where \( B_L \sim 5 \times 10^{15} \text{ G} \) is the Larmor field for which the Larmor radius of a mildly relativistic electron equals the classical electron radius. The flow is initially sufficiently optically thick to trap the radiation.

2. **“Warm” acceleration** (\( r_0 < r < r_{\text{thin}} \)). The plasma is accelerated by the electromagnetic field and the bulk Lorentz factor increases linearly with radius until the flow becomes optically thin at \( r_{\text{thin}} \sim 10^8(\sigma_0/100)^{-1/4} \). A small admixture of baryons will extend \( r_{\text{thin}} \) but it cannot delay the escape of photons by much.

3. **Electromagnetic bubble.** Beyond the photosphere the radiation and \( e^\pm \) decouple from magnetic field - loading drops by 7 orders of magnitude, leaving plasma strongly magnetized \( \sigma \sim 10^9 \). At this moment the flow becomes a relativistically expanding magnetically dominated bubble. Several stages of the bubble expansion can be identified:
3.1. **Magnetic acceleration** \((r_{\text{thin}} < r < ct_s)\). The radial Lorentz factor of the frame in which the electric vector vanishes can reach \(\Gamma \sim 10^4\), as long as it does not exceed \(\eta^{-1}\). A filled electromagnetic vanishes can reach \(\Gamma \sim 10^4\), as long as it does not exceed \(\eta^{-1}\). A filled electromagnetic bubble will be produced with polar and axial current that complete as a “Chapman-Ferraro” current along a relativistically expanding contact discontinuity (CD) that separates the bubble from the swept up circumstellar medium. The magnetic field will be primarily toroidal and the electric field should be primarily poloidal in the frame of the explosion. This phase will continue until \(\sim ct_s \sim 3 \times 10^{12}\) cm, when the source switches off.

3.2. **“Coasting” electromagnetic shell** \((ct_s < r < r_{\text{sh}} \equiv (L\Omega t_s^2/\rho c)^{1/4})\). At this time, the bubble becomes a relativistically expanding shell of thickness \(\sim ct_s\). The shell still contains toroidal magnetic field but the current now detaches from the source and completes along the shell’s inner surface. At this stage the CD is constantly re-energized by the fast-magnetosonic waves propagating from the central source so that the Lorentz factor of the CD is \(\Gamma \sim (L\Omega/\rho c^3)^{1/4} r^{-1/2}\) (in a constant density medium) or \(\Gamma \sim \text{const}\) (in a \(\rho \sim r^{-2}\) wind). This stage is limited by one dynamical time scale \(t_{\text{dyn}} \sim 2t_s\Gamma^2\).

3.3. **Self-similar electromagnetic shell** \((r_{\text{sh}} < r < r_{\text{NR}} \equiv (L\Omega t_s/\rho c^2)^{1/3})\). After one dynamical time scale all the regions of the bubble come into a causal contact – most of the waves reflected from the CD have propagated throughout the bubble. As the expanding bubble performs a work on the surrounding medium its total energy decreases; the amount of energy that remains in the bubble at the self-similar stage needs to be calculated numerically. Most energy in the bubble is still concentrated in a thin shell with \(\Delta R \sim R/\Gamma^2\) near the surface of the bubble which is moving according to \(\Gamma \sim \sqrt{E_{\Omega}/\rho c^2} r^{-3/2}\) (in a constant density medium), or \(\Gamma \sim r^{-1/2}\) (in a \(\rho \sim r^{-2}\) wind). Interestingly, the structure of the magnetic bubble resembles at this stage the structure of the hydrodynamical relativistic blast wave (Blandford&McKee 1976). After the bubble came into a causal contact it starts to evolve in lateral direction trying to adjust magnetic pressures. This evolution may be accompanied by electro-magnetic instabilities which lead to particle acceleration and \(\gamma\)-rays production. The result of the lateral energy redistribution is a creation of an anisotropic expansion, being faster at a given time In addition, \(\gamma\)-rays may be produced throughout the CD surface due to development of current instabilities or inertial acceleration (Smolsky & Usov 1996).

4. **Relativistic blast wave** \((r_{\text{sh}} < r < r_{\text{NR}} \equiv (L\Omega t_s/\rho c^2)^{1/3})\). As the bubble expands its energy is gradually transfered to the preceding forward shock wave. Most efficiently this transfer occurs at the end of the coasting phase (at the coasting phase \(dE/dt \sim r\)). During the self-similar phase the energy in the magnetic bubble decreases slowly (logarithmically in times since at this stage \(dE/dt \sim 1/r\)), so that the relativistic blast wave stage is coexistent with the self-similar stage of the magnetic bubble. At the forward shock wave relativistic particles are accelerated producing the observed afterglow. Magnetic flux is either incorporated into the blast wave from
the bubble or, perhaps, amplified at the relativistic shock front. This is the afterglow phase which usually becomes unobservably faint after the expansion speed becomes mildly relativistic at $r \sim 10^{18} \text{ cm}$.

5. Non-relativistic blast wave ($r_{\text{NR}} < r$). Eventually the source will expand non-relativistically and become more spherical with time, resembling a normal supernova remnant.

2 Dynamics of magnetic explosions

2.1 Relativistic MHD vs force-free formalism

The conventional method for handling relativistic, magnetized flows is to use the relativistic extension of regular, non-relativistic magnetohydrodynamics (RMHD). However, there is a simpler extension which is appropriate when the plasma is sufficiently tenuous that its inertia can be ignored, though sufficiently dense that it can supply the space charge and current density ($1 << \sigma << 10^{16}$). Under these circumstances, we adopt the relativistic force-free (RFF) approximation

$$\rho \mathbf{E} + \mathbf{j} \times \mathbf{B} = 0$$

This implies that $\mathbf{E} \cdot \mathbf{B}$ and its temporal derivative can be set to zero. In addition, we restrict our attention to the case $E < B$. Eq. (1) allows us to define an electromagnetic velocity $\mathbf{v} = \mathbf{E} \times \mathbf{B}/B^2$ perpendicular to the magnetic field (it is not useful to define a component along the magnetic field).

Now, Maxwell’s equations can be written

$$\frac{\partial \mathbf{E}}{\partial t} = \nabla \times \mathbf{B} - 4\pi \mathbf{j}, \quad \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E},$$

where we can use $\partial(\mathbf{E} \cdot \mathbf{B}/\partial t = 0$ to derive

$$\mathbf{j} = \left[ (\mathbf{E} \times \mathbf{B})\nabla \cdot \mathbf{E} + (\mathbf{B} \cdot \nabla \times \mathbf{B} - \mathbf{E} \cdot \nabla \times \mathbf{E}) \mathbf{B} \right]/B^2.$$ (3)

This RFF equation set represents a simple, evolutionary dynamical system (Uchida 1997). When one includes the constraints $\mathbf{E} \cdot \mathbf{B} = \nabla \cdot \mathbf{B} = 0$, there are four, independent electromagnetic variables to evolve and four characteristics along which information is propagated. In the linear approximation, these correspond to forward and backward propagating fast and intermediate wave modes with phase speeds $c$ and $c \hat{k} \cdot \hat{B}$ respectively.

RFF dynamics can be developed in a manner that is quite analogous to regular hydrodynamics, with the anisotropic Maxwell stress tensor taking the place of the regular pressure and the electromagnetic energy density playing the role of inertia. There is an important difference, though, in that the existence of a luminal fast mode means that electromagnetic “flows” do not become truly “supersonic”.
The RMHD approach, which must be used in the presence of significant inertia is based upon the fluid velocity \( u \). The electric field is generally supposed to be related to the magnetic field through an infinite conductivity Ohm’s law, \( E + u \times B = 0 \) and there are seven independent variables to evolve, with seven independent characteristics (two fast, two intermediate, two slow and one adiabatic) to track.

### 2.2 Suppression of lateral dynamics

Relativistic flows do not collimate easily on account of relativistic, kinematic effects. A simple way to see this is by analyzing the MHD force balance equation in the \( \theta \) direction

\[
\partial_t [(w + b^2) \gamma^2 \beta_\theta] + \frac{1}{r \sin \theta} \partial_\theta [\sin \theta (p + b^2/2)] - \cot \theta \frac{p - b^2}{r} = 0
\]

where \( w \) is the enthalpy and \( b = (B^2 - E^2)^{1/2} \) is the magnetic field in the comoving frame. Eq. (4) shows that typically on a flow expansion time \( \beta_\theta \sim 1/\gamma^2 \theta \) - the lateral dynamics is frozen-out for ultrarelativistic flow.

In the context of our model, the flow pattern is established in the vicinity of the source. In the subsequent motion, the flow at different latitudes drops out of causal contact until \( r \sim r_{dyn} \), when connection is re-established and lateral motion becomes possible (the situation is analogous to the “Hello–Goodbye–Hello” kinematics familiar from the theory of inflation). As a consequence, steady state solutions based on the Grad-Shafranov equation are not likely to become valid on an expansion time-scale.

### 2.3 Radial motion

As a consequence of freezing of lateral dynamics we can separate out the radial motion, except, perhaps, close to the axis. To find the simplest RFF solution during the expanding shell phase, we suppose that the only non-zero field components are \( B_\phi, E_\theta \).

The system (3) can be solved by separation of variables:

\[
B_\phi = r^{-1}[f_1(t - r) + f_2(t + r)]g(\theta), \quad E_\theta = r^{-1}[f_1(t - r) - f_2(t + r)]g(\theta)
\]

We now impose two boundary conditions at the contact discontinuity, \( r = R \), specifically pressure balance and velocity matching

\[
\frac{B^2}{8\pi \Gamma^2} = 2\rho_{ext}c^2\Gamma(R)^2, \quad E_\theta = 0 \to B(R)^2 - E_\theta(R)^2 = B(R)^2/\Gamma(R, \theta)^2
\]

During the self-similar wave phase, the waves emitted by the source have all caught up with the CD – the magnetic bubble relaxes to a self-similar (in \( t - r \) coordinates) structure. Assuming that in the self-similar regime \( \Gamma^2 = \Gamma_0^2 t^{-m} \) (the
coasting phase with the constant energy source is equivalent to self-similar solution
with power supply, \( m = 1 \) we find

\[
\begin{align*}
  f_1(t - r) &= \sqrt{16\pi \rho_{\text{ext}} c^2 \Gamma^2 t^{2m/(1+m)}} \left(2(m + 1)\Gamma^2 (t - r)\right)^{(1-m)/(1+m)} \\
  f_2(t + r) &= \sqrt{16\pi \rho_{\text{ext}} c^2 (t + r)/8}
\end{align*}
\]  

(7)

The reflected (in-going wave), \( f_2 \), is \( \Gamma^2 \) times weaker than the outgoing - Doppler red-shifting during the reflection from the CD. Magnetic field:

\[
B \approx \frac{f_1(t - r)}{r} g(\theta) = \sqrt{16\pi \rho_{\text{ext}} c^2 \Gamma^2 t \chi^{(1-m)/(1+m)}/r} g(\theta)
\]  

(8)

\( \chi = 2(m+1)\Gamma^2(1-r/t) \). The self-similar structure of the magnetic bubble looks similar to the structure of hydrodynamic blast wave (Blandford&McKee 1974)! This result is a bit surprising since the two systems are completely different (electro-magnetic bubble and hydrodynamical shock wave) and solutions come from different equations (Maxwell and Euler). An important property of the self-similar bubble is that for \( 1 < m < 3 \) the magnetic field is concentrated near CD in a thin sheath \( \sim R/\Gamma^2 \).

In particular, for point explosion in a homogeneous medium \( \rho_{\text{ext}} = \text{const} \ (m = 3) \) we find

\[
\begin{align*}
  B &\propto \frac{1}{t^2 r \sin \theta \sqrt{\chi}}, \\
  E_\Omega &\propto \frac{E_0}{\sin^2 \theta} \ln \frac{E_0}{\rho_{\text{ext}} c^2 r^3} \\
  \Gamma^2 &\propto \frac{1}{\sin^2 \theta} \left( \frac{r_{nr}}{r} \right)^3, \quad r_{nr} = \left( \frac{3E_0}{2\rho_{\text{ext}} c^2} \right)^{1/3} \sim 10^{18}\text{cm}
\end{align*}
\]  

(9)

Interestingly, the energy contained within the magnetic bubble decreases logarithmically with time, so that the forward blast wave fully decouples from the magnetic bubble only when the flow becomes trans-relativistic.

### 2.4 Lateral dynamics and collimation.

At large distances, \( r \sim 10^{16} \text{ cm} \), the flow slows down and the lateral dynamics “un-freezes”. The flow then tries to adjust to a lateral force balance, which becomes \( g = 1/\sin \theta, \Gamma \sim 1/\sin^2 \theta, L_\Omega \sim 1/\sin^2 \theta \) when the toroidal field dominates over pressure. Thus, at \( r \sim 10^{16} \text{ cm} \) the flow relaxes to a universal lateral distribution of energy independent of the initial conditions. The energy flow is strongly peaked along the axis.

### 3 \( \gamma \)-ray emission

In the RFF limit the fast speed is the speed of light and so no fast shocks form. If we add a limited quantity of plasma and use RMHD, the shocks are weak and not
likely to be efficient particle accelerators. There are no intermediate shocks in the RFF limit, though rotational discontinuities can be present.

We therefore propose that the $\gamma$-ray-emitting electrons are accelerated by current instabilities during the magnetic shell phase. Intense line and sheet currents are traditionally unstable as is well-documented by laboratory experiments. There are two possible locations of the emission, along the poles and in the body of the magnetic shell. We consider these in turn.

3.1 Polar Emission

We can continue the cosmological analogy and note that as the flow decelerates, angular scales $\sim \Gamma^{-1}$ will “enter the horizon”. Specifically, electromagnetic instabilities on the axis can grow on progressively larger scales. The fastest growing modes are likely to be pinch, kink and helical modes. with progressively larger scale modes becoming unstable as the flow develops, also analogous to cosmology.

There are several ways in which these instabilities can develop. Let us outline one scenario that we find to be quite plausible. If we continue to make the RFF approximation and ignore the inertia and pressure of the plasma outflow then the solution outlined above will have an unbalanced stress near the axis where the current flows. This will cause the electromagnetic field to flow towards the axis. This inflow will be accompanied by development of current instabilities – pinches and kinks. We suspect that the nonlinear development of these instabilities will produce a turbulence spectrum down to a high $k$ inner scale where the particle acceleration is able to absorb the wave energy on the wave turnover time-scale. Simple estimates suggest that the slope of the wave turbulence spectrum is $3/2$ as opposed to the Kolmogorovian value of $5/3$ and that the energy of the emitted radiation can, indeed, lie in the $\gamma$-ray band, (after Doppler boosting). Numerical computations of this nonlinear development are underway (MacFadyen & Blandford, in preparation).

One merit of this explanation is that it allows the GRB to originate at a much larger radius, up to $\sim 10^{16}$ cm than in the standard, baryonic, intermediate shock model $\sim 10^{13}$ cm. This means that the bulk outflow Lorentz factor can be much smaller at the emission generation radius. (One objection that has been raised to this type of model is that the it may not be possible to achieve the large variability on $\sim 10$ ms time-scales that is observed. However, this turns out not to be a problem if the emission zone contains large amplitude waves moving with speed $c$, as is likely to occur in an intermittent turbulence spectrum.)

3.2 Shell Emission

The expanding shell will be preceded by a surface current emanating from the poles and flowing to the equator (or vice versa). It will be followed, at a distance of the order of the shell thickness by a reverse current. We strongly suspect (though have not demonstrated) that this electromagnetic configuration is strongly unstable and,
after a few light crossing times in the frame of the source, the shell will break up and create a local turbulence spectrum which can accelerate particles as described above. This will occur at \( r \sim 10^{16} \text{ cm} \). The variation, particle acceleration and emission are much as in the polar model. Alternatively, acceleration of external electrons due to inertia-induced electric fields at the contact discontinuity \( (\text{Smolsky & Usov 1996}) \) may lead to the production of \( \gamma \)-rays.

An attractive feature of the shell emission is that it predicts \( \gamma \)-ray emission in all directions and few orphan afterglows. The strength of the burst is expected to be related to the inferred energy per sterad in the afterglow although large variations are indeed possible. Burst seen at small angle \( (\text{as may be inferred from achromatic breaks in the afterglow emission}) \) should be seen to larger distances although a large burst to burst dispersion should be expected. It could be that short bursts are polar and long bursts are from the shell. Simulations of shell emission are also underway which will clarify some of these points.

4 Afterglow Emission

Under this model, the afterglow is produced during the relativistic blast wave phase when the energy contained in the electromagnetic bubble is transferred to the swept up circumstellar medium. However, if the electromagnetic dynamics is as conjectured above, then this will be reflected in the subsequent blast wave dynamics. The form of the blast wave would reflect both the form of the driver (magnetic bubble) and subsequent evolution of the shock. We have considered the expansion of non-spherical relativistic blast waves in a relativistic Kompaneets approximation \( (\text{Kompaneets 1960, Shapiro 1980, Lyutikov 2002b}) \). We find that only extremely strongly collimated shocks, with the opening angle \( \Delta \theta \leq 1/\Gamma^2 \) show modification of profiles due to sideways expansion. Thus, the motion of the forward shock will be determined by the form of the electromagnetically driven. In particular, the energy per sterad in the shock is \( L_\Omega \propto 1/\theta^2 \). What is inferred as a jet is a non-spherical relativistic outflow. This implies that, whatever the observer orientation, the inferred blast wave energetics is roughly the same, to within a logarithmic factor. The starting Lorentz factor for the afterglow is likely to be \( \Gamma \gg \theta^{-1} \). The emission should exhibit an achromatic break when \( \Gamma \) falls to \( \sim \theta^{-1} \). Thus, all bursts are observable, although the fluency depends strongly upon angle of observation. This has important implications for the incidence of orphan afterglows and perhaps for the interpretation of X-ray flashes.

5 Conclusion

We have explored the “electromagnetic hypothesis” for ultra-relativistic outflows, namely that they are essentially electromagnetic phenomena which are driven by energy released by spinning black holes or neutron stars and that this electromagnetic behavior continues into the source region even when the flows become non-relativistic.
The most striking implications of the electromagnetic hypothesis are that particle acceleration in the sources is due to electromagnetic turbulence rather than shocks and that the outflows are cold and electromagnetically-dominated, with very few baryons, at least until they become strongly dissipative.

The most important prediction that is likely to be tested in the coming years is the form of the external shock wave generated by the magnetic bubble. We predict $L_\Omega \sim \theta^{-2}$. Observational properties of such blast wave have been already discussed (Rossi at al. 2002). Current data are consistent with such an energy distribution. Further data are expected from optical polarization observations, which should exhibit a characteristic temporary evolution as well as correlation with intensity and the times of the jet achromatic breaks (Rossi at al. 2002).

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Questions

J. Trier Frederiksen: What are the assumptions of the medium that the magnetic bubble is pushing?

M. Lyutikov: There is no specific requirement on the external medium (except that it is tenuous): it can be hot or cold, homogeneous or a power-law in radius. The internal structure of the bubble will be somewhat different in these cases, but will remain qualitatively similar.

S. Shibata: What is the physics leading to ”delayed reconnection” in the distance far from the central engine?

M. Lyutikov: Relativistic radial motion leads to an effective freezing of lateral motion and of current instabilities, which becomes important only when the flow slows down.

E. Berger: What are the relevant length scales (10^{16} cm for GRB, 10^{17} for afterglow, 10^{18} cm for non-relativistic phase) and what determines these scales?

M. Lyutikov: $\gamma$-rays are emitted at $ct \sim \Gamma^2 c t_s \sim (Et_s/\rho c)^{1/4} \sim 10^{16}$ cm at the end of the coasting phase when lateral dynamics of the bubble un-freezes. Starting from this radius, most of the energy is transferred to the forward shock which becomes non-relativistic at $r \sim (E/\rho c^2)^{1/3} \sim 10^{18}$ cm.