ON THE EXTERNAL SHOCK SYNCHROTRON MODEL FOR GAMMA-RAY BURSTS’ GeV EMISSION

TSVI PIRAN1 and EHUD NAKAR2

1 Racah Institute of Physics, Edmund J. Safra Campus, Hebrew University of Jerusalem, Jerusalem 91904, Israel; tsvi@phys.huji.ac.il
2 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel; udini@wise.tau.ac.il

ABSTRACT

The dominant component of the GeV gamma-ray burst emission detected by the Large Area Telescope begins after the prompt soft (sub-MeV) gamma rays and lasts longer. This has led to the intriguing suggestion that the GeV emission is generated via synchrotron emission of the external shock. Moreover, the limits on the MeV afterglow emission lead to the suggestion that at least in bright GeV bursts the field is not amplified beyond compression in the shock. We show here that considerations of confinement (within the decelerating shock), efficiency, and cooling of the emitting electrons constrain, within this model, the magnetic fields that arise in both the upstream (unshocked circumburst) and downstream (shocked circumburst) regions, allowing us to put direct limits on their values. The well-known limit on the maximal synchrotron emission, when combined with the blast wave evolution, implies that late photons (arriving more than ~100 s after the burst) with energies higher than ~10 GeV do not arise naturally from an external shock synchrotron and almost certainly have a different origin. Finally, even a modest seed flux (a few mJy) in IR–optical would quench, via Inverse Compton cooling, the GeV emission unless the magnetic field is significantly amplified behind the shock. An observation of a burst with simultaneous IR–optical and GeV emission will rule out this model.

Key words: gamma-ray burst: general

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1. INTRODUCTION

Recent Fermi observations of the GeV emission (100 MeV–50 GeV) from gamma-ray bursts (GRBs) revealed an interesting pattern. The GeV emission is delayed relative to the onset of the prompt MeV emission and it shows a constant power-law decay after the prompt emission dies out (Abdo et al. 2009a, 2009b; Ghisellini et al. 2010). This suggests that the bulk of the GeV emission arises from an external shock afterglow (Kumar & Barniol Duran 2009a, 2009b; Ghisellini et al. 2010). While a detectable high-energy external shock emission was expected for a long time (Meszaros & Rees 1994) and it was noted that the external shock synchrotron emission may be the strongest afterglow GeV component (see, e.g., Fan et al. 2008; Fan & Piran 2008; Zou et al. 2009), the observation that this may be the dominant GeV emission over the whole burst, including the prompt phase, was surprising.

Kumar & Barniol Duran (2009a, 2009b) proposed a revolutionary model in which they revise a critical component of the standard external shock scenario suggesting no magnetic field amplification beyond the usual shock compression. Namely, the downstream (shocked) magnetic field is amplified only by a factor of 4Γ (where Γ is the bulk Lorentz factor behind the shock). In doing so they are able to fit the overall afterglow spectrum (ranging from optical to GeV), as the low magnetic field in the emitting region quenches the lower energy emission.

The magnetic field plays a triple role in synchrotron-shock acceleration. It accelerates the electrons and confines them to the shock. It also controls the synchrotron emission. A weaker magnetic field poses two challenges to the model: cooling and confinement. First, a comparison of the acceleration and the cooling times sets an absolute limit on the energy of a synchrotron photon in the radiating fluid frame. Together with the hydrodynamics of the decelerating blast wave this puts a time-dependent limit on the maximal energy of the observed synchrotron photons. Photons above this limit are (almost certainly) not emitted by an external shock synchrotron. Efficient cooling poses another limit. A significant (though not dominant) amount of energy is emitted in the GeV emission. This implies that the emitting electrons must be fast cooling. Otherwise the system would be inefficient and the energy requirement unreasonable. As the cooling takes place mostly in the downstream region this last condition constrains the magnetic field there. While our original motivation was to examine the “unamplified” magnetic field scenario, our analysis is more general and we allow for an amplification factor. We show that the observations of a significant GeV flux pose strong limits on the downstream magnetic field. These limits can be translated to limits on the upstream circumburst field (in the case of no amplification) or on the amplification factor.

Confinement is most important in the upstream region, where the magnetic field is weakest. Thus, the observations of GeV photons limit the upstream magnetic field with a weak dependence on the shock’s field amplification. Finally, we turn to the influence of inverse Compton (IC) cooling on the observed GeV emission. Given the strong low-energy (IR–optical) radiation fields (from the prompt, reverse shock and the forward shock itself), the magnetic field density should be strong enough so that IC cooling will not quench the GeV emission. This sets yet another, independent, limit on the downstream magnetic field. These considerations shed a direct light on the magnetic fields which are among the most elusive parameters of the external shock model. We assume that the external shock is adiabatic. For a radiative shock (e.g., Ghisellini et al. 2010) the constraints will be more stringent.

We examine these limits that arise from the GeV emission. We do not attempt to provide a complete solution to the whole multiwavelength afterglow. Note that the radio-to-X-ray afterglow modeling suggested a strong downstream field (e.g., Panaitescu & Kumar 2002; Yost et al. 2003), while similar
arguments to those used in Section 4 imply (when applied to the X-ray afterglow) a strong upstream field (Li & Waxman 2006). Nevertheless, here we constrain the magnetic field in GeV bursts based on the observations in these bursts alone, without any prior from radio-X-ray observations of other bursts. As such our analysis is general and it depends only on the assumptions of synchrotron, shock acceleration, and the blast wave hydrodynamics.

2. THE MAXIMAL SYNCHROTRON ENERGY

By equating the cooling to the acceleration rate, one can obtain an upper bound on the maximal energy of a synchrotron photon (e.g., de Jager & Harding 1992; Lyutikov 2009; Kirk & Reville 2010):

$$h\nu_{\text{max}}' = \frac{m_e c^2}{\alpha [1 + \gamma(Y_{\gamma}')]},$$  \hspace{1cm} (1)

where $h$, $m_e$, $c$, and $\alpha$ are the Planck constant, the electron’s rest mass, the speed of light, and the fine-structure constant, respectively. IC cooling (see Section 4) reduces $\nu_{\text{max}}'$ by a factor $1 + Y(Y_{\gamma}')$, where $Y(Y_{\gamma}')$ is the Compton parameter in the downstream region (where the dominant cooling takes place) and $\gamma_{\gamma}'$ is the Lorentz factor of the electrons whose synchrotron frequency is $\nu_{\text{max}}'$. Interested in a maximal upper limit we consider $Y \ll 1$ (see Section 4). This limit is in the fluid’s rest frame, denoted by “’”. The maximal observed energy is boosted from the fluid frame to the observer frame by $D = [\Gamma(1 - \beta \mu)(1 + z)]^{-1}$, where $\Gamma$ is the fluid’s Lorentz factor and $\mu$ is the cosine of the angle between the fluid velocity and the line of sight.

The observer simultaneously receives photons emitted from a range of radii (and therefore a range of Lorentz factors) from the decelerating external shock. Photons observed at a time range of radii (and therefore a range of Lorentz factors) from the line of sight.

$$D_{\text{los}} = 2 \Gamma_{\text{los}}/(1 + z),$$  \hspace{1cm} (2)

we find

$$D_{\text{los}} = \frac{\Gamma_{\text{los}}}{\Gamma_{\text{los}}\left[1 + \frac{2(4 - k)}{7 - 2k + (\Gamma/\Gamma_{\text{los}})^{44/27}}\right]}.$$  \hspace{1cm} (3)

Maximizing $D_{\text{los}}$ for $\Gamma \gg \Gamma_{\text{los}}$ shows that in a constant density medium ($k = 0$), e.g., interstellar medium (ISM), $D_{\text{max}} = 1.2D_{\text{los}}$ while in a circumburst wind ($k = 2$) $D_{\text{max}} = D_{\text{los}}$. For a self-similar adiabatic shock that propagates into ISM with a constant particle density, $n$, $\Gamma_{\text{los,ISM}} = \left[17 E^1 t^{-1} / 164 \pi^3 m_p c^5 n (1 + z)\right]^{1/8}$ while in a wind with a mass density $\rho = A r^{-2}$, $\Gamma_{\text{los,wind}} = [9 E t / 128 \pi^3 c^2 (A(1 + z))^{1/4}]$ (Blandford & McKee 1976). Here, $E$ is the blast wave kinetic energy, $m_p$ is the proton mass, and $z$ is the burst’s redshift.

Using these expressions we find the maximal observed energy of a synchrotron photon emitted by a decelerating adiabatic external shock:

$$h\nu_{\text{max}} = \begin{cases} \frac{9 \text{ GeV}}{\left(E_{54} \left[\frac{n}{A}\right]^{1/8}} \left(1 + z\right)^{-5/8} t_2^{-3/8} \text{ ISM} \\ \frac{5 \text{ GeV}}{\left(E_{54} \left[\frac{A}{A_s}\right]^{1/4}} \left(1 + z\right)^{-3/4} t_2^{-1/4} \text{ wind} \end{cases},$$  \hspace{1cm} (4)

where we use the common notations of $t_2 = t/100$, $E_{54} = E/10^{54}$ in cgs units, etc., $n$ is the ISM density, and $A_s$ is the wind parameter in units of $5 \times 10^{-11}$ gr cm$^{-1}$. The dependence on the burst’s parameters of this rather general condition is very weak. Moreover, for a given observed flux, when the burst redshift (and energy) is unknown, this limit peaks at $z \sim 1$.

In principle, this limit can be violated by synchrotron emission in a special magnetic field configuration, for example, if the electrons are accelerated by a weak magnetic field but radiate where the field is strong (Lyutikov 2009; P. Kumar 2010, private communication). Still, it is unlikely that synchrotron generates $\gtrsim 10$ GeV afterglow photons.

Such photons were already observed in two bursts. Most notable is the detection of an 18 GeV photon by EGRET 90 minutes after the burst from GRB940217 (Hurley et al. 1994), a factor of ten larger than the limit of Equation (4) which at this time $\approx 2$ GeV. The Large Area Telescope (LAT) detected a 33 GeV photon 82 s after the burst from GRB090902B (Abdo et al. 2009b). One or two photons cannot rule out the external shock synchrotron model for the GeV emission. Nevertheless, they pose a major difficulty, especially if the observations of late afterglow photons much above this limit will continue.

3. CONFINEMENT AND COOLING

Synchrotron external shock emission constrains both the upstream and downstream magnetic fields. The first by the requirement that the radiating electrons are confined while being accelerated and the second by the requirement of the radiating electrons radiate efficiently. The limits are particularly interesting when the downstream field is not amplified beyond the usual shock compression ($B_d = 4\Gamma B_u$). Such a case is interesting for this scenario because a rather weak magnetic field is needed to suppress the synchrotron MeV emission of the forward shock (Kumar & Barniol Duran 2009b). However, in order to consider the most general case, and since IC emission may suppress the MeV emission without affecting the GeV luminosity, we introduce an amplification factor, $f_B \gtrsim 1$, so that $B_d \equiv 4 f_B \Gamma B_u$. In the following, we present these constraints using $f_B$ and the upstream field, which for abbreviation we denote simply as $B$.

3.1. Confinement

The condition that electrons are confined while they are accelerated sets a second limit on the maximal synchrotron energy. The confinement criterion on the upstream gyro radius of an electron with the Lorentz factor $\gamma_e'$ is

$$R_L = \frac{\gamma_e' m_e c^2}{e B} \leq f_a \Gamma R.$$  \hspace{1cm} (5)

The external shock slows down while it propagates and it will not catch the rapid electron by the time it turned somewhat later (see Figure 1). This leads to the confinement factor, $f_a \lesssim 1$. Assuming an optimal field configuration for confinement (i.e., a coherent field perpendicular to the shock
Figure 1. Motion of electrons in the upstream (right: red) and downstream (left: purple) regions. Note that the shock moves forward and slows down while the electron gyrates in the upstream magnetic field.

(A color version of this figure is available in the online journal.)

In the upstream region \( \gamma' = \gamma f_u R/\Gamma \), where \( f_u \approx 0.1 \). The resulting maximal \( \gamma' \) is \( 4 f_u \Gamma \gamma^2 B \) while \( \gamma \propto \gamma^2 B = \Gamma^2 \gamma^2 B \). Therefore, the confinement upper limit for synchrotron external shock photons is

\[
h_{\text{conf}} = 4 f_u \hbar \left( \frac{e B}{m c^2} \right)^3 \frac{f_u^2 \Gamma^2 \gamma^2}{(1 + z)c^2}.
\]

The average blast wave Lorentz factor and radius at time \( t \) in an ISM (Sari et al. 1998) or in a wind (Chevalier & Li 2000) are

\[
\Gamma = \begin{cases} 
180 \left( \frac{E_{54}}{n} \right)^{1/8} \left( \frac{1 + z}{2} \right)^{3/8} t^{-3/8} & \text{ISM} \\
100 \left( \frac{E_{54}}{A_\ast} \right)^{1/4} \left( \frac{1 + z}{2} \right)^{1/4} t_2^{-1/4} & \text{wind} 
\end{cases}
\]

and

\[
R = \begin{cases} 
2 \times 10^{17} \text{cm} \left( \frac{E_{54}}{n} \right)^{1/4} \left( \frac{1 + z}{2} \right)^{-1/4} t_2^{1/4} & \text{ISM} \\
3.7 \times 10^{16} \text{cm} \left( \frac{E_{54}}{A_\ast} \right)^{1/2} \left( \frac{1 + z}{2} \right)^{-1/2} t_2^{1/2} & \text{wind} 
\end{cases}
\]

Substitution of these expressions into Equations (6) and (7) yields

\[
y_{\text{conf}} = \begin{cases} 
3 \times 10^8 f_u \frac{B_{-5}}{\mu} \left( \frac{E_{54}}{n} \right)^{1/4} \left( \frac{1 + z}{2} \right)^{-1/4} t_2^{1/4} & \text{ISM} \\
10^8 f_u \frac{B_{-5}}{\mu} \left( \frac{E_{54}}{A_\ast} \right)^{1/2} \left( \frac{1 + z}{2} \right)^{-1/2} t_2^{1/2} & \text{wind} 
\end{cases}
\]

and

\[
h_{\text{conf}} = \begin{cases} 
1 \text{GeV} f_{u, \perp}^2 f_B B_{-5}^2 \left( \frac{E_{54}}{n} \right)^{1/2} \left( \frac{1 + z}{2} \right)^{-1/2} t_2^{1/2} & \text{ISM} \\
30 \text{MeV} f_{u, \perp}^2 f_B B_{-5}^3 \left( \frac{E_{54}}{A_\ast} \right)^{1/2} \left( \frac{1 + z}{2} \right)^{-1/2} t_2^{1/2} & \text{wind} 
\end{cases}
\]

Therefore, GeV synchrotron photons from an external shock implies

\[
B > \begin{cases} 
20 \mu G \frac{h\nu_0}{10 \text{GeV}} f_{u, \perp}^2 f_B B_{-5}^2 \left( \frac{E_{54}}{n(1 + z)} \right)^{-1/2} t_2^{-1/2} & \text{ISM} \\
70 \mu G \frac{h\nu_0}{10 \text{GeV}} f_{u, \perp}^2 f_B B_{-5}^3 \left( \frac{E_{54}}{n(1 + f_\ast)} \right)^{-1/2} t_2^{-1/2} & \text{wind} 
\end{cases}
\]

3.2. Cooling

The conditions found in the previous subsection are sufficient to produce the highest energy photons. However, the bulk of the energy typically observed by the LAT is around 100 MeV. To obtain an efficient, fast cooling, 100 MeV emission one needs the cooling frequency, \( \nu_c \leq 100 \) MeV. In both upstream and downstream frames, \( \nu_\text{Max} \) is obtained from the condition \( t_\text{cool} = t_\text{acc} \), while \( \nu_{\text{conf}} \) is obtained from the condition \( \nu_{\text{conf}} = \nu_\text{dyn} \). Since cooling is more efficient in the downstream region, comparing the two conditions in the downstream frame implies that \( \nu_c \) (for which \( t_\text{cool} = t_\text{dyn} \)) satisfies

\[
\nu_c = h_{\nu_\text{Max}} \frac{v_\text{conf}}{v_\text{conf, d}},
\]

where \( v_{\text{conf, d}} = (4 f_u B/\nu u)^2 v_{\text{conf}} \). This equation of the cooling frequency is equivalent to the one obtained by the traditional derivation (e.g., Sari et al. 1998). Thus, instead of calculating the exact value of \( f_u \) we use the normalization of \( \nu_c \) derived by Granot & Sari (2002) finding

\[
h_{\nu_\text{c}} = \begin{cases} 
60 \text{GeV}(f_B B_{-5})^{-3} \left( \frac{E_{54}}{n} \right)^{-1/2} \left( \frac{1 + z}{2} \right)^{-1} t_2^{-1} & \text{ISM} \\
200 \text{GeV}(f_B B_{-5})^{-3} \left( \frac{E_{54}}{A_\ast} \right)^{-1} t_2^{-1} & \text{wind} 
\end{cases}
\]

The condition \( h_{\nu_\text{c}} < 100 \) MeV imposes

\[
f_B B > \begin{cases} 
85 \mu G \left( \frac{E_{54}}{n} \right)^{-1/6} \left( \frac{1 + z}{2} \right)^{1/2} t_2^{1/6} & \text{ISM} \\
125 \mu G \left( \frac{E_{54}}{A_\ast} \right)^{-1/3} \left( \frac{1 + z}{2} \right)^{2/3} t_2^{-1/3} & \text{wind} 
\end{cases}
\]

This relatively high value for the upstream field suggests that either some magnetic field shock amplification takes place or the external density is extremely low.

Some interesting properties arise when there is no magnetic field amplification. The upstream and downstream timescales are then comparable and each electron is characterized by only
two timescales, its acceleration time, $t_{\text{acc}}$, and its cooling time, $t_{\text{cool}}$. It is the interplay between these two timescales and the dynamical timescale, $t_{\text{dyn}}$, together with the requirement that the electron is bound to the system, that determines $\gamma_{\text{Max}}, \gamma_{\text{conf}}$, and $\gamma_*$. The first satisfies $t_{\text{acc}}(\gamma_{\text{Max}}) = t_{\text{cool}}(\gamma_{\text{Max}})$. It is independent of the system dynamical time and as it turns out, $\gamma_{\text{Max}}$ also becomes independent of the strength of the magnetic field (Equation (1)). Equating $t_{\text{acc}} = t_{\text{cool}}$ results in the maximal electron energy, ignoring cooling and escape. In our case, this energy is also that of an electron that is barely confined to the system, that determines $\gamma_{\text{Max}}$. Finally, $\gamma_*$ satisfies $t_{\text{cool}}(\gamma_*) = t_{\text{dyn}}$. Therefore, there are two possibilities. If $t_{\text{acc}}(\gamma_{\text{Max}}) = t_{\text{cool}}(\gamma_{\text{Max}}) < t_{\text{dyn}}$, then the maximal electron’s energy is limited by cooling, which takes place at a shorter time than $t_{\text{dyn}}$. Thus, less energetic electrons than $\gamma_{\text{Max}}$ can cool over $t_{\text{dyn}}$ implying $v_c < v_{\text{Max}} < v_{\text{conf}}$. In such a case, a spectral break is observed at $v_c$ and a cutoff at $v_{\text{Max}}$, while $v_{\text{conf}}$ is not observed. On the other hand if $t_{\text{Dyn}} < t_{\text{acc}}(\gamma_{\text{Max}}) = t_{\text{cool}}(\gamma_{\text{Max}})$ then the maximal electron’s energy is limited by the ability to accelerate and confine the electrons over $t_{\text{dyn}}$, when cooling does not play any role. Thus, $v_{\text{conf}} < v_{\text{Max}} < v_c$, where $\gamma_{\text{Max}}$ and $\gamma_*$ do not exist in the system (cannot be accelerated). Therefore, a cutoff is observed at $v_{\text{conf}}$, while $v_{\text{c}}$ and $v_{\text{Max}}$ are not observed. For an ISM there is a triple coincidence of the three energies for our canonical parameters when $B = 20 \mu G$ so that $v_{\text{conf}} = v_{\text{Max}} = v_c$.

4. INVERSE COMPTON

IC effects maybe important if a strong low-energy radiation is present. The very energetic electrons emitting GeV photons are in the Klein–Nishina (KN) regime and hence the $Y$ parameter is a function of $\gamma$. For the efficient synchrotron emission $Y(\gamma) \lesssim 1$. This constrains the downstream field. Independently, IC cooling should not prevent the acceleration of the downstream field (Li & Waxman 2006). Since IC cooling is similar in both the downstream and upstream regions while the accelerated electron spends most of the time in the upstream region, this last condition constrains the upstream magnetic field (with a weak dependence on $f_B$).

IC cooling is determined by the radiation field (in the shock frame), $U_{\text{rad}}'(\nu)$, below the relevant KN frequency, $\nu_{kn}(\gamma')$:

$$h\nu_{kn}(\gamma') \equiv \frac{m_ee^2\Gamma}{\gamma'(1+z)}, \quad (16)$$

with

$$Y(\gamma') = \frac{U_{\text{rad}}'(\nu < \nu_{kn}(\gamma'))}{U_B'} \quad (17).$$

One can estimate $U_{\text{rad}}'$ using a given model for the external shock emission, but it is best to use the multiwavelength observations at early time. This is especially important since other radiation fields (e.g., prompt emission and reverse shock emission) may coexist with the external shock. Given an observed spectral flux density $F_{\nu}$:

$$U_{\text{rad}}'(\nu < \nu_{kn}) = \max[\nu F_{\nu}(\nu < \nu_{kn})] \frac{d^2r(1+z)}{R^3}, \quad (18)$$

where $d$ is the comoving distance. We assume for simplicity that max$(\nu F_{\nu}(\nu < \nu_{kn}))$, the maximal flux below $\nu_{kn}$, is at $\nu_{kn}$. For a given observed photon with $h\nu_{\nu}$, the relevant KN frequency is

$$\nu_{kn}(\nu_{\nu}) = \left\{ \begin{array}{ll} 0.12 \ eV \left( \frac{f_{BB}}{10^{10}} \right)^{\frac{1}{2}} \left( \frac{h\nu_{\nu}}{\text{GeV}} \right)^{-\frac{1}{2}} \left( \frac{E_{\nu_{\nu}}}{3} \right)^{\frac{1}{2}} \left( \frac{t_{\text{acc}}}{t_{\text{cool}}} \right)^{\frac{1}{2}} \text{ ISM} & \\
0.04 \ eV \left( \frac{f_{BB}}{10^{10}} \right)^{\frac{1}{2}} \left( \frac{h\nu_{\nu}}{\text{GeV}} \right)^{-\frac{1}{2}} \left( \frac{E_{\nu_{\nu}}}{3} \right)^{\frac{1}{2}} \left( \frac{t_{\text{acc}}}{t_{\text{cool}}} \right)^{\frac{1}{2}} t_{\text{dynt}}^{-\frac{1}{2}} \text{ wind} & \end{array} \right. \quad (19)$$

which for GeV energies is typically in the IR–optical.

The condition $Y(\gamma') < 1$ implies

$$f_{BB} > \left\{ \begin{array}{ll} 6 \mu G \nu_{28}^2 F_{26} \left( \frac{n}{\text{cm}^{-3}} \right)^{\frac{1}{2}} t_{\text{dynt}}^{\frac{1}{2}} \left( \frac{h\nu_{\nu}}{\text{GeV}} \right)^{-\frac{1}{2}} \text{ ISM} & \\
150 \mu G \nu_{28}^2 F_{26} \left( \frac{n}{\text{cm}^{-3}} \right)^{\frac{1}{2}} t_{\text{dynt}}^{\frac{1}{2}} \left( \frac{h\nu_{\nu}}{\text{GeV}} \right)^{-\frac{1}{2}} \text{ wind} & \end{array} \right. \quad (20)$$

where $F_\nu = F_{26} \text{ mJy} = F_{26}10^{-26} \text{ ergs cm}^{-2} \text{ Hz}$. The condition that the emitting electrons are not IC cooled in the upstream region while being accelerated implies

$$f_{BB} > \left\{ \begin{array}{ll} 3 \mu G \nu_{28}^2 F_{26} \left( \frac{n}{\text{cm}^{-3}} \right)^{\frac{1}{2}} t_{\text{dynt}}^{\frac{1}{2}} \left( \frac{h\nu_{\nu}}{\text{GeV}} \right)^{-\frac{1}{2}} \text{ ISM} & \\
100 \mu G \nu_{28}^2 F_{26} \left( \frac{n}{\text{cm}^{-3}} \right)^{\frac{1}{2}} t_{\text{dynt}}^{\frac{1}{2}} \left( \frac{h\nu_{\nu}}{\text{GeV}} \right)^{-\frac{1}{2}} \text{ wind} & \end{array} \right. \quad (21)$$

As expected, this second condition has a weaker dependence on $f_B$. Both limits show that without amplification even a modest IR–optical flux of a few mJy for an ISM and 10 μJy for a wind would suppress the GeV flux. Using the latter condition, but assuming a lower limit on the downstream magnetic field, Li (2010) derived a much higher limit on the upstream field, $B$. As stressed earlier, we do not make any such a priori assumptions on either the downstream or the upstream fields.

Although we do not consider here a complete model for the external shock synchrotron emission, we stress that when such a model is constructed KN effects should be carefully considered. The reason is that if the magnetic field is not amplified close to the equipartition level then $U_{\text{rad}}' \gg U_B'$. IC by electrons emitting the MeV–GeV emission is suppressed by KN, but over a large range of the parameter phase the $Y$ parameter of these fast cooling electrons (which now depends on the electron energy) will be larger than 1 and the synchrotron spectrum will be significantly modified (Nakar et al. 2009). An extreme example may be apparent if there is no field amplification. In such a case, $v_{kn}$ of fast cooling electrons is below the typical synchrotron frequency $\nu_m$. If their $Y < 1$, the synchrotron emission is not strongly affected. But, once $Y$ becomes larger than 1 for fast cooling electrons, the back-reaction of the IC emission on the electron distribution results in the cooling frequency “jumping” by orders of magnitude on a short timescale, significantly revising the whole synchrotron spectrum (Nakar et al. 2009).

5. CONCLUSIONS

Using confinement and cooling conditions we have obtained limits on the values of the magnetic fields needed in the downstream and upstream regions in order to produce the observed GRB GeV emission via an external shock synchrotron. These constraints are based on minimal assumptions of synchrotron
cooling and blast wave hydrodynamics. Both are essential ingredients of the external shock synchrotron model. The arguments we present allow us to directly explore the magnetic fields in both the upstream and downstream regions, which are among the least constrained physical parameters of the model.

We find that with no amplification the minimal fields required are on the high end (100 μG), unless the external density is very low. The limits are even higher for a radiative solution. It is, of course, possible that this is a condition for the GeV emission. However, the detection of the GeV emission from all MeV bright GRBs that are within the LAT field of view suggests that the emission is generic. In this case, at least a modest amplification is probably needed.

Finally, we point out two critical predictions of the external shock synchrotron model: (1) no detection of late very energetic (≫10 GeV) photons and (2) no simultaneous detection of a bright (>mJy) IR–optical (depending on the specific case) signal with the GeV photons unless the upstream magnetic field is strongly amplified by the shock. Continued observations should be compared with these predictions and can provide future tests of this model.

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REFERENCES

Abdo, A. A., et al. 2009a, Science, 323, 1688
Abdo, A. A., et al. 2009b, ApJ, 706, L138
Blandford, R. D., & McKee, C. F. 1976, Phys. Fluids, 19, 1130
Chevalier, R. A., & Li, Z. 2000, ApJ, 536, 195
de Jager, O. C., & Harding, A. K. 1992, ApJ, 396, 161
Fan, Y., & Piran, T. 2008, Front. Phys. China, 3, 306
Fan, Y., Piran, T., Narayan, R., & Wei, D. 2008, MNRAS, 384, 1483
Ghisellini, G., Ghirlanda, G., Nava, L., & Celotti, A. 2010, MNRAS, 403, 926
Granot, J., & Sari, R. 2002, ApJ, 568, 820
Hurley, K., et al. 1994, Nature, 372, 652
Kirk, J. G., & Reville, B. 2010, ApJ, 710, L16
Kumar, P., & Barniol Duran, R. 2009a, arXiv:0910.5726
Kumar, P., & Barniol Duran, R. 2009b, MNRAS, 400, L75
Li, Z. 2010, arXiv:1004.0791
Li, Z., & Waxman, E. 2006, ApJ, 651, 328
Lyutikov, M. 2009, arXiv:0911.0349
Meszaros, P., & Rees, M. J. 1994, MNRAS, 269, L41
Nakar, E., Ando, S., & Sari, R. 2009, ApJ, 703, 675
Panaitescu, A., & Kumar, P. 2002, ApJ, 571, 779
Sari, R. 1998, ApJ, 494, L49
Sari, R., Piran, T., & Narayan, R. 1998, ApJ, 497, L17
Yost, S. A., Harrison, F. A., Sari, R., & Frail, D. A. 2003, ApJ, 597, 459
Zou, Y., Fan, Y., & Piran, T. 2009, MNRAS, 396, 1163