THE EXTREMELY HIGH PEAK ENERGY OF GRB 110721A IN THE CONTEXT OF A DISSIPATIVE PHOTOSPHERE SYNCHROTRON EMISSION MODEL

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ABSTRACT

The Fermi observations of GRB 110721A have revealed an unusually high peak energy \( \sim 15 \text{MeV} \) in the first time bin of the prompt emission. We find that an interpretation is unlikely in terms of internal shock models, and confirm that a standard blackbody photospheric model also falls short. On the other hand, we show that dissipative photospheric synchrotron models ranging from extreme magnetically dominated to baryon dominated dynamics are able to accommodate such high peak values.

Key words: gamma-ray burst: general – gamma-ray burst: individual (GRB 110721A) – radiation mechanisms: non-thermal – radiation mechanisms: thermal

1. INTRODUCTION

High-energy (>100 MeV) observations of gamma-ray bursts (GRBs) have gained renewed interest since the launch of Fermi Large Area Telescope (Atwood et al. 2009). This instrument has revealed a curious diversity in the high-energy behavior of GRBs and consequently represents a new challenge for models (see Mészáros 2012, for a recent review). For GRB 110726A (Axelsson et al. 2012), the extremely high \( \varepsilon_{\text{peak}} \approx 15 \text{MeV} \) peak energy (peak of the \( \varepsilon F_\varepsilon \) spectrum), which was observed right after the onset of the burst, makes its interpretation in the framework of a simple internal shock synchrotron model challenging. Interpreting the peak as a modified blackbody from a simple photosphere is also difficult, as it can only account for energies up to a few MeVs, and even the subsequent time bins show peak fluxes which, although lower, are still unusually high. Such blackbody photosphere models have been considered by Fan et al. (2012) to explain a \( L \propto \varepsilon_{\text{peak}}^{0.4} \) correlation found by Ghirlanda et al. (2012), but as shown by Zhang et al. (2012), they must lie below a line in the \( \varepsilon_{\text{peak}}-L \) plane, which excludes the observed values for GRB 110721A.

Here we show that the high peak energy and luminosity of GRB110721A can be interpreted in the framework of a different class of photospheres, where dissipation occurs near the photospheric radius, and the spectrum is characterized by a synchrotron peak. Dissipative synchrotron photospheres have been considered for baryonic dominated regimes by, e.g., Rees & Mészáros (2005), Pe’er et al. (2006), and Beloborodov (2010), and for magnetically dominated regimes by Giannios (2006, 2012). Here we consider such photospheres for an arbitrary acceleration law, characteristic of either a baryonic or a magnetic dominated regime. The observed thermal bump close to 100 keV is also naturally incorporated in this model.

2. DYNAMICS, PHOTOSPHERES, AND EMISSION REGIONS

The initial acceleration behavior of the jet material is taken to be given by

\[
\Gamma(r) \propto \begin{cases} 
\rho^{-\mu} & \text{if } r < r_{\text{sat}} \\
\text{const.} & \text{if } r_{\text{sat}} < r 
\end{cases}
\]

where \( r_{\text{sat}} \) is the saturation radius beyond which the flow reaches its asymptotic coasting value \( \eta = (L)/(Mc^2) = \Gamma_{\text{final}} \). Based on the analysis of, e.g., Drenkhahn (2002) and Mészáros & Rees (2011), for simple conical magnetically dominated models \( \mu = 1/3 \), while in the simple baryonically dominated case \( \mu = 1 \). More general cases involving different magnetic geometries or flows where the opening angle varies with radius will generally lie between 1/3 and 1. The case of \( \mu = 1/3 \) has been further developed by Veres & Mészáros (2012), including the effects of the shocked electrons at the external deceleration radius; the generalized magnetic model including an arbitrary acceleration law \( 1/3 \lesssim \mu \lesssim 1 \) is considered in more detail in Veres et al. (2012).

The models typically invoked to explain the prompt emission spectral peak fall into two broad categories. The most widely used category involves internal shocks occurring outside the scattering photosphere. The other category ascribes the peak to effects in or near the scattering photosphere, and within this category the location of the photosphere and the dissipation details depend on whether baryonic or magnetically dominated jet dynamics are assumed.

The standard internal shock picture occurring outside the photosphere (Rees & Meszaros 1994) uses an outflow variability timescale \( t_v \), of usually tens of seconds and an average Lorentz factor \( \eta \), for which the internal shocks occurring at a radius \( r_{\text{IS}} = 2\eta^2 c t_v \approx 5 \times 10^{13} t_v^{-1} \eta^2_5 \text{cm} \). With the usual magnetic field prescription one expects an observer frame peak energy of \( \varepsilon_{\text{peak}} \approx 1 L_{52}^{-1/2} \eta_{5}^{-1} \epsilon_{\text{e}}^{1/2} \epsilon_{B,0.3}^{3/2} \epsilon_{r,0.5}(2/1+z) \text{MeV} \), an upper limit based on a variability \( t_v = 10^{-1} \text{s} \) (the light curve of GRB 110721A is rather smooth, FRED-like, suggesting a longer variability time). A somewhat different calculation including pair formation (Guetta et al. 2001) indicates an upper limit \( \varepsilon_{\text{peak}} \lesssim 1 L_{52}^{-5/3} \epsilon_\gamma^{2/3} \epsilon_{\text{e}}^{4/3} \eta_5^{4/3} t_v^{-3} (2/1+z) \text{MeV} \) that is more stringent. Thus, standard internal shocks do not straightforwardly explain this burst.

In the standard photosphere model using the usual \( \mu = 1 \) baryonic dynamics, as pointed out by Zhang et al. (2012), the photospheres generally arise in the coasting regime at \( r > r_{\text{sat}} \), where \( \Gamma \sim \eta \sim \text{constant} \), and in the absence of dissipation the blackbody peak energy and flux representing a putative band spectrum peak would fall below a line that excludes the observations of GRB 110721A.
Recently, more detailed photospheric models have been calculated (Beloborodov 2010; Vurm et al. 2011; see also Pe'er et al. 2006; Pe'er & Ryde 2011; Beloborodov 2012; Vurm et al. 2012), which show a peak energy emerging from the opaque parts of jets, through Comptonization of a thermal or synchrotron seed component. The numerical studies yield spectra consistent with the observed band shape. These analyses generally involve dissipation below the photosphere, and some include the effects of neutron and proton collisions as well, assuming baryonic dynamics, with the synchrotron radiation typically playing a subdominant or seed role. Beloborodov (2012) also showed that peak energies as high as 20 MeV can be obtained, explaining, e.g., the high $\epsilon_b$ of GRB 110721A in the framework of these models. Other detailed models have argued for magnetically dominated dynamics and magnetic dissipation controlling the photospheric radiation (Drenkhahn & Spruit 2002; Giannios & Spruit 2005, 2007; Metzger et al. 2011; McKinney & Uzdensky 2012). Along these lines, here we propose a simple model based on magnetically dominated dynamics, where synchrotron radiation can be expected to play a stronger role. We calculate the relation between the luminosity and the peak energy from synchrotron radiation based on a photospheric dissipation model for values of $\mu$ between the two extremes, in the context of GRB 110721A.

3. A DISSIPATIVE PHOTOSPHERE MODEL

Photospheric radius. We consider a dissipative photosphere, where a substantial fraction of the magnetic and bulk kinetic energy is converted into random particle energy. An extra spectral component coming from the interaction of the photospheric photons with shock-accelerated electrons at the external deceleration radius is neglected here, as this produces a GeV range contribution, whereas 110721A has only a tentative GeV component. The photosphere arises at optical depth $\tau = 1$, in a jet which initially accelerates as $\Gamma = (r/r_0)$. Here $r_0$ is launching radius at the base of the jet. The value of the photospheric radius can be expressed in terms of a critical Lorentz factor (Mészáros & Rees 2000), which, generalized to an arbitrary $\mu$, is given by

$$\eta_T \equiv (L/8\pi m_p c^3 r_0)^{1/(1+\mu)}.$$  

For $\eta > \eta_T$, the photosphere occurs in the accelerating phase, $r_{\text{ph}} = \eta_T^{1/\mu} (\eta_T/\eta)^{1/(1+\mu)}$, while for $\eta < \eta_T$, it is $r_{\text{ph}} = \eta_T^{1/\mu} (\eta_T/\eta)^3$. The saturation radius is $r_{\text{sat}} = r_0 \eta_T^{1/\mu}$.

The photosphere occurs in the acceleration phase if $\eta > \eta_T$, which is typical for a magnetically dominated ($\mu = 1/3$) case, where $\eta_T \simeq 120 L_{53}^{1/6} r_0^{-1/6}$. On the other hand, the photosphere is in the coasting phase for $\eta < \eta_T$, which is typical for baryonic cases ($\mu = 1$), where $\eta_T \simeq 1300 L_{53} r_0^{-1/4}$. The photospheric radius can be increased by a factor of $\sim 2$ by the presence of pairs (Beloborodov 2010; Vurm et al. 2011; Bošnjak & Kumar 2012; Veres & Mészáros 2012). Also, some of the mentioned models (e.g., Beloborodov 2010; McKinney & Uzdensky 2012) involve a wider dissipation region than the more narrow range around $r_{\text{ph}}$.

Spectral peak energy. The fraction of the total luminosity dissipated and converted into radiation close to the photosphere depends on various uncertain model parameters, a rough estimate being $\sim 0.5$ (as, for example, in Giannios 2012; Metzger et al. 2011; McKinney & Uzdensky 2012). Calculations of the radiation from magnetic dissipation in the photosphere proceed mainly along phenomenological lines, due to the complicated nature of the process and the uncertainties. However, reconnection is expected to lead to MHD turbulence, and relativistic turbulent bulk random motions rapidly become semi-relativistic (Zhang & MacFadyen 2009). Semi-relativistic shocks with relative Lorentz factor $\Gamma_r \sim 1$ can be expected from such turbulent motions. This provides a simple alternative model for the radiation production, based on the Fermi acceleration of electrons in these photospheric shocks.5 The minimum random Lorentz factor of the electrons resulting from these photospheric shocks is $\eta_{\text{ph}} \simeq \epsilon_e (m_p/\mu) \Gamma_r$, where $\epsilon_e \approx 1/3$ is the fraction of the energy in electrons. The synchrotron peak energy from the electrons accelerated in such shocks is $\epsilon_{\text{peak}} = (3q_e B^2_{\text{ph}}/4\pi m_e c^3) \Gamma_r^2 \epsilon_e (\Gamma_r/1 + z)$, where $B_{\text{ph}} = (32\pi \epsilon_e B^2_{\text{ph}} m_e^2 c^2 n_{\text{ph}}^2)^{1/2}$. The physical constants have the usual meaning, $\epsilon_B \lesssim 1$ is the fraction of the energy in magnetic form, $n_{\text{ph}} = L/4\pi \epsilon_B \mu c^4 \Gamma_r^2$, and the co-moving baryon density. This latter quantity scales as $r^{-2-\mu}$ up to the saturation radius, and as $r^{-2}$ in the coasting phase. The Lorentz factor of the photosphere is $\Gamma_{\text{ph}} = (r_{\text{ph}}/r_0)^{1/\mu}$ if the photosphere occurs in the acceleration phase, and it is $\eta$ otherwise. This results in a peak energy that is in the MeV range (see Section 4), which is the same range as that obtained from phenomenological magnetic dissipation heating and cooling estimates by, e.g., Giannios & Spruit (2005, 2007), etc. The dependence on the parameters of this peak energy is

$$\epsilon_{\text{peak}} \propto \left\{ \begin{array}{ll}
L_5^{1/3} \eta_5^{-1} \eta^{-1/2} \eta_5^{3/2} \epsilon_e^{2/3} \Gamma_r^{2} / (1 + z) & \text{if } \eta > \eta_T \ \\
L_5^{-1/3} \eta_5^{3/2} \epsilon_e^{2/3} \Gamma_r^{2} / (1 + z) & \text{if } \eta < \eta_T.
\end{array} \right.  \ (3)$$

We provide exact values for GRB 110721A for the representative cases discussed here in Section 4.

The spectral indices below and above the peak are affected by various factors. The low energy slope can be affected by synchrotron self-absorption, which in magnetic photospheres can be in the tens of keV range (e.g., Giannios & Spruit 2005). Recent studies (Sakamoto et al. 2011) also indicate that constraints on synchrotron low energy slopes appear in only 10% of bursts and are less stringent than in previous studies. Above the peak, pairs can have an effect. Pairs created by $\gamma\gamma$ processes depend significantly on the photon index of the spectrum above the peak energy. The result of pair formation is a steepening break in the original spectrum. The photon index in the interval with the extreme peak energy is rather steep ($\beta = -3.5$), which points to an increase in the photospheric radius due to pair creation, which is not significant, consistent with our estimate of at most few. If a pair component is present, which modifies the photospheric radius by $a \approx$ few, the peak energy decreases by $a^{-\mu+2+1}$, which would alter the peak energy, but not enough to change our conclusions. A model closely related to ours ascribes the prompt emission to magnetic turbulence (Thompson 1994), which results in a natural cutoff in the spectrum at 4 If the flow is baryonically dominated, where the magnetic fields are subdominant, one can in principle also envisage shock dissipation near the photosphere resulting from other effects, such as variable outflows with a wide range of variability, recollimation, etc.

5 Note that, for the same typical magnetic field, the typical acceleration time from reconnection and from Fermi acceleration leads formally to similar expressions (e.g., Giannios 2010). We emphasize that these are not the usual internal shocks occurring well outside the photosphere. While usual internal shocks require large relative Lorentz factors to achieve better radiative efficiency and occur at radii $\sim 10^{14}$ cm, here the radiation from magnetic dissipation arises at smaller radii, and the magnetic dissipation efficiency leading to turbulence and radiation is variously estimated to be high by the authors cited above.
\[ \Gamma \nu m_e c^2 / (1 + z) \]

In this case, we would expect only minor effects from pair production.

**Thermal peak.** Besides the synchrotron component, we expect also a (modified) thermal component from the photosphere. This component is observed as a thermal peak and it is advected from the launching radius, and cooled according to the generalized dynamics. We present concrete values for the temperature in Section 4; here we only show the general dependence on the parameters:

\[ T_{\text{obs}}(r_{\text{ph}}) \propto \begin{cases} L^{-4/3} \eta^{-8/3} r_0^{1/6} / (1 + z) & \text{if } \eta > \eta_T \\ L^{-5/12} \eta^{1/3} r_0^{1/6} / (1 + z) & \text{if } \eta < \eta_T. \end{cases} \] (4)

There were hints of a separate thermal component below the band peak (Page et al. 2011; Guiriec et al. 2011; Zhang et al. 2011; McGlynn 2012) in previous bursts, and there are reportedly significant thermal components also in GRB 110721A (Axelsson et al. 2012).

4. EXTREME MODELS

Here we consider the \( \varepsilon_{\text{peak}} - L \) pairs for different \( \mu \) values to show that in the framework of a dissipative photosphere, the high peak energy of GRB110721A can be obtained in a straightforward manner.

From Equation (3), \( \eta > \eta_T \) case (photosphere in the acceleration phase), one sees that higher luminosities, and lower Lorentz factors and launching radii, will result in larger peak energies. Increasing \( L \) and decreasing \( r_0 \) will increase \( \eta_T \), eventually leading to the \( \eta < \eta_T \) case (photosphere in the coasting phase). This transition is shown by the break in the evolution of \( \varepsilon_{\text{peak}} \) with luminosity (see Figures 1 and 2 and note that in the extreme magnetic case, the peak energy does not depend on the luminosity).

Figures 1 and 2 show that the observed highest peak energy–luminosity pair for GRB 110721A is in the admissible region of the diagrams, and for other reasonable parameters the peak energy is comfortably within the operating range of these models (admissible regions are under the modeled broken power laws, represented by dotted, dashed, and dash-dotted lines).

Here we present cases to illustrate the peak energy dependence of the luminosity, and show that within dissipative synchrotron photospheric models we can reproduce the high peak energy. We have taken a redshift \( z = 0.3826 \) (Berger 2011) for the calculations presented here. The luminosity values in the time bins are scattered around \( L = 10^{52} \text{ erg s}^{-1} \) (see, e.g., Figure 1), and thus we take this as a reference value.

4.1. Baryonic Photosphere Model (\( \mu = 1 \))

In this model, the magnetic field is subdominant, the dynamics are governed by the baryons in the outflow. The critical Lorentz factor is \( \eta_T \approx 740L_{52}^{-1/3} r_0^{-1/6} \), which puts the photosphere in the coasting phase for moderately high \( \eta \lesssim 600 \) values. The peak energy will become \( \varepsilon_{\text{peak}} \approx 16L_{52}^{-1/2} \eta_{2.6}^{1/6} r_0^{1/6} \text{ MeV} \). This is the right order of magnitude for parameter values that are not too extreme. Lending further support for this model (the baryonic variant) is the temperature of the thermal component, which also turns out the right order of magnitude,

\[ T \approx 70L_{52}^{-5/12} \eta_{2.6}^{1/6} r_0^{1/6} \text{ keV}. \]

4.2. Extreme Magnetic Model (\( \mu = 1/3 \))

In this extreme case, the break energy does not depend on the luminosity or on the coasting Lorentz factor. Still, for reasonable values, we can get (see Equation (3)) a peak energy

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\footnote{Some observations indicate a redshift of \( z \approx 3.5 \) for this burst. In this case, in order to incorporate the high peak energy we need a slightly higher \( \Gamma_r \lesssim 3 \), which is still not unrealistic.}
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The body radiation is the baryonic photosphere case, and not the magnetic. The temperature of the blackbody is lower than in the extreme magnetic case. The peak energy in this intermediate variant of the model is \( \epsilon_{\text{peak}} \approx 14 \eta_{2.5}^{-1/8} r_{0.7}^{-1/8} T_{3}^{-1/8} \epsilon_{B,0}^{1/8} \text{MeV} \). Again, this model can incorporate the rather large peak energy for not too exceptional parameters. The temperature of the blackbody is lower than in the baryonic photosphere case, \( T \approx 24 L_{\text{p}}^{1/12} \eta_{2.5}^{-1/6} r_{0.7}^{1/6} \text{keV} \), but might still be consistent with the observations.

4.3. Moderate Magnetic Model (\( \mu = 0.5 \))

Here magnetic fields are dominant, but the role of baryons is more marked than in the extreme magnetic case. The peak energy in this intermediate variant of the model is \( \epsilon_{\text{peak}} \approx 13 r_{0.7}^{-1/2} L_{r,0.5}^{1/2} \text{MeV} \). The temperature of the blackbody is \( T \approx 3 L_{\text{p}}^{-1/20} \eta_{2.5}^{-1/30} \text{keV} \). The dependence on the parameters is weak and this model cannot account for the observed temperature of the blackbody component.

5. DISCUSSION

We have considered the high peak energy values of the prompt spectrum of GRB 110721A, which reach as high as \( \epsilon_{\text{peak}} \sim 15 \text{MeV} \) (Axelsson et al. 2012). A consideration of the usual internal shock prompt emission spectrum model shows that such high values are unlikely in this model. Furthermore, we confirm the conclusion of Zhang et al. (2012) that a (non-dissipative) standard blackbody baryonic photosphere model also cannot explain such high peak values and fluxes. However, we show that dissipative photospheric models, with a typical peak energy due to synchrotron radiation, are able to accommodate such high peak energies and flux values, with reasonable parameters, for cases where the dynamics is either baryonically or magnetically dominated. If the temperature of the putatively observed blackbody component can be used as a discriminant, this would seem to favor a more baryon-dominated dissipative photosphere model, \( \mu \) closer to 1, although a moderate magnetically dominated photosphere may also be possible.

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Figure 2. Same notation and parameters as Figure 1, except for the coating Lorentz factor, which is \( \eta = 600 \) here.