AN OBSERVED CORRELATION BETWEEN THERMAL AND NON-THERMAL EMISSION IN GAMMA-RAY BURSTS

J. Michael Burgess\textsuperscript{1,2,3}, Robert D. Preece\textsuperscript{1,2}, Felix Ryde\textsuperscript{4,3}, Peter Veres\textsuperscript{5}, Peter Mészáros\textsuperscript{5}, Valerie Connaughton\textsuperscript{2}, Michael Briggs\textsuperscript{2}, Asaf Pe'er\textsuperscript{6}, Shabnam Iyyani\textsuperscript{1,4,7}, Adam Goldstein\textsuperscript{8}, Magnus Axelsson\textsuperscript{4,3,9}, Matthew G. Baring\textsuperscript{10}, P. N. Bhat\textsuperscript{2}, David Byrne\textsuperscript{11}, Gerard Fitzpatrick\textsuperscript{11}, Suzanne Foley\textsuperscript{11,12}, Daniel Kocevski\textsuperscript{13}, Nicola Omodei\textsuperscript{13}, William S. Paciesas\textsuperscript{14}, Veronique Pelassa\textsuperscript{2}, Chryssa Kouveliotou\textsuperscript{7}, Shaolin Xiong\textsuperscript{2}, Hoi-Fung Yu\textsuperscript{12}, Binbin Zhang\textsuperscript{2}, and Sylvia Zhu\textsuperscript{15}

1 Department of Space Science, University of Alabama in Huntsville, Huntsville, AL 35899, USA; jmichaelburgess@gmail.com, rob.preece@nasa.gov
2 Center for Space Plasma and Aeronomic Research (CSPAR), University of Alabama in Huntsville, Huntsville, AL 35899, USA
3 The Oskar Klein Centre for Cosmoparticle Physics, AlbaNova, SE-106 91 Stockholm, Sweden
4 Department of Physics, Royal Institute of Technology (KTH), AlbaNova, SE-106 91 Stockholm, Sweden; felix@particle.kth.se
5 Department of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802, USA; veres@gwu.edu, npp@astro.psu.edu
6 Physics Department, University College Cork, Cork, Ireland
7 Department of Physics, Stockholm University, SE-106 91 Stockholm, Sweden
8 Space Science Office, VP62, NASA/Marshall Space Flight Center, Huntsville, AL 35812, USA
9 Department of Astronomy, Stockholm University, SE-106 91 Stockholm, Sweden
10 Department of Physics and Astronomy, Rice University, MS-108, P.O. Box 1892, Houston, TX 77251, USA
11 University College Dublin, Belfield, Dublin 4, Ireland
12 Max-Planck-Institut für extraterrestrische Physik, Giessenbachstrasse 1, D-85748 Garching, Germany
13 W. W. Hansen Experimental Physics Laboratory, Kavli Institute for Particle Astrophysics and Cosmology, Department of Physics and SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94305, USA
14 Universities Space Research Association, Huntsville, AL 35805, USA
15 Department of Physics and Department of Astronomy, University of Maryland, College Park, MD 20742, USA

Received 2014 January 16; accepted 2014 March 4; published 2014 March 21

ABSTRACT

Recent observations by the Fermi Gamma-ray Space Telescope have confirmed the existence of thermal and non-thermal components in the prompt photon spectra of some gamma-ray bursts (GRBs). Through an analysis of six bright Fermi GRBs, we have discovered a correlation between the observed photospheric and non-thermal $\gamma$-ray emission components of several GRBs using a physical model that has previously been shown to be a good fit to the Fermi data. From the spectral parameters of these fits we find that the characteristic energies, $E_\gamma$ and $kT$, of these two components are correlated via the relation $E_\gamma \propto T^\alpha$ which varies from GRB to GRB. We present an interpretation in which the value of the index $\alpha$ indicates whether the jet is dominated by kinetic or magnetic energy. To date, this jet composition parameter has been assumed in the modeling of GRB outflows rather than derived from the data.

Key words: gamma-ray burst; general – radiation mechanisms: non-thermal – radiation mechanisms: thermal

Online-only material: color figures

1. INTRODUCTION

Gamma-ray bursts (GRBs) are believed to arise from the deaths of massive stars or the coalescence of two compact stellar objects such as neutron stars or black holes. The resulting explosion gives rise to an expanding fireball with a jet pointed at the observer but hidden from the observer until the density of radiation and particles in this highly relativistic outflow is low enough for radiation to escape, a region called the photosphere (for a review, see Mészáros 2006). While the emission from this fireball is expected to be thermal (Goodman 1986; Paczynski 1986), observations over the past three decades suggest the prompt emission to be highly non-thermal (Mazets et al. 1981; Fenimore et al. 1982; Matz et al. 1985; Kaneko et al. 2006; Goldstein et al. 2012), with only a few exceptions (Ryde et al. 2010; Ghirlanda et al. 2013). The conversion of the fireball energy into non-thermal $\gamma$-ray radiation involves the acceleration of electrons in the outflow and their subsequent cooling via an emission process such as synchrotron radiation (Sari et al. 1998; Tavani 1996). Insight into these energy radiation emission processes in GRBs is obtained by comparing the observed $\gamma$-ray photon spectra directly to different radiation models. The Fermi Gamma-ray Space Telescope offers a broad energy range for these comparisons. Recent observations (Guiriec et al. 2010; Zhang et al. 2011; Axelsson et al. 2012; Guriec et al. 2013; Iyyani et al. 2013; Preece et al. 2014; Burgess et al. 2014) show that at least two mechanisms can be present: a non-thermal component that is consistent with synchrotron emission from accelerated electrons in the jet and a typically smaller blackbody contribution from the photosphere. This photospheric emission is released when the fireball becomes optically thin so that an observer may see a mixture of thermal and non-thermal emission with different temporal characteristics that, when viewed together, can probe the development and structure of the fireball jet. This simple photospheric model has been used to quantitatively interpret several observed correlations such as the Amati correlation (e.g., Thompson et al. 2007; Lazzati et al. 2011; Pan et al. 2012).

We are thus motivated to investigate correlations among spectral parameters derived by fitting the non-thermal component with a synchrotron photon model and the thermal component with a blackbody, an approach developed in previous investigations (Burgess et al. 2012, 2014). The synchrotron model consists of an accelerated electron distribution, containing a
2. OBSERVATIONS

The Fermi Gamma-ray Burst Monitor (GBM; Meegan et al. 2009) has detected more than 1200 GRBs since the start of operations on 2008 July 14. A smaller number have been seen by the Fermi Large Area Telescope (LAT; Atwood et al. 2009) at energies greater than 100 MeV, but these are particularly interesting because they are among the brightest GRBs and offer the greatest opportunity for spectral analysis across a broad energy range. GRBs can last from a few milliseconds to hundreds of seconds or longer and have a variety of temporal profiles, from single spikes to multi-episodic overlapping pulses. Single-pulse GRBs exhibit the simplest spectral evolution, providing the “cleanest” signal for fitting physical models to the data (Burgess et al. 2012, 2014; Ryde & Pe’er 2009).

In this work, we analyze six bright, single-pulse GRBs detected by Fermi (see Table 1 and Figure 1) and find correlations between the $E_p$ and $kT$ values within each of these GRBs. The GRBs in our sample are GRB 081224A (Wilson-Hodge et al. 2008), GRB 090719A (van der Horst 2009), GRB 100707A (Wilson-Hodge & Foley 2010), GRB 110721A (Tierney & von Kienlin 2011), GRB 110920A, and GRB 130427A (von Kienlin 2011). The time histories of these GRBs are shown in Figure 1, with vertical dotted lines indicating the time binning used for the analysis of the spectral evolution of each spectral component. In a previous analysis (Burgess et al. 2014), the viability of fitting relativistic Maxwellian and a high-energy power-law tail that is convolved with the standard synchrotron kernel (Burgess et al. 2012, 2014; Rybicki & Lightman 1979). We find that the characteristic energies ($E_p$ for synchrotron and $kT$ for the blackbody) of the synchrotron and blackbody components are highly correlated across all the GRBs in our sample. We show that this correlation can be used to address the key question of how the energy of the outflow is distributed, i.e., whether the energy is in a magnetic field or is imparted as kinetic energy to baryons in the jet, and how this energy distribution evolves with time.

![Figure 1](image1.png)

Figure 1. Each of the light curves in (a)–(f) shows the count rates detected by Fermi GBM for a GRB in our sample. The panels show the sodium iodide detector count rates between 8 and 300 keV. For each GRB in the sample, the time binning was selected by a Bayesian blocks algorithm (Scargle et al. 2013; Burgess et al. 2014) which operates by searching for significant changes in the count intensity. The bin selections are indicated by the vertical dotted lines.

Table 1

| GRB Name      | $\alpha$ | Jet Type     | $\mu$ | $F_{\text{BB}}/F_{\gamma}$ |
|---------------|----------|--------------|-------|-----------------------------|
| GRB 081224A   | 1.01 ± 0.14 | Baryonic     | -     | 0.29                        |
| GRB 090719A   | 2.33 ± 0.27 | Magnetic     | 0.39 ± 0.01 | 0.27                      |
| GRB 100707A   | 1.77 ± 0.07 | Magnetic     | 0.42 ± 0.01 | 0.33                      |
| GRB 110721A   | 1.24 ± 0.11 | Baryonic     | -     | 0.01                        |
| GRB 110920A   | 1.97 ± 0.11 | Magnetic     | 0.4 ± 0.01 | 0.39                       |
| GRB 130427A   | 1.02 ± 0.05 | Baryonic     | -     | 0.22                        |

Notes. The inferred jet type and blackbody ($F_{\text{BB}}$) to total flux ($F_{\gamma}$) ratios are also given. The values of $\alpha$ for the GRBs vary but are within the constraints of the model derived via our interpretation. Values of $\mu$ are listed only for those GRBs that are inferred to be magnetically dominated. No significant correlation between $\alpha$ and the flux ratios was found in the data.
with the empirical Band function (Band et al. 1993) that is the common choice for GRB spectroscopy. However, the Band function, being empirical, makes it difficult to deduce a more physical understanding. The fits with the synchrotron model provide a direct association of the observed spectrum with a physical emission mechanism and therefore the fit parameters can be used to study properties of the GRB jet without ambiguity.

All of these GRBs were shown to be consistent with a physical model containing both a synchrotron and a blackbody component. For five of those GRBs we investigate herein correlations between the previously derived $E_p$ and $kT$ values, and we add to our sample the first pulse of the ultra-bright burst, GRB 130427A, for which a similar analysis has been performed (Preece et al. 2014). GRB 130427A is the brightest GRB detected by Fermi to date. Although its temporal structure is complex (Ackermann et al. 2014), it begins with a bright single pulse that is ideal for our physical modeling, which was used to show that internal shocks cannot explain the observed emission (Preece et al. 2014). GRB 081224A, GRB 110721A, and GRB 130427A were analyzed with GBM and LAT data; the rest of the sample were analyzed with GBM data alone. While this sample is limited by the number of bright, single-pulsed GRBs in the Fermi data set, this requirement allows reliable interpretation of the fits without confusion from overlapping pulses with different underlying spectra, which is essential to measure the evolution of the thermal and non-thermal components throughout the duration of the GRB.

### 3. A CORRELATION BETWEEN SPECTRAL COMPONENTS

Figure 2 shows an example of the spectral evolution of the two separate components. A strong correlation is found between $E_p$ and $kT$, as illustrated in Figures 3 and 4. A power law of the form $E_p \propto T^\alpha$ was fit to the $E_p$, $kT$ pairs of the individual GRBs yielding values of $\alpha$ ranging from $\sim 1$ to 2 (see Table 1). The general temporal trend of both $E_p$ and $kT$ is an evolution from higher to lower energies. As can be seen from Figure 2, the evolution of the flux of each component is not necessarily tied to the change in the characteristic energies. This is very evident during the rise phase of a pulse during which the flux rises while $E_p$ and $kT$ fall with time. However, during the decay phase of the pulse, the flux decreases along with the characteristic energies. Table 1 lists the ratio of the blackbody flux to the total flux for each burst.

### 4. INTERPRETATION

To interpret these observations, we assume an emission process in which the thermal and non-thermal emission occur in close proximity to one another with the non-thermal synchrotron...
emission arising in an optically thin region above the photosphere of the jet. The range of the indices observed in the correlation suggests that the relation between the thermal and non-thermal emission varies from burst to burst. One way to achieve this is to assume that the composition of GRB outflows vary in their ratio of magnetic content from being magnetically dominated jets have their photospheres in the acceleration phase and baryonically dominated jets have their photospheres in the coasting phase.

Under these assumptions, there are two regions of interest for which we can define the radial evolution of the bulk Lorentz factor:

\[
\Gamma(r) = \begin{cases} 
(r/r_0)^\mu & \text{if } r < r_{\text{sat}} \\
\eta & \text{if } r_{\text{sat}} < r.
\end{cases}
\]

(2)

Here, \(r_{\text{sat}} = r_0\eta^{\frac{1}{2}}\) and is clearly larger when the jet is magnetically dominated. The emission of the blackbody is assumed to originate at the photospheric radius \(r_{\text{ph}}\), where the optical depth of the jet drops to unity. Following Mészáros et al. (1993), the photospheric radius is

\[
r_{\text{ph}}/r_0 = \left(\frac{L\sigma_T}{8\pi m_p c^3 r_0}\right)^\frac{1}{\eta\Gamma_{\text{ph}}^2},
\]

(3)

where \(\Gamma_{\text{ph}}\) is the Lorentz factor of the outflow at \(r_{\text{ph}}\). The value of \(\Gamma_{\text{ph}}\) depends on the magnetic content of the outflow; therefore, \(r_{\text{ph}}\) can take on two values,

\[
r_{\text{ph}}/r_0 = \eta r_0^{1/\mu} \begin{cases} 
(\eta/\eta_T)^{1/(1+2\mu)} & \text{if } \eta > \eta_T \\
(\eta/\eta_T)^3 & \text{if } \eta < \eta_T.
\end{cases}
\]

(4)

The introduction of the critical Lorentz factor,

\[
\eta_T = \left(\frac{L\sigma_T}{8\pi m_p c^3 r_0}\right)^{-\mu/(1+3\mu)},
\]

(5)

provides an important discriminator for the location of the \(r_{\text{ph}}\) relative to \(r_s\). Outflows with \(\eta = \eta_T\) have their photospheres at the saturation radius. Typical observed Lorentz factors of GRBs derived via different methods indicate values of \(\eta\) from \(\mu \approx 0.36\), but for values up to \(\mu < 0.6\) (these are the values of \(\mu\) for which the photosphere will occur in the acceleration phase) we are able to explain values of \(\alpha\) from 2 down to 1.4.

1. In the magnetic case, considering the appropriate powers of \(L\), we have \(E_p \propto T^{6(3\mu-1)/(4\mu-5)}\). The exponent is singular at \(\mu \approx 0.36\), but for values up to \(\mu < 0.6\) (these are the values of \(\mu\) for which the photosphere will occur in the acceleration phase) we are able to explain values of \(\alpha\) from 2 down to 1.4.

2. In the kinetic (baryonic) case, we have \(E_p \propto T^{1.2}\). This is observed in some GRBs.
5. DISCUSSION

The analysis of GRBs in the framework of this model can indicate whether the photosphere is in the acceleration or cooling phase, which in turn can be translated to the composition of the jet. We find that for exponents close to 2 the jet dynamics are dominated by the magnetic field while exponents close to 1 indicate baryonic jets. In our sample of six GRBs observed with Fermi, the exponents $\alpha$ of the relation between the characteristic energies of non-thermal and thermal components (Table 1) span the range of possible values, showing that energy content of GRB jets ranges from being dominated by the magnetic field to being contained mostly in the kinetic energy of baryons in the jet. A possible validation of this interpretation would be the future measurement of polarization in GRBs which will allow for the direct determination of the magnetization of GRB jets (see, for example, Lundman et al. 2013).

We note that the lack of a correlation between the ratio of the thermal flux to the total flux with the inferred magnetic content of the jet is puzzling (see Table 1). Naively, it is expected that a photosphere occurring deep in the acceleration phase of the outflow will have its thermal emission be much brighter than the non-thermal emission. A possible explanation for the weakness of the observed thermal component has been addressed by several authors (Zhang & Yan 2011; Hascoët et al. 2013). These works consider the effect of the magnetization parameter ($\sigma = (B^2/4\pi \Gamma \rho c^2)$) on the intensity of the thermal component where $\rho$ is the matter density of the outflow. For $\sigma \gg 1$, most of the jet internal energy remains in the advected magnetic field, reducing the intensity of the observed thermal component from the photosphere. Another possibility for explaining the lack of correlation of the thermal flux ratios to the different jet modes is to consider that if the non-thermal flux is due to synchrotron following reconnection events above the photosphere, the amount of reconnection may not be simply given by the amount of magnetic energy and by the radius, but may depend also on the degree of tangledness of the field at that radius. For reconnection one needs field lines of opposite polarity near each other, and if the degree of randomness is stochastic (as it probably is), this could introduce a randomness in the amount of non-thermal electrons accelerated as well as the synchrotron flux produced. However, time-dependent simulations of magnetically dominated outflows in GRBs are not advanced enough to accurately test these assumptions and therefore the reduced intensity of the thermal component is still open to interpretation.

The Fermi GBM collaboration acknowledges support for GBM development, operations, and data analysis from NASA in the U.S.A and BMWi/DLR in Germany. We also thank the anonymous referee for very useful comments that aided in refining this work.

REFERENCES

Ackermann, M., Ajello, M., Asano, K., et al. 2014, Sci, 343, 42
Atwood, W. B., Abdo, A. A., Ackermann, M., et al. 2009, ApJ, 697, 1071
Axelsson, M., Baldini, L., Barbiellini, G., et al. 2012, ApJL, 757, L31
Band, D., Matteson, J., Ford, L., et al. 1993, ApJ, 413, 281
Burgess, J. M., Preece, R. D., Baring, M. G., et al. 2012, ApJ, 741, 24
Burgess, J. M., Preece, R. D., Connaughton, V., et al. 2014, ApJ, 784, 17
Drenkhahn, G. 2002, A&A, 387, 714
Drenkhahn, G., & Spruit, H. C. 2002, A&A, 391, 1141
Fan, Y.-Z., Wei, D.-M., Zhang, F.-W., & Zhang, B.-B. 2012, ApJL, 755, L6
Fenimore, E., Klebesadel, R. W., Laros, J. G., Stockdale, R. E., & Kane, S. R. 1982, Natur, 297, 665
Ghirlanda, G., Pescalli, A., & Ghisellini, G. 2013, MNRAS, 432, 2327
Goldstein, A., Burgess, J. M., Preece, R. D., et al. 2012, ApJS, 199, 19
Goodman, J. 1986, ApJL, 308, L47
Guiriec, S., Connaughton, V., Briggs, M. S., et al. 2010, ApJL, 727, L33
Guiriec, S., Daigne, F., Hascoët, R., et al. 2013, ApJ, 770, 32
Hascoët, R., Daigne, F., & Mochkovitch, R. 2013, A&A, 551, A124
Iyyani, S., Ryde, F., Axelsson, M., et al. 2013, MNRAS, 433, 2739
Kaneko, Y., Preece, R. D., Briggs, M. S., et al. 2006, ApJS, 166, 298
Kirk, J. G., & Skjærbaek, O. 2003, ApJ, 591, 366
Lazzati, D., Morsony, B. J., & Begelman, M. C. 2011, ApJ, 732, 34
Lithwick, Y., & Sari, R. 2001, ApJ, 555, 540
Lundman, C., Pe’er, A., & Ryde, F. 2013, MNRAS, 428, 2430
Matz, S., Forrest, D. J., Vestrand, W. T., et al. 1985, ApJL, 288, L37
Mazets, E., Golenetskii, S. V., Aptekar, R. L., Gurian, Iu. A., & Ilinskii, V. N. 1981, Natur, 290, 378
McKinney, J. C., & Uzdensky, D. A. 2012, MNRAS, 419, 573
Meeegan, C., Lichti, Giselher, Bhat, P. N., et al. 2009, ApJ, 702, 791
Mészáros, P. 2006, RPPh, 69, 2259
Mészáros, P., Laguna, P., & Rees, M. J. 1993, ApJ, 415, 181
Mészáros, P., & Rees, M. J. 2011, ApJL, 733, L40
Paczynski, B. 1986, ApJL, 308, L43
Pe’er, A., Ryde, F., Wijers, R. A. M. J., Mészáros, P., & Rees, M. J. 2007, ApJL, 667, L1
Preece, R. D., Burgess, J. M., von Kienlin, A., et al. 2014, Sci, 343, 51
Rybicki, M. J., & Lightman, A. 1979, Radiative Processes in Astrophysics (New York: Wiley)
Scargle, J., Norris, J., Jackson, B., & Chiang, J. 2013, ApJ, 764, 167
Thompson, C., Mészáros, P., & Rees, M. J. 2007, ApJL, 666, 1012
von der Horst, A. 2009, GCN Circ., 9693
Veres, P., Zhang, B. B., & Mészáros, P. 2013, ApJL, 764, 94
von Kienlin, A. 2013, GCN Circ., 14473
Wilson-Hodge, C., Connaughton, V., Longo, F., & Omodei, N. 2008, GCN Circ., 8723
Wilson-Hodge, C., Foley, S., et al. 2010, GCN Circ., 10944
Wilson-Hodge, C., Connaughton, V., Longo, F., & Omodei, N. 2008, GCN Circ., 8723
Zhang, B., & Yan, H. 2011, ApJL, 726, 1121
Zhang, B.-B., Zhang, B., Liang, E.-W., et al. 2011, ApJ, 730, 141
Zhang, B., Yan, H. 2011, ApJL, 733, L40
Zhang, B.-B., Zhang, B., Liang, E.-W., et al. 2011, ApJ, 730, 141