A NEW METHOD OF DETERMINING THE INITIAL SIZE AND LORENTZ FACTOR OF GAMMA-RAY BURST FIREBALLS USING A THERMAL EMISSION COMPONENT

Asaf Pe’er\textsuperscript{1}, Felix Ryde\textsuperscript{2}, Ralph A.M.J. Wijers\textsuperscript{3}, Peter Mészáros\textsuperscript{3} and Martin J. Rees\textsuperscript{4}

Draft version March 29, 2007

ABSTRACT

In recent years there is increasing evidence for a thermal component in the \(\gamma\)- and X-ray spectrum of the prompt emission phase in gamma-ray bursts. The temperature and flux of the thermal component show a characteristic break in the temporal behavior after few seconds. We show here, that measurements of the temperature and flux of the thermal component at early times (before the break) allow the determination of the values of two of the least restricted fireball model parameters: the size at the base of the flow and the outflow bulk Lorentz factor. Relying on the thermal emission component only, this measurement is insensitive to the inherent uncertainties of previous estimates of the bulk motion Lorentz factor. We give specific examples of the use of this method: for GRB970828 at redshift \(z = 0.9578\), we show that the physical size at the base of the flow is \(r_0 = (3.3 \pm 2.1) \times 10^8\) cm and the Lorentz factor of the flow is \(\Gamma = 305 \pm 28\), and for GRB990510 at \(z = 1.619\), \(r_0 = (1.9 \pm 2.0) \times 10^8\) cm and \(\Gamma = 384 \pm 71\).

Subject headings: gamma rays: bursts — gamma rays: theory — plasmas — radiation mechanisms: non-thermal — radiation mechanisms: thermal

1. INTRODUCTION

In recent years there is increasing evidence that, during the first stages of the prompt emission of long duration gamma-ray bursts (GRBs), a thermal component accompanies the underlying non-thermal emission \cite{ryde04, ryde05, campana06}; see also \cite{ghirlanda03, kaneko03}. An analysis of BATSE bursts that are dominated by quasi-thermal emission \cite{ryde04, ryde05} showed that the observed temperature exhibits a similar behavior in all of them: an initially (approximately) constant temperature at a canonical value \(T_\text{obs} \approx 100\) keV which after \(\sim 1 - 3\) seconds decreases as a power law in time \(T_\text{obs} \propto t^{-\alpha}\), with power law index \(\alpha \approx 0.6 - 1.1\). The redshifts of most of these bursts are unknown. An additional analysis \cite{ryde07} shows that a short rise, the flux of the black body component of these bursts also decreases with time as \(F_\text{BB} \propto t^{-\beta}\), with \(\beta \approx 2.0 - 2.5\). We showed \cite{ryde07} that this temporal behavior can be explained as due to the high latitude emission phenomenon \cite{fennimore96, granot99, oj02}.

According to the standard fireball scenario, the non-thermal photons originate from dissipation of the fireball kinetic energy. The dissipation mechanism (e.g., internal shocks \cite{paczynski94, rees94}, magnetic reconnection \cite{giannios05, giannios06} or external shocks \cite{meszaros93, dermer99}) is yet uncertain, and can in principle occur at various locations. As opposed to this ambiguity in understanding the origin of the non-thermal component, the thermal component must originate at the photosphere. According to the high latitude emission interpretation of the data, the highest temperature and the maximal thermal flux initially observed are emitted from the photosphere on the radial axis towards the observer. Thus, in principle the radius of the emission site of these photons can be determined.

In this Letter we show that combined early time measurements of the observed temperature and thermal flux for bursts with known redshift allow us to directly determine the values of the bulk motion Lorentz factor, the physical size at the base of the flow and the photospheric radius. This is due to the fact that the observed temperature and flux of the thermal component depend on three internal parameters only: the isotropic equivalent luminosity of the thermal component \(L_\text{BB}\), the Lorentz factor of the bulk motion of the flow at the photospheric radius \(\eta\) and the physical size at the base of the flow \(r_0\), and that \(L_\text{BB}\) can be directly measured for bursts with known redshift and measured thermal flux. In \textsection 2 we give a short description of the model, and implications are given in \textsection 3. In \textsection 4 we summarize and compare our results to previous methods of estimates of the bulk motion Lorentz factor.

2. MODEL: EXTENDED PHOTOSPERIC EMISSION

In the classical fireball model of gamma-ray bursts \cite{goodman86, paczynski86, paczynski94}, a thermal plasma of electrons, positrons and photons expands rapidly from an initial radius \(r_0\). Conservation of energy and entropy imply that the bulk Lorentz factor of the flow increases as \(\Gamma(r) \propto r\), until the plasma reaches the saturation radius \(r_s = \eta r_0\), above which the plasma Lorentz factor coasts with \(\Gamma = \eta = \lim_{r \rightarrow \infty} \Gamma\). Here, \(L\) is the isotropic equivalent luminosity of the burst, \(M\) is the mass ejection rate and \(c\) is the speed of light (from here on we restrict the discussion to long bursts, characterized by extended emission of relativistic
The photospheric radius $r_{ph}$ is the radius above which the flow becomes optically thin to scattering by the baryon related electrons. Depending on the values of the free model parameters ($\eta$, $L$ and $r_0$) this radius can be smaller or larger than $r_s$ \cite{Meszaros2002}: for $\eta > (\leq) \eta_0 \equiv (L/4\pi r_0^2 c r_0)^{1/4}$, $r_{ph} < (>) r_s$. Here, $\sigma_T$ is Thomson cross section and $m_p$ is the proton mass. In the expression for $\eta$, the luminosity $L$ is directly measured for bursts with known redshift, $L = 4\pi d_L^2 F^{ob}$, where $d_L$ is the luminosity distance and $F^{ob}$ is the total (thermal + non thermal) observed flux. As we show below, the measurement of $r_0$ is similar in both scenarios considered, $r_{ph} > (\leq) r_s$. Thus, it is possible to determine whether $r_{ph}$ is below or above $r_s$ from measurable quantities, and to determine $\eta$ in the second case.

The thermal component originates from the photosphere of an expanding plasma jet. The observed thermal flux (integrated over all frequencies) is given by integrating the intensity over the emitting surface, $F_{BB}^{ob} = (2\pi/d_L^2) \int d\mu \mu \sigma_T d'^4(\sigma_T d'^4/\pi)$. Here, $T'$ is the comoving temperature at the photospheric radius, $\sigma$ is Stefan’s constant and $D = D(\theta)$ is the Doppler factor, $D = [1 - (1 - \beta^2)]^{1/2}$. The angle $\theta$ is the angle between the direction of the outflow velocity vector ($\beta$) and the line of sight, $\mu \equiv \cos(\theta)$, and $\Gamma = (1 - \beta^2)^{-1/2}$ is the outflow Lorentz factor. For plasma Lorentz factor much larger than the jet opening angle $\Gamma \gg \beta$, and for early enough times, at a given observed time the integration boundaries are determined uniquely by the emission duration, regardless of the value of $\beta$.

Due to the Doppler effect and to the cosmological redshift, photons that are emitted at frequency $\nu'$ in the comoving frame of a relativistically expanding plasma with Lorentz factor $\Gamma$ at redshift $z$, are observed at frequency $\nu^{ob} = D(\theta)\nu'/(1 + z)$. For $\Gamma \gg 1$ and emission on the line of sight, $\nu^{ob} \approx 2\Gamma \nu'/(1 + z)$. In the extended emission interpretation of the data \cite{RydePe'er2007}, an observer sees simultaneously photons that originate from a range of angles, $\theta_{max} \leq \theta \leq \theta_{min}$ ($\theta$ is the angle to the line of sight). In this case, a thermal spectrum (with temperature $T'$) in the comoving frame is observed as a modified black-body spectrum. Nonetheless, as showed in Pe'er \cite{Pe'er2007}, the observed spectrum is very similar to a pure black-body spectrum.

At the first few seconds, when the observed temperature is nearly constant, the observed radiation is dominated by photons emitted close to the line of sight, i.e., $\theta_{min} = 0$. According to this interpretation, the break time that occurs in the temperature’s temporal behavior after a few seconds marks the end of the first episode of significant inner engine activity, afterward emission is dominated by high latitude effects. Before the break, the observed spectrum is very close to a black body spectrum with temperature $T^{ob} \approx 1.45 \Gamma T'/(1 + z)$ \cite{Pe'er2007}.\footnote{The relation between $T^{ob}$ and $T'$ is often written in the literature as $T^{ob} \approx T'/(1 + z)$. In fact, $D(\theta) = 1 \approx 2\Gamma$, thus one should add an extra factor of 2. The factor 1.45 used here results from the angular integration. See Pe'er \cite{Pe'er2007} for details.}

During this period, the upper integration boundary in the equation for the thermal flux is $\mu_{max} = \cos(\theta_{min}) = 1$, and the ratio $F_{BB}^{ob}/\sigma_T^{ob}$ is 1/2 which we denote as $R$, is equal to

\[
R \equiv \left( \frac{F_{BB}^{ob}}{\sigma_T^{ob}} \right)^{1/2} = (1.06) \left( 1 + z \right)^2 \frac{r_{ph}}{d_L} \Gamma. \tag{1}
\]

The prefactor (1.06) originates from the dependence of the photospheric radius on the angle to the line of sight \cite{Pe'er2007}.

We can now make the discrimination between the two possible cases: $r_{ph} < (>) r_s$. If $r_{ph} < r_s$, then $\Gamma(r) \propto r$. In this case, $r_{ph}/r_0$, and equation 1 becomes

\[
r_0(r_{ph} < r_s) = \frac{1}{(1.06)} \left( 1 + z \right)^2 R. \tag{2}
\]

In this case, it is not possible to determine the photospheric radius, or the value of $\Gamma(r_{ph})$.

In the case $r_{ph} > r_s$, the photospheric radius is given by $r_{ph} = (L/8\pi \eta^3 m_e c^3)$ \cite{Meszaros2002,DaigneMoChkovitch2002,BrodieRiek2003}. At this radius, the comoving temperature is given by

\[
T'(r_{ph}) = \left( \frac{L}{4\pi \sigma_T c^4 \alpha} \right)^{1/4} \eta^{-1} \left( \frac{r_{ph}}{r_s} \right)^{-2/3}. \tag{3}
\]

Equations 1, 3 and 4 now give the physical size at the base of the flow,

\[
r_0(r_{ph} > r_s) = \frac{4^{3/2}}{(1.45)^6(1.06)^4} \left( 1 + z \right)^2 \left( \frac{F_{BB}^{ob}}{F^{ob}} \right)^{3/2} \frac{d_L}{R}. \tag{5}
\]

We thus find that a measurement of $R$ and the ratio of the black body flux to the total flux at the very early observed times from bursts with known redshift give a direct measurement of $r_0$, and that the result is similar (up to a numerical factor of the order unity), for the two considered cases, $r_{ph} < (>) r_s$. The measured values of $r_0$ and $L$ can be used to determine the value of $\eta$, which is independent on the specific scenario. One can then use the measured values of $R$ and $F_{BB}^{ob}$ to determine the value of $\eta$ using equation 3. If the obtained value is larger than the value of $\eta_s$, then $r_{ph} < r_s$, in which case equation 4 should not be used and the value of $\eta$ remains undetermined.

3. IMPLICATIONS

Relations 4 and 5 allow a direct measurement of the size at the base of the flow, $r_0$ and of the bulk motion Lorentz factor of the flow from GRBs with known redshift. In addition, it is possible to determine the photospheric radius $r_{ph}$ and the saturation radius $r_s$, if measurements of the thermal flux and temperature are available at early enough times.

We illustrate the use of this method on two bursts with known redshifts, namely GRB970828 and GRB990510 observed by the BATSE detectors aboard the Compton Gamma Ray Observatory. BATSE detected bursts in the
Parameters determination using thermal component

20 keV – 2 MeV energy range. The time-resolved spectra for the selected bursts were fitted using a Planck function and a single power-law to model the photospheric and the non-thermal emission components, following the method presented in Ryde (2004) (see also Ryde & Pe'er 2007).

The analysis of the thermal component of GRB970828 is presented in figures 1. This burst, at redshift $z = 0.9578$, had a good temporal coverage for the first 100 seconds. The left hand panel in Figure 1 shows the temporal behavior of the temperature of the thermal component. During the first $\sim 8$ seconds the observed temperature slightly rises to a value of 78.5 keV, after which it shows a rapid decrease that can be fitted as a power law in time with power law index $\alpha = -0.51$. In the right hand panel of Figure 1 we show the temporal behavior of the function $R$. This function shows a slight increase during the first $\sim 7$ seconds, after which it rises as power law in time with power law index $\beta = 0.67$. The smooth increase of $R$ before the break implies that there is no significant energy dissipation below the photosphere, which, if occurred would result in a strong fluctuation and affect the smoothness of $R$. The break times in the temporal behavior of the observed temperature and $R$ (of thermal flux) are the same within the errors.

According to the extended high latitude emission interpretation of this result (Ryde & Pe'er 2007), we deduce that the first episode of significant inner engine activity took place during the first $7 \sim 8$ seconds, and at later times we are observing photons emitted off axis (we neglect here late time episodes of engine activities that occur after $\sim 25$ s and $\sim 60$ s in this burst). The values of $r_0$ and $\eta$ are calculated using the observed values of the temperature $T^{ob} = 78.5 \pm 4.0$ keV, $R = (1.88 \pm 0.28) \times 10^{-19}$, and the ratio of thermal to total flux $F^{ob}_{BB}/F^{ob} = 0.64 \pm 0.20$ at the break time. The error bars on the measured quantities are averaged over the first seconds, before the temporal break. Considering a flat universe with $\Omega\Lambda = 0.73$, $H_0 = 71$ km/s/Mpc, the luminosity distance for this burst is $d_L = 1.94 \times 10^{28}$ cm. Using equations 2 and 5 we find that $r_0 = (3.3 \pm 2.1) \times 10^{18}$ cm and the Lorentz factor of the flow is $\Gamma = 305 \pm 28$. In this calculation we assume that the observed $(\text{thermal} + \text{non thermal})$ luminosity is equal to the total luminosity of this burst. The calculated value of $\eta_* = 463$ for this burst proves that indeed $r_{ph} = 2.7 \times 10^{11}$ cm is larger than $r_s = 1.0 \times 10^{11}$ cm, which thus imply that $\eta = \Gamma = 305$ is the coasting value of the outflow Lorentz factor of this burst. The error presented here, $\lesssim 10\%$ on the value of $\eta_*$ is the best constraint on the estimated value of this parameter measured so far.

A similar analysis was carried out for GRB990510 at $z = 1.619$. The obtained results are similar, $r_0 = (1.9 \pm 2.0) \times 10^{28}$ cm and $\eta = 384 \pm 71$. For this burst, the larger statistical errors compared to GRB970828 mainly reflect the fewer available data points. The value of $\eta_* = 830$ measured for this burst proves that indeed the photospheric radius $r_{ph} = 7.7 \times 10^{11}$ cm is larger than the saturation radius, $r_s = 7.1 \times 10^{10}$ cm, in this burst. The temporal behavior of the observed temperature and $R$ was found to be similar in a large sample of BATSE bursts, providing further evidence for our model. However, the redshift of most of these bursts is unknown, thus definite values of $\eta$ and $r_0$ could not be obtained. The full sample appears in Ryde & Pe'er (2007).

4. DISCUSSION

In this Letter we showed that by measuring the observed temperature and thermal flux of the thermal component that accompanies the prompt emission of GRBs, it is possible to determine the values of two of the least restricted parameters of the fireball model: the size at the base of the flow and the outflow bulk Lorentz factor (in the case that the photospheric radius is larger than the saturation radius). In this case, it is also possible to determine the saturation radius $r_s$ and the photospheric radius $r_{ph}$. We showed that the calculation of the initial size of the flow (equations 2, 3) is similar (up to a constant of the order unity) for the cases $r_{ph} > (<) r_s$. This allows a comparison between the measured value of $\eta$ (equation 4) and the derived value of $\eta_*$, and a discrimination between the two cases. We have given examples of the use of this method in determination of $\eta$ and $r_0$ for specific GRBs. A more comprehensive analysis of bursts with known redshift is given in Ryde & Pe'er (2007).

Other methods of estimating the bulk motion Lorentz factor in GRBs relied on a large number of uncertain model assumptions and uncertainties in the values of the free model parameters. A widely used lower limit for $\eta$ is obtained by calculating the minimum Lorentz factor required in order for the observed energetic photons not to annihilate (Krolik & Pier 1991; Fenimore, Epstein & Ho 1993; Woods & Loeb 1995; Baring & Harding 1993; Lithwick & Sari 2001). In addition to providing only a lower limit, in order to get a good estimate of $\eta_{min}$ a wide spectral coverage of the GRB emission, from the optic band to the $\gamma$-rays is required. In many cases, a simple broken power law spectrum is assumed in the calculation (e.g., Lithwick & Sari 2001), an assumption which may be too simplified for the prompt emission spectrum (e.g., Pe'er & Waxman 2004).

An alternative method to estimate the Lorentz factor is by modeling the early afterglow emission, under the assumption that the optical flash observed in few cases results from synchrotron emission by electrons heated by the reverse shock (Sari & Piran 1999). A serious drawback of this method is that the estimate relies on the poorly known shock microphysics parameters (such as $\epsilon_e$, $\epsilon_B$ etc.). A more advanced method, introduced by Zhang, Kobayashi & Mészáros (2003), relies on com-
paring the emission from the forward and reverse shock during the early afterglow. An underlying assumption in this estimate is that the values of the microphysics parameters at the forward and the reverse shocks are similar. Other methods rely on measurements of the physical parameters during the late afterglow emission, assuming that the flow expands in a self-similar manner during this phase. The initial value of the Lorentz factor is deduced by measuring the rise time of the early afterglow (Sari 1999; Soderberg & Ramirez-Ruiz 2002; Kobayashi & Zhang 2003). An inherent drawback of this method is the assumption that the microphysical parameters are constant in time during the late afterglow.

The method presented here of estimating $\eta$ is independent on any of the uncertainties inherent to the former methods. Moreover, it gives a direct measurement of $\eta$, rather than lower limit. The results presented in (see also Ryde & Pe’er 2007) indicate values of $\eta$ close to the earlier estimates. In addition, the values found for the size at the base of the flow $r_0$ could further constrain GRB progenitor models. The statistical errors on the values of these numbers are much smaller than any previous estimates.

These facts have several important consequences. First, they strengthen the interpretation of the prompt emission as being composed of a thermal component, in addition to the non-thermal component. Therefore, any interpretation of the prompt emission data must take this thermal component into account. Second, it shows that the extended high latitude emission interpretation of the late time temporal behavior of the thermal component is consistent with the fireball model predictions. Thus, this interpretation may also be used to understand the strong X-ray flares observed by the SWIFT satellite. Third, the consistency found between the different methods for estimating the value of the bulk motion Lorentz factor $\eta$ can be used to strengthen the validity of the underlying assumptions in previous estimates of $\eta$, such that the values of the microphysical parameters ($\epsilon_e$, $\epsilon_B$, etc.) are indeed constant in time during the afterglow emission phase. This is an important observational fact needed to be considered in models that attempt to derive the values of the microphysical parameters from first principles (Silva et al. 2003; Frederiksen et al. 2004). And last, the direct measurement of the physical size at the base of the flow is another, independent indication that a massive star is indeed the progenitor of long duration GRBs. Since $\eta$ is related to the mass ejection rate, our measurements could be useful to constrain models of GRB progenitors.

This research was supported by NWO grant 639.043.302 to R.W. and by the EU under RTN grant HPRN-CT-2002-00294. F.R. acknowledge the support by the Swedish National Space Board. P.M. wishes to acknowledge the support by NASA NAG5-12826 and NSF AST0307376. This research made use of data obtained through the HEASARC Online Service provided by the NASA Goddard Space Flight Center. F.R. wishes to express his gratitude to the Department of Astronomy at Amsterdam University for their hospitality.

REFERENCES

Giannios, D. A&A 457, 763
Giannios, D., & Spruit, H.C. A&A 430, 1
Kaneko, Y., Preece, R.D., & Briggs, M.S. 2003, AAS meeting, 203, 80.04
Pe’er, A. 2007, (in preparation)
Ryde, F., & Pe’er, A. 2007, in preparation