HOW UNUSUAL IS XRF 060218?

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ABSTRACT

Light curves are calculated for an off-axis observer due to the scattering of primary radiation by extended baryonic material. The unusually long duration and the chromaticity of the light curves above several keV of XRF 060218 can be explained as a result of the acceleration of the baryonic scattering material by the primary radiation. The observed light curves by our model and detailed fits to the data are presented. The model predicts that the peak photon energy is usually shown as a plot of GRB spectral peak energy $E_{\text{peak}}$, on the y-axis, as a function of isotropic equivalent energy $E_{\text{iso}}$. This can be understood as being due to the observer’s line of sight being offset relative to the direction of motion of the material at which the emission or last scattering took place (Eichler & Levinson 2004; Yamazaki et al. 2004). However, the absence of GRBs below the “edge”—defined by the Amati relation to be $E_{\text{peak}} \sim [E_{\text{iso}}/10^{54} \text{ erg}]^{1/2} \text{ MeV}$—is curious. For it states that the isotropic equivalent photon number in a GRB decreases in proportion to the peak photon energy. It thus strongly constrains the scattering of primary photons in any process within a GRB fireball that reduces photon energy without decreasing the number of photons, e.g., adiabatic losses of photons emitted in an optically thick region. Similarly, it constrains the photon number emitted in a GRB having a given spectral peak, e.g., the number of energetic particles emitting in an optically thin region in a given magnetic field.

That the lower right side of the Amati graph is free of any GRB of known redshift is particularly remarkable considering that it represents the brightest GRBs at a given spectral peak. It suggests that there is no such thing as a “slightly compromised” GRB whose photons are softened without being lost, e.g., as in a dirty fireball. In this Letter, however, we suggest that the X-ray flash (XRF) 060218 is a dirty fireball. We note that, unlike most XRFs, the low-energy component has, despite its much softer spectrum, a similar photon number to classical GRBs, as opposed to most XRFs, which have far fewer photons. XRF 060218 was detected with the Burst Alert Telescope (BAT) instrument on board the Swift spacecraft. The spectrum peaks below 10 keV, thus classifying this transient as an XRF. XRF 060218 is distinguished by its unprecedentedly long duration (∼2000 s) with a smooth light curve. The light curves show a significant spectral lag, with soft photons lagging behind the hard photons, as usually seen in long GRBs (Norris et al. 2000).

The peaks of the light curves are at 405 ± 25, 735 ± 9, 919 ± 7, and 1082 ± 13 s (Liang et al. 2006) in energy bands 15–150 keV, 5–10 keV, 2–5 keV, and 0.3–2 keV, respectively. The X-ray Telescope (XRT) spectrum (0.3–10 keV) shows a thermal component in soft X-ray with temperature $K_T \approx 0.17 \text{ keV}$ (Campana et al. 2006). The high-energy spectra (15–150 keV) from BAT show spectral softening with time.

The unusually long duration of this event raises the question of whether the central engine goes on this long, or whether the duration represents something downstream of the central engine, e.g., shock breakout through the surface of the star or a light echo from slowly moving, extended material. The chromaticity of the duration of the event and the location of the peak is significant. It challenges breakout and light echo models, in which the duration is established by hydrodynamics. We focus on this issue. We propose that the radiation pressure of the photons on the matter can accelerate it up to relativistic Lorentz factors, which makes the duration appear longer than the actual activity of the central engine. We show that the intrinsic duration of central engine activity need not be pathologically long for an XRF, but appears longer because of the relativistic motion of the scatterer. We also show that the apparent duration is expected to be wavelength dependent, and we fit the observed light curves.

1. INTRODUCTION

Nearly all known gamma-ray bursts (GRBs) with known redshift lie either on or to one side of the Amati relation, which is usually shown as a plot of GRB spectral peak energy $E_{\text{peak}}$ on the y-axis, as a function of isotropic equivalent energy $E_{\text{iso}}$. This can be understood as being due to the observer’s line of sight being offset relative to the direction of motion of the material at which the emission or last scattering took place (Eichler & Levinson 2004; Yamazaki et al. 2004). However, the absence of GRBs below the “edge”—defined by the Amati relation to be $E_{\text{peak}} \sim [E_{\text{iso}}/10^{54} \text{ erg}]^{1/2} \text{ MeV}$—is curious. For it states that the isotropic equivalent photon number in a GRB decreases in proportion to the peak photon energy. It thus strongly constrains scatter in the extent of any process within a GRB fireball that reduces photon energy without decreasing the number of photons, e.g., adiabatic losses of photons emitted in an optically thick region. Similarly, it constrains scatter in the number of photons emitted in a GRB having a given spectral peak, e.g., the number of energetic particles emitting in an optically thin region in a given magnetic field.

That the lower right side of the Amati graph is free of any GRB of known redshift is particularly remarkable considering that it represents the brightest GRBs at a given spectral peak. It suggests that there is no such thing as a “slightly compromised” GRB whose photons are softened without being lost, e.g., as in a dirty fireball. In this Letter, however, we suggest that the X-ray flash (XRF) 060218 is a dirty fireball. We note that, unlike most XRFs, the low-energy component has, despite its much softer spectrum, a similar photon number to classical GRBs, as opposed to most XRFs, which have far fewer photons.

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The unusually long duration of this event raises the question of whether the central engine goes on this long, or whether the duration represents something downstream of the central engine, e.g., shock breakout through the surface of the star or a light echo from slowly moving, extended material. The chromaticity of the duration of the event and the location of the peak is significant. It challenges breakout and light echo models, in which the duration is established by hydrodynamics. We focus on this issue. We propose that the radiation pressure of the photons on the matter can accelerate it up to relativistic Lorentz factors, which makes the duration appear longer than the actual activity of the central engine. We show that the intrinsic duration of central engine activity need not be pathologically long for an XRF, but appears longer because of the relativistic motion of the scatterer. We also show that the apparent duration is expected to be wavelength dependent, and we fit the observed light curves.

2. THE MODEL

We assume that the primary radiation is scattered by an extended baryonic cloud of optical depth unity and that the scattered radiation is seen by an observer at an angle $\theta$ with the motion of the scatterer (Figure 1). The entire scattering cloud is within the cone of the primary hard radiation, and the observer sees the hard radiation due to scattering from the cloud whereas the extended soft component may also reach the observer directly (see below).

The scatterer itself is offset from the axis of the primary radiation and scatters only the soft fringes of the primary photon jet. The off-axis observer sees a fast rise, slow decay light curve due to acceleration of the scattering baryons by the primary radiation pressure which causes the beam of the
scattered radiation to narrow, intensify (the rise), and finally narrow down to below the offset angle (the decay). We have calculated the light curve for different energy bands following Eichler & Manis (2007). It produces an energy-dependent delay in the light curve because, for the same primary photon energy, the observer sees a photon energy that decreases with time due to the acceleration of the scatterer (Eichler & Manis 2008). In reality the scatterer can be an extended one. This may prolong the light curve at all photon energies (i.e., create a light echo) as the contribution from the closer part of the cloud is less delayed than that from the furthest part of the cloud.

We have calculated the light curves by assuming the primary photon spectrum to be a broken power law, i.e.,

\[ N(E) = \begin{cases} E^{\alpha}, & E < \xi \\ E^{\beta}, & E > \xi \end{cases} \]

where \( E \) is the photon energy. We have taken the low-energy photon index \( \alpha = -0.9 \) with a break at \( \xi = 9 \) keV and the high-energy index \( \beta = -2.2 \) to explain the light curves of XRF 060218. This is much softer than assumed in previous papers, and the assumption is that the primary radiation is that of an XRF. The picture is that the scattering material itself is off the GRB jet axis, and sees an XRF, which then further scatters into the line of sight of the observer. The duration of the primary radiation, as seen by the scatterer, may then be itself prolonged by kinematical effects relative to the actual duration of activity of the central engine. Moreover, the primary emission may contain in part an intrinsically longer event such as shock breakout from the surface of the host star, or a “dirty fireball,” either of which would be emitted over a larger angle than that of a baryon-poor inner jet.

The primary source isotropic luminosity is taken to be \( 1.2 \times 10^{47} \) erg s\(^{-1} \) (Liang et al. 2006). The luminosity of the source starts to decay exponentially after 400 s with a decay constant 300 s. The overall duration of the source activity is 590 s which corresponds to 2500 s in the observer frame. We assume that the baryonic cloud is moving radially within the primary radiation cone with an initial radial expansion speed \( \beta = 0.5 \) and the center of the cloud makes an angle \( \theta = 20^\circ \) with respect to the observer. We have considered an extended scattering cloud of diameter 400 lt-s which, at an initial distance of \( 2 \times 10^{15} \) cm from the source, makes an opening angle 16:6, so that the closest point of the scatterer moves in a direction 3:4 off the line of sight. All the primary radiation that hits the cloud is assumed to have been scattered isotropically in the frame of the cloud by the time it exits. In Figure 2, we plot the observational data (histograms) with the model light curves (solid lines) from the scattered primary emission, illustrated by the blue cone in Figure 1. The red, green, blue, and magenta colors represent the data in energy bands 0.3–2 keV, 2–5 keV, 5–10 keV, and 15–150 keV, respectively; for parameters see the text. The observational data have been taken from Liang et al. (2006). The velocity \( \beta \) (vertical axis right to the graph) of the scatterer is plotted by the dashed line (black color). This indicates that the long duration is due to the acceleration of the scatterer by the primary radiation.

In subsequent figures, we explore the dependence of different parameters of the model on the resulting light curve. We compare the light curves in two different energy bands (2–5 keV) and (15–150 keV) by changing the model parameters. In Figures 3–5, we use red and magenta lines to represent the light curves in 2–5 keV and 15–150 keV energy bands, respectively, with the same set of parameters as in Figure 2. Also the green and blue lines in Figures 3–5 represent the light curves in 2–5 keV and 15–150 keV energy bands, respectively, but with a change of one parameter from Figure 2. Figure 3 shows the light curves for observing angles \( \theta = 20^\circ \) (red and magenta) and \( \theta = 25^\circ \) (green and blue). Clearly, as the observing angle increases the pulses rise, peak, and decay faster, and the observed flux decreases.

The light curve profile is sensitive to the nature of the assumed primary spectrum. The relative contributions between the pulses of different energy bands are sensitive to both the low-energy index \( \alpha \) and the high-energy power-law index \( \beta \) of the primary spectrum. Figure 4 shows that as the low-energy index decreases from \( \alpha = -0.9 \) (red and magenta) to \( \alpha = -1.1 \) (green and blue), the low-energy flux decreases and the pulse peak shifts to an earlier time and decays more rapidly. This change in the low-energy index will decrease the normalization at the break energy (\( \xi = 9 \) keV) and so the flux of the high-energy pulse also decreases. Figure 5 shows the effect of high-energy index \( \beta \) on the light curve as it increases from \( \beta = -2.2 \) (red
Figure 3. Comparison between the light curves for observing angles $\theta = 20^\circ$ (red and magenta) and $\theta = 25^\circ$ (green and blue). (A color version of this figure is available in the online journal.)

Figure 4. Light curves from a broken power-law primary spectrum with different values of low-energy indexes $\alpha = -0.9$ (red and magenta) and $\alpha = -1.1$ (green and blue). (A color version of this figure is available in the online journal.)

Figure 5. Light curves from a broken power-law primary spectrum with different values of high-energy indexes $\beta = -2.2$ (red and magenta) and $\beta = -2.0$ (green and blue). (A color version of this figure is available in the online journal.)

and magenta) to $\beta = -2.0$ (green and blue). The high-energy index $\beta$ has almost the same effect as $\alpha$ on the light curve in the high-energy band, but the low-energy light curve is not sensitive to $\beta$. As before, the low-energy pulses are unaffected by changing $\xi$ to high energy since the break energy is well above the low-energy band. But the high-energy contribution decreases as $\xi$ increases since it reduces the high-energy band.

The overall amount of kinetic energy imparted to the cloud for the above choice of parameters is $3.8 \times 10^{48}$ erg. This is in good agreement with the value estimated from radio afterglow calorimetry (Soderberg et al. 2004), provided that there is no other component of blast energy. Perhaps most baryon kinetic energy, then, is from entrained baryons that have been accelerated by an otherwise baryon poor jet. There could be significant scatter in the extent of such entrainment, and the small value for kinetic energy obtained from this very close XRF, relative to cosmologically distant GRBs, may simply be due to selection of brighter afterglows for the more distant events. The same selection may of course apply to prompt emission, as nearby XRFs and GRBs are generally underluminous relative to distant ones.

3. CONCLUDING REMARKS

We have accounted for both the chromaticity of the light curve of GRB 060218/SN2006aj component and the exceptionally long duration (relative to most GRBs and XRFs), as being a result of our seeing the photons after they have scattered off baryonic material (e.g., wind material) that is accelerated by the radiation pressure of primary protons. The scatterer may lie at the periphery of the primary jet of photons. These assumptions are quite reasonable: one would expect material blown out of the path of the primary GRB emission to be found at the periphery of the latter. An optical depth of order unity at a distance of order $10^{13.5}$ cm, which we have tacitly assumed in order to match the amount of scattered radiation with the observed fluence, is somewhat high for a typical Wolf–Rayet wind, but, just prior to an SN, the optical depth of the wind could be atypically high. Moreover, if the material includes matter from the body of the progenitor itself that is ejected in the early stages of, or just prior to the GRB/SN, then large transverse gradients are expected near the periphery of the jet, and one expects some region to be of optical depth of order unity. Even if the optical depth is greater than unity, the photons can nevertheless escape by reflecting into the backward hemisphere. Once the matter is accelerated to relativistic velocities, it is mostly beamed forward even if it reflects back into the backward hemisphere in the frame of the scattering material. While there are many parameters in the model, it should be recalled that there are several nearby
GRB-SN associations, each with different high-energy emission properties, and we suggest that the differences can be accounted for by variations in the parameters of the scattering material.

Because we have used a very soft X-ray spectrum, we conclude that our model may be spectrally consistent with a breakout shock from the SN together with a GRB. However, the total isotropic equivalent energy, $\sim 6 \times 10^{49}$ erg, is probably too high for a breakout shock from the envelope, and may instead be powered by a GRB within.

The preferred alternative to a breakout shock is that the soft component is the emission of a dirty fireball, as it contains the isotropic equivalent of nearly $10^{59}$ photons, close to that of a typical GRB, which peaks at a much higher energy. The KeV photons that dominate the total emitted energy can be interpreted as GRB photons that have been adiabatically decelerated while being trapped in the baryons.

That the peak energy is so far below that of a typical GRB is curious. It still leaves open the question of why there are still no examples of GRBs in the lower right of the Amati graph that are closer to GRBs in $(E_{\text{peak}}, E_{\text{iso}})$ space. Perhaps there is a sharp distinction between the baryon rich outflow, which traps and adiabatically decelerates photons, and the baryon poor outflow, which does not. Adiabatic deceleration would then take place either to a great extent, or to a very small extent.

The model and fit illustrate that significant quantities of matter may be injected into a fireball at large distance from the central engine and accelerated by the fireball to relativistic energies. That the energetics are modest here may be a result of the source being very close and viewed from a large off-axis angle, and that even the scattering material may have been somewhat off-axis. This is consistent with the otherwise coincidental situation that GRB 060218 is one of the longest, closest, and softest GRBs. Thus, the various distinguishing features of this GRB can be attributed to a large off-axis viewing angle.

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