X-ray flares, neutrino-cooled discs and the dynamics of late accretion in gamma-ray burst engines

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ABSTRACT

We compute the average luminosity of X-ray flares as a function of time, for a sample of 10 long-duration gamma-ray burst (GRB) afterglows. The mean luminosity, averaged over a time-scale longer than the duration of the individual flares, declines as a power law in time with index approximately $-1.5$. We elaborate on the properties of the central engine that can produce such a decline. Assuming that the engine is an accreting compact object, and for a standard conversion factor between accretion rate and jet luminosity, the switch between a neutrino-cooled thin disc and a non-cooled thick disc takes place at the transition from the prompt to the flaring phase. We discuss the implications of this coincidence under different scenarios for the powering of the GRB outflow. We also show that the interaction of the outflow with the envelope of the progenitor star cannot produce flares out of a continuous relativistic flow, and conclude that it is the dynamics of the disc or the jet launching mechanism that generates an intrinsically unsteady outflow on time-scales much longer than the dynamical time-scale of the system. This is consistent with the fact that X-ray flares are observed in short-duration GRBs as well as in long-duration ones.

Key words: gamma-rays: bursts.

1 INTRODUCTION

The Swift mission, with its ability to localize gamma-ray bursts (GRBs) in real time, has revolutionized our understanding of these phenomena in many ways. One of the most interesting discoveries is that the light curve of the X-ray afterglow displays a large diversity of behaviours (Nousek et al. 2006), rather than being a relatively featureless power law.

The X-ray afterglow sets in as a rapidly fading source at the end of the prompt emission (Tagliaferri et al. 2005). This early phase is understood as the radiation of the prompt phase reaching the observer from off-axis angles $\theta \gg \Gamma^{-1}$ (Kumar & Panaitescu 2000; Kumar et al. 2006; Lazzati & Begelman 2006; Zhang, Liang & Zhang 2007). The steep decay phase is usually followed by a flat component, whose origin is still highly debated (Granot & Kumar 2006; Genet, Daigne & Mochkovitch 2007; Ghisellini et al. 2007; Uhm & Beloborodov 2007). Finally, at random times between a few hundred seconds up to several tens of thousands of seconds after the onset, the X-ray afterglow displays sudden brightenings, known as X-ray flares (Burrows et al. 2005; Falcone et al. 2006; Chincarini et al. 2007, hereafter C07; Falcone et al. 2007). X-ray flares could be due to a variety of causes, either related to external shock activity or to the inner engine itself. It can be shown that any mechanism related to the external shock would produce flares with a characteristically long time-scale (Lazzati et al. 2002; Lazzati & Perna 2007). Most of the observed flares have fast rise and decay times (C07; Kocevski, Butler & Bloom 2007) and must therefore be related to activity of the central engine at times comparable to those at which the flare is observed. For this reason, they are of great importance for our understanding of the mechanism that powers the GRB outflows. They are potentially unique laboratories to investigate the properties of relativistic outflows from compact objects over a broad range of luminosities. As we will see in the following, the isotropic equivalent luminosity of the outflow ranges from $\sim 10^{53}$ erg s$^{-1}$ during the prompt phase to $\sim 10^{47}$ erg s$^{-1}$ during flares at late times.

We study a sample of GRBs with X-ray flares that have been observed by the Swift X-ray Telescope (XRT) for a sufficiently long time and for which redshift information is available. We compute the average energy output from the inner engine as a function of the time elapsed since the GRB explosion, and we compare it to several mechanisms for energy extraction from a magnetar or a black hole.

This Letter is organized as follows. In Section 2, we discuss the sample and the procedure used to derive the cumulative light curve; in Section 3, we discuss different mechanisms that could power the flares; in Section 4, we discuss the role of the progenitor star in shaping the late-time outflow and in Section 5, we discuss our results, their limitations and implications.

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Table 1. Properties of the bursts selected for the analysis.

| GRB    | $z$   | $N_{\text{Flares}}$ | $T_{\text{max}}$ (s) |
|--------|-------|---------------------|----------------------|
| 050724 | 0.258 | 3                   | $3.4 \times 10^4$    |
| 050730 | 3.967 | 4                   | $9.9 \times 10^4$    |
| 050802 | 1.71  | 1                   | $3.0 \times 10^5$    |
| 050814 | 5.3   | 2                   | $1.1 \times 10^5$    |
| 050820a| 2.612 | 1                   | $1.1 \times 10^6$    |
| 050904 | 6.29  | 7                   | $4.3 \times 10^4$    |
| 050908 | 3.344 | 2                   | $2.8 \times 10^4$    |
| 051016b| 0.9364| 1                   | $6.9 \times 10^3$    |
| 060115 | 3.53  | 1                   | $7.9 \times 10^4$    |
| 060124 | 2.296 | 2                   | $6.3 \times 10^5$    |

Figure 1. Average flare light curve of the subsample of Swift afterglows that show flaring activity and for which a redshift has been measured. The dashed line shows the best power-law fit, while the shaded area shows the 1σ confidence region of the slope and normalization. The white lozenges show the result obtained by using the power-law fluences in F07 rather than the band ones. The horizontal lines in the bottom of the plot show the times at which flares have been observed. Their ordinate is arbitrary.

2 DATA ANALYSIS AND RESULTS

We selected from the tables in Falcone et al. (2007; hereafter F07), the subsample of bursts with X-ray flares for which redshift information is available. The bursts and some of their key properties are listed in Table 1. The sample consists of 10 GRBs for a total of 24 flares. All the bursts have XRT observations up to comoving time $t \sim 3 \times 10^4$ s.

The flare isotropic equivalent energy was computed from the fluence $F$ in table 6 of F07. The average light curve between the times $t_1$ and $t_2$ was computed as

$$\langle L \rangle_{t_1,t_2} = \frac{1}{n_{\text{GRB}}} \sum_{i=1}^{n_f} L_i \delta t_{i,1,2},$$

(1)

where $L_i$ is the average luminosity of the $i$th flare during its active time, $n_{\text{GRB}} = 10$ is the total number of GRBs considered, $n_f = 24$ is the total number of flares and $0 \leq \delta t_{i,1,2} \leq 1$ is the fraction of time in the interval $(t_1, t_2)$ during which the $i$th flare is active. This prescription is equivalent to the assumption that the flares have a square shape. Even though this is a very poor approximation to the real shape of the flares, its effect is negligible when many flares are averaged to compute the light curve. We tested both, a Gaussian shape (C07) and a triangular shape, and we obtained consistent results within the errors.

The computation of the errors in the average light curve is non-trivial, since the main contribution is not the uncertainty in each fluence measurement, but rather the uncertainty in the number of flares that are observed on average during a given time interval. For this reason, we assume that the uncertainty of each fluence is as large as the measurement itself, and we compute the errors on the average light curve as

$$\sigma_{\langle L \rangle_{t_1,t_2}} = \frac{1}{n_{\text{GRB}}} \left[ \sum_{i=1}^{n_f} (L_i \delta t_{i,1,2})^2 \right]^{1/2}.$$

(2)

This prescription ensures that if the average flux at a certain time is dominated by a single bright flare, the error is large. Small errors occur only in time intervals with a large number of flares.

The resulting light curve is shown in Fig. 1, where $\langle L \rangle_{t_1,t_2}$ is shown versus time $t = (t_2 - t_1)/2$. The solid dark points with error bars show the results assuming a Band model spectrum for the flares (Band et al. 1993; F07), while the white lozenges show the results of the power-law spectral model (F07). We model the average light curve as a power law, excluding the first point (at $t \sim 40$ s) since it is still contaminated by the prompt emission in many cases. We find that the average light curve is very well described by a power law with index (1σ errors):

$$\alpha = -1.5 \pm 0.16.$$  

The fit has $\chi^2$/d.o.f. = 0.2, a small value that is not surprising given the very conservative assumptions on the uncertainties. The formal error of 0.16 is, as a consequence, very conservative. In order to check the result, we computed the average light curve also as the derivative of the cumulative energy produced as a function of time since the GRB onset, finding analogous results.

Averaging many bursts together allowed us to increase the signal-to-noise ratio of the flare light curve. We now examine whether the resulting slope can be recovered in individual GRBs that display a large number of flares. When we compute the flare light curve for an individual event, the knowledge of the redshift is not necessary and we can select the GRBs from a larger pool of events. There are three GRBs in the F07 catalogue with six or more flares. One is GRB 050904, which is in our sample and has seven flares. Another is GRB 051117a, which has seven flares according to F07. However, the seven flares of GRB 051117a overlap one another and therefore we discard this event from our analysis. Finally, GRB 050803 has six flares.

Fig. 2 shows the flare light curve, in observed time and flux, for these two bursts. Power-law fits were performed for these cases, yielding $\alpha = -1 \pm 0.4$ and $-1 \pm 0.3$ for GRB 050803 and GRB 050904, respectively. Even though the uncertainties are larger, as expected given the smaller statistics, the individual cases confirm that flares produce more luminosity at early times than at late times, their light curve is consistent with a power law, and the index of the power law is consistent with the cumulative curve of Fig. 1.

GRB 050904 has seven flares and is also a part of our main sample. Since it has so many flares, we checked that the results for the average flare energy are not dependent on the presence of GRB 050904 in the sample. Reproducing Fig. 1 without the seven flares of GRB 050904 yields similar results, with a slope $\alpha = -1.8 \pm 0.3$, in agreement with the result of equation (3).

3 POWERING MODES

Even though collimated outflows originating from compact objects accreting matter from a disc are ubiquitous in the Universe (e.g.
The accretion rate into jet luminosity is 0.1 per cent, and that these two parameters are constant. The two parameters are rather standard (e.g. Podsiadlowski et al. 2004; Chen & Beloborodov 2007). Changing them by a factor of up to 10 would not affect the main conclusion since the prompt and flare luminosities would scale in the same way. The average luminosity of the prompt phase of the 10 GRBs is also shown in the figure with a thick solid line. Such accretion rates are compared to the one at which neutrino cooling is switching on/off (Chen & Beloborodov 2007). This transition lies suggestively at the boundary between the prompt phase and the flaring phase. We argue that this could be an indication of the fact that the prompt phase of GRBs, the most luminous one, is powered by accretion on to a black hole in the form of a geometrically thin – neutrino cooled – disc. As the accretion rate drops under the critical value, the fast accretion is switched off and the prompt phase ends. The disc swells under the effect of internal pressure and a new accretion geometry, with a thick disc, sets in. This gives rise to the flares that we observe during the afterglow phase.

In the case of a magnetically driven jet, the change in the outflow dynamics would be brought about by the fact that a thick disc has a lower pressure and therefore can anchor a magnetic field with lower intensity. It would also change the pitch angle of low-inclination magnetic field lines. In the case of a neutrino powered outflow, the switch-off of the neutrino cooling would shut off completely the outflow. It seems therefore that the observations of late time, low-luminosity flares provide evidence against the powering of GRB outflows exclusively by neutrino annihilation.

The material necessary to provide the accretion at late stages can be provided, in long-duration GRBs, by the fallback of material that did not reach the escape velocity in the stellar explosion (Chevalier 1989; MacFadyen, Woosley & Heger 2001; Zhang, Woosley & Heger 2008). Alternatively, especially in the case of short GRBs, the natural evolution of an accretion disc can supply the accretion rate necessary to explain the observations. Consider an accretion disc that forms in a short time-scale (comparable to or smaller than the duration of the GRB prompt phase) and is left to evolve without any sizable mass input thereafter. The accretion rate depends on the assumptions made on the nature of viscosity. The case of a thin disc has been studied thoroughly, Frank, King & Raine (2002) report the exact solution for the case of a thin disc with constant
viscosity. They show that, after several tens of viscous time-scales, the accretion rate on to the central object approaches the asymptotic form $\dot{m} \propto t^{-1.25}$. Cannizzo, Lee & Goodman (1990) performed numerical simulations for the same initial conditions using the prescriptions of $\alpha$-viscosity (Shakura & Sunyaev 1973). They find that the accretion rate at late times-scales with time as $\dot{m} \propto t^{-1.2}$, independently of the value of $\alpha$, assumed. The case of a thick disc needs to be studied in detail (Lazzati & Begelman, in preparation).

The comparison of the observed flare luminosity to the theoretical rates of late-time accretion implies that there is an almost linear relation between accretion and the luminosity of the outflow. In our favoured scenario, where the outflow is powered by magnetic processes, this relation would be caused by the decay of the magnetic field as the disc becomes less massive and dense. The reason why we observe such a linear relation is not entirely clear and deserves further investigation.

An alternative to the accretion disc–black hole system is a rapidly spinning magnetar that powers the outflow as a consequence of spin-down (Thompson, Chang & Quataert 2004; Bucciantini et al. 2008). This system can provide late-time energy either through neutrino emission or dipole radiation. The neutrino emission decays exponentially and cannot provide the power required (Thompson et al. 2004). In the simple vacuum dipole scenario, the decay of the late-time energy deposition is too steep ($L \propto t^{-2}$). However, the interaction of the field with the stellar material can create shallower slopes consistent with the observations. In this scenario, the fact that the neutrino cooling switch coincides with the transition from the prompt to the flaring phase is purely coincidental. In addition, it is not clear how the continuous luminosity produced by the spin-down of the magnetar can be converted into a flaring source.

4 FROM STEADY STATE TO IMPULSIVE

Even though the average flare curve of Fig. 1 is featureless, we ought to keep in mind that flares are episodic events. The fact that an accretion disc or a spinning magnetar can provide energy at late time does not ensure that the energy will be released intermittently. It is not surprising to observe variability of relativistic sources on time-scales comparable to the dynamical time of the system. However, in the case of flares, the variability time-scale is many orders of magnitude longer than the dynamical one for a solar mass black hole, and it grows approximately linearly with time (C07). It is more likely that this variability is associated to a viscous time-scale rather than to the dynamical time-scale. We must therefore seek either a mechanism that can release energy episodically from the inner engine, or a way to transform a continuous output of energy into a highly variable one as it propagates from the engine to the radiation zone.

The propagation of the jet through the cold stellar progenitor material provides, in principle, a way by which a continuous outflow can be converted into a succession of individual fireballs. Morsony, Lazzati & Begelman (2007) showed that even if a continuous jet is injected into the core of a massive star, the ensuing light curve is highly variable. Consider an engine releasing an outflow with continuous but decreasing luminosity. Inside the star the jet is in pressure equilibrium with a high-pressure cocoon of material (Lazzati & Begelman 2005). As the jet luminosity decreases, the cocoon becomes overpressured and squeezes the jet. At the same time, the cocoon pressure decreases due to the fact that the cocoon material is escaping from the surface of the star. If, at any point in time, the cocoon pressure overcomes the stagnation pressure of the jet, the jet would be choked and the flow of energy interrupted.

The stagnation pressure of a relativistic outflow with Lorentz factor $\Gamma$ and cross-section $\Sigma$ is given by $p_{stag} = L_j \Gamma^2 / (4c^3 \Sigma)$, where $L_j$ is the luminosity of the jet. Following Lazzati & Begelman (2005), the cocoon pressure can be written as

$$p_{cocoon} = \left( \frac{L_{j_{1.0}}}{3 \rho_4 b_{tot}} \right) 1/2 \left( \frac{\Gamma}{c} \right)^{3/2} \left( \frac{\rho_4}{\Sigma_1} \right)^{-1}$$

where $L_{j_{1.0}}$ is the average jet luminosity before breakout, $\rho_4$ is the average stellar progenitor density and $r_4$ is its radius and $b_{tot}$ is the breakout time.

A condition for the stagnation of the jet can be obtained by comparing the stagnation pressure with equation (4). It can be seen that the cocoon pressure cannot reach the jet stagnation pressure for any reasonable parameter set. We conclude therefore that the instability giving rise to the flaring behaviour of the late-time activity of the inner engine has to be intrinsic to the jet release process or to its transition from the non-relativistic to the relativistic stage, and cannot be brought about by the propagation of the relativistic outflow in the star.

5 DISCUSSION AND CONCLUSIONS

We have computed the average energy released in the form of X-ray flares overlaid on the power-law decay of the afterglow of long-duration GRBs. A sample of 10 long-duration GRBs from the catalogue of F07 with redshift measurements was used for the analysis. We conclude that, on average, the late-time energy release approximately follows the power-law scaling $L \propto t^{-1.5}$. Our analysis is possibly affected by several biases. First, the definition of a flare is fraught with uncertainty, as the comparison of the C07 and F07 catalogues easily reveals. We here adopt the definition of F07 and refer to that paper for a discussion of their selection criteria. Secondly, the measurement of the slope of the power law depends on our capability to select flares. Low-brightness flares could be lost in the early phases when the afterglow can easily outshine them. On the other hand, very short duration flares could be missed at late times when the observations are not continuous in time. It appears that the first bias is most serious (since no very short duration flare was ever detected in the late phases) and that the slope is possibly underestimated. We do not believe this should affect our conclusions, since almost all the GRBs we considered have an early flare and so the contribution of shallow flares would be minimal. One important effect could, however, create a systematic overestimation of the slope. The late-time flares may be less beamed than the early ones, and therefore their isotropic equivalent luminosities would appear smaller than the one of early flares due, in part, to geometric end not intrinsic effects. According to simulations, however, most of the opening angle evolution takes place at very early times (Morsony et al. 2007), as long as the injection opening angle does not evolve.

The energy to power the flares may come from accretion or from the spinning down of a magnetar. In the first case, we were able to estimate the accretion rate required to power the prompt emission as well as the flaring phase. Interestingly, during the prompt phase the accretion rate is so large that neutrino emission cools the flow and accretion takes place in the form of a thin disc. At accretion rates of about 0.001 to 0.01 solar masses per year, the neutrino luminosity drops and the accretion disc becomes thick. We find that the switch-off of the neutrino cooling and the transition from a thin to a thick disc, take place between the prompt and the flaring phase. Indeed, the prompt emission spikes and the late-time flares exhibit some differences. While the prompt spikes do not show any evolution in their duration or peak luminosity, the flares become longer and...
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shallower with time. This property naturally arises in a disc that fragments and accretes the various blobs of material on their viscous time-scales (Perna, Armitage & Zhang 2006). In addition, flares are very episodic and the engine is ‘off’ most of the time at late stages, while during the prompt phase the engine is ‘on’ most of the time. We propose that the differences are due to the switch from a thin disc to a thick disc configuration. A more detailed analysis of the thick disc accretion dynamics is on-going (Lazzati & Begelman, in preparation).

An alternative scenario is that of a spinning-down pulsar. In this case, the fact that the neutrino switch coincides with the transition from the prompt to the flare phase would be a pure coincidence. More observations and a better understanding of both engine models are needed before definitive conclusions can be drawn. Although we have focused on long-duration GRBs in this Letter, from a theoretical point of view, short-duration GRBs may also have a flaring phase, as long as they are powered by accretion from a disc or by the spin-down of a magnetar. The late-time accretion provided by a disc that is draining into the black hole is sufficient to power the flares independently of the presence or not of fall-back material from the progenitor star.

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