The interpretation of the \textit{Swift} GRB X-ray afterglows

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\textbf{Summary.} — We discuss the current interpretations of the \textit{Swift} GRB X-ray afterglows, mainly focusing on the sharp decline at the prompt tail emission, and the shallow decay afterward, which is then followed by the conventional pre-\textit{Swift} decay behavior, and the possible X-ray flares during the latter two stages. We emphasize the role of the central engine in interpreting the GRB afterglows.

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Many surprises, mainly in X-ray band, have been brought since the successful launch of the \textit{Swift} satellite in Nov 2004. A canonical \textit{Swift} GRB X-ray afterglow lightcurve has been summarized by Zhang et al. \textsuperscript{1} and Nousek et al. \textsuperscript{2}. As shown in Figure 1.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig1.png}
\caption{The schematic cartoon X-ray light curve based on the \textit{Swift} XRT data (see \textsuperscript{1} \textsuperscript{2} for quite similar plots) as well as the chromatic break in optical/X-ray afterglows.}
\end{figure}
some interesting features are emerging (detected in a good fraction of but not all bursts),
including the very early sharp decline preceding the conventional afterglow component
(i.e., phase-I), a shallow decline of the X-ray afterglow before the “normal” decay phase
(i.e., phase-II), and the energetic X-ray flares (i.e., phase-V). In this work, we discuss the
interpretation of these features.

Phase-I: The rapid decline of the very early X-ray lightcurve. A steep initial
X-ray decay $F_\nu \propto t^{-\alpha}$ ($\alpha \sim 3 - 5$) has been seen in a good fraction of Swift GRBs [3],
for which the most widely considered explanation is the off-axis emission from regions
at $\theta > \Gamma^{-1}$ (the curvature effect, or high latitude emission) [4]. In the uniform ejecta
model, provided that the sub-outflow powering a prompt $\gamma$-ray pulse is ejected at a time
$t_0$, even after the gamma-rays along the sightline have ceased (i.e., $t > t_0 + \delta t$, where $\delta t$
is the duration of the pulse), still there is the off-axis emission observed from $\theta > \Gamma^{-1}$
which follows $F_{\nu X} \propto [(t - t_0)/(\delta t)]^{-2 - \beta}$, where $\beta \sim 1$ is the X-ray spectral index of the
emission. Since the central engine turns off at $t_{\text{turn}}$, what we observed is the high latitude
emission of the earlier pulses. The flux declines as $F_X = \sum F_{\nu X,i}[(t - t_{0,i})/(\delta t_i)]^{-(2 + \beta_i)}$,
where $i$ represents the $i$-th pulse. Such a decline is much steeper than $(t/t_{\text{turn}})^{-(2 + \beta)}$
as long as $t_{\text{turn}} \gg \max\{\delta t_i\}$. What we faced is thus not why phase-I is so steep but why
it is not significantly steeper unless $\max\{\delta t_i\} \sim t_{\text{turn}}$, as shown in Figure 2 of [5].

Here we mention two alternatives naturally giving rise to sharp but not too sharp
X-ray decline (i.e., $F_X \propto t^{-3}$ or so). One is the “dying central engine” model, in which
the central engine does not turn off abruptly. The more and more dimmer X-ray emission
generated in the more and more weaker energy dissipation may dominate over the
curvature effect of the early pulses, resulting in a shallower decay [5]. The other is the
“hot cocoon model”. In this model the sharp decline is explained as due to emission from
the hot plasma “cocoon” associated with the GRB ejecta, which expands relativistically
after the ejecta has broken through the stellar envelope, if a substantial fraction of the
cocoon kinetic energy is dissipated at scattering optical depths $\sim 10^{2} - 10^{3}$ [6].

Phase-V: The energetic X-ray flares. So far, energetic X-ray flares have been
detected in several pre-Swift GRBs and about half Swift GRBs [7]. The most widely
considered interpretation is the so-called “late internal shock” model, suggested by Fan
& Wei [8] and Zhang et al. [1]. This model is in light of the following facts: the very steep
decline of the X-ray flares could be interpreted naturally; the multi flares detected in one
burst, as in GRB 050730, could be accounted if the central engine restarts repeatedly; the
simultaneous optical emission is very weak [7] and may be suppressed by the synchrotron
self-absorption, requiring an energy dissipation radius $< 10^{15}$ cm. Considering that the
magnetic mechanism may be more efficient than the neutrino mechanism to extract the
energy needed to power the X-ray flare, Fan et al. [8] suggested that the outflow might be
highly magnetized and the flares were linearly polarized. In both the “late internal shock”
model and the “late internal magnetic dissipation” model, the central engine has
to be able to restart repeatedly. One natural speculation is that such re-activities are
caused by the intermittent fall-back accretion (see [9] for a recent review) (*).

(*) We propose a strange star (SS)-white dwarf (WD) merger model for short GRBs with X-
ray flare (Detailed treatment will be presented elsewhere). We do not discuss a neutron star
(NS)-WD merger because the hard surface of NS acts as a plug, stopping up the accretion. The
SS-WD coalescence is quite similar to a solar mass black hole (BH) merging with a WD [10].
The short hard $\gamma$-ray spike(s) is produced when and only when the SS collapses to BH. The
accretion of WD material onto the nascent BH lasts a few hundred seconds with an accretion
Here we discuss the “internal refreshed shock” model. It is speculated that in some bursts, a significant part of the GRB ejecta energy is carried by the material moving with a Lorentz factor $\Gamma_{e} \sim 10^{11}$. Provided that at a time $\delta T \sim 100s$ after the burst, the central engine re-starts and launches ultra-relativistic outflow. The newly launched ejecta (moving with a Lorentz factor $\Gamma_{inj} \sim$ a few hundred) would catch up with the slow material at a radius $R_{c} \sim 2\Gamma_{e}^{2}c\delta T$ and generate forward/reverse shock emission. For simplicity, we don’t discuss the detailed process but to assume that surface $A$ (the shocked slow material and the shocked new ejecta) has a Lorentz factor $\Gamma_{acc}$. When the central engine re-activity turns off, surface $A$ is at a radius $R_{s} \sim R_{c} + 2\Gamma_{acc}^{2}cT_{reac}$, where $T_{reac}$ is the reactivity timescale of the central engine. The duration of emission of surface $A$ (essentially a single pulse) can be estimated as $T_{A} \sim R_{s}/(2\Gamma_{acc}^{2}c) = (\frac{1}{2\Gamma_{acc}^{2}c})^{2}\delta T + T_{reac}$.

The observer’s timescale $t$ is “calibrated” to the trigger of the GRB. The forward shock emission of the GRB ejecta at $R_{c}$ and $\theta = 0$ will be observed at $\sim R_{c}/(2\Gamma^{2}c)$. The emission from surface $A$ at the same point will reach us at a time $\sim \delta T + T_{90}$, where $T_{90}$ is the duration of the prompt $\gamma$–ray emission. After the ceasing of the re-activity of the central engine, the curvature emission component follows

$$F_{A}(t) \propto \left(\frac{T_{90} + \delta T + t}{T_{A}}\right)^{-(2+\beta)},$$

the decline could be very steep as long as $T_{90} + \delta T \gg T_{A}$ and thus could account for some X-ray flare observations.

**Phase-II:** The shallow decline of the early X-ray lightcurve and the chromatic break. In about half Swift GRBs, the X-ray lightcurves are distinguished by a long term flattening and there is no spectral evolution detected before and after the shallow-to-“normal” decline transition, which is consistent with a strong energy injection \[1\] [2] [11]. However, for some GRBs with good quality multi-wavelength afterglow data, the X-ray and optical lightcurves break chromatically (see Figure 1 for an illustrative plot) and thus challenge the energy injection model \[12\] \[13\].

One possible solution is to modify the basic assumption made in the standard external shock model. Following \[12\] \[13\] \[14\], we assume that (i) The density of the medium is a function of $R$ as $n \propto R^{-k}$; (ii) The shock physical parameters $\epsilon_{e}$ and $\epsilon_{B}$, i.e., the fractions of shock energy going to the downstream electrons and magnetic field, are shock strength dependent; (iii) There might be an energy injection taking a form $dE_{inj}/dt \propto t^{-q}$ and thus changes the dynamics/emission of the GRB ejecta. The last two assumptions yield $(\epsilon_{e}, \epsilon_{B}) \propto (\Gamma^{-b}, \Gamma^{-c}) \propto (t^{\frac{2-k}{2-k-b}}, t^{\frac{2-k}{2-k-c}}) \equiv (t^{b'}, t^{c'})$ for $\Gamma \geq \Gamma_{0}$, otherwise $(\epsilon_{e}, \epsilon_{B}) \propto (\Gamma^{-d}, \Gamma^{-e}) \propto (t^{\frac{2-k}{2-k-d}}, t^{\frac{2-k}{2-k-e}}) \equiv (t^{d'}, t^{e'})$, where $\Gamma_{0}$ is the Lorentz factor of the outflow at the X-ray decline transition. The parameters ($b$, $c$, $d$, $e$) are assumed to be constant and may be different from each other, so are ($b'$, $c'$, $d'$, $e'$).

With these three assumptions and following the standard afterglow treatment \[13\], the rate $\sim a few \times 10^{-3} M_{\odot} \text{s}^{-1}$. The outflow luminosity could be high to $\sim 10^{48} - 10^{49}$ erg s$^{-1}$ \[10\]. The accretion rate is unsteady, so is the energy output. In this model, the timescale, the luminosity, and the multiple structure of the X-ray flare following short GRBs could be well reproduced. The very late X-ray flares are powered by the fall-back accretion of the material ejected in the WD-SS merger. There could also be some precursors—Before the SS collapses to BH, the accretion of the WD material on the SS may give rise to significant emission.
we have the scaling laws (i.e., an extension of Table 2 of [1])

\[ F_{\nu_{\odot}} \propto \begin{cases} 
\frac{\epsilon_B (1 + Y)^{2/3} t^{(1-q)+\frac{4-6k-2q+3q}{4(1-q)}}}{\epsilon_B^{1/4} (1 + Y)^{-1} t^{(1-q)+\frac{2k-8-ak+4q}{4(1-q)}}} & \text{for } \nu_{\odot} < \nu_c < \nu_m; \\
\frac{\epsilon_c^{1/3} t^{(1-q)+\frac{k(1-q)}{4}}}{\epsilon_B^{1/4} (1 + Y)^{-1} t^{(1-q)+\frac{k(1-q)}{4}}} & \text{for } \nu_c < \nu_{\odot} < \nu_m; \\
\frac{\epsilon_c^{-1} \epsilon_B^{(p+1)/4} t^{(1-q)-\frac{k(1-q)}{4}}} {\epsilon_c^{-1} \epsilon_B^{(p+1)/4} t^{(1-q)-\frac{k(1-q)}{4}} + \frac{k(1-q)}{4}} & \text{for } \nu_m < \nu_c < \nu_{\odot}; \\
\frac{\epsilon_c^{-1} \epsilon_B^2 (1 + Y)^{-1} t^{(1-q)-\frac{k(1-q)}{4}} + \frac{k(1-q)}{4}} {\epsilon_c^{-1} \epsilon_B^2 (1 + Y)^{-1} t^{(1-q)-\frac{k(1-q)}{4}} + \frac{k(1-q)}{4}} & \text{for } \nu_{\odot} > \max\{\nu_c, \nu_m\},
\end{cases} \]

where \( \nu_{\odot} \) is the observer frequency; \( \nu_c \) and \( \nu_m \) are the standard cooling frequency and the typical synchrotron radiation frequency of the shocked electrons, respectively; \( Y \) is the synchrotron self-Compton parameter. However, the time evolving shock parameters render an estimate on \( Y \) very difficult. For simplicity, one can assume that \( Y \sim 0 \) when the synchrotron self-Compton is unimportant and \( Y \sim (1 + Y) \sim \sqrt{\epsilon_c/\epsilon_B} \) when the synchrotron self-Compton is important (i.e., \( Y \gg 1 \)).

Substituting such a simplified \( Y \) into equation (2) and assuming each set of \( (k, q) \) is fixed (i.e., they take standard values \( (0, 1) \), respectively) or \( b' = d' \) and \( c' = e' \), one thus can constrain the parameters \( (b', c', d', e') \) or \( (k, q, b', c') \) with the optical and X-ray temporal indexes—the solution is straightforward since four parameters to be determined using four relations. But one crucial problem is that such an approach, in particular the consideration of evolving shock parameters, is phenomenological and lacks the physical basis.

**Conclusion and Implication.** The GRB afterglow may be attributed to the continued activity of the central engine and thus should be named as the “central engine afterglow” [6]. This idea was first proposed in the context of GRB 970228 [17]. However, the consistency between the predictions of the afterglow external shock model and most pre-Swift afterglow multi-wavelength observations leads to that this model has been widely accepted. The situation might change in the Swift era. Now it’s evident that central engine plays an important role on shaping the early afterglow. For example, the dying of the central engine could give rise to the sharp but not very sharp early X-ray decline, i.e., phase-I. The re-activity of the central engine could power the energetic X-ray flares, i.e., phase-V. The long activity of the central engine could give rise to the power-law decaying X-ray afterglow, as found in GRB 060218 [18][16]. We conclude that the role of the central engine should be taken into account seriously when interpreting GRB afterglows, in contrast to what we believed before.

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