Sw 1644+57/GRB 110328A: THE PHYSICAL ORIGIN AND THE COMPOSITION OF THE RELATIVISTIC OUTFLOW

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ABSTRACT

Sw 1644+57/GRB 110328A is a remarkable cosmological X-ray outburst detected by the Swift satellite. Its early-time ($t \lesssim 0.1$ days since the trigger) X-ray emission resembles some gamma-ray bursts (GRBs), e.g., GRB 090417B. However, the late-time temporal behavior of Sw 1644+57/GRB 110328A is coincident with an optical source at redshift $z = 0.355$ (Levan et al. 2011), as well as a radio source (Zauderer et al. 2011). The total isotropic energy in X-ray and $\gamma$-ray is $\approx 10^{53}$ erg and the luminosity of the flaring X-ray afterglow is $\approx 10^{47}$–$10^{48}$ erg s$^{-1}$, both comparable to regular gamma-ray bursts (GRBs). However, the source was detectable and variable in the Burst Alert Telescope (BAT) more than 40 hr after the initial trigger (BAT re-triggered for quite a few times), with peak brightness on the order of 200 mCrab (Sakamoto et al. 2011). Moreover, the flaring X-ray plateau remains for up to $\approx 40$ days. These features are rather peculiar and have not been reported in any GRBs before.

In this work, we first compare the X-ray emission of Sw 1644+57/GRB 110328A with some Swift GRBs and examine whether such an ultra-long outburst can be explained within the regular GRB framework. We then focus on the model of tidal disruption of a (giant) star by a massive black hole. The mass of the tidal-disrupted star is estimated to be $\lesssim$ few solar masses. A simple/straightforward argument for a magnetic origin of the relativistic outflow is presented.

1. INTRODUCTION

Sw 1644+57/GRB 110328A was discovered on 2011 March 28 at 12:57:45 UT by the Swift satellite (Burrows et al. 2011). It is coincident with an optical source at redshift $z = 0.355$ (Levan et al. 2011), as well as a radio source (Zauderer et al. 2011). The total isotropic energy in X-ray and $\gamma$-ray is $\approx 10^{53}$ erg and the luminosity of the flaring X-ray afterglow is $\approx 10^{47}$–$10^{48}$ erg s$^{-1}$, both comparable to regular gamma-ray bursts (GRBs). However, the source was detectable and variable in the Burst Alert Telescope (BAT) more than 40 hr after the initial trigger (BAT re-triggered for quite a few times), with peak brightness on the order of 200 mCrab (Sakamoto et al. 2011). Moreover, the flaring X-ray plateau remains for up to $\approx 40$ days. These features are rather peculiar and have not been reported in any GRBs before.

In this work, we first compare the X-ray emission of Sw 1644+57/GRB 110328A with some Swift GRBs and examine whether such an ultra-long outburst can be explained within the regular GRB framework. We then focus on the model of tidal disruption of a star by a massive black hole. Within such a scenario, we propose a simple/straightforward argument for a magnetic origin of the relativistic outflow and estimate the mass of the tidal-disrupted star.

2. IS Sw 1644+57/GRB 110328A A SUPER-LONG GRB?

As a type of cataclysmic outbursts, GRBs have exhibited very diverse characteristics in their observational properties. But for the X-ray (afterglow) emission, a canonical behavior has been established (e.g., Zhang et al. 2006). Following Shao et al. (2010), in Figure 1 we present the X-ray emission light curves of 138 long GRBs together with Sw 1644+57/GRB 110328A in their rest frames. Interestingly, for $t < 0.1$ days since the trigger, Sw 1644+57/GRB 110328A resembles some specific GRBs, say, the super-long event GRB 090417B at a similar redshift ($z = 0.345$). Moreover, both events exhibit spectral softening at $\approx 10^4$ s and their optical emission is highly suppressed which may suggest very strong dust extinction (Holland et al. 2010; Bloom et al. 2011). Please see Table 1 for more details.

However, the late-time temporal behavior of Sw 1644+57/GRB 110328A makes it unique. For $t > 10^5$ s, the X-ray emission is strongly flaring and appears as a plateau, while for regular GRBs, the late-time X-ray emission declines with time very quickly ($t^{-1.4}$ or so). As a result, at $t \approx 10^6$ s, the X-ray flux of Sw 1644+57/GRB 110328A is brighter than that of any known GRB by more than two orders of magnitude, in spite of the fact that the outburst is under-luminous when compared with other regular GRBs in the early phase (see Figure 1).

The extremely long duration of the flaring X-ray plateau imposes a stringent constraint on the physical origin (see also Dokuchaev & Eroshenko 2011). For long GRBs, the duration is usually governed by the activity of the central engine that is determined by the accretion process, depending on the size/structure of the progenitor star. As a very simple estimate, the prompt accretion has a duration comparable to the free-fall timescale of the progenitor material, $t_{ff} \approx 40(1 + z)R_{ff}^2(M_{BH}/3M_\odot)^{-1/2}$ s. Please bear in mind that throughout this work the convention $Q_r = Q/10^4$ has been adopted except for some special notations. One needs a progenitor star with a size larger than $R \approx 10^{33}(M_{BH}/3M_\odot)^{1/3}$ cm and a number density profile roughly $dn/dR \propto R^{-3/2}$ to account for the ongoing X-ray plateau of Sw 1644+57/GRB 110328A (e.g., Shao et al. 2010). Such a giant star however is not expected to launch an energetic relativistic outflow. Within the framework of GRBs, the highly variable X-ray emission has been taken as evidence of the prolonged activity of the central engine (e.g., Fan & Wei 2005; Zhang et al. 2006; Wu et al. 2007), which could either be due to the fallback accretion onto the nascent black hole or, alternatively, the dipole radiation of a quickly rotating pulsar.

In the fallback accretion scenario, the central engine can operate for a very long time. For example, the long lasting (up to $\sim 10^6$ s) but rather soft spectrum of the “normally” declining X-ray afterglow of XRF 090218 calls for a central engine origin (e.g., Fan et al. 2006). As found in the numerical simulation, the initial plateau given by the collapse of a GRB progenitor star only lasts $\lesssim 10^3$ s and the following fallback accretion rate can be approximated by $M \propto t^{-5/3}$ (MacFadyen et al. 2001). Such
Figure 1. Evolution of the spectral luminosity (top) and the photon indices (bottom) at 10 keV of Sw 1644+57/GRB 110328A (blue) together with GRB 090417B (red) and other 137 long GRBs (gray) in their rest frames (Evans et al. 2010; Shao et al. 2010).

Table 1

| GRB      | $z$  | Duration (s) (15–150 keV) | Photon Index (15–150 keV) | $N_H$ (Host Galaxy) (cm$^{-2}$) | $A_v$ (mag) | Ref. |
|----------|------|---------------------------|---------------------------|---------------------------------|-------------|-----|
| 090417B  | 0.345| > 2130                    | 1.89 ± 0.12               | (1.1–2.4) $\times$ 10$^{22}$    | $\gtrsim$12 | 1   |
| 110328A  | 0.353| > 10$^5$                  | 1.72 ± 0.18               | ~ 2 $\times$ 10$^{22}$          | $\gtrsim$4.5–10 | 2,3,4 |

References. (1) Holland et al. 2010; (2) Bloom et al. 2011; (3) Burrows et al. 2011; (4) Levan et al. 2011.

In the pulsar scenario, the central engine would not turn off until it has lost most of its rotation energy. The relevant timescale can be quite long. Within the simplest dipole radiation model, the spin-down luminosity of the pulsar can be estimated by

$$L_{\text{dip}} = 4 \times 10^{45} \text{erg s}^{-1} B_{p,13}^2 R_{s,6}^6 \Omega_{3.8}^3 (1 + z)^{-2} (1 + \frac{(1 + z)t}{\tau_0})^{-2}, \quad (1)$$

where $B_p$ is the dipole magnetic field strength of the neutron star at the magnetic pole, $R_s$ is the radius of the pulsar, $\Omega$ is the angular frequency of rotation at $t = 0$, and

$$\tau_0 = 4 \times 10^6 s (1 + z) B_{p,13}^{-2} \Omega^{-2}_{3.8} I_{45}^{-2} R_{s,6}^{-6}$$

is the corresponding spin-down timescale of the pulsar, and $I \sim 10^{45}$ g cm$^2$ is the typical moment of inertia of the pulsar (e.g., Pacini 1967; Gunn & Ostriker 1969). For $B_{p,13}^{-2} \Omega_{3.8}^{-2} I_{45}^{-2} R_{s,6}^{-6} > 1$ (i.e., $\tau_0 > 5 \times 10^6$ s), the long duration of Sw 1644+57/GRB 110328A can be accounted for, while the spin-down luminosity is...
given by Equation (1) is too low to be consistent with the observed X-ray luminosity $L_X \sim 10^{47}$ erg s$^{-1}$ unless the outflow has been collimated into a narrow cone with a half-opening angle

$$\theta_j < 0.09 \epsilon_x^{-1/2} \Omega^{3.8} \Omega^{1/2} L_X^{-1/2},$$

where $\epsilon_x$ is the radiative efficiency in the X-ray band and $L_X$ is the observed luminosity of the long-lasting X-ray plateau. However, it is unclear whether such a narrow collimation can be achieved via interaction with the expanding material of the associated supernova. The other potential challenge of the pulsar model is how to produce the highly variable X-ray emission.

3. TIDAL DISRUPTION MODEL

Though the long-lasting activity of a GRB central engine seems possible, the luminous X-ray plateau lasting $>40$ days may favor a very different physical origin—“tidal disruption of a star by a massive black hole” (e.g., Hills 1975; Rees 1988; Ulmer 1999; Lu et al. 2008)—which has already been applied to Sw 1644+57/GRB 110328A by Barres de Almeida & De Angelis (2011) and Bloom et al. (2011).

3.1. Tidal Disruption Model: A Brief Discussion

The minimum variability timescale of the X-ray emission of Sw 1644+57/GRB 110328A is $\sim 78$ s (Bloom et al. 2011), suggesting a black hole mass $M_{\text{BH}} \sim 7.8 \times 10^5 M_\odot / [3(1+z)] \sim 2 \times 10^6 M_\odot$, where $M_\odot$ is the solar mass (e.g., Lu et al. 2008). The tidal radius of a star captured by the massive black hole can be estimated by

$$R_T \sim 6.3 \times 10^{13} \text{ cm} r_s m_*/0.6 M_{\text{BH}}^{1/3} R_\odot^2,$$

where $m_* = M_*/M_\odot$, $r_s = R_*/R_\odot$, and $m_*$ ($R_*$) is the mass (radius) of the captured star. Some material is unbound. The bound part may create flares as it accretes onto the black hole. The most bound material returns to the pericenter on a timescale (e.g., Ulmer 1999)

$$t_{\text{fallback}} \sim 4.4 \text{ days} (1+z)(5 R_p/R_T)^{3/2} r_s^{-1/2} m_*/0.6 M_{\text{BH}}^{1/3} R_\odot^2,$$

where $R_p$ is the pericenter of the star’s orbit. Therefore, the duration of the X-ray transient may be accounted for if the captured star is a (red) giant or alternatively an “S-star” as found in the Galactic center (e.g., Alexander 2005). The highly variable X-ray emission may reflect the instability involved in the accretion process.

3.2. The Relativistic Movement: Constraint on the Physical Process Launching the Outflow

The analysis of current observational data of Sw 1644+57/GRB 110328A suggests that the outflow is likely relativistic with an initial bulk Lorentz factor $\Gamma_i \gtrsim 10$ (Bloom et al. 2011). If such an estimate can be confirmed by the late superluminal expansion measurement, the outflow should be launched and then accelerated via some magnetic processes since the pure hydrodynamic acceleration is disfavored, as shown below.

A baryonic ejecta will be accelerated by the thermal pressure until it becomes optically thin or saturates at a radius $R_t$, depending on the baryon loading of the outflow. The optical depth of the photon at the radius $R_t$ can be estimated as (e.g., Paczynski 1990; Jin et al. 2010)

$$\tau \sim \int_{R_t}^{\infty} (1 - \beta)n \sigma_T dR \sim 1,$$

where $n \sim L/4\pi c^3 \rho m_e c^3$ is the number density of electrons coupled with protons in the observer’s frame, $\sigma_T$ is the dimensionless entropy of the initial ejecta, $R$ is the Thompson cross section, $\beta$ is the velocity of the outflow in units of $c$ (the speed of light), and $m_p$ is the rest mass of protons. Combining with the relations $R_t \sim \Theta R_0$ (e.g., Piran 1999) and $\beta \sim 1 - 1/2\Gamma_i^2$, Equation (4) gives

$$L_{\sigma_T} \sim 1,$$

where $R_0 \gtrsim R_s$ is the initial radius of the outflow getting accelerated. The final bulk Lorentz factor of accelerated outflow is related to $L$ and $R_0$ as

$$\Gamma \lesssim \Gamma_M \equiv 8.6 (\eta/\Gamma) L_{49}^{1/4} R_{12}^{-1/4} \lesssim 8.6 L_{49}^{1/4} R_{12}^{-1/4},$$

where the fact that $\Gamma \lesssim \eta$ has been taken into account (see also Mészáros & Rees 2000). Therefore, the hydrodynamic process is unable to accelerate the outflow to a bulk Lorentz factor $\Gamma_0 \gtrsim 10$, which in turn suggests that the outflow is not baryonic. Actually it is unlikely to launch an energetic baryonic outflow with $\eta \lesssim 1$ for an accreting massive black hole ($M_{\text{BH}} \sim 10^6-10^9 M_\odot$). The reason is that the inner region of the surrounding disk is very cool with a temperature $T_{\text{in}} \sim 10^4$ K. The magnetic field is shock-generated/random. The linear polarization of the synchrotron radiation of electrons accelerated by the magnetic reconnection in the relativistic outflow is expected.

Bower et al. (2011) set a $2\sigma$ upper limit on the linear polarization fraction of $4.5\%$ at a frequency of 8.4 GHz. Such a low linear-polarization degree favors an external-shock origin of the radio emission, as suggested by Bloom et al. (2011). This is because in the external-shock model the electrons are accelerated at the forward shock front and the magnetic field is shock-generated/random. The linear polarization of the synchrotron radiation of the electrons cancels with each other and the net linear polarization degree is expected to be very low.

3.3. Estimating the Mass of the Tidal-disrupted Star

Up until 2011 May 12, the isotropic-equivalent X-ray/γ-ray emission energy has been $E_{\text{iso}} \gtrsim 10^{53}$ erg. Such a huge amount of energy sheds some light on the mass accreted onto the central black hole. The possible physical origins of the X-ray emission

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5 For a Schwarzschild (or a slowly rotating) black hole $R_s/R_\odot \sim 11.5 r_s m_*/0.6 M_{\text{BH}}^{2/3}$, the smallest distance to which the test particle on a parabolic orbit can approach and yet not be swallowed by the black hole is $R \sim 2R_s$, where $R_\odot$ is the Schwarzschild radius (Kobayashi et al. 2004).
have been discussed in some detail by Bloom et al. (2011). Instead of going into the details of these possibilities, here we make the simplest assumption and then estimate the mass of the captured star.

Case I: The X-ray emission is mainly from the disk. In order of magnitude, the total disk luminosity is (e.g., Shapiro & Teukolsky 1983)

\[ L \lesssim 0.1 M^2 c^5 \sim 2 \times 10^{47} \text{erg s}^{-1} M_{-6}, \]

(7)

where \( \dot{M} \) is the accretion rate (in units of \( 1 M_\odot \text{s}^{-1} \)). Please note that the disk emission is not narrowly collimated and just about half of the star’s material is bound; to account for the ongoing X-ray emission one needs a tidal-disrupted star with a mass

\[ M_* \gtrsim E_{\text{iso}}/0.1 c^2 \gtrsim \text{a few } M_\odot. \]

Case II: The X-ray emission is mainly from the relativistic outflow. As shown in Section 3.2, the relativistic outflow should be launched by some MHD processes. In the most widely discussed Blandford–Znajek process (Blandford & Znajek 1977; Lee et al. 2000), the luminosity of the electromagnetic outflow can be estimated by

\[ L_{\text{BZ}} \sim 1.8 \times 10^{45} \text{erg} (a/0.4)^2 R_{H, 1.7} B_{H, 6.5} M_{-5.5}^{-1} \sim 1.1 \times 10^{47} \text{erg} s^{-1}, \]

where \( a \) is the spin parameter of the massive black hole, \( R_{H} \sim 10^{15} \text{G} M_{-6}^{-1} \), is the magnetic field strength on the horizon, and \( R_{H} = (1 + \sqrt{1 - a^2}) R_{S}/2 \). With a proper collimation, the X-ray emission could have a luminosity

\[ L_X \sim 2 \epsilon_x L_{\text{BZ}} / \theta_{-1}^2 \sim 10^{47} \text{erg s}^{-1} \epsilon_{x, -1} (a/0.4)^2 M_{-5.5}^{-1} \theta_{-0.5}^{-2} \epsilon_{x, -1}. \]

(8)

Again, one needs \( M_* \gtrsim \text{a few } M_\odot \) to account for the data of Sw 1644+57/GRB 110328A.

4. CONCLUSION AND DISCUSSION

Sw 1644+57/GRB 110328A was detectable and variable in BAT more than 40 hr after the initial trigger (the BAT re-triggered for quite a few times). The early-time (\( t \lesssim 0.1 \text{ days} \)) X-ray emission of this cosmological outburst does not seem unusual, as it actually mimics GRB 090417B. But the late-time flaring X-ray plateau lasting \( \gtrsim 40 \text{ days} \) renders it remarkable and disfavors the speculation that it is a super-long hardening outburst (\( \lesssim 4 \text{ days} \)). The early-time (\( t \lesssim 1 \text{ days} \)) X-ray emission could have a luminosity \( \gtrsim 10^{47} \text{ erg s}^{-1} \). We thank the anonymous referee for helpful comments.

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smaller than the rate of the tidal disruption of only one star, with the other ejected with a high velocity (e.g., Ginsburg & Loeb 2006, 2007). Even so, the latter would probably suffer strong tidal perturbations and mass loss before ejection (Antonini et al. 2010).

Though Sw 1644+57/GRB 110328A is likely powered by an accreting massive black hole, the early (\( t < 10^4 \text{ s} \)) X-ray emission, including the luminosity, the spectral evolution, and the temporal behavior, is rather similar to that of GRB 090417B, for which the central engine is plausibly a stellar black hole. This fact suggests that very different central engines can produce rather similar X-ray outbursts in a selected time interval, possibly via the same kind of energy extraction process. In this work we did not investigate the forward shock emission of the relativistic outflow. Since the central engine has not turned off yet, any reliable calculation should take into account the energy injection of the outflow as well as the cooling of the forward shock electrons by the photons generated in the internal energy dissipation (the byproduct is a high-energy emission component due to the inverse Compton scattering). A self-consistent approach can be found in Fan et al. (2008).

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6 This parameter is hard to estimate/constrain. Recently, Kato et al. (2010) found that the spin parameters of black holes in Sgr A* and in Galactic X-ray sources have a unique value of \( a \sim 0.44 \). Hence, we normalize the poorly known \( a \) to a value \( \sim 0.4 \).

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