Enhanced emission from GRB 110328A could be evidence for tidal disruption of a star

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ABSTRACT

On March 28, Swift’s Burst Alert Telescope discovered a source in the constellation Draco when it erupted in a series of X-ray blasts. The explosion, catalogued as gamma-ray burst (GRB) 110328A, repeatedly flared in the following days, making the interpretation of the event as a GRB unlikely. Here we suggest that the event could be due to the tidal disruption of a star that approaches the pericentric distance of a black hole, and we use this fact to derive bounds on the physical characteristics of such system, based on the variability timescales and energetics of the observed X-ray emission.

Key words. black holes – tidal disruption – active galactic nuclei

1. Introduction

The capture and tidal disruption of a star in the vicinity of a super-massive black hole (SMBH) has been considered as one of the ways in which an active galactic nucleus (AGN) can be fueled (Rees 1988). In particular, this phenomenon has been used by several authors to support the existence of “dormant quasars”, consistent with the now widely-believed conjecture that a SMBH is harboured at the nucleus of every large galaxy. Despite much detailed theoretical work in the field, direct observational evidence for the tidal disruption and accretion of a star by a SMBH is somewhat scarce. Studies based on soft X-ray survey data, for example, have found evidence for intense and short-lived flare periods in otherwise low-active galaxies that are consistent with the theoretical prognostics for such an event (e.g., Komossa & Bade 1999, Komossa et al. 2004, Maksym et al. 2010). Although the timescales associated with this phenomenon are such that it would be possible to follow its unfolding in time with great detail, such detection had not been reported yet.

On March 28, the Burst Alert Telescope (BAT) onboard the Swift satellite triggered on a source in the constellation of Draco when it erupted in a series of X-ray blasts. The satellite determined the position for the explosion, initially classified as gamma-ray burst (GRB) 110328A (a.k.a. Swift J164449.3+573451), at coordinates $RA = 251.2054\, h$ and $DEC = 57.5808\, degrees$, at a location in the sky where no catalogued X-ray source existed (Cummings et al. 2011). GRB 110328A repeatedly flared in the days following its discovery, presenting a behaviour incompatible with that of a gamma-ray burst (Barthelmy et al. 2011). Identification of an optical counterpart from pre-burst images of the region followed shortly, revealing an object of magnitude $R \sim 22$ which was independently confirmed by others (Leloudas et al. 2011). The extragalactic nature of the optical counterpart was determined from observations of Hβ and OIII emission lines at a common redshift of $z \sim 0.35$ by the Gemini Telescope (Levan et al. 2011).

Figure 1 shows the brightness changes recorded by Swift in the first two weeks after the trigger$^1$. The light-curve clearly shows the highest activity period concentrated in the first 2 days of observations, with the two brightest flare peaks separated by approximately one day and followed by smaller peaks, of decaying relative amplitude and durations of the order of $10^4$ seconds. The emission then attains a minimum and after a few days regains intensity, but now at a more stable rate and with an average intensity about one order of magnitude fainter than that of the bright flares. As of today, this emission persists.

In this note we will discuss the basic evidence in favour of the X-ray data of GRB 110328A being the direct observational signature of a star being disrupted and subsequently accreted after a close passage to a SMBH in the centre of the galaxy identified as the probable optical counterpart of the X-ray source.

2. Dynamical considerations and energetics

The optical counterpart of GRB 110328A was identified with a red galaxy at $z \sim 0.35$. At this distance, the absolute R-band magnitude of the host is of about $M_R \approx -18$. According to the mass-luminosity relation for spheroids, this magnitude implies a mass for the SMBH at the centre of the galaxy of the order of $M_\bullet \approx 10^6\, M_\odot$ (Graham et al. 2007), which will dictate the dynamical scales of our system. In our notation $M_\bullet$ denotes the black hole mass in units of $10^6\, M_\odot$. Observe that according to Graham et al. 2007, $10^6$ and $10^8\, M_\odot$ can be considered as strong lower and upper bounds for the mass of the SMBH, respectively.

The distinctive observational signature of the capture of a star by a SMBH (Rees 1988) is a series of more or less short-
which for $M_6 = 10$ implies a beaming of $\Gamma \sim 10$.

This beaming could be realised in the form of jets, as usually observed from quasars (see Figure 2). If the observed emission has origin in jets then it is likely to be at least in part nonthermal, though contributions from a thermal emission from the accretion disk might be present.

### 3. Characteristics of the tidal disruption event

A star of mass $m_*$ and radius $r_*$ becomes vulnerable to tidal distortions (Rees 1988) when the pericentre of its orbit becomes small enough to be comparable to the tidal radius $R_T$. In terms of the Schwarzschild radius $R_S \approx 3 \times 10^{11} M_6$ cm, this quantity is:

$$\left( \frac{R_T}{R_S} \right) \approx 15 M_6^{-2/3} \left( \frac{r_*}{r_0} \right) \left( \frac{m_*}{m_0} \right)^{-1/3} > 1,$$

(3)

where the condition of $R_T/R_S > 1$ corresponds to $M_6 \leq 100$. The tidal disruption process as envisaged here is depicted in Figure 2.

Let us therefore suppose that a star with an orbit of semi-major axis $a$ will have a periastron passage by the SMBH at a distance $\sim R_T$. The period of the orbital motion for such a star is:

$$T = 88 M_6 \left( \frac{a}{R_S} \right)^{3/2} s.$$  

(4)

The X-ray light-curve observed for GRB 110328A presents two distinctively bright peaks separated by approximately $10^5$ s, which we can tentatively associate with two sequential periastron passages of the star, after which it is completely disrupted. The bright peaks seen in the X-ray light-curve at these times are associated to the fact that the most tightly bound debris after each passage will quickly fall inside the black hole, sustaining a strong luminosity comparable to or higher than $L_{\text{Edd}}$ (Rees 1988).

Referring to Equations 3 and 4, one can see that the condition $T \approx 10^5 s$ is easily verified for a SMBH close to $10^7 M_6$ when

$$\left( \frac{r_*}{r_0} \right) \left( \frac{a}{R_T} \right) \sim 10.$$  

(5)

Given that $a \gtrsim R_T$, this implies a value of $r_* \lesssim 10 R_\odot$, comfortably within the range for giant stars evolved from the main sequence (i.e., $0.5 M_\odot < m_* < 5 M_\odot$), which are likely to populate red ellipticals.

While the timescale between the two major flares could be related to the orbital period of the star, the duration of the bright flaring periods that follow them are likely to be related to the infall time of the debris in the innermost orbits. According to Rees (1988), such debris will enter in an orbit around the BH with pericentric distance $\approx R_T$, and so the falling time is

$$\tau = 0.03 M_6^{1/2} \text{ years}.$$  

(6)

For a BH of $\sim 10^7 M_\odot$ this gives $\tau \sim 3 \times 10^6$ s, consistent with the duration of the high luminosity emission seen in the XRT light-curve at the beginning of the event. These timescales are of the same order as those for which a BH of mass $M_6 \approx 10$
first pericentric passage

after second pericentric passage

Fig. 2. A solar-type star approaching a massive black hole on an elliptic orbit with pericentre distance $R_T$ is distorted and spun up during, and then tidally disrupted, leaving behind a disk of debris that are accreted by the hole.

can sustain an accretion luminosity $\sim L_{\text{Edd}}$ before $\dot{M}$ starts to fall. This provides an independent confirmation of the order of magnitude of the BH mass. Furthermore, it should be observed that, by the same argument (Rees 1988), the maximum rate at which the BH can accrete at the Eddington level with a radiative efficiency $\epsilon$ is

$$\dot{M} = \left(0.02 \epsilon_{0.1}^{-1} M_6\right) M_\odot/\text{year},$$  

(7)

corresponding, for a typical efficiency of 10%, to about $0.1 M_\odot$ in the observed timescale of two days, as reported in the circular GCN 11847 [Bloom et al. 2011].

Finally, we had already observed that after the second day, the X-ray emission decreased to a more or less steady flux, a factor $\lesssim 10$ below $L_{\text{Edd}}$. Above, we had assumed that the duration of the high-luminosity state was dictated by the infall time of the innermost bound debris from the disrupted star. Another prediction of the models of tidal disruption is that an extended disk of material will be created, as schematically shown in Figure 2 (Gurzadyan & Ozernoy 1980). If this is the case, after the innermost bound material has been swallowed, the remaining mass will continue to accrete the BH but at a slower rate, dictated by the viscous timescale of the disk (Gurzadyan & Ozernoy 1980 and Lynden-Bell & Pringle 1974). In our scenario, this is the likely origin of the steadier emission seem from the object during the last 10 days or so.

The viscous timescale of the disk has an upper bound on the free-fall timescale, and is likely to be only a modest multiple of this value (Rees 1988). Thereafter, if the outermost bound material is within a few $10 R_T$ of the hole, the expected timescale for accretion will be within a few months, which corresponds to a prediction that the X-ray flux should decrease significantly within this time after the brightest period.

4. Conclusions

The energetics and temporal behavior of the transient GRB 110328A can be explained as the first detection “in the act” of the disruption of a solar-type star by a supermassive black hole of the order of $10^7 M_\odot$.

The emission appears to be beamed and is likely to be at least in part nonthermal, which could imply the existence of a yet undetected higher energy component of the spectrum.

If our predictions are correct, the X-ray emission is expected to fade within a few months.

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