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# A search for pulsations from the compact object of GRB 060218

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## ABSTRACT

**Aims.** A fraction of massive stars are expected to collapse into compact objects (accreting black holes or rapidly rotating neutron stars) that successfully produce gamma-ray bursts (GRBs). We examine the possibility of directly observing these gamma-ray burst compact objects (GCOs) using post-explosion observations of past and future GRB sites.

**Methods.** We present a search for early pulsations from the nearby ( $z=0.0335$ ) gamma-ray burst GRB 060218, which exhibited features possibly consistent with a rapidly spinning neutron star as its underlying GCO. We also consider alternative techniques that could potentially achieve a detection of GCOs either in the Local Volume or near the plane of our own Galaxy.

**Results.** We report the non-detection of pulsations from the GCO of GRB 060218. In particular, fast Fourier transform analysis applied to the light curve shows no significant power over the range of frequencies  $0.78 \text{ mHz} < f < 227 \text{ Hz}$  with an upper limit on the pulsed fraction of  $\sim 2\%$ . In addition, we present detection limits of current high-resolution archival X-ray images of galaxies within the Local Volume. The existing data could be harnessed to rule out the presence of any background contaminants at the GRB position of future nearby events.

**Conclusions.** The null detection of pulsations from the GCO of GRB 060218 is most likely explained by the fact that the afterglow emission occurs near the head of the jet and should be far removed from the compact object. We also find that the comparison of pre- and post-explosion images of future GRBs within the Local Volume, as well as the firm identification of a GCO within an ancient GRB remnant near the Galactic plane are extremely challenging with current GeV/TeV capabilities. Finally, we conclude that only under some very exceptional circumstances will it be possible to directly detect the compact object responsible for gamma-ray bursts.

**Key words.** Gamma rays: bursts – Gamma rays: observations

## 1. Introduction

Optical spectroscopy has verified the long-hypothesized origin of gamma-ray bursts (GRBs) in the deaths of massive stars (e.g., Stanek et al. 2003; Hjorth et al. 2003). It is now accepted that “long-duration” ( $> 2 \text{ s}$ ) GRBs accompany some core-collapse supernovae of Type Ic, in which a compact object produced during the collapse of a Wolf-Rayet progenitor powers a focused jet that bores its way through the stellar envelope (Woosley & Bloom 2006). Unfortunately, the exact nature and eventual fate of the gamma-ray burst compact object (GCO) responsible for the launch of the GRB jet remains unknown. The most promising alternatives include highly magnetized neutron stars (Wheeler et al. 2000; Thompson, Chang, & Quartaert 2004) and accreting black holes characterized as “collapsars” (Woosley 1993; MacFadyen & Woosley 1999). The detection of such GCOs would not only open a new frontier in our understanding of compact object formation, but it would help us address the circumstances that give rise to a variety of stellar explosions.

Much of the effort aimed at revealing the nature of GCOs has centered on the possible interaction of the GRB with its surroundings. Brown et al. (2000) suggested that GRB explosions could lead to the formation of X-ray binaries with a black hole primary. The identification of GRB remnants in our Galaxy or in nearby galaxies has also been proposed as a possible way to pinpoint the GCO responsible for the ex-

plosion (Perna, Raymond, & Loeb 2000; Ayal & Piran 2001; Ramirez-Ruiz 2004). Looking for the compact object produced at the site of historical core-collapse supernovae has also been addressed by Perna et al. (2008). Using data from the Burst and Transient Experiment (BATSE) onboard the Compton Gamma Ray Observatory (CGRO), McBreen et al. (2002) inspected cumulative light curves of GRBs for possible signatures of a black hole being either spun up or down during the accretion process. Other surveys have focused on the search for gravitational waves associated with GRBs (Abbott et al. 2008). Most recently, Mazzali et al. (2006) have used spectral analysis of the broad-lined supernova SN 2006aj to infer the formation of a magnetar associated with GRB 060218. While these studies provide important insight into the origins of the explosion, further observational work is required to detect and distinguish GCOs directly.

Theoretical studies of GRBs suggest that the combination of rapid rotation and large magnetic fields in neutron stars (*magnetars*) could generate an energy of  $10^{51}$ – $10^{52}$  erg on a 10–100 s timescale required to power a long-duration GRB (Thompson, Chang, & Quartaert 2004). A direct detection of pulsations at the site of a GRB would provide strong support for such hypothesized neutron star at the center of the explosion. So far, searches for pulsation signatures have found no significant evidence of periodicity in the prompt gamma-ray (25–320 keV energy range) light curves of GRBs (Deng & Schaefer 1997). However, very recent observations have produced tantalizing but controversial evidence of quasi-periodic variations in the gamma-ray light curve of

GRB 090709A (Markwardt et al. 2009; Golenetskii et al. 2009; Gotz et al. 2009; Mirabal & Gotthelf 2009).

Owing to its close proximity ( $z=0.0335$ ) and the early detection of an associated supernova with the *Swift* satellite, the observations of GRB 060218/SN 2006aj (Campana et al. 2006; Mirabal et al. 2006; Modjaz et al. 2006; Pian et al. 2006; Soderberg et al. 2006) constitute an ideal dataset to search for pulsations following the GRB onset. Additional motivation for a thorough pulsation search is provided by spectral modeling of its associated supernova SN 2006aj suggesting a nascent neutron star as the likely GCO for GRB 060218 (Mazzali et al. 2006).

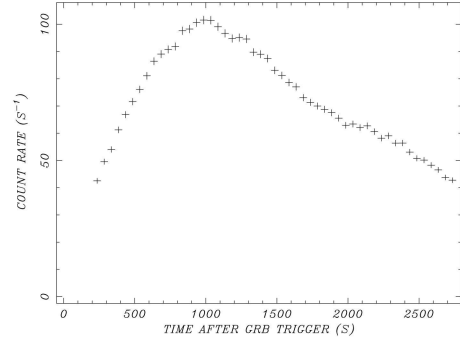
In this paper, we present an early search for pulsations from the GCO of nearby GRB 060218, and an analysis of alternative observations that may produce a direct view of the GCO in the future. The paper is organized as follow. In Sect. 2, we describe a search for coherent pulsations from the GRB 060218. Sect. 3 discusses our results and examines potential techniques that could reveal the nature of GCOS. Finally, conclusions are presented in Sect. 4. Throughout we adopt a concordance cosmology model ( $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_m = 0.27$  and  $\Omega_\Lambda = 0.73$ ).

## 2. Observations and Data Analysis

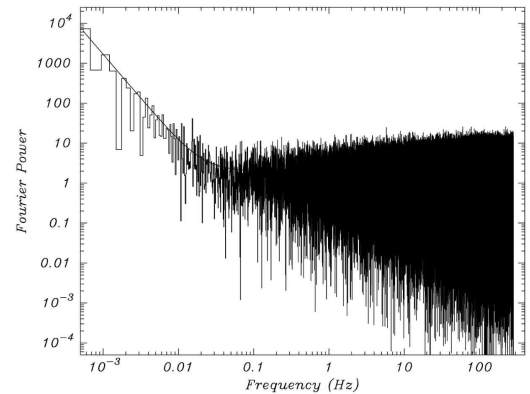
Timing observations of GRB 060218 were obtained with the X-ray telescope (XRT; Gehrels et al. 2004) on-board the *Swift* satellite. The XRT focal plane sensor is a  $600 \times 602$  pixel CCD sensitive to photons in the 0.2–10 keV energy range. Data were acquired in Windowed Timing (WT) mode starting 159 s after the burst. This mode provides 1.77 ms time resolution by rapidly clocking out the central 200 columns in the column direction with the resulting loss of imaging in one spatial dimension. We analyzed standard pipeline products created using processing version v3.9.10 made available in the *Swift* archive<sup>1</sup>.

Data collected in the first orbit spanned an initial 2540 s with a mean count rate of  $72 \text{ counts s}^{-1}$  in a  $1'$  wide extraction aperture centered on the source. The light curve rises to a peak  $100 \text{ counts s}^{-1}$  at the 800 s mark before slowly falling back to the initial detected rate of  $30 \text{ counts s}^{-1}$ . In the next interval, following a 3160 s spacecraft orbit gap due to Earth block, the source is barely detectable (mean rate of  $0.7 \text{ counts s}^{-1}$  over 120 s), then nearly undetectable during  $22 \times 40\text{s}$  orbit-to-orbit monitoring intervals over 35 hrs, for a total of 808 s of exposure, resulting in 32 source counts and 8 background counts. Apart from the highly variable source flux rate, the background remained constant during all observation intervals. A light curve of the *Swift* events for the first interval following detection is shown in Fig. 1; note that count rates for the later observations are essential zero on this scale.

We searched for a coherent signal in the initial *Swift* XRT data of GRB 060218 using a fast Fourier transform (FFT). The barycenter-corrected data taken during the first orbit was rebinned in 1.77 ms steps and transformed using a  $N = 2^{21}$  element FFT. No significant power is found over the range of search frequencies  $0.78 \text{ mHz} < f < 227 \text{ Hz}$  searched. The resulting power spectrum for GRB 060218 is displayed in Fig. 2 and shows characteristics of both white (power independent in frequency, mean of 2) and red noise (power modeled by a power law with best fit index  $\Gamma = -2.2$ ), the latter dominating at frequencies above 30 mHz. In the white noise regime, the maximum FFT power is  $S = 25.67$  at 223 Hz ( $P = 4.48 \text{ ms}$ ). This power is consistent with random fluctuations, corresponds to a false detection probability of  $\varphi = N_{\text{trials}} \exp^{-S/2} = 2^{21} \times 2.6 \times 10^{-6} > 1$  for a



**Fig. 1.** Initial *Swift* XRT light curve of GRB 060218 acquired 159 s after the GRB trigger, in the 0.2–10 keV energy band.



**Fig. 2.** Power spectrum of GRB 060218. The spectrum shows no significant coherent signal and it is dominated by red noise at low frequencies  $\lesssim 0.03 \text{ Hz}$ .

coherence sinusoidal. Formally, the corresponding pulsed fraction limit is  $f = 1.8\%$  ( $= \sqrt{2S/N}$ ,  $N = 162 \text{ k}$  detected photons), with 50% probability. For periods in the magnetar range ( $0.01 \lesssim f \lesssim 1 \text{ Hz}$ ), which partially overlap the red noise regime, the peak FFT power is  $S = 37.51$  after allowing for the modeled red noise contribution, corresponding to a blind search false positive detection probability of  $\varphi = 0.015$  ( $\approx 2.5\sigma$ ) and pulsed fraction limit of  $f = 2.1\%$ . Similar results are obtained using the Rayleigh, or  $S = Z_1^2$  test, where the power is distributed like  $\chi^2$  with two degrees of freedom, as for the FFT power.

To look for possible non-stationary oscillations, a similar timing analysis was done on 100-s intervals using the burst and no significant signal is found to a pulsed fraction limit of 10%, (maximum FFT power  $S \approx 10$ ,  $N \approx 4000$  counts), with 50% probability.

## 3. Discussion

In a different astrophysical context, the absence of coherent pulsations from a newly formed compact object would be intriguing. In the case of GRBs; however, the absence of coherent pulsation is not totally unexpected. The reason is that the observed afterglow/breakout emission most likely occurs near the jet head far removed from the central engine (Zhang, Woosley, & MacFadyen 2003). As a result, temporal and spectral signatures (if any) associated with the GCO are probably swamped by the afterglow emission

<sup>1</sup> See <http://heasarc.gsfc.nasa.gov/docs/swift/archive/>

(Mirabal, Paerels, & Halpern 2003; Sako, Harrison, & Rutledge 2005; Butler 2007).

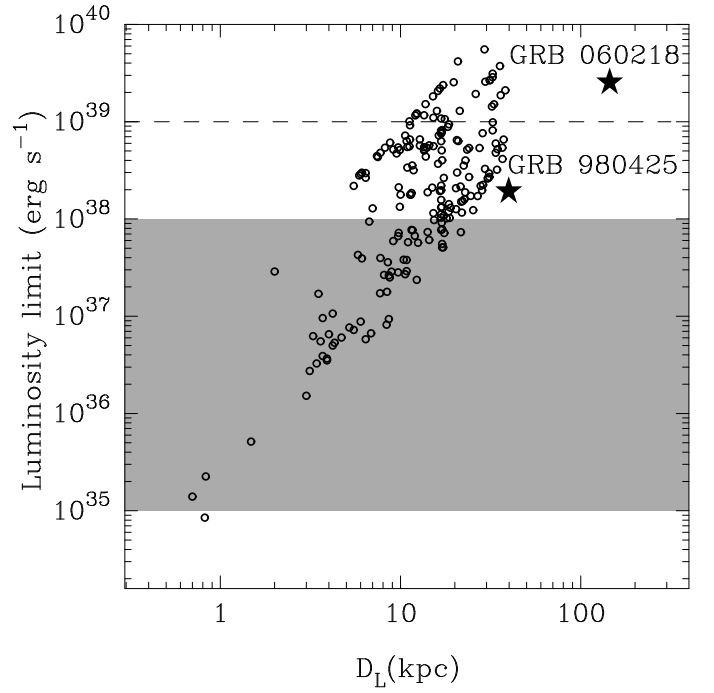
Even in the absence of a bright afterglow, as is the case for GRB 060218, it is not entirely clear that the temporal signatures will be retained during the expansion of the jet. Consequently, we argue that early searches for pulsations in GRBs will not always provide clues about the nature of GCOs. We note, however, that our results do not necessarily rule out neutron star models for GCOs. In fact, the range of frequencies considered here may only rule out millisecond pulsars with relative slow spin periods  $f < 283$  Hz. As argued by Thompson, Chang, & Quartaert (2004), an energy release  $E_\gamma \sim 10^{50}$  erg implies that the spin period of the neutron star at birth might be as low as 0.1 ms.

Interestingly, our failed search forces us to consider alternative approaches for observing GCOs directly such as direct comparison of pre- and post-explosion X-ray images of future nearby GRB localizations (Pian et al. 2004; Kouveliotou et al. 2004) or the firm identification of a GCO within the interior of a GRB remnant in our own Galaxy (Ioka & Mészáros 2009). In the case of pre- and post-explosion comparisons, the appearance of an X-ray source at the GRB localization, once the early GRB afterglow and underlying supernova have significantly subsided (Kouveliotou et al. 2004), would provide direct access to the GCO itself.

If GRBs originate in binary systems and the binary remains bound after the explosion (Davies et al. 2002), it is possible that a soft X-ray transient will be formed after the explosion via black hole accretion (Brown et al. 2000); or through accretion onto a neutron star from the stellar wind of an O or B companion (Lewin, van Paradijs, & van den Heuvel 1995). Since GRBs are a subset of supernovae that in some cases may give birth to rapidly rotating magnetars, it makes sense to look for X-rays from an isolated rotation powered pulsar, not just an accreting binary. Perna, Raymond, & Loeb (2000) has computed the expected X-ray luminosity as a function of time for neutron stars born with different magnetic fields and spin periods. While the detection of a steady X-ray source at the site of the explosion would not by itself distinguish between a black hole or neutron star compact object, it would provide direct access to the compact object underlying the explosion.

Apart from modeling the SN and afterglow evolution, the main challenge with pre- and post-explosion comparisons is ruling out unrelated background sources such as AGN and pre-existing X-ray binaries sources at the GRB site. Fortunately, there already exists an extensive high-resolution X-ray image archive of nearby galaxies acquired during the past decade (Liu 2008). The recent compilation by Liu (2008) includes 383 galaxies within 40 Mpc. After excluding early-type galaxies, this leaves a subset of 200 late-type, irregular, and peculiar galaxies within 40 Mpc. Potentially, this extensive X-ray sample can be used to set restrictive upper limits on the X-ray emission at the GRB site prior to the explosion. Fig. 3 shows the X-ray luminosity limits  $L_X$  for 200 galaxies listed in Liu (2008) as a function of distance. Overplotted in Fig. 3 are the luminosity limits reachable for nearby GRB 980425 (Galama et al. 1998) and GRB 060218 with current X-ray telescopes assuming an X-ray flux limit  $f_X \sim 10^{-15}$  ergs cm $^{-2}$  s $^{-1}$ . In the case of GRB 060218, a detection of a newly formed X-ray binary would have to exceed the levels of Eddington luminosity for a stellar-mass black hole. The situation improves for less distant events.

Barring the highly unlikely explosion of a GRB in our Galactic neighborhood (Stanek et al. 2006), a direct detection of a GCO embedded in a GRB remnant near the Galactic plane will have to rely heavily on studies based on morphol-



**Fig. 3.** X-ray luminosity limits in the 0.3–10 keV band for the subsample of galaxies tabulated in (Liu 2008) plotted as a function of distance  $D_L$  (open circles). For comparison we also show the respective limits for GRB 980425 (Galama et al. 1998) and GRB 060218 (stars) assuming an X-ray flux limit of  $f_X = 10^{-15}$  ergs cm $^{-2}$  s $^{-1}$ . The shaded region shows the expected range in X-ray luminosities for X-ray binaries (Grimm, Gilfanov, & Sunyaev 2002). The dashed line near the top denotes the Eddington limit for a stellar mass black hole.

ogy alone (Perna, Raymond, & Loeb 2000; Ioka & Mészáros 2009). Numerical simulations suggest that the evolution of the GRB explosion would create non-spherical topologies that could stand out against the remnants of other stellar explosions (Ayal & Piran 2001; Ramirez-Ruiz & MacFadyen 2008). However, the stability of such non-spherical morphology has been called into question given the sideways evolution of the relativistic jet (Zhang & MacFadyen 2009). Indeed, GRB remnants may lurk within the numerous shells identified near the Galactic plane, but distinguishing them from other types of stellar remnants will be a very tall task (Daigle, Joncas, & Parizeau 2007). In practical terms, the actual probability of GRB remnant detection is determined simply by the available volume that can be sampled and accurately classified. Currently, the likelihood of detecting such a GRB remnant with the available sample of high-energy sources appears limited (Aharonian et al. 2006; Holder et al. 2006; Rico 2008; Abdo et al. 2009). Fortunately, future dedicated GeV/TeV surveys could bring such detection within reach (Buckley et al. 2008).

#### 4. Conclusions

In this paper we have conducted a search for early pulsations from the compact object of the nearby GRB 060218. No significant evidence of pulsations is observed. This null detection suggests that the afterglow continuum most likely swamps any pulsation/modulation signature or that the viewing angle into the progenitor is rather unfavorable. By itself, this result is not sufficient to rule out neutron star models. It should be noted that

high redshifts and bright relativistic jets will challenge a sensitive search for pulsations in other GRBs detected by *Swift*.

Based on our analysis, opportunities of observing GCOs directly either through their interaction with a bound stellar binary companion or via the detection of a compact object embedded within a GRB remnant near the Galactic plane offer modest hope for moving beyond afterglow science in the near future. The situation could radically change with a reasonably placed GRB in the Local Volume (*e.g.*, SN 1987A) or through substantial progress in our GeV/TeV capabilities. Thus, we conclude that observational progress on the nature of GCOs will once again have to rely heavily on the serendipity that is central to the origin and history of the GRB field.

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