PROCEEDINGS OF SCIENCE

The State of Magnetars

Ersin Göğüş[*†]

Sabancı University, Faculty of Engineering and Natural Sciences, Orhanlı− Tuzla, İstanbul, 34956 Turkey

E-mail: ersing@sabanciuniv.edu

We have witnessed a remarkable advancement in the field of magnetars, neutron stars with extremely strong magnetic fields in recent years. The number of magnetar systems has tripled in less than a decade, and almost all known sources exhibited extraordinary observational characteristics, such as extremely energetic giant flares, various timing anomalies (glitches and anti-glitches), sudden X-ray brightening, etc. The latest two sources appended to the family of magnetars are not shy in disseminating their unique features: 1E 161348–5055 is the longest spin period neutron star system, and PSR J1119−6127 is an energetic rotation powered pulsars. Here, we review some of their unique characteristics; in particular, what binds them to the family of magnetars, which is their energetic bursts.

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[*] Speaker.

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1. Introduction

Magnetars are isolated neutron stars that are characterized by emitting highly energetic bursts in hard X-rays and soft gamma rays. The burst energetics and repetition characteristics of magnetars during their occasional burst active episodes are quite diverse: Some magnetars can emit as few as a single burst, while prolific magnetars emit hundreds of bursts during their activity period (Göğüş 2014). The most common bursts are the short duration ones, lasting only for a fraction of a second but the energy released during such a short interval is very large, ranging from $\sim 10^{37}$ erg to 10^{40} erg (see e.g., Göğüş et al. 2001, Gavriil et al. 2004, van der Horst et al. 2012). Very rarely, magnetars emit extremely energetic giant flares, which last for several minutes and releasing energy in excess of 10^{44} erg (assuming isotropic emission). Only three giant flares have been observed so far (Mazets et al. 1979, Hurley et al. 1999, Palmer et al. 2005). Magnetars also emit intermediate events whose typical energies are in between those of short bursts and giant flares (Lenters et al. 2003, Göğüş et al. 2011). Moreover, during burst active phases, some magnetar exhibit increased X-ray emission in conjunction with their outburst (Kaspi et al. 2003, Woods et al. 2004) while some others do not exhibit any significant persistent X-ray increase after emitting burst (Lin et al. 2011). See Kaspi & Beloborodov (2017) for a recent review on burst and persistent emission properties of magnetars.

Both persistent X-ray emission and luminous bursts are expected from strongly magnetized neutron stars (or simply magnetars Duncan & Thompson 1992). Within the context of the magnetar model, the decay of very strong magnetic fields ($10^{14}-10^{15}$ G) can power the persistent emission from magnetars (Thompson & Duncan 1996, Thompson, Lyutikov & Kulkarni 2002), while the energetic bursts can be either due to fracturing of the neutron star crust that is strained by magnetic stress (Thompson & Duncan 1995) or due to the split and reconnection of its magnetic field lines (Lyutikov 2003; 2015).

The family of magnetars has been growing steadily over the last decade with new magnetar source discoveries, as well as magnetar-like behavior of isolated neutron star systems. Since 2008, eight new magnetar candidates were discovered when they emitted short energetic bursts. At least two of these new members possess an inferred dipole magnetic field lower than the quantum critical limit of 4.4×10^{13} G. In Figure 1 we present the P$-\dot{\mathrm{P}}$ diagram of radio pulsars, rotating radio transients, and magnetars (Soft Gamma Repeaters, SGRs and Anomalous X-ray Pulsars, AXPs). Also in 2008, there was an intriguing report of magnetar-like bursts from an energetic rotation-powered pulsar in Kes 75 (Gavriil et al. 2008). The inferred dipole magnetic field of this source, PSR J1846$-$0258, is in excess of the quantum critical field ($B = 4.9\times10^{13}$G), and its place on the P$-\dot{P}$ diagram is encircled (Figure 1). The latest additions to the magnetar population in 2016 were also quite astonishing: 1E 161348–5055, a very long period X-ray pulsar in the heart of a young supernova remnant RCW 103, and PSR J1119$-$6127, a strongly magnetized rotation-powered neutron star exhibited magnetar-like energetic bursts, similar to PSR J1846$-$0258. Here, we briefly review observational characteristics of these two sources, and discuss their implications in our understanding of the the evolutionary relation between magnetars and isolated neutron stars.

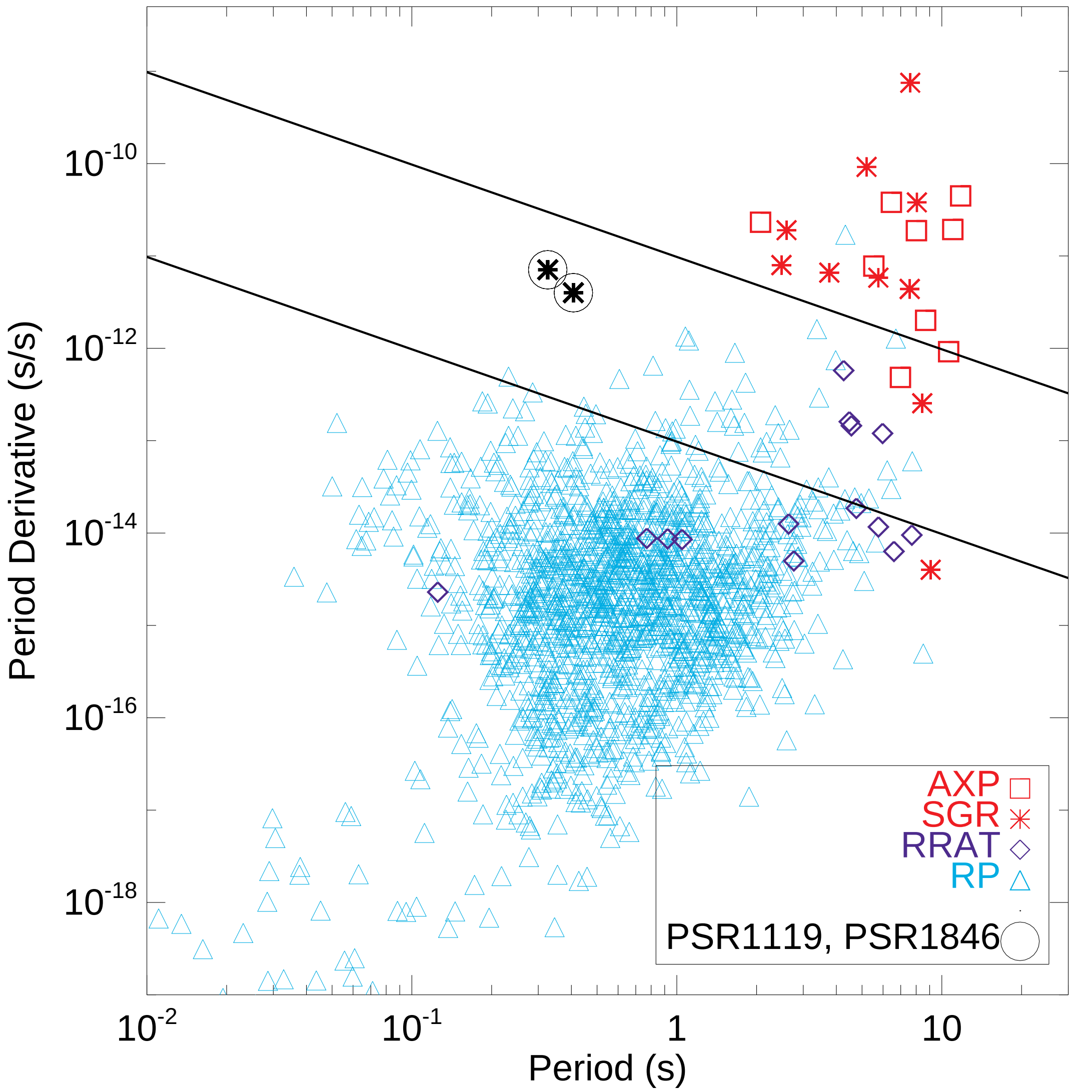

Figure 1: P$-\dot{P}$ distribution of radio pulsars (RP), anomaluous X-ray pulsars (AXP), soft gamma repeaters (SGR) and rotating radio transients (RRAT). The upper and lower solid lines show the constant magnetic field lines of 10^{14} and 10^{13} G, respectively. Encircled sources are the two strongly magnetized rotation-powered pulsars, PSR J1846−0258 (left) and PSR J1119−6127 (right).

2. 1E 161348–5055

The point X-ray source 1E 161348–5055 is located at the center of a $\sim$ 2000 years old shell-type supernova remnant RCW 103. A deep *XMM-Newton* observation of the source revealed extremely long periodic modulations at 6.67±0.03 hours (De Luca et al. 2006). Subsequent monitoring observations with *Swift* indicate that the source has been emitting at a low flux level for the last decade. Based on these monitoring observations from April 2006 till April 2011, Esposito et al. (2011) placed an upper limit to the period derivative, $|\dot{P}| < 1.6 \times 10^{-9}$ s s^{-1} at a 3σ level.

The interpretation of the long periodic modulation of 6.7 hours had been a dilemma, as it could arise from the orbital motion in a binary, or from the spin of an isolated neutron star. There is no observational evidence of binary nature in this system, therefore, a putative companion needed to be a M-type star with mass $\lesssim 0.4\ M_{\odot}$. This led De Luca et al. (2006) to suggest that 1E 161348–5055 might a peculiar system in a low-mass X-ray binary, powered by accretion onto a recently born compact object via both wind and disk. Alternatively, 1E 161348–5055 could be a magnetar in a binary system. In this case, both magnetic breaking and accretion torque might take place in rapid spin-down of the neutron star so that it could slow down to 6.7 hr in just two kyr. Note that there are at least two other very long period X-ray sources, suggested as accreting magnetars: IGR J16358−4726 (Patel et al. 2007) and 4U 2206+54 (Reig et al. 2012).

A magnetar-like burst from the direction of 1E 161348–5055 was recorded with *Swift* Burst Alert Telescope at 02:03:13 UT on 2016 June 22 (D'Ai et al. 2016). With this activity, the association of the source with magnetars was established, and the known source gained a new designation: SGR 1617-5103 (Stamatikos et al. 2016). We present below the 15-25 keV and 25-100 keV light curves of the event, as well as the hardness ratio (i.e., the ratio of the number of counts per bin in the upper energy band to that in the lower band) evolution in Figure 2. The duration of the event is about 8 ms long, and consists of two resolved pulses (Stamatikos et al. 2016, Rea et al. 2016). The time-integrated hard X-ray spectrum of the burst is described the best using a power law model with index 1.77, while a blackbody model with a temperature of 9.9 keV also provides an acceptable fit but relatively poorer fit statistics (Stamatikos et al. 2016). We find in our hardness ratio investigation throughout the event that there are evidences of hard-to-soft spectral evolution in both emission episodes (see the bottom panel of Figure 2). However, the number of burst counts during the very short duration was not enough to perform time-resolved spectral investigation, and determine the spectral nature conclusively.

A long-term persistent X-ray emission characteristics of 1E 161348–5055 was comprehensively investigated by Rea et al. (2016). Based on extensive archival observations spanning more than 15 years, they showed that the source was in outburst in 1999, with a source luminosity reaching more than 3.6×10^{35} erg/s, that is the highest level observed from this source to date (Rea et al. 2016). Overall outburst decay properties (e.g., energetics, time scales, etc.) resemble general characteristics of magnetar outbursts (see Rea & Esposito 2011 for a review). In the case of 2016 outburst of 1E 161348–5055, however, the source was already found to be in a high luminosity state before it emitted the energetic magnetar-like burst (Rea et al. 2016).

3. PSR J1119−6127

A young rotation-powered neutron star, PSR J1119−6127 was already at the center of attention for its extraordinary characteristics. It is among the group of isolated neutron star with high inferred surface dipole field strength; for PSR J1119−6127 it is 4.1×10^{13} G (Camilo et al. 2000). Its inferred rotational energy loss is extreme, $\dot{E} = 2.3\times10^{36}$ erg/s and pulsed emission was detected even en gamma rays (Parent et al. 2011). The source was also observed to exhibit sudden timing anomalies, glitches. Its 2007 glitch was phenomenal; following the glitch, PSR J1119−6127 started exhibiting rotating radio transient (RRAT, McLauhglin et al. 2006) type of behavior for a while. The recovery of its spin frequency evolution was also distinct, and standard glitch models were

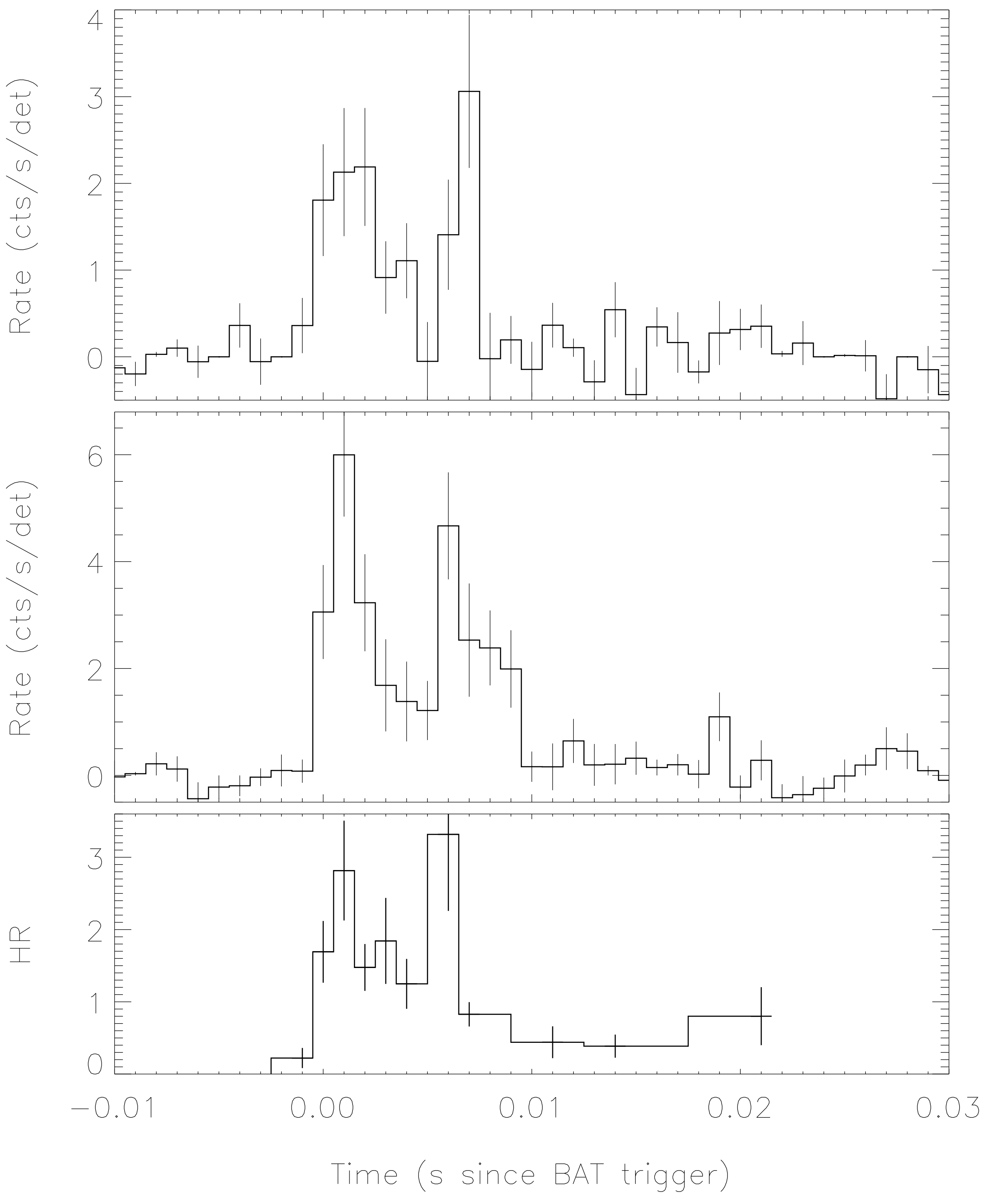

Figure 2: *Swift* Burst Alert Telescope light curves of the burst from 1E 161348–5055 observed in the 15−25 keV (top panel) and 25−100 keV (middle panel) bands. The bottom panel shows the hardness ratio variations during the event, that is the ratio of the curve in the middle panel to that in the top panel.

unable to explain them. The last but not the least, unlike many other glitching neutron stars, there were glitch induced changes in its radio emission properties (Weltevrede, Johnston, & Espinoza 2011, Antonopoulou et al. 2015).

On 2016 July 27 and 28, there were magnetar-like bursts from the direction of PSR J1119 − 6127: The first was detected with the *Fermi*/Gamma-ray Burst Monitor (GBM) (Younes et al. 2016), and the second with the *Swift*/BAT (Kennea et al. 2016). In Figure 3 below, we present the 15-25 keV and 25-100 keV light curves of the second event, as well as the hardness ratio evolution. A deep search for other low intensity bursts revealed other 10 bursts detected with GBM and BAT, therefore, making the total number of emitted bursts 12 (Göğüş et al. 2016). The spectral shape of these events in the 8−200 keV band are similar to that of typical magnetar bursts; they are describe the best with the sum of two blackbody functions with temperatures of about 4 and 11 keV. We also uncovered a burst induced persistent X-ray flux enhancement, which is spectrally softer than the burst, and exhibits evidence of cooling over a short timescale of minutes (Göğüş et al. 2016).

The onset of the bursting episode in PSR J1119 − 6127 was coincident with numerous other exceptional facts. The persistent X-ray flux of the source suddenly increased by a factor of larger than 160, and the source experienced another large timing anomaly (Archibald et al. 2016). Morever, pulsed radio emission of the source was suddenly interrupted for two weeks before it resumed (Burgay et al. 2016). After reappearance of the pulsed emission in radio, multi-component emission structures were detected (Majid et al. 2017), indicating that similar to the 2007 glitch ant its aftermath, the 2016 activity also caused changes in the radiative behavior of the source.

4. Discussion

Since their emergence as a distinct class of objects in late 80s until about a decade ago, magnetars were regarded as a small subset of isolated neutron stars. The discovery of transient magnetars was a major step (Ibrahim et al. 2004). Now there are about 30 known magnetars or candidate (Olausen and Kaspi 2014). If those systems that are closely related to magnetars are also taken into account, the number of the family exceeds 40. Those closely related systems are rotating radio transients (McLaughlin et al. 2006), newly emerging fast radio burst sources in particular the repeating one (Spitler et al. 2016), and some extragalactic neutron star ultra-luminous X-ray sources (Israel et al. 2017).

The addition of the two sources described here to the family of magnetars is particularly staggering. On one hand, we have the young neutron star with the longest known spin period. Magnetars are expected to born with very short initial spin period of 1−3 ms (Thompson & Duncan 1993) and slow down efficiently under magnetic breaking. In the case of 1E 161348–5055, the situation is extreme: In order to slow down to about 24000−s spin period in 2 kyr, a secular spin-down rate should be about 4×10^{-7} s/s. To supply additional torque to slow the neutron star down, a long-lived fall-back disk was also suggested (De Luca et al. 2006).

The other intriguing addition to magnetars, PSR J1119 − 6127 has opened an exceptional avenue: We now have a source that emits energetic high intensity bursts and undergoes outburst episode (which are typical characteristics of transient magnetars), as well as exhibiting large timing anomalies, that is a characteristic of Vela-like rotation powered pulsar. Coincident bursts and large glitch are strongly indicative of either a common origin for both phenomena or a causal relation

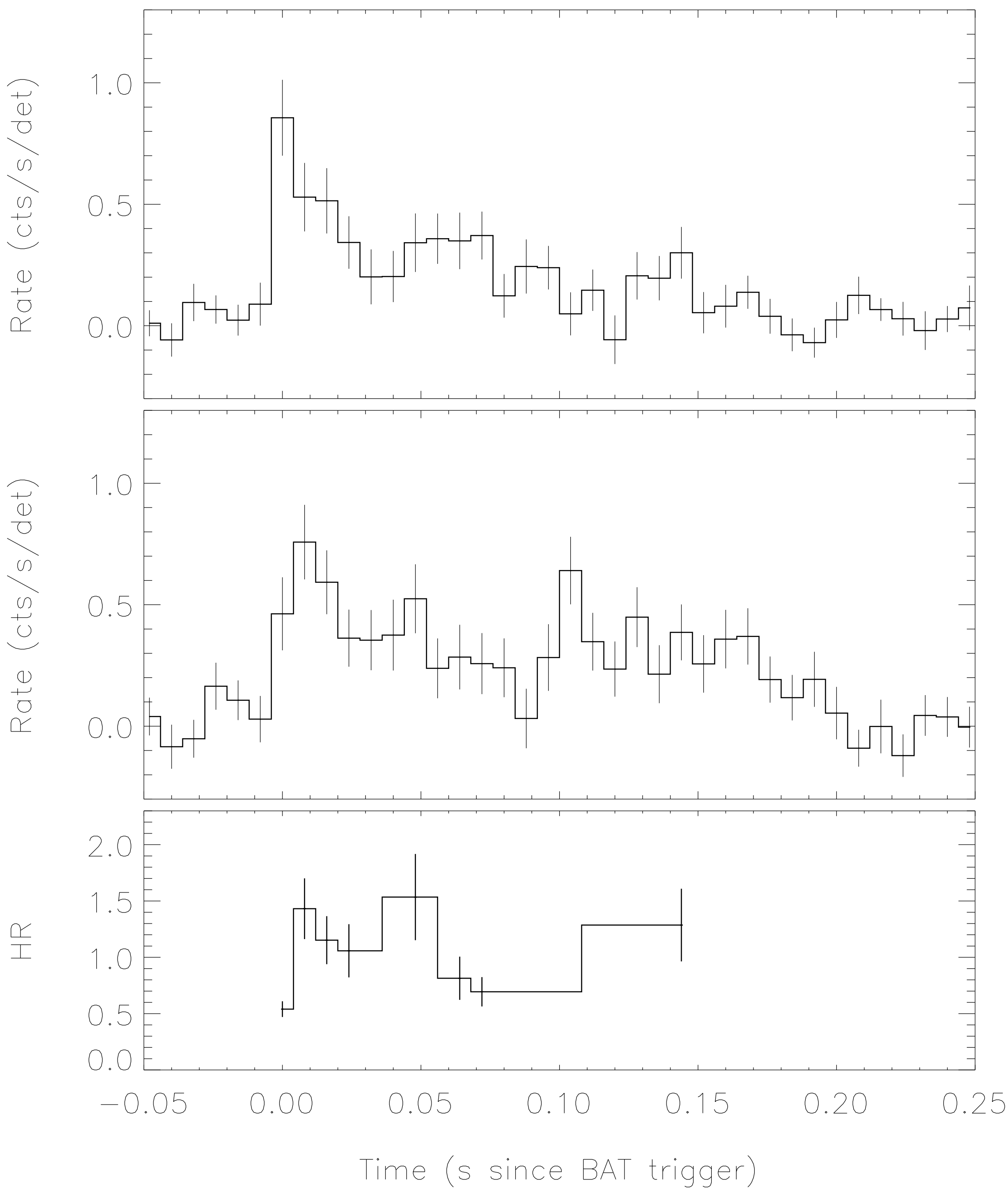

Figure 3: *Swift* Burst Alert Telescope light curves of the burst from PSR J1119 − 6127 observed in the 15−25 keV (top panel) and 25−100 keV (middle panel) bands. The bottom panel shows the hardness ratio variations during the event, that is the ratio of the curve in the middle panel to that in the top panel.

between the two. Akbal et al. (2015) successfully employed a starquake induced vertex-unpinning scenario to account for the recovery of its 2007 glitch. On the other hand, the large glitch in 2016 and the coincident magnetar-like bursts we presented in Göğüş et al. (2016) hint more at crustquake origin for both kind of events. However, associated radiative variations, most likely via magnetospheric rearrangements still leaves a room for the magnetic reconnection process to take place in this source. The issue of magnetar-like burst and glitch connection will likely be addressed more conclusively when more post-glitch temporal observations are accumulated.

Acknowledgments

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