Optical and infrared flares from a transient Galactic soft γ-ray repeater

A. J. Castro-Tirado[1], A. de Ugarte Postigo[2,1], J. Gorosabel[1], M. Jelínek[1], T. A. Fatkhullin[3], V. V. Sokolov[3], P. Ferrero[4], D. A. Kann[4], S. Klose[4], D. Sluse[5], M. Bremer[6], J. M. Winters[6], D. Nuernberger[2], D. Pérez-Ramírez[7], M. A. Guerrero[1], J. French[8], G. Melady[8], L. Hanlon[8], B. McBreen[8], F. J. Aceituno[1], R. Cunniffe[1], P. Kubánek[1], S. Vitek[1], S. Schulze[4], A. C. Wilson[9], R. Hudec[10], J. M. González-Pérez[11], T. Shahbaz[11], S. Guziy[12], S. B. Pandey[13] L. Pavlenko[14], E. Sonbas[3,15], S. A. Trushkin[3], N. N. Bursov[3], N. A. Nizhelskij[3] and L. Sabau-Graziati[16]

[1] Instituto de Astrofísica de Andalucía (IAA-CSIC), P.O. Box 03004, 18080 Granada, Spain.

[2] European Southern Observatory, Casilla 19001, Santiago 19, Chile.

[3] Special Astrophysical Observatory of Russian Academy of Science (SAO-RAS), Nizhnij Arkhyz, Karachai-Cherkessia, 369167 Russia.

[4] Thüringer Landessternwarte Tautenburg, Sternwarte 5, D-07778 Tautenburg, Germany.

[5] Laboratoire d´Astrophysique, École Polytechnique Fédérale de Lausanne (EPFL) Observatoire, 1290 Sauverny, Switzerland.

[6] Institute de Radioastronomie Millimétrique (IRAM), 300 rue de la Piscine,

38406 Saint Martin d´Héres, France.

[7] Facultad de Ciencias Experimentales, Universidad de Jaén, Campus Las Lagunillas, E-23071 Jaén, Spain.

[8]School of Physics, University College Dublin, Dublin 4, Ireland.

[9]Department of Astronomy, University of Texas, Austin, TX 78712, USA.

[10]Astronomical Institute of the Czech Academy of Sciences, Fricova 298, 25165 Ondřejov, Czech Republic.

[11]Instituto de Astrofísica de Canarias (IAC), Via Láctea s/n, E-38205 La Laguna (Tenerife), Spain.

[12] Nikolaev State University, Nikolskaya 24, 54030 Nikolaev, Ukraine.

[13] Aryabhatta Research Institute of Observational-Sciences (ARIES), Manora Peak, NainiTal, Uttarakhand, 263129, India.

[14] Crimean Astrophysical Observatory, 98409 Nauchny, Ukraine.

[15] University of Cukurova, Department of Physics, 01330 Adana, Turkey.

[16] Instituto Nacional de Técnica Aerospacial (INTA), Ctra. de Ajalvir km. 4, 28750 Torrejón de Ardoz (Madrid), Spain.

Soft γ-ray repeaters (SGRs) are a rare type of γ-ray transient sources that are ocasionally detected as bursts in the high-energy sky[1]. They are thought to be produced by *magnetars*, young neutron stars with very strong magnetic fields of the order of 10^{14-15} G (refs 2, 3). Only three such objects are known in our Galaxy,

and a fourth one is associated with the supernova remnant N49 in the Large Magellanic Cloud[4]. In none of these cases has an optical counterpart to either the γ-ray flares or the quiescent source been identified. Here we present multi-wavelength observations of a puzzling source, SWIFT J195509+261406, for which we detected more than 40 flaring episodes in the optical band over a time span of 3 days, plus a faint infrared flare 11 days later, after which it returned to quiescence. We propose that SWIFT J195509+261406 is a member of a subgroup of SGRs for which the long-term X-ray emission is transient in nature. Furthermore, it is the first SGR for which bursts have been detected in the optical and near-infrared bands and maybe the link between the "persistent" SGRs and the dim isolated neutron stars.

On 10 June 2007, 20:52:26 UT *Swift*/BAT detected GRB 070610 / SWIFT J195509+261406, as a gamma-ray burst (GRB) with a single "FRED"-like (fast rise phase and exponential decay) profile, lasting about 8 s in total[5]. Following typical procedures for GRB follow-ups, *Swift*/XRT began to observe the field shortly after the discovery and detected an X-ray counterpart[6]. Ground based observations also detected an optical source consistent with the high-energy detections. However, it was soon realized that this counterpart behaved differently from the "classical" GRB afterglows observed so far, i.e. the light curves showed evidence of rapid variability with intense flaring activity[7]. The X-ray spectrum, obtained during the first 8000 s of observation, was modeled with an absorbed power law, with a total column density consistent with the Galactic value of $N(H) = 1 \times 10^{22}$ cm^{-2}. This, together with the location of the source in the Galactic plane ($l^{II} = -1°$), supports the view that the source is hosted by the Milky Way[8] as we show in this work.

We triggered a multi-wavelength observing campaign including radio observations at RATAN-600, millimeter observations at Plateau de Bure, optical photometry at several ground-based observatories, infrared adaptive optics imaging at the ESO Very Large 8.2m Telescope, optical spectroscopy at the Russian 6.0m telescope and late time X-ray observations with *XMM-Newton*. We also carried out CO (J = 1-0) millimeter observations at Pico Veleta in order to search for molecular clouds towards the line of sight. This campaign was supplemented by available *Swift*/XRT data. For further details, see the Supplementary Material provided with this work.

Our data were collected starting ~1 min after the burst trigger time. In the first three nights of our observations, the source displayed strong flaring activity[9] (Fig. 1). The flares of SWIFT J195509+261406 (see Table 2 of the Supplementary Material) had durations in the range of tens of seconds to a few minutes and flux amplitudes of up to $\sim 10^2$ with respect to the "outburst" basal flux (or $\geq 10^4$ with respect to the quiescent state; Fig. 2). Strong optical and X-ray flaring was detected over a 3 day activity period. After 13 June, the activity decayed abruptly (Fig. 3) and no further flares were seen until 21 June, when a late-time, lower-brightness flare was detected in the

H-band using the 8.2m VLT (+NACO). A late-time observation by *XMM-Newton* $\sim$ 170 days after the burst, failed to detect the source, imposing an upper limit (3σ) to any underlying X-ray flux of $\leq 3.1 \times 10^{-14}$ erg cm^{-2} s^{-1} (0.2-10 keV).

It has been suggested that the source is similar to the black hole candidate V4641 Sgr[10], a Galactic microquasar for which rapid optical variations of a factor up to 500 on a timescale of tens of seconds were also detected[11] and X-ray flares with peak luminosities of up to $\sim 4 \times 10^{39}$ erg s^{-1} (ref. 12), far above the Eddington luminosity of a 10 $M_\odot$ black hole. In fact, it has been proposed that V4641 Sgr (a high-mass X-ray binary) and SWIFT J195509+261406 belong to the same class of astrophysical objects[13]. However, several lines of evidence point against this association. First, the lack of further detections at γ-ray (by *Swift*/BAT), millimeter ($<$ 0.6 mJy, 3σ) and centimeter wavelengths ($<$ 0.3 mJy, 3σ, ref. 14) implies a different behaviour from Galactic microquasars, which produce considerable gamma-ray and radio emission at the time of the outbursts[15,16]. Moreover, the lack of Hα emission ($< 9.0 \times 10^{-16}$ erg s^{-1} cm^{-2} within a $2''$ aperture) in our spectra and in our narrow-band images obtained at the 6.0m BTA makes it unlikely that it is an accreting black hole candidate in a binary system.

Another possibility is that this source is mimicking the "bursting pulsar" GRO J1744–28, a low-mass X-ray binary which displayed $\sim$20 hard X-ray bursts per hour following its discovery, before it entered a regime of hourly bursting lasting for nearly 4 months, with the burst rate decreasing dramatically after that time[17,18]. Flare peak luminosities reached up to $\sim 10^{39}$ erg s^{-1} (ref. 19), far above the Eddington luminosity of a 1.4 $M_\odot$ neutron star. No burst episodes were reported at other wavelengths for this pulsar, possibly due to the high Galactic extinction along the line of sight.

Contrary to GRO J1744–28, however, the fact that *Swift*/BAT has not recorded any other gamma-ray burst from SWIFT J195509+261406 after the initial one, points to the interesting possibility that SWIFT J195509+261406 is a new soft gamma-ray repeater (SGR) in our Galaxy, from which only the initial hard spike of a bursting activity period has been recorded in γ rays. If this is the case, SWIFT J195509+261406 becomes the first SGR detected at optical wavelengths, as a previous claim of such a detection for SGR 0526–66 (ref. 20) could not be firmly established. The lognormal distribution of the optical flares strengthens this association (see Fig. 4).

In contrast to SGR 0526–66, SGR 1806–20 and SGR 1900+14, which all show "persistent" X-ray emission in the range $\sim 10^{-11}$ to 10^{-12} erg cm^{-2} s^{-1}, SWIFT J195509+261406 strongly resembles the "transient" behaviour of SGR 1627–41. The latter source experienced an activity period for 6 weeks in 1998 (ref. 21) and its underlying X-ray flux was observed to decrease by a factor of ~ 50 over a timespan of 1,000 days, flattening off at $\sim 3 \times 10^{-13}$ erg cm^{-2} s^{-1}. Based on this, we suggest that SWIFT J195509+261406 is, together with SGR 1627–41, a "transient" soft gamma-ray repeater, being the first SGR (either persistent or transient) that shows strong and protracted optical flaring activity in our Galaxy. Assuming a distance of ~ 11 kpc for

SGR 1627–41, its quiescent luminosity in the 2-10 keV band is $L_X \sim 4 \times 10^{33}$ erg s^{-1} (ref. 22). The X-ray luminosity of SWIFT J195509+261406 during the first 8,000 s that followed the initial γ-ray spike was $\sim 4.7 \times 10^{34}$ (D/10 kpc)^2 erg s^{-1} and $\leq 3.6 \times 10^{32}$ (D/10 kpc)^2 erg s^{-1} at the time of our late-time X-ray observation after $\sim$ 170 days. If the *SWIFT* source has the same quiescent L_X as SGR 1627-41 (the other member of the transient SGR class), then from the limit imposed by *XMM-Newton* it would lie at $\geq$ 35 kpc, far beyond the outer spiral arm in our Galaxy. In fact, an upper limit to the distance of D $<$ 100 kpc can be derived assuming that the peak of the X-ray flare observed on 11 June does not exceed by a factor of $\sim$ 10 the Eddington luminosity for a 1.4 $M_\odot$ neutron star[23]. On the other hand, taking into account the lower limit to its distance inferred by us from the CO observations (D $>$ 7.0 kpc, see Supplementary Material), we can conclude that the distance of SWIFT J195509+261406 is in the range 7-20 kpc (comparable to the three known SGRs in the Galaxy), and that its quiescent $L_X \leq$ (2.5-7.2) $\times 10^{32}$ erg s^{-1}.

A deeper X-ray observation together with a detailed study of future activity periods of SWIFT J195509+261406 can shed light into this new "transient" SGR class and whether it constitutes a possible link between "persistent" SGRs (with $L_X \sim$ (2-4) $\times 10^{35}$ erg s^{-1}) and dim isolated neutron stars[24] (with $L_X \sim$ (2-20) $\times 10^{30}$ erg s^{-1}).

References.

1. Mazets, E. P., Golenetskii, S. V., Gurian, Iu. A. & Ilinskii, V. N. The 5 March 1979 event and the distinct class of short gamma bursts: Are they of the same origin? *Astrophys. and Sp. Sci.* **84**, 173-189 (1982).

2. Kouveliotou, C. *et al.* The Rarity of Soft Gamma-Ray Repeaters Deduced from Reactivation of SGR 1806-20, *Nature* **368**, 125-127 (1994).

3. Thompson, C. & Duncan, R. C. The Soft Gamma Repeaters as Very Strongly Magnetized Neutron Stars. II. Quiescent Neutrino, X-Ray, and Alfven Wave Emission, *Astrophys. J.* **473**, 322-342 (1996).

4. Hurley, K. The 4.5±0.5 Soft Gamma Repeaters in Review, in *Gamma-Ray Bursts, 5th Huntsville Symposium, Huntsville*, Eds. R. M. Kippen, R. S. Mallozzi, and G. J. Fishman, AIP Conf. Proc. **526**, 763-770 (2000).

5. Tueller, J., Barbier, L., Barthelmy, S. D. *et al.* GRB 070610, Swift-BAT refined analysis, *GCN Circ.* 6491 (2007).

6. Pagani, C. & Kennea, J. A. GRB 070610; Swift-XRT position, *GCN Circ.* 6490 (2007).

7. Stefanescu, A. *et al.* Very fast optical flaring from a possible new Galactic magnetar, *Nature*, submitted (2008).

8. Kann, D. A., Wilson, A. C., Schulze, S. et al. GRB 070610: TLS RRM sees flaring behaviour - Galactic transient?, *GCN Circ.* 6505 (2007).

9. de Ugarte Postigo, A., Castro-Tirado, A. J. & Aceituno, F. GRB 070610: Optical observations from OSN, *GCN Circ.* 6501 (2007).

10. Markwardt, C., Pagani, C., Evans, P. et al. SWIFT J195509.6+261406 / GRB 070610: A Potential Galactic Transient, *Astronomer´s Telegram* 1102 (2007).

11. Lindstrom, C. *et al.* New clues on outburst mechanisms and improved spectroscopic elements of the black hole binary V4641 Sagittarii, *Monthly Not. Royal Astron. Soc.* **363**, 882-890 (2005).

12. Revnivtsev, M., Gilfanov, M., Churazov, E. & Sunyaev, R. Super-Eddington outburst of V4641 Sgr, *Astron. Astrophys.* **391**, 1013-1022 (2002).

13. Kasliwal, M. M. *et al.* GRB 070610: A curious galactic transient, *Astrophys. J.* submitted, preprint available at http://arXiv.org/astro-ph/0708.0226

(2007).

14. Frail, D. A. & Chandra, P. VLA upper limit on GRB 070610, *GCN Circ.* 6539 (2007).

15. Mirabel, I. F. & Rodríguez, L. F. A Superluminal Source in the Galaxy, *Nature* **371**, 46-48 (1994).

16. Hjellming, R. M. *et al.* Light Curves and Radio Structure of the 1999 September Transient Event in V4641 Sagittarii (=XTE J1819-254=SAX J1819.3-2525), *Astrophys. J.* **544**, 977-992 (2000).

17. Kouveliotou, C. *et al.* A new type of transient high-energy source in the direction of the Galactic Centre, *Nature* **379**, 799-801 (1996).

18. Finger, M. H. *et al.* Discovery of hard X-ray pulsations from the transient source GRO J1744-28, *Nature* **381**, 291-293 (1996).

19. Sazonov, S., Sunyaev, R. & Lund, N. Super-Eddington X-ray Luminosity of the Bursting Pulsar GRO J1744-28: WATCH/GRANAT Observations, *Astronomy Letters* **23**, 326-334 (2005).

20. Pedersen, H. *et al.* Detection of possible optical flashes from the

gamma-ray burst source GBS0526-66, *Nature* **312**, 46-48 (1984).

21. Woods, P. M. *et al.* Discovery of a new soft gamma-ray repeater, SGR1627-41, *Astrophys. J.* **519**, L139-142 (1999).

22. Mereghetti, S., Esposito, P. & Tiengo, A. XMM-Newton observations of soft gamma-ray repeaters, *Astrophys Space Sci* **308**, 13-23 (2007).

23. Begelman, M. C. Super-Eddington fluxes from thin accretion disks?, *Astrophys. J.* **568**, L97-L100 (2002).

24. Treves, A., Turolla, R., Zana, S. & Colpi, M. Isolated neutron stars: accretors and coolers, *Publ. Astron. Soc. Pacific* **112**, 297-314 (2000).

25. Schlegel, E. M., Finkbeiner, D. P. & Davis, M. Maps of Dust Infrared Emission for Use in Estimation of Reddening and Cosmic Microwave Background Radiation Foregrounds, *Astrophys. J.* **500**, 525-553 (1998).

26. The SGR/AXP online catalog provided by the McGill Pulsar Group is available at http://www.physics.mcgill.ca/~pulsar/magnetar/main.html .

27. Israel, G. *et al.* Discovery and monitoring of the likely IR counterpart of SGR 1806-20 during the 2004 γ-ray burst-active state, *Astron. Astrophys.*

438, L1-L4 (2005).

28. Kosugi, G., Ogasawara, R. & Terada, H. A variable infrared counterpart to the soft gamma-ray repeater SGR 1806-20, *Astrophys. J.* **623**, L125-L128 (2005).

29. Hurley, K., McBreen, B., Delaney, M. & Britton, A. Lognormal Properties of SGR 1806-20 and Implications for Other SGR Sources, *Astrophys. Space Sci.* **231**, 81-84 (1995).

30. Göğüş, E. *et al.* Statistical Properties of SGR 1900+14 Bursts, *Astrophys. J.* **526**, L93-96 (1999).

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FIGURE CAPTIONS.

Figure 1. Flaring activity of SWIFT J185509+261406 on 11/12 June 2007. During a 4 hr period, the 1.2m Mercator telescope continuously observed the object with a sequence of 42 s exposures (plus 18 s readout) with an I_c-band filter. The dark area at the bottom of the plot represents the limit to any flaring activity of these observations. The brightest flare in this period (inset) reaches $I_c \sim 17.8$, which is still three magnitudes dimmer than the brightest flare, detected with WATCHER (reaching $I_c \sim 14.7$) which corresponds to a peak flux density of 2.96 mJy (not de-reddened, or 0.68 Jy de-reddened, for $A_I = 5.9$, ref. 25) A late-time flare (not shown here) was observed with the 8.2m VLT telescope on 22 June 2007 (08:09:27 UT). By analysing the different optical frames, we derive the following position for the source ($\pm$ 0″.27): R.A. (J2000) = 19h 55m 09.653s, Decl.:(J2000) = +26° 14′ 05″.84.

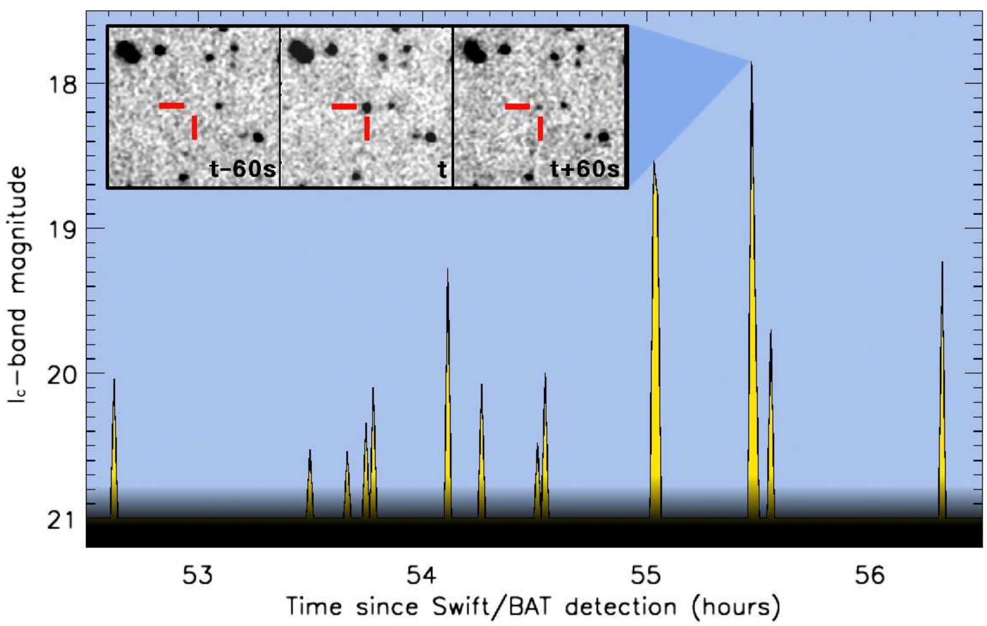
Figure 2. Optical and X-ray light curves of SWIFT J195509+261406 (June-November 2007). **a,** Optical detections (I_c-band magnitudes, filled circles, with 1σ s.d. error bars) are shown together with upper limits (3σ, downward pointing triangles). **b,** *Swift* X-ray data (0.2-10 keV, filled circles, with 1σ s.d. error bars) together with the late time limit (3σ) obtained with *XMM-Newton*. Both light curves show a strong activity during the first three days, reaching the maximum around one day after the bursts and gradually

decaying after the third day until the source became undetectable. The X-ray observations performed by *Swift* do not overlap with the times of any of the optical flares we have recorded. However, observations in both X-ray and optical agree that the strongest flaring activity is found around one day after the γ-ray event. A powerful X-ray flare, for which the flux increased by $\sim$100 in a timescale of less than 10^4 s, was followed by several optical flares of similar amplitude.

Figure 3. Deep, late observations of the SWIFT J195509+261406 field. a, Deep I_c-band image obtained with the 6.0m BTA (+SCORPIO) obtained on 12 October 2007. **b,** Deep H-band image obtained on 30 Sep 2007 with the 8.2m VLT (+ NACO) using laser guide star adaptive optics. Both images show that the source has disappeared. The location for SWIFT J185509+261406, is marked with a circle (error radius of $0''.27$). The limiting magnitudes are $I_c > 23.5$ and $H > 23.0$. Four anomalous X-ray pulsars (AXPs), a subclass of magnetars, have been detected at near-IR wavelengths[26] but no H-band counterpart of any SGR is known. SGR 1806–20, which is hidden by more than 30 mag visual extinction, was only seen in the K-band when it was in an active state[27,28]. All other three SGRs known so far have no NIR counterpart at all.

Figure 4. Lognormal distribution of flare fluxes for SWIFT J195509+261406. The magnitude distribution of the optical flares detected from SWIFT J195509+261406 in the I_c band is shown. Using all I_c-

Band detections of the source, we find that the flare fluxes are lognormally distributed as seen in the high-energy flares of SGR 1806–20 (ref. 29) and SGR 1900+14 (ref. 30), supporting the belief that SWIFT J195509+261406 is a new SGR. We find that the observed data is well fit by a truncated normal distribution (solid line) with $N = \frac{A}{w\sqrt{\pi/2}} e^{-2\frac{(x-x_c)2}{w^2}}$. Here, N is the number of flares in a one magnitude bin, x is the magnitude, x_c is the center of the distribution, w is the width and A is the amplitude. The fit is moderately well acceptable with χ^2=49.7 for 35 degrees of freedom, and we find as parameters: $x_c = 20.80 \pm 0.61$, $w = 2.96 \pm 0.76$ and $A = 64.5 \pm 22.7$. The truncation of the distribution is a natural result of the limiting magnitude of the observations. Such a lognormal distribution of fluxes is typical for high-energy bursts from SGRs.



t-60s
t
t+60s
18
19
20
21
I$_c$−band magnitude
53
54
55
56
Time since Swift/BAT detection (hours)

Figure 1:

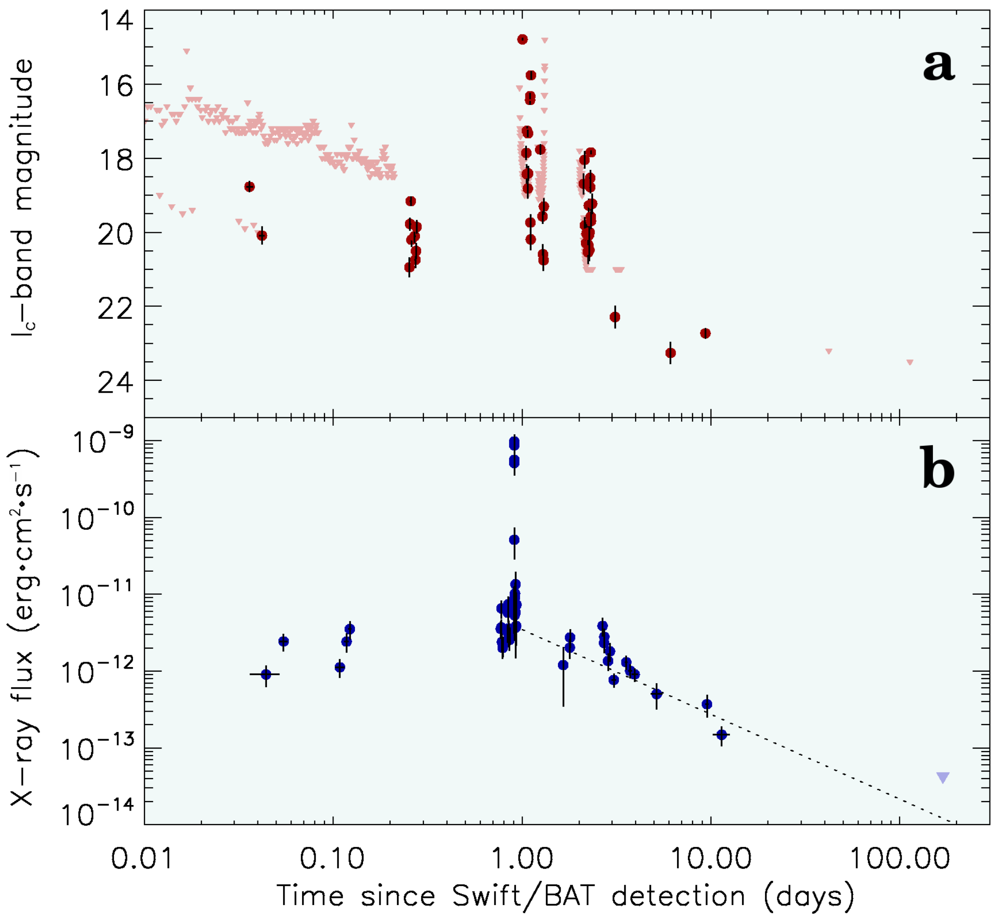

a
b
14
16
18
20
22
24
I_c–band magnitude
10^-9
10^-10
10^-11
10^-12
10^-13
10^-14
X–ray flux (erg•cm^2•s^-1)
0.01
0.10
1.00
10.00
100.00
Time since Swift/BAT detection (days)

Figure 2:

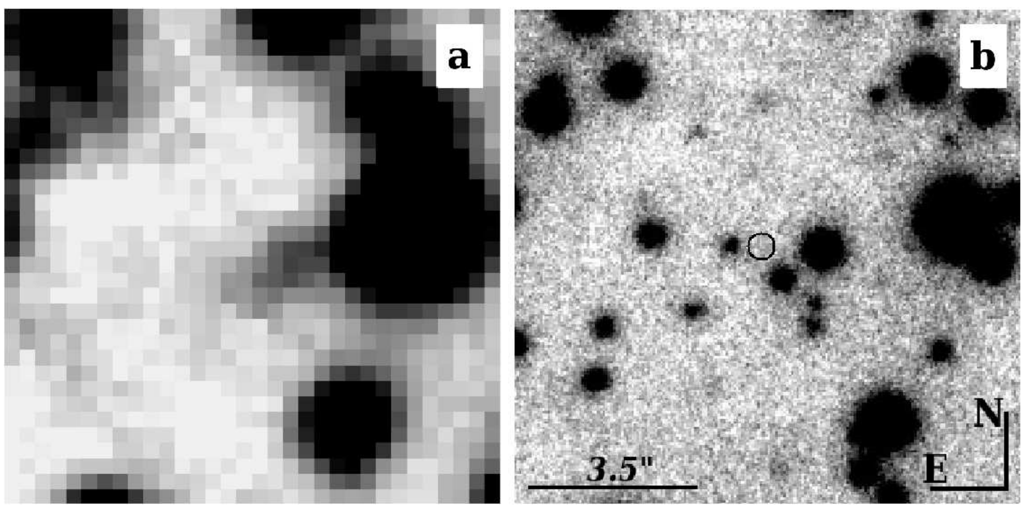


Figure 3:

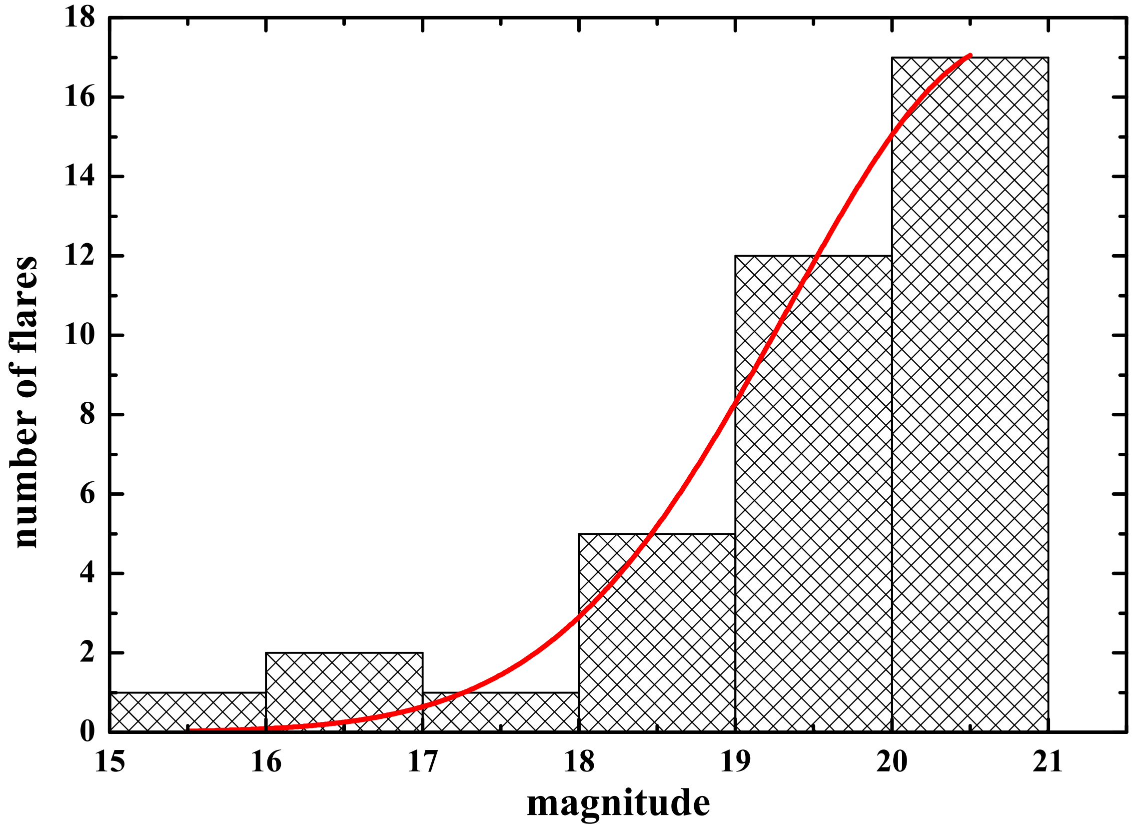

number of flares
magnitude
18
16
14
12
10
8
6
4
2
0
15
16
17
18
19
20
21

Figure 4: