Very fast optical flaring from a possible new Galactic magnetar

A. Stefanescu[1], G. Kanbach[1], A. Słowikowska[2,3], J. Greiner[1], S. McBreen[1] & G. Sala[1]

Highly luminous rapid flares are characteristic of processes around compact objects like white dwarfs, neutron stars and black holes. In the high-energy regime of X-rays and γ-rays, outbursts with variabilities on timescales of seconds or less are routinely observed, for example in γ-ray bursts[1] or soft γ-ray repeaters[2]. At optical wavelengths, flaring activity on such timescales has not been observed, other than from the prompt phase of one exceptional γ-ray burst[3]. This is mostly due to the fact that outbursts with strong, fast flaring are usually discovered in the high-energy regime; most optical follow-up observations of such transients use instruments with integration times exceeding tens of seconds, which are therefore unable to resolve fast variability. Here we show the observation of extremely bright and rapid optical flaring in the Galactic transient[4–7] SWIFT J195509.6+261406. Our optical light curves are phenomenologically similar to high-energy light curves of soft γ-ray repeaters and anomalous X-ray pulsars[8], which are thought to be neutron stars with extremely high magnetic fields (magnetars). This suggests that similar processes are in operation, but with strong emission in the optical, unlike in the case of other known magnetars.

SWIFT J195509.6+261406 was discovered as the γ-ray burst GRB 070610 (ref. 9) using the Burst Alert Telescope (BAT)[10] on board the NASA Swift spacecraft[11]. Subsequent observations in the X-ray (using Swift's X-ray telescope (XRT)[12] and the NASA Chandra X-ray Observatory[13]) and the optical bands have shown a point source compatible with the BAT error circle. The optical[4–6,14] and X-ray afterglow behaviour indicates that the source was probably not a γ-ray burst, but rather a Galactic X-ray transient[6,15]. It was therefore re-assigned the name SWIFT J195509.6+261406 (hereafter SWIFT J1955)[15].

Optical observations began just 421 s after the BAT trigger, using the OPTIMA-Burst[16] photo-polarimeter at the 1.3-m telescope of the Skinakas Observatory, Crete. A total of ~8.5 h of data was obtained during the five nights after the burst (Fig. 1). The overall optical light

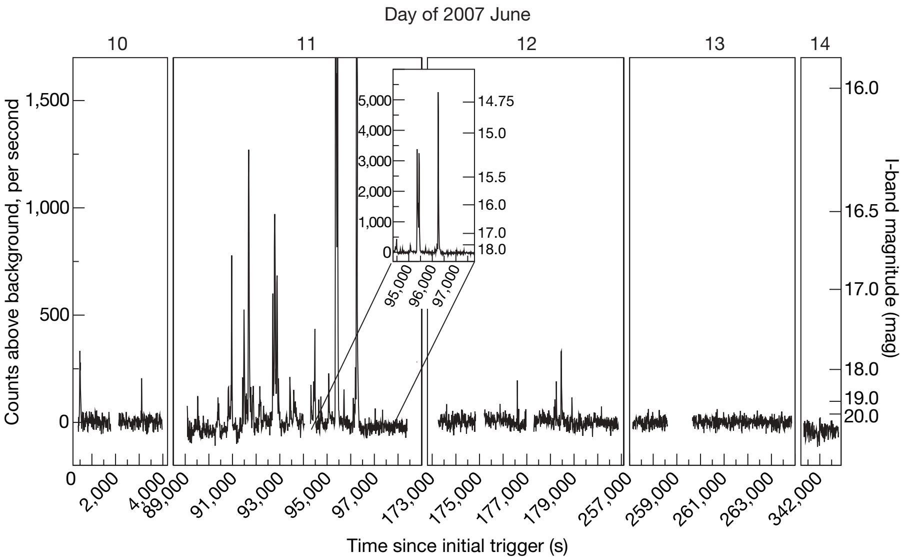

Figure 1 | Overview of overall optical high-time-resolution light curves of SWIFT J1955. The observations were obtained with OPTIMA-Burst[16], mounted at the 1.3-m Telescope of the Skinakas Observatory, Crete. OPTIMA-Burst is a fibre-fed system using six fibre apertures in a hexagonal bundle around the target fibre, plus one additional, more distant background fibre to determine and subtract the sky background. All apertures are of 300 μm diameter, corresponding to 6 arcsec on the sky with the SKO 1.3m telescope. The photon-counting mode of OPTIMA-Burst has an intrinsic photon-arrival-time resolution of 4 μs and records unfiltered white light radiation in the wavelength range 450–900 nm, with peak efficiency around 700 nm. To achieve a high signal-to-noise ratio, the recorded photon arrival times are binned into 10-s bins in the overview light curve shown here. The two most prominent flares, at 95,400 s and 96,250 s post trigger, are too bright to be shown adequately next to the rest of the flares, and are therefore displayed on a different scale in the inset (same axes as main panels). Owing to the very crowded field of SWIFT J1955, most of the available background channels were severely contaminated by field stars. The three least polluted background channels were used for background subtraction, but owing to changes in observing conditions from night to night, slight shifts (at the per cent level) in the zero-level occur between observation epochs. The observations were taken during a period of mediocre seeing, ranging from 1.5 to 2 arcsec. Simultaneous I-band (~630–1010-nm) observations, obtained with the IAC80 telescope of the Instituto de Astrofísica de Canarias (de Ugarte Postigo and Castro-Tirado, personal communication), were used to calibrate count rate to magnitudes.

---

[1]Max-Planck-Institute for Extraterrestrial Physics, PO Box 1312, 85741 Garching, Germany. [2]IESL, Foundation for Research and Technology - Hellas, PO Box 1385, GR-711 10 Heraklion, Greece. [3]Copernicus Astronomical Center, Rabiańska 8, 87-100 Toruń, Poland.

curve shows two brief flares shortly after the high-energy trigger on the first night[4] (2007 June 10). The second night shows a marked increase in flaring activity, culminating in two extremely bright flares with complex substructures[14] (2007 June 11). The morphology of the light curve, that is, isolated, brief bursts consisting of just one short peak and a bunching of these bursts in spurts of activity, is reminiscent of major X-ray outbursts in soft γ-ray repeaters (SGRs)[17].

The two most prominent flares, recorded near the end of the build-up in activity on 2007 June 11, are shown in detail in Fig. 2. A notable feature of these light curves is a very bright flare with an extremely steep rise followed by a slower, exponential decay. Superimposed on both flares are a number of secondary flares, again with a distinct FRED shape. The brightness on the rising edge changes by a factor of more than 200 over only 4 s, and possibly by even more than a factor of 10,000 when taking into account independent upper limits on the quiescent emission[7,18].

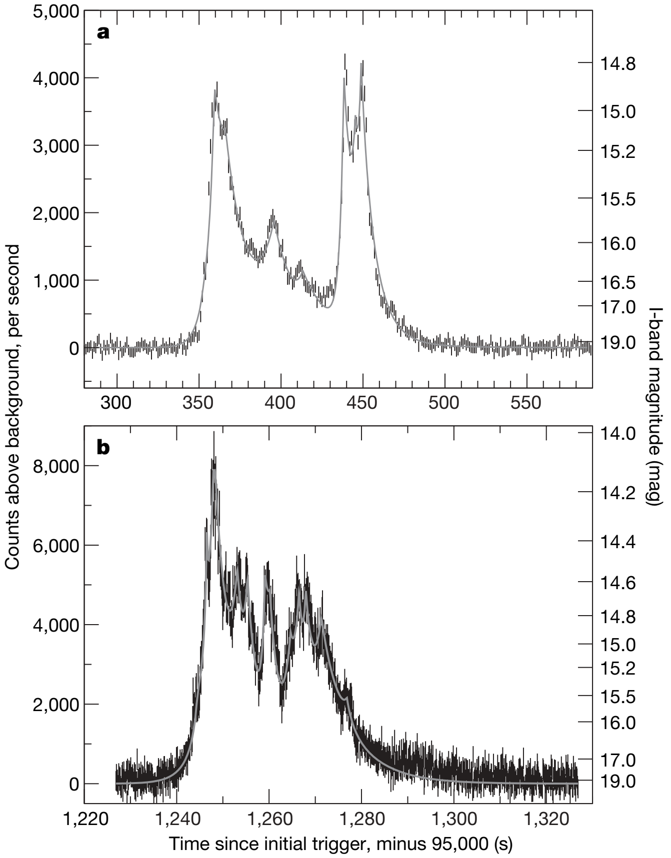

Figure 2 | Detailed light curves of the two most prominent flares of the epoch 2007 June 11 of Fig. 1. The data shown in **a** are binned to 1-s resolution and those in **b** to 0.1-s resolution to achieve reasonable signal-to-noise ratios but also resolve the fastest variabilities detected in the data. The error bars are 1σ statistical errors. Extremely fast variability is clearly visible and well resolved. The solid line in each panel is the result of a simple model, consisting of a superposition of several fast-rise, exponential-decay (FRED) subflares. The FRED shape is modelled by an exponential rise followed by an exponential decay, typically with a longer time constant in the exponential decay. The rise-time constants of the FRED curves fitted to the light curve in **a** range from 2.5 to 10 s, the decay-time constants range from 3 to 26 s. In **b**, the rise-time constants fitted to the light curve range from 0.4 to 3 s, and the decay timescales range from 0.3 to 7 s. The two flares are very bright, with peak I-band magnitudes of 14.8 mag (**a**) and 14.2 mag (**b**). The upper limit on the quiescent emission can be determined to be >20 mag (I band) using our data, and has been independently found to be >23.5 mag (I_c band) using Very Large Telescope data[18] or >24.5 mag (i′ band) using the Hale Telescope[7]. This means that the source changed brightness by a factor of at least 200 in the 4 s it took to go from the 1σ level to maximum brightness. If the quiescent emission was the same as in the Very Large Telescope and Hale Telescope data, the source possibly brightened by a factor $>10^4$.

The high intrinsic time-resolution of OPTIMA-Burst (4 μs) and the signal-to-noise ratio of the brightest parts of the light curve means that we can resolve the brightest features with a time resolution of ~10 ms. This enables us to fit a simple model of several superimposed FRED curves to the light curve segments shown in Fig. 2. The shortest timescales found in this analysis are 0.3–0.4 s. This places a limit on the maximum size of the emitting region of $\sim 10^{10}$ cm (about one-tenth of the Solar radius), because the light travel time across a larger region would blur the observed features.

To judge the luminosity and estimate the total optical-region energy output of the flares shown in Fig. 2, information about the source distance is required. Using X-ray extinction, plus optical, near infrared and radio observations, the distance to SWIFT J1955 can be estimated to be greater than 2–4 kpc, with a most probable distance of 4–8 kpc (ref. 18). In this work, we adopt a reference distance of 5 kpc.

Assuming a distance d (and that $A_V = 5$), the flares have maximum extinction-corrected I-band isotropic luminosities of $1.0 \times 10^{35}(d/5\,\mathrm{kpc})^2\,\mathrm{erg\,s^{-1}}$ (Fig. 2a) and $1.8 \times 10^{35}(d/5\,\mathrm{kpc})^2\,\mathrm{erg\,s^{-1}}$ (Fig. 2b), and total emitted energies in the I-band of $4.6 \times 10^{36}(d/5\,\mathrm{kpc})^2$ erg (Fig. 2a) and $3.2 \times 10^{36}(d/5\,\mathrm{kpc})^2$ erg (Fig. 2b). Taking into account the aforementioned size of the emitting region and putting the source at a distance of 5 kpc, a black-body temperature of several 10^7 K is necessary to explain the observed I-band flux in terms of thermal radiation. However, the extreme contrast ratio between quiescent emission and peak brightness, and the very short rise and decay times observed in these transitions, make it more probable that a non-thermal process is the source of the observed flares.

One possible non-thermal explanation is that the source is a magnetar, similar to an anomalous X-ray pulsar (AXP) or SGR. Optical and near-infrared emission has been observed previously in AXPs[19,20] and one SGR[21], but not with flaring variability. Considering the similarities between the optical light curve observed from SWIFT J1955 and X-ray light curves of SGR outbursts[17], it is conceivable that these are observations of optical flares in a magnetar. It is surprising that the strong X-ray flaring activity usually observed from such sources was not detected in this case. There were no simultaneous high-energy/optical observations during any observed period of flaring activity, so the amount of correlated X-ray/optical activity can only be assessed indirectly. The optical flaring activity during the first and second nights of observation (2 flares per hour and >7 flares per hour, respectively) contrasts significantly with the X-ray activity detected by XRT[7,18] between these two epochs. During the 5.5 h observed using the XRT, 10–40 flares would be expected if there were a strict correlation between optical and X-ray emission (which is not necessarily so, as in the case of the AXP XTE J1810-197 (ref. 22)) and the activity of the source were the same. However, only one significant X-ray flare, of 35-s duration, was observed by the XRT.

Because most of the observational data on magnetars so far gathered has been in the high-energy regime, the implications for optical emission have been somewhat neglected in theoretical works on magnetars. One intriguing model of an optical magnetar proposes optical ion cyclotron emission[23]. In this model, coherent microwave and radio emission emitted near the neutron star is absorbed higher in the magnetosphere by ions at their cyclotron resonance, and then re-emitted in the optical nearer to the poles, where the ion cyclotron cooling and transit times become comparable.

The power spectral densities of the two very bright flares (Fig. 2) are shown in Fig. 3. The power spectrum remains flat in the range between a few hertz and 1 kHz, which confirms very low variability on timescales shorter than ~0.1 s. Both power spectral densities show features similar to those in the X-ray regime that are called quasi-periodic oscillations. Although these features stem from only few oscillations and are therefore only moderately significant, it is notable that the features at a frequency of 0.16 ± 0.02 Hz (Fig. 3a) and

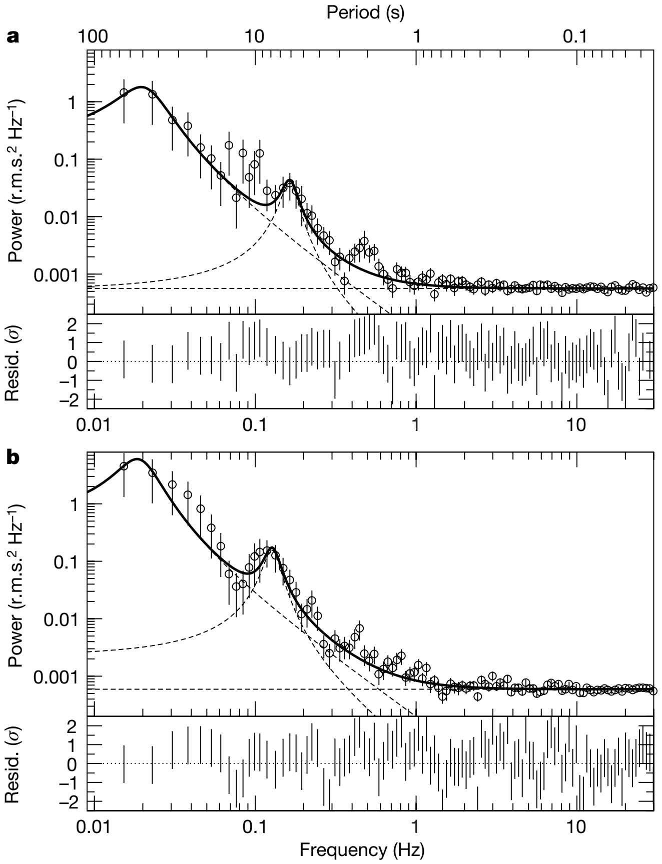

Figure 3 | Power spectral densities of the two prominent flares shown in Fig. 2. Each power spectrum is normalized such that its integral gives the squared root-mean-square (r.m.s.) fractional variability (expressed by giving each spectrum in units of r.m.s.^{2} Hz^{-1}). The error bars are 1σ statistical errors, calculated using the 'powspec' task of the Xronos timing-analysis software package (http://heasarc.gsfc.nasa.gov/docs/xanadu/xronos/). In each panel, the solid line is the result of a best-fit model consisting of two Lorentzians and a constant component. The dashed lines represent the individual components. In **a**, the reduced χ^2 statistic (sum of squared residuals divided by degrees of freedom) is 0.88, which is somewhat lower than desirable. The prominent Lorentzian peak in this panel has a central frequency of 0.163 ± 0.007 Hz and a full-width at half-maximum (FWHM) of 0.020 ± 0.009 Hz. In **b**, the reduced χ^2 statistic is 0.98. The central frequency of the peak in this panel is 0.127 ± 0.006 Hz and the FWHM is 0.015 ± 0.007 Hz. Note that the higher frequency Lorentzians in **a** and **b** have central frequencies that overlap within their respective FWHMs. Both power spectra stay flat in the frequency range between a few hertz and 1 kHz (not plotted here), confirming the limit on the fastest variability timescales from the multi-component fits. Resid., residual of the fit.

0.13 ± 0.02 Hz (Fig. 3b) overlap within their FWHMs. These features also coincide with a suggestion of possible X-ray periodicity reported at a frequency of 0.1446 Hz (ref. 7). The period of 6–8 s indicated by these observations lies in the range of typical rotational periods for AXPs[8] and SGRs[2]. If this is the rotational period of the magnetar, the radius of its light cylinder is about 3×10^{10} cm. This is consistent with the assumption of magnetospheric emission, as the upper limit for the size of the emitting region ($\sim 10^{10}$ cm) is less than the size of the light cylinder.

Two groups have proposed a similarity between SWIFT J1955 and the black hole X-ray binary V4641 Sgr[7,15]. However, the optical properties described here are quite different from those reported for V4641 Sgr. The light curve of SWIFT J1955 is dominated by variability that is extremely bright (>5 mag) and very fast (from a few seconds to <1 s), whereas the optical variability of V4641 Sgr is much less extreme, with flares of ~ 1 mag and ~ 50-s length[24,25]. Despite the fact that these values were derived from charge-coupled-device-based observations with a shortest time resolution of 30 s to minutes, it is clear that SWIFT J1955 is much more extreme in the magnitude and timescales of its variability. The timing properties of the fast, bright flares of SWIFT J1955, as well as independent multi-wavelength arguments[18], suggest a connection between this transient and optical magnetars.

Received 29 January; accepted 28 July 2008.

1. Mészáros, P. Gamma ray bursts. *Rep. Prog. Phys.* 69, 2259–2321 (2006).
2. Kouveliotou, C. in *From X-Ray Binaries to Gamma-Ray Bursts* (eds van den Heuvel, E. P., Kaper, L., Rol, E. & Wijers, R. A. M. J.) 413–423 (Astronomical Society of the Pacific, 2003).
3. Racusin, J. L. *et al.* Broadband observations of the naked-eye γ-ray burst GRB 080319B. *Nature* 455, 183–188 (2008).
4. Stefanescu, A. *et al.* GRB 070610: OPTIMA-Burst high-time-resolution optical observations. *GCN Circ.* 6492 (2007).
5. de Ugarte Postigo, A., Castro-Tirado, A. J. & Aceituno, F. GRB 070610: Optical observations from OSN. *GCN Circ.* 6501 (2007).
6. Kann, D. A. *et al.* GRB 070610: TLS RRM sees flaring behaviour - Galactic transient? *GCN Circ.* 6505 (2007).
7. Kasliwal, M. M. *et al.* GRB070610: A curious Galactic transient. *Astrophys. J.* 678, 1127–1135 (2008).
8. Kaspi, V. Recent progress on anomalous X-ray pulsars. *Astrophys. Space Sci.* 308, 1–11 (2007).
9. Pagani, C. *et al.* GRB 070610: Swift detection of a burst. *GCN Circ.* 6489 (2007).
10. Barthelmy, S. D. *et al.* The Burst Alert Telescope (BAT) on the SWIFT Midex Mission. *Space Sci. Rev.* 120, 143–164 (2005).
11. Gehrels, N. *et al.* The Swift Gamma-Ray Burst Mission. *Astrophys. J.* 611, 1005–1020 (2005).
12. Burrows, D. N. *et al.* The Swift X-Ray Telescope. *Space Sci. Rev.* 120, 165–195 (2005).
13. Weisskopf, M. C. *et al.* An overview of the performance and scientific results from the Chandra X-Ray Observatory. *Publ. Astron. Soc. Pacif.* 114, 1–24 (2002).
14. Stefanescu, A. *et al.* GRB 070610: OPTIMA-Burst detection of continued strong flaring activity. *GCN Circ.* 6508 (2007).
15. Markwardt, C. B. *et al.* SWIFT J195509.6+261406 / GRB 070610: A potential Galactic transient. *Astronom. Telegr.* 1102 (2007).
16. Kanbach, G. *et al.* in *High Time Resolution Astrophysics* (eds Phelan, D., Ryan, O. & Shearer, A.) 153–169 (Springer, 2008).
17. Hurley, K. *et al.* Reactivation and precise interplanetary network localization of the soft gamma repeater SGR 1900+14. *Astrophys. J.* 510, L107–L109 (1999).
18. Castro-Tirado, A. J. *et al.* Flares from a candidate Galactic magnetar suggest a missing link to dim isolated neutron stars. *Nature* doi:10.1038/nature07328 (this issue).
19. Kaspi, V. *et al.* A major soft gamma repeater-like outburst and rotation glitch in the no-longer-so-anomalous X-Ray Pulsar 1E 2259+586. *Astrophys. J.* 588, L93–L96 (2003).
20. Durant, M. & van Kerkwijk, M. H. Multiwavelength variability of the magnetar 4U 0142+61. *Astrophys. J.* 652, 576–583 (2006).
21. 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).
22. Testa, V. *et al.* Adaptive optics, near-infrared observations of magnetars. *Astron. Astrophys.* 482, 607–615 (2008).
23. Beloborodov, A. M. & Thompson, C. Corona of magnetars. *Astrophys. J.* 657, 967–993 (2007).
24. Uemura, M. *et al.* Outburst of a black hole X-ray binary V4641 Sgr in 2004 July. *Info. Bull. Var. Stars* 5626, 1 (2005).
25. Uemura, M. *et al.* Optical observation of the 2003 outburst of a black hole X-Ray binary, V4641 Sagittarii. *Publ. Astron. Soc. Jpn* 56, 823–829 (2004).

Acknowledgements We thank the Skinakas Observatory for their support and allocation of telescope time, and acknowledge the allocation of Chandra DDT time. We thank F. Schrey, T. Kougentakis and G. Paterakis for technical support, A. de Ugarte Postigo for access to private data taken simultaneous to some of our observations and A. Castro-Tirado for discussions. Skinakas Observatory is a collaborative project of the University of Crete, the Foundation for Research and Technology - Hellas, and the Max-Planck-Institute for Extraterrestrial Physics. A. Stefanescu acknowledges support from OPTICON. A. Słowikowska acknowledges support of the European Union through a Marie Curie Transfer of Knowledge Fellowship within the Sixth Framework Programme. S.McB. acknowledges the support of the European Union through a Marie Curie Intra-European Fellowship within the Sixth Framework Programme. G.S. is supported through DLR.

Author Information Reprints and permissions information is available at www.nature.com/reprints. Correspondence and requests for materials should be addressed to A. Stefanescu (astefan@mpe.mpg.de) or G.K. (gok@mpe.mpg.de).