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LETTERS

Flares from a candidate Galactic magnetar suggest a missing link to dim isolated neutron stars

A. J. Castro-Tirado[1], A. de Ugarte Postigo[1,2], 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[7,8], M. A. Guerrero[1], J. French[9], G. Melady[9], L. Hanlon[9], B. McBreen[9], K. Leventis[10], S. B. Markoff[10], S. Leon[11], A. Kraus[12], F. J. Aceituno[1], R. Cunniffe[1,13], P. Kubánek[1,14], S. Vítek[1], S. Schulze[4], A. C. Wilson[15], R. Hudec[16], M. Durant[17], J. M. González-Pérez[17], T. Shahbaz[17], S. Guziy[18], S. B. Pandey[19], L. Pavlenko[20], E. Sonbas[3,21], S. A. Trushkin[3], N. N. Bursov[3], N. A. Nizhelskij[3], C. Sánchez-Fernández[22] & L. Sabau-Graziati[23]

Magnetars[1] are young neutron stars with very strong magnetic fields of the order of 10^{14}–10^{15} G. They are detected in our Galaxy either as soft γ-ray repeaters or anomalous X-ray pulsars. Soft γ-ray repeaters are a rare type of γ-ray transient sources that are occasionally detected as bursters in the high-energy sky[2–4]. No optical counterpart to the γ-ray flares or the quiescent source has yet been identified. Here we report multi-wavelength observations of a puzzling source, SWIFT J195509+261406. We detected more than 40 flaring episodes in the optical band over a time span of three days, and a faint infrared flare 11 days later, after which the source returned to quiescence. Our radio observations confirm a Galactic nature and establish a lower distance limit of ~3.7 kpc. We suggest that SWIFT J195509+261406 could be an isolated magnetar whose bursting activity has been detected at optical wavelengths, and for which the long-term X-ray emission is short-lived. In this case, a new manifestation of magnetar activity has been recorded and we can consider SWIFT J195509+261406 to be a link between the 'persistent' soft γ-ray repeaters/anomalous X-ray pulsars and dim isolated neutron stars.

Following the detection[5] of GRB 070610 as a single peaked γ-ray burst (GRB) lasting about 4.6 s and its bizarre X-ray counterpart[6–8] (dubbed SWIFT J195509+261406), we mounted a multi-wavelength observing campaign (see Supplementary Information sections 1–4 for details). Our data were collected starting ~1 min after the burst trigger time. In the first three nights of our observations, the source displayed strong optical flaring activity[7–9]. This, together with the location of the source in the Galactic plane, supported the view that the source is hosted by the Milky Way[10], and we give strong evidence for this here.

The flares from SWIFT J195509+261406 had durations ranging from tens of seconds to a few minutes and flux amplitudes up to about 100 times the 'outburst' baseline flux (or $\gtrsim 10^4$ times the quiescent state). After 13 June, the activity decayed abruptly (Fig. 1) and no further flares were seen until 22 June, when a late-time, lower-brightness flare was detected in the near-infrared using the 8.2-m Very Large Telescope. A late-time observation by the XMM-Newton spacecraft ~173 days after the burst failed to detect the source, imposing an upper limit (3σ) to any underlying X-ray flux of $L_{\mathrm{X}} \leq 3.1 \times 10^{-14}$ erg cm^{-2} s^{-1} (0.2–10 keV).

Our ^{12}CO ($J = 1-0$) spectrum towards the SWIFT J195509+261406 source reveals a molecular cloud at ~30 km s^{-1}, which contributes ~50% to the total column density N(H) derived by Swift/XRT (see Supplementary Information section 5.1). In fact, the overall Galactic column density along the line of sight towards $(l^{\mathrm{II}}, b^{\mathrm{II}}) = (63.5^{\circ}, -1.0^{\circ})$ is $N(\mathrm{H}) = N(\mathrm{H\,I}) + 2N(\mathrm{H_2}) = (14.1 \pm 2.0) \times 10^{21}$ cm^{-2} which should be compared with the X-ray absorption column derived from the Swift/XRT data: $10^{+4}_{-3} \times 10^{21}$ cm^{-2} from this work, or[7] $7.2^{+3}_{-2} \times 10^{21}$ cm^{-2} (all quoted errors here being 3σ). Therefore we conclude that SWIFT J195509+261406 is located in the Galaxy and beyond this particular molecular cloud at a kinematic distance of $D \approx 3.7$ kpc from the Sun. This value is consistent with ~4 kpc derived from the 'red clump' method (see Supplementary Information 5.2). Hereafter, we consider a reference distance of 5 kpc.

To discern the nature of the source, we explored several possibilities. The first is that the source resembles the 'bursting pulsar' GRO J1744–28 (refs 11,12). However, Swift/BAT has not recorded any other γ-ray burst from SWIFT J195509+261406 after the initial one. A second possibility is based on the proposed similarity to the black hole candidate V4641 Sgr[13,14]. This black hole, orbiting an intermediate-mass companion (a B9 subgiant), was suggested as the first member of the 'fast X-ray novae' group[15], and it has been proposed that SWIFT J195509+261406 is a member of this class[7]. However, several lines of evidence indicate otherwise. First, the lack of further detections of the baseline (non-flaring) flux during the outburst phase at γ-ray (Swift/BAT), millimetre (during the outburst, <0.6 mJy, 3σ; Supplementary Information 2) and centimetre

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[1] Instituto de Astrofísica de Andalucía del Consejo Superior de Investigaciones Científicas (IAA-CSIC), PO Box 03004, E-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] Department of Physics and Astronomy, The University of Leicester, Leicester, LE1 7RH, UK. [9] School of Physics, University College Dublin, Dublin 4, Ireland. [10] Astronomical Institute 'Anton Pannekoek', University of Amsterdam, 1098 SJ Amsterdam, The Netherlands. [11] Institute de Radioastronomie Millimétrique (IRAM), Avda. Divina Pastora 7, Núcleo Central, E-18012 Granada, Spain. [12] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany. [13] Cork Institute of Technology, Rossa Avenue, Bishopstown (Cork), Ireland. [14] Universidad de Valencia, Edif. Institutos de Investigación (GACE-ICMOL), Campus de Paterna, E-46980 Paterna (Valencia), Spain. [15] Department of Astronomy, University of Texas, Austin, Texas 78712, USA. [16] Astronomical Institute of the Czech Academy of Sciences, Fričova 298, 25165 Ondřejov, Czech Republic. [17] Instituto de Astrofísica de Canarias (IAC), Via Láctea s/n, E-38205 La Laguna (Tenerife), Spain. [18] Nikolaev State University, Nikolskaya 24, 54030 Nikolaev, Ukraine. [19] Aryabhatta Research Institute of Observational-Sciences (ARIES), Manora Peak, NainiTal, Uttarakhand, 263129, India. [20] Crimean Astrophysical Observatory, 98409 Nauchny, Ukraine. [21] University of Cukurova, Department of Physics, 01330 Adana, Turkey. [22] European Space Astronomy Centre (ESAC), Avenida de los Castillos s/n, Urbanizacion Villafranca del Castillo, E-28691 Villanueva de la Cañada (Madrid), Spain. [23] Instituto Nacional de Técnica Aeroespacial (INTA), E-28750 Torrejón de Ardoz (Madrid), Spain.

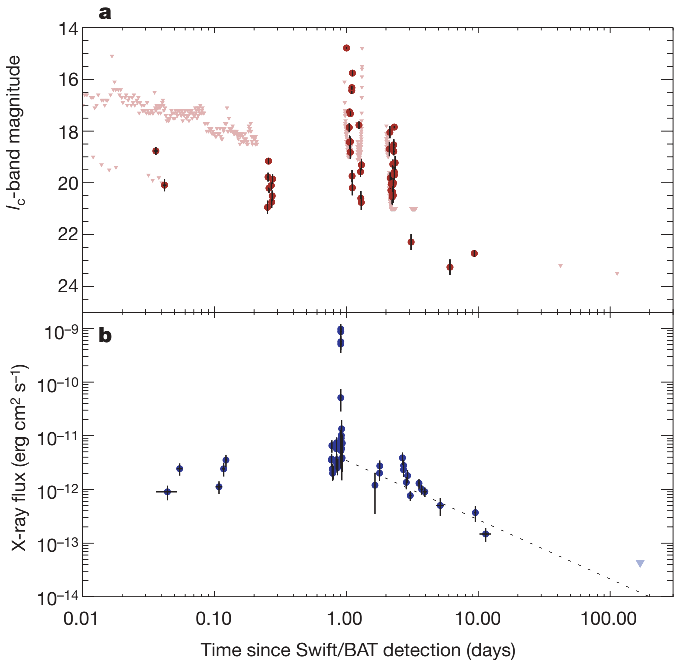

Figure 1 | Optical and X-ray light curves of SWIFT J195509+261406 (June–November 2007). **a**, Optical detections (I_c-band magnitudes, filled circles, with 1σ error bars) are shown together with 3σ upper limits (triangles). **b**, Swift X-ray data (0.2–10 keV, filled circles, with 1σ error bars) together with the late-time 3σ limit obtained with XMM-Newton (triangle). Both light curves show strong activity during the first three days, reaching the maximum around one day after the γ-ray burst and gradually decaying after the third day until the source became undetectable. The X-ray observations made by Swift do not overlap with the times of any of the optical flares that 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 short (~30-s) powerful X-ray flare, for which the flux increased by a factor of $\Delta f/f \approx 100$ on a timescale of $\Delta t/t \approx 10^{-4}$, was followed by several optical flares of similar amplitude. The X-ray data one day after the giant flare event (excluding minor flaring-like activity) can be fitted by a power-law decay $F \propto t^{\alpha}$ with $\alpha = -0.75 \pm 0.25$, consistent with the values seen in the decline phase of the anomalous X-ray pulsar[22] XTE J1810-197 and the transient magnetar[23] SGR 1627-41. The baseline X-ray luminosity of SWIFT J195509+261406 during the first 8,000 s that followed the initial γ-ray spike was $\sim 1.2 \times 10^{34}$ $(D/5\,\text{kpc})^2$ erg s^{-1} whereas the quiescent X-ray luminosity was $\leq 9.0 \times 10^{31}$ $(D/5\,\text{kpc})^2$ erg s^{-1} (0.2–10 keV) at our late-time X-ray observation after ~173 days. This is in any case significantly smaller than the values of $\sim 4 \times 10^{33}$ erg s^{-1} and $\sim 1.3 \times 10^{35}$ erg s^{-1} derived for SGR 1627-41 and some anomalous X-ray pulsars, respectively.

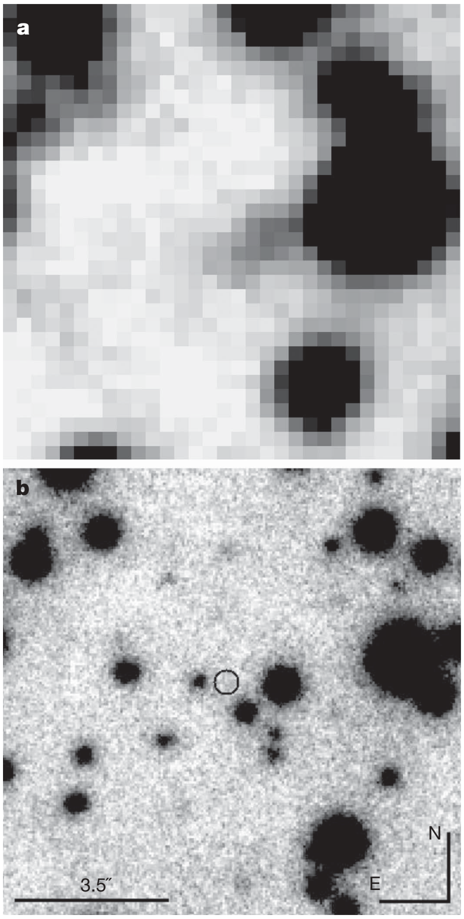

Figure 2 | Deep, late observations of the SWIFT J195509+261406 field. **a**, Deep I_c-band image obtained with the 6.0-m Big Telescope Altazimuthal (using SCORPIO) on 12 October 2007. **b**, Deep H-band image obtained on 30 September 2007 with the 8.2-m Very Large Telescope (using NACO) using natural guide-star adaptive optics. Both images show that the source has disappeared. The location for SWIFT J195509+261406 is marked with a circle (error radius of 0.26″). The limiting magnitudes are $I_c > 23.5$ and $H > 23.0$. There is no evidence for an underlying supernova remnant or a massive star cluster. Four anomalous X-ray pulsars, a subclass of magnetars, have been detected at near-infrared wavelengths[26] but no H-band counterpart of any SGR is known. SGR 1806–20, which is hidden by more than 30 mag of visual extinction, was only seen in the K-band when it was in an active state[27]. The other three known SGRs have no near-infrared counterparts.

wavelengths[7] (during the decline phase, < 0.09 mJy, 3σ) implies a different physical mechanism, because considerable γ-ray and radio emission (the latter arising from a collimated jet) was recorded at the time of the V4641 Sgr outbursts[16]. Moreover, the near-infrared limit imposed on the quiescent counterpart of SWIFT J195509+261406 ($H > 23$; that is, $M_{\rm H} > 8.1$ assuming $D \approx 5$ kpc and $E(B-V) = 1.9 \pm 0.6$ towards the source; see Fig. 2 and Supplementary Information 5) constrains the spectral type of any companion to a main-sequence star with spectral type later than[17] M5V (that is, $\leq 0.12M$ solar masses) unless the donor was a hydrogen-poor (semi-) degenerate star in an ultra-compact X-ray binary[18] (with orbital period less than 1 h).

In fact, an ultra-compact low-mass X-ray binary with blobs of homogeneous synchrotron-emitting plasma of size $\sim 10^7$ cm and magnetic fields of strength $\sim 10^5$ G can explain both the observed baseline flux and the flaring episodes in X-ray and optical wavelengths. This third scheme allows such blobs to be found in a magnetized corona[19] (an extended region of low-density, X-ray irradiated material above and below the accretion disk) or a wind, rather than in the outer regions of a collimated jet. Thus, SWIFT J195509+261406 could be part of such a system.

On the other hand, we point to a final possibility: that the SWIFT source is an isolated compact object, that is, a new magnetar in our Galaxy, which displays activity like that of a soft γ-ray repeater (SGR) in the optical; and from which only one hard burst was recorded in γ-rays, near the onset of its bursting activity. If this is the case, SWIFT J195509+261406 becomes the first SGR detected at optical wavelengths. This would be supported by the burst durations (Fig. 3) and the timing properties of the flares[8].

How could the optical flares be produced in SWIFT J195509+261406? One possibility is, according to magnetar corona models[20], that the flares are due to coherent plasma bunches, and their luminosity depends on the unknown bunching factor, leading easily to $L_{\rm opt} \approx 10^{35}$ $(D/5\,\text{kpc})^2$ erg s^{-1}, as observed at optical frequencies[8].

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

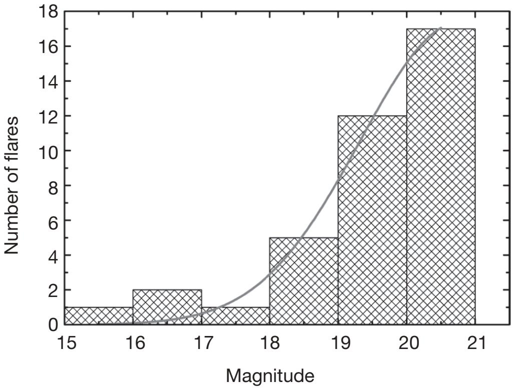

Figure 3 | Log-normal distribution of flare fluxes for SWIFT J195509+261406. The magnitude distribution of the optical flares detected from SWIFT J195509+261406 in the I_c band is shown. Using all I_c-band detections of the source, we find that the flare fluxes are log-normally distributed as seen in the high-energy flares of SGR 1806-20 (ref. 28) and SGR 1900+14 (ref. 29), supporting the claim that SWIFT J195509+261406 is a new SGR, although this is not conclusive. We find that the observed data are well fitted by a truncated normal distribution (solid line) with $N = \frac{A}{w\sqrt{\pi/2}} e^{-2(x-x_c)^2/w^2}$. Here, N is the number of flares in a one-magnitude bin, x is the magnitude, x_c is the centre of the distribution, w is the width and A is the amplitude. The fit is moderately acceptable with $\chi^2 = 49.7$ for 35 degrees of freedom, and we find as parameters $x_c = 20.80 \pm 0.61$ mag, $w = 2.96 \pm 0.76$ mag and $A = 64.5 \pm 22.7$. The truncation of the distribution is a natural result of the limiting magnitude of the observations. In addition, we note that intermediate-duration bursts (~1–30 s) have been recorded in SGR 1627-41 and SGR 1900+14. In particular, two events arising from SGR 1900+14 (at ~7 kpc) and lasting about 1 s displayed unusual hard power-law spectra[30] similar and comparable in energy, $E = (6.5\text{–}11) \times 10^{39}$ erg, to[5] GRB 070610, the burst of γ-rays associated with SWIFT J195509+261406 ($E = 1.9 \times 10^{39}$ $(D/5\,\mathrm{kpc})^2$ erg). Thus, both the γ-ray burst duration and the log-normal distribution of the optical flares strengthen the association of the SWIFT source with a magnetar, although the lack of persistent X-ray pulses (which would allow us to determine the spin period derivative and thus the magnetic field) currently prevents us from proving the existence of extreme magnetic fields typical of magnetars, including SGRs and anomalous X-ray pulsars.

'transient' behaviour of SGR 1627–41 (ref. 21) and another magnetar, XTE J1810-197 (ref. 22). The former source experienced an activity period for 6 weeks in 1998 and its underlying X-ray flux was then 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}, implying a quiescent X-ray luminosity[23] $\sim 4 \times 10^{33}$ erg s^{-1}, which is still significantly higher than the value of $\leq 9.0 \times 10^{31}$ $(D/5\,\mathrm{kpc})^2$ erg s^{-1} derived for the SWIFT source from our late-time X-ray observation after ~173 days. Therefore we suggest that SWIFT J195509+261406 could be the first magnetar (either persistent or transient) in our Galaxy that shows strong and protracted optical flaring activity.

A deeper X-ray observation together with a detailed study of future activity periods of SWIFT J195509+261406, including simultaneous X-ray/optical monitoring, could shed light onto its nature and discern whether the source is an ultra-compact low-mass X-ray binary or an isolated neutron star displaying a new manifestation of magnetar activity. In the latter case, it would represent a link between 'persistent' SGRs/anomalous X-ray pulsars (with $L_X \approx (2\text{–}4) \times 10^{35}$ erg s^{-1} and $\sim(0.2\text{–}5) \times 10^{35}$ erg s^{-1} respectively) and dim isolated neutron stars[24] (with $L_X \approx (2\text{–}20) \times 10^{30}$ erg s^{-1}), being one of a few hundred Galactic magnetars to become active[25] in the past $\sim 10^4$ years.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions A.J.C.T. wrote the paper. A.U.P., D.A.K., S. S. and A.C.W. prepared the figures and together with M. B., P. F., A. K., S. K., S. L. and D.P.R. participated in the data analysis. S. M. and K. L. helped in the modelling. The remaining coauthors provided observational data, discussed the results and commented on the manuscript.

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