Optical and infrared flares from a transient Galactic soft $\gamma$-ray repeater


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Soft $\gamma$-ray repeaters (SGRs) are a rare type of $\gamma$-ray transient sources that are occasionally 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. 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. Following typical procedures for GRB follow-ups, Swift/XRT began to observe the field shortly after the discovery and detected an X-ray counterpart. 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. 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 ($l^{HI} = -1^\circ$), supports the view that the source is hosted by the Milky Way 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 $\sim$1 min after the burst trigger time. In the first three nights of our observations, the source displayed strong flaring activity (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 ($3\sigma$) 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 $\gamma$-ray (by Swift/BAT), millimeter ($< 0.6$ mJy, $3\sigma$) and centimeter wavelengths ($< 0.3$ mJy, $3\sigma$, 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 H$\alpha$ 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 dramat-
ically after that time\textsuperscript{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 \textit{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 $\gamma$ 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 $\sim 50$ 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 $\sim 11$ kpc for
SGR 1627–41, its quiescent luminosity in the 2-10 keV band is \( L_X \sim 4 \times 10^{33} \text{ erg s}^{-1} \) (ref. 22). The X-ray luminosity of SWIFT J195509+261406 during the first 8,000 s that followed the initial \( \gamma \)-ray spike was \( \sim 4.7 \times 10^{34} \) (D/10 kpc)\(^2\) \text{ erg s}^{-1} \) and \( \leq 3.6 \times 10^{32} \) (D/10 kpc)\(^2\) \text{ 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 \( L_X \leq (2.5-7.2) \times 10^{32} \text{ erg s}^{-1} \).

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 \( L_X \sim (2-4) \times 10^{35} \text{ erg s}^{-1} \)) and dim isolated neutron stars\(^{24}\) (with \( L_X \sim (2-20) \times 10^{30} \text{ erg s}^{-1} \)).
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**Acknowledgements.** Based on observations carried out with the IRAM Plateau de Bure Interferometer. IRAM is supported by INSU/CNRS (France), MPG (Germany) and IGN (Spain). We thank S. Leon for obtaining the CO (J = 1-0) data at Pico Veleta. We also thank the ESO Director’s Discretionary Time Committee for accepting the observation a few days after the onset of the event. We are also indebted to N. Schartel for alloting XMM-Newton DDT time to get a late time X-ray observation. We thank E. Alfaro for very fruitful conversations. P.F., D.A.K., and S.K. acknowledge financial support by DFG grant Kl 766/13-2. This work was partially supported by the Spanish projects AYA 2004-01515, AYA 2007-63677 and ESP2005-
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 $\gamma$-ray event. A powerful X-ray flare, for which the flux increased by \(~100\) 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 $N = \frac{A}{\sqrt{\pi/2}w} e^{-\frac{(x-x_c)^2}{w^2}}$. 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 $\chi^2=49.7$ 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.
Figure 1:
Figure 2:
Figure 4: