SEARCH FOR THE OPTICAL Counterpart to SGR 0418+5729

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ABSTRACT

We report broadband Hubble Space Telescope imaging of the field of soft γ-ray repeater SGR 0418+5729 with Advanced Camera for Surveys/Wide Field Channel and Wide Field Camera 3/IR. Observing in two wide filters, F606W and F110W, we find no counterpart within the positional error circle derived from Chandra observations, to limiting magnitudes $m_{F606W} > 28.6$ and $m_{F110W} > 27.4$ (Vega system), equivalent to reddening-corrected luminosity limits $L_{F606W} < 5 \times 10^{28}$ and $L_{F110W} < 6 \times 10^{28}$ erg s$^{-1}$ for a distance $d = 2$ kpc, at $3\sigma$ confidence. This, in turn, imposes lower limits on the contemporaneous X-ray/optical flux ratio of $\lesssim 1100$ and the X-ray/near-infrared flux ratio of $\lesssim 1000$. We derive an upper limit on the temperature and/or size of any fall-back disk around the magnetar. We also compare the detection limits with observations of other magnetars.

Key words: stars: neutron – X-rays: individual (SGR 0418+5729)

Online-only material: color figures

1. INTRODUCTION

Soft gamma-ray repeaters (SGRs) are believed to be magnetars: neutron stars (NSs) powered primarily by the decay of a super-strong magnetic field (Thompson & Duncan 1995). Their primary observational characteristics are X-ray luminosities higher than the spin-down power, $L_X \gg E$, relatively slow rotation $P \sim 1$–$10$ s, and fast spin-down $\dot{P} \sim 10^{-12}$ to $10^{-9}$ s$^{-1}$, implying characteristic ages $\sim 1000$ yr and dipole magnetic field strengths $B_{\text{dipole}} \gtrsim 10^{13}$ G. Most SGRs were discovered by their outbursts, either giant flares (Hurley et al. 2005) or rapid burst series (Gavriil et al. 2002). Since the discovery of mid-infrared emission from the magnetar 4U 0142+61 (Wang et al. 2006), passive (non-accreting) disks have been suggested to exist around magnetars and could, in principle, have some effect on the observed luminosity and/or spin evolution (see Ertan et al. 2009 and references therein).

So far, only three magnetars (SGRs and the related anomalous X-ray pulsars (AXPs)) have been detected in the optical: SGR 0501+4516 (Ofek et al. 2008; Fathkullin et al. 2008), 4U 0142+61 (Hullemann et al. 2000), and 1E 1048.1−5937 (Durant & van Kerkwijk 2005). The detections are challenging, due to their faintness and significant reddening (all Galactic magnetars lie close to the Galactic plane). Although other magnetars have been seen in the near-infrared (NIR), SGRs were detected only during their active states, so their quiescent NIR or optical luminosities are not known. See Mereghetti (2008) for a review of magnetar properties.

SGR 0418+5729 was discovered on 2009 June 9 via magnetar-like bursts detected by the Fermi Gamma-Ray Burst Monitor and confirmed with the Swift Burst Alert Telescope (van der Horst et al. 2010). The 9.1 s pulsations were first detected by RXTE (Gogus et al. 2009), while Swift X-Ray Telescope (XRT) spectral fits suggested thermal emission with $kT \approx 900$ eV (Cummins et al. 2009). No radio counterpart was found (Lorimer et al. 2009). Esposito et al. (2010) summarized the results of the follow-up XRT observations, and found thermal emission slowly cooling, with the emitting area decreasing on a timescale of months. The extinction column inferred from the X-ray fits was $N_H \approx 1.1 \pm 0.3 \times 10^{21}$ cm$^{-2}$, lower than for any other Galactic magnetar. Using a limit on the pulsar spin-down rate, $\dot{P}$, Rea et al. (2010) derived an upper limit on the pulsar dipole magnetic field, $B_{\text{dipole}} < 7.5 \times 10^{12}$ G, more typical for an ordinary pulsar than a magnetar. Alpar et al. (2011) argued that this contradicts the magnetar model and instead supports the fall-back disk model.

Woods et al. (2009) measured the most accurate position of the SGR from Chandra data, R.A. = $04^h18^m33^s.867$, decl. = $+57\degree32\arcmin22\arcsec.91$ (J2000), with the positional uncertainty of $0\farcs35$ at 95% confidence. The direction of SGR 0418+5729 ($i = 147.98\degree$ and $b = +05\arcmin12\arcsec$) suggests a distance of 2 kpc, corresponding to the Perseus Arm (van der Horst et al. 2010). The proximity and low extiction of SGR 0418+5729 made it a promising candidate for detailed study in the optical/NIR. Esposito et al. (2010) failed to detect it in optical imaging with the Gran Telescopio Canarias, setting a magnitude limit $F606W < 28$ in $\lesssim 1$ kpc, lower than for any other Galactic magnetar. Using a limit on the pulsar spin-down rate, $\dot{P}$, Rea et al. (2010) derived an upper limit on the pulsar dipole magnetic field, $B_{\text{dipole}} < 7.5 \times 10^{12}$ G, more typical for an ordinary pulsar than a magnetar. Alpar et al. (2011) argued that this contradicts the magnetar model and instead supports the fall-back disk model.

In Section 2, we present the data and analysis. In Section 3, we discuss the detection limits and conclusions.

2. OBSERVATIONS and DATA REDUCTION

The field of SGR 0418+5729 was imaged on 2010 October 19 by HST (GO program 12183). In the optical, the Advanced Camera for Surveys/Wide Field Channel (ACS/WFC) was used in conjunction with the broad filter F606W (pivot wavelength 5921 Å and rms bandwidth 672 Å; roughly a broader V-band). The 2484 s observation consisted of four dithered exposures with the WFC1 aperture. In the NIR, the Wide Field Camera 3, IR channel (WFC3/IR) was used in MULTIACCUM mode with the broad filter F110W (pivot wavelength 11534 Å and rms bandwidth 4430 Å; roughly a broad J-band). The total exposure was 2811 s, taken at four dithered pointings with the read parameters SPAR50, NREAD16 (16 reads, every 50 s, giving 15 net images at each location). The images were processed by the standard pipeline and combined using multidrizzle, which

4 http://stsdas.stsci.edu/multidrizzle/
Figure 1. Images of the SGR 0418+5729 field in the F606W (top) and F110W (bottom) filters. The $r=0\farcs35$ positional error circle from Woods et al. (2009) is indicated. The nearest stars are labeled and their positions and photometry are given in Table 1.

Figure 2. Color–magnitude diagram of stars in the field of SGR 0418+5729. The stars nearest the position of SGR 0418+5729 are marked (see Figure 1).

(A color version of this figure is available in the online journal.)

Table 1  
Point Sources in the Field

| Star | R.A. (J2000) | Decl. (J2000) | $m_{F606W}$ | $m_{F110W}$ |
|------|--------------|--------------|-------------|-------------|
| A    | 64.641821    | 57.539883    | 23.773 ± 0.013 | 20.627 ± 0.022 |
| B    | 64.641448    | 57.540451    | 21.213 ± 0.016 | 19.023 ± 0.020 |
| C    | 64.638586    | 57.540671    | 27.337 ± 0.069 | 23.109 ± 0.028 |
| D    | 64.641397    | 57.538482    | 24.510 ± 0.029 | 20.871 ± 0.028 |
| E    | 64.638012    | 57.538750    | 21.308 ± 0.016 | 14.947 ± 0.017 |
| F    | 64.640854    | 57.542242    | 23.537 ± 0.014 | 19.968 ± 0.018 |
| G    | 64.644254    | 57.541679    | 21.371 ± 0.015 | 18.964 ± 0.013 |
| H    | 64.642619    | 57.537232    | 22.559 ± 0.010 | 20.307 ± 0.024 |
| I    | 64.644363    | 57.537078    | 19.888 ± 0.017 | 17.752 ± 0.018 |

Notes. Uncertainties do not include the uncertainty in the photometric zero points. Magnitudes are in the Vega system.

The final HST images are shown in Figure 1, together with the positional uncertainty circle.

We calibrated the photometry using the tabulated zero points for the F110W and F606W images, respectively. The uncertainty in the zero points is less than 0.05 mag.

3. RESULTS AND CONCLUSIONS

In the images shown in Figure 1, no bright source is seen within or near the SGR error circle. The 3σ limits are $m_{F110W} > 27.4$ and $m_{F606W} > 28.6$ (Vega magnitudes). The locations and magnitudes of the nearest stars, marked in Figure 1, are listed in Table 1. The color–magnitude diagram of all the matched field stars is shown in Figure 2, with the point sources from Table 1 labeled. They are all consistent with main-sequence stars behind $A_V \sim 1$ reddening, except Star E, which likely is a red giant.

Rea et al. (2010) give the SGR X-ray flux $F_X = (1.2 \pm 0.1) \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ (0.5–10 keV, absorbed; Chandra ObsID 12312) on 2010 July 23, which is a factor of 150 fainter than during the discovery observations a year earlier. The X-ray observation nearest in time to our HST observation occurred on 2010 September 24 (XMM observation 0605852201) and had a poorly constrained flux, consistent with the July 23 observation,

5  http://www.stsci.edu/hst/wfc3/phot_zp_lbn
6  http://www.stsci.edu/hst/acs/analysis/zeropoints
albeit with lower signal-to-noise ratio. Our limit in F110W corresponds (e.g., Bessell 1979) to a spectral flux limit $f_{\nu,\text{NIR}} < 4.4 \times 10^{-31}$ erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$, where we have assumed the reddening $A_V = 0.7$ from the X-ray extinction measure (Predehl & Schmitt 1995; Schlegel et al. 1998). Thus, we derive a limit on the X-ray/NIR$^4$ flux ratio $F_X/F_{\text{NIR}} > 1000$. Likewise in the optical $f_{\nu,\text{O}} < 2.3 \times 10^{-31}$ erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$ and the X-ray/optical flux ratio is $F_X/F_O > 1000$. The flux ratio limits are still consistent with the ratios found for persistent magnetars detected in the optical/NIR (see Durant & van Kerkwijk 2005; Mereghetti 2008). We also retrieved the X-ray observation of SGR 0418+5729 closest in time after our $HST$ observation, by $Chandra$ ACIS (ObsID 13148 on 2010 November 29). We measure a flux of $(1.8 \pm 0.3) \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$, indicating that the source had continued to fade. We plot the spectrum in Figure 3 alongside the one from 2010 July 23 (Rea et al. 2010). The spectral peak shifted to lower energies, indicating a lower temperature (assuming a thermal spectrum).

Only three magnetars have so far been detected in the optical, 4U 0142+61 (a persistent AXP-type magnetar; Hulemann et al. 2000), SGR 0501+4516 (Fakhfakhlin et al. 2008), and 1E 1048.1–5937 (another AXP, detected only in the I-band; Durant & van Kerkwijk 2005). In each case, the observed emission is pulsed at the pulsar period, with pulsed fractions >50%, i.e., higher than in soft X-rays (Kern & Martin 2002; Dhillon et al. 2009, 2011). This clearly indicates the magnetospheric origin of the optical emission. It is illuminating to compare the optical properties of these magnetars with those of SGR 0418+5729.

The measured magnitudes and inferred flux ratios of all the optically detected magnetars are given in Table 2 alongside our limits for SGR 0418+5729. Our flux ratio limits are near the lowest values for the other magnetars and imply that SGR 0418+5729 still could have similar spectral properties to the other magnetars, although the flux ratios must be higher than those for 1E 1048.1–5937. Note that the two AXPs have been observed in quiescence (but both are known to be variable), whereas both SGRs were observed after outbursts and may still have been fading.

The IR-X-ray spectra of the four magnetars in Table 2 are shown in Figure 3. The two AXPs have similar multiwavelength spectra, but the X-ray spectrum of SGR 0501+4516 appears to be closer to a power law ($\Gamma \sim 3$), whereas the spectrum of SGR 0418+5729 is more like a cooling blackbody.

The direction and low extinction to SGR 0418+5729 strongly suggests a distance of 2.0 \pm 0.5 kpc, which is the distance to the Perseus arm (there is no further dense Galactic structure in this direction; Cordes & Lazio 2002). For such a distance, the upper limits on NIR and optical luminosities ($L = 4\pi d^2 f_{\nu}$) are

\begin{align*}
L_{\text{F110W}} &< 6 \times 10^{29} \text{ erg s}^{-1} \\
L_{\text{F606W}} &< 5 \times 10^{28} \text{ erg s}^{-1}
\end{align*}

respectively, lower than the luminosities of any detected magnetars.

The passive disk model for 4U 0142+61 by Wang et al. (2006) predicts $f_{\nu} = 1.3 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ at 1.1 \mu m, for the distance of 3.9 kpc. If a similar disk were around SGR 0418+5729, it would have $f_{\nu} = 5 \times 10^{-14} \mu m^2$ erg s$^{-1}$ cm$^{-2}$.

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### Table 2

| Magnetar   | $d$ (kpc) | $F_X$ (0.5–10 keV) | NIR | $v_{f,\text{NIR}}^4$ | Optical | $v_{f,\text{O}}^4$ | $F_X/F_{\text{NIR}}$ | $F_X/F_O$ | Refs$^b$ |
|------------|-----------|--------------------|-----|----------------------|---------|-------------------|-------------------|----------|---------|
| 4U 0142+61 | 3.6 ± 0.4 | 7.0 \times 10^{-11} | $J = 22.2$ | $2.1 \times 10^{-14}$ | $V = 25.6$ | 2.9 \times 10^{-14} | 5700 | 2400 | 1 |
| SGR 0501+4516 | 2.5 ± 0.5 | 8.7 \times 10^{-11} | $K = 19.2$ | $3.0 \times 10^{-14}$ | $I = 23.3$ | 6.9 \times 10^{-14} | 2900 | 1300 | 2.4 |
| SGR 0418+5729 | 9.0 ± 1.7 | 1.2 \times 10^{-13} | 23 | 1.2 \times 10^{-16} | $m_{\text{160nm}} > 28.6$ | < 1.1 \times 10^{-16} | > 1000 | > 1100 | 7.8 |

Notes. The optical and infrared magnitudes listed are corrected for extinction before conversion to flux. The X-ray fluxes are unabsorbed. All fluxes are in units erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$. $^a$ Here the NIR and optical fluxes are defined as $F = v_{f,\nu}$. $^b$ References: (1) Durant & van Kerkwijk 2006b, (2) Rea et al. 2008, (3) Enoto et al. 2009, (4) Fakhfakhlin et al. 2008, (5) Dhillon et al. 2011, (6) Durant & van Kerkwijk 2005, (7) Rea et al. 2010, and (8) this work.

$^c$ Here we list two X-ray and optical observations, shortly after outburst and when approaching quiescence.

$^d$ Near the quiescent value, and consistent with contemporaneous low-S/N Swift observations (see the text).

$^e$ Values at quiescence.

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Figure 3. Multiwavelength spectra of the optically detected magnetars, together with SGR 0418+5729. For SGR 0418+5729, we show two X-ray spectra from 2010 July 23 (upper, blue) and 2010 November 29 (lower, green), and the spectral flux limits established in this paper.

(A color version of this figure is available in the online journal.)

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2 Here we adopt $F = v_{f,\nu}$ as a measure of the NIR/optical flux. The actual flux in a given filter, $F = \int R f_{\nu} d\nu$, where $R_{\nu}$ is the filter throughput at frequency $\nu$, is smaller by a factor of a few. The definition $F = v_{f,\nu}$ is, however, convenient to compare fluxes measured with different broad filters.

8 Note that the extinction to SGR 0501+4516 is rather high and uncertain.
where $d_0$ is the distance in units of 2 kpc. We measure $v_f < 1.2 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$, i.e., 2.5 orders of magnitude smaller. For a disk of the same size as in Wang et al. (2006), the disk inner temperature would need to be $T \leq 600$ K, i.e., cooler than plausible values for the (non-ice) dust sublimation temperature (Kobayashi et al. 2011). Alternatively, the disk could be more tenuous, or there may be no disk. Our measurements thus suggest that, if indeed disks contribute significantly to the luminosities of magnetars, then a different disk configuration (surface density and inner radius) is needed for SGR 0418+5729 compared to 4U 0142+61. If so, it could be connected to either the former being a transient magnetar and the latter persistent, or the much lower magnetic field of SGR 0418+5729.

Malheiro et al. (2011) discussed an alternative source of power for SGRs and AXPs: the spin-down of a rapidly rotating, magnetized WD. Our photometry limits allow us to place an upper limit on the temperature of a WD-sized ($R \sim 10^9$ cm) blackbody emitter of $T \leq 3000$ K at 2 kpc. Whereas WDs with temperatures $T < 4000$ K are known (e.g., M. Durant et al. 2011, submitted), the cooling time required is $\tau \gtrsim 10$ Gyr. Our flux limits therefore constrain the WD interpretation for SGRs.

In conclusion, although SGR 0418+5729 is the nearest and least extincted magnetar known, we have not detected it in very deep optical and NIR observations. The source still offers a good opportunity to observe the optical spectrum of a magnetar, but this will only be possible following a new outburst. On the other hand, AXP 4U 0142+61 is the only persistent magnetar known, we have not detected it in very faint NIR spectrum can be measured, but the faintness requires extensive observation time.

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Note after proof: After this work appeared in preprint, we were contacted by J. Rueda, who pointed out that the model in Malheiro et al. (2011) specifically requires a high-mass white dwarf, with a radius, therefore, smaller than we assumed. Here we give the explicit dependence on radius of the limit one can place on the black-body surface temperature, one limit for each filter:

$$ T < \frac{12.48}{\ln (1 + 48.8 R_9^2)} \times 1000 \text{ K} $$

$$ T < \frac{24.39}{\ln (1 + 696 R_9^2)} \times 1000 \text{ K} $$

where $R_9$ is the radius in units of 10,000 km ($10^9$ cm), for the F110W and F606W filters, respectively.

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