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The infrared counterpart and proper motion of the soft-gamma repeater SGR 0501+4516

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ABSTRACT

We present the identification and long term monitoring of the optical and infrared counterpart of the soft-gamma repeater SGR 0501+4516, and the detection of its proper motion. Unlike most known SGRs, the source has moderate foreground extinction with minimal crowding. Moreover, it exhibits the brightest long-lived optical/near-infrared emission yet seen for an SGR, with $K \sim 19$ at discovery. Our observations began only ~ 2 hours from the first activation of SGR 0501+4516 in August 2008, and monitoring continued for ~ 4 years. The near-infrared (nIR) source faded slowly during the first week, thereafter following a steeper power-law fading. The behaviour is satisfactorily fit by a broken power-law decay, broadly tracking the X-ray emission. Two epochs of *Hubble Space Telescope* imaging with a 2-year baseline allow us to determine a quiescent level for the counterpart, and to measure a proper motion of $\mu = 6.5 \pm 1.7$ milliarcseconds yr^{-1}. This suggests a low tangential velocity of $v \sim 45$ km s^{-1} d$_{1.5\mathrm{kpc}}$, in contrast to some magnetar models which posit high natal kicks. Both the magnitude and direction of the proper motion rule out the proximate supernova remnant HB9 as the possible birth-site of SGR 0501+4516, and we can find no likely birth-sites (i.e. SN-remnants, or groups of massive stars) within the region traversed by SGR 0501+4516 during its characteristic lifetime ($\sim$ 10,000 years), in contrast to other magnetar candidates which have been traced to young massive clusters. This suggests that in some cases SGRs may be either significantly older than expected, or be formed via an alternative mechanism, such as an accretion induced collapse (AIC) following the merger of two magnetic white dwarfs.

Key words: stars:neutron stars:individual (SGR 0501+4516) ISM: supernova remnants

1 INTRODUCTION

Soft gamma-repeaters (SGRs) are characterized by irregular short bursts of soft γ- and X-rays, often repeating on timescales of hours to days, followed by longer periods of inactivity. They are conjectured to be manifestations of magnetars (for review, see Mereghetti 2008). SGRs are posited to be young (typical spin-down ages of 10^3-10^4 yr), isolated, slowly rotating neutron stars (periods 2-12 s) with inferred magnetic fields in the range $10^{14}-10^{15}$ G (Kouveliotou et al. 1998,1999), larger than the electron quantum critical field ($B_{cr} \simeq 4.4 \times 10^{13}$ G). However, progress in understanding SGRs has been slow due to the difficulty of observing them in other wavebands and dearth of clear evidence of their progenitors and birth places. This is in part a consequence of their scarcity and typical location behind large column densities in the Galactic plane. Nonetheless, it also impacts on uncertainties in their distances (e.g. Bibby et al. 2008), and hence birth rates and energetics.

First discovered in 1979, the sample of SGRs has built up slowly over the subsequent 30 years, to the $\sim$ 10 definite examples now known within the Milky Way and Magellanic Clouds today(see Olausen & Kaspi (2014) for a list [1]). Even when complemented with the comparable number of Anomalous X-ray pulsars (AXPs), which are thought to be closely related objects, the population of magnetars is clearly dwarfed by the young radio pulsar population. This may suggest that magnetars are not the dominant compact objects produced during core collapse, and perhaps come only from more massive progenitors (Gaensler et al. 2005).

In principle, studies of SGR environments and their

[1] http://www.physics.mcgill.ca/p̃ulsar/magnetar/main.html

multiwavelength spectra can play a major role in understanding their nature. By identifying their natal environments it might be possible to independently estimate their age from that of their putative parent stellar population, which, in turn, has major implications for the estimate of their birth rates. Furthermore, studying the multiwavelength emission itself can provide valuable insight into the mechanisms of energy production from the SGR, possibly enabling one to discriminate between the magnetar model and alternative ones based on accretion from a disc of fall-back material formed after the supernova explosion that created the SGR (e.g. Marsden et al. 2001).

SGRs (and AXPs) have been well studied at high energies as they are usually strong persistent X-ray emitters, with X-ray luminosities of about $10^{34} - 10^{36}$erg s^{-1}, thought to be powered by the ultra-strong magnetic field of these neutron stars (Duncan & Thompson 1992; Thompson & Duncan 1993). More recently, hard X-ray emission has also been discovered (Kuiper et al. 2004; den Hartog et al. 2008), while some AXPs have also been detected in the radio (Camilo et al. 2006; 2007).

However, establishing the properties of SGRs and AXPs at optical and nIR wavelengths has proven to be especially challenging. The majority of these sources lie in the Galactic plane, in regions where the combination of high extinction, coupled with crowding greatly complicates the detection and identification of counterparts. Despite these difficulties, searches for optical/nIR counterparts have been partially successful, with a handful of candidates being found, mainly for AXPs. These magnetar counterparts are faint, with magnitudes $K \sim 20$ (Israel et al. 2002, 2005; Rea et al. 2004; Kosugi et al. 2005; Testa et al. 2008), and can potentially be differentiated from confused stellar sources by their unusual colours, and variability on long time scales.

Improvements in adaptive optics technology have improved the certainty of these identifications by greatly enhancing the resolution of the observations and removing confusion. In turn these IR detections have enabled proper motions to be determined for two SGRs and two AXPs (Tendulkar, Cameron, & Kulkarni 2012, 2013), demonstrating velocities of $v_t \sim 100 - 300$ km s^{-1} (with 3/4 at the lower end) significantly lower than previous limits (DeLuca et al. 2009). In 3 out of the four cases these proper motion vectors point back towards either clusters of massive stars (in the case of SGR 1806-20 and SGR 1900+14) or towards a recent supernova remnant (in the case of AXP 1E 2259+586). Only in one case does the proper motion not allow the identification of a likely birth site. These observations, along with the Galactic distribution of magnetar candidates tightly aligned with the plane (Olausen & Kaspi 2014), offer strong support for a model in which magnetars are indeed young neutron stars, born in a population of young, and potentially very massive stars.

Two main mechanisms have been suggested to explain the magnetar nIR radiation; notably, emission from a fossil disc around the magnetar (see e.g. Perna et al. 2000; Perna & Hernquist 2000), through X-ray radiation reprocessing, or emission from the magnetar magnetosphere (Beloborodov & Thompson 2006). The infrared variability of magnetar candidate counterparts has been sometimes observed to be correlated with their X–ray outbursts, allowing a scenario in which the nIR emission results from the reprocessing of the X-rays via a fossil-disc (Rea et al. 2004; Tam et al. 2004; Israel et al. 2005). However, cases in which the nIR variability does not simply follow the X-ray activity have also been observed, leaving open any conclusive interpretation (Rea et al. 2004; Durant & van Kerkwijk 2006; Testa et al. 2008).

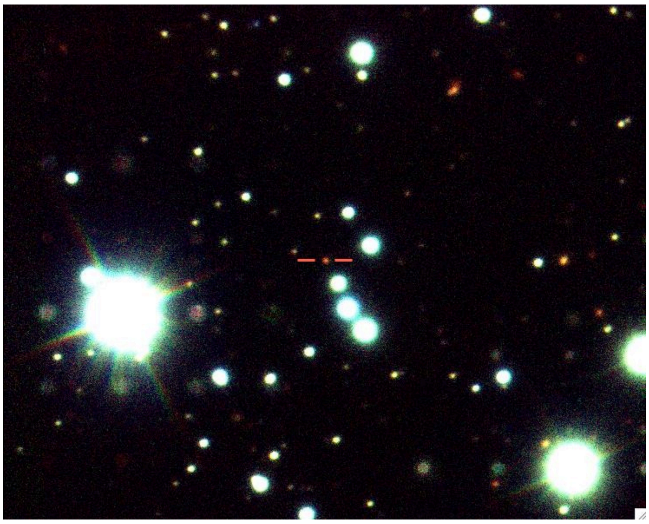

Figure 1. The field of SGR 0501+4516 as imaged with Gemini/NIRI. The SGR is marked with a crosshair and is apparently redder than the surrounding field stars, likely indicating that it lies at a larger distance, although it could also be due to a redder intrinsic spectrum.

SGR 0501+4516, was discovered on 2008 August 22nd by the Swift Burst Alert Telescope (BAT), through the detection of SGR-like bursts (Barthelmy et al. 2008; Holland et al. 2008; Rea et al. 2009). The activation of this new SGR followed a very long period of quiescence. Indeed, none of the X-ray satellites which were operational in the last 3 decades observed persistent emission from this source. In the days following the onset of activity, tens of bursts were observed, with fluxes exceeding the underlying continuum by a factor $> 10^5$. The bursts reached maximum luminosities of $\sim 10^{41}$erg s^{-1}and had durations of <1 s, typical of those usually emitted by SGRs. Thanks to the rapid response of many X-ray satellites (Swift, *Suzaku*, *XMM-Newton*, *Chandra*, *INTEGRAL*, *Fermi*-GBM, *AGILE*, *Konus-WIND*; Palmer et al. 2009; Rea et al. 2009; Göğüş et al. 2009; Enoto et al. 2009, Aptekar et al. 2009) the source was repeatedly observed during and after its "burst forest" emission, leading to the best monitoring of an SGR outburst ever performed.

Here, we report one the discovery of the nIR counterpart to SGR 0501+4516, following its initial outburst, and on the results of the subsequent ∼4 year campaign of nIR monitoring. The location in the Galactic anti-centre direction, and consequent lack of crowding and relatively low extinction to this object, make it the ideal case for investigating the optical/nIR properties of SGRs.

2 OBSERVATIONS & ANALYSIS

After the first detection of flares from SGR 0501+4516 by Swift-BAT, nIR data were obtained promptly with the 3.8 m United Kingdom InfraRed Telescope's (UKIRT) Fast-Track Imager (UFTI) at the Mauna Kea Observatory, us-

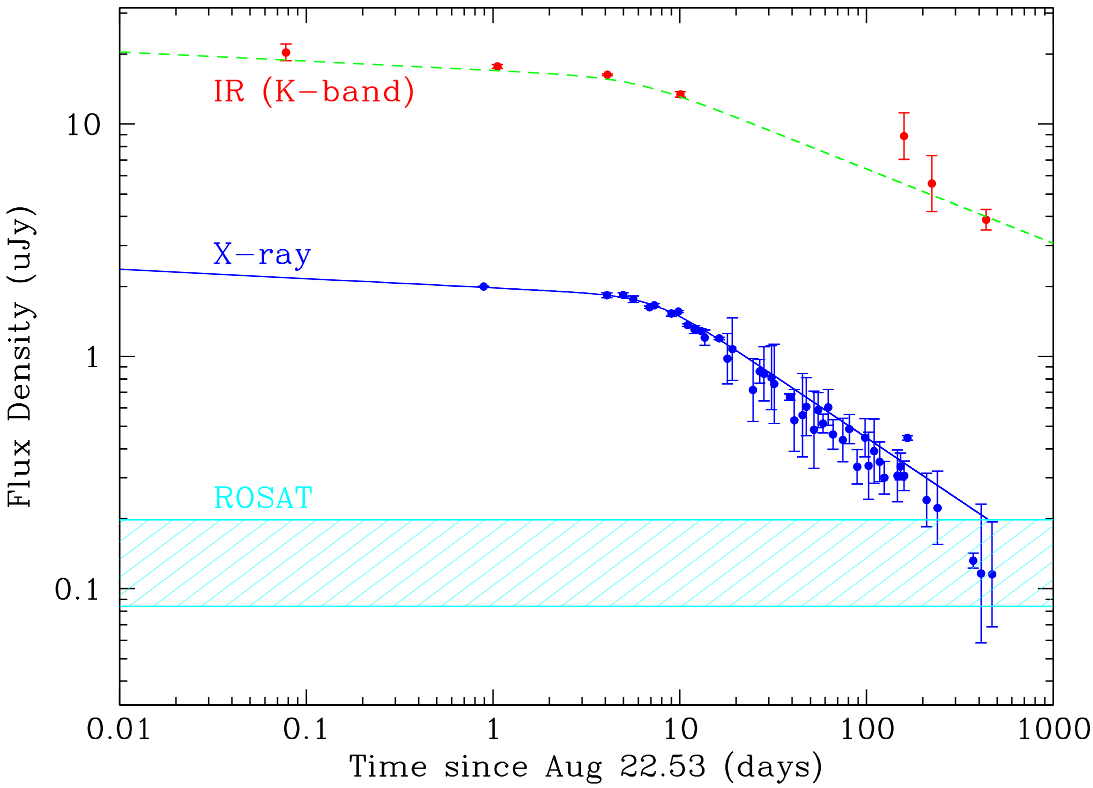

Figure 2. The optical and X-ray lightcurve of SGR 0501+4516. The red points correspond to the nIR and the blue to the X-ray from Rea et al. (2009), supplemented with later time *Swift* observations, the cyan shaded box represents the *ROSAT* quiescent level, and its associated error (also from Rea et al. 2009). Due to the difficulty of fully accounting for colour terms between Ks and K-band we have plotted only the K-band observations on this figure. The X-ray lightcurve is plotted as a specific flux (F_ν) at 1 keV based on the spectral model and countrate obtained from *XMM-Newton* observations over the 0.3-10 keV range, and assumes no X-ray spectral variability, although such effects have only small effects on the observed flux.

ing its rapid-response mode through eSTAR[2]. Subsequent nIR data were obtained over the following 4 years using the 8.1 m Gemini-North's Near-InfraRed Imager and spectrometer (NIRI) at Mauna Kea, and the Long-slit Intermediate Resolution Infrared Spectrograph (LIRIS) on the 4.2 m William Herschel Telescope at the Roque de Los Muchachos Observatory. Finally, we obtained two epochs of observations with the *Hubble Space Telescope* in October 2010 and October 2012.

Ground based data were reduced using the respective instrument pipelines. Photometric calibration was performed using the two micron all-sky survey (2MASS; Skrutskie et al. 2006), which has also been used for astrometric calibration. The UFTI and NIRI K-band filters are K, while the LIRIS and 2MASS K-band filters are K_s; a small correction of about 0.07 magnitudes can be applied to bring all K-band filters to K_s, using $K_s = K + 0.002 + 0.026(J-K)$[3].

We obtained two epochs of observation of SGR 0501+4516 with the *Hubble Space Telescope* on 19 October 2010 and 08 October 2012, approximately 720 days apart. At each epoch we obtained a single orbit of observation in the F160W (broad H) filter. Each observation consisted of four dither exposures in a standard box pattern, and the orientation was chosen such that diffraction spikes from nearby bright stars did not impinge on the source position.

The data were retrieved from the archive[4] after on-the-fly processing. Since we are interested in astrometric fidelity we used the most up to date distortion tables, and determined shifts between each dithered image directly from sources in the image (using tweak-shifts) rather than from the pre-programmed offsets. These images were then drizzled to a common reference frame using `astrodrizzle`. The two epochs were subsequently aligned via cross-correlation of galaxies in the background of each image.

A single source coincident with the position of the X-ray counterpart to SGR 0501+4516 (Woods, Göğüş & Kouveliotou 2008; Holland et al. 2008) is visible in all co-added observations. The position of this source, referenced to 2MASS, is RA (2000) = $05^{\mathrm{h}}01^{\mathrm{m}}06\overset{\mathrm{s}}{.}75$, Dec. (2000) = $45^\circ16'34\overset{''}{.}0$, with an error of 0.2 arsecond in both coordinates. This is 0.10 arcseconds from the centroid of the *Chandra* image. We therefore identify this source as the nIR counterpart to SGR 0501+4516 (see Figure 1), subsequent variability

[2] http://www.estar.org.uk
[3] Explanatory Supplement to the 2MASS All Sky Data Release and Extended Mission Products: http://www.ipac.caltech.edu/2mass/releases/allsky/doc/explsup.html
[4] http://archive.stsci.edu

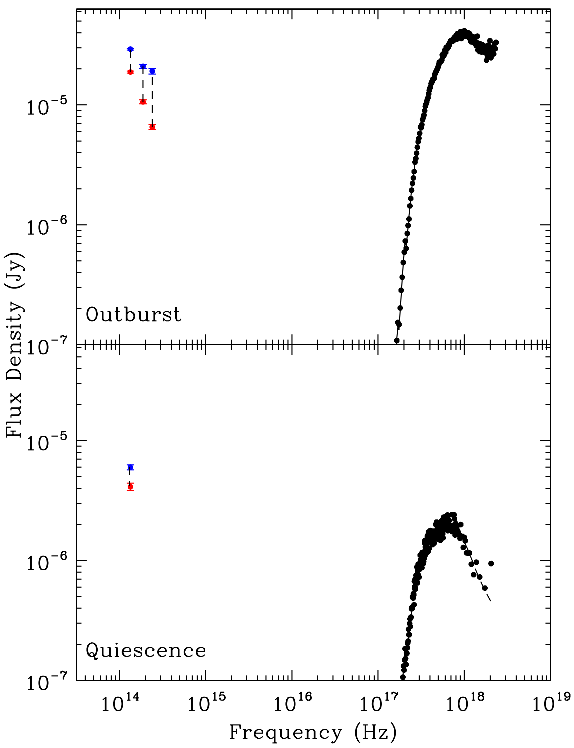

Figure 3. Top panel: The spectral energy distribution of SGR 0501+4516 from the X-ray to the nIR as measured one day after the first outburst. Bottom panel: The spectral energy distribution in quiescence, at $\sim$ 200 days. The X-ray spectrum is that obtained by *XMM-Newton*, while for the nIR data, the two colours correspond to nIR observations with i) no extinction correction (lower, red points) and ii) extinction corrected (upper, blue points) assuming the total Galactic $E(B-V)$ in that direction. The true extinction will lie between these extremes. The X-ray data are fitted with the models from Rea et al. (2009), namely an absorbed black body plus powerlaw.

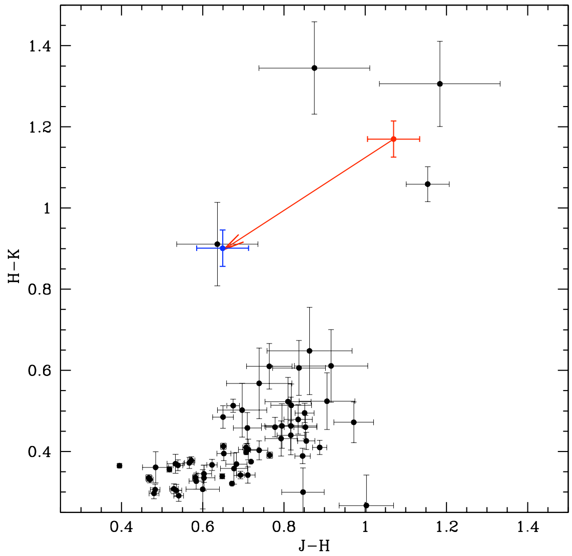

Figure 4. Colour–colour diagram, showing the location of SGR 0501+4516 in colour space, along with point sources within the frame. The red point shows the magnitudes as observed, while the blue on shows them as they would appear corrected for a foreground extinction equivalent to the total MW column in the line of sight. The arrow represents the reddening vector. As can be seen the location of SGR 0501+4516 in this figure lies well away from the stellar locus. Other sources with comparable colours are likely to be compact galaxies which are unresolved at the resolution of our observations, and show no obvious clustering across the field.

clinches this association. For the NIRI data, the source is also detected in the individual 60 second exposure frames, although at a very low significance level in the *J*- and *H*-bands.

Photometry of the infrared images was performed using IRAF(Tody 1986) aperture photometry routines. We calibrated to a sequence of nearby 2MASS stars, ensuring the accuracy of the relative photometry, our *HST* observations were photometred using the published *HST* zero points for WFC3. The results for the SGR counterpart are provided in Table 1, while the *K*-band lightcurve is shown in Figure 2. The counterpart is clearly variable, and is characterized by a prolonged plateau, followed by late time steepening. At very late times (i.e. those of the *HST* observations) it appears to plateau, suggesting that these observations reach the quiescent level.

We additionally searched for short time scale variability, on the time scales permitted by the individual frames (NIRI; individual frames with exposure times of 30 – 60 seconds) or sub-coadded frames (UFTI; integration times of 5 minutes). We find no evidence for such variability: the source remains essentially constant over periods of 15 – 30 minutes. However, much higher cadence observations (<1 second) in both the optical and infrared have revealed coherent pulsations with a period of 5.7 seconds, identical to the X-ray derived period (Dhillon et al. 2011), thus confirming the counterpart identification.

3 PROPERTIES OF THE NIR COUNTERPART OF SGR 0501+4516

3.1 The infrared light-curve

The infrared light-curve of SGR 0501+4516 is shown in Figure 2, in addition to the X-ray light-curve from Rea et al. (2009) for comparison. The X-ray light-curve is extrapolated to a specific flux at 1 keV based on the powerlaw plus blackbody model obtained for the outburst phase by Rea et al. (2009). The light-curve shows a prolonged plateau, with a slow fading, followed by a more rapid fading. This can be fit with a broken power-law, with break time $t_b = 6.6^{+2.2}_{-1.6}$ days, and pre- and post-break decay indices of $\alpha_1 = 0.03 \pm 0.04$ and $\alpha_2 = 0.34 \pm 0.05$ (where α_1 and α_2 are the pre- and post-break decay slopes defined as $F_\nu \propto t^\alpha$ and t_b is the break time). This can be compared to the behaviour of the X-ray flux over the same baseline, which yields $t_{b,x} = 7.5^{+0.4}_{-0.5}$, with slopes of $\alpha_1 = 0.05 \pm 0.02$ and $\alpha_2 = 0.54 \pm 0.01$, suggesting that the X-ray and IR light curves are broadly tracking each other, although the optical decay is slower than the X-ray. However, the late time IR observations with *HST* are suggestive of a quiescent level. Since these are H-band observations

Start time (2008 UT)	exposure time (seconds)	filter	magnitude	telescope + instrument
2008 08 / 25 03:11:12	6525	K_S	19.12 ± 0.05	WHT + LIRIS
2008 08 / 31 02:31:01	2085	K_S	19.22 ± 0.11	WHT + LIRIS
2008 09 / 01 03:44:35	2250	K_S	19.27 ± 0.10	WHT + LIRIS
2008 09 / 06 04:35:00	1188	K_S	19.05 ± 0.16	WHT + LIRIS
2008 09 / 20 03:43:15	3735	K_S	19.24 ± 0.15	WHT + LIRIS
2008 08 / 23 14:27:03	1020	J	21.02 ± 0.05	Gemini + NIRI
2008 09 / 01 14:28:09	960	J	21.07 ± 0.07	Gemini + NIRI
2008 08 / 23 14:15:25	480	H	19.95 ± 0.04	Gemini + NIRI
2008 08 / 23 14:03:44	510	K	18.78 ± 0.02	Gemini + NIRI
2008 08 / 26 15:04:16	480	K	18.87 ± 0.01	Gemini + NIRI
2008 09 / 01 14:53:07	900	K	19.08 ± 0.03	Gemini + NIRI
2009 01 / 28 07:42:57	170	K	19.53 ± 0.27	Gemini + NIRI
2009 04 / 03 06:16:53	270	K	20.04 ± 0.33	Gemini + NIRI
2009 11 / 02 10:57:00	3120	K	20.43 ± 0.07	Gemini + NIRI
2008 08 / 22 14:31:39	270	H	19.67 ± 0.14	UKIRT + UFTI
2008 08 / 22 14:27:52	405	J	21.28 ± 0.34	UKIRT + UFTI
2008 08 / 22 14:34:43	270	K	18.63 ± 0.09	UKIRT + UFTI
2010 10 / 19 02:37:24	2797	F160W	22.45 ± 0.02	HST + WFC3/IR
2012 10 / 08 19:23:37	2797	F160W	22.48 ± 0.02	HST + WFC3/IR

Table 1. Results of differential photometry relative to 2MASS stars within the field of view of NIRI, UFTI and LIRIS. An error of about 0.07 magnitude should be added in quadrature to obtain absolute photometry with respect to 2MASS: this is the scatter found when performing photometry versus various 2MASS reference stars. Magnitudes are not corrected for Galactic extinction of $E(B-V) = 1.3$ (Schlegel et al. 1998)

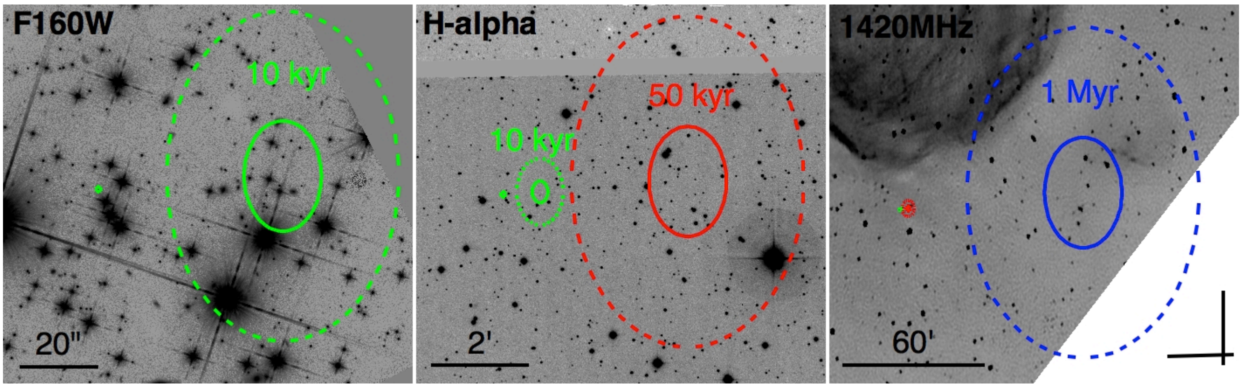

Figure 5. Constraints on the proper motion of SGR 0501+4516. The left hand panel shows a UKIRT/WFCAM K-band image of the field surrounding SGR 0501+4516. The cross indicates the current position of the SGR, while the constraints on its birth location are indicated with concentric circles corresponding to 1, 2 and 3σ limits on the proper motion, multiplied by the characteristic age of the SGR of $t_{\rm spin} = 13,000$ years. As discussed in the text, there is no evidence for any region of intensive star formation within this area, which might also have given rise to the progenitor star of SGR 0501+4516. The right hand panel shows a radio image obtained at 1.4 GHz from the Canadian Galactic Plane Survey covering a wider field, and in particular covering the nearby Galactic supernova remnant, HB9. Once again the proper motion limits are plotted and do not overlap with this remnant, which had been proposed as a possible birth place for the SGR. The dark points on the radio image are compact sources, the vast majority of these are expected to be extragalactic (Leahy & Roger 1996). For scale, the largest of the concentric circles are 40 arcmin in radius.

rather than K we cannot directly subtract the flux, but note that a significant quiescent contribution at moderate times (tens of days) would push the IR decay to a steeper level, closer to that exhibited by the X-ray.

3.2 Spectral energy distribution

The spectral energy distribution of SGR 0501+4516 one day after outburst is shown in Figure 3. The *XMM-Newton* spectra are those obtained from early and late *XMM-Newton* observations, and have been reduced as described in Rea et al. (2009). The figure shows the nIR fluxes as observed, and as they would appear corrected for Galactic extinction. However, since SGR 0501+4516 lies within the Galactic disc it is not necessarily appropriate to correct the observed fluxes for the total Galactic column from Schlegel et al. (1998), and the true fluxes will lie between the two values. It may be possible to estimate the correct reddening values based on the X-ray hydrogen column density, which was found to be $(0.89 \pm 0.01) \times 10^{22}$ cm^{-2} (Rea et al. 2009). Using a typical Milky Way extinction law with $N_{\rm H}/A_V = 0.18 \times 10^{22}$ (Schady et al. 2008) this corresponds to $A_V \sim 4.7$, rather close to the value implied via the Schlegel et al. (1998) maps ($A_V \sim 4.3$), although we note that the more recent calibration of Schlafly & Finkbeiner (2011) suggests a rather lower $A_V = 3.7$, highlighting the relative difficulty in measuring A_V accurately in these regions at low Galactic latitude. The high A_V inferred from the X-ray may suggest a relatively large distance for the SGR (i.e. looking through much of the dust and gas in the direction), but could simply be indicative of a high column local to the X-ray emitting region.

Additionally we plot in Figure 4 the location of the counterpart in colour–colour space, again showing both the observed and extinction-corrected locations. As can be seen the counterpart has markedly non-stellar colours, and lies well away from the stellar locus. This is encouraging for future searches for SGR counterparts in the infrared. In the case of SGR 0501+4516, it was initially not obvious that the source seen in the X-ray location was the counterpart, rather than an unrelated source, and searching for unambiguous fading in the nIR took several months. Snapshot identification of SGR counterparts, lying well away from the stellar populations may well be effective in their rapid identification and hence the ability to pursue further observations (e.g. spectroscopy of polarimetry, which hold great diagnostic value, but have yet to be obtained for an SGR) while the source remains brighter.

Finally, we note that between the two Gemini/NIRI epochs on 23 August 2008 and 1 September 2008 the counterpart, in addition to fading, showed evidence for becoming bluer in the infra-red bands, specifically evolving from $J - K = 2.24 \pm 0.05$ to $J - K = 1.99 \pm 0.08$.

3.3 Comparison with other sources

SGR 0501+4516 is at an unusual galactic location with respect to the other magnetars, in that it lies in the direction of the Galactic anticentre, towards the Perseus arm at ∼1–2 kpc and the Outer arm at ∼5 kpc. Only SGR 0418+5729 has a comparable location within the Galaxy (Durant, Kargaltsev, & Pavlov 2011; Esposito et al. 2010) Since the majority of the stars in this direction lie in the Perseus arm, in the following we assume its distance as a reference for SGR 0501+4516 (the properties can be straightforwardly scaled to a 5 kpc distance). The key advantage of the sky location of SGR 0501+4516 is that the field suffers from only moderate foreground extinction of $E(B - V) \sim 1.3$, compared to the much more extreme values seen for the majority of SGR sources (e.g. the integrated $E(B - V) = 17.4$ for SGR 1806-20 or $E(B - V) = 4.27$ for SGR 1900+14 (Schlegel, Finkbeiner, & Davis 1998)). The low interstellar extinction is coupled with a relatively low stellar density, and little chance of confusion. There is only a single optical source within the *Chandra* error circle of SGR 0501+4516, and, given the relatively sparse field, the chance of this being a random association is small. Indeed, this uncertainty has been removed altogether with the discovery of both fading and coherent optical pulsations from the source with a 5.7 sec period – unambiguously confirming that the optical source is SGR 0501+4516 (Dhillon et al. 2011).

The discovery and behaviour of SGR 0501+4516 adds to the growing complexity and diversity in the small number of SGR nIR counterparts discovered to date. The proposed nIR counterpart to SGR 1806-20 shows a gradual brightening over the SGR active phase in 2004 (Kosugi et al. 2005; Israel et al. 2005), with a broad correlation with the X-ray light-curve (Israel 2007). For some AXPs a broad correlation between the X-ray and optical brightness has been reported (e.g Rea et al. 2004). SGR 0501+4516 makes the first case of an SGR where such a clear correlation has been seen. *ROSAT* observations of SGR 0501+4516 prior to its 2005 outburst have revealed what is presumed to be the quiescent flux level (Rea et al. 2009), and *Swift* observations appear to show that SGR 0501+4516 has now returned to this flux. The stable IR flux over a two year time baseline suggests that this is also the IR quiescent level.

At a distance of 1.5 kpc the observed K-band magnitude corresponds to an absolute magnitude of $M_K \approx 7.5$. The absolute magnitude of the counterpart of SGR 1806-20 is $M_K \approx$-4.5 at its brightest, for a distance of ~ 9 kpc as suggested by Bibby et al. (2008), this is much brighter (a factor of $\sim 10^5$) than the counterpart of SGR 0501+4516, and may indicate very different physics is responsible for their emission[5], or that the distance of SGR 0501+4516 is too low. However, in the latter case, even in the outer arm at 5 kpc the magnitude of the counterpart would only be a factor of ∼10 brighter, and not close to the absolute magnitude inferred for SGR 1806-20.

4 PROPER MOTION MEASUREMENT

In principle, measuring proper motions for magnetars can constrain both their space velocities and possible birth sites, both of importance in terms of understanding their origins. Until recently well spaced X-ray observations with *Chandra* (e.g. SGR 1900+14 and AXP 1E 2259+586, Kaplan et al. 2009) had yielded only upper limits with the only measurement arising from very long-baseline radio interferometry of AXP XTEJ1810-197 (Helfand et al. 2007). More recently adaptive optics imaging of SGRs 1806-20 and 1900+14 has provided direct measurements of their proper motions, strengthening suggestions of their origin in young stellar clusters (Tendulkar, Cameron, & Kulkarni 2012). Similar velocity constraints have also been placed on AXP 1E 2259+586 and AXP 4U 0142+61 (Tendulkar, Cameron, & Kulkarni 2013). In the case of AXP 1E 2259+586, the proper motion makes a compelling case for an origin in the supernova remnant CTB 109, although in the latter example of AXP 4U 0142+61 it has not been possible to find an association with either a young star cluster of SNR.

SGR 0501+4516 offers a new opportunity to obtain proper motion measurements. Its location somewhat away from the plane offers the advantage of no crowding issues, while its relatively bright counterpart is easily identified. Coupled with this its location in the direction of the Galactic anti-centre ($l = 151$) means that the reflex motion due to the differential rotation of the Galaxy is very small, in contrast to events towards the Galactic centre that require detailed modelling, and suffer from potential uncertainty due to difficulties in measuring the rotation curve (Tendulkar, Cameron, & Kulkarni 2012).

[5] Although the foreground extinction to SGR 1806-20 is poorly constrained due to its location within the Galactic plane, and the uncertain extinction to ~ 9 kpc

To determine the proper motion of SGR 0501+4516 we utilised our two epochs of observations with HST with a time baseline of almost two years. The source is well detected in both epochs with comparable magnitudes of F160W(VEGA) = 22.45 ± 0.02 and 22.48 ± 0.02 (statistical only). This yields a signal to noise of ~ 100, suggesting that the location of the source can be determined via a centroid to better than 0.005 pixels (FWHM / 2.3 × S/N) or < 1 mas.

To attempt a proper motion measurement we must define an astrometric reference frame. It is standard to do this via the use of stars within the field. The moderate Galactic latitude of SGR 0501+4516 does allow for this. Utilizing this approach we find that the RMS scatter of stars is $\sim$. This is likely to be dominated by the genuine proper motions of the stars themselves, rather than by any systematic offset in the images. To improve this we therefore utilised the galaxies within the field. These were cross-correlated with one another following a method developed by Hounsell et al. (in prep). Since their distances are so large they have no intrinsic proper motion, and so utilising 19 galaxies in the field we were able to determine a scatter of XXX. Based on this measurement we determine a positional offset for the SGR of $\Delta(RA) = (0.01333 \pm 0.00199)''$, $\Delta(\delta) = (-0.00067 \pm 0.00283)''$. Over the time baseline of 2 years this corresponds to $\Delta(RA) = (0.00676 \pm 0.00010)''\mathrm{yr}^{-1}$, $\Delta(\delta) = (-0.000340 \pm 0.001415)''\mathrm{yr}^{-1}$.

We note that these observations were obtained at approximately the same dates, such that in the case of a relatively local origin the parallax reflex motion is expected to be small. Further, the Galactic longitude of $l = 161$ degrees, places SGR 0501+4516 almost radially outward from the Galactic centre. At this location the rotation velocity of the Milky Way is essentially flat with the same $v_{circ} \sim 220$ km s^{-1} as observed at the solar location. Hence, the dominant source of proper motion induced from the Galaxy is in the form of reflex motion due to differential rotation. The Oort constants suggest that this level is small (¡$0.2masyr^{-1}$) with the Galactic plane running at ~ 45 degrees to the measured proper motion vector. Therefore we conclude that the effects of Galactic rotation for this location (and level of proper motion) can be neglected.

It has been suggested that magnetars could experience large kicks at their formation, yielding high spatial velocities. This may be caused by the high B-fields present in the SGR progenitor, which can suppress convection and hence lead to large-scale anisotropy in the core collapse process (Duncan & Thompson 1992). In this case we might expect to see rapid proper motion from SGR 0501+4516. At a distance of 1.5 kpc, within the Perseus arm of the Milky Way the proper motion of SGR 0501+4516corresponds to a tangential velocity of $v_{sgr} < 430$ km s^{-1} $d_{1.5\mathrm{kpc}}$

Our observations show that the 3σ limit on the proper motion, combined with a distance of 1.5 kpc imply that $v_{sgr} 46 \pm 12$ km s^{-1} $d_{1.5\mathrm{kpc}}$. This value is lower than $\sim 95\%$ of the proper motions as measured by (Hansen & Phinney 1997), and is inconsistent with a significant kicks larger than the median observed for pulsars for any location with either the Perseus or Outer arms of the Milky Way.

XXX - this is where I am now editing

5 THE BIRTHPLACE OF SGR 0501+4516

In Figure 5 we show the extrapolated vector of the SGR proper motion, and its plausible birth sites for ages of 10 kyr, 50 kyr and 1 Myr. In each case we have examined broad-band optical/IR imaging (from DSS and WFCAM, Galactic Plane Survey), $H-\alpha$ (from IPHAS) and radio 1.4 GHz (from CGPS) observations. This highlights regions in which SGR 0501+4516could have been born for a variety of ages. We note that the spindown age of SGR 0501+4516($t_{\rm spin} = P/2\dot{P} = 13{,}000$ years, as well as the age inferred from more detailed modelling are strongly indicative of an age at the lower-end of this range. This means that the region that must be searched for a likely birthsite is commensurately smaller.

5.1 Association with supernova remnant HB9

The position of SGR 0501+4516 is close to the Galactic SNR HB9, whose centre lies roughly $80'$ from the SGR. Gaensler and Chatterjee (2008) suggest the two could both be remnants of the same progenitor. HB9 has a distance of ~ 1 kpc, and a suggested age of $t_{\rm SNR} = 4,000 - 7,000$ years (Leahy & Tian 2007), which is consistent with suggestions that it may appear on ancient star charts from a similar period, although such claims are clearly speculative (Joglekar et al. 2011). This age is somewhat younger than the characteristic age of SGR 0501+4516. However, uncertainties in both ages indicate that such an association should be considered. Our measured proper motion rules out this origin at high significance. HB9 is in the wrong direction (~ 90 degrees away from the proper motion vector) and could only be reached by the magnetar in lifetimes of $\sim 10^6$ years, much longer than the plausible age of the SN remnant, and of the SGR.

We also note that a radio pulsar, PSR B0458+46, lies within the SNR boundaries, and could very well be the compact object born from the SN explosion. The kinematic distance to HB9 (0.8±0.4 kpc) is consistent with the weak constraints on the distance to the pulsar, although its spin down age $t_{\rm spin} = 1.8 \times 10^6$ yr and inferred kinematic age if associated with HB9 (the time taken to travel from its current location to the centre of the remnant) of $t_{kin} =$.

5.2 Association with other star formation

In addition to HB9 the field around SGR 0501+4516is notable for two star forming complexes Sh217 and Sh219. They appear to lie at much larger distance that HB9, probably in the outer arm at $\sim$ 5kpc, suggesting that there is some massive star formation at these distances. However, both of these events have larger offsets from the location of SGR 0501+4516than HB9, and are offset in directions will away from the proper motion vector. We therefore rule these out as the origin of the SGR.

5.3 Stars within the proper motion ellipse

Within our smallest ellipse (10 kyr) there are numerous individual stars, although none of these appear to form in obvious bright clusters of stars. Given the excellent PSF of our *HST* observations ($\sim 0.1''$) it is unlikely that these stars are masking a compact stellar cluster which we would expect to observe. Individually the stars have optical magnitudes of $R \sim$ and IR magnitudes of $K \sim$. They often exhibit proper motion in our observations which suggests that they are more local than SGR 0501+4516. At a distance of 1.5-5 kpc O or B stars (necessary for the formation of SNe) would have magnitudes in the range $6 < R < 16$. **More detail needed here**. The moderate (but variable with distance) extinction in the direction of SGR 0501+4516precludes the detailed fitting of the available SEDs to determine stellar types.

Isolated O-stars that have run-away from their progenitor clusters do exist, and indeed some have relatively high velocities. However, in these cases we would expect the interstellar pressure around the star to be relatively low, and so would expect to observe a large and readily identifiable supernova remnant.

Hence we cannot identify any likely candidate for the origin of SGR 0501+4516. This is a stronger statement that can be made for systems closer to the Galactic centre, where star formation may be missed due to high extinction, and numerous smaller star forming regions are likely present. We therefore conclude that either SGR 0501+4516was created from a process other than massive star collapse, or that it has an age that is *much* larger than expected. We examine each of these possibilities in turn.

5.4 White dwarf – white dwarf mergers

5.5 An ancient magnetar

We therefore turn our attention to locating alternative possible birth places for SGR 0501+4516. The field in which it lies is close to the Galactic plane, in the region surveyed by both the INT/WFC Photometric Hα Survey of the Northern Galactic Plane (IPHAS; Drew et al. 2005), and the UKIRT Infrared Deep Sky Survey (UKIDSS) Galactic Plane Survey (GPS; Lucas et al. 2008). This offers the opportunity to survey the environs of SGR 0501+4516 at higher resolution, and to greater depth than is possible via the Digital Sky Survey (DSS) or 2MASS. In addition, the Hα survey is ideal for locating star forming regions, or supernova remnants which could represent the birthplace of the SGR. Young clusters have been suggested as the birthplaces for progenitors of SGR 0526-66, SGR 1900+14 and SGR 1806-20 (Klose et al. 2004; Vrba et al. 2000; Bibby et al. 2008). Within a giant molecular cloud the density may be of order $10^2 - 10^3$ cm^{-3}, compared to typical ISM densities of order 1 cm^{-3}. In such cases, the SNR rapidly sweeps up its own mass and hence is confined within a small volume, as it cannot expand significantly during the free streaming phase. For example, the compact supernovae remnants observed in M82 are thought to be only 0.6-4 pc in radius (Chevalier & Fransson 2001). This corresponds to 55 $d_{1.5\mathrm{kpc}}^{-1}$ $''$. Inspection of the available imaging shows no sign of such a cluster or compact SNR within the region constrained by the observed limits on the proper motion combined with the spin-down age.

It is possible, of course, that the progenitor star of SGR 0501+4516 was not in a cluster at the time of its explosion. Under the most popular variants of models for SGR production this seems unlikely, since the progenitor is expected to be a $\sim$40M$_\odot$ star (e.g. the suggested progenitor mass for SGR 1806-20; Bibby et al. 2008), which is unlikely to travel large transverse distances in its short lifetime. This may be mitigated somewhat if the true masses of SGR progenitors can be lower, as has been recently suggested for SGR 1900+14 (17 $M_\odot$ Davies et al. 2009). However, in the case of a progenitor not in a cluster, we would expect to easily locate the associated supernova remnant, since the ISM density within the Galactic disk is sufficiently high to produce a bright shock, though low enough to enable the SNR to grow to a moderate size in $\sim 10,000$ years, as is the case for HB9.

We conclude that with the available data there is no sign of a plausible birth-site for the progenitor of SGR 0501+4516, either a young cluster or a supernova remnant, that is consistent with it being a young neutron star of age less than $\sim$ 20000 years.

5.6 SGR 0501+4516 as an older magnetar

A further possibility is that SGR 0501+4516 is much older than its characteristic age implies. The characteristic age relies on measurements of the period derivative at the *current* time, and to provide an accurate measurement of the age requires that spin down has proceeded in a relatively uniform manner. It is possible that due to outburst activity an SGR exhibits a period of accelerated spin-down (a large value of $\dot{P}$) causing the characteristic age of the neutron star to be underestimated. If this is the case the true age of the SGR may be a factor of several larger than the characteristic age. Interestingly, by contrast, the AXP 1E 2259+586 lies within the supernova remnant CTB 109, but has a characteristic age approximately 20 times the SNR age, suggesting that sometimes the characteristic age can significantly *overestimate* the age of the magnetar, and that any variations in $P/2\dot{P}$ may operate in both directions.

In such circumstances, the lack of an obvious nearby parental supernova remnant becomes less surprising since the transverse distance possible in $\sim 10^5$ years is > 1 degree. Even within this region there is only a single SNR (HB9) and, as discussed above, its age is not consistent with an older SGR. However, at ages of 10^5 years SNRs can become extremely diffuse and hence may be essentially invisible to our observations.

Interestingly, Helfand et al. (2007), exploiting the well-determined proper motion of AXP XTEJ1810-197, found no compelling candidate birth sites for an age of less than $\sim 10^5$ yrs.

A previous study of AXP and SGR associations with SNRs by Gaensler et al. (2001) offers partial support for this explanation, at least in the case of SGR 0501+4516. They suggest, based admittedly on limited statistics, that while AXPs are frequently associated with supernova remnants, SGRs are more often not. They further suggest that SGRs may be an older population whose remnants have become dispersed over their longer lifetimes. However, it is also plausible that several SGRs (e.g. SGR 1806-20 and SGR 1900+14) were born in nearby bright clusters. In these cases, the high ISM pressure inside the clusters could effectively mask the presence of the SNR (see also Section 5.1), explaining the lack of an apparent association.

Indeed, if the lifetimes of SGRs can be significantly longer than the canonical 10^4 years this would help to ameliorate concerns over the rate of magnetar production. The rate of discovery of Galactic magnetars (or candidate magnetars) has increased in recent years thanks to the flow of new systems from *Swift* and *Fermi* (e.g. van der Horst et al. 2010), while further new candidates are being found by a variety of techniques (e.g. Halpern & Gotthelf 2010). All told this amounts to > 20 magnetar candidates. For the Milky Way we can expect ~ 100 SNe in the past 10^4 years, while stars with masses > 20 and $40 M_{\odot}$ contribute $\sim 25\%$ and $\sim 10\%$ of the total SN rate respectively (for a typical initial mass function). Should the observed magnetars all represent young systems this suggests that $> 20\%$ of massive stars create magnetars (perhaps significantly more if, as seems likely, there remain more to discover within the Milky Way). Cast differently, if we consider magnetars to arise from more massive stars, it would require almost all stars $> 20 M_{\odot}$ to create one. This appears to be a rather high rate, especially if we also need to create a diverse population of compact objects including black holes etc. Conversely, should the magnetars (or even just the SGRs) have, on average, much larger ages, then this rate would drop dramatically, again making magnetar creation a rare, rather than standard event.

5.7 SGR 0501+4516 as the product of accretion induced collapse

A final alternative is that SGR 0501+4516 did not form via the traditional massive star channel to the production of magnetars, but via the accretion induced collapse of white dwarfs (Levan et al. 2006). This may occur via mass transfer within a binary, or the merger of two white dwarfs, one of which is magnetic. In these scenario's, when the mass of the white dwarf exceeds the Chandrasaker mass it undergoes collapse to a neutron star. In the most simple model the magnetic flux is conserved during collapse ($BR^2 =$ constant), and hence, for a change in radius of a factor 500–1000 (typical for a white dwarf and neutron star) the change in the magnetic field can be a factor of 10^6. Hence, highly magnetic white dwarfs, with B-fields of $10^8 - 10^9$G, will become magnetars (Levan et al. 2006). Furthermore, given the necessarily high angular momentum associated with the merger it is plausible that magnetic dynamos will act, and could increase the rate of production of magnetars via WD-WD mergers.

This channel is appealing for SGR 0501+4516 since it is rather likely that minimal mass is ejected in such a merger. The mean mass of a WD is ~ 0.6 M$_{\odot}$, and so the majority of WD-WD systems which exceed the Chandrasaker mass may well do so only marginally. In this case the majority of the mass is likely to remain in the newly formed neutron star, leading to low mass ejection and energy, and hence a faint remnant. Thus, in this model the lack of either a supernova remnant, or a young cluster can naturally be explained.

It is reasonable under this scenario to wonder if the rates of such channels are plausible. The rate of magnetar production via the WD-WD channel is rather comparable to the core collapse rate (Nelemans et al. 2001; Levan et al. 2006), and in fact larger by a factor of $\sim 5-10$ than the rate of production of 40 $M_{\odot}$ stars (Podsiadlowski et al. 2004). These rates are uncertain due to the nature of population synthesis (especially for the WD-WD mergers). However, they suggest that under the assumption that a WD-WD merger leads to a collapse to a NS, rather than SN Ia, it is reasonable to expect some fraction of SGRs to originate via this route, and that locating objects such as SGR 0501+4516, would not be unexpected in these circumstances.

6 CONCLUSIONS

We have presented the discovery of the nIR counterpart of SGR 0501+4516, and supplemented this with observations SGR 0418+5729. These observations show that the nIR flux of the counterpart of SGR 0501+4516 broadly followed the X-ray variability. Further, the long time baseline of the observations enabled us to place strong constraints on the proper motion of the SGR, and have shown that it is not associated with the close-by supernova remnant HB9, nor is there any obvious star formation region located close to the SGR. This suggests either than SGR 0501+4516 is much older than typically anticipated, or that it may have formed via a route that does not involve massive star collapse, such as accretion induced collapse of a magnetic white dwarf. Future monitoring of the nIR counterpart can establish its flux level, and hence the plausibility of long time baseline observations to track any small scale variability and place stringent constraints on the proper motion. Ultimately these may enable us to directly pin down the dynamics of an SGR for the first time, in turn allowing us new insight into their formation and emission mechanisms.

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