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SU Lyncis, a hard X-ray bright M giant: clues point to a large hidden population of symbiotic stars

K. Mukai,[1,2★] G. J. M. Luna,[3] G. Cusumano,[4] A. Segreto,[4] U. Munari,[5] J. L. Sokoloski,[6] A. B. Lucy,[6] T. Nelson[7] and N. E. Nuñez[8]

[1] *CRESST and X-ray Astrophysics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA*
[2] *Department of Physics, University of Maryland, Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250, USA*
[3] *Instituto de Astronomía y Física del Espacio (IAFE, CONICET-UBA), Av. Inte. Güiraldes 2620, C1428ZAA Buenos Aires, Argentina*
[4] *INAF – Istituto di Astrofisica Spaziale e Fisica Cosmica, Via U. La Malfa 153, I-90146 Palermo, Italy*
[5] *INAF – Astronomical Observatory of Padova, I-36012 Asiago (VI), Italy*
[6] *Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA*
[7] *Department of Physics and Astronomy, University of Pittsburgh, 3941 O'Hara St, Pittsburgh, PA 15260, USA*
[8] *Instituto de Ciencias Astronómicas de la Tierra y del Espacio (ICATE-UNSJ, CONICET), Av. España (S) E-1512, J5402 DSP, San Juan, Argentina*

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ABSTRACT

Symbiotic star surveys have traditionally relied almost exclusively on low resolution optical spectroscopy. However, we can obtain a more reliable estimate of their total Galactic population by using all available signatures of the symbiotic phenomenon. Here we report the discovery of a hard X-ray source, 4PBC J0642.9+5528, in the *Swift* hard X-ray all-sky survey, and identify it with a poorly studied red giant, SU Lyn, using pointed *Swift* observations and ground-based optical spectroscopy. The X-ray spectrum, the optical to UV spectrum, and the rapid UV variability of SU Lyn are all consistent with our interpretation that it is a symbiotic star containing an accreting white dwarf. The symbiotic nature of SU Lyn went unnoticed until now, because it does not exhibit emission lines strong enough to be obvious in low resolution spectra. We argue that symbiotic stars without shell-burning have weak emission lines, and that the current lists of symbiotic stars are biased in favour of shell-burning systems. We conclude that the true population of symbiotic stars has been underestimated, potentially by a large factor.

Key words: binaries: symbiotic – stars: individual: SU Lyn – X-rays: binaries.

1 INTRODUCTION

The traditional, phenomenological definition of a symbiotic star is a late type giant with a companion, hot enough to result in prominent high-excitation emission lines in the optical (Kenyon 1986). While we know of several symbiotic X-ray binaries with neutron star accretors (see e.g. Masetti et al. 2007; Corbet et al. 2008; Enoto et al. 2014), and symbiotic stars with main-sequence accretors may exist, the majority of symbiotic stars appear to be wide binaries in which white dwarfs accrete from red giants.

In recent years, we have gained new insights into the symbiotic phenomenon through X-ray observations. First was the discovery of four symbiotic stars, CH Cyg, T CrB, RT Cru, and V648 Car (also known as SS73 17 and CD −57 3057), in the *Swift* Burst Alert Telescope (BAT) survey of the 14–195 keV sky (Kennea et al. 2009; see also Luna & Sokoloski 2007; Luna, Sokoloski & Mukai 2008; Smith et al. 2008). The hard X-ray spectra of these sources can be described as optically thin, thermal emission with a high temperature, and are interpreted as due to accretion on to the white dwarf surface via the boundary layer. Subsequently, pointed *Swift* X-Ray Telescope (XRT) survey of known symbiotic stars (Luna et al. 2013 and references therein) showed that many other symbiotic stars had a similar X-ray emission component, although not luminous and/or hard enough to be detectable in the BAT survey. Luna et al. (2013) called this type of X-ray emission δ-type, expanding the earlier classification scheme of Muerset, Wolff & Jordan (1997). The δ-type X-ray component is often highly absorbed and cannot be detected in the soft X-rays. The column density of the absorber often far exceeds that expected from the interstellar medium (ISM), and is seen to be variable from observation to observation: the absorber is intrinsic to the system.

These observations allow us to divide symbiotic stars into shell-burning systems, powered by nuclear fusion as well as accretion, and non-burning systems, powered by accretion alone. There is no known instance of a shell-burning system in which a δ-type X-ray

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★ E-mail: Koji.Mukai@nasa.gov

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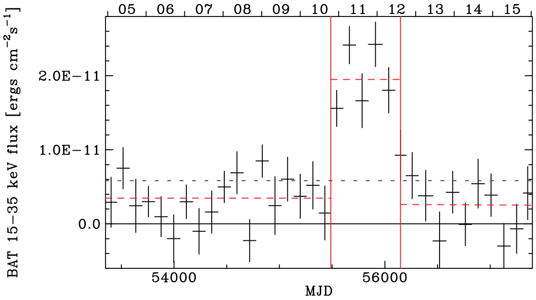

Figure 1. The 11-yr 15–35 keV BAT light curve of SU Lyn in 120 d bins. Vertical red lines indicate the high state (2010 October 14 to 2012 August 1) as identified by the survey pipeline. The short dashed blue line is the overall weighted average, while long dashed red lines show the weighted average during the high state and the periods before and after.

emission is detected. In addition, the *Swift* UV and Optical Telescope (UVOT) data show a high degree of UV variability in the non-burning symbiotic stars, interpreted as flickering of the accretion disc, while shell-burning symbiotics have steady UV emission (Luna et al. 2013).

Kennea et al. (2009) showed that 4 out of 461 BAT sources in the 22-month survey catalogue (Tueller et al. 2010) were non-burning symbiotic stars. In this Letter, we report the first discovery since then of a new symbiotic star among BAT sources.

2 OBSERVATIONS AND DATA ANALYSIS

2.1 BAT survey detection and analysis

The *Swift* mission (Gehrels et al. 2004) performs a sensitive all-sky survey of the hard X-ray (14–195 keV) sky as a by-product of its main objective to detect and observe Gamma-ray bursts. GC and AS have been engaged in an effort to produce a series of catalogues of BAT sources (see e.g. Cusumano et al. 2010) using the BAT_Imager code (Segreto et al. 2010), and are preparing the fourth version of the catalogue covering the first 100 months of the mission (2004 December to 2013 April) and containing 1710 sources.[1] One new source in this catalogue is 4PBC J0642.9+5528.

The batch processing for the catalogue indicated that this source had its highest signal to noise (S/N) in the 15–35 keV range, and during 2010 October 14 to 2012 August 1 (hereafter ‘high state’). The survey products include the average and the high state spectra of 4PBC J0642.9+5528. To investigate its variability further, we extracted 15–35 keV light curve over the period 2004 December 8 to 2016 January 11 in 15 d bins, in which we converted BAT count rate to flux using a factor of 3.147×10^{-7} ergs cm^{-2} s^{-1} per 1 ct s^{-1}, appropriate for the spectral shape of SU Lyn; we show the light curve rebinned into 120 d bins in Fig. 1.

The only previously known X-ray source in the BAT error circle is 1RXS J064255.9+552835, and the only known optical object within its error circle is SU Lyn, listed in the General Catalog of Variable Stars as a semiregular variable (magnitude range: 10.5–9.6). There do not appear to be any publications that discuss in-depth studies of SU Lyn. A single M giant is a very weak, almost undetectable, *soft* X-ray source at most (see e.g. Ayres, Brown & Harper 2003), and never a hard (>10 keV) X-ray source. We therefore arranged for follow-up *Swift* and optical observations to confirm this association.

Table 1. Pointed *Swift* observations of SU Lyn.

ObsID	Date	XRT exposure (s)	*UVOT* filter
00034150001	2015-11-20	2963	*UVM*2
00085853001	2015-11-30	2274	*U*
00085853002	2015-12-05	649	*UVW*2
00085853003	2015-12-07	318	*UVW*1

2.2 Pointed *Swift* observations

KM and GC each requested a 3 ks *Swift* observation to confirm the association of 4PBC J0642.9+5528 with SU Lyn, and these observations were carried out between 2015 November 20 and December 7 (see Table 1). During observation 0003415001, UVOT data were taken with the *UVM*2 filter in event mode; the other observations took UVOT image mode data in *U*, *UVW*2 and *UVW*1 filters.

The *Swift* data were analysed using HEASOFT version 6.18 with the latest calibration files. We first combined the XRT event files from the four observations. The spectrum and light curve of the sources were extracted from a circular region with a radius of 20 pixels (∼47 arcsec) centred on the SIMBAD coordinates of SU Lyn, and the background from an annular region with the inner and the outer radii of 27 and 54 pixels, respectively. We used the response file `swxpc0to12s6_20130101v014.rmf` in the calibration data base, and used `xrtmkarf` to construct the ancillary response file. In our timing analysis, we used the `xrtlccorr` tool to correct for the presence of dead columns.

We used the `uvotsource` tool to extract the magnitudes from the UVOT image mode data, with a source aperture of 5 arcsec radius. We discarded the *U*-band image, since SU Lyn was found to be saturated. In the UV filters, SU Lyn suffered some coincidence losses that were correctable. We used the same aperture to extract the light curves from the event mode data using `uvotevtlc`, which applied the corrections for coincidence losses and large-scale sensitivity variations (Poole et al. 2008).

2.3 Optical spectroscopy

One of us (UM) initiated a campaign to obtain optical spectra of SU Lyn, and selected field stars around it, using two telescopes at Asiago. We use the 1.82-m telescope with the Echelle spectrograph to obtain high resolution spectra covering 3650–7350 Å with a resolving power of 20 000 in 30 orders without inter-order gaps. We use the 1.22-m telescope with the Boller and Chivens spectrograph to obtain low resolution spectra covering 3300–7850 Å with 2.31 Å per pixel and a full width half-maximum of 2.2 pixels. From this ongoing campaign, we describe in this Letter a subset of results obtained between 2015 October and 2016 January to provide the essential context for interpreting the X-ray and UV observations.

3 RESULTS

In the *Swift* XRT data, there is one and only one 2–10 keV X-ray source within the error circle of 4PBC J0642.9+5528, 1.3 arcsec from the SIMBAD position of SU Lyn with an error circle of 3.8 arcsec radius. There is one UVOT source within the XRT error circle, 0.2 arcsec from SU Lyn with an error circle of 0.42 arcsec radius: SU Lyn almost certainly is the counterpart of the BAT source.

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[1] http://bat.ifc.inaf.it/100m_bat_catalog/100m_bat_catalog_v0.0.htm

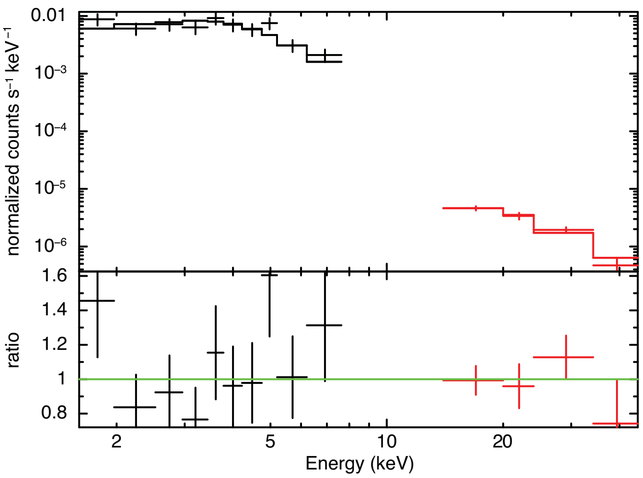

Figure 2. The joint fit of the BAT high-state data and 2016 November/December XRT data for SU Lyn. See text for details.

3.1 X-ray variability

Fig. 1 clearly demonstrates the long-term variability of SU Lyn. The average BAT 15–35 keV band flux was $(0.58 \pm 0.05) \times 10^{-11}$ ergs cm^{-2} s^{-1}. The high state flux was $(1.95 \pm 0.12) \times 10^{-11}$ ergs cm^{-2} s^{-1}, while the normal states flux was at (0.35 ± 0.07) and $(0.26 \pm 0.10) \times 10^{-11}$ ergs cm^{-2} s^{-1}, respectively, before and after the high state. The high state flux was ∼6.5 times higher than in normal state, and elevated the overall average by a factor of ∼2.

We calculated the average *Swift* XRT count rates for the four observations in the hard (2–10 keV) and the soft (0.3–2 keV) bands. While the hard rate stayed approximately constant at 0.04 ± 0.01 ct s^{-1}, the soft rate varied from $(2.2 \pm 1.1) \times 10^{-3}$ ct s^{-1} in the first observation to 0.05 ± 0.01 ct s^{-1} in the last, implying variable X-ray absorption.

3.2 X-ray spectrum

We combined all XRT data in our spectral analysis because spectra from individual observations were noisy. We fit the average XRT spectrum simultaneously with the BAT high-state spectrum, allowing for a cross-normalization factor to account for the long-term variability, which we assume to be energy independent. In one fit, we used an `APEC` thermal plasma model with `tbabs` absorber model and obtained $\mathrm{N_H} = 2.9^{+1.1}_{-0.9} \times 10^{22}$ cm^{-2} and $\mathrm{kT} = 17^{+6}_{-4}$ keV. The BAT cross-normalization constant was 7.7, and the inferred 0.3–50 keV unabsorbed flux during the XRT observations was 1.05×10^{-11} ergs cm^{-2} s^{-1}. Given the spectral shape, we expect little additional flux outside this band. We show this fit in Fig. 2. We have also fitted the data using the cooling flow model, `mkcflow`. A similar quality fit was obtained, with the maximum temperature (kT_{max}) of 26^{+12}_{-7} keV. When we used the average BAT spectrum instead, again with the average XRT spectrum, the results were similar except that the cross-normalization factor was ∼2, and the parameter values had larger errors. While better data are necessary for a definitive fit, these results are consistent with those on well-studied δ-type symbiotic stars (see e.g. Luna & Sokoloski 2007; Smith et al. 2008).

3.3 UV variability

We used the *UVM*2 event mode data to investigate the UV variability of SU Lyn. We extracted the light curves of both SU Lyn and another bright star in the UVOT field of view, HD 237533, in 15 s bins, and show them in Fig. 3. SU Lyn is clearly highly variable both within individual *Swift* orbits, and from one *Swift* orbit to the next. To quantify the degree of variability, we calculated the fractional RMS variability (s_{frac}) and also compared the measured light curve standard deviation (s) with the average error bar (s_{exp}). We find s_{frac} of 7 per cent and $s/s_{\mathrm{exp}} = 1.73$ during the first orbit; 7 per cent and 1.69 during the second; and 10 per cent and 2.42 during the third.

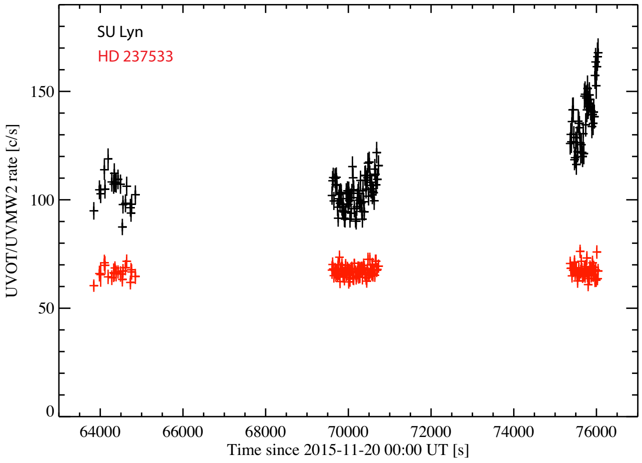

Figure 3. The UVOT *UVM*2 band light curve of SU Lyn in 15 s bins. We also show that of HD 237533 for comparison.

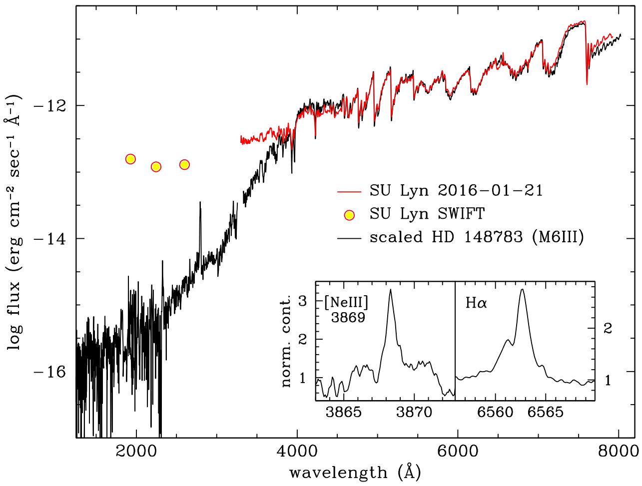

Figure 4. Low resolution optical spectrum of SU Lyn with *Swift* UVOT points, compared with optical and IUE spectra of MIII star, HD 14783. Insets show the H α and [Ne III] 3869 profiles from the high resolution spectra taken on the same night.

We also analysed archival *GALEX* data. SU Lyn had NUV (1771–2831 Å) and FUV (1350–1780 Å) magnitudes of 17.42 ± 0.02 and 16.64 ± 0.03 on 2006 December 21, and 15.80 ± 0.02 and 16.11 ± 0.03 on 2007 January 27. That is, SU Lyn was much fainter and variable during the *GALEX* observations.

3.4 Optical to UV spectrum of SU Lyn

A comparison of our low resolution optical spectrum of SU Lyn, obtained on 2016 January 21, with that of HD 148783, the MKK spectral standard for M6III, highlights the evidence for mass transfer. As shown in Fig. 4, they match nicely longwards of 4000 Å,

Table 2. The distance (from *Hipparcos* and spectroscopic parallaxes) and interstellar Na D1 line equivalent widths of SU Lyn and six field stars.

Star	Spectral type	Distance (pc)	Na D1 EqW (Å)
HD 46608	A2.5V	117	0.030
HD 48841	A1V	226	0.121
HD 237526	A2V	304	0.147
HD 46732	A0V	327	0.201
HD 237529	K2III	506	0.260
SU Lyn	M5.8III	640	0.290
HD 237549	B8V	689	0.360

suggesting that this is close to the spectral type of the giant in SU Lyn. We investigated this further by fitting a series of templates constructed by linearly interpolating M5III and M6III spectra taken from the atlas of Fluks et al. (1994). We found a near-perfect match between SU Lyn and an M5.8III cool giant subjected to a reddening of $E(B-V) = 0.07$ following a standard $R_V = 3.1$ extinction law. The allowed range of the spectral type is found to be between M5.6 and M5.9, correlated with the ±0.02 uncertainty on $E(B-V)$.

SU Lyn has a Tycho-2 V magnitude of 8.642, which equals $V = 8.46$ in the standard Johnson system (Bessell 2000). For the M5.8III spectral type, the $R_V = 3.1$ reddening law implies $A_V = 3.75E(B-V) = 0.263$ (Fiorucci & Munari 2003). The absolute magnitude of an M5.8III star is $M_V = -0.83$ on the Sowell et al. (2007) scale. Thus we estimate the distance to SU Lyn to be 640 pc. The dominant source of uncertainty is likely to be the accuracy of the Sowell et al. (2007) scale, to which we assign ±0.25 mag. The resulting uncertainty on the distance is ∼10 per cent.

Our Echelle spectra of SU Lyn show that the each line of the NaI D doublet consists of three components. For comparison, we have collected the spectra of five hot stars (which therefore do not show intrinsic NaI lines) within 1° of the position on the sky of SU Lyn. We also observed a sixth, cooler star (HD 237529), with a radial velocity high enough to decouple the stellar Na I doublet from the interstellar one. This allowed us to identify the component with the lowest heliocentric velocity (-4.1 km s^{-1}) in the SU Lyn spectra as interstellar.

We present the equivalent width of interstellar Na I D1 line (at 5889.953 Å) in SU Lyn and these six field stars in Table 2 and in Fig. 5. The stars are listed from the nearest to most distant, estimated using *Hipparcos* and spectroscopic parallaxes. On the one hand, the equivalent width (EqW) we measure for SU Lyn of 0.290 Å would suggest $E(B-V) = 0.109$, somewhat larger than the value we obtained from the template fit, using the Munari & Zwitter (1997) calibration for the ISM. On the other hand, it nicely fits with the progression of the field stars from HD 46608 (117 pc, EqW = 0.030 Å) to HD 237549 (689 pc, EqW = 0.360 Å), suggesting that our distance estimate is reasonably accurate. Considering both the template fitting and Na I D1 line results, we conservatively estimate the distance to SU Lyn to be 640 ± 100 pc.

Finally, we find clear evidence for UV emission powered by binary interaction by combining low resolution optical spectrum and our *Swift* UVOT data converted to fluxes using the calibration of Poole et al. (2008). While we find an excellent match between the optical spectrum of SU Lyn and the scaled optical spectrum of HD 148783, the UVOT data of SU Lyn are more than 2 orders of magnitude above the scaled archival IUE spectra of HD 14783 (Fig. 4). Moreover, we observe variable emission lines of hydrogen Balmer series, [Ne III], and Ca II in our high resolution data. That is, SU Lyn is a symbiotic star.

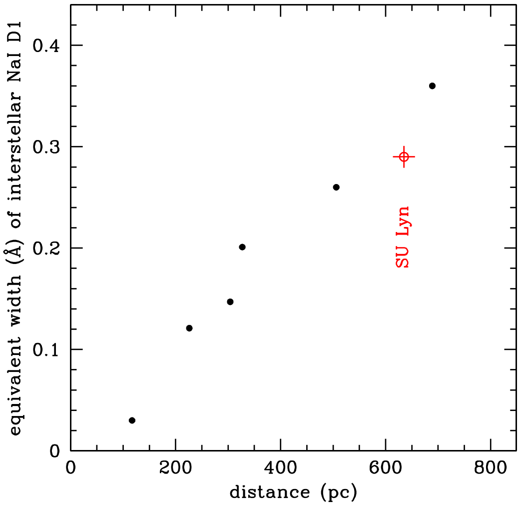

Figure 5. The equivalent widths of the interstellar Na I line at 5889.953 Å of SU Lyn and six field stars, plotted against their estimated distances.

4 DISCUSSION

We have shown that SU Lyn, previously catalogued as a semiregular variable, is in fact a hard X-ray luminous symbiotic star. We use our *Swift* results to infer the nature of the hot component as follows. Assuming a distance of 640 pc, the X-ray luminosity was $\sim 5.2 \times 10^{32}$ ergs s^{-1} during the XRT observations, and $\sim 4.0 \times 10^{33}$ ergs s^{-1} during the high state. We estimate the UV flux to be about 1.2×10^{-13} ergs cm^{-2} s^{-1} Å^{-1}, for a total UV (2000–4000 Å) flux of 2.4×10^{-10} ergs cm^{-2} s^{-1}, or UV luminosity of 1.2×10^{34} ergs s^{-1}. Thus, the UV luminosity exceeds the X-ray luminosity by a substantial margin, even before applying a bolometric correction. This strongly argues against a symbiotic X-ray binary interpretation, in which the accreting object is a neutron star, since accreting neutron stars release most of the gravitational potential energy in the X-rays.

The X-ray and UV luminosities of SU Lyn indicate that it contains an accreting white dwarf. Moreover, when compared to the nine known symbiotic stars whose δ-type X-ray emission was discovered by Luna et al. (2013), SU Lyn appears more X-ray luminous than at least five. In the UVOT event mode data on SU Lyn, we have found a strong UV variability down to a sub-minute time-scale for the first time in such a system. The observed variability was of the same order as that obtained by Luna et al. (2013) in several other symbiotic stars, although they were only sensitive to variability on longer time-scales since they used UVOT image mode data. Luna et al. (2013) found that such strong UV variability is a characteristic of non-burning symbiotic stars. Therefore, we infer that SU Lyn is also powered purely by accretion, with the observed UV luminosity predominantly from the accretion disc.

We can constrain the white dwarf mass in SU Lyn using our X-ray spectral fits, because the white dwarf mass determines the maximum shock temperature that can be reached in an optically thin boundary layer (Byckling et al. 2010). The observed $kT_{\max}$ is consistent with a 1 M$_{\odot}$ white dwarf (with a predicted $kT_{\max}$ of 28 keV). In this scenario, the observed X-ray luminosity implies an accretion rate of 7.0×10^{-11} M$_{\odot}$ yr^{-1}. The observed UV luminosity corresponds to an accretion rate of 1.6×10^{-9} M$_{\odot}$ yr^{-1}, assuming that it is entirely from the accretion disc, and is likely to be higher due to bolometric correction. Thus, although the boundary layer could be optically thin if an additional source of UV luminosity such as shocks is present, the rapid UV variability constrains the possible nature of, or the contribution by, such a source.

Alternatively, the boundary layer in SU Lyn may be partially optically thick, which is thought to require an accretion rate above $\sim 1.0 \times 10^{-8}$ $M_{\odot}$ yr^{-1} (see Nuñez et al. 2016 and references therein), and hence a factor of >6 bolometric correction for the disc UV luminosity. Such a boundary layer emit a residual optically thin X-ray emission with a lower luminosity and with a lower temperature than the pure optically thin case (see e.g. Wheatley, Mauche & Mattei 2003a). In this interpretation, the white dwarf in SU Lyn is likely to be more massive than ~ 1 $M_{\odot}$.

The manner of discovery of SU Lyn is very similar to that of 4 Dra, whose hot component was discovered in the UV (Reimers 1985). Later observations established this as a symbiotic star with a δ-type X-ray emission (Wheatley, Mukai & de Martino 2003b; Nuñez et al. 2016). The symbiotic nature of SU Lyn and 4 Dra were not recognized from the ground because neither has emission lines strong enough to show up in low resolution surveys. In typical symbiotic stars, prominent emission lines arise when the red giant wind is photoionized by a central hot source which is thought to be a $\sim 10^5$ K blackbody-like source with luminosities 100–10000 $L_{\odot}$ (see e.g. Skopal 2015), or 4×10^{35}–4×10^{37} ergs s^{-1}. The UV luminosity of T CrB is estimated to be lower, and the optical emission lines are prominent only some of the time (see e.g. Munari, Dallaporta & Cherini 2016). The UV luminosity of SU Lyn may well be lower still, similar to that of 4 Dra (2.6×10^{34} ergs s^{-1}; Skopal 2015). It is therefore reasonable that the resulting emission lines in the optical are too weak to show up in low resolution spectroscopic surveys.

The large difference in the hot component luminosity, in turn, is due to the different energy sources: nuclear fusion versus accretion. The former produces ~50 times more energy per nucleon than the latter. The shell-burning symbiotic stars exhibit prominent emission lines; non-burning ones have weak lines at most. The existing catalogues of symbiotic stars rely heavily on the emission lines and are therefore biased in favour of shell-burning symbiotics.

SU Lyn and 4 Dra are two examples of non-burning symbiotics without prominent lines, and other similar systems likely exist. This hidden population is potentially large. The BAT detection of SU Lyn was possible because of its relative proximity, and because of its X-ray high state. Without the high state, the BAT survey can only detect SU Lyn out to <500 pc. The *ROSAT* all-sky survey could only detect 4 Dra out to <200 pc. Scaling by the area of the Galactic disc, these suggest of order 4 SU Lyn-like systems and of order 25 4 Dra-like systems within 1 kpc, implying a higher space density than that of known symbiotic stars. The three hard X-ray emitting, UV excess AGB stars discovered by Sahai et al. (2015) are likely to be part of this same population.

Munari & Renzini (1992) estimated the total Galactic population of symbiotic stars to be up to $\sim 3 \times 10^5$, up from the previous estimate of ~3000. Both estimates are extrapolation from the ~150 systems known at the time, but with different estimates of their distances. We believe it is quite possible that we may face another significant revision in the total Galactic population of symbiotic stars, once a survey for SU Lyn-like systems can be performed.

5 CONCLUSIONS

We have discovered that SU Lyn, previously catalogued as a semiregular variable, is a hard X-ray source in the *Swift* BAT survey catalogue. Based on the *Swift* and ground-based data, we interpret SU Lyn as a symbiotic star powered purely by accretion on to a white dwarf. The lack of shell burning leads to SU Lyn having very weak symbiotic signatures in the optical. Since existing catalogues of symbiotic stars rely heavily on prominent emission lines, non-burning symbiotics are likely severely under-represented in these catalogues. Further observations of SU Lyn are highly desirable for us to tune our search strategy for other members of this hidden population of symbiotic stars.

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