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Revealing a new symbiotic X-ray binary with Gemini Near-infrared Integral Field Spectrograph

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ABSTRACT

We use *K*-band spectroscopy of the counterpart to the rapidly variable X-ray transient XMMU J174445.5−295044 to identify it as a new symbiotic X-ray binary. XMMU J174445.5−295044 has shown a hard X-ray spectrum (we verify its association with an *INTEGRAL*/Imager on-Board the *INTEGRAL* Satellite 18–40 keV detection in 2013 using a short *Swift*/X-Ray Telescope observation), high and varying $N_{\rm H}$, and rapid flares on time-scales down to minutes, suggesting wind accretion on to a compact star. We observed its near-infrared counterpart using the Near-infrared Integral Field Spectrograph at Gemini-North, and classify the companion as ∼M2 III. We infer a distance of $3.1^{+1.8}_{-1.1}$ kpc (conservative 1σ errors), and therefore calculate that the observed X-ray luminosity (2–10 keV) has reached to at least 4×10^{34} erg s^{-1}. We therefore conclude that the source is a symbiotic X-ray binary containing a neutron star (or, less likely, black hole) accreting from the wind of a giant.

Key words: binaries: symbiotic – stars: late-type – stars: neutron – infrared: stars – X-rays: binaries – X-rays: individual: XMMU J174445.5−295044.

1 INTRODUCTION

Symbiotic binaries transfer mass via the winds of cold (usually late K or M) giants on to compact objects: white dwarfs, neutron stars, or black holes (Kenyon 1986), with orbital periods typically in the 100–1000s of days (Belczyński et al. 2000). They were first identified by the presence of high-ionization emission lines in optical spectra of otherwise cold giants, indicating the presence of two components of vastly different temperatures. *ROSAT* X-ray studies of symbiotic binaries distinguished three classes (α, β, γ) by the X-ray spectral shape (Murset, Wolff & Jordan 1997), with higher energy X-ray measurements adding two further classes showing highly absorbed spectra (Luna et al. 2013). A small but rapidly increasing number of symbiotic systems have been identified as containing a neutron star as an accretor, through the measurement of pulsations and/or hard X-ray emission above 20 keV, and are known as symbiotic X-ray binaries (Masetti et al. 2006).

Only seven symbiotic X-ray binaries have been positively identified so far: GX 1+4 (Davidsen, Malina & Bowyer 1977); 4U 1700+24 (Masetti et al. 2002); 4U 1954+319 (Masetti et al. 2006); Sct X-1 (Kaplan et al. 2007); IGR J16194−2810 (Masetti et al. 2007); IGR J16358−4726 (Nespoli, Fabregat & Mennickent 2010); and XTE J1743−363 (Bozzo et al. 2013). Several other likely candidate systems have also been proposed (e.g. Nucita, Carpano & Guainazzi 2007; Masetti et al. 2011; Hynes et al. 2014). The identification and characterization of a symbiotic X-ray binary require clear information on the nature of the accretor (e.g. from pulsations or unusual luminosities) and the donor (e.g. from spectroscopy).

Heinke et al. (2009) identified XMMU J174445.5−295044 as a rapidly variable (time-scales down to 100s of seconds) Galactic transient, using nine *XMM–Newton*, *Chandra*, and *Suzaku* observations. It showed 2–10 keV X-ray fluxes up to $>3 \times 10^{-11}$ erg cm^{-2} s^{-1}, and variations in $N_{\rm H}$ from 8×10^{22} up to 15×10^{22} cm^{-2}. The rapid variations and variable $N_{\rm H}$ suggested accretion from a clumpy wind, rather than an accretion disc. Heinke et al. (2009) also identified a bright near-infrared (IR) counterpart (2MASS J17444541−2950446) within the 2 arcsec *XMM* error circle. Heinke et al. (2009) calculated the probability of a star of this brightness in $K_{\rm S}$ appearing in the X-ray error circle as only 2 per cent, indicating that it is almost certainly the true counterpart. This star appears highly obscured and shows IR colours typical of late-type stars, which Heinke et al. suggested indicates that XMMU J174445.5−295044 is a symbiotic star or symbiotic X-ray binary.

The *INTEGRAL* Galactic bulge monitoring program (Kuulkers et al. 2007) reported an X-ray transient detected by the Joint European X-Ray Monitor (JEM-X) on 2012 March 23

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(Chenevez et al. 2012), at 17:44:48, −29:51:00, with an uncertainty of 1.3 arcmin at 95 per cent confidence, consistent with XMMU J174445.5−295044. The 10–25 keV flux of $1.5 \pm 0.3 \times 10^{-10}$ erg cm^{-2} s^{-1} is larger than previously reported for XMMU J174445.5−295044, but the high estimated $N_{\rm H}$ (not specified, but the JEM-X source was undetected below 10 keV, indicating $N_{\rm H} > 10^{23}$ cm^{-2}) suggests that this is likely the same source, as it is known to exhibit similarly large intrinsic extinction (Heinke et al. 2009). In 2013 March, the *INTEGRAL*/Imager on-Board the *INTEGRAL* Satellite (IBIS) telescope detected a hard transient at $9.3 \pm 1.4 \times 10^{-11}$ erg cm^{-2} s^{-1} (17–60 keV), at position 17:44:41.76, −29:48:18.0, uncertainty 4.2 arcmin (Krivonos et al. 2013). Krivonos et al. note that this position is consistent with XMMU J174445.5−295044, but suggest that follow-up observations are needed to verify whether it is the same source.

In this paper, we present Gemini Near-infrared Integral Field Spectrograph (NIFS) spectroscopy of 2MASS J17444541−2950446, and conclude that its spectral type indicates a M2 III giant. We also describe a *Swift*/X-Ray Telescope (XRT) observation permitting the confident identification of the 2013 *INTEGRAL*/IBIS transient (Krivonos et al. 2013) with XMMU J174445.5−295044. We combine these results to infer a peak $L_{\rm X} > 4 \times 10^{34}$ erg s^{-1}. These results together allow us to confidently identify XMMU J174445.5−295044 as a symbiotic X-ray binary containing a neutron star or black hole accretor, rather than a white dwarf.

2 DATA AND ANALYSIS

2.1 *Swift*/XRT

We observed XMMU J174445.5−295044 with *Swift*/XRT on 2013 March 30 (2 d after the *INTEGRAL*/IBIS detection of Krivonos et al. 2013) in photon-counting mode. The observation was interrupted after an on-source exposure of ∼150 s due to a gamma-ray burst alert. We detect a single source in the 23.6 arcmin diameter field, showing seven counts. Using FTOOLS XRTCENTROID we determine the position to be RA = $17^{\rm h}$:$44^{\rm m}$:$46\overset{\rm s}{.}26$ and Dec. = $-29°$:$50'$:$56\overset{''}{.}08$ with positional uncertainty of 9 arcsec, consistent within $<2\sigma$ with the position of XMMU J174445.5−295044. Given the lack of other X-ray sources nearby (see fig. 4 of Heinke et al. 2009), the *Swift*/XRT source is thus certainly the same as XMMU J174445.5−295044.

We reprocessed the *Swift*/XRT data (using HEASOFT 6.14), extracted a spectrum with XSELECT, and created an effective area file with XRTMKARF. We fit the *Swift*/XRT spectrum with an absorbed power law using CSTAT statistics (Cash 1979) in XSPEC 12.8.1, fixing the photon index to 1.18 (as found in the deepest and most constrained observation of Heinke et al. 2009). We measure $N_{\rm H} = 4.5^{+7.2}_{-3.3} \times 10^{22}$ and an unabsorbed 2–10 keV flux of $8.5^{+10.3}_{-5.0} \times 10^{-12}$ erg s^{-1} cm^{-2}, the second-highest 2–10 keV flux recorded from XMMU J174445.5−295044.

If the *INTEGRAL*/IBIS measurement is extrapolated (using the spectrum above) to the 2–10 keV band, the *Swift*/XRT flux measurement is 1/3 of the *INTEGRAL* measurement. Such a high flux from XMMU J174445.5−295044 only 2 d after the *INTEGRAL*/IBIS detection, combined with the lack of other detections within the 4.2 arcmin *INTEGRAL*/IBIS error circle, indicates that XMMU J174445.5−295044 was the origin of the *INTEGRAL*/IBIS detection. The 2012 *INTEGRAL*/JEM-X detection (Chenevez et al. 2012), with a smaller error circle of 1.3 arcmin, can also be confidently assigned to XMMU J174445.5−295044.

We created long-term X-ray light curves of XMMU J174445.5−295044, calculating X-ray luminosities in the 2–10 keV band using our calculated 3.1 kpc distance (see below). In Fig. 1, we show the published detections of XMMU J174445.5−295044 (including our *Swift* measurement,

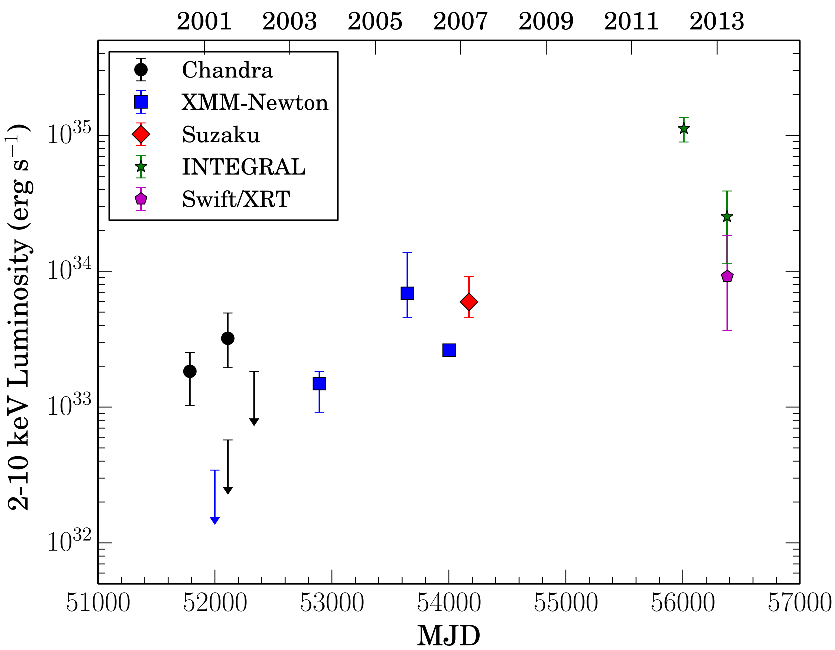

Figure 1. Long-term X-ray light curve of XMMU J174445.5−295044, calculating X-ray luminosities in the 2–10 keV band using our calculated 3.1 kpc distance (Section 3.2). Error bars do not include the distance uncertainty, so that intrinsic variations can be more clearly seen. *Chandra* (black circles and upper limits), *XMM–Newton* (blue squares and upper limits) and *Suzaku* (red diamonds) fluxes from Heinke et al. (2009). *INTEGRAL* 2–10 keV fluxes (green stars) are extrapolated from the fluxes reported by Chenevez et al. (2012, JEM-X, 10–25 keV) and Krivonos et al. (2013, IBIS/ISGRI, 17–60 keV). Our *Swift*/XRT observation (magenta pentagon) is reported in Section 2.1. The final *XMM–Newton* data point has statistical error bars smaller than the marker size.

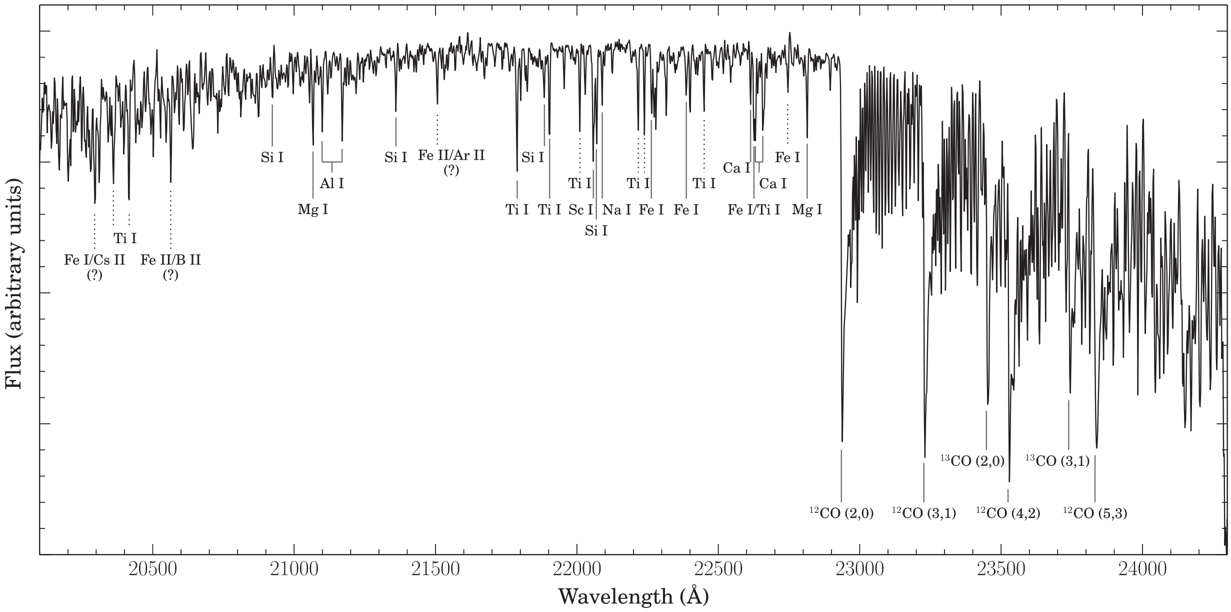

Figure 2. *K*-band spectrum of XMMU J174445.5−295044. Identified line profiles are listed in Table 1. Features identified using spectral libraries (Kleinmann & Hall 1986; Ramirez et al. 1997) are marked with solid lines while features identified using NIST-ASD are marked with dashed lines. Ambiguous and uncertain identifications are labelled with '?'.

and associating the two *INTEGRAL* detections, extrapolating their flux down to 2–10 keV).

2.2 Infrared data

2.2.1 Data and reduction

We observed XMMU J174445.5−295044 with NIFS (McGregor et al. 2002) mounted on the Fredrick C. Gillett telescope at Gemini-North Observatory. The observation was done in queue mode on 2012 July 9 under program ID GN-2012A-Q-114 (PI: C. O. Heinke). NIFS provides spectroscopy with spectral resolving power $R \sim 5000$ over a 3.0×3.0 arcsec^2 field of view in the *Z* through *K* band (9500–24 000 Å). We performed the observation in *K* band with standard methods for near-IR, with a series of observations pointing on-source and blank sky. Blank sky observations were done in order to subtract sky emission from on-source observations. In order to remove telluric features in the spectrum of our target, we observed the A0V star HIP 88566 at similar airmass. For wavelength calibration, an exposure of argon/xenon arc lamps was taken. Also for spatial distortion removal and calibration, exposures with a Ronchi mask were taken.

We reduced and reprocessed the data using Gemini IRAF package V1.12 beta 2 included in IRAF[1] (V2.16) distributed in UREKA[2] 1.0 beta 5. NIFS package contains recipes for three stages of data reduction (baseline calibration, telluric data, and science data) in 'NIFSEXAMPLES'.[3] In baseline calibration we made flat-field and bad pixel map, performed wavelength calibration and determined the spatial curvature and spectral distortion in the Ronchi flat.

The spectra of A0V stars in the *K* band only show one significant feature, at Brγ (21661 Å). We removed this stellar feature from our reference spectrum to obtain a pure telluric spectrum. After extracting the one-dimensional spectrum of the telluric star, we divided the spectrum with a blackbody spectrum and included a Voigt profile fit to the Brγ feature (following Barbosa et al. 2008) to mimic the A0V spectrum of our calibration source. This spectrum was created using MK1DSPEC in ARTDATA package. We assumed a temperature of ∼9800 K for the blackbody continuum of the A0V telluric star (Adelman 2004) and determined the Voigt profile parameters by fitting with the task SPLOT. We then eliminated telluric features in the science spectrum using the achieved pure telluric spectrum with the task NFTELLURIC. The final output of the reduction stage is calibrated telluric-corrected data in the form of a three-dimensional data cube with two spatial dimensions, each 62 pixels wide, and one spectral (wavelength) dimension of 2040 pixels. We extracted a one-dimensional spectrum by merging spatial dimensions inside a circular region with radius of 7 pixels centred on the source using DS9.

2.2.2 Spectral analysis

We measured the radial velocity of the source, using the RVIDLINES task in IRAF RV package to achieve a red/blueshift-corrected spectrum. In order to do this we first needed to identify a small number of prominent lines in the spectrum of this source. These include Al I (21 170 Å), Si I (21 360 Å), Ti (21 789, 21 903 Å), Na I (22 090 Å), and Ca I (22 614 Å). RVIDLINES provided us with a velocity correction of -12 ± 3 km s^{-1}, which was applied to the full spectrum. This corrected spectrum can be seen in Fig. 2.

We used various available spectral libraries for late-type stars (Kleinmann & Hall 1986; Ramirez et al. 1997; Wallace & Hinkle 1997) to identify spectral features present in the spectrum.

[1] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

[2] UREKA is provided by Association of Universities for Research in Astronomy (AURA).

[3] http://www.gemini.edu/sciops/instruments/nifs/?q=node/10356

Table 1. Identified spectral lines in the spectrum. Reported wavelengths are in rest frame.

Species	Wavelength (Å)	Reference
Fe I/Cs II (?)	20 295	3
Ti I	20 361	3
Fe II/B II (?)	20 563	3
Si I	20 923	1, 3
Mg I	21 067	1, 3
Al I	21 170	1, 3
Si I	21 360	1
Fe II/Ar II (?)	21 506	3
Ti I	21 789	1, 3
Si I	21 885	1
Ti I	21 903	1, 3
Ti I	22 010	3
Sc I	22 058	2, 3
Si I	22 069	2, 3
Na I	22 090	1, 3
Ti I	22 217	3
Fe I	22 263	1, 3
Fe I	22 387	1, 3
Ti I	22 450	3
Ca I	22 614	1, 3
Fe I	22 626	2, 3
Ti I	22 627	2, 3
Ca I	22 657	1, 3
Fe I	22 745	3
Mg I	22 814	1, 3
^{12}CO (2, 0)	22 935	1
^{12}CO (3, 1)	23 227	1
^{13}CO (2, 0)	23 448	1
^{12}CO (4, 2)	23 524	1
^{13}CO (3, 1)	23 739	1
^{12}CO (5, 3)	23 832	1

References: 1 – Kleinmann & Hall (1986); 2 – Ramirez et al. (1997); 3 – NIST-ASD. '?' indicates uncertain identifications.

To obtain accurate identification and vacuum wavelength values we compared these identifications with data available in National Institute of Standards and Technology-Atomic Spectra Database (NIST-ASD; Kramida et al. 2013). Fig. 2 shows the rest-frame spectrum of XMMU J174445.5−295044 with all identified features. These features are tabulated in Table 1.

For two-dimensional stellar classification (spectral and luminosity) of the source we followed the method discussed by Ramirez et al. (1997), Ivanov et al. (2004), and Comerón et al. (2004). This method consists of comparing the strength of a feature which is temperature dependent with a feature which is temperature- and surface gravity dependent. Following the method outlined in Comerón et al. (2004), we selected wavelength regions encompassing significant temperature-dependent features (Na I, Ca I), and one region representing a temperature- and surface gravity-dependent feature (^{12}CO). For each feature, we use two nearby, featureless continuum regions to approximate the expected continuum level within the feature by linear interpolation. We used nearly the same feature and continuum definitions as Comerón et al. (2004; Table 2). We made a small modification to the range of the blue continuum region for the Ca I feature given by Comerón et al. (2004), shortening it by 4 Å to avoid including the relatively strong nearby Ti I (22 450 Å) line. This modification has an effect of <0.2 per cent on the equivalent width (EW) measurement. These features and continua are represented in Fig. 3. Finally, we calculated a EW for each feature, and compared these values to the values reported in Comerón et al. (2004).

To estimate errors, we divided the continuum regions into halves, and computed the EWs using either half alone. We took the largest variation from our reported values as an estimate of the error in each measurement.

3 RESULTS AND DISCUSSION

3.1 Two-dimensional spectral classification

Comerón et al. (2004) demonstrate that the ^{12}CO feature for supergiants always shows a EW of >25 Å (see their figs 8–13). We obtained EW[^{12}CO] ≈ 19.4 ± 0.1 Å, which is typical for giants or dwarfs (Comerón et al. 2004). Thus we can rule out the possibility of a supergiant.

Ramirez et al. (1997) and Ivanov et al. (2004) show that log [EW(CO)/(EW(Ca I)+EW(Na I))] can be used to separate giants from dwarfs. Ramirez et al. (1997) show that this quantity should be between −0.22 and 0.06 for dwarfs, versus between 0.37 and 0.61 for giants. We found this quantity to be 0.67 ± 0.06 for our source, in agreement with the estimated range for giants. Presence of fairly strong ^{13}CO bands in our spectrum is another indicator for a giant, as these features are invisible in a dwarf.

To estimate the temperature of this source, we used the first-order relationship between effective temperature ($T_{\rm eff}$) in K and EW[^{12}CO] (in Å) for giants proposed by Ramirez et al. (1997):

$$T_{\rm eff} = (5019 \pm 79) - (68 \pm 4)\mathrm{EW}[^{12}\mathrm{CO}]. \quad (1)$$

Considering the uncertainty in EW[^{12}CO], we found $T_{\rm eff} = 3700 \pm 160$ K. According to van Belle et al. (1999), $T_{\rm eff} = 3700$ K indicates M2 giant; using Richichi et al. (1999) suggests M1.5 while the relation in Ramirez et al. (1997) gives an M1.7 giant. Thus, adopting either the van Belle or Richichi calibration, the resulting spectral type is M2 III, with a reasonable range from M0 to M3. If we used the less detailed calibration from Ramirez et al. (1997), we obtain a similar result of M1.7 (M0–M3). Thus, we adopt M2 III as our spectral type, with a possible range from M0 to M3 III.

There is no evidence for a feature at Brγ in our spectrum, either before or after our telluric subtraction. Nespoli et al. (2010) see Brγ

Table 2. Definition of spectral features, chosen continuum intervals and measured EW. We used definitions in Comerón et al. (2004) with a small modification to Ca I blue continuum (Section 2.2.2).

	Band		Blue continuum		Red continuum		
Feature	Centre (Å)	$\Delta\lambda$	Centre (Å)	$\Delta\lambda$	Centre (Å)	$\Delta\lambda$	EW (Å)
Na I	22 075	70	21 940	60	22 150	40	2.23 ± 0.14
Ca I	22 635	110	22 507	53	22 710	20	1.93 ± 0.40
^{12}CO	22 955	130	22 500	160	22 875	70	19.36 ± 0.13

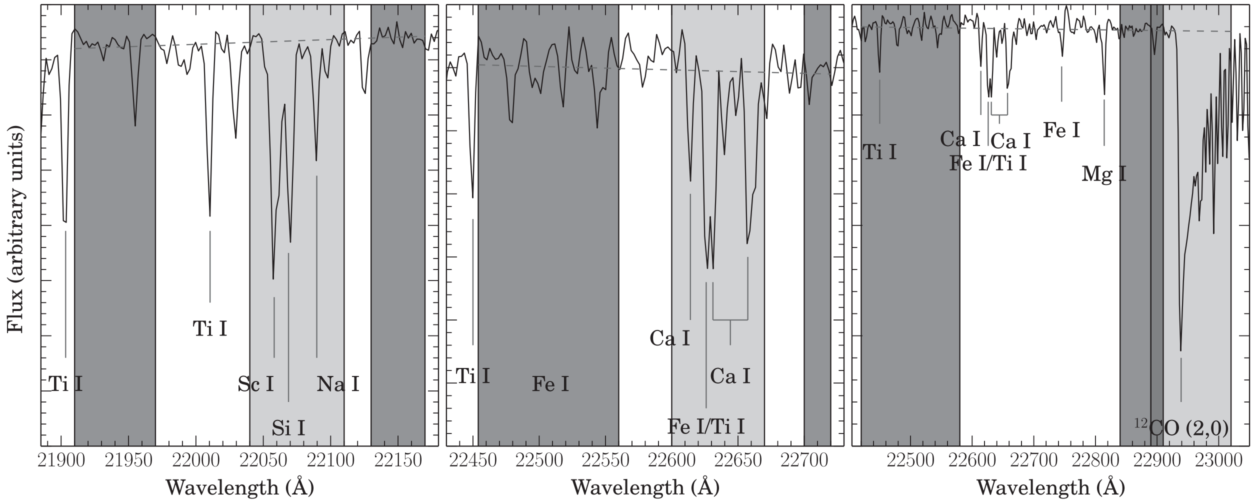

Figure 3. Chosen features and continua intervals used to obtain the spectral classification of the companion in this system. Left to right: Na I, Ca I, ^{12}CO(2, 0). Light shaded regions show chosen regions for features and dark shaded regions represent chosen continua regions. These regions are tabulated in Table 2. The dashed lines represent interpolated continuum level in each case.

emission from two symbiotic X-ray binaries. However, the similar P-Cygni shape of the Brγ feature in both stars, and also in the supergiant X-ray binary IGR J16493−4348 studied by them with the same method, lend support to their hypothesis that this feature is a residual artefact of their telluric removal procedure (which is more complex than ours, involving using a G star as a second telluric reference).

3.2 Extinction, distance, and nature of the accretor

We use our identification of the spectral type, with the Two Micron All Sky Survey (2MASS) photometry (Skrutskie et al. 2006) reported by Heinke et al. (2009), to estimate the extinction, and thus the distance, to XMMU J174445.5−295044, in a similar way as Kaplan et al. (2007), but explicitly accounting for the difference between the K_S and K bands. Although the 2MASS colours were measured at a different time from the NIFS spectroscopy reported here, we do not expect large variations in the temperature or observed extinction of the giant, as the stars most affected by this are of later (>M5) spectral types (Habing 1996).

M2 III stars have an absolute magnitude of $M_J = -3.92$ and intrinsic $J - K_S$ colours of 1.12 (Covey et al. 2007). Heinke et al. (2009) report a 2MASS magnitude of $m_J = 14.89$ in J for our object, and an observed $J - K_S = 4.72$.

We use $A_J/A_V = 0.282$ (Cardelli, Clayton & Mathis 1989), and $A_J/A_{K_S} = 2.5 \pm 0.2$ (Indebetouw et al. 2005). Thus we infer $A_V = \frac{(J-K_S)_{\rm obs}-(J-K_S)}{(A_J/A_V)-(A_{K_S}/A_V)} = 21.3^{+1.9}_{-0.1}$, and $A_J = 6.0^{+0.5}_{-0.3}$. The extinction measurement converts [using N_H (cm^{-2}) = (2.21 ± 0.09) × $10^{21} A_V$; Güver & Özel 2009] to $N_H = (4.7 \pm 0.5) \times 10^{22}$ cm^{-2}, which is below the X-ray measured values (measurements of $8.6 \pm 0.4 \times 10^{22}$ and $16^{+5}_{-4} \times 10^{22}$ cm^{-2} from different observations) in Heinke et al. (2009). This is consistent with expectations for a wind-accreting system, where much of the N_H is expected to be local to the compact object, and with the evidence for variation in N_H between different observations shown by Heinke et al. (2009).

Using this A_J estimate, the expected M_J for a M2 III star, and the observed J magnitude, we can thus estimate $d = 3.1$ kpc as the most likely distance to our object. The largest uncertainty in our distance estimate is our estimate of the absolute magnitude of the companion star. Allowing for a conservative 1-mag uncertainty on the absolute magnitude (estimated from Breddels et al. 2010; this is probably more precise than 1σ), we find $d = 3.1^{+1.8}_{-1.1}$ kpc. This distance is consistent with our (small) radial velocity estimate, which would be typical of a disc star observed at a very small Galactic latitude ($l = 359.1$), and with our measurement of the relative strengths of the CO and Na lines, the ratio of which is more consistent with disc giants than with giants in the bulge (Comerón et al. 2004).

From this distance estimate, we can infer the X-ray luminosities of XMMU J174445.5−295044, as plotted in Fig. 1 (errors there do not include the distance uncertainties). The majority of the X-ray detections are between 10^{33} and 10^{34} erg s^{-1}, but the *INTEGRAL*/JEM-X detection in 2012 March (Chenevez et al. 2012) gives a (2–10 keV) X-ray luminosity of (1.1 ± 0.2) × 10^{35} erg s^{-1} for $d = 3.1$ kpc; even at the lower limit on the distance ($d = 2.0$ kpc), the luminosity exceeds 4 × 10^{34} erg s^{-1}. [Similarly, the 2013 March *INTEGRAL*/IBIS detection gives a (2–10 keV.) $L_X = 2.5 \times 10^{34}$ erg s^{-1} for 3.1 kpc, or 1.1 × 10^{34} erg s^{-1} for the 2.0 kpc lower distance limit, which further confirms the high X-ray luminosity of XMMU J174445.5−295044.] Combining this high peak X-ray luminosity (four times the maximum seen for any accreting white dwarf; Stacey et al. 2011) with the hard X-ray spectrum inferred from the later *INTEGRAL*/IBIS detection above 17 keV (Krivonos et al. 2013), we can confidently rule out a white dwarf nature for the accretor. Thus, we securely identify XMMU J174445.5−295044 as a symbiotic X-ray binary, with a neutron star (or, less likely, black hole) accreting from the wind of an M2 giant star.

XMMU J174445.5−295044 stands out from other symbiotic X-ray binaries only in not showing detectable X-ray pulsations (Heinke et al. 2009). The complete absence of near-IR spectroscopic evidence of accretion in our NIFS spectrum is typical of other symbiotic X-ray binaries with relatively low accretion rates. The lack of detected pulsations also means that the accretor could be a black hole, though black hole symbiotic X-ray binaries should be less common.

The increasing number of symbiotic binaries without detected emission lines in high-quality spectra being detected recently (van den Berg et al. 2006, 2012; Hynes et al. 2014) strongly suggests that there should be many more symbiotic stars (with white dwarf accretors) which also do not show optical/near-IR spectroscopic evidence of accretion (van den Berg et al. 2006). Symbiotic systems may make up an important portion of the faint Galactic X-ray source population.

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