A deep survey for symbiotic stars in the Magellanic Clouds - 1. Methodology and first discoveries in the SMC

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ABSTRACT

We have initiated a survey aimed at locating a nearly complete sample of classical symbiotic stars (SySt) in the Magellanic Clouds. Such a sample is nearly impossible to obtain in the Milky Way, and is essential to constrain the formation, evolution and demise of these strongly interacting, evolved binary stars. We have imaged both Clouds in Hα and He II 4686 narrow-band filters deeply enough to detect all known symbiotic stars. While He II 4686 is not present in all SySt, our method should yield a high success rate because the mimics of SySt are not as likely as true symbiotics to show this emission line. We demonstrate the viability of our method through the discovery and characterization of three new SySt in the Small Magellanic Cloud: 2MASS J00411657-7233253, 2MASS J01104404-7208464 and 2MASS J01113745-7159023. Enigmatic variability was observed in 2MASS J01113745-7159023, where changes in the amplitude of its quasi-periodic variability may suggest an enhanced mass transfer rate during a periastron passage on an elliptical orbit. 2MASS J01104404-7208464 is an ellipsoidal variable with an orbital period of 403 d.

Keywords: binaries: symbiotic – binaries: general – Galaxies: individual: SMC

1. INTRODUCTION

Symbiotic stars (SySt) are the longest orbital period interacting binaries composed of an evolved cool giant (either a normal red giant (RG) in S-type, or a Mira surrounded by an opaque dust shell in D-type SySt) and an accreting hot, and luminous companion (usually a white dwarf, WD). The interacting stars are surrounded by rich and complex circumstellar environments, including both ionized and neutral regions, dust forming regions, accretion/excretion disks, interacting winds, bipolar outflows and jets. SySt are very important and luminous tracers of the late phases of low- and medium-mass binary star evolution, and excellent laboratories to test models of close binary evolution. They are also promising nurseries for type Ia supernovae, regardless of whether the path to the thermonuclear explosion of a Chandrasekhar mass CO WD is through the accretion (single degenerate, SD) scenario or through merging a double WD system (double degenerate, DD) scenario. The most recent extensive review of SySt is in Mikolajewska (2012).

While about 300 Galactic SySt are known (e.g. Belczynski et al. 2000; Miszalski et al. 2013; Miszalski & Mikolajewska 2014; Rodríguez-Flores et al. 2014, and references therein), and a few dozen are relatively well studied, their distances (and hence their component luminosities and other distance-related parameters) remain poorly determined. This makes confrontation of
Theoretical models of SySt with observed parameters of real SySt, to test theories of their evolution and interactions, very challenging. A much more complete and systematic search for SySt in multiple galaxies of different types is essential to provide deep and complete samples suitable for tests of binary evolution theory.

Fortunately, ten bright SySt have been detected in each of the Magellanic Clouds (Belczyński et al. 2000; Miszalski et al. 2014; Ilkiewicz et al. 2018 and references therein), and recently SySt have become detectable even at several hundred kpc in Local Group Galaxies (Gonçalves et al. 2008; Kniazev et al. 2009; Mikołajewska et al. 2014; Mikołajewska et al. 2017; Ilkiewicz & Mikołajewska 2017).

Almost all SySt discovered before 2000 were found serendipitously. Since then, increasing numbers were located by using Hα surveys of the Galaxy (Miszalski & Mikołajewska 2014; Rodríguez-Flores et al. 2014, and references therein) and the Local Group of galaxies (Mikołajewska et al. 2015; Mikołajewska et al. 2017). Success rates, defined as the fraction of spectrographically observed candidates to confirmed SySt in these surveys, are typically 10% or less. For this reason the survey we have initiated is based on both narrowband Hα and He II 4686 imaging. While not all SySt display He II 4686 emission, a major fraction do, e.g., 68% of SySt included in the spectrophotometric atlas of symbiotic stars published by Munari & Zwitter (2002) have He II 4686/Hβ > 0.1, and this will greatly reduce the waste of spectrographic time spent on mimics.

In this paper we present the methodology of our survey, and the first results of our search of the Small Magellanic Cloud (SMC) aiming at finding new SySt. Section 2 describes the survey and our candidate selection method. In Section 3 we present our spectroscopic observations. Characterization of the newly discovered SySt is presented in Section 4. Our results are summarized in section 5.

2. CANDIDATE SELECTION

We carried out photometric observations with the Swope 1.0m telescope and E2V CCD231-84 CCD camera on the nights of 2016.09.07-2016.09.22. The survey consisted of observations in Hα and He II 4686 narrowband filters and a broad-band R and B filters. For each field we stacked 5 images with 45 second exposure time in R and B filters and 450 second exposure times in Hα and He II 4686 filters. This resulted in a limiting magnitude of ∼18.5 mag in each filter, corresponding to absolute magnitudes ∼0 in the LMC and ∼0.3 in the SMC. The uncertainties in the measured magnitudes are ∼0.02 mag in all filters.

The E2V CCD231-84 CCD camera is build from four separate quadrants. We corrected the images for differences in linearity of these quadrants, and for the shutter pattern which was a result of the finite shutter speed. The images were reduced using the standard IRAF procedures. The astrometric calibration was done using Astrometry.net software (Lang et al. 2010). The images were combined using SWarp (Bertin et al. 2002). Point-spread function fitting photometry was done using PSFEx (Bertin 2011) and SExtractor (Bertin & Arnouts 1996).

We selected the SySt candidates among the stars that show the colors He II − B < −0.1 mag and Hα − R < −1.0 mag. These colors effectively isolate emission line stars with equivalent widths of 10 Å and 100 Å, respectively. While not all SySt show the He II line, the stars that mimic SySt are less likely to show this line (Miszalski & Mikołajewska 2014), which will result in a smaller contamination rate. The Swope images of the first three successful SySt candidates are presented in Fig. 1.

3. SALT SPECTROSCOPY

We carried out spectroscopic followup of ten uncrowded candidates in the SMC with the Southern African Large Telescope (SALT; O’Donoghue et al. 2006) under programme 2017-1-SCI-049 (PI: Ilkiewicz). We used the Robert-Stobie Spectrograph (Burgh et al. 2003; Kobulnicky et al. 2003) with a slit width of 1.5 arcsec and a PG0900 grating, resulting in a resolution of R∼1000. The wavelength covered in each spectrum was 3900–6900 Å. The reduction was carried out with the standard IRAF tasks and the pysalt package (Crawford et al. 2010). The spectra were flux calibrated by scaling them to the known V magnitudes of the candidates. The log of observations is presented in Table 1. The spectra of confirmed SySt are presented in Fig. 2. The fluxes of emission lines are presented in Table 2. The fluxes have uncertainties of 15% for the strong lines and 30% for the weak lines.

4. NEW SYMBIOTIC STARS

Of our sample of ten candidates we found three new SySt: 2MASS J00411657-7233253, 2MASS J01104404-7208464 and 2MASS J01113745-7159023. Each of these new SySt show strong emission lines of the H I Balmer series, as well as the He II 4686 line, in addition to absorption features of K-type giants (Fig. 2). These spectra are very reminiscent of the SALT spectra of the known SMC SySt LIN 9 and LIN 358 (see fig. 3 of Miszalski et al. 2014). The SySt natures of 2MASS J01104404-7208464 and 2MASS J01113745-7159023 are further confirmed by the presence of the Raman scattered O VI 6825 emission line, which is only present in SySt. In the case
Figure 1. Swope images of the new SySt.
Figure 2. SALT spectra of the new SySt.
**Table 1.** The log of SALT observations, OGLE $V$ magnitudes used for scaling the spectra and the Swope magnitudes from our survey.

| ID            | Date     | MJD    | $V$ [mag] | $B$ [mag] | He II [mag] | $R$ [mag] | H$\alpha$ [mag] |
|---------------|----------|--------|-----------|-----------|-------------|-----------|-----------------|
| 2MASS J00411657-7233253 | 2016-11-11 | 57704 | 16.8      | 16.60     | 16.33       | 15.16     | 13.35           |
| 2MASS J01104404-7208464 | 2016-11-11 | 57704 | 16.4      | 17.53     | 17.16       | 15.82     | 15.29           |
| 2MASS J01113745-7159023 | 2016-11-12 | 57705 | 16.0      | 17.77     | 16.33       | 15.16     | 13.35           |

**Table 2.** Observed emission line fluxes in the new SySt.

| ID             | Flux [$10^{-15}$ erg cm$^{-2}$ s$^{-1}$] |
|----------------|------------------------------------------|
| $H_{\epsilon}$ | 7.2                                      |
| He I 4026      | 1.1                                      |
| $H_{\delta}$  | 11                                       |
| He I 4143      | 0.8                                      |
| $H_{\gamma}$  | 19                                       |
| He I 4387      | 1.5                                      |
| He I 4471      | 1.2                                      |
| He II 4686     | 9.8                                      |
| He I 4713      | 1.2                                      |
| $H_{\beta}$   | 37                                       |
| He I 5876      | 8.8                                      |
| $H_{\alpha}$  | 163                                      |
| He I 6678      | 9.4                                      |
| O VI 6825      | 1.4                                      |

of 2MASS J00411657-7233253 the emission line ratio log(He I 6678 / He I 5876)=0.16 is consistent with a SySt (Ilkiewicz & Mikołajewska 2017). In addition, the positions of the three stars in an infrared color-magnitude diagram confirm the presence of a RG in the systems (Fig. 3).

The locations of the three new SySt and ten previously known SySt in the SMC are presented in Fig. 4. The black and white inset on the right hand image of Fig. 4 shows the survey area we completed in 2016. Almost all of the known SySt are well outside the central regions of the SMC, i.e. where the SMC in the Digitized Sky Survey image is the brightest. This is purely a selection effect, as locating SySt in the crowded central regions is more challenging than in its periphery. The large majority of SySt in the SMC are still not discovered, but as our survey covers the densest and mostly unexplored region of the SMC, we should significantly increase the number of known SySt in the SMC at its conclusion.

### 4.1. Variability

In order to study the variability of the SySt we collected the Optical Gravitational Lensing Experiment (OGLE) data from Sośnizki et al. (2011) catalogue. The OGLE identification numbers of the stars are OGLE-SMC-LPV-03426 for 2MASS J00411657-7233253, OGLE-SMC-LPV-17942 for 2MASS J01104404-7208464 and OGLE-SMC-LPV-18122 for 2MASS J01113745-7159023. The light curves have been updated with the
fourth phase of OGLE photometry covering years 2010-2018 (Udalski et al. 2015). The OGLE light curves are presented in Figs. 5-7. We searched for periodicity in the data using a Lomb-Scargle periodogram (Scargle 1982) and phase dispersion minimization (PDM; Stellingwerf 1978). The accuracy of periods was estimated by calculating the half-size of a peak in the periodogram. All of the three new SySt were classified previously as OGLE Small Amplitude Red Giants (OS-ARGs) by Soszyński et al. (2011) based on the data from the third phase of OGLE alone.

The light curve of 2MASS J00411657-7233253 is dominated by a $\sim 70\,$d quasi-periodic variability found by Soszyński et al. (2011). We also find a $\sim 400\,$d period at a low significance and a longer set of data is necessary to confirm this periodicity. If confirmed, the $\sim 400\,$d period could be interpreted as an orbital period. Additionally to the quasi-periodic variability 2MASS J00411657-7233253 showed also an increase in the brightness in $V$ band (Fig. 5). While more data is needed to study the nature of this brightening, it is most probably a result of a small outburst or an active phase.

In the case of 2MASS J01104404-7208464 the most prominent period detected in the Lomb-Scargle periodogram is 202$\,$d, while in the case of PDM the most prominent period is 403$\,$d (Fig. 8). This suggests that the system shows ellipsoidal variations and the real or-
orbital period is 403 d, twice as long as the period from the Lomb-Scargle periodogram. The phase plot of 2MASS J01104404-7208464 is presented in Fig. 9. The system showed an increase in the V brightness during a gap in observations at JD~2455000 (Fig. 6). While this is the time of change from OGLE III to OGLE IV and may be associated to changes in the photometric system, the reality of this brightening is confirmed by a change of the shape of I band data in the phaseplot (Fig. 9). The reality of ellipsoidal variations and the 403 d period is confirmed by the phase plot of V − I color, where the star is getting redder at phase 0 as a result of an eclipse (Fig. 9). The second decrease in brightness at the phase of 0.5 is not associated with change of color, as expected for ellipsoidal variability. Moreover, the RG radius (see Tab. 3) is comparable to its Roche lobe radius (assuming a total mass of ≈2 M⊙ and P_orb=403 d). The ephemerides of 2MASS J01104404-7208464 is:

\[ JD_{\text{min}} = 2454792 + (403 \pm 8) \times E \]  (1)

Figure 6. OGLE light curve of 2MASS J01104404-7208464.

Figure 7. OGLE light curve of 2MASS J01113745-7159023.

The variability of 2MASS J01113745-7159023 is dominated by a quasi-periodic variability with a period of ~160 d. However, the maximum of this quasi-periodic variability in some periods of time is higher by a ~0.4 mag in the I band (Fig. 7). This periodic increase in the maximum of variability is reminiscent of variability in a symbiotic X-ray binary GX 1+4 (Ilkiewicz et al. 2017). In GX 1+4 this behavior is associated with a periastron passage during elliptical orbital motion, i.e. when enhanced mass transfer rate can be expected. If this is the case in 2MASS J01113745-7159023 then the orbital period of the system is ~3500 d.

4.2. Stellar components parameters

In order to estimate WD parameters we estimated the reddening to the SySt by using a map of SMC reddening that includes foreground and average internal SMC reddening (Skowron, D. et al., 2019, in preparation). Because this does not include the SySt intrinsic reddening our estimate might be underestimated. This method gave us A_V=0.23 mag in the case of 2MASS
and that both H\textsc{i} and He\textsc{ii} emission lines are produced by photoionization followed by recombination (case B), and they are accurate to a factor of 2. The temperatures and luminosities of these three white dwarfs are similar to those found for the white dwarfs in other Magellanic SySt.

In order to derive the RG effective temperature we used a relation \( T_{\text{RG}} = 7070/[(J - K) + 0.88] \) derived by Bessell et al. (1983). Using 2MASS All-Sky Catalog of Point Sources (Jarrett et al. 2000) magnitudes we get \( T_{\text{RG}} = 3570 \text{ K} \) for 2MASS J00411657-7233253, \( T_{\text{RG}} = 3970 \text{ K} \) for 2MASS J01104404-7208464 and \( T_{\text{RG}} = 3770 \text{ K} \) for 2MASS J01113745-7159023. The magnitudes used were \( J = 12.973 \text{ mag} \) and \( K = 11.872 \text{ mag} \) for 2MASS J00411657-7233253, \( J = 13.909 \text{ mag} \) and \( K = 12.999 \text{ mag} \) for 2MASS J01104404-7208464 and \( J = 14.104 \text{ mag} \) and \( K = 13.109 \text{ mag} \) for 2MASS J01113745-7159023. The RG radii were then estimated using the \( K \) magnitudes and adopting the bolometric corrections \( \text{BC}_K \), calculated from the \( (\text{BC}_K,(J - K)) \) relation given by Bessell & Wood (1984).

All the stellar parameters derived for the new SySt are presented in Tab. 3.

5. CONCLUSIONS

We presented first results of the first search for new SySt using H\textsc{o} and He\textsc{ii} 4686 narrow-band filters. We found three new SySt in SMC: 2MASS J00411657-7233253, 2MASS J01104404-7208464 and 2MASS J01113745-7159023. This confirms the viability of this method. Two of them, 2MASS J0104404-7208464 and 2MASS J01113745-7159023, showed Raman scattered O\textsc{vi} 6825 emission line characteristic for SySt. We derived and discussed the physical characteristics for all of them. Their light curves are also presented and analyzed.

2MASS J00411657-7233253 shows quasi-periodic variability and a marginally detectable variability on timescale of \( \sim 400 \text{ d} \). 2MASS J01104404-7208464 is an ellipsoidal variable with an orbital period of 403 d. 2MASS J01104404-7208464 also experienced a brightening by \( \sim 0.2 \text{ mag} \) in \( V \) band, which was associated with a change of shape of orbitally related variability.

### Table 3. Properties of stellar components in the new SySt.

| 2MASS       | \( T_{\text{WD}} \) | \( L_{\text{WD}} \) | \( T_{\text{RG}} \) | \( R_{\text{RG}} \) |
|-------------|----------------------|----------------------|----------------------|----------------------|
| J00411657-7233253 | 120 | 750 | 3570 | 165 |
| J01104404-7208464 | 160 | 230-250 | 3970 | 98 |
| J01113745-7159023 | 230 | 410-440 | 3770 | 93 |

Figure 9. Phase plot of OGLE data of 2MASS J01104404-7208464. The data is separated at JD\textsubscript{sim}2455000, at the time of brightening. Only observations obtained on the same date in the two filters are plotted in the case \( V - I \) data.
variability observed in GX 1+4, a symbiotic X-ray binary. This suggested an enhanced mass-transfer during a periastron passage during orbital motion. This is particularly interesting because WD in 2MASS J01113745-7159023 is among the hottest in SySt (Mikolajewska 2010), which confirms high mass transfer rate in the system or a recent outburst.

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