Discovery of five new Galactic symbiotic stars in the VPHAS+ survey

Stavros Akras1,2,*, Denise R. Gonçalves3, Alvaro Alvarez-Candal4,†, Claudio B. Pereira4

1Instituto de Matemática, Estatística e Física, Universidade Federal do Rio Grande, Rio Grande 96203-900, Brazil
2Institute for Astronomy, Astrophysics, Space Applications and Remote Sensing, National Observatory of Athens, GR 15236 Penteli, Greece
3Observatório do Valongo, Universidade Federal do Rio de Janeiro, Ladeira Pedro Antonio 43, 20080-090 Rio de Janeiro, Brazil
4Observatório Nacional/MCTIC, Rua Gen. José Cristino, 77, 20921-400 Rio de Janeiro, Brazil

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ABSTRACT
We report the validation of a recently proposed infrared selection criterion for symbiotic stars (SySts). Spectroscopic data were obtained for seven candidates, selected from the SySt candidates of Akras et al. (2019, MNRAS, 483, 5077) by employing the new supplementary infrared selection criterion for SySts in the VST/OmegaCAM Photometric H-Alpha Survey (VPHAS+). Five of them turned out to be genuine SySts after the detection of Hα, He ii and [O iii] emission lines as well as TiO molecular bands. The characteristic O vi Raman-scattered line is also detected in one of these SySts. According to their infrared colours and optical spectra, all five newly discovered SySts are classified as S-type. The high rate of true SySts detections of this work demonstrates that the combination of the Hα-emission and the new infrared criterion improves the selection of target lists for follow-up observations by minimizing the number of contaminants and optimizing the observing time.

Key words: binaries: symbiotic – techniques: spectroscopic – methods: data analysis – general: catalogues

1 INTRODUCTION
Symbiotic stars (SySts) are long-period interacting binary systems composed by a white dwarf and an evolved red giant (see review by Munari 2019, and references therein). The symbiosis of the two companions lead to a number of physical phenomena which can provide further insights into the interaction and evolution of binary systems, mass transfer process, accretion disk formation, formation of jets and bipolar circumstellar envelopes, nova-like thermonuclear outbursts, flickering, and soft X-ray emission, among others. Besides all these intriguing phenomena, SySts have also been suggested as progenitors of type Ia supernovae (Munari & Renzini 1992; Di Stefano 2010; Dilday et al. 2012; Munari 2019).

The recently updated catalogues of SySts (Akras et al. 2019a; Merc et al. 2019) lists only 257 Galactic and 66 extragalactic members. Since the publication of these two catalogues, three more Galactic SySts were discovered: Hen 3-1678 (Lucy et al. 2018), HBBa 1704-05 (Munari & et al. 2018; Skopal et al. 2019) and Gaia18aen (Merc et al. 2020). Yet, the overall population of Galactic SySts is still incompatible with the theoretical predictions (3,000 to 400,000 SySts; Kenyon 1986; Munari & Renzini 1992; Kenyon et al. 1993; Magrini et al. 2003; Lü et al. 2006).

A search of SySts in the INT Photometric H-Alpha Survey (IPHAS, Drew et al. 2005) resulted in the discovery of 19 new members (Corradi et al. 2008; Rodríguez-Flores et al. 2014, and references therein). However, the IPHAS list of SySt candidates turned out to be substantially contaminated with Be stars and young stellar objects (YSOs). Rodríguez-Flores et al. (2014) refined the IPHAS selection criterion and ended up with a shorter list of only 162 candidates. Despite this refinement, the second follow-up spectroscopic survey of 18 candidates resulted in five new SySts or 27.7 per cent of identification rate, and the authors argued for the need of even more robust selection criteria in order to distinguish SySts from other Hα-emitters in a more efficient way.

Machine learning and data mining have gained significant popularity in astronomy over the past few years due to the large amount of data provided from several on-going photometric surveys star-galaxy classification (e.g. Fadely et al. 2012; Clarke et al. 2020); symbiotic stars (Akras et al. 2019b); planetary nebulae (Akras et al. 2019c; Awang Iskandar et al. 2020); low-metallicity stars (Whitten et al. 2019); exoplanet transits (Schanche et al. 2019); Herbig Ae/Be and classical Be stars (Vioque et al. 2020); automatic classification of variable stars (Hosenie et al. 2020); automatic determination of stellar temperatures and metallicities (Antoniadis-Karnavas et al. 2020), among many others.

Akras et al. (2019b) devised a number of new infrared (IR) selection criteria using a machine learning approach which, in conjunction with the IPHAS optical criterion (Hα-1), can better distinguish SySts from other Hα-sources in the IPHAS. The new IR criterion was also applied to the VST/OmegaCAM Photometric H-Alpha Survey (VPHAS+, Drew et al. 2014). In total, 72 new SySt candidates were found, whilst up to 90 per cent of the known SySts in both catalogs were recovered.

The spectroscopic follow-up results of the application of the optical+IR selection criteria to identify genuine SySts is the focus of this letter, which demonstrates that the new IR selection criterion is valid and very efficient. This letter is organised as follows: an overview of the observations is described in Section 2. In Section 3, we present the results of this mini-spectroscopic survey and we finish with the conclusions in Section 4.
3 RESULTS

Seven SySt candidates were selected from Akras et al. (2019b) for this pilot spectroscopic survey. All of them satisfy both the IPHAS criterion (i), Corradi et al. (2008) and the new IR criterion (ii), Akras et al. (2019b):

(i) \( H_\alpha \) IPHAS criterion

\[ (r-H_\alpha) \geq 0.25 \times (r-i) + 0.65 \]

(ii) IR selection criterion for S-type SySts

\[ J-H \geq 0.78 \& 0 < K_s-W_3 \leq 1.18 \& W_1-W_2 < 0.09 \text{ or} \]
\[ J-H \geq 0.78 \& 0 < K_s-W_3 \leq 1.18 \& W_1-W_2 \geq 0.09 \& 0 < W_1-W_4 < 0.92 \]

(iii) IR selection criterion among SySts / K-giants / M-giants

\[ H-W_2 \geq 0.206 \& K_s-W_3 \geq 0.27 \]

(iv) IR criterion for S+S+IR/D/D' scheme classification

(a) S-type criterion

\[ K_s-W_3 < 1.93 \& W_3-W_4 < 1.46 \]

(b) S+IR-type criterion

\[ K_s-W_3 < 1.93 \& W_3-W_4 \geq 1.46 \text{ or} \]
\[ K_s-W_3 \geq 1.93 \& H-W_2 < 2.72 \]

(c) D-type criterion

\[ K_s-W_3 \geq 1.93 \& H-W_2 \geq 2.72 \& W_3-W_4 < 1.52 \]

(d) D'-type criterion

\[ K_s-W_3 \geq 1.93 \text{ and } H-W_2 \geq 2.72 \text{ and } W_3-W_4 \geq 1.52 \]

For the confirmation of a candidate as a genuine SySt, specific optical lines must be detected such as \( H_\alpha \), [O \text{ ii}], \( J5007 \), He \( i \), \( \lambda 4686 \), and O \( vi \) at 6380, commonly found in the spectra of SySts. These lines originate from the highly ionized circumstellar envelope illuminated by the strong UV field of the white dwarf. Moreover, a number of molecular bands like TiO and VO associated with the cold red giant, are also present in the spectra. The latter features are easily perceptible in the S-type SySts but not in the heavily dusty D-types (see Munari & Zwitter 2002).

Most of these features are detected in our candidates, thus confirming their symbiotic nature (Figs. 1 and 2). In particular, strong \( H_\alpha \) emission line is found in all the candidates, as it was expected based on their positions in the IPHAS \( r-H_\alpha \) versus \( r-i \) diagnostic diagram. The recombination He \( i \) and He \( ii \) lines are also detected. Five of the candidates clearly exhibit the He \( ii \) \( \lambda 4686 \) line. [O \text{ ii}] 5007Å and 4363Å emission lines are detected in four and three candidates, respectively. Of particular interest is the candidates DR2J175320.4-295327.1, in which the [O \text{ ii}] 507Å line is not detected, while we detected the [O \text{ iii}] 4363Å line. The same has been found in other known SySts (e.g. Hen 3-863, AG Peg, AS 327, see Luna & Costa 2005) and all of them have extreme high electron densities (\( 10^8 \text{ cm}^{-3} \)). Such high densities lead to the attenuation of the [O \text{ iii}] 5007Å emission relative to the 4363Å one and to the different loci of SySts and planetary nebulae in the [O \text{ iii}] 5007/\( H_\beta \) versus [O \text{ iii}] 4364/\( H_\gamma \) diagnostic diagram (Gutierrez-Moreno et al. 1995; Clyne et al. 2015). Emission lines such as [Ne \text{ ii}], [Ne \text{ iv}], [Fe \text{ ii}], and [Fe \text{ iii}] are also detected implying a high excitation circumstellar envelope. The O \text{ vi} Raman-scattered line at 6830Å, present in principle only in SySts (Allen 1980; Akras et al. 2019a; Angeloni et al. 2019) is also detected in one of our candidates (DR2J181154.5-243536.2).

Four of the candidates clearly show TiO molecular bands associated with the presence of a red giant with an M spectral type assigned. The Ca I 4227Å absorption line is also detected in three of them with
Figure 1. Low resolution spectrum of the VPHAS+ SySts selected from (Akras et al. 2019b). Top left panels show the observed spectra. The top right panels display the VPHAS+ H $\alpha$ images of the sources in a logarithmic scale. North is up, east to the left. Bottom panels zoom in the H $\beta$ and [O iii] 5007 Å lines, and H $\alpha$ emission lines. The order of the sources is the same as in Table 1.

TiO bands in 4760 and 4955 Å. The absence or very weak TiO bands of DR2J181123.2-2414301.0 implies a late K or early M type red giant.

Two of the newly classified SySts (DR2J141301.4-6533201.1, DR2J181123.2-2414301.0) and the probable one (DR2J175346.2-2848261.6) display a seemingly double-peak [O iii] $\lambda$5007 line. Notice that the second peak is found at 5015Å and it corresponds to the He i recombination line.

Overall, five out the seven candidates are classified as genuine SySts and one as probable due to the absence of the He i 4686Å and weak [O iii] 5007Å emission lines (Table 1). It should be noted that the candidate DR2J175346.2-2848261.6 is also included in the recent work by Vioque et al. (2020), who employed a machine learning approach to identify new YSOs (Herbig Ae/Be or T Tauri types) and Be stars in GAIA DR2. The probability of DR2J175346.2-2848261.6 to be a YSO or a Be star is as low as 0.04 and 0.003 percent,
SySts are classified either as stellar (S- and S+IR-type) or dusty (D- and D’-type) based on their spectral energy distribution (SED) (e.g., Rodríguez-Flores et al. 2014; Akras et al. 2019a). Instead of their SEDs, we make use of the criterion (iv) devised by Akras et al. (2019b). The Ks-W3 colour is the main criterion that separate the S-type from the rest of them. All the newly discovered SySts have Ks-W3 < 1.93 and they are classified as S-type (iv-a). The candidate SySt (DR2J175346.2-2848261.6) exhibits W3-W4 > 1.46 and satisfies the criterion for S+IR-type (iv-b) – SySts with S-type SED and a potential excess in W3 and/or W4 bands (see Akras et al. 2019a).

This spectroscopic study yields to an identification rate of 71 percent which is very close to the expected rate of the IR selection criterion (Akras et al. 2019b). Our results also validate the use of the new IR criterion for S-type SySts, and they should be used by the community in order to get higher confidence regarding the symbiotic nature of potential candidates, as well as to select better targets for follow-up spectroscopic surveys and thus optimise the use of observing facilities.

Besides the new discoveries presented here, it is worth mentioning that Lucy et al. (2018) reported the discovery of 10 candidate SySts using the SkyMapper (Keller et al. 2007; Wolf et al. 2018). Seven of them satisfy the new IR selection criterion of SySts (ii). Two of these seven candidates, Hen 3-1768 and GSC 09276-00130, were observed during the verification tests of the RAMSES-II project (Angeloni et al. 2019) and a Raman-scattered O v1 J6830 line excess was reported for both objects. Follow-up spectroscopic observation of Hen 3-1768 shows clearly the presence of the O v1, He ii and H α emission lines (Lucy et al. 2018). GSC 09276-00130, on the other hand, was found to be an M-type giant (Angeloni et al. 2019), without satisfy the IR criterion from the SySts/K-giant/M-giant model.
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DATA AVAILABILITY

The spectroscopic data underlying this article are available at the SOAR Archive (http://ast.noao.edu/data/archives). The photometric data were obtained from publicly available catalogues.

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