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SEARCHING FOR NEW YELLOW SYMBIOTIC STARS: POSITIVE IDENTIFICATION OF StHα63*

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ABSTRACT

Yellow symbiotic stars are useful targets for probing whether mass transfer has happened in their binary systems. However, the number of known yellow symbiotic stars is very scarce. We report spectroscopic observations of five candidate yellow symbiotic stars that were selected by their positions in the 2MASS $(J - H)$ versus $(H - K_s)$ diagram and which were included in some emission-line catalogs. Among the five candidates, only StHα63 is identified as a new yellow symbiotic star because of its spectrum and its position in the $[TiO]_1$–$[TiO]_2$ diagram, which indicates a K4–K6 spectral type. In addition, the derived electron density ($\sim 10^{8.4}$ cm^{-3}) and several emission-line intensity ratios provide further support for that classification. The other four candidates are rejected as symbiotic stars because three of them actually do not show emission lines and the fourth one only Balmer emission lines. We also found that the *WISE* W3–W4 index clearly separates normal K-giants from yellow symbiotic stars and therefore can be used as an additional tool for selecting candidate yellow symbiotic stars.

Key words: binaries: symbiotic – stars: fundamental parameters – stars: individual (StHα63)

1. INTRODUCTION

Symbiotic stars are interacting binary systems formed by a red giant star and a hot source (in most cases a white dwarf) that ionizes the stellar wind from the cool component. They can be divided into three different infrared types, D, D′, and S, which are related to the nature of the cool giant in the system, orbital separation, and physical conditions in the emitting nebulae (see Mikolajewska 1997). The number of currently identified symbiotics is much smaller than the predicted number. The catalog of Belczyński et al. (2000) contains 173 Galactic symbiotics, while the predicted number ranges from 3×10^3 to 4×10^5 (Allen 1984; Munari & Renzini 1992; Kenyon et al. 1993; Magrini et al. 2003). Recently, several surveys have discovered new symbiotic stars, increasing their number. Corradi et al. (2008, 2010) and Rodríguez-Flores et al. (2014) discovered 12 S-type and 4 D-type new symbiotics by combining the IPHAS survey and the position of the candidate stars in the 2MASS color–color diagram. Miszalski et al. (2013) used the SuperCosmos Hα Survey (SHS; Parker et al. 2005), selected Hα emission candidates toward the Galactic bulge, and discovered 13 S-type, 1 D′-type, and 6 D-type new symbiotics. Miszalski & Mikolajewska (2014), also using the SHS catalog, found 1 D-type and 11 S-type new symbiotics in the southern hemisphere. Therefore, a total of 48 new symbiotic stars have been added to the 173 that were already known.

Among S-type symbiotic stars, there is a group known as "yellow type symbiotics" in which the cool component is a K-type star rather than an M-type giant. Yellow symbiotics are useful objects for probing whether mass transfer has taken place in the past of these binary systems. The atmospheres of the K-type components of yellow symbiotics will be free from strong molecular opacities due to TiO, CN, and C_2 absorption features that are present in the S-type symbiotics with an M-type giant, thereby enabling the determination of stellar abundances based on atomic lines. Studies of chemical abundances in yellow symbiotics indeed show that these stars are enriched in s-process elements. Because these stars are not luminous enough to be self-enriched in s-process elements, the observed enrichment can be attributed to mass transfer from the former AGB star (now the white dwarf) of the system (see Smith et al. 1996, 1997; Pereira & Roig 2009). Therefore, yellow symbiotics are valuable objects for testing models of AGB nucleosynthesis (Busso et al. 2001). However, they are very rare objects: only 12 Galactic yellow symbiotics are included in the catalog of Belczyński et al. (2000), representing only ∼5.4% of the total number of 221 S-type symbiotics identified to date (see above). Moreover, yellow symbiotics are members of the field Galactic halo population (Schmid & Nussbaumer 1993; Jorissen 2003). Therefore, there is not a specific Galactic direction where they can be surveyed, and consequentially they are very difficult to find. In fact, among the ∼3.6 million stellar spectra obtained with the LAMOST survey, only one new yellow symbiotic was found: LAMOST J12280490-014825.7, a K3 star with a high radial velocity and located at a high Galactic latitude (Li et al. 2015), similar to some yellow symbiotics that had previously been analyzed (Pereira & Roig 2009).

Due to the rarity of these objects and the absence of a particular Galactic location, surveys searching for new yellow symbiotics were inhibited in the past. However, Baella (2012) showed that combining their infrared properties and emission spectrum, yellow symbiotics are located in a particular region of the 2MASS color–color diagram. This led to the discovery of SS 383 as our first candidate yellow symbiotic that has been identified following the criteria above mentioned (Baella et al. 2013, hereafter BPM13).

In this work we report further spectroscopic results from our survey specifically dedicated to searching for and to identifying new yellow symbiotics. Our major result is the identification of StHα63 as a new yellow symbiotic star.

* Based on observations collected at the Centro Astronómico Hispano-Alemán, Calar Alto, jointly operated by the Max-Planck-Institut für Astronomie (Heidelberg) and the Instituto de Astrofísica de Andalucía (CSIC), and at the 4.1 m telescope at Cerro Pachón Observatory, Chile.

Table 1
List of Objects Spectroscopically Observed, with the Equatorial Coordinates, V-magnitudes, Used Spectrograph, and Observed Infrared Color-indexes

Star	Date Obs	α_{2000}	δ_{2000}	V (GSC)[a]	T/G[b]	$J-H$[c]	$H-K$[c]
[KW97] 37-26	2013 Jun 26	19 26 12.5	+00 55 20.3	10.0	T	0.88	0.24
[KW97] 61-27	2013 Jun 26	22 07 38	+49 00 18.0	11.8	T	0.92	0.26
SS 360	2014 Jul 18	18 17 37.7	−28 37 05.6	12.3	G	0.93	0.25
StHα63	2013 Oct 15	07 58 05.9	−07 43 55.5	13.2[d]	T	0.80	0.25
StHα116	2013 Jun 26	15 52 19.7	+14 15 19.8	10.4	T	0.79	0.22

Notes.
[a] The Guide Star Catalog, Lasker et al. (2008).
[b] T: Twin spectrograph; G: Goodmann spectrograph.
[c] Cutri et al. (2003).
[d] Nomad Catalog, Zacharias et al. (2004, 2005).

2. TARGET SELECTION

The selection of the candidates followed the same method as we applied for the identification of SS 383 as a new candidate yellow symbiotic star (BPM13). Basically our method relies on the two observed properties of the yellow symbiotic stars, the emission-line spectrum, and the K-type continuum. It was already well-established that symbiotics occupy particular regions in the 2MASS $(J-H)$ versus $(H-K_s)$ diagram (Phillips 2007; Corradi et al. 2008, 2010). Furthermore, Baella (2012) showed that after reddening correction, yellow symbiotics are clustered around $(H-K_s) \sim 0.2$ and $(J-H) \sim 0.8$ because their positions in the two-color diagram are mainly determined by the K-type component and they are clearly separated from S-type symbiotics with M-type components. By using the emission-line catalogs of Stephenson & Sanduleak (1977), Stephenson (1986), Schwartz et al. (1990), and Kohoutek & Wehmeyer (1997) we have identified five more stars that are located in the region of yellow symbiotics of the 2MASS color–color diagram and therefore, are good candidates to be yellow symbiotics. Table 1 lists the candidates and Figure 1 shows their position in the $(J-H)$ versus $(H-K_s)$ diagram. To determine the corresponding reddening value for each object, we used the Galactic Dust Reddening and Extinction Service of IRSA (Infrared Science Archive): http://irsa.ipac.caltech.edu/applications/DUST/ to obtain the "$E(B-V)$ Reddening" values, and converted $E(B-V)$ to $A(J)$, $A(H)$, and $A(K_s)$ extinctions using the relationships given by Bilir et al. (2008), which are used to draw the corresponding reddening vectors in Figure 1. In particular, for StHα63 we used a mean $E(B-V) = 0.14$ (Schlegel et al. 1998; Schlafly & Finkbeiner 2011), and obtained $A(J-H) = 0.05$ and $A(H-K_s) = 0.03$.

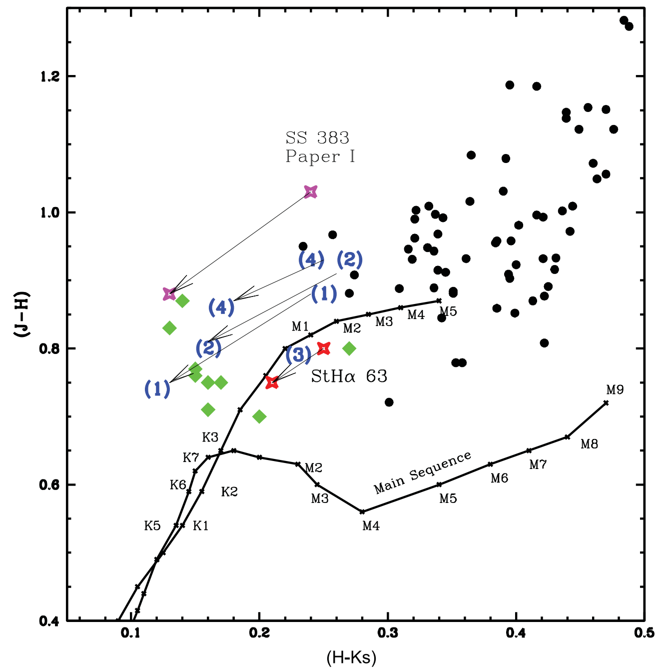

Figure 1. Position of the candidate yellow symbiotic stars [KW97] 37-26 (1), [KW97] 61-27 (2), StHα116 (3), SS 360 (4), and StHα63 (red star) in the 2MASS color–color diagram. The arrows connect the observed and reddening-corrected $(J-H)$ and $(H-K_s)$ colors. For StHα116 we do not show any correction due to the low extinction in the direction of this object. Green diamonds represent the reddening-corrected infrared colors of seven S-type yellow symbiotic stars. SS 383 (magenta star), previously identified as a candidate yellow symbiotic, is also shown. Black circles represent the S-type symbiotics.

3. OBSERVATIONS AND REDUCTIONS

Spectroscopic observations of the five targets in Table 1 were performed on 2013 and 2014 with the Cassegrain Twin Spectrograph (TWIN) attached to the 3.5 m telescope of the Calar Alto Observatory (Spain), and with the Goodman spectrograph attached to the 4.1 m telescope of the SOAR Observatory (Chile). Table 1 also includes the date of observations and the used spectrograph. TWIN includes two separate spectroscopic channels (blue and red) behind the common entrance slit aperture. The detectors were a SITe CCD 22b in the blue channel and a SITe CCD 20b in the red channel. We used gratings T08 (blue) and T04 (red) to cover the spectral ranges 3200–5800 Å and 5500–7600 Å, respectively, at a spectral resolution of 1.08 Å pixel^{-1} in both channels. The slit was oriented east–west and its width was 2″. The Goodman spectrograph was used with the Farchild CCD 486 and three gratings: blue, mid, and redmode, covering the spectral ranges 3550–6300 Å, 4500–7250 Å, and 6400–9150 Å, respectively, at a spectral resolution of 0.65 Å pixel^{-1} in the three spectral ranges. The slit was oriented north–south and its width was 1″. Spectra of each target were obtained with several exposure times between 15 and 1200 seconds; the short exposures were to avoid saturation of possibly strong emission lines (e.g., Hα) and the long exposures were to detected faint emission lines.

The spectra were reduced using standard IRAF tasks, from bias subtraction and flat-field correction, through spectral extraction and wavelength and flux calibration. Spectrophotometric standards from Massey et al. (1988) and Hamuy et al.

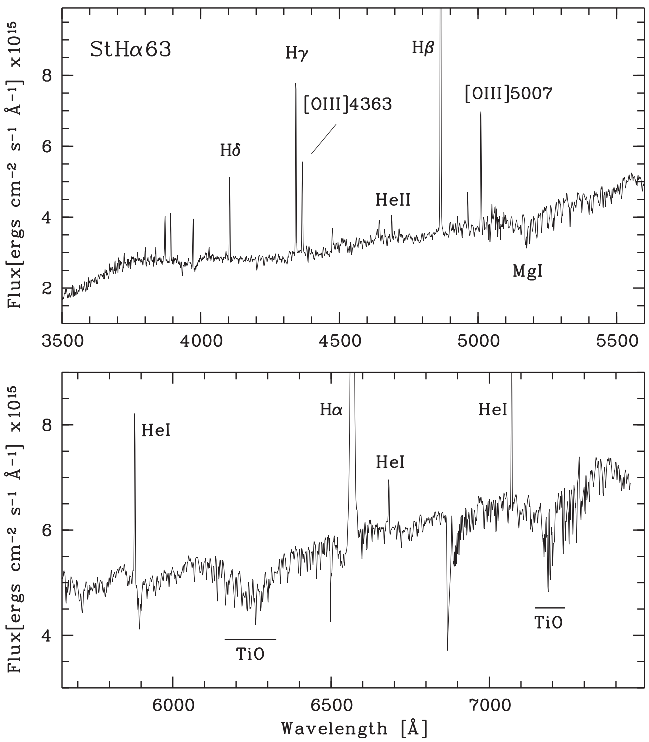

Figure 2. Flux-calibrated spectra of StHα63. Several emission and absorption lines, and TiO absorption bands are indicated.

(1994) were also observed with the same instrumental configuration before and after the objects for flux calibration.

4. STHα63: A NEW YELLOW SYMBIOTIC STAR

Figure 2 presents the spectrum of StHα63 and Table 2 lists the observed fluxes of the identified emission lines. The spectrum of StHα63 shows recombination Balmer, He I, and He II λ4686 emission lines, and forbidden [O III] λ4363,4959,5007 emission lines. The absorption spectrum presents the TiO bands at 6200, 7125, and 7160 Å, and absorption lines due to Fe I at 4202, 5227, 5269, 5227, 5415 Å, Ca I at 4226 Å, Mg I at 5183 Å, Cr I at 5206 Å, Na I at 5890 Å, and a strong absorption around 6500 Å that is due to the contributions of several strong absorption lines of Fe I at 6494, 6496 Å, Ba II at 6497 Å, and Ca I at 6499 Å. The spectrum clearly points to a symbiotic nature for StHα63. Moreover, the spectrum is very similar to that of the yellow symbiotic CD-43°14304 with a K7 spectral type (Schmid & Nussbaumer 1993; Mürset & Schmid 1999), and to that of the candidate yellow symbiotic SS 383 with a spectral type K7–M0 (BPM13). These similarities strongly suggest a K spectral type for StHα63 and, consequentially, that StHα63 is a yellow symbiotic.

To obtain a more precise estimate for the spectral type of StHα63 we proceeded as we did for SS 383: we measured the quantitative TiO indexes (Kenyon & Fernández-Castro 1987) and put StHα63 in the $[\mathrm{TiO}]_1$–$[\mathrm{TiO}]_2$ diagram. Figure 3 shows the position of StHα63 in this diagram, which lies between the positions of AG Dra and TV CVn, two stars with spectral types K4 III and K5.3 III, respectively (Kenyon & Fernández-Castro 1987). Therefore, we estimate a spectral type between K4 and K6 for StHα63, which confirms the yellow symbiotic nature of the object.

Table 2
Observed Emission Line Fluxes (Relative to $F(\mathrm{H}\beta) = 100$) in StHα63

Wavelength (Å)	Identification	$F(\lambda)$
3869	[Ne III]	7.8
3889	He I	6.3
3970	Hϵ	7.5
4101	Hδ	13.9
4340	Hγ	29.6
4363	[O III]	17.0
4471	He I	5.0
4686	He II	6.6
4861	Hβ	100.0
4959	[O III]	6.6
5007	[O III]	25.3
5876	He I	16.2
6563	Hα	596.0
6678	He I	7.4
7065	He I	20.2
$F(\mathrm{H}\beta)$ erg cm^{-2} s^{-1}	5.1×10^{-14}	

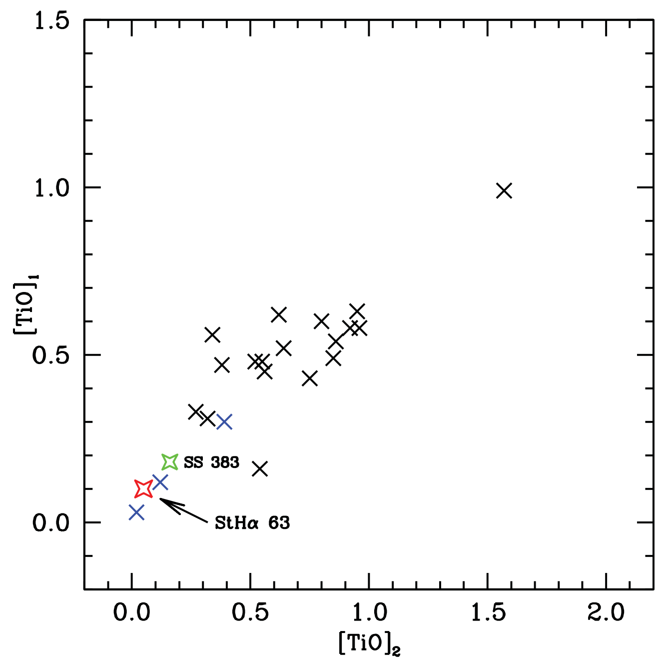

Figure 3. Position of StHα 63 (red star) in the $[\mathrm{TiO}]_1$ vs. $[\mathrm{TiO}]_2$ diagram for a sample of symbiotic stars analyzed by Kenyon & Fernandez-Castro (1987b). Black crosses represent the S-type and the D-type symbiotics with spectral types later than M0. The smaller sample of S-type symbiotics with spectral types no later than K9 (the yellow symbiotics) AG Dra, RS Oph, and TX CVn, also analyzed by Kenyon & Fernndez-Castro (1987b), are represented in this diagram by red crosses. The green star represents SS 383 and the red star represents StHα63.

Some physical parameters of StHα63, such as the color excess $E(B-V)$, the optical depth in Hα ($\tau_{\mathrm{H}\alpha}$), the electron density (N_e), and the infrared type based on He I line intensity ratios can be obtained directly from the observed spectrum. To obtain these parameters we follow the same basic procedures as outlined in BPM13 (see also Proga et al. 1994, and Gutiérrez-Moreno & Moreno 1996). Table 3 shows the results. The electron density derived from the [O III] emission lines intensity ratio is $\log N_e \sim 8.4$ (see Table 3), a value that is typical of S-type symbiotics ($\log N_e \sim$ 8–10) but larger than the values found in D-type symbiotics ($\log N_e \sim$ 6–7, e.g., Schmid &

Table 3
Physical Parameters of StHα63

Parameter	Value
$E(B-V)$	0.19 ± 0.04
A_V	0.59 ± 0.12[a]
$\tau_{H\alpha}$	1.1 ± 0.1
$\log(N_e)$[b] cm^{-3}	8.4
He I $\lambda6678/\lambda5876$[c]	0.31
He I $\lambda7065/\lambda5876$[c]	0.78
Spectral Type[d]	K4–K6

Notes.
[a] Using $R = 3.1$.
[b] From the [O III] emission lines and $T_e = 10\,000$ K.
[c] Reddening-corrected.
[d] From $[TiO]_1$ and $[TiO]_2$ indexes.

Schild 1990; Mikolajewska & Kenyon 1992). As for the infrared D- or S-types (Proga et al. 1994), the line ratios I(He Iλ6678)/(He Iλ5876) and I(He Iλ7065)/(He Iλ5876), corrected for reddening, are 0.31 and 0.78, respectively. The value of the I(He Iλ6678)/(He Iλ5876) ratio is not typical for S-type symbiotics according to Proga et al. (1994), although the PU Vul investigated in their sample also presents a similar ratio of 0.30. The I(He Iλ7065)/(He Iλ5876) intensity ratio in StHα63 is similar to that observed in the yellow symbiotic AG Dra (Proga et al. 1994).

Finally, our spectrum allows us to analyze the position of StHα63 in the [O III]5007/Hβ versus [O III]4363/Hγ diagnostic diagram that was previously used in our studies of planetary nebulae (Pereira & Miranda 2005; Pereira et al. 2010) and of the yellow symbiotic SS 383 (BPM13). The line intensity ratios (see Table 2) place StHα63 in the region of the diagram occupied by S-type symbiotics (see BPM13, their Figure 5), thus further reinforcing our conclusions regarding the symbiotic nature for this object.

5. THE SPECTRA OF [KW97] 37-26, [KW97] 61-27, STHα116, AND SS 360

Figure 4 presents the spectra of the four candidates in Table 1 that were rejected as symbiotics either due to the absence of emission lines or, when present, because they were not the appropriate spectra to classify the star as a symbiotic. Noticeably, [KW97] 37-26, [KW97] 61-27, and StHα116 do not show the Hα emission line even though they are included in Hα emission-line star catalogs (see MacConnell 1981; Stephenson 1986; Kohoutek & Wehmeyer 1999). In the cases of [KW97] 61-27 and StHα116 we note that these two stars are characterized by very strong TiO absorption bands (Figure 4) that produce an "apparent emission peak" around 6540 Å, blueward of the position of Hα, which may be confused with the Hα emission line in very low-resolution (objective-prism) spectra. Only SS 360, discovered as an emission-line star by Stephenson & Sanduleak (1977), presents Balmer emission lines. However, the other typical emission lines of symbiotics (e.g., [O III]) are absent, discarding a symbiotic classification.

The spectrum of [KW97] 37-26 (=[M81] I-734 = BD +00°4203) is very similar to those of HD 1069 and HD 26946 with K2 I and K3 III spectral types, respectively (Jacoby et al. 1984), if we apply to these two stars a reddening of 1.4 as used in Figure 1 for [KW97] 37-26. This points out that [KW97] 37-26 is an early K supergiant or giant star. A more precise classification is not possible because our spectra do not cover the oxygen line at 7774 Å, the calcium infrared triplet, and/or the CN band at 7925 Å, which are useful spectral features for discriminating among supergiants, giants, and dwarf stars (see Pereira & Miranda 2007). The spectra of StHα116 (=BD+14°2953) and [KW97] 61-27 are similar to that of SAO 21753, a K7 III star, whereas the spectrum of SS 360 is similar to that of the M3 III star SAO 63340 (see Jacoby et al. 1984 for the spectra of the used comparison stars).

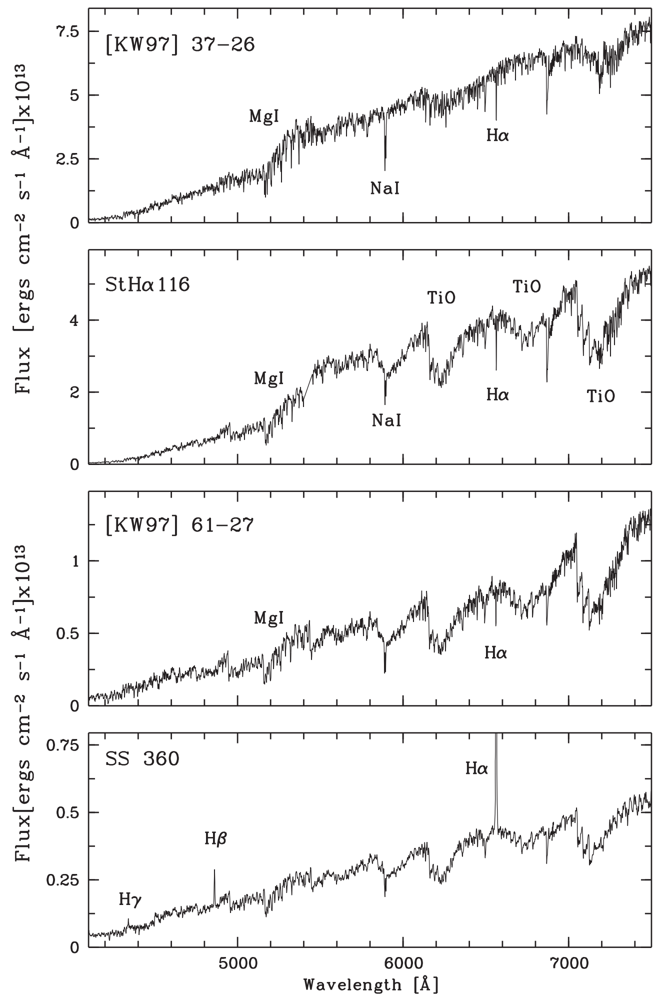

Figure 4. Flux-calibrated spectrum of the four candidate yellow symbiotics [KW97] 37-26, StHα116, [KW97] 61-27, and SS 360. Some emission and absorption features are indicated.

6. THE W34-INDEX FROM *WISE* BANDS AS AN ADDITIONAL CONSTRAINT TO SEARCH FOR S-TYPE YELLOW SYMBIOTIC STAR CANDIDATES

As shown above, SS 360 fulfills the two criteria used by us to select candidate yellow symbiotics, but its spectrum rules out this classification. This suggests that we should look for additional constraints for a better selection of candidates. We have explored the data provided in the *WISE* (*Wide-field Infrared Survey Explorer*) archive. The *WISE* satellite scanned the whole sky in the 3.4, 4.6, 12, and 22 μm bands (Wright et al. 2010), commonly named W1, W2, W3, and W4, respectively. We used the W3–W4 (W34) index and created five histograms to analyze the possibility of identifying true

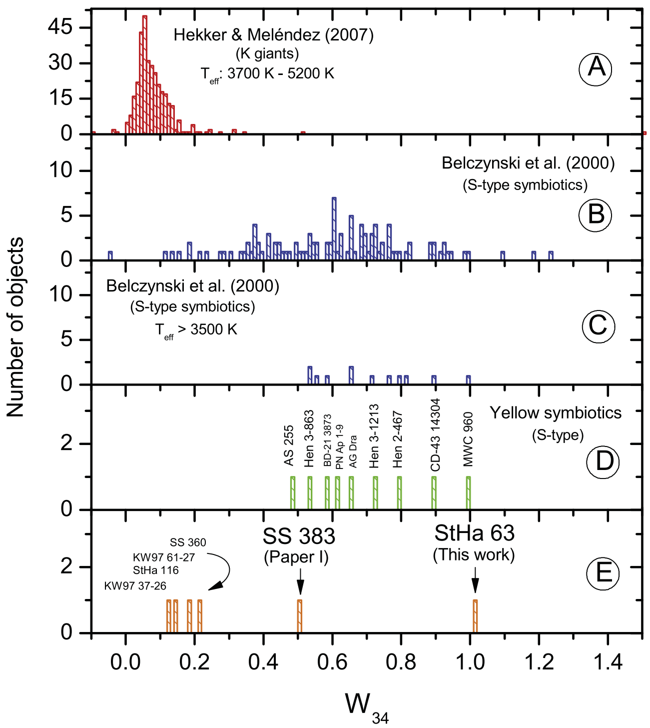

Figure 5. Distribution of the *WISE* W3–W4 (W34) index for five samples of K-giant and symbiotic stars. The content of the histograms is explained within each panel (see the text for details).

S-type yellow symbiotics stars among the candidate objects in Figure 1.

Figure 5 shows these five histograms. Histogram A presents a sample of about 340 K-giant stars with effective temperatures between 3700 and 5200 K (Hekker & Meléndez 2007). It shows that the probability of finding K-giant stars with $W34 > 0.4$ is very low. Histogram B presents the distribution of S-type symbiotic stars from Belczyński et al. (2000). These objects cover the entire range of W34 values in the figure, although there is a small increase in the number of S-type symbiotics in the W34 0.4–0.8 range. This could be an indication that S-type symbiotics have an emission excess between 12 and 22 μm. To check this possibility, histogram C shows a sub-sample of objects from histogram B, namely those S-type symbiotics that contain giant stars with effective temperatures higher than 3500 K; these symbiotics present W34 values higher than 0.4. It is worth noting that effective temperatures higher than ~3500 K are required for yellow symbiotics. Histogram D shows a sample of nine true S-type yellow symbiotics. Remarkably, they all have $W34 > 0.4$, indicating that the difference between S-type yellow symbiotics and "normal" K-giants (without symbiotic activity) is the W34 value. This is probably due to the presence of a dust shell in true S-type yellow symbiotics. The dust shell could add an excess of emission between 12 and 22 μm, which is revealed through the W34 index that appears as a useful tool to distinguish between yellow symbiotic and "normal" K-giants.

To further investigate these results, we constructed histogram E using the five objects in Table 1 and SS 383 (BPM13). Only SS 383 and StHα63 have $W34 > 0.4$, which is compatible with the yellow symbiotic classification for StHα63, and provides further support for the yellow symbiotic nature of the candidate SS 383. Moreover, SS 360 has $W34 \sim 0.21$ and therefore it is not located in the region of yellow symbiotics, in agreement with its non-yellow symbiotic nature established above, even though it is an emission-line star and its position on the 2MASS two-color diagram favors such a classification. From these findings, we conclude that the W34 index can be used as a useful tool to identify candidate yellow symbiotics, in combination with emission-line star catalogs and the 2MASS color–color diagram.

7. CONCLUSIONS

In this work we presented spectroscopic observations of five emission-line stars that are candidates for yellow symbiotics on the basis of their position in the 2MASS color–color diagram. Only one of them, StHα63, has been positively identified as a new yellow symbiotic. Its spectrum and position in the $[TiO]_1$–$[TiO]_2$ diagram indicate a spectral type between K4 and K6. In addition, He I emission-line ratios, derived electron density, and its position in the [O III]5007/Hβ versus [O III]4363/Hγ diagram provide further support for the yellow symbiotic nature of StHα63. The other four candidates are rejected as symbiotics because three of them do not show emission lines (although they were classified as emission-line stars) or one shows only Balmer emission lines.

Our survey for yellow symbiotics based on their particular position in the 2MASS color–color diagram and four emission-line star catalogs raised only six candidates (SS 383 and the five stars analyzed in this work). This small number is not surprising given the rarity of yellow symbiotics. Two of them (SS 383 and StHα63) have been identified as new yellow symbiotics, which provides strong support for our method of target selection. The success of this survey becomes clearer if one takes into account that three of the six selected objects were erroneously classified as emission-line stars.

We used the *WISE* archive to explore the possibility of identifying yellow symbiotic stars. We found that yellow symbiotics have a W3–W4 (W34) index >0.4 and are clearly separated from "normal" K-giant stars. Therefore, the W34 index is a useful tool for improving the selection of candidate yellow symbiotics.

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