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St 2-22 – Another Symbiotic Star with High-Velocity Bipolar Jets

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ABSTRACT

We report the detection of high-velocity components in the wings of Hα emission line in spectra of symbiotic binary star St 2-22 obtained in 2005. This finding encouraged us to start the present investigation in order to show that this poorly-studied object is a jet-producing system. We have used high-resolution optical and low-resolution near-infrared spectra, as well as available optical and infrared photometry, to evaluate some physical parameters of the St 2-22 components and characteristics of the jets. We confirm that St 2-22 is a S-type symbiotic star. Our results demonstrate that an unnoticed outburst, similar to those in classical symbiotic systems, occurred in the first half of 2005. During the outburst, collimated bipolar jets were ejected by the hot component of St 2-22 with an average velocity of about 1700 km/s.

Key words: *binaries: symbiotic – Stars: individual: St 2-22 – ISM: jets and outflows*

1. Introduction

Collimated jets have been observed in many types of astrophysical objects – from pre-main sequence stars to active galactic nuclei (Livio 1999, 2011). Recently, it became clear that the most powerful jets are likely related to the gamma-ray bursts (Granot and van der Horst 2014). It is generally accepted that the existence of an accretion disk around the central object is a common feature for all jet-producing systems. According to Livio (1999, 2011) the jet acceleration and collimation mechanisms are the same in all classes of astrophysical objects which produce jets and the production of powerful jets requires an additional heat/wind source associated with the central object.

Symbiotic stars are wide binary systems with orbital periods of the order of years. They consist of a red giant and a compact companion that accretes matter from the cool giant's wind. In nearly all systems, the compact companion is a white dwarf (Kenyon 1986). Symbiotic stars belong to the group of astrophysical objects in which high-velocity bipolar outflows are not very rare. Many symbiotic systems are relatively bright and can be studied in detail with middle class telescopes, what makes them one of the most promising targets for studying jets. Such investigations will shed more light on the processes of ejection, collimation and acceleration of jets not only in systems with white dwarfs as central objects but in all jet-producing systems. The recent high-resolution observations of the central part of the R Aqr jets are good example (Schmid *et al.* 2017).

Until now, in about a dozen among over 200 known symbiotic stars high-velocity bipolar jets have been observed. These outflows are detectable by imaging and spectroscopy in a wide spectral range from X-ray to radio (*e.g.,* Taylor *et al.* 1986, Tomov *et al.* 1990, Karovska *et al.* 2007, Angeloni *et al.* 2011). In some objects, *e.g.,* Hen 3–1341 and Z And the jets are transient and appear during outburst only (Tomov *et al.* 2000, Munari *et al.* 2005, Skopal *et al.* 2009), while in other objects, like MWC 560, they seem to be permanent (Tomov and Kolev 1997, Schmid *et al.* 2001). Because of the intrinsic, long-term variability of the symbiotic stars it is very difficult to carry out a systematic monitoring in the search for high-velocity bipolar jets. Therefore, most of them have been discovered by chance.

In this paper, we report such a detection of high-velocity collimated bipolar jets in the southern symbiotic system St 2-22. It is a poorly-studied object, included in the Allen (1984) and Belczyński *et al.* (2000) catalogs of symbiotic stars as St 2-22 and listed in SIMBAD as PN Sa 3-22 ($\alpha_{2000} = 13^{\rm h}14^{\rm m}30\overset{\rm s}{.}30, \delta_{2000} = -58^{\circ}51'49\overset{''}{.}6$). Discovered by Sanduleak (1976), St 2-22 was classified as a planetary nebula, which caused a long-term confusion concerning the nature of the object. Allen (1984) identified the Raman scattered line 6825 Å in its spectrum, which gave him an undoubted argument to include St 2-22 in the catalog of symbiotic stars. The data for St 2-22 in the literature are very scarce. There is no information on observed outbursts of the star so far. Van Winckel *et al.* (1993) observed the Hα line in 1988 and 1992. They reported that "the object underwent marked brightness variations in recent years", but they did not provide any details about the nature of these variations. García *et al.* (2003) observed the system while searching for linear polarization, but the detection was negative. In the paper of Zamanov *et al.* (2008), St 2-22 is included among the symbiotic systems for which the rotational velocities of the giant companions were studied. Mürset and Schmid (1999) estimated a spectral class M4.5 for the giant in the system. Mikołajewska *et al.* (1997) derived the reddening $E(B-V) \approx 1$ mag and distance $d \approx 5$ kpc of the system and the temperature $T_{\rm h} \approx 54 \div 100 \times 10^3$ K and luminosity $L_{\rm h} \approx 600$ $\rm L_{\odot}$ of the hot component.

2. Observations and Data Reduction

We used optical spectra of St 2-22 obtained with FEROS at the 2.2-m MPG/ESO telescope at La Silla Observatory in Chile, under program 074.D-0114, on February 1 and May 16, 2005. FEROS is a fiber-fed echelle spectrograph, providing a high resolution of 48 000, wide wavelength coverage from about 3600 Å to 9200 Å in one exposure, and high efficiency (Kaufer *et al.* 1999). The 39 orders of the echelle spectrum are registered on a $2\text{k}\times 4\text{k}$ EEV CCD. The spectra were reduced using the dedicated FEROS data reduction software implemented in the ESO MIDAS system. The achieved S/N ratio in the region of Hα is ≈ 30. The spectra were calibrated in fluxes using spectrophotometric standard stars HR 3454 and HR 4963, which were observed at similar zenith distances during the first and the second night, respectively. The fluxes were dereddened assuming $E(B-V) = 1.0$ mag (see Section 3.2) and a standard interstellar medium extinction curve from Fitzpatrick (1999). As an example, the spectral region between 4625Å and 5025Å is shown in Fig. 1.

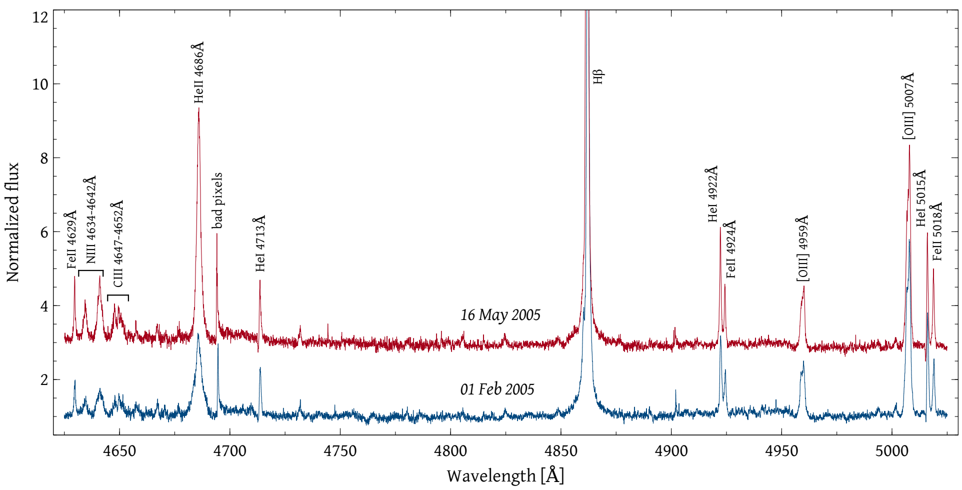

Fig. 1. A sample of the FEROS spectra of St 2-22 obtained on February 1 and May 16, 2005. The strongest Hβ emission is truncated for clarity.

Near-infrared spectra of St 2-22 were obtained with SOFI spectrograph on the ESO NTT telescope in the low-resolution mode using Blue and Red grisms. The observations were acquired on June 18, 2016 in the framework of the observational program 097.D-0338. For each spectral range, four frames were taken in the ABBA sequence. The data were corrected for telluric lines by using a spectrum of hot B3 standard star HIP 65630 and synthetic spectra of the atmosphere over La Silla, generated by the TAPAS service[1].

[1]TAPAS (Transmissions Atmosphériques Personnalisées Pour l'Astronomie), Bertaux *et al.* (2014), *http://ether.ipsl.jussieu.fr/tapas/*

The processing of the SOFI spectra, the reduction of the FEROS spectra into fluxes and all measurements were made with IRAF[2]. The journal of our spectroscopic observations is presented in Table 1.

Table 1

Journal of spectroscopic observations

Date	UT middle	Instrument	Wavelength range	R $\lambda/\Delta\lambda$	Exposure time [sec]
2005 Feb 01	06:16:41	FEROS	3600–9200 Å	48000	2×1800
2005 May 16	02:04:47	FEROS	3600–9200 Å	48000	2×1800
2016 Jun 18	23:38:36	SOFI	0.94–1.64 μm	600–700	4×80
2016 Jun 18	23:48:05	SOFI	1.50–2.53 μm	600–900	4×70

The fluxes of several emission lines measured by integrating the area under the whole profile are shown in Table 2. Considering the inaccuracies of the reduction, the measurement error for these fluxes is $\approx 20\%$ and $\approx 30\%$ for strong and weak lines, respectively.

Table 2

Dereddened emission line fluxes in units of 10^{-13} ergs cm^{-2} s^{-1}

Date	JD	Hγ 4341 Å	[OIII] 4363 Å	HeI 4471 Å	HeII 4686 Å	Hβ 4861 Å	[OIII] 4959 Å	[OIII] 5007 Å
2005 Feb 01	2453402.252	7.82	2.18	1.64	6.98	29.5	2.90	8.62
2005 May 16	2453506.077	35.3	10.0	4.90	30.0	82.4	6.74	21.4

The All Sky Automated Survey (ASAS, Pojmański 1977) monitored St 2-22 in *V*-band when our spectra were obtained. Photometry in *I*-band was secured by the Optical Gravitational Lensing Experiment (OGLE-IV, Udalski *et al.* 2015) between 2013 May and 2016 June. We use photometry of St 2-22 from the Wide-field Infrared Survey Explorer (WISE, Wright *et al.* 2010). A multi-epoch photometry is available in the AllWISE database for two sets of observations in 2010 February and August. The object was detected also by the Two Micron All Sky Survey (2MASS, Skrutskie *et al.* 2006). The Yale/San Juan Southern Proper Motion Catalog 4 (SPM4, Girard *et al.* 2011) gives for St 2-22 $B = 16.92$ mag and $V = 15.32$ mag. The existing photometry in different bands is summarized in Table 3.

[2]IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

T a b l e 3

Available optical and infrared photometry of St 2-22

Band	λ [μ]	Magnitude	Uncertainty	Catalog
B	0.44	16.92		SPM4
V	0.55	15.32		SPM4
J	1.25	9.73	0.02	2MASS
H	1.65	8.68	0.03	2MASS
K_s	2.17	8.21	0.02	2MASS
W1	3.4	8.13	0.02	WISE
W2	4.6	8.20	0.02	WISE
W3	12	7.77	0.02	WISE
W4	22	7.26	0.07	WISE

3. Results

3.1. Bipolar Jets Ejected during an Unnoticed Outburst

For most of the time, the ASAS observations of St 2-22 are below the detection limit. Only for about five months, between January and June 2005, the star was brighter than 14.6 mag in *V* (Fig. 2), reaching a maximum of about 13.8 mag in the beginning of March. If we assume that the *V*-band brightness of 15.32 mag from SPM4 is close to quiescence, then we find the amplitude of the 2005 event of ≈ 1.5 mag. This value is typical for outbursts in classical symbiotic stars such as Z And and AG Dra.

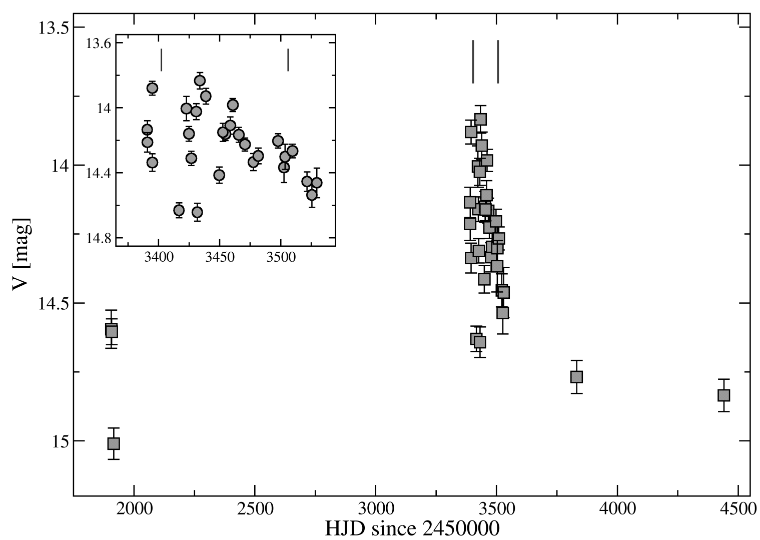

Fig. 2. ASAS *V*-band light curve of St 2-22 (squares) with a zoom around the maximum (circles). The vertical lines mark the moments of our spectroscopic observations.

The FEROS spectra also support our hypothesis that an outburst of St 2-22 occurred in 2005. In the blue part, a hot continuum fills the M spectrum features and they became well visible around and redward of the Hα line. The line spectrum is dominated by emission features and the strongest are the Balmer series members. Most numerous among the other emission lines are the lines of FeII, HeI, and SiII (Fig. 1). In near infrared, well visible in emission are higher members of the Paschen series and the CaII triplet. The emission line OI 8446 Å is remarkably stronger in comparison to OI 7774 Å, suggesting Lyβ fluorescence excitation. The line of HeII 4686 Å and the blends NIII 4634–4642 Å and CIII 4647–4652 Å (Fig. 1) are present in both spectra, while weak emission lines of HeII 5412 Å and [FeVII] 6087 Å appear in the spectrum from May 16 only. The forbidden lines of [OIII] 5007 Å, 4959 Å and 4363 Å (Fig. 1) are present in the spectrum as well. Weak emission lines [OI] 6300 Å, 6364 Å and [NII] 6584 Å are also apparent.

Weak absorption features in the blue emission wings of some HeI lines in the spectrum obtained in February 2005 are visible. In the spectrum obtained later in May 2005, these features slightly increased in intensity and their profiles became of P Cyg type. The terminal velocity of the P Cyg absorption components does not exceed 100 km/s.

A comparison of the Hα line observed by Van Winckel *et al.* (1993) with our observations (Fig. 3) shows that the general line shape did not vary too much. The most remarkable change is the weakening of the absorption component in the spectrum from May 16, 2005. Our measurements also show that there are no significant shifts in the radial velocities. We estimate the average radial velocity for the central emission peak of the Hα line from all four observations (Fig. 3) as of 31.9 ± 1.1 km/s. Using the absorption lines in the 8400–8850 Å wavelength range (most probably from the M giant spectrum), we obtained radial velocities of 36.4 ± 0.3 km/s and 35.0 ± 0.5 km/s, on February 1 and May 16, 2005, respectively. Accordingly, the average radial velocities measured for the metallic emission lines, mainly of FeII, on these dates are 29.2 ± 0.7 km/s and 22.3 ± 0.4 km/s.

A careful inspection of the 2005 spectra revealed two satellite emission components, marked S^- and S^+ in Fig. 3, in the emission wings on both sides of the main Hα profile. We interpret these satellite components as emissions originating in high-velocity, bipolar outflows, ejected by the hot component of St 2-22. Such emission components are not visible in the 1988 and 1992 Hα profiles (Fig. 3). However, we cannot conclude that they are completely missing because, the region around Hα, covered by the observations of Van Winckel *et al.* (1993), is very limited.

To separate the jet emission components and to estimate their parameters we fitted the complete Hα line profile being a combination of Gaussian and Lorentzian functions. The satellite emissions are best fitted with Gaussian curves, whose parameters are shown in Table 4. Uncertainty in the determination of the parameters

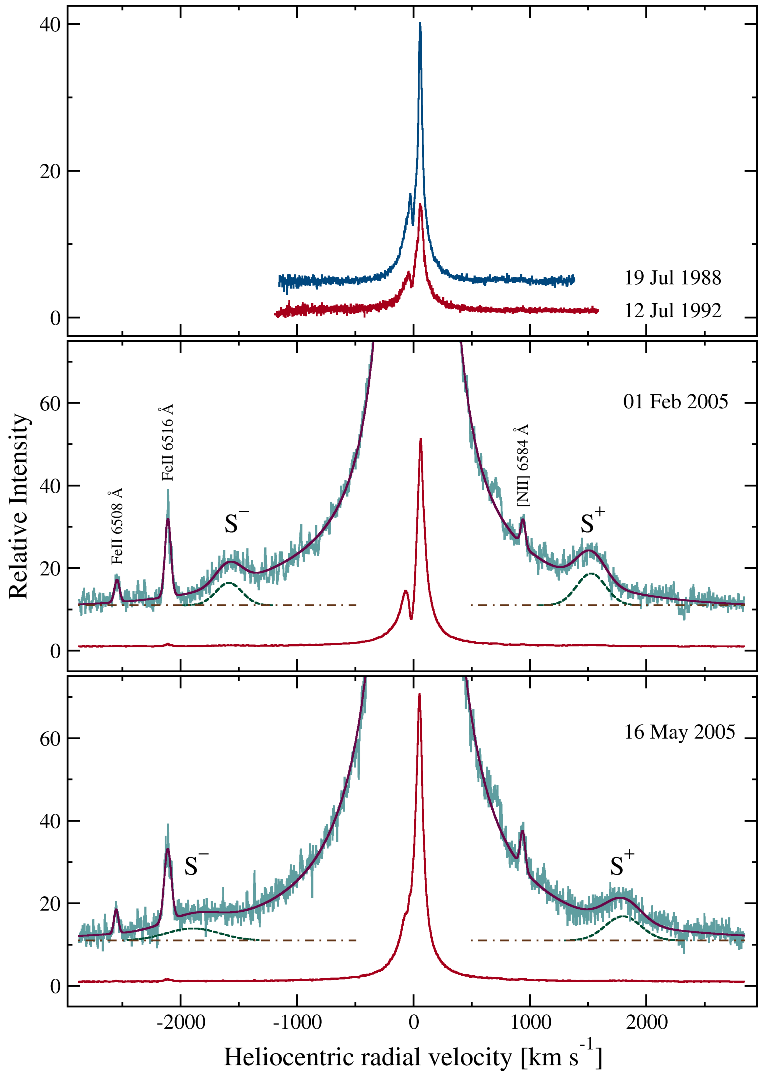

Fig. 3. Hα profiles in the spectrum of St 2-22 obtained by Van Winckel *et al.* (1993) in 1988 and 1992 (*upper panel*), compared to our observations in 2005 (*middle and lower panels*). The profiles are normalized to the local continuum and when necessary shifted for clarity. The 2005 profiles are multiplied by 40 to enlarge their wings and show better the jets emission components S^- and S^+. The dark continuous lines represent the fit to the enlarged Hα profiles (see text for details). With dashed lines are shown the Gaussian fits to the jet emission components. The dot-dashed lines mark the local continuum level for the enlarged profiles.

is the highest for the blue jet emission component in the 2005 May 16 spectrum (Fig. 3), as it is blended with a relatively strong line of FeII 6516 Å.

Using the parameters from Table 4 and taking into consideration the shift of the Hα central emission peak, the estimated velocities of the bipolar jets are 1555 ± 13 km/s on February 1 and 1847 ± 20 km/s on May 16, 2005. The average FWHM values of the fitted Gaussians are 277 ± 16 km/s and 447 ± 21 km/s, respectively, which indicates a high collimation of the outflowing matter. An increase of the jets velocity, by about 300 km/s, apparently took place in 2005, between February and May.

Table 4

Heliocentric radial velocities ($RV_{\odot}$), FWHM, and equivalent width (EW_{λ}) of the Gaussian fit to the jet emission components

Date	$RV_{\odot}$ [km/s]		FWHM [km/s]		EW_{λ} [Å]	
	S^-	S^+	S^-	S^+	S^-	S^+
2005 Feb 01	-1585 ± 10	1525 ± 8	262 ± 13	292 ± 10	0.82	1.30
2005 May 16	-1893 ± 19	1800 ± 6	535 ± 19	359 ± 8	0.81	1.21

3.2. Reddening and Distance

The above mentioned values, $E(B-V)\approx 1$ mag and $d\approx 5$ kpc, reported by Mikołajewska *et al.* (1997), are the only estimates of the reddening and distance to St 2-22 existing in the literature. The NASA/IPAC Infrared Science Archive gives $E(B-V)=0.80\pm0.03$ mag and $E(B-V)=0.93\pm0.04$ mag for the mean color excess in the direction of St 2-22, in accordance with Schlafly and Finkbeiner (2011) and Schlegel *et al.* (1998), respectively.

The NaI and KI interstellar lines in our spectra cannot be used to estimate interstellar extinction, because they are heavily blended. Using the equivalent widths of diffuse interstellar bands 5780 Å, 5797 Å, 6614 Å and the dependencies given by Puspitarini *et al.* (2013), we obtain the color excess for St 2-22 of $E(B-V)\approx 0.9\pm0.5$ mag.

The contribution of the hot component to the star brightness in V could be significant and because of this we tried to determine the distance modulus of the object based on its brightness in the near IR. With the color excess obtained by us, we have dereddened the 2MASS magnitudes of St 2-22 in the way described by Li *et al.* (2016). Then, using their empirical fit for the M giants in the Sgr stream core region, for the absolute magnitude of St 2-22 in filter J we obtained $M_J\approx -5$ mag. This value corresponds to the distance of about 7 kpc. Based on the relation between the M_{K_s} and the color $J-K_s$ (Sheffield *et al.* 2014), for a M giant with parameters similar to the determined in Section 3.4, we can estimate an absolute magnitude $M_{K_s}\approx -5.4$ mag. The corresponding distance is about 5.2 kpc.

Obviously, we are far from accurate estimates of the reddening and distance to St 2-22. Therefore, for the purposes of this work, we will adopt the values from Mikołajewska *et al.* (1997): $E(B-V)\approx 1$ mag and $d\approx 5$ kpc.

3.3. Hot Component

We used the Iijima (1981) method to estimate the hot component temperature. The method is based on the measurements of fluxes of the emission lines of HeII 4686 Å, Hβ, and HeI 4471 Å, assuming Case B recombination. The temperatures, calculated with dereddened fluxes from Table 2 for 2005 February 1 and May 16 are 115 000 K and 130 000 K, respectively, with an accuracy of an order of 20%. The lower limit for T_h can be derived from the maximal observed ionization potential (IP), using the relation proposed by Mürset and Nussbaumer (1994) for temperatures below 150 000 K, $T_h = \mathrm{IP} \times 1000$ K. Emission lines with the highest IP ≈ 55 eV in the February spectrum are HeII 4686 Å and [OIII] 5007 Å. In May, a weak emission of [FeVII] 6087 Å, with IP of about 125 eV – Kramida *et al.* (2015).

To calculate the luminosity of the hot component from the dereddened fluxes of HeII 4686 Å and Hβ we used Eqs. 6 and 7 from Mikołajewska *et al.* (1997). To evaluate the number of H^0 and He^+ ionizing photons, we used the number of ionizing photons $G_i(T_*)$ tabulated by Nussbaumer and Vogel (1987). The difference between the luminosity calculated based on the HeII 4686 Å and Hβ does not exceed 20%. As a result, we adopted the average of the values obtained from both equations for the hot component luminosity. This gives an estimate of $L_h \approx 285 \pm 30$ $L_\odot$ for St 2-22 on 2005 February 1 and $L_h \approx 940 \pm 200$ $L_\odot$ on May 16. Considering uncertainties in the reddening and the distance, the error in luminosity can increase by a factor of two. From the values of the temperature and the luminosity, we can evaluate the radius of the pseudo photosphere of the hot component to $R_h = 0.04 \pm 0.01$ $R_\odot$ and $R_h = 0.06 \pm 0.01$ $R_\odot$ on 2005 February 1 and May 16, respectively.

The relatively small ratios of [OIII] 5007 Å to Hβ (0.27 ± 0.02) and [OIII] 4363 Å to Hγ (0.29 ± 0.01) indicate a comparatively high electron density N_e, for the environment in which the forbidden lines originate. Using the task temden in the IRAF package STSDAS and by adopting a value of $N_e \approx 10^7$, we obtained the electron temperature of $T_e \approx 11000$ K on February 1 and $T_e \approx 14000$ K on May 16.

3.4. Cool Companion

Photometry

To evaluate the physical parameters of the cool companion in St 2-22 we used the 2MASS JHK_s data. First, they were transformed to the homogenized system of Bessell and Brett (1988, BB) and then dereddened with the corresponding A_λ, calculated for $E(B-V) = 1.0$ mag. The bolometric correction $BC_K = 2.78$ mag for the color $(J-K)_{\mathrm{BB}} = 1.06$ mag was estimated from the respective equation in the paper of Bessell and Wood (1984). Using the dereddened value $K_{\mathrm{BB}} = 7.81$ mag and BC_K we derived a bolometric absolute magnitude for the red giant $M_{\mathrm{bol}} = -2.9$ mag, which corresponds to the bolometric luminosity $L_{\mathrm{bol}} = 1140$ $M_\odot$. Using the above value of $(J-K)_{\mathrm{BB}}$ and $(H-K)_{\mathrm{BB}} = 0.25$ mag, and assuming $[\mathrm{Fe/H}] = 0$ and $\log g = 1$, we evaluated, from Worthey and Lee (2011), the cool

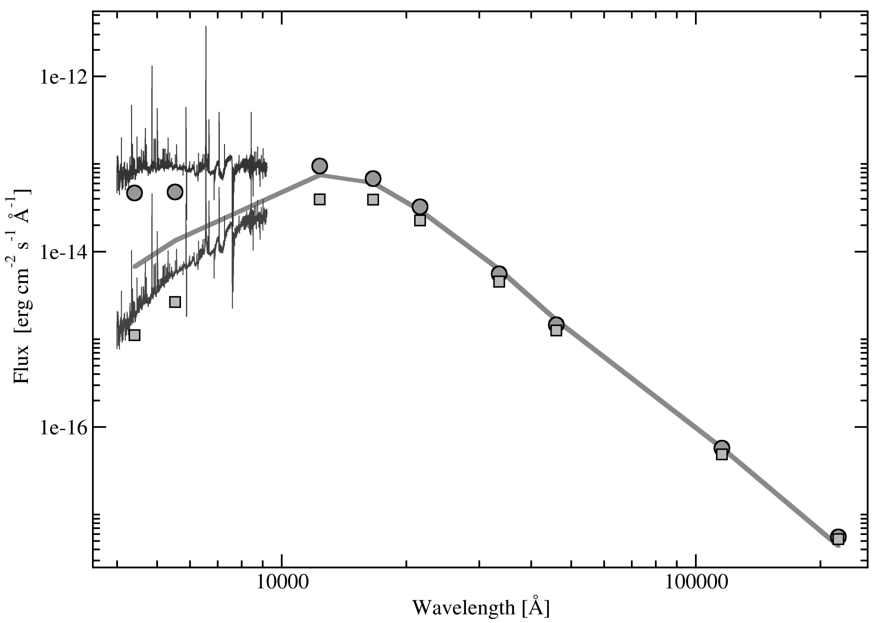

Fig. 4. St 2-22 SED based on SPM4 *B* and *V*, 2MASS *J, H,* K_s, WISE *W1, W2, W3* and *W4* magnitudes. The squares indicate the observed values. The dereddened magnitudes are shown with circles. Observed and dereddened optical spectrum of St 2-22, obtained on 2005 February 1, is also plotted. Thick continuous line represents the NextGen theoretical spectrum SED (see text for details).

companion temperature as of $T_{\rm eff} = 3580 \pm 100$ K. We have also calculated the giant radius of $R_g = 90$ R$_\odot$. A comparison of the obtained physical parameters with the calibrations of Straižys and Kuriliene (1981), points to a M3-M4 red giant.

We used the VO Sed Analyzer (VOSA) tool (Bayo *et al.* 2008) to study the spectral energy distribution (SED) of St 2-22, shown in Fig. 4. The same value of $E(B-V) = 1.0$ mag and the extinction law by Fitzpatrick (1999), improved in the infrared by Indebetouw *et al.* (2005), were used for dereddening of the observed magnitudes. The disagreement between the optical brightness and the optical spectrum obtained around the 2005 outburst maximum, indicates that the *BV* magnitudes were measured during quiescence. The IR magnitudes were fitted by a NextGen theoretical spectrum (Allard *et al.* 2012) with $T_{\rm eff} = 3500$ K, $\log g = 1.0$, $[{\rm Fe/H}] = 0$, with the corresponding $L_{\rm bol} = 1017 \pm 4$ L$_\odot$, and using the assumed distance of 5 kpc. The fitted model demonstrates a good accordance between the IR SED, the M4.5 giant proposed by Mürset and Schmid (1999) and the parameters estimated above for the cool companion of St 2-22. Also, the lack of IR excess in Fig. 4 is obvious.

The OGLE data include only *I*-band measurements of St 2-22, obtained at 140 epochs during a time interval of 1120 d (Fig. 5). The observations are scarce, unevenly distributed and with large gaps in between. It should be noted, that because the final calibration to the OGLE-IV Galactic disk photometry is yet to be done, an offset from the zero point of the *I*-band photometry may reach ≈ 0.4 mag. Full

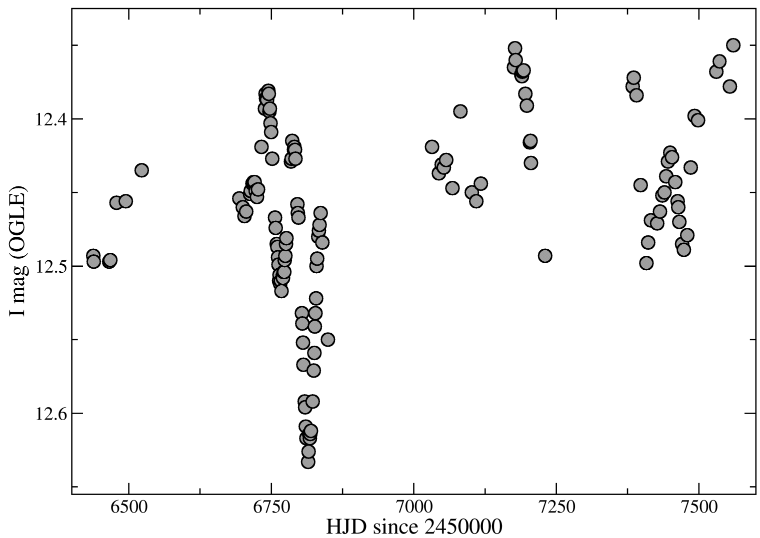

Fig. 5. OGLE *I*-band light curve of St 2-22 covering the time interval between 2013 May and 2016 June. The error of all measurements is 0.003 mag.

range of the brightness changes over the observed interval is ≈ 0.3 mag. A gradual increase in brightness by about 0.1 mag is also seen. A periodogram analysis of the complete OGLE light curve of St 2-22, carried out using the phase dispersion minimization method (Stellingwerf 1978) and Period04 (Lenz and Breger 2005) program, did not show any significant periodicities of the brightness variations. While analyzing only the part of the light curve between JD 2456693 and JD 2456850 with the best coverage, a period of 51 ± 7 d becomes significant. This period is most likely caused by pulsations of the cool companion in the system. It is in a good agreement with the minimal pulsation periods of red giants in symbiotic stars published by Gromadzki *et al.* (2013) and Angeloni *et al.* (2014). However, additional observations and more detailed analysis of the pulsations are needed for a definitive conclusion whether the giant companion in St 2-22 belongs to the class of OGLE small amplitude red giants (OSARGs) or semi-regular variables (SRVs). For a discussion on OSARGs, SRVs, and symbiotic red giants see Gromadzki *et al.* (2013) and Angeloni *et al.* (2014). The deep minimum at JD 2 456 814 is most likely due to a superposition of the 51-d pulsations with a longer period.

The multi-epoch AllWISE photometry (Fig. 6) also shows small changes in the IR brightness of the M giant in the St 2-22 system. In the WISE bands *W1* and *W2*, the magnitude values in 2010 February are clearly below the average brightness, marked with dashed lines in Fig. 6. *Vice versa*, these values in 2010 August are evidently above the average brightness. These differences are of the order of 0.05 mag and 0.03 mag for *W1* and *W2*, respectively. In the remaining two WISE bands, *W3* and *W4*, the measured magnitudes are more or less equally distributed around the average values during both periods of observation.

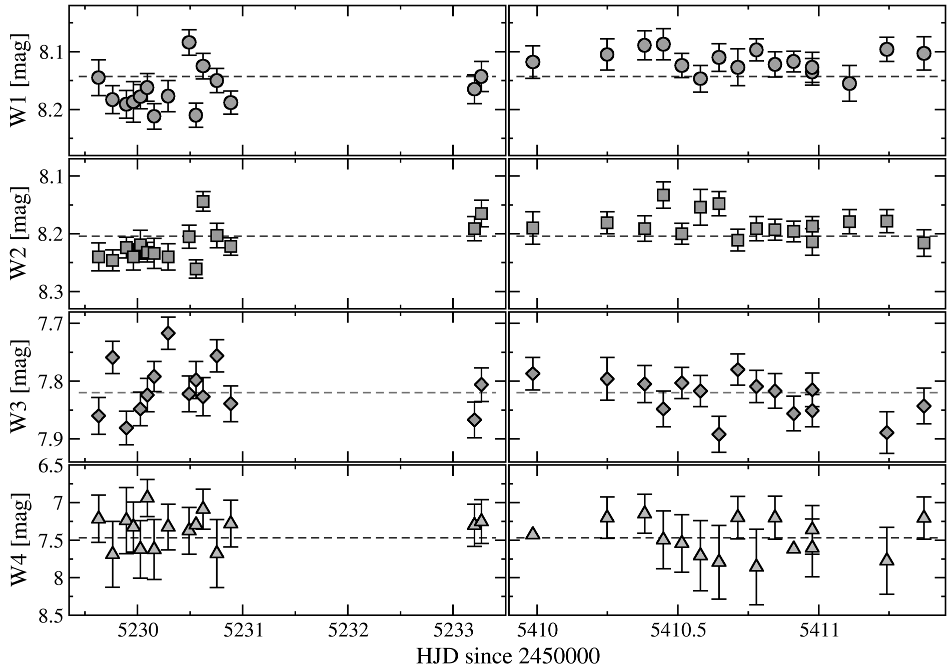

Fig. 6. AllWISE multi-epoch photometry of St 2-22. In the *left* and *right panels* the observations taken in 2010 February and 2010 August are respectively shown. Dashed lines mark the average magnitude of all WISE observations in the corresponding bands.

Near-infrared spectroscopy

In the SOFI blue spectra, emission lines of HeI 10838 Å, OI 11292 Å, Paβ 12823 Å are clearly seen, indicating that the blue part of the spectrum is substantially affected by the nebular continuum, while emission lines form helium and the hydrogen Bracket series are absent in the red part. We used parts of the H-band (15 310–17 450 Å) and K-band regions (20 250–24 600 Å), which are poorly affected by the nebula and where the absorption features are relatively strong to estimate stellar parameters, to analyze the metallicity, and to obtain relative abundances between C, N, and O, and the carbon isotopic ratio $^{12}C/^{13}C$.

Synthetic spectra were calculated using a grid of MARCS model atmospheres (Gustafsson *et al.* 2008) with the following atmospheric parameters: $T_{\rm eff}$ from 3400 K to 3800 K, $\log g$ from $+0.5$ to $+1.5$, metallicity [Fe/H] from -4 to $+1$ dex. The best fitted solutions were obtained for [Fe/H]≈ -0.25 dex. This value is in agreement with the typical metallicity of red giants in the S-type symbiotic systems, between -0.5 and 0 (Gałan *et al.* 2016, 2017). The gravity, $\log g$ was between $+0.5$ and $+1.0$, with a preference to the higher value. The dependence on the temperature is very weak and the best results are placed around 3600–3700 K. The errors are difficult to estimate. Due to the continuum problem (a particularly strong degeneracy in $T_{\rm eff}$), the accuracy is not better than $\Delta T_{\rm eff} \approx 200$ K, $\Delta \log g \approx 0.5$, Δ[Fe/H]≈ 0.5. There are ^{12}CO and ^{13}CO bands beyond 22 900 Å in

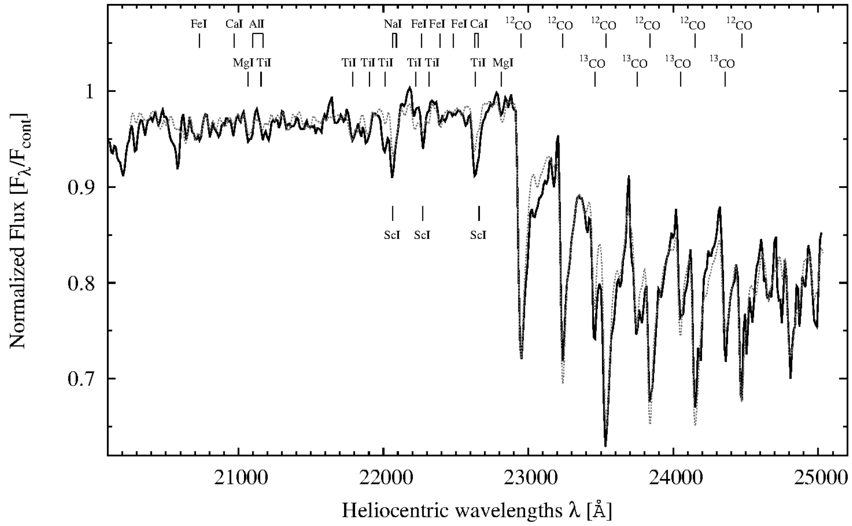

Fig. 7. Synthetic spectrum (doted line) generated by the use of MARCS model atmosphere ($T_{\rm eff} = 3600$ K, $\log g = 1.0$, [Fe/H]$= -0.5$) compared to the observed spectrum (continuous line) of St 2-22. Apart from the CO bands the positions of some of the strongest neutral atomic lines of Na, Mg, Al, Ca, Sc, Ti, and Fe are marked.

the spectra of St 2-22, (Fig. 7). This enables us to measure the abundance of carbon, $C \approx 7.8$ dex (assuming the model value $O \approx 8.4$ dex), the ratio of C/O ≈ 0.3, and the carbon isotopic ratio $^{12}{\rm C}/^{13}{\rm C} \approx 15$. Also weak CN lines are present in both H- and K-band regions from which we can roughly estimate the nitrogen abundance, $N \approx 8.3$ dex, and thus the ratios of ${\rm C/N} \approx 0.3$ and ${\rm O/N} \approx 1.1$. The obtained values indicate that the giant has experienced the first dredge-up, common to all giants in the S-type symbiotic systems studied so far (Gałan *et al.* 2016, 2017). An increased abundance of Sc in the giant companion also seems to be possible when comparing synthetic and observed spectra of St 2-22.

4. Discussion

Our study confirms the classification of St 2-22 as a S-type symbiotic star in the Catalogue of Belczyński *et al.* (2000). In fact, in the [OIII] 5007 Å/Hβ *vs.* [OIII] 4363 Å/Hγ diagnostic diagram by Gutierrez-Moreno *et al.* (1995), the measured line ratios (Section 3.3) place St 2-22 in the same region as the S-type symbiotics. The observed colors $J-H = 1.06$ mag and $H-K_s = 0.47$ mag also place St 2-22 exactly among the S-type symbiotic stars in the 2MASS color–color diagram, used by Corradi *et al.* (2008), in combination with the INT Photometric Hα survey of the Northern Galactic plane (IPHAS), to distinguish symbiotic binaries from other types of objects. The determined by us $M_{\rm bol} = -2.9$ $M_\odot$, $R_g = 90$ $R_\odot$ and $T_{\rm eff} = 3580$ K put the cool companion of St 2-22 on the evolutionary track for the red giants with mass around 1.5 $M_\odot$ in Fig. 3 in Mikołajewska (2007), in which symbiotic giants in the HR diagram are presented.

Using low resolution spectra, obtained between 1984 and 1990, Mikołajewska *et al.* (1997) estimated the luminosity of the St 2-22 hot component as of about 600 $L_\odot$. This coincides with the mean value of our estimates of the luminosity during the outburst in 2005, obtained in Section 3.3. In our spectra, Raman scattered OVI emission lines at 6825 Å and 7082 Å are not present. Mikołajewska *et al.* (1997) pay particular attention to the Raman scattered lines and found an apparent correlation between hot component luminosity and the flux of the emission line OIV 6825 Å. In their Table 1, the flux measured for this line in the spectrum of St 2-22 is missing which suggests that the Raman scattered emission was also absent during their observations. On the other hand, Allen (1984) pointed out to the presence of a strong 6825 Å emission in the spectrum of St 2-22. Taking into account that the Raman scattered features typically disappear from the spectra of the classical symbiotic stars during outburst (Tomov *et al.* 2000, Skopal *et al.* 2009, Shore *et al.* 2010), we can suppose that the spectra used by Mikołajewska *et al.* (1997) have been obtained during one previous, also unnoticed, outburst of St 2-22.

As we mentioned above, it is commonly accepted that in all systems producing collimated jets, there is an accretion disk around the central object and the jet velocity is of an order of the escape velocity from this object. To evaluate the inclination angle i of the orbit of St 2-22, we assume that the jets are ejected perpendicularly to the accretion disk and that the disk lies in the orbital plane. As the minimum and maximum masses of the WD in the St 2-22 system, we assume the values of 0.4 $M_\odot$ and 0.8 $M_\odot$, respectively, adopted from Mikołajewska (2003). As the minimum radius of the WD we use the typical value of 0.01 $R_\odot$, and as the maximum radius we take the mean radius of the pseudo photosphere of $R_h = 0.05 \pm 0.01$ $R_\odot$ estimated by us in Section 3.3. As jet's velocity we use the mean value of 1700 ± 25 km/s obtained for 2005 February 1 and May 16 (Section 3.1). Thus, we find that the inclination of the St 2-22 orbit is in a wide range between 13° and 72°.

Skopal *et al.* (2009) proposed a formula for estimating the jet's opening angle $\Theta_{\rm jet}$, based on the FWHM of the emission components originating in the jets, the jet's velocity and the orbital inclination. Applying this formula for St 2-22 with the FWHM values from Table 4, we obtain a very large, unreal $\Theta_{\rm jet} \approx 105^\circ$ for the lower limit of $i \approx 13^\circ$. The estimated jet's opening angle for the upper limit of $i \approx 72^\circ$ is $\Theta_{\rm jet} \approx 7^\circ$.

For the jets in Z And, which are very similar in observed velocity and FWHM of the jet emissions to those in St 2-22, Skopal *et al.* (2009) calculated $\Theta_{\rm jet} = 6.1^\circ$ for $i = 76^\circ$. An inclination very close to the defined by us upper limit for the orbit of St 2-22. Another indication that the orbital inclination of St 2-22 is large comes from its comparison with object MWC 560. In this system, the axis of the jets is almost parallel to the line of sight. In the spectrum, only the blue jet is visible and, moreover, in absorption (Tomov *et al.* 1990). Schmid *et al.* (2001) estimated the orbital inclination of MWC 560 as of $i < 16^\circ$. Similarly, for inclination angles close to 13° the red jet in St 2-22 would be totally obscured by the accretion disk and the blue jet would be visible in absorption. In our spectra, the jets are seen as strong shifted emission components (Fig. 3). Moreover, it seems that the red component is slightly stronger than the blue one, $EW_{S^-}/EW_{S^+} < 1$.

Taking into account the above-mentioned facts, we can assume that the inclination of the orbit of St 2-22 is large and very likely to be close to the determined by us upper limit of about 72°.

It is unclear, where the mentioned before difference of ≈ 300 km/s between the velocity of the jets in February and May 2005 comes from. It is difficult to explain this on the basis of the jets ejection mechanism, which has not yet been clarified. From the observational point of view, two types of jets velocity changes in symbiotic stars have been observed so far. In some cases, the velocity of the jets gradually changes within 200–300 km/s in a time scale of several months, which has been observed in Z And (Skopal *et al.* 2009). Changes in the MWC 560 jets velocity during the discrete ejections in 1990 reached from several hundred to several thousand km/s in spectra obtained in two consecutive nights (Tomov *et al.* 1992). The jets in St 2-22 were observed only on two occasions, separated by two and a half months. This does not allow us to trace in detail their evolution and velocity changes.

Zamanov *et al.* (2008) estimated the projected rotational velocity of the cool companion in St 2-22 as $v\sin i = 9.8 \pm 1.5$ km/s. Assuming that the rotational axis of the M giant is perpendicular to the orbital plane, and using the determined upper limit of 72° for the orbital inclination, we obtain the rotational period of the giant of $P_{\rm rot} \approx 445$ d. There are suggestions that the rotational period of the giant companion and the orbital period in S-type symbiotic systems are synchronized (see for instance Zamanov *et al.* 2007). Assuming that the synchronization also occurs in the case of St 2-22, the derived value of $P_{\rm orb} \approx 445$ d is in good agreement with the known orbital periods in the S-type symbiotic stars (see Table 1 in Mikołajewska 2003). Assuming 1.5 $M_\odot$ and 0.5 $M_\odot$ as the masses of the red giant and the white dwarf, respectively, we obtain the value of $a \approx 307$ $R_\odot$ for the binary semi-major axis from the third Kepler's law. This gives $a\cos i \approx 95$ $R_\odot$, which is larger but close to the sum of the M giant radius $\approx 90 R_\odot$ and the radius of the pseudo photosphere of the hot component ≈ 0.05 $R_\odot$. Taking into account the accuracy of the estimated stellar and orbital parameters, and the fact that we do not consider the accretion disk, whose radius is certainly greater than R_h, we can conclude that eclipses in St 2-22 may occur at $i \approx 70^\circ$. Presumably, it will be easier to detect a possible eclipse of the hot component by the red giant in the *UBV* filters, in which the hot component radiation dominates or at least is substantial.

5. Conclusions

The main results in this paper can be summarized as follows:

(i) We bring to light a recorded but unnoticed outburst of St 2-22 that occurred in

2005. Its amplitude of ≈ 1.5 mag and duration of about half a year, resemble outbursts in classical symbiotic systems.

(ii) Our study confirms that St 2-22 is a S-type symbiotic system. The parameters of the cool companion evaluated by us agree, within a subclass, with the spectral class M4.5III proposed by Mürset and Schmid (1999). Indications of a possible pulsation period of about 51 d were found in the OGLE light curve.

(iii) The estimated temperature and the luminosity for the hot component during the 2005 outburst are similar to that obtained by Mikołajewska *et al.* (1997). This result and the lack of the Raman scattered emissions in the spectrum of St 2-22 at both occasions can be considered as an indication that the spectra used in the paper of Mikołajewska *et al.* (1997) were also obtained during a previous, unnoticed outburst.

(iv) Hα satellite emission components, originating in high-velocity, collimated bipolar jets, were identified in the outburst spectra of St 2-22. Therefore, this poorly studied star, should be added as a new member of the jet-producing group of symbiotic systems.

(v) Based on only two spectra of St 2-22 obtained during the outburst, we estimated an average velocity of the jets of about 1700 km/s. Most likely, the orbital inclination is large, and close to the defined upper limit of about 72°. In this case, the opening angle, being in good accordance with the profiles of the satellite emissions, will be of about 7°.

Here we tried to present all the available, very scarce, observational data for St 2-22. Additional, new or archival data are necessary, to better understand the nature of this interesting, but until now neglected symbiotic star.

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