VLT/UVES spectroscopy of V4332 Sagittarii in 2005: The best view on a decade-old stellar-merger remnant

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ABSTRACT

Context. V4332 Sgr is a red transient (red nova) whose eruption was observed in 1994. The remnant of the eruption shows a unique optical spectrum: strong emission lines of atoms and molecules superimposed on a M-type stellar spectrum. The stellar-like remnant is however not directly observable. Presumably it is embedded in a disc-like dusty envelope orientated almost face-on. The observed optical spectrum is supposed to result from interactions of the central-star radiation with dust and gas in the disc and outflows initiated in 1994.

Aims. We aim at studying the optical spectrum of the object in great detail to better understand the origin of the spectrum and the nature of the object.

Methods. We have reduced and measured a high-resolution (R ≃ 40 000) spectrum of V4332 Sgr obtained with VLT/UVES in April/May 2005. The spectrum comes from the ASO archives and is the best quality spectrum of the object ever obtained.

Results. We have identified and measured over 200 emission features belonging to 11 elements and 6 molecules. The continuous, stellar-like component can be classified as ∼M3. The radial velocity of the object, as derived from narrow atomic emission line, is ≃ −75 km s⁻¹. The interstellar reddening was estimated as being 0.35 ≤ Eₐ₋ₐ ≤ 0.75. From radial velocities of interstellar absorption features in the Na D lines we have estimated a lower limit of ~5.5 kpc to the distance of V4332 Sgr. When compared to spectroscopic observations done in 2009, the spectrum of V4332 Sgr considerably evolved between 2005 and 2009. The object significantly faded in the optical (by ~2 mag. in the V band), which resulted from the main remnant cooled by 300–350 K corresponding to its spectral type changed from M3 to M5-6. The object however increased in luminosity by ~50%, implying a significant expansion of its dimensions. Most of the emission features seen in 2005 significantly faded or even disappeared from the spectrum of V4332 Sgr in 2009. These results from fading of the optical central-star radiation, as well as decreasing of the optical thickness of the circumstellar matter, presumably due to its expansion. V4332 Sgr bears several resemblances to V1309 Sco, which erupted in 2008. This can evidence a similar nature of the eruptions of both objects. In case of V1309 Sco the outburst resulted from merger of a contact binary.

Key words. stars: individual: V4332 Sgr - stars: emission-line - stars: late-type - stars: activity - stars: winds, outflows - stars: variables: other

1. Introduction

V4332 Sagittarii (V4332 Sgr) was discovered as Nova Sgr 1994 in February 1994 (Hayashi et al. 1994). Spectroscopic observations however showed narrow Balmer lines in emission superimposed on a K-type (super)giant spectrum quickly evolving to M-type (super)giant (Tomayey et al. 1994; Martini et al. 1999). This spectral appearance and evolution was at variance with what is observed in classical novae but bore a resemblance to the luminous red variable observed in M31 in 1988 (M31 RV) (Mould et al. 1990). At present, stellar eruptions of this type are named red transients, red novae or V838 Mon-type objects. The latter name comes from the gigantic eruption of V838 Monocerotis observed in 2002 (Munari et al. 2003; Crase et al. 2003), which aroused a great interest of astrophysicists, as well as public media, partly due to the spectacular light-echo event accompanying the outburst (Bond et al. 2003).

Apart from the three above mentioned objects the class of red transients in our Galaxy includes V1309 Scorpii (V1309 Sco) (Mason et al. 2010) and OGLE-2002-BLG-360 (Tylenda et al. 2013). V1148 Sagittarii (Nova Sgr 1943) probably also belonged to this class, as can be inferred from its spectral evolution described by Mayall (1949). There are also observational evidences that CK Vulpeculae (CK Vul, Nova Vul 1670) (Shara et al. 1985) was rather a red transient then a classical nova (Kato 2003; Tylenda et al. 2013). A few extragalactic objects, usually referred to as intermediate-luminosity optical transients, e.g. M85 OT2006 (Kulkarni et al. 2007), NGC300 OT2008 (Bond et al. 2009), and SN 2008S (Smith et al. 2009), could also be of a similar nature.

Although they are different in the light curve, time scale and peak luminosity, red transients show always a similar spectral evolution, i.e. in course of the eruption the objects evolve to progressively lower effective temperatures and decline as M-type (super)giants. Their remnants also resemble a late M-type (super)giants with a significant (often dominating) infrared excess.

Several mechanisms have been proposed to explain the red-transient events, including an unusual nova (Iben & Tutukov 1992), a late He-shell flash (Lawlor 2005), and a stellar merger (Soker & Tylenda 2003). They have critically been discussed in Tylenda & Soker (2006). These authors conclude that the only mechanism that can satisfactorily account for the observational data of red transients is a merger of two stars. For the case of V838 Mon they argued that this eruption might have been due to...
a merger of a low-mass pre-main-sequence star with an $\sim 8 M_\odot$ main-sequence star.

V1309 Sco, which erupted in 2008 (Mason et al. 2010), appeared to be a sort of Rosetta stone in understanding the nature of red transients. Thanks to the archive data from the Optical Gravitational Lensing Experiment (OGLE) Udalski (2003) it was possible to follow the photometric evolution of the object during six years prior to the outburst (Tylenda et al. 2011). The result was amazing: the progenitor of V1309 Sco was a contact binary quickly losing its orbital angular momentum and evolving to the merger of the components. Thus V1309 Sco provided us with a strong evidence that the red transients are indeed due to stellar mergers.

After the 1994 outburst, V4332 Sgr was forgotten by astrophysicists and observers. Only when V838 Mon erupted in 2002 and astronomers realized that both objects most probably belong to the same class, V4332 Sgr regained astrophysical interest. Several spectroscopic observations done in 2002-2003 revealed an unusual, as for stellar objects, spectrum: strong and numerous emission lines of atomes and molecules were superimposed on a weak, early M-type stellar spectrum (Banerjee & Ashok 2004; Tylenda et al. 2005; Kimeswenger 2006).

A detailed study of the emission-line spectrum and the spectral energy distribution (SED) of V4332 Sgr led Kamiński et al. (2010) to conclude that the main remnant of the 1994 eruption is now obscured for us, most probably the central object is embedded in a dusty disc seen almost edge-on. The observed optical spectrum is supposed to be produced by interactions of the central star’s radiation with the matter in the disc and the outflows originating from the 1994 eruption: the M-type continuum results from scattering on dust grains, while the emission-line spectrum is due to resonant scattering by atoms and molecules. This conclusion was subsequently confirmed by polarimetric (Kamiński & Tylenda 2011) and spectropolarimetric (Kamiński & Tylenda 2013) observations, which showed that the optical continuum is strongly polarized, while the emission features are mostly unpolarized.

In the present paper we present an optical spectrum of V4332 Sgr obtained in 2005. The data come from the archives of the Very Large Telescope (VLT) and were nowhere published, as yet. The quality and resolution of the spectrum is exceptional so the data present the best quality spectrum of V4332 Sgr ever obtained. Since 2005, the object has significantly faded (see Fig. 1) and its spectrum has considerably evolved. Therefore the spectrum described and analysed in the next sections presents a unique set of data on V4332 Sgr and this is the main reason, why we have decided to reduce and publish the data.

2. Observations and data reduction

In the ESO Data Archives we have found high resolution spectra of V4332 Sgr carried out with UVES/VLT in 2005 on 22 April and 12 May. The observations were done in the framework of the 075.D-0511 (PI: Banerjee) observing programme. The spectra were obtained with three different spectrograph settings covering the range 3756–10253 Å with two small overlapping regions of 5750–5833 Å and 8520–8656 Å. Technical details of the observations are provided in Table 1.

Figure 1 shows the light curve of V4332 Sgr in the $V$ photometric band since the discovery of the object in February 1994. The data are from the compilation of V. Goranskij. Two vertical dashed lines indicate the time moments of the VLT spectroscopic observations analysed in the present paper and the observations obtained with the Subaru telescope in June 2009 and presented in Kamiński et al. (2010).

One blue and two different red standard UVES configurations were used to observe the target. The observations centered at 8600Å initially splited into two exposures were later merged. Since in the case of the red configurations there are two separate “lower” and “upper” parts the final spectra consists of five independently registered elements. The CCDs were read with 2x2 binning in all configurations. The total useful spectral range covers 3760-9500Å with two small overlapping regions of individual sections and some gaps between lower and upper parts of the red configurations.

From the ESO Data Archive we have downloaded the spectra in their raw, unreduced form together with the full set of reduction and calibration files for each of the standard configurations. The reduction and calibration of the spectra were done with the ESO-MIDAS reduction software.

The background was subtracted from flatfield, arc and science frames. The Th-Ar lamps were used for wavelength calibration. Flatfielding was performed in the pixel-pixel space. The signs of cosmic and other defects of the CCD were removed from each science frame using the standard MIDAS procedures. The extracted spectra were wavelength calibrated and corrected for atmospheric extinction. The flux calibration was performed using the master response calibration files prepared by ESO for each of the standard UVES configurations. The individual heliocentric velocity corrections were applied to each individual spectrum of V4332 Sgr. As a last step the five parts were combined into a single file, averaging the overlapping regions.

\[ http://jet.saao.ru/~goray/v4332sgr.ne3 \]

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Fig. 2. Spectrum of V4332 Sgr obtained in April–May 2005 with the UVES/VLT. The displayed spectrum was smoothed from the original resolution with boxcar 10. The strongest atomic and molecular spectral features are indicated by red and magenta markers, respectively. Blue horizontal bars indicate spectral regions affected by telluric absorption bands.

3. The spectrum

The final flux-calibrated 1D spectrum of V4332 Sgr is presented in Fig. 2. The spectrum above ~8100 Å is not shown in the figure as it is heavily disturbed by telluric absorption lines and shows only a few emission features from the object (see Table 3). The wavelength is given in the heliocentric rest frame and the flux is in the units of $10^{-16}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$. The strongest atomic and molecular features in emission are indicated in the figure.

The atomic lines identification was based mainly on the NIST Atomic Spectra Database (Kramida et al. 2013)\textsuperscript{2}, the Atomic Line List v2.04 by van Hoof\textsuperscript{3}, and on the multiplet tables by Moore (1945). All the identified atomic lines seen in emission in the spectrum of V4332 Sgr are listed in Table 2. The observed wavelengths (in Å) of the lines are given in column (1) of the table, while their laboratory wavelengths and ion identification can be found in columns (2) and (3), respectively. Column (4)

\textsuperscript{2} http://physics.nist.gov/asd
\textsuperscript{3} http://www.pa.uky.edu/~peter/atomic/
Table 1. Log of observations of V4332 Sgr with UVES/VLT

| date & time       | configuration | range(Å)   | resolution | exp. time |
|------------------|---------------|------------|------------|-----------|
| 2005.04.22 06:22:01 | RED 580       | 4727 – 6835 | 42310      | 3000 sec  |
| 2005.05.12 06:10:19 | RED 860       | 6650 – 10250| 42310      | 1480 sec  |
| 2005.05.12 06:10:23 | BLUE 437     | 3730 – 5000 | 40970      | 2960 sec  |
| 2005.05.12 06:43:16 | RED 860       | 6650 – 10250| 42310      | 1100 sec  |

presents the measured fluxes (in units of $10^{-16}$ erg s$^{-1}$ cm$^{-2}$) of the lines with their estimated uncertainties. Column (5) gives the full widths at half maximum (FWHM in Å) of the lines. The last column lists notes on the lines and their measurements. The explanations of the symbols used in Table 2 are given in Table 4.

All the identified molecular bands seen in emission in the spectrum of V4332 Sgr are listed in Table 3. The method used to identify the bands with appropriate references for molecular data can be found in Kamiński et al. (2009) and Kamiński et al. (2010). The first column of the table gives wavelengths of the bands. These are mostly values from laboratory measurements and refer to the heads of the bands. In a few cases the wavelengths come from theoretical estimates. The identification of the bands is provided in column (2), while column (3) displays the measured fluxes (in $10^{-16}$ erg s$^{-1}$ cm$^{-2}$) in the bands with their accuracies. The last column gives notes on the bands and their measurements. The symbols used in these two columns are explained in Table 4.

### 4. Spectral classification of the stellar-like continuum

In order to estimate the spectral type of the stellar-like continuum observed in V4332 Sgr, we attempted to fit standard and model spectra to the results of our observations. Standard stellar spectra were taken from Jacoby et al. (1984), while model atmosphere spectra were obtained using the MARCS grid (Gustafsson et al. 2008).

Fig. 3 shows M2 and M4 giant spectra fitted to the observations. An interstellar reddening was applied to the standard spectra to get a good fit at the short and long wavelength edges of the spectra. These were $E_{B-V} = 0.4$ and 0.15 for the M2 and M4 spectra, respectively. As can be seen from Fig. 3, neither of the two standard spectra satisfactorily fits the observations. The M2 spectrum presents absorption bands somewhat too shallow when compared to the observed continuum, while its flux in the middle spectral region, i.e. between ~5000 Å and ~6500 Å, is systematically too high. On the contrary, the M4 spectrum has too deep absorption bands and its flux in the middle region is too low. The observed continuum generally lies in between the M2 and M4 standard spectra, suggesting that an M3 giant spectral type should satisfactorily reproduce the observations.

Indeed, as shown in Fig. 4, the M3 standard spectrum, as well as the MARCS model spectrum calculated for stellar parameters typical for a M3 (super)giant ($T_{\text{eff}} = 3600$ K, log g = 5.5, Levesque et al. 2005), fit well the observed continuum. Some absorption bands, see e.g. that at ~6200 Å may seem to be too deep in the reference spectra when comparing to the observed one. However in the spectrum of V4332 Sgr these absorption features are partly filled by strong, partly overlapping emissions. Note that both reference spectra shown in Fig. 4 were reddened with $E_{B-V} = 0.35$.

Fig. 3. Standard giant spectra fitted to the observed spectrum of V4332 Sgr (black). Magenta: M2 standard spectrum reddened with $E_{B-V} = 0.4$. Green: M4 standard spectrum reddened with $E_{B-V} = 0.15$.

### 5. Interstellar reddening

The interstellar extinction towards V4332 Sgr was estimated in a number of papers (Martini et al. 1999; Tylenda et al. 2005; Kimeswenger 2006). These results as well as their own determinations were discussed in Kamiński et al. (2010). Most of the estimates relied on a comparison of the observed continuum of V4332 Sgr with stellar standards. Kamiński et al. (2010) finally adopted $E_{B-V} = 0.32$, although the values varied between 0.22 and 0.45. The above value well agrees with our analysis done in Sect. 4 where the best fit to the observed continuum was obtained with a M3 giant spectrum reddened with $E_{B-V} = 0.35$.

However, as proposed in Kamiński et al. (2010) and confirmed by spectropolarimetric observations in Kamiński & Tylenda (2013), the observed stellar continuum in V4332 Sgr is not a direct spectrum of the main, central object but results from scattering the central-star radiation on dust grains. Since scattering on cosmic dust grains usually "blues" the incident spectrum the result of $E_{B-V} = 0.35$ obtained in Sect. 4 as well as that in Kamiński et al. (2010), may be regarded as a lower limit to the reddening of V4332 Sgr.

Kamiński et al. (2010) proposed that the emission features observed in the spectrum of V4332 Sgr result from resonant scattering of the central-star radiation by molecules and atoms in a circumstellar matter. They also concluded that the strongest emission lines, such as Na i 5890, 5896 Å and K i 7665, 7699 Å,
are optically thick in the sense that they scatter all the incident stellar radiation. The main argument was that the observed intensity ratio of the two components of the Na\text{ii} and K\text{i} doublets was close to 1:1, while in the optically thin case this ratio should be 2:1. The spectrum of V4332 Sgr discussed in the present paper shows much more numerous and strong emission features than that of Kamiński et al. (2010). Thus apart from the Na\text{ii} and K\text{i} doublets we can look for other emission lines, which are likely to be optically thick. These are the Cr\text{i} lines at 4254,4275,4290 Å. In the optically thick case the intensity ratio of these lines should be 1.8:1.4:1.0. As can be seen from Table 2 the observed ratio is 1.02:0.89:1.0. Almost certainly the Ca\text{i} lines at 4227 Å is optically thick as it presents the highest value of the product of element abundance and transition probability among all the observed emission features in our spectrum. Finally, the line ratio of the Mn\text{i} lines at 4031,4033,4034 Å suggests that these lines are almost optically thick, at least the first one. The theoretical optically-thin line ratio for these Mn\text{i} lines is 2.0:1.5:1.0. The lines are strongly blended but from the observed profile we can estimate a ratio of 1.4:0.8:1.0.

In this way we have a set of emission lines, whose monochromatic fluxes in central, most opaque regions of their profiles are expected to measure the monochromatic flux from the central star. These lines span a wide spectral region, i.e. 4000–8000 Å, so they can be used to estimate the interstellar reddening when compared to a reference spectrum supposed to represent the spectrum of the central object of V4332 Sgr. This is done in Fig. 5. The lower part of the figure present essentially the same as Fig. 4 (i.e. the standard M3 and model, $T_{\text{eff}} = 3600$ K, spectra reddened with $E_{B-V} = 0.35$ and compared to the observed spectrum) but in the logarithm scale of the flux. The upper plots show the same reference spectra but shifted upwards to match the maximal fluxes of the strongest emission lines. The spectrum of V4332 Sgr (black). Red: M3 standard spectrum, green: model atmosphere ($T_{\text{eff}} = 3600$ K, log $g = 0.5$). Reference spectra in the upper plots are reddened with $E_{B-V} = 0.35$. Reference spectra in the lower plots are reddened with $E_{B-V} = 0.75$ and shifted upward to match the maximal fluxes of the strongest emission lines.

Na\text{i} 5890,5896 Å, and K\text{i} 7665,7699 Å. A pure upward shift did not suffice to fit the level of the maximal fluxes in the lines. It was also necessary to increase the reddening up to $E_{B-V} \approx 0.75$. Thus we can conclude that the emission-line spectrum of V4332 Sgr is significantly more reddened than the stellar-like continuum. As discussed above, the difference in the reddening is most likely due to "bluering" of the stellar continuum being scattered on circumstellar dust grains.

There is however a process, which can affect the relative fluxes of the lines we have used to estimate the reddening of the emission spectrum. All the lines we are considering above are from resonant transitions in atoms. If the lines are optically thick, the resonance photons must suffer from numerous scattering before they escape the emitting region. This increases a chance of being absorbed by dust in the region. Since absorption coefficient of dust grains is expected to increase with decreasing wavelength, the lines at 4000–4300 Å, would suffer more from dust absorption than the lines at 7600–7800 Å. Detailed line transfer calculations are necessary to investigate this effect, which is out of the scope of the present study. In any case the process, if effective, would mimic an additional interstellar extinction. Therefore we conclude the discussion in the present section that the interstellar reddening to V4332 is $0.35 \leq E_{B-V} \leq 0.75$.

6. Radial velocity

All clear absorption features in the spectrum of V4332 Sgr can be identified as molecular bands (mostly TiO). They are wide, shallow, and usually filled near their heads with strong emission components. We were not able to identify any atomic absorption line. Therefore a reliable determination of the radial velocity of V4332 Sgr is not possible on the basis of its absorption spectrum.
Table 2. Components of the interstellar absorption in the profile of the Na$i$ 5890 Å line (see Fig. 6).

| designation | $\lambda_{\text{abs}}$(Å) | $V_r$(km s$^{-1}$) | distance (kpc) |
|-------------|-----------------|-----------------|---------------|
| a           | 5889.779        | $-8.7$          | 0.48          |
| b           | 5890.104        | 7.8             | 2.50          |
| c           | 5890.573        | 31.7            | 4.23          |
| d           | 5890.817        | 44.2            | 4.85          |
| e           | 5891.110        | 59.1            | 5.44          |

However, many of the observed atomic emission lines are relatively narrow (FWHM ≤ 1 Å, see column 5 in Table 2) and they can be used to determine the radial velocity of the object. The strongest emission lines are not particularly suitable for this purpose, as they are wide and their observed wavelengths are poorly determined. We have selected a set of 28 unblended lines of middle intensities. All of them gave consistent values of the radial velocity, ranging between $-82$ and $-69$ km s$^{-1}$. A mean value and a standard deviation derived from this sample are $-75.4 \pm 3.5$ km s$^{-1}$. This value can be compared with $-65 \pm 7$ km s$^{-1}$ obtained in Kamiński et al. (2010) but that was an estimate based on strong and wide emission lines.

In any case it should be noted that the above estimates refer to the line emitting region and it is not clear to what extent they measure the radial velocity of the main, stellar-like object of V4332 Sgr. If the above values measure the real radial velocity of V4332 Sgr than the object does not follow the standard rotation of the Galaxy (see e.g. Brand & Blitz 1993) as for the position of V4332 Sgr the heliocentric radial velocity at any distance is expected to be $\sim -10$ km s$^{-1}$.

7. Interstellar lines and distance to V4332 Sgr

There is no reliable estimate of the distance to V4332 Sgr. Martini et al. (1999) proposed 300 pc assuming that the object was a K-type giant at maximum of the 1994 outburst. Tylden et al. (2005) obtained 1.8 kpc assuming that the progenitor was a solar-type main-sequence star. Kamiński et al. (2006) estimated 2.9 or 10 kpc depending on the assumed luminosity class V or III of the progenitor. Kamiński et al. (2010) derived a kinematic distance $\gtrsim 1.0$ kpc from the radial velocity of the interstellar absorption lines of the Na$i$ 5890, 5896 Å and K$i$ 7665, 7699 Å lines. These authors identified a single component of these lines in their spectrum of V4332 Sgr. Our spectrum is of a much better quality than that of Kamiński et al. (2010) and we can identify several components of the interstellar Na$i$ lines.

Fig. 6 displays observed profiles of the Na$i$ 5890 and 5896 Å lines superimposed in the radial velocity scale. Up to five components of the interstellar absorptions are clearly seen, particularly in the Na$i$ 5890 Å line. They are marked with letters in the figure and listed in Table 2. The observed wavelengths of the individual components were obtained from fitting Gaussian profiles to the observed features. Note that an absorption feature seen at $V_r \approx 110$ km s$^{-1}$ in the Na$i$ 5890 Å line, or at $V_r \approx -195$ km s$^{-1}$ in the Na$i$ 5896 Å line, cannot be of interstellar origin as it has no counterpart in the other line.

The observed wavelengths of the interstellar components given in the second column of Table 2 can be used to calculate heliocentric radial velocities, which are listed in the third column of the table. These values, after being transformed into radial velocities in the LSR frame (adding 12.0 km s$^{-1}$ in the case of the position of V4332 Sgr) and adopting the Galactic rotation curve of Brand & Blitz (1993), give estimates of distances of the interstellar regions responsible for the observed features. The results are listed in the last column of Table 2. From these data we can conclude that V4332 Sgr is at a distance $\gtrsim 5.5$ kpc. This with the galactic latitude of the object ($b = -9^\circ 40$) implies that V4332 Sgr is situated $\sim 0.89$ kpc below the Galactic plane.

8. Evolution of the spectrum of V4332 Sgr between 2005 and 2009

Four years after the spectrum described in this paper had been registered a high resolution spectrum of V4332 Sgr was obtained by Kamiński et al. (2010) using the Subaru telescope. As can be seen from Fig. 4 the object in meantime fainted by $\sim 2$ mag. The MARCS model fit to the observed ones are also plotted in the figure. Note that both model spectra have been reddened with $E_{B-V} = 0.35$. Note also that the model fit to the 2009 spectrum is not perfect in the long-wavelength range. This point, a possible source of extra absorption in the 7300–7500 Å range in particular, was discussed in Kamiński et al. (2010). One of the clear differences between the 2005 and 2009 spectra displayed in Fig. 7 is that the 2009 stellar-like continuum is definitely of a later spectral type than the 2005 one. Indeed, Kamiński et al. (2010) classified the 2009 spectrum as M5-6, while we have concluded with a M3 type in Sect. 4. This has obvious consequences on the effective temperature of the central stellar-like object in V4332 Sgr. Our MARCS model fitted to the observed spectra have $T_{\text{eff}} \approx 3300$ K in 2009 compared to $T_{\text{eff}} \approx 3600$ K in 2005. However, when fitting the model spectra to the observed ones in the flux scale we had to assume that the emitting surface in 2009 increased by a factor of $\sim 2.08$ comparing to 2005. This implies an increase of the effective radius of
the object by a factor of $\sim 1.44$ if a spherically-symmetric case is assumed. The luminosity of the object would thus increase by a factor of $\sim 1.47$ between 2005 and 2009.

Similar conclusions to those drawn above from the optical spectroscopy of V4332 Sgr can be derived from analysing photometric measurements of the object in the optical (BVRI) and near-IR (JHKLM) bands. In Fig. 8 we plot the results of photometric measurements done in 2003 and compiled in Tylenda et al. (2005) (red filled symbols), as well as those obtained in 2009 and given in Kamiński et al. (2010) (blue open symbols). (There were no near-IR measurements of V4332 Sgr in 2003.) The data were fitted with standard stellar photometric spectra supplemented with black-body dust components in the same way as in Tylenda et al. (2005), for details of the fitting procedure see Tylenda (2005). The final fits (sum of the stellar and dust components reddened with $E_{B-V} = 0.35$) are shown with the full curves in Fig. 8. The fit for the 2003 data (red in the figure) is the same as those in Tylenda et al. (2005), see their Fig. 5), i.e. a M2.7 supergiant ($T_{\text{eff}} = 3620$ K according to the temperature scale of Levesque et al. 2005) and a 750 K black-body dust. That for 2009 (blue in the figure) consists of a M6.2 ($T_{\text{eff}} = 3280$ K) supergiant and a 900 K black-body dust. When the luminosities of the components are compared, it appears that both components increased by a similar factor between 2003 and 2009, i.e. the stellar one 1.48 times, while the dust one 1.51 times.

Thus we can quite safely conclude that the optical decline of V4332 Sgr observed between 2005 and 2007 (see Fig. 1) was due to a decrease of the effective temperature of the central stellar-like object by 300–350 K. The object however expanded during this event and its luminosity increased by $\sim 50\%$.

Fig. 7 reveals another important difference between the spectra in 2005 and 2009. In the 2009 spectrum the emission features are significantly fainter than in 2005, not only in absolute flux scale but also relative to the M-type continuum. The scale of fading is however not the same for all the features. The strongest atomic lines, e.g. those of Na i and K i, show a similar strength relative to the local continuum in both epochs. On the other hand, many fainter features clearly present in 2005 completely disappeared in 2009. To investigate the problem more quantitatively, we calculated relative contributions of the emission features to the total flux in selected wavelength ranges in both spectra. For a given wavelength range, we derived $F_{\text{obs}}$ as an integral of the observed flux over the wavelength and $F_{\text{mod}}$ as an integral of the MARCS model flux. We assume that the MARCS spectrum, when fitted to the observed spectrum as in Fig. 7 is a good representation of the stellar-like continuum of V4332 Sgr. Then we can define a parameter $f_{\text{em}} = (F_{\text{obs}} - F_{\text{mod}})/F_{\text{obs}}$ as a measure of the relative contribution of the emission features to the total observed flux.

For the whole spectral range common for both spectra, i.e. 5500–8000 Å, we get $f_{\text{em}} = 0.43$ and 0.25 for the 2005 VLT spectrum and 2009 Subaru spectrum, respectively. Thus the global contribution of the emission spectrum to the total observed flux decreased by $\sim 40\%$ between 2005 and 2009. For narrow spectral ranges encompassing the Na i and K i emission lines, i.e. 5880–5910 Å and 7650–7720 Å, the result is $f_{\text{em}} = 0.93$ and 0.91, respectively, in 2005 compared to $f_{\text{em}} = 0.91$ and 0.89 in 2009. Thus, as stated above, the strongest emission features remain practically at the same level, when compared to the local continuum. For the 6560–6580 Å range, which includes the Ca i line, the figures are $f_{\text{em}} = 0.60$ and 0.49 for 2005 and
2009, respectively. More important fading affected molecular emission features. For series of the TiO bands observed within 6590–6760 Å and 7040–7220 Å we derive \( f_{\text{em}} = 0.27 \) and 0.57, respectively, in 2005, while from the 2009 spectrum the figures are 0.14 and 0.30. In other words, these emission features faded by a factor of 2 relative to the continuum between 2005 and 2009. Even greater fading affected the VO-B-X(0-0) bands gathered between 7850–8010 Å. The result is \( f_{\text{em}} = 0.37 \) and 0.13 (2005 versus 2009) in this case. Thus a general (although not strict) tendency is that the fainter emission feature, the greater fading affects it.

The above behaviour can be easily explained within the scenario proposed by Kamiński et al. (2010), according to which the emission features in V4332 Sgr are produced by radiative excitation of atomic and molecular resonant transitions in a circumstellar matter by strong radiation from the invisible-for-us central stellar-like object. The fading of the emission features can then be understood in terms of a decreasing optical thickness of the circumstellar matter, e.g. due to its expansion. For optically thin transitions the fading would be proportional to the decrease of the optical thickness. However for optically thick lines, as probably the Na i and K i resonant transitions are, a modest decrease of their optical thickness would not affect their observed strengths relative to the continuum. The flux in these lines is limited by the available radiative flux from the central source. Thus these emission features fade proportionally to the incident flux, so their ratio to the observed M-type continuum remains unchanged.

9. Summary and discussion

We have reduced the best quality optical spectrum ever obtained for V4332 Sgr. The spectrum was recorded in April/May 2005 with the VLT/UVES equipment and is unique not only because of its quality but also because the object has considerably evolved since that time. Most of the numerous, in 2005, emission features disappeared, so it will not be possible, in the future, to repeat the observations of the object in a similar stage. Therefore we have decided to reduce and publish the spectrum, so that it is made available for the astrophysical community. In this paper we present the spectrum and results of its measurements and general analysis. Forthcoming papers will be devoted to detailed analysis of the emission features, their profiles, intensities, and chemical species that produce them.

The spectrum is dominated by numerous atomic and molecular emission features superimposed on a M-type continuous spectrum. Among the emission features we have identified over 70 atomic lines belonging to 11 elements (Na, Mg, Al, K, Ca, Cr, Mn, Fe, Rh, Sr, Ba) (see Table 2) and about 140 bands belonging to 6 molecules (AlO, ScO, TiO, VO, CrO, YO) (see Table 3). There is no other late-type stellar object showing that rich and that intense emission spectrum.

The underlying stellar-like continuum in the spectrum of V4332 Sgr can be classified as \( \sim M3 \) (see Sect. 3). A giant spectrum of this spectral type fits the observed continuum quite well. Also a MARCS model spectrum calculated for an effective temperature characteristic of \( \sim M3 \), i.e. \( \sim 3600 \) K, reproduces the observations. Strong molecular emissions partly filling the absorption features in the observed continuum does not allow us to make a more detailed analysis of the stellar-like continuum of V4332 Sgr.

From fitting the standard stellar spectrum as well as the MARCS model spectrum to the observed continuum of V4332 Sgr we have derived an interstellar reddening, \( E_{B-V} \approx 0.35 \) (see Sect. 5). This value is consistent with previous determinations (Tylenda et al. 2005; Kimeswenger 2006; Kamiński et al. 2010). However, since the observed continuum is supposed to result from scattering on dust grains, this value is likely to underestimate the interstellar reddening. Therefore we attempted to estimate the extinction from the strongest emission lines, as the maximum flux in these lines is expected to follow the flux from the central star. Comparing these data with the standard M3 spectrum and the MARCS model we obtained \( E_{B-V} \approx 0.75 \). This value should be regarded as an upper limit to the real reddening because of possible dust absorption effects of multiply scattered resonant-line photons. Thus we concluded that the interstellar reddening of V4332 Sgr is \( 0.35 \leq E_{B-V} \leq 0.75 \).

In Sect. 6 we have derived the radial velocity of V4332 Sgr from a set of relatively narrow middle-intensity emission lines. Our result of \( -75.4 \pm 3.5 \) km s\(^{-1} \) is consistent with the results from other determinations (Martini et al. 1999; Tylenda et al. 2005; Kamiński et al. 2010) in the sense that all of them gave negative values, although the values range between \( -180 \) to \( -56 \) km s\(^{-1} \). As already discussed in Tylenda et al. (2005) these values show that V4332 Sgr does not follow the Galactic rotation curve, as from the latter for the coordinates of the object one would expect a heliocentric radial velocity of \( \geq -10 \) km s\(^{-1} \) for any distance. The problem becomes even more evident if one takes into account the lower limit of the distance derived in Sect. 7 which, assuming the Galactic rotation curve, implies a radial velocity \( \geq 60 \) km s\(^{-1} \). One possible explanation is that what we measure in the emission lines is not a radial velocity of the object but the expansion of the matter ejected in 1994. It is however difficult to understand while, a decade after the eruption, we would not see the receding part of the ejecta, especially if the radial velocity was determined from middle intensity lines, which are expected to be optically thin. Another possibility is that V4332 Sgr is not a Galactic disc object, hence its strange radial velocity. This interpretation would be supported by a relatively large distance of the object from the Galactic plane, i.e. \( \geq 0.89 \) kpc (see Section 7).

Our comparison of the 2005 VLT spectrum to the one obtained in 2009 and described in Kamiński et al. (2010) shows that the M-type continuum evolved from a \( \sim M3 \) spectral type to M5-6, so that the effective temperature of the central stellar object decreased by 300-350 K. The same conclusion also results from photometric measurements done in 2003 and 2009. This relatively small (\( \sim 10\% \)) decrease in the effective temperature is fully responsible for the optical fading of the object observed in 2006. The object however expanded during this event so that its luminosity increased by \( \sim 50\% \). This is evident not only from fitting the optical observations but also from the infrared photometry, which is of particular importance as the infrared emission dominates the observed spectral energy distribution of the object (see e.g. Kamiński et al. 2010). The origin of this behaviour is not clear but it could be a manifestation of a long-term relaxation of the remnant of the presumable merger event in 1994. The main object is embedded in a massive dusty envelope, probably in form of a thick disc. An accretion event from the envelope to the central stellar object can here be invoked.

The good resolution and quality of the spectrum analysed in this paper allowed us to detect several components of the interstellar absorption in the Na i 5890 and 5896 Å lines (see Sect. 7). The radial velocities of these features, if interpreted as due to interstellar matter moving according to the Galactic rotation curve, imply a lower limit to the distance of V4332 Sgr of \( \sim 5.5 \) kpc. This result has important consequences on estimates...
of global parameters of V4332 Sgr. In particular, the luminosity of the object during the 1994 eruption, as obtained from photometric measurements in [Tylenda et al. (2005)], increases now to \( \geq 4.5 \times 10^4 \, L_\odot \), while its effective radius becomes \( \geq 450 \, R_\odot \). These values are not as high as those derived for V838 Mon in its 2002 eruption (see e.g. [Tylenda (2005)], but are of a similar order as those of V1309 Sco in its 2008 eruption (Tylenda et al. 2011).

There are, in fact, other similarities between V4332 Sgr and V1309 Sco. The eruptions of both objects were of a similar time scale, i.e. about one month. That of V4332 Sgr was probably a bit longer as its rising part was not observed. The progenitor of V4332 Sgr was variable and the archive data suggest that it was slowly rising in brightness on a time scale of decades [Kimeswenger (2007), Goranskij et al. (2007)]. This resembles the slow systematic rise of V1309 Sco observed during a few years before its eruption [Tylenda et al. (2011)]. The remnants of both objects are strongly dominated by infrared dust emission [Kamiński et al. (2010), Nicholls et al. (2013)]. Finally, our optical and near-IR spectrum of V1309 Sco obtained in 2012 (unpublished yet) show an emission-line spectrum similar to that of V4332 Sgr although not that rich and intense as in the latter case. Clearly the remnant of V1309 Sco is heavily embedded in dust as in the case of V4332 Sgr. It is thus tempting to suggest that the nature of the progenitor and the eruption of V4332 Sgr was similar to those of V1309 Sco. We know that the eruption of V1309 Sco resulted from merger of a contact binary (Tylenda et al. 2011).

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Table 2. Atomic lines of V4332 Sgr spectrum. Flux is in $10^{-16}$ erg cm$^{-2}$ s$^{-1}$. Wavelengths and FWHM are in Å.

| $\lambda_{\text{obs}}$ | $\lambda_{\text{lab}}$ | identification | flux $\pm$ | FWHM | notes |
|------------------------|------------------------|----------------|-----------|------|-------|
| 3860.47                | 3859.91                | FeI            | 0.37      | 2.1: | f     |
| 3885.48                | 3886.28                | FeI            | 2.12      | 2.55 |       |
| 3922.26                | 3922.91                | FeI            | 1.38      | 2.5: |       |
| 3929.29                | 3930.30                | FeI            | 0.89      | 2.1: |       |
| 3932.86                | 3933.66                | CaII           | 0.77      | 3.4: |       |
| 3943.40                | 3944.01                | All            | 1.07      | 2.3: |       |
| 3960.79                | 3961.52                | All            | 6.64      | 2.70 |       |
| 3967.84                | 3968.47                | CaII           | 1.73      | 3.5: |       |
| 4029.8                 | 4030.75                | MnI            | 11.60     | 5.3: | |B     |
| 4031.8                 | 4033.06                | MnI            | 11.60     | 5.3: | |B     |
| 4033.5                 | 4034.48                | MnI            | 11.60     | 5.3: | |B     |
| 4076.66                | ?                      |                | 0.20      | 0.6: | f     |
| 4170.99                | ?                      |                | 0.58      | 2.5: | f     |
| 4205.66                | 4206.70                | FeI            | 0.20      | 0.9: | f     |
| 4215.16                | 4216.18                | FeI            | 4.39      | 3.17 |       |
| 4226.9                 | 4226.73                | CaI            | 20.17     | 3.31 |       |
| 4253.58                | 4254.33                | CrI            | 18.43     | 3.00 |       |
| 4274.01                | 4274.80                | CrI            | 16.02     | 3.06 |       |
| 4289.08                | 4289.72                | CrI            | 18.04     | 3.17 |       |
| 4336.46                | 4337.57                | CrI            | 0.28      | 0.58 |       |
| 4338.44                | 4339.45                | CrI            | 0.62      | 0.98 | |B     |
| 4339.72                | CrI                    |                |           |      | |B     |
| 4343.39                | 4344.50                | CrI            | 0.34      | 0.66 |       |
| 4349.92                | 4351.05                | CrI            | 0.39      | 0.87 | b     |
| 4350.79                | 4351.76                | CrI            | 0.30      | 0.60 | b     |
| 4359.63                | CrI                    |                |           |      | p     |
| 4370.22                | 4371.26                | CrI            | 0.20      | 0.69 |       |
| 4374.94                | 4375.93                | FeI            | 12.19     | 2.43 |       |
| 4384.98                | CrI                    |                |           |      | p     |
| 4426.23                | 4427.31                | FeI            | 0.47      | 0.58 |       |
| 4460.53                | 4461.65                | FeI            | 0.32      | 0.93 |       |
| 4495.73                | 4496.84                | CrI            | 0.11      | 0.60 |       |
| 4544.72                | 4545.94                | CrI            | 0.25      | 1.2: |       |
| 4552.95                | 4554.12                | Ball           | 0.23      | 0.59 |       |
| 4569.95                | 4571.10                | MgI            | 4.03      | 0.95 |       |
| 4578.87                | 4580.04                | CrI            | 0.16      | 0.67 |       |
| 4599.62                | 4600.74                | CrI            | 0.44      | 1.29 |       |
| 4606.15                | 4607.33                | SrI            | 8.85      | 1.33 |       |
| 4612.29                | 4613.36                | CrI            | 0.20      | 0.92 |       |
| 4614.98                | 4616.12                | CrI            | 0.39      | 0.92 |       |
| 4624.98                | 4626.17                | CrI            | 0.65      | 1.04 |       |
| 4644.99                | 4646.15                | CrI            | 0.86      | 0.98 |       |
| 4650.18                | 4651.28                | CrI            | 0.13      | 0.50 | b,c   |
| 4650.98                | 4652.15                | CrI            | 0.25      | 0.56 | b,c   |
| 4932.87                | 4934.08                | Ball           | 0.33      | 0.59 |       |
| 5109.14                | 5110.41                | FeI            | 28.39     | 1.48 | b     |
| 5166.28                | FeI                    |                |           |      | B,u   |
| 5168.90                | FeI                    |                |           |      | B,u   |
| 5203.07                | 5204.51                | CrI            | 13.93     | 1.29:| b     |
| 5204.68                | 5206.04                | CrI            | 16.17     | 1.22:| b     |
| 5207.04                | 5208.42                | CrI            | 24.17     | 1.37:| b     |
| 5246.23                | 5247.57                | CrI            | 1.15      | 0.91 |       |
| 5262.86                | 5264.15                | CrI            | 2.46      | 0.79 | b,c   |
| 5264.49                | 5265.72                | CrI            | 0.30      | 0.3: | b,c   |
| 5268.27                | 5269.54                | FeI            | 1.05      | 0.61 | c     |
| 5295.34                | 5296.69                | CrI            | 2.53      | 0.97 | b     |
| 5296.94                | 5298.28                | CrI            | 2.31      | 0.77 | b     |
| 5299.18                | 5300.74                | CrI            | 0.73      | 1.5: | b,f   |
| $\lambda_{\text{obs}}$ | $\lambda_{\text{lab}}$ | identification | flux        | FWHM   | notes |
|----------------------|----------------------|----------------|------------|--------|-------|
| 5326.72              | 5328.04              | FeI            | 0.99 ($\pm$0.24) | 1.4: s |       |
| 5344.46              | 5345.80              | CrI            | 4.54 ($\pm$0.16) | 0.93   | b     |
| 5346.94              | 5348.31              | CrI            | 2.93 ($\pm$0.18) | 1.0: b |       |
| 5394.68              | 5391.10              | MnI            | 6.23 ($\pm$0.22) | 0.82   |       |
| 5431.17              | 5432.55              | MnI            | 0.58 ($\pm$0.14) | 0.84 f,c |       |
| 5534.20              | 5535.48              | BaI            | 0.96 ($\pm$0.22) | 1.4:   |       |
| 5666.76              | 5668.28              | MnI            | 0.08 ($\pm$0.05) | 0.3:   | f,c   |
| 5688.96              | 5690.43              | MnI            | 0.21 ($\pm$0.10) | 0.65   | f,c   |
| 5727.10              | 5728.57              | MnI            | 0.43 ($\pm$0.26) | 1.6:   |       |
| 5861.20              | 5862.69              | MnI            | 0.99 ($\pm$0.19) | 1.27 c |       |
| 5889.2               | 5889.95              | NaI            | 252.10 ($\pm$0.60) | 4.0: E,b |       |
| 5894.6               | 5895.92              | NaI            | 183.35 ($\pm$0.40) | 2.8: E,b |       |
| 6279.10              | 6280.62              | FeI            | 0.24 ($\pm$0.06) | 0.4: f,b |       |
| 6328.26              | 6330.09              | CrI            | 0.41 ($\pm$0.18) | 1.3: s |       |
| 6571.10              | 6572.78              | CaI            | 49.19 ($\pm$0.17) | 1.12 B |       |
| 7663.1               | 7664.91              | KI             | 1358.74 ($\pm$2.26) | 3.34 E,b |       |
| 7697.0               | 7698.97              | KI             | 1291.33 ($\pm$2.19) | 3.23 E,b |       |
| 7798.52              | 7800.27              | Rbl            | 37.01 ($\pm$2.10) | 2.11 b |       |
| 7946.14              | 7947.60              | Rbl            | 6.15 ($\pm$0.49) | 1.55 B |       |
Table 3. Molecular bands of V4332 Sgr spectrum. Flux is in $10^{-16}$ erg cm$^{-2}$ s$^{-1}$. Wavelengths are in Å.

| $A_{\text{lab}}$ | Identification | Flux     | Notes |
|------------------|----------------|----------|-------|
| 4470.5           | $\text{AlO}\ B^2\Sigma^+ - X^2\Sigma^+$ (2,0) | 0.38 (±0.06) |       |
| 4494.0           | $\text{AlO}\ B^2\Sigma^+ - X^2\Sigma^+$ (3,1) | 0.28 (±0.05) | f     |
| 4516.4           | $\text{AlO}\ B^2\Sigma^+ - X^2\Sigma^+$ (4,2) | 0.29 (±0.08) | f     |
| 4648.2           | $\text{AlO}\ B^2\Sigma^+ - X^2\Sigma^+$ (1,0) | 9.07 (±0.61) | b     |
| 4672.0           | $\text{AlO}\ B^2\Sigma^+ - X^2\Sigma^+$ (2,1) | 6.43 (±0.55) |       |
| 4694.6           | $\text{AlO}\ B^2\Sigma^+ - X^2\Sigma^+$ (3,2) | 2.26 (±0.60) |       |
| 4715.5           | $\text{AlO}\ B^2\Sigma^+ - X^2\Sigma^+$ (4,3) | 0.62 (±0.42) | f     |
| 4735.6           | $\text{AlO}\ B^2\Sigma^+ - X^2\Sigma^+$ (5,4) |             | p     |
| 4760.9           | $\text{TiO}\ \alpha$ (2,0) $R_2$ | 0.41 (±0.09) | c     |
| 4804.3           | $\text{TiO}\ \alpha$ (3,1) $R_2$ |             | p     |
| 4842.3           | $\text{AlO}\ B^2\Sigma^+ - X^2\Sigma^+$ (0,0) | 43.52 (±0.83) |       |
| 4866.4           | $\text{AlO}\ B^2\Sigma^+ - X^2\Sigma^+$ (1,1) | 16.26 (±0.67) |       |
| 4889.0           | $\text{AlO}\ B^2\Sigma^+ - X^2\Sigma^+$ (2,2) | 3.63 (±0.89) | c     |
| 4954.6           | $\text{TiO}\ \alpha$ (1,0) | 5.02 (±0.51) | c     |
| 4999.1           | $\text{TiO}\ \alpha$ (2,1) | 2.82 (±0.74) | c     |
| 5010.5           | $\text{VO}\ C^4\Sigma^- - X^4\Sigma^+$ (3,0) | 3.23 (±0.20) | s,c   |
| 5079.4           | $\text{AlO}\ B^2\Sigma^+ - X^2\Sigma^+$ (0,1) | 31.41 (±0.90) |       |
| 5102.1           | $\text{AlO}\ B^2\Sigma^+ - X^2\Sigma^+$ (1,2) | 17.71 (±0.92) | b     |
| 5123.3           | $\text{AlO}\ B^2\Sigma^+ - X^2\Sigma^+$ (2,3) | 7.83 (±0.94) |       |
| 5142.9           | $\text{AlO}\ B^2\Sigma^+ - X^2\Sigma^+$ (3,4) | 1.94 (±0.57) |       |
| 5161.0           | $\text{AlO}\ B^2\Sigma^+ - X^2\Sigma^+$ (4,5) |             | p     |
| 5166.7           | $\text{TiO}\ \alpha$ (0,0) | 14.46 (±0.52) |       |
| 5166.3           | Fel | 16.89 | [B] |
| 5168.9           | Fel | 16.89 | [B] |
| 5228.2           | $\text{VO}\ C^4\Sigma^- - X^4\Sigma^+$ (2,0) | 1.15 (±0.32) | f,c   |
| 5275.8           | $\text{VO}\ C^4\Sigma^- - X^4\Sigma^+$ (3,1) |             | p     |
| 5336.5           | $\text{AlO}\ B^2\Sigma^+ - X^2\Sigma^+$ (0,2) | 2.07 (±0.41) | b     |
| 5357.6           | $\text{AlO}\ B^2\Sigma^+ - X^2\Sigma^+$ (1,3) | 2.43 (±0.88) | c     |
| 5376.8           | $\text{AlO}\ B^2\Sigma^+ - X^2\Sigma^+$ (2,4) | 1.61 (±1.13) | f,c   |
| 5448.2           | $\text{TiO}\ \alpha$ (0,1) | 10.13 (±1.42) |       |
| 5469.3           | $\text{VO}\ C^4\Sigma^- - X^4\Sigma^+$ (1,0) | 9.84 (±1.80) |       |
| 5496.4           | $\text{TiO}\ \alpha$ (1,2) | 7.33 (±1.40) |       |
| 5517.3           | $\text{VO}\ C^4\Sigma^- - X^4\Sigma^+$ (2,1) | 1.85 (±0.92) | f,c   |
| 5564.3           | $\text{CrO}\ B^3\Pi_1 - X^3\Pi_1$ (2,0) | 3.79 (±0.97) | [B] |
| 5565.9           | $\text{CrO}\ B^3\Pi_0 - X^3\Pi_0$ (2,0) |             | [B] |
| 5567.7           | $\text{CrO}\ B^3\Pi_1 - X^3\Pi_1$ (2,0) |             | [B] |
| 5570.2           | $\text{CrO}\ B^3\Pi_2 - X^3\Pi_2$ (2,0) |             |       |
| 5576.4           | $\text{CrO}\ B^3\Pi_3 - X^3\Pi_3$ (2,0) |             |       |
| 5736.7           | $\text{VO}\ C^4\Sigma^- - X^4\Sigma^+$ (0,0) | 10.47 (±1.14) | c     |
| 5847.6           | $\text{TiO}\ \gamma'$ (1,0) $F_1 F_1$ | 7.22 (±0.65) | c     |
| 5872.7           | $\text{TiO}\ \gamma'$ (1,0) $F_2 F_2$ | 5.14 (±0.87) |       |
| 5898.9           | $\text{TiO}\ \gamma'$ (1,0) $Q_5 P_3$ |             | p,B   |
| 5821.2           | $\text{TiO}\ \gamma'$ (2,1) $F_2 F_2$ | 1.50 (±0.43) |       |
| 5947.7           | $\text{TiO}\ \gamma'$ (2,1) $R_3$ | 0.90 (±0.35) |       |
| 5954.6           | $\text{TiO}\ \gamma'$ (2,1) $Q_0 P_3$ | 1.74 (±0.37) |       |
| 5972.2           | $\text{VO}\ A^2\Pi_{3/2} - X^2\Sigma^+$ (0,0) | 5.24 (±0.55) |       |
| 6036.2           | $\text{ScO}\ A^2\Pi_{3/2} - X^2\Sigma^+$ (0,0) | 51.23 (±2.02) |       |
| 6051.8           | $\text{CrO}\ B^3\Pi_1 - X^3\Pi_1$ (0,0) | 21.66 (±1.63) | [B] |
| 6053.3           | $\text{CrO}\ B^3\Pi_0 - X^3\Pi_0$ (0,0) |             | [B] |
| 6054.8           | $\text{CrO}\ B^3\Pi_1 - X^3\Pi_1$ (0,0) |             | [B] |
| 6058.5           | $\text{CrO}\ B^3\Pi_2 - X^3\Pi_2$ (0,0) |             | [B] |
| 6063.5           | $\text{CrO}\ B^3\Pi_3 - X^3\Pi_3$ (0,0) |             | [B] |
| 6064.3           | $\text{ScO}\ A^2\Pi_{3/2} - X^2\Sigma^+$ (0,0) $^8R_{1G}$ |             |       |

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Table 3. Continued

| λ_{obs} | identification | flux | notes |
|---------|---------------|------|-------|
| 6072.6 | SeO $\text{A}^2\Pi_{1/2}$-$X^2\Sigma^+$ (1,1) | 2.44 (±0.22) | b |
| 6079.3 | SeO $\text{A}^2\Pi_{1/2}$-$X^2\Sigma^+$ (0,0) | 74.26 (±2.49) | J,B |
| 6086.4 | VO $\text{C}^4\Sigma^+-X^4\Sigma^-$ (0,1) | | J,B |
| 6116.0 | SeO $\text{A}^2\Pi_{1/2}$-$X^2\Sigma^+$ (1,1) | 3.12 (±0.60) | |
| 6132.1 | VO $\text{A}^2\Pi_{1/2}$-$X^2\Sigma^+$ (0,0) | 11.16 (±1.01) | J,B |
| 6138.8 | VO $\text{C}^4\Sigma^+-X^4\Sigma^-$ (1,2) | | J,B |
| 6148.7 | TIO $\gamma'$ (0,0) R_{21} | 1.95 (±0.28) | b |
| 6158.5 | TIO $\gamma'$ (0,0) F_{1}-F_{1} | 63.61 (±1.86) | |
| 6163.2 | TIO $\gamma'$ (0,0) Q_{12} | 2.37 (±0.19) | b |
| 6186.3 | TIO $\gamma'$ (0,0) F_{2}-F_{2} | 37.64 (±1.44) | |
| 6210.8 | TIO $\gamma'$ (1,1) R_{1} | 3.27 (±0.22) | B |
| 6214.9 | TIO $\gamma'$ (0,0) F_{3}-F_{3} | 45.47 (±1.64) | b |
| 6239.0 | TIO $\gamma'$ (1,1) R_{2} | 0.98 (±0.08) | |
| 6242.2 | TIO $\gamma'$ (1,1) Q_{2}, P_{2} | 5.75 (±0.55) | |
| 6268.9 | TIO $\gamma'$ (1,1) F_{3}-F_{3} | 7.30 (±1.07) | b |
| 6321.2 | TIO $\gamma$ (2,0) R_{2} | 0.28 (±0.07) | f |
| 6351.3 | TIO $\gamma'$ (2,2) Q_{3} | 1.33 (±0.46) | c,f |
| 6394.2 | CrO $\text{B}^3\Pi_{1/2}$-$X^3\Pi_{1/2}$ (0,1) | 33.37 (±2.00) | J,B |
| 6396.2 | CrO $\text{B}^3\Pi_{0}$-$X^3\Pi_{0}$ (0,1) | | J,B |
| 6397.8 | CrO $\text{B}^3\Pi_{1/2}$-$X^3\Pi_{1/2}$ (0,1) | | J,B |
| 6401.4 | CrO $\text{B}^3\Pi_{1/2}$-$X^3\Pi_{1/2}$ (0,1) | | J,B |
| 6407.7 | CrO $\text{B}^3\Pi_{1/2}$-$X^3\Pi_{1/2}$ (0,1) | | J,B |
| 6451.7 | CrO $\text{B}^3\Pi_{1/2}$-$X^3\Pi_{1/2}$ (1,2) | 14.65 (±1.92) | J,B |
| 6451.9 | CrO $\text{B}^3\Pi_{0}$-$X^3\Pi_{0}$ (1,2) | | J,B |
| 6455.2 | CrO $\text{B}^3\Pi_{1/2}$-$X^3\Pi_{1/2}$ (1,2) | | J,B |
| 6459.5 | CrO $\text{B}^3\Pi_{1/2}$-$X^3\Pi_{1/2}$ (1,2) | | J,B |
| 6465.4 | CrO $\text{B}^3\Pi_{1/2}$-$X^3\Pi_{1/2}$ (1,2) | | J,B |
| 6477.8 | VO $\text{C}^4\Sigma^+-X^4\Sigma^-$ (0,2) | 5.46 (±1.30) | b |
| 6533.3 | VO $\text{C}^4\Sigma^+-X^4\Sigma^-$ (1,3) | 11.48 (±2.08) | b |
| 6562.6 | TIO $\gamma'$ (0,1) F_{1}-F_{1} | 24.37 (±1.02) | B |
| 6594.0 | TIO $\gamma'$ (0,1) R_{2} | 11.84 (±1.22) | J,B |
| 6597.9 | TIO $\gamma'$ (0,1) Q_{2}, P_{2} | | J,B |
| 6618.0 | TIO $\gamma'$ (1,2) F_{1}-F_{1} | 8.18 (±1.00) | c |
| 6635.4 | TIO $\gamma'$ (0,1) Q_{3}, P_{3} | 5.70 (±0.51) | |
| 6651.3 | TIO $\gamma$ (1,0) F_{3}-F_{3} | 12.07 (±0.66) | c,J,B |
| 6649.8 | TIO $\gamma'$ (1,2) F_{3}-F_{2} | | J,B |
| 6680.8 | TIO $\gamma$ (1,0) F_{2}-F_{2} | 12.58 (±1.50) | J,B |
| 6681.8 | TIO $\gamma'$ (1,2) F_{5}-F_{3} | | J,B |
| 6714.5 | TIO $\gamma$ (1,0) F_{1}-F_{1} | 25.94 (±1.90) | J,B |
| 6717.6 | TIO $\gamma$ (2,1) F_{3}-F_{3} | | J,B |
| 6747.6 | TIO $\gamma$ (2,1) F_{2}-F_{2} | 9.64 (±1.54) | |
| 6772.3 | CrO $\text{B}^3\Pi_{1/2}$-$X^3\Pi_{1/2}$ (0,2) | 24.66 (±1.89) | J,B |
| 6774.2 | CrO $\text{B}^3\Pi_{0}$-$X^3\Pi_{0}$ (0,2) | | J,B |
| 6775.9 | CrO $\text{B}^3\Pi_{1/2}$-$X^3\Pi_{1/2}$ (0,2) | | J,B |
| 6779.6 | CrO $\text{B}^3\Pi_{1/2}$-$X^3\Pi_{1/2}$ (0,2) | | J,B |
| 6781.8 | TIO $\gamma$ (2,1) F_{1}-F_{1} | | J,B |
| 6785.7 | CrO $\text{B}^3\Pi_{1/2}$-$X^3\Pi_{1/2}$ (0,2) | | J,B |
| 6815.1 | TIO $\gamma$ (3,2) F_{2}-F_{2} | 0.51 (±0.18) | f |
| 6830.7 | TIO $\text{b}^3\Pi_{1}$-$X^3\Pi_{1}$ (0,0) R_{12} | 18.24 (±2.45) | J,B |
| 6836.5 | CrO $\text{B}^3\Pi_{1}$-$X^3\Pi_{1}$ (1,3) | | J,B |
| 6836.5 | TIO $\text{b}^3\Pi_{1}$-$X^3\Pi_{1}$ (0,0) Q_{12} | | J,B |
| 6836.6 | CrO $\text{B}^3\Pi_{0}$-$X^3\Pi_{0}$ (1,3) | | J,B |
| 6839.9 | CrO $\text{B}^3\Pi_{1/2}$-$X^3\Pi_{1/2}$ (1,3) | | J,B |
| 6844.5 | CrO $\text{B}^3\Pi_{1/2}$-$X^3\Pi_{1/2}$ (1,3) | | J,B |
| 6850.9 | CrO $\text{B}^3\Pi_{1/2}$-$X^3\Pi_{1/2}$ (1,3) | | J,B |
| 6919.0 | VO $\text{C}^4\Sigma^+-X^4\Sigma^-$ (0,3) | 1.51 (±0.43) | f,E |
| 6976.2 | VO $\text{C}^4\Sigma^+-X^4\Sigma^-$ (1,4) | 1.05 (±0.42) | f,c |
### Table 3. Continued

| $\lambda_{\text{obs}}$ | Identification | Flux | Notes |
|------------------------|----------------|------|-------|
| 7054.2 TiO $\gamma$ (0,0) $F_3-F_3$ | 119.27 (±3.68) | &B |
| 7087.6 TiO $\gamma$ (0,0) $F_2-F_2$ | 118.40 (±3.85) | &B |
| 7125.5 TiO $\gamma$ (0,0) $F_1-F_1$ | 184.10 (±3.67) | &B |
| 7124.9 TiO $\gamma$ (1,1) $F_3-F_3$ | 26.39 (±3.40) | E |
| 7158.8 TiO $\gamma$ (1,1) $F_2-F_2$ | 119.27 (±3.68) | &B |
| 7197.4 TiO $\gamma$ (1,1) $F_1-F_1$ | 33.24 (±2.42) | &B E,s |
| 7196.4 TiO $\gamma$ (2,2) $F_3-F_3$ | 7124.9 TiO $\gamma$ (1,1) $F_3-F_3$ | 0.73 (±0.26) | c,f |
| 7343 VO $B^4\Pi_{3/2}-X^4\Sigma^-$ (1,0) | 14.38 (±2.06) | c |
| 7378 VO $B^4\Pi_{3/2}-X^4\Sigma^-$ (1,0) | 17.74 (±3.61) | c |
| 7408 VO $B^4\Pi_{3/2}-X^4\Sigma^-$ (1,0) | 17.23 (±4.42) | c |
| 7454 VO $B^4\Pi_{1/2}-X^4\Sigma^-$ (1,0) | 21.77 (±3.94) | c |
| 7589.3 TiO $\gamma$ $F_3-F_3$ (0,1) | >14.01 (±0.75) | |
| 7627.7 TiO $\gamma$ $F_2-F_2$ (0,1) | p,u,s |
| 7665.8 TiO $\gamma$ $F_3-F_3$ (1,2) | B,u |
| 7671.6 TiO $\gamma$ $F_1-F_1$ (0,1) | p,B,u |
| 7704.9 TiO $\gamma$ $F_2-F_2$ (1,2) | p,B,u |
| 7743.0 TiO $\gamma$ $F_3-F_3$ (2,3) | p,B |
| 7749.5 TiO $\gamma$ $F_1-F_1$ (1,2) | 27.48 (±3.71) | |
| 7782.8 TiO $\gamma$ $F_2-F_2$ (2,3) | 4.77 (±1.64) | b |
| 7828.1 TiO $\gamma$ $F_1-F_1$ (2,3) | 5.69 (±1.85) | f |
| 7867.1 VO $B^4\Pi_{3/2}-X^4\Sigma^-$ (0,0) | 87.16 (±7.38) | b |
| 7910.4 VO $B^4\Pi_{3/2}-X^4\Sigma^-$ (0,0) | 87.96 (±7.15) | b |
| 7941.9 VO $B^4\Pi_{1/2}-X^4\Sigma^-$ (0,0) | 100.888: (±6.321) | b |
| 7982.6 VO $B^4\Pi_{1/2}-X^4\Sigma^-$ (0,0) | 158.93 (±13.30) | b |
| 8030.3 VO $B^4\Pi_{1/2}-X^4\Sigma^-$ (1,1) | 19.69 (±4.72) | |
| 8433.2 TiO $\epsilon$ (0,0) $R_1$ | 76.36 (±6.87) | &B |
| 8442.3 TiO $\epsilon$ (0,0) $R_2,Q_1,P_1$ | &B |
| 8451.8 TiO $\epsilon$ (0,0) $R_3,Q_2,P_2$ | &B |
| 8462.7 TiO $\epsilon$ (0,0) $Q_3,P_3$ | &B |
| 8682.6 VO $B^4\Pi_{1/2}-X^4\Sigma^-$ (0,1) | 33.45 (±3.67) | c |
| 8736.7 VO $B^4\Pi_{1/2}-X^4\Sigma^-$ (1,2) $R_1$ | 2.62 (±0.66) | f |
| 8760.0 VO $B^4\Pi_{1/2}-X^4\Sigma^-$ (1,2) $P_1$ | 7.58 (±1.70) | c |

### Table 4. Meaning of symbols used in Tables 2 & 3.

- B - measurements refer to the whole blend
- c - uncertain continuum level
- f - faint feature
- s - problem to fit the shape
- b - blended features
- E - very strong blending
- c - corrected for interstellar and/or telluric absorptions
- : - uncertain
- > - lower limit
- p - present or probably present but unmeasurable
- u - unmeasurable (cannot be deconvolved)