

## ORIGINAL ARTICLE

# Study of the variability of Nova V5668 Sgr, based on high-resolution spectroscopic monitoring

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**Background:** We present results of our dense spectroscopic monitoring of Nova V5668 Sgr.

**Materials and Methods:** Starting on March 19, 2015, only a few days after its discovery, we have obtained a series of spectra with the Telescopio Internacional en Guanajuato, Robótico y Espectroscópico telescope and its Heidelberg extended range optical spectrograph échelle spectrograph, which offers a resolution of  $R = 20,000$  and covers the optical wavelength range 3,800–8,800 Å. We performed a line identification of the discernible features for four spectra, which are representative of the respective phases in the light curve evolution of that nova. We simultaneously analyzed the variations in the visual light curve and the corresponding spectra of Nova V5668 Sgr.

**Results:** We found that, during the declining phases of the nova, the absorption features in all hydrogen and many other lines had shifted to higher expansion velocities of about  $-2,000 \text{ km s}^{-1}$ . Conversely, during the rise toward the following maximum, these observed absorption features had returned to lower expansion velocities. We found that the absorption features of some Fe II lines displayed the same behavior, but in addition disappeared for a few days during some declining phases. Features of several N I lines also disappeared, while new N II lines appeared in the emission for a few days during some of the declining phases of the light curve of Nova V5668 Sgr. The shape of the emission features is changing during the evolution, and shows a clear double-peak structure after the deep minimum.

**Conclusions:** Thanks to the dense spectral monitoring we could observe several interesting developments of the Nova V5668 Sgr.

**KEYWORDS**

stars: novae, cataclysmic variables – stars: individual: Nova V5668 Sgr – techniques: spectroscopic – line: identification – line: profiles

## 1 | INTRODUCTION

A white dwarf (WD) in a close binary system can accrete hydrogen from a Roche-lobe-filling companion star. A layer of hydrogen accumulates in an accretion disk and, eventually, on the degenerate surface of the WD. At some point, the hydrogen ignites, and a thermonuclear runaway starts and ejects material from the surface of the WD. These explosive events are observed as classical novae (see Bode, (2010);

Bode & Evans, (2008); Gallagher & Starrfield, (1978); or Payne-Gaposchkin, (1964) for reviews). It is believed that the hydrogen keeps burning on the surface of the WD, as indicated by the detection of X-ray and its light curve. Nova envelopes are usually found to be close to the Eddington limit, and it is likely that this results in a continuous ejection of gas comparable to a very strong stellar wind with the respective expansion velocity profile.

To understand in more detail the physics of this explosive ejection of gas in a nova event, dense spectroscopic monitoring of the nova is an important tool, since whatever is causing rapid changes in the light curve of a nova should also have direct effects on its spectrum on the same very short time scales. Performing the spectroscopic monitoring with high resolution is also desirable in order to observe details in the respective nova absorption and emission features of the characteristic spectral lines. De Gennaro Aquino et al. (2015) studied the bright Nova V339 Del, which appeared in August 2013, based on observations using spectroscopic monitoring with high resolution obtained with the robotic telescope Telescopio Internacional en Guanajuato, Robótico y Espectroscópico (TIGRE) and presented a detailed atlas of lines that show features in the optical spectra of that nova.

On March 15, 2015, a new and very bright classical nova appeared in the constellation of Sagittarius (Williams, Darnley, & Bode, (2015)). The Nova V5668 Sgr has been studied by many observers and also in different wavelength regions. Near-infrared observations clearly show the formation of dust in this nova when it drops to a deep minimum in the light curve after about 90 days after its discovery (Banerjee, Ashok, & Srivastava, (2015); Banerjee, Srivastava, Ashok, & Venkataraman, (2016)). Carbon monoxide has also been detected in its spectra (Banerjee, Ashok, Venkataraman, & Srivastava, (2015)). During the later phases, Nova V5668 Sgr could also be observed in X-rays (Page, Beardmore, & Osborne, (2015); Page, Kuin, Beardmore, Osborne, & Schwarz, (2015); Page, Kuin, Osborne, & Schwarz, (2015)) as well as in  $\gamma$ -rays (Cheung, Jean, Collaboration, F. L. A. T., & Shore, (2015); Cheung, Jean, & Shore, (2015)). The Hubble Space Telescope has observed the nova with observations performed in the ultraviolet wavelength region using the space telescope imaging spectrograph (STIS) instrument (Kuin et al., 2015). Furthermore, polarimetry data have been collected of that nova (Harvey, Berdyugin, & Redman, (2015)). The observations resumed once Nova V5668 Sgr was again observable after its conjunction with the Sun, showing that dust emission is still present but has weakened over the months (Banerjee, Joshi, Srivastava, & Ashok, (2016)).

In this paper, we present the results of our analysis of the spectroscopic monitoring of Nova V5668 Sgr with the TIGRE telescope. We give the details of our observations and a short discussion of the light curve of the nova in Section 2. The results that we obtained from our spectroscopic monitoring of the nova during the different phases of the light curve evolution are shown in Section 3. We close this paper with Section 4, where we present a discussion and our conclusions.

## 2 | OBSERVATIONS OF NOVA V5668 SGR

Starting from March 19 UT, 2015, we observed a dense time series of spectra of Nova V5668 Sgr (Kazarovets & Samus, 2015) —also known as Nova Sagittarii 2015 No. 2

or PNV J18365700-2855420— with the 1.2-m robotic telescope TIGRE situated near Guanajuato, Central Mexico, and equipped with the échelle spectrograph Heidelberg extended range optical spectrograph (HEROS). The time series was interrupted on June 17, when the nova was in a steep decline, about 90 days after its discovery. Between March 19 and June 17, we were able to obtain a total of 46 spectra during the 91 possible days of observation. Starting on July 26, 133 days after discovery, when the light curve of Nova V5668 Sgr had recovered from the deep minimum, we resumed monitoring until October 11, 2015, that is, 210 days after discovery, when the nova was starting to get too close to the Sun and was eventually heading for its conjunction. During this phase, we obtained 26 spectra, which makes a total of 72 spectra of Nova V5668 Sgr.

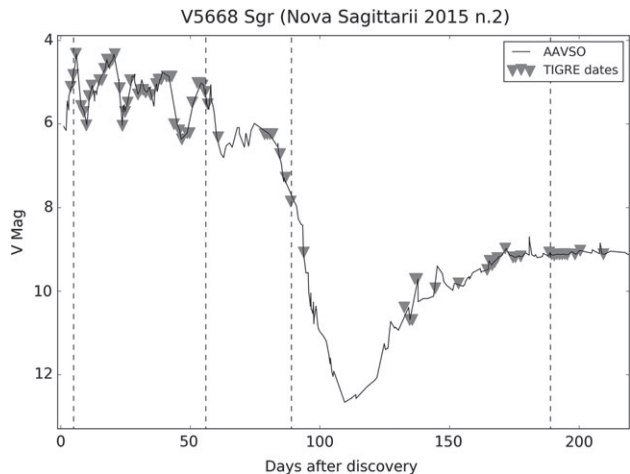
With the échelle spectrograph HEROS, the spectra have a quite high resolution of  $R \approx 20,000$  and cover the optical wavelength range 3,800–8,800 Å, with just a small gap of about 130 Å around 5,800 Å. The spectra were obtained in two channels (red and blue) simultaneously. For the observations, we aimed for exposure times of 1 h to obtain a high signal-to-noise ratio (SNR) of  $> 100$ . The spectra after the deep minimum have only an SNR of  $S/N \approx 15$ , which is due to the lower brightness of the nova and the low continuum emission during that phase. However, the emission lines in the spectra show an SNR that is significantly higher, therefore still allowing the studies of these features in detail. Since TIGRE is a robotic telescope, the observations and data reduction were performed automatically. It needs to be stated that we could not calibrate the observed spectra for absolute fluxes, but we were able to obtain all the spectra with relative fluxes. For a more detailed technical description of the TIGRE instrumentation and its capabilities, see Schmitt et al. (2014). The TIGRE telescope, although originally not designed for it, has turned out to be very useful for spectroscopic monitoring of high-energy astrophysical events like novae (De Gennaro Aquino et al., 2015) and supernovae (Jack et al., 2015).

Nova V5668 Sgr also has been observed with an even higher resolution of  $R \approx 60,000$  by Tajitsu et al. (2016), but they only obtained one spectrum on May 29 and, therefore, did not perform a dense spectroscopic monitoring, which is the major advantage of our observation campaign. Observations with the PEPSI spectrograph and a resolution of  $R \approx 270,000$  have also been reported (Wagner et al., 2016).

### 2.1 | Visual light curve

Figure 1 shows the visual light curve of Nova V5668 Sgr starting from its day of discovery until the beginning of November 2015, when the nova started to get too close to the Sun for further observations. The data points were taken from the American Association of Variable Star Observers (AAVSO) database,<sup>1</sup> and March 15, 2015 was taken as day

<sup>1</sup><http://www.aavso.org>



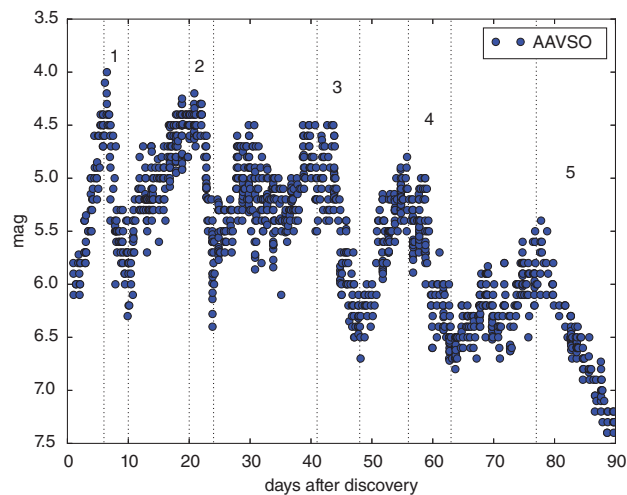
**FIGURE 1** Visual light curve of Nova V5668 Sgr after its discovery on March 15, 2015. The data points were taken from American Association of Variable Star Observers (AAVSO) observations. The vertical lines indicate the days on which we performed a thorough line identification. The triangles mark the days on which we obtained Telescopio Internacional en Guanajuato, Robótico y Espectroscópico (TIGRE) spectra.

zero after the discovery. The triangles mark the days on which we obtained spectra with the TIGRE telescope. As can be seen in the graph, during the first 90 days, there were significant variations in the light curve of up to 2 mag, while the magnitude stayed more or less between 5 and 7 mag. This phase will be discussed in detail in Section 2.2. After the variation phase, the light curve of Nova V5668 Sgr shows a very steep decline down to a minimum with a magnitude of  $\approx 13.5$  mag. After this deep minimum, the visual light curve rose again up to a magnitude of  $\approx 9$  mag. The light curve then stayed almost constant, and subsequently declined very slowly. The vertical lines in Figure 1 mark the days after discovery on which we performed a detailed line identification in the observed spectra (see Section 3.1.1).

The observed visual magnitude during the first maximum of Nova V5668 Sgr is about 4.2 mag. Using the accurate charge-coupled device measurements of the AAVSO database, the color in  $B - V$  is found to be 0.26 mag during the first days. During this phase, the intrinsic  $(B - V)_0$  due to an effective temperature of  $\approx 9000$  K is about 0.05 mag. This gives an estimate of the interstellar extinction of  $E(B - V) = 0.21$  mag, which corresponds to a moderate extinction of  $A_V = 0.7$  mag. Assuming an absolute magnitude of  $M_{\text{vis}} \approx -7.5$  mag, like the one observed for DQ Her, we obtain a distance modulus of 11.0 mag, which places the Nova V5668 Sgr at a distance of about 1.6 kpc. Banerjee, Srivastava, et al. ((2016)) determined the distance to Nova V5668 Sgr to have a value of 1.54 kpc and state that this is in good agreement with the maximum magnitude vs. rate of decline (MMRD) estimate using the relation of della Valle and Livio (1995).

## 2.2 | Light curve variation phase

In Figure 2, the visual light curve of Nova V5668 Sgr is shown for the first 90 days after its discovery. The data points were



**FIGURE 2** Visual light curve of Nova V5668 Sgr during the first 90 days after its discovery on March 15, 2015. The data points were taken from AAVSO observations. Five clear declining phases have been identified.

taken from AAVSO observations. This part of the light curve shows five clear declining phases that are indicated in the graph. These declines occur during just few days and are also, in general, steeper than the following phases of increasing brightness. We will study the corresponding changes that are observed in the optical spectra in the following section.

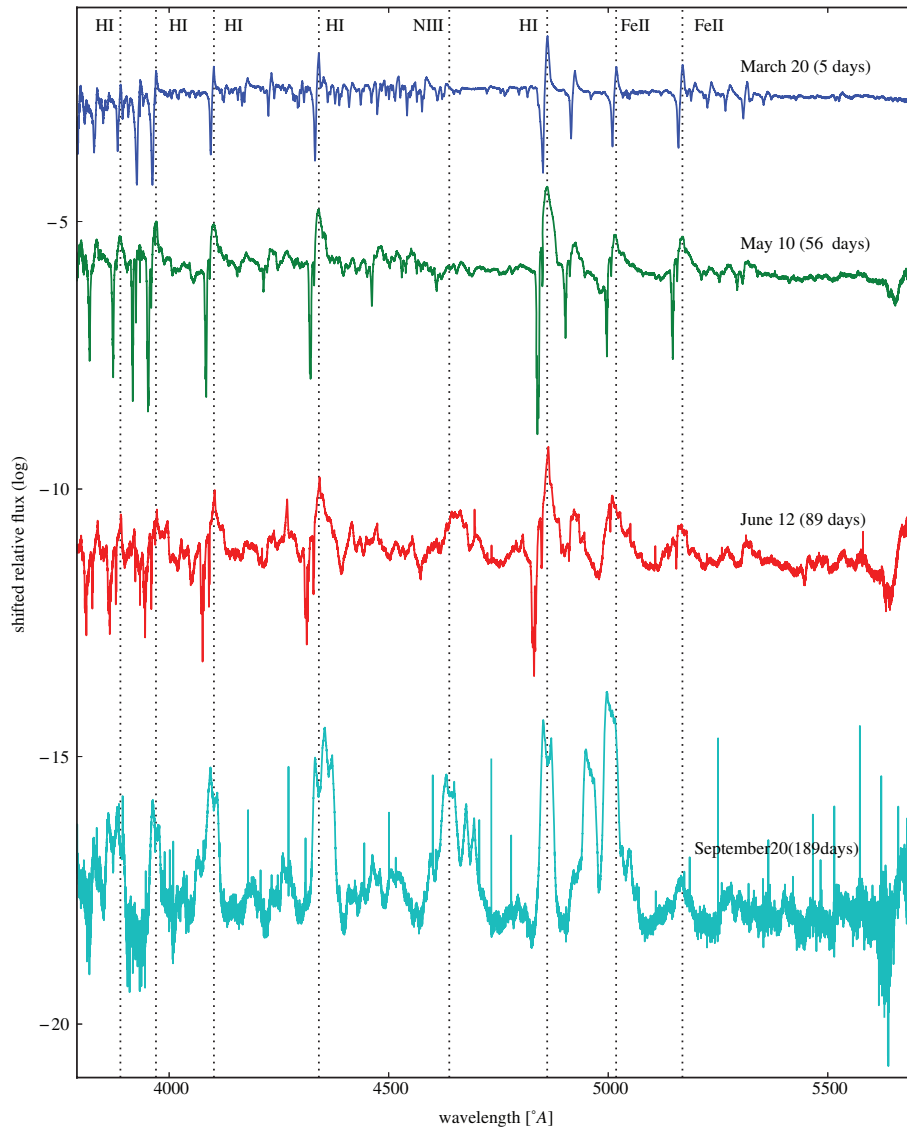
In comparison with that of other novae, the light curve of Nova V5668 Sgr displays the typical characteristics of the very bright Nova DQ Herculis from 1934 (Gaposchkin, 1956), with many variations during a long period and a final decline around 90 days after discovery. After a deep minimum, the light curve recovers to show a very slow declining phase. See also Strope, Schaefer, and Henden ((2010)) for other novae of that type and with similar light curves.

## 3 | SPECTROSCOPIC MONITORING OF NOVA V5668 SGR

Our spectroscopic monitoring of Nova V5668 Sgr covers all different phases of the light curve evolution as presented above. In this section, we first present four of our high-resolution spectra taken at very different stages of the outburst, along with detailed line identification. We then offer a detailed analysis of the spectra of Nova V5668 Sgr and their evolution until after the deep minimum of the light curve, when all lines are seen only in emission.

### 3.1 | High-resolution spectroscopic monitoring

Figure 3 shows four spectra of the nova observed in the blue channel of the HEROS spectrograph between 3,800 and 5,800 Å. The spectra were taken at the dates indicated in the graph. To represent the different phases of the nova, we chose a spectrum during the first maximum, as well as two spectra during the variation phase: one during a maximum, the other when the light curve was declining toward the big minimum.

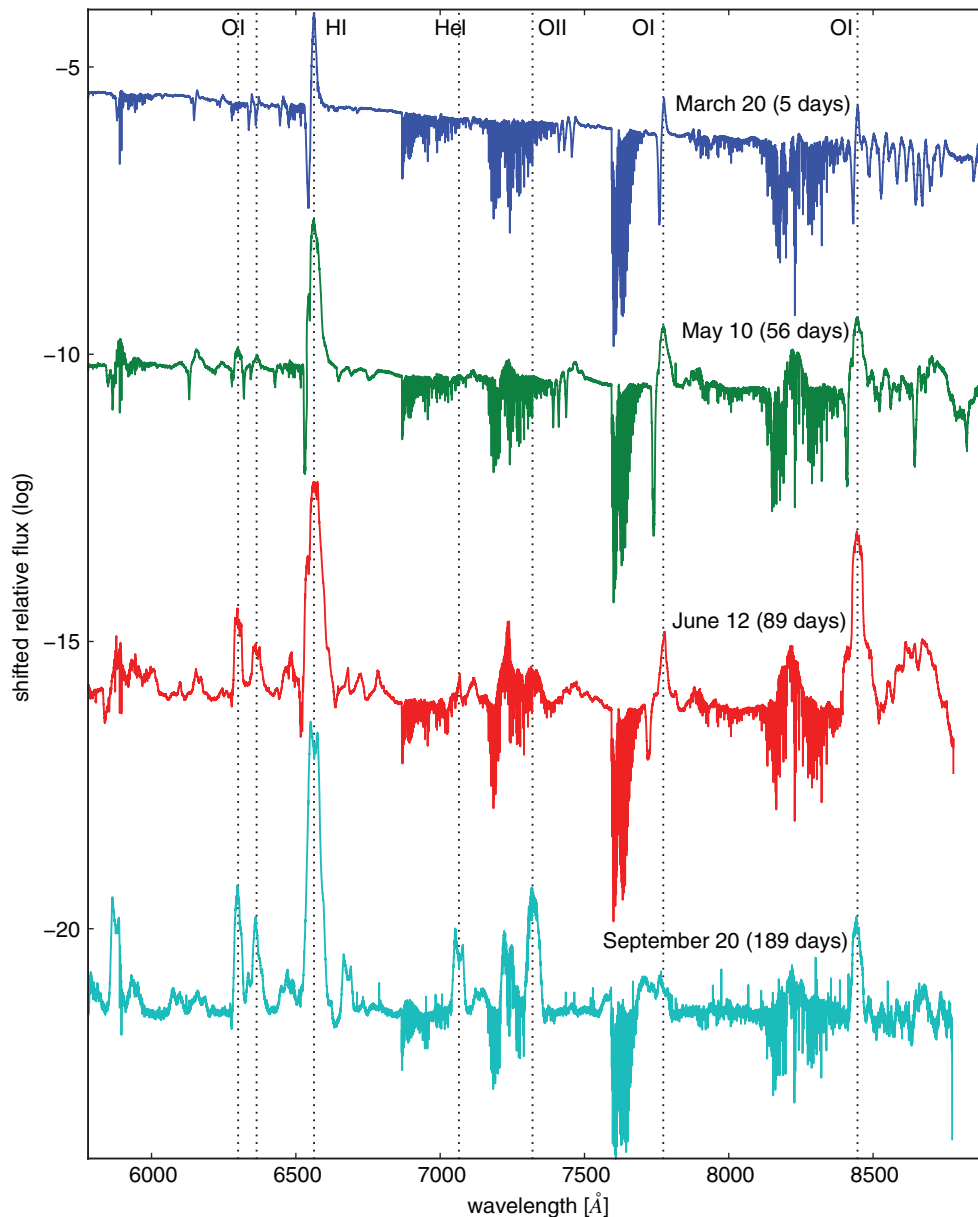


**FIGURE 3** Four spectra of Nova V5668 Sgr observed in the blue channel of the Heidelberg extended range optical spectrograph (HEROS) spectrograph. Dates are of 2015, and the corresponding days after discovery are given in brackets.

The fourth spectrum was taken after the minimum during the emission line or dust phase. In Figure 1, the corresponding days after discovery are marked by vertical lines.

The first spectrum presented was taken on March 20, 2015, which corresponds to 5 days after the discovery when the nova was around its maximum brightness. The spectrum shows the characteristic P Cygni profile features that one expects during this phase. We have marked some of the strongest and most important features in the spectrum with vertical lines at their respective rest wavelengths. All features show the emission peak at around the rest wavelength and a blue-shifted absorption feature corresponding to a negative expansion velocity caused by the ejected gas of the nova event that is moving toward the observer. Features of all the hydrogen Balmer lines that can be observed in this wavelength range are clearly visible ( $H\beta$  at 4,861 Å,  $H\gamma$  at 4,341 Å,  $H\delta$  at 4,102 Å, etc.). Two clear Fe II features are also marked in Figure 3, but there are many more iron lines present in the spectrum (see Section 3.1.1 for a detailed list of identified

lines). The second spectrum presented was taken on May 10 during the light curve variation phase around the fourth maximum, 56 days after discovery. All Balmer lines are still present, but the line profiles have already changed. The emission features are now broader, and the absorption features are still present. Looking closely, one can see that there are now two distinct absorption features in most of the lines. On June 12, we took the third spectrum presented here. It was taken 89 days after its discovery when the light curve was in the steep decline toward the deep minimum. The Balmer lines show mainly emission features but still have some absorption features, while the marked features of the Fe II lines are present only in the emission. In the last presented spectrum, which was observed after the deep minimum 189 days after discovery on September 20, no absorption features were found, but some new emission lines appeared, such as the one at 4,638.0 Å, presumably due to N III, as can be seen in Figure 3.



**FIGURE 4** Four spectra of Nova V5668 Sgr observed in the red channel of the HEROS spectrograph. Dates are of 2015, and the corresponding days after discovery are given in brackets. Broad bands of telluric lines are present in this wavelength range.

In Figure 4, we present four spectra of Nova V5668 Sgr observed by the TIGRE telescope and in the red channel of the HEROS spectrograph in the wavelength range from 5,800 to 8,800 Å. The spectra were taken on the same days as those presented in Figure 3 and as indicated by the vertical lines in Figure 1. Comparing the spectra of the two channels, it can be seen that the spectra of the red channel show fewer features than those in the blue channel. The observations in the red channel are affected by telluric lines, which we did not get removed in our spectra. In the spectra, the telluric lines are visible in Figure 4 around the wavelength ranges 6,800–7,300 Å, 7,600–7,700 Å and 8,000–8,400 Å. The first spectrum in Figure 4 from March 20 shows features of lines with clear P Cygni profiles, as was already observed in the blue channel. Strong lines are H  $\alpha$  at a wavelength of 6,562.7 Å and an O I line at 7,773.0 Å. The lines in the sec-

ond spectrum from May 10 still show P Cygni profiles, but the emission features are now broader than before. In the H  $\alpha$  line, there appeared an additional small absorption feature that can also be seen in the two strong lines of O I marked in the spectrum. In the third spectrum from June 12, the line profiles have started to change to present now mainly emission features, but some lines still show absorption features. Two new clear emission features of the [O I] at wavelengths 6,300.3 and 6,363.7 Å appear in the spectrum and are still visible in the fourth presented spectrum from September 20. There also arises a new emission feature of the [O II] line at 7,320.0 Å, which is clearly visible in this last spectrum. In the spectrum from June 12, there are too many telluric lines in that wavelength region so that a clear identification is difficult. A further new strong emission feature in this spectrum is the He I line at 7,065.2 Å, which is also present in the

spectrum of Nova V5668 Sgr from September 20, which was observed after the deep minimum 189 days after the discovery. As one can clearly see, many of the emission features have a double-peak shape.

### 3.1.1 | Line identification

The four selected characteristic spectra described above were used to identify all the lines that show spectral features. For this thorough analysis, we made use of the spectral atlas in De Gennaro Aquino et al. (2015), which was obtained from observations with the same telescope using spectra of Nova V339 Del. In Table 1 for the blue and Table 2 for the red channel, we list all the identified lines for which we found features in the respective spectra. The tables are sorted by the rest wavelength of the lines, and it contains also the element and ionization stage to which the line belongs. Tick marks indicate the four spectra in which the presence of a feature was clearly identified.

The first spectrum around the first maximum brightness contains the largest number of lines with features in Nova V5668 Sgr. We found many Balmer and also Paschen lines of hydrogen as well as Fe II lines and strong lines of O I in the spectra of the nova. Additionally, we could identify some lines of Ti II, Mg II, Si I, Si II, N II, and Na I, among others. The hydrogen lines are present in all of four spectra. Other lines like some of Fe II could only be observed in the first spectra of Table 1 and then disappeared in the later spectra. There are also lines that were not observed in the first spectra but appeared in the later ones. These are some lines of He II, O III, and N III, among others. We could also identify some forbidden lines of oxygen ([O I] and [O II]), which appear in the later spectra when the nova is in its optically thin nebular phase after the deep minimum. There might also be forbidden lines of nitrogen present in the spectra of Nova V5668 Sgr. These lines are [N II] at 6,548 Å and [N II] at 6,583 Å. However, the possible features of these lines coincide with the broad emission feature of H $\alpha$ , and it is difficult to clearly identify them. Figure 11 might indicate the possible presence of these [N II] lines.

### 3.2 | The light curve variation phase

During the light curve variation phase, we have recorded the optical spectra of Nova V5668 Sgr between 4 and 94 days after discovery covering all five clear declining phases, as indicated in Figure 2. This dense spectroscopic time series enables us to relate the spectral evolution directly to the changes seen in the visual light curve and may reveal the physical circumstances during this phase of small variations in the light curve.

A general observation during all of the declining phases of the nova is that, when the light curve decreases, the continuum flux decreases as well. The same occurs also during the rising phases of the light curve, namely the continuum flux

**TABLE 1** List of lines in the blue channel that have been identified in four selected spectra of Nova V5668 Sgr during characteristic light curve phases

Line (Å)	Element	March 20	May 10	June 12	September 20
3,835.4	H I	✓	✓	✓	✓
3,856.0	Si I	✓			
3,862.6	Si I	✓			
3,889.1	H I	✓	✓	✓	
3,900.5	Ti I	✓			
3,906.0	Fe II	✓			
3,913.5	Ti II	✓			
3,933.7	Ca II	✓	✓	✓	
3,968.5	Ca II	✓	✓		✓
3,970.1	H I	✓	✓	✓	
3,995.0	N II			✓	
4,077.7	Sr II			✓	
4,101.7	H I	✓	✓	✓	✓
4,130.9	Si II	✓	✓		
4,173.5	Fe II	✓			
4,178.9	Fe II	✓			
4,233.2	Fe II	✓	✓	✓	✓
4,267.2	C II			✓	
4,303.2	Fe II	✓	✓		
4,340.5	H I	✓	✓	✓	✓
4,351.8	Fe II	✓	✓		
4,385.4	Fe II	✓			
4,416.3	Fe II	✓			
4,416.8	Fe II		✓	✓	
4,471.5	He I			✓	
4,481.2	Mg II	✓	✓	✓	
4,491.4	Fe II	✓	✓		
4,514.9	N III			✓	
4,522.6	Fe II	✓			
4,549.5	Fe II	✓			
4,555.8	Fe II	✓	✓		
4,572.0	Ti II	✓	✓		
4,583.8	Fe II	✓	✓		
4,629.3	Fe II	✓	✓		
4,638.0	N III			✓	✓
4,685.8	He II				✓
4,824.1	Cr II	✓			
4,861.3	H I	✓	✓	✓	✓
4,923.9	Fe II	✓	✓	✓	
4,923.9	Fe II	✓	✓	✓	
5,006.8	O III			✓	✓
5,018.4	Fe II	✓	✓		
5,045.1	N II	✓			
5,169.0	Fe II	✓	✓		
5,197.6	Fe II	✓			
5,234.6	Fe II	✓	✓		
5,276.0	Fe II	✓	✓		
5,316.6	Fe II	✓	✓		
5,362.8	Fe II	✓			
5,532.1	Fe II	✓			

**TABLE 2** List of lines in the red channel that have been identified in four selected spectra of Nova V5668 Sgr during characteristic light curve phases

Line [Å]	Species	Mar. 20	May 10	Jun. 12	Sep. 20
5,875.6	He I			✓	
5,889.9	Na I	✓	✓	✓	✓
5,895.9	Na I	✓	✓	✓	✓
6,247.6	Fe II	✓			
6,300.3	[O I]		✓	✓	✓
6,347.1	Si II	✓			
6,363.7	[O I]				✓
6,371.4	Si II	✓			
6,456.4	Fe II	✓	✓		
6,562.7	H I	✓	✓	✓	✓
7,065.2	He I			✓	✓
7,115.0	C I		✓		
7,320.0	[O II]				✓
7,442.3	N I	✓			
7,468.2	N I		✓		
7,773.0	O I	✓	✓	✓	
8,446.3	O I	✓	✓	✓	✓
8,498.0	Ca II	✓	✓		
8,542.1	Ca II	✓	✓		
8,598.4	H I	✓			
8,629.2	H I	✓			
8,750.5	H I	✓			
8,862.8	H I	✓	✓		

increases. Although we do not have flux-calibrated spectra, we find that during declining phases the emission line flux increases relative to that of the continuum. This rules out the possibility that the changes in the light curve are only due to changes in the emission line profiles, and is consistent with the constant color in the AAVSO light curve of Nova V5668 Sgr. In addition, we observed that some spectral features undergo significant changes as well. These allow the study of the physical properties of the envelope during variations in the visual light curve. It needs to be emphasized that this is possible only due to the dense time series of high-resolution spectra, which we obtained with the TIGRE telescope.

Regarding the spectra observed during the first maximum in the visual light curve, before the maximum the lines in the observed spectra show clear P Cygni profile features, which are caused by an optically thick expanding envelope, as is the case for a nova. After the first maximum, the nova seems to change into its transition phase. The spectra are now showing more complex features, which are also beginning to change into emission. This is the typical behavior of a classical nova, and the first maximum of the light curve of Nova V5668 Sgr can be understood in this normal context as well. However, one (and only one) forbidden line of O I already appears in the spectra of the nova at that time (see Section 3.2.4).

As is typical for DQ Her-type novae, the visual light curve rises again after the first declining phase. In our time series

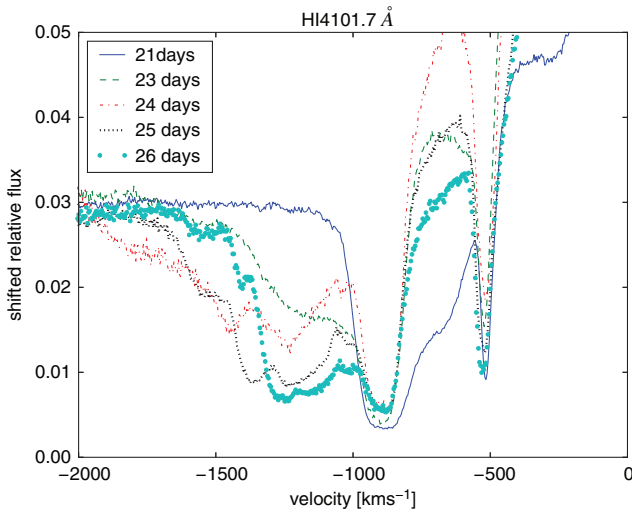
**TABLE 3** List of lines that show absorption features moving to higher expansion velocities during the second to fifth declining phase of the visual light curve of Nova V5668 Sgr

Species	Line (Å)	2	3	4	5
H I	3,835.4		✓	✓	✓
H I	3,889.1	✓	✓	✓	✓
Ca II	3,933.7	✓			
Ca II	3,968.5	✓	✓	✓	✓
H I	4,101.7	✓	✓	✓	✓
H I	4,340.5	✓	✓	✓	✓
H I	4,861.3	✓	✓	✓	✓
Fe II	4,923.9	✓			
Na I	5,895.9	✓	✓	✓	✓
H I	6,562.7		✓	✓	✓
He I	6,678.2	✓	✓	✓	✓
He I	7,065.2	✓	✓	✓	✓
O I	7,773.0	✓	✓	✓	✓
H I	8,862.8	✓			

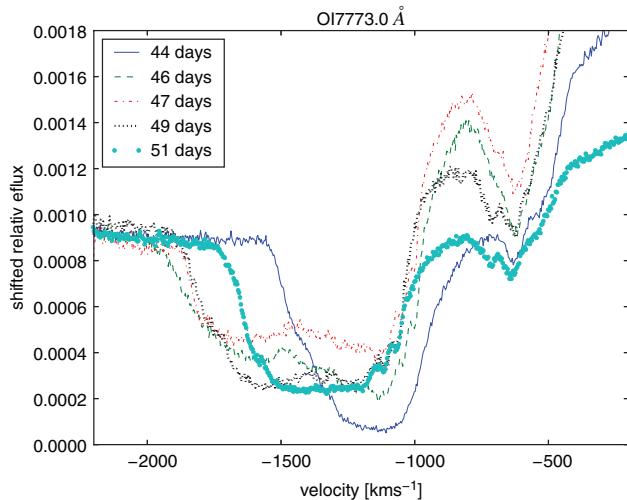
of the spectra, we see that, when the nova brightness declines steeply after its second maximum, the absorption features shift to notably higher expansion velocities in several lines. Table 3 gives a list of lines which have features that show clearly this behavior during the various declining phases toward the following minima. The Na I D doublet also shows the high expansion velocity absorption trough, but it needs to be stated that the two individual lines are overlapping and that there is also a He I line at 5,875.6 Å in the same wavelength range that could have been blended into this features. There are other lines, probably more Fe II lines, that showed this behavior, but it was not clearly seen in our spectra because of a low SNR or other reasons. We have listed only the lines whose behavior could be definitely seen.

As an example of the different lines that show the described behavior, we present in Figure 5 the changes observed in the H  $\delta$  line at the wavelength 4,101.7 Å. We concentrate on the negative expansion velocity part of the line profile and ignore the emission part of the line which has its maximum around the rest wavelength at 0 km s<sup>-1</sup>. Twenty-one days after the discovery, the light curve is still in its secondary maximum, and the spectrum displays only absorption features below an expansion velocity of  $\approx -1,000$  km s<sup>-1</sup>. These absorption features then shift to expansion velocities between  $-1,500$  and  $-1,000$  km s<sup>-1</sup>, and during the minimum of the light curve 24 days after discovery, these features reach their maximum expansion velocities of over  $-1,500$  km s<sup>-1</sup>. During the following rise, they shift slowly toward slower expansion velocities. The absorption feature at  $\approx -500$  km s<sup>-1</sup> can also be observed in many different lines. However, it does not seem to change its position during the light curve variations.

As a representative example for the third declining phase, we show in Figure 6 the spectral evolution of the O I line at 7,773.0 Å. Forty-four days after discovery, during the third maximum, absorption features between  $-1,500$  and



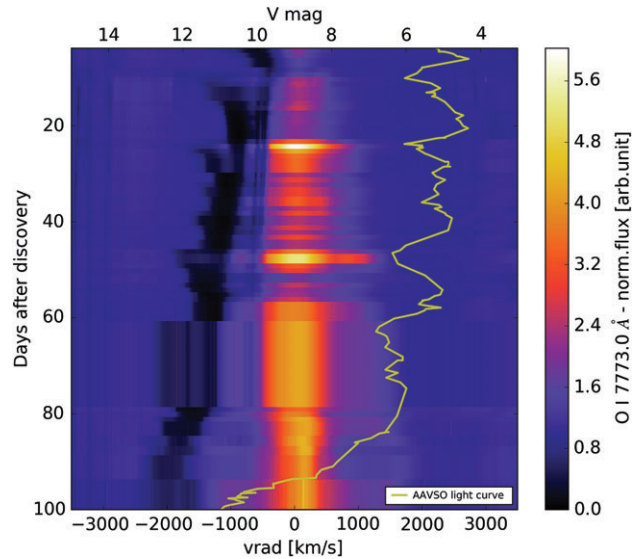
**FIGURE 5** Evolution of the H I line at the wavelength 4,101.7 Å during the second minimum phase observed in the visual light curve of Nova V5668 Sgr. The spectra shown are of different days after discovery.



**FIGURE 6** Evolution of the O I line at the wavelength 7,773.0 Å during the third minimum phase observed in the visual light curve of Nova V5668 Sgr. The spectra shown are of different days after discovery.

$-1,000 \text{ km s}^{-1}$  were observed. During the following minimum, 46 days after discovery, absorption features appear at expansion velocities between  $-2,000$  and  $-1,500 \text{ km s}^{-1}$  and shift during the following rise to smaller expansion velocities, as can be seen in the spectra of 49 and 51 days after discovery.

During the fourth declining phase, we observed the nova 56 and 57 days after discovery, that is, during the maximum phase. Because of bad weather and scheduled maintenance of the telescope, we obtained only one spectrum during the declining phase, 61 days after discovery. However, we could again observe high-velocity absorption features appearing in some of the lines, this time at relatively high expansion velocities of between  $-2,500$  and  $-2,000 \text{ km s}^{-1}$ . Unfortunately, we cannot say anything about the subsequent behavior of these features since we did not cover the following rising phase of the visual light curve. The observed expansion



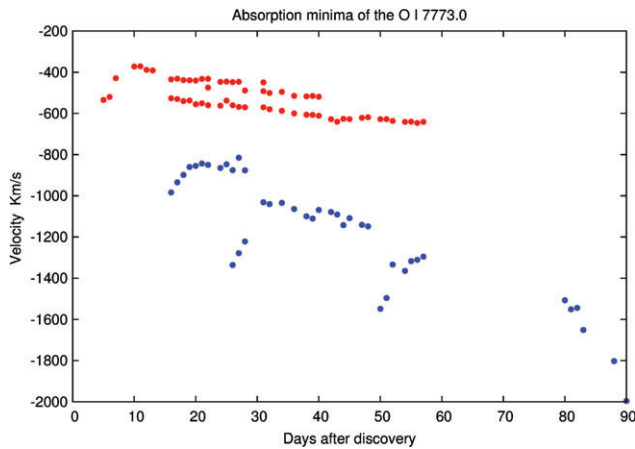
**FIGURE 7** Evolution of the O I line profile at the wavelength 7,773.0 Å during the light curve variation phase of the visual light curve (continuous line) of Nova V5668 Sgr during the first 100 days after discovery.

velocities of the absorption features during the fifth declining phase move to between  $-2,100$  and  $-1,700 \text{ km s}^{-1}$ . This fifth declining phase has eventually a steep decline down to the deep minimum in the light curve of Nova V5668 Sgr.

As a further illustration, we present the complete evolution of the O I line at 7,773.0 Å during the whole light curve variation phase covering the observed spectra of the first 100 days after discovery. Figure 7 shows the variations in expansion velocities of the respective absorption features. The variations in the light curve can be directly related to these changes in the expansion velocities. Figure 7 is also a great visualization that the Nova V5668 Sgr shows all the classical systems of spectra, which are principal, diffuse enhanced, and Orion (Kuiper & Greenstein, 1960; McLaughlin, 1943; 1944).

To further illustrate and quantify the behavior of the absorption features, we measured the expansion velocity of the respective minima for each day in the O I line at 7,773.0 Å. We used this line because it showed a simpler structure than the hydrogen lines, which have various subfeatures and on some days many more minima. In Figure 8, we show a graph of the position of all the minima of the absorption features of the O I line. There is one group of minima at around  $-500 \text{ km s}^{-1}$  (red circles), which slowly changes position to higher negative expansion velocity. This group of absorption features disappears later, but because of an observation gap, we cannot determine on which day this happens. The other group of absorption features can be found between expansion velocities  $-1,000$  and  $-2,000 \text{ km s}^{-1}$  (blue circles). While the slow expansion velocity group does not display large changes, the group of higher velocity illustrates quite well the changes that occur during a change in the visual light curve, as can be seen in Figure 2. Comparing the graph of the absorption feature minima with the visual light curve, one finds a good agree-





**FIGURE 8** Evolution of the expansion velocities of the minima of the absorption features of the O I line at 7,773.0 Å. There are two groups of minima, one at around 500 km s<sup>-1</sup> and the other between 1,000 and 2,000 km s<sup>-1</sup>.

ment. When the light curve is in a minimum, the velocity of the absorption feature minimum also jumps to higher negative expansion velocities. During the following rise in the light curve, this absorption feature moves back to lower negative velocities. The overall trend shows that, while the visual light curve slightly decreases during the variation phase of 90 days, the absorption features also move to higher negative expansion velocities. When the light curve eventually shows the steep decline toward the deep minimum, the expansion velocities of the absorption feature also move to significantly higher negative values.

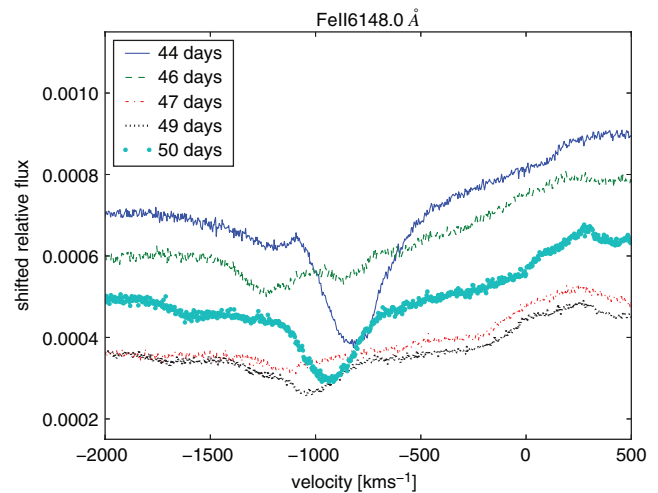
### 3.2.1 | Appearance of He I features

The list of lines that have features, that is, showing the characteristic behavior of Table 3, contains two He I lines at wavelengths 6,678.2 and 7,065.2 Å. These two lines were not observed during the maximum before the second declining phase. Instead, they appear in emission and show the high expansion velocity absorption component only during the secondary minimum phase. This means that only the respective He I lines get excited and become visible during this second minimum phase.

During the third minimum phase, the absorption features of these lines were already observed during the maximum before, and show the same shift in expansion velocity as the features of the other lines. In the few spectra that we could obtain during the fourth declining phase, we observed the same behavior. During the fifth declining phase, the lines already show absorption features during the maximum, which then shift during the declining phase to higher expansion velocities.

### 3.2.2 | Disappearance of Fe I features

During the third declining phase of the visual light curve of Nova V5668 Sgr, the features of the Fe II line at the wave-



**FIGURE 9** Evolution of the absorption features of the Fe II line at 6,148.0 Å during the third minimum phase of the visual light curve of Nova V5668 Sgr. The features disappear for a few days. The spectra shown are of different days after discovery.

length 6,148.0 Å show a very interesting behavior in its spectral evolution, which is presented in Figure 9. During the third maximum, 44 days after discovery, clear absorption features at an expansion velocity of  $\approx -800$  km s<sup>-1</sup> are observed in the spectrum. During the following declining phase (46 and 47 days after discovery), these features disappear. However, 49 days after discovery, they start to appear again, now at higher expansion velocities of  $\approx -1,000$  km s<sup>-1</sup>. In the spectrum 50 days after discovery, the absorption features become more clearly visible. They also shift back to lower expansion velocities, reaching almost their original position in the spectrum 51 days after discovery. Basically, the expansion velocity evolution observed in the features of this Fe II line is very similar to those observed in other lines. However, it is interesting that this Fe II line disappears for a few days while the light curve is in the declining phase. Explanations may be that the Fe II might be ionized to Fe III for a few days or that one just sees different layers with different abundances of the expanding envelope.

Actually, absorption features of several Fe II lines disappear during the third declining phase of Nova V5668 Sgr. Features of the Fe II line at the wavelength 4,232.0 Å that were observed during the third maximum disappear during the third declining phase. In addition, there are several lines of Fe II in the wavelength range 5,000-5,300 Å, that is, 4,232.5, 5,018.4, 5,169.0, 5,234.6 and 5,276.0 Å, showing the same behavior. We also found a small emission feature at a wavelength of  $\approx 6,090$  Å appearing during exactly this phase.

Although we only have one spectrum during the fourth declining phase, we found that, again, some of the Fe II features observed during the maximum phase disappeared in the spectrum 61 days after discovery during this phase. Namely, these are the absorption features of the Fe II lines at wavelengths 4,491.4, 5,316.6, and 6,148.0 Å. Additionally, we observed that the absorption features of the Si II line at the

wavelength 6,347.1 Å disappear during the fourth declining phase. During the fifth declining phase, the absorption features of the Fe II lines at 4,491.4 and 6,148.0 Å finally disappear.

### 3.2.3 | Disappearance of N I, appearance of N II

We found also an interesting behavior of the absorption features of the nitrogen lines in the spectra of Nova V5668 Sgr in the light curve variation phase. During the declining phase toward the third minimum, absorption features of two N I lines at the wavelengths 7,442.3 and 7,468.2 Å disappear. At the same time, small emission features of N II lines appear at the wavelengths 3,995.0, 5,935.0 and 6,483.8 Å. During the fourth declining phase, the N I lines at wavelengths of 7,442.3 and 7,468.2 Å disappear in the spectrum observed 61 days after discovery. At the same time, emission features of two N II lines appear at wavelengths 3,995.0 and 6,483.8 Å. During the fifth declining phase, emission features of the N II line at the wavelength 3,995.0 Å appear in the observed spectra of Nova V5668 Sgr.

### 3.2.4 | The forbidden [O I] 5,577.3 Å line

The only forbidden line that appears in the early observed spectra of Nova V5668 Sgr is that of [O I] at the wavelength 5,577.3 Å. The first time it is visible is in the spectrum 9 days after discovery during the first declining phase. The line was observed in emission, and the flux increased during the declining phases relative to the continuum flux. However, this may be explained by a decreasing continuum flux, as already noted above. During the following evolution of the visual light curve during the variation phase, we see the same behavior. During a minimum phase, the emission feature of the [O I] line is clearly visible, while during a maximum phase it seems to disappear (in comparison to the continuum flux). In the later spectra, there appear features of other forbidden [O I] lines at wavelengths 6,300.3 and 6,363.7 Å, as can be seen in Figure 4.

### 3.2.5 | Daily variations in the Na I D doublet line

From April 25 to 28, 2015, which corresponds to 41–44 days after discovery, we were able to obtain a spectrum of Nova V5668 Sgr each night. On comparing these spectra, we found the features of the Na I D doublet lines at wavelengths 5,895.9 and 5,889.9 Å showing daily variations. In Figure 10, we present the corresponding spectra in the wavelength range of the Na I doublet, where we took the 5,889.9 Å line as the reference for the velocities. The two strong, narrow lines on the right-hand part of the graph are features from interstellar absorption of both Na I lines. Several absorption features of the expanding nova envelope can be seen in the blue part of the Na I doublet lines. The structure of the features changes every day. It is difficult to quantify this evolution, since the features of both lines overlap and therefore can cause the

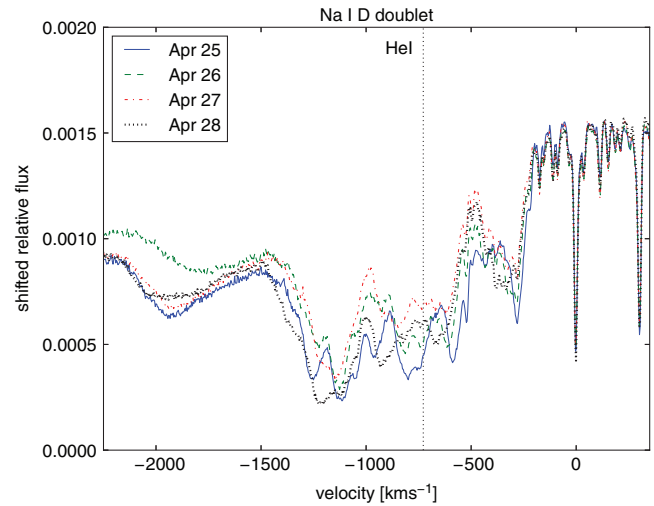


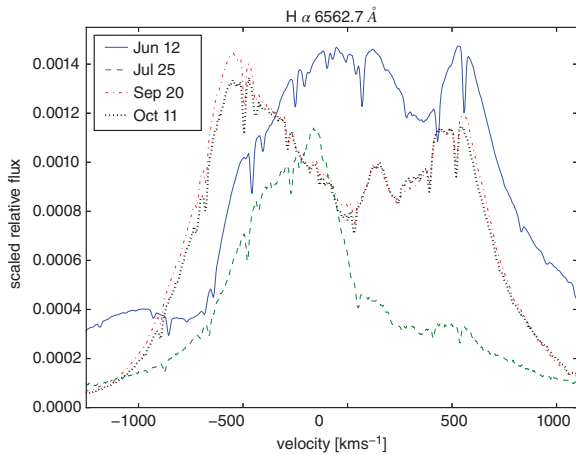
FIGURE 10 Daily variations observed in the absorption features of the Na I doublet line in the spectra of Nova V5668 Sgr.

daily changes. There is also the above-mentioned He I line at 5,875.6 Å, which might have absorption and/or emission features that could contribute to the flux in that wavelength region and, therefore, affect the daily changes. The position of this He I line has been marked in the spectra shown in Figure 10.

### 3.3 | Emission line phase

After recovering from the deep minimum in the light curve, all lines show only emission features in our spectra of Nova V5668 Sgr, meaning that the nova is now in its nebular phase. During the rising phase after the minimum, the visual light curve of the nova (Figure 1) shows some fluctuations, for example, at around 150 days after discovery. However, our observed spectra show for all lines a simple one-peak emission line feature, but that is probably due to the low SNR of the spectra during that phase, since the nova was still too dim for good observations with the TIGRE telescope. The only line showing more complex features is the H  $\alpha$  because by far it is the strongest line. In Figure 11, we show the evolution of the shape of the emission features of the H  $\alpha$  line at 6,562.7 Å. The spectrum from June 12, that is, 89 days after discovery, observed during the steep decline toward the deep minimum, shows an emission feature that has a maximum close to 0 km s<sup>-1</sup>. The feature is almost symmetrical, but it shows a small peak around +600 km s<sup>-1</sup> and a dip around -750 km s<sup>-1</sup>.

The narrow absorption features that can be seen in all the spectra are due to telluric lines. The emission feature of the H  $\alpha$  line in the spectrum from July 25, that is, 132 days after discovery, when the light curve is rising again, is strong on the blue side with a negative expansion velocity, while on the positive expansion velocity side only a small emission is observed. The maximum of the emission feature can be found at around -200 km s<sup>-1</sup>. When the light curve is in the almost



**FIGURE 11** Evolution of the emission features of the  $H\alpha$  line at  $6,562.7 \text{ \AA}$  in the spectra of Nova V5668 Sgr during the later phases.

constant phase after the deep minimum, the  $H\alpha$  emission feature of Nova V5668 Sgr has a clear double-peak structure. This can be seen in the observed spectrum from September 20 (189 days after discovery) as well as October 11 (210 days after discovery). The peak on the negative expansion velocity side is a bit higher than the second peak on the other side. Comparing the spectra from September 20 with those from October 11, one can see that there are hardly any changes in the shape of the emission feature of the  $H\alpha$  line.

#### 4 | CONCLUSIONS AND DISCUSSION

With the TIGRE robotic telescope, we obtained a dense time series of high-resolution spectra ( $R \approx 20,000$ ) of Nova V5668 Sgr, which was discovered on March 15, 2015, in the optical wavelength range between  $3,800$  and  $8,800 \text{ \AA}$ . The nova is a typical DQ Her-type nova, and it shows all the known classical systems of the spectra: principal, diffuse enhanced, and Orion spectra. We used the AAVSO visual light curve of Nova V5668 Sgr to spectroscopically characterize the different phases, beginning with a phase of strong variations followed by a deep, prolonged minimum, leading then to a recovery and a phase at an almost constant brightness level. We could place Nova V5668 Sgr at an estimated distance of  $1.6 \text{ kpc}$  assuming a moderate extinction and a characteristic absolute magnitude of a classical nova type of DQ Her.

We presented four characteristic spectra of Nova V5668 Sgr and performed detailed line identification on these respective spectra. We found that all the hydrogen Balmer lines were present in all of the observed spectra, with  $H\alpha$  being the strongest line. The nova also showed many lines of iron in form of Fe II and oxygen mainly in form of O I. In addition, we found some lines of Si II, Ti II, N II, Mg II, and Na I, among others. In the later spectra, we found some forbidden lines of oxygen ([O I] and [O II]). During the light curve evolution, the profiles of the features changed from P Cygni profiles to only emission features later.

We studied the observed spectra in order to find a correlation with the variations observed during the first 90 days in the visual light curve of Nova V5668 Sgr. We found that it was mainly the continuum flux that varied during the changes in the visual light curve. We could distinguish five relatively steep declines in the visual light curve of the nova. Our dense series of spectra revealed that, during the fast declining phases, the absorption features of many lines, especially those of hydrogen, shifted to higher expansion velocities of about  $-2,000$  to  $-1,500 \text{ km s}^{-1}$ . During the following, generally slower rises of the light curve, these absorption features shifted back to lower expansion velocities.

We also found that some absorption features, such as those of Fe II, disappeared for a few days during the third, fourth, and fifth declining phases of the visual light curve, as well as one Si II line during the fourth declining phase. During the third declining phase, new He I lines appeared in the spectra, which had not been recorded before. In addition, we found that absorption features of some N I lines disappeared, while new emission features of N II lines appeared in the spectra during the third, fourth, and fifth declining phases in the light curve. The Na I D doublet line at around  $5,900 \text{ \AA}$  had many features and showed daily variations during the first 90 days after discovery, which were probably due to the blending of the absorption features of the two Na I lines with the He I line at  $5,875.6 \text{ \AA}$ .

Since a nova has a typical radial wind profile of increasing velocity with increasing radius, one might suggest that what is seen during the minimum phases are layers of the envelope that lie farther outside and, therefore, show higher expansion velocities, occulting the layers and their less shifted line contributions from below. Such an optical depth effect would also explain the synchronization of these changes in several different lines. Comparing a graph of the positions of the minima of the absorption features of the O I line at  $7,773.0 \text{ \AA}$ , we found good agreement with the visual light curve. Whenever the light curve decreased, the absorption features moved to higher expansion velocities. The second group of absorption features around  $-500 \text{ km s}^{-1}$ , which were also visible in many other lines, only showed the general trend of moving toward higher negative expansion velocities while the light curve was decreasing. However, the strong appearance of the highly blue-shifted absorption just after any decline might also be explained by real temporary changes in the expansion velocity, synchronized by some physical process with the steep brightness decreases of the nova. The same process might then also explain the synchronized changes in ionization reported above. In any case, more further analyses will be required to investigate these or other possible interpretations of the rich spectroscopic evidence presented here.

After having been enshrouded by dust (Banerjee, Ashok, & Srivastava, (2015); Walter, (2015)) since around 90 days after discovery, the light curve of Nova V5668 Sgr started to rise again around 130 days after discovery. The nova brightness then returned to about 9 mag, at which point we were

able to resume our spectroscopic monitoring. After the deep minimum, the lines in the spectra showed only emission features and no absorption features. The emission features had a clear double-peak structure, as could be clearly seen in the strongest line of H  $\alpha$  at 6,562.7 Å. The peak on the blue side was a bit higher than that on the red side.

The unique dataset obtained by our ongoing dense spectroscopic monitoring of Nova V5668 Sgr will be further analyzed in a future publication, which will include detailed modeling of some spectra and will give us the opportunity to study the spectral evolution of this DQ Her-type nova in much more detail.

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