Contributing to the spectral evolution of the nova V1405 Cas

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(Submitted on 23 June 2023; Accepted on 15 August 2023)

Abstract. The cataclysmic variable Nova Cas 2021, also known as V1405 Cas, exploded as a nova on March 18, 2021. Here we report the results of our optical spectroscopic monitoring that lasted from late 2021 to early 2023 and was conducted using the 0.4 m telescope at the University of Jaén observatory. These data are intended to contribute to the observational coverage of the nova spectral evolution, both in the permitted line and nebular phases. The development of high ionization conditions could be followed through the progression of the Bowen blend, He II and C IV emission features. Hydrogen lines were also studied in an attempt to disentangle the late ejecta components and estimate their total mass. Finally, the neon stage of V1405 Cas is suspected to have occurred earlier than previous reports.

Key words: binaries: close – novae, cataclysmic variables - V1405 Cas

Introduction

Novae are among the most explosive events of stellar binary origin observed both inside the Milky Way and other galaxies in its neighborhood. The reader is referred to Chomiuk et al. (2021) and references therein for a recent updated review. A relevant historical review can also be found at Gallagher & Starrfield (1978). While consensus exists as being triggered by the thermonuclear runaway of captured matter onto the surface of a white dwarf, we still lack a robust and detailed understanding of this phenomenon and its multiple faces. For instance, the discovery of gamma-ray emission from several classical novae was originally unexpected and boosted the interest about these systems as a new kind of particle accelerators (see Albert et al. 2022 and references therein). In parallel to new windows of the electromagnetic spectrum being open to novae studies, the majority of data gathered on them remains predominantly in the optical range. Their often relatively bright optical counterparts, sometimes even reaching naked-eye visibility, render these objects accessible to modest astronomical equipment during both their maximum and the following, often month-long, decay. In this context, the photometric and spectroscopic capabilities of small telescopes dedicated to long-term monitoring can provide a noticeable contribution to our knowledge of these violent events (see e.g. Morgan et al. 2003).

Nova Cas 2021, also known as V1405 Cas, was originally discovered by Yuji Nakamura from Japan on 2021 March 18 and soon confirmed to be a classical slow nova (Maehara et al. 2021; Gehrz et al. 2021). Pre-outburst photometry (Schaefer 2022) was already indicative of a binary system with a short orbital period of about 4.5 hours. In this paper, we report about its spectral evolution during the permitted line and nebular spectrum phases as observed with an educational telescope. The outburst of V1405 Cas was a remarkable naked-eye event also detected in gamma-rays with the *Fermi* Large Area Telescope (LAT) about 10 days after the optical maximum (Buson et al. 2021). The system is located at distance of 1.7 kpc according to its accurate parallax in the 3$^{\mathrm{rd}}$ *Gaia* data release[1], that probably helped to the successful LAT detection. A significant reddening of around $E(B-V) = +0.53$ has been estimated from optical interstellar absorption features (Munari et al. 2021a).

Novae are usually classified into two main categories: 'Fe II' and 'He/N' (Williams 1992). In the V1405 Cas case, the type of nova event underwent noticeable changes in its classification. While at early-times its appearance was that of an He/N nova (Taguchi et al. 2021), weeks later it evolved into a 'textbook' example of a Fe II class (Munari et al. 2021b). Although not too common, the evolution from one spectral class to another has been previously observed in $\sim 5\%$ of cases on a time scale of weeks after the outburst (Williams 2012). The case of LMC 1988 #2 (Sekiguchi et al. 1989) is a representative example transitioning from its original Fe II to He/N type. Emission lines originating in the ejecta from the white dwarf, rich in He and CNO-cycle products, are behind the He/N class. Alternatively, the Fe II classification arises when the lines mostly come from an extended circumbinary disk whose composition is dominated by the donor star. It is noteworthy that both classes of novae may occasionally develop into a 'neon phase' displaying strong forbidden lines of highly ionized atoms of this noble gas (Williams 1992). This seems to have been the case of V1405 Cas as will be commented below. Furthermore, it is worth to pay attention here to the extremely detailed spectral coverage of this nova event recently reported by Valisa et al. (2023) available as a server preprint at the time of writing.

The rest of the paper is organized as follows. We first present the details of the observation procedure and the results of our spectroscopic monitoring. Secondly, we report on the different emission lines detected and some interesting aspects of their evolution as the nova ejecta expanded and faded. It is our hope that this work modestly contributes to improve the description of observational facts related to the V1405 Cas event. Although the quality of our data is certainly not as good as that of Valisa et al. (2023), more than 70% of our observation dates are remarkably coincident with holes in their otherwise dense time sampling.

1. Observations and results

V1405 Cas was observed using the University of Jaén Telescope (UJT) located in an urban area in the outskirts of Jaén in Spain (Martí et al. 2017). The UJT is an automated Meade 16 inch (41 cm) f/8 Schmidt-Cassegrain telescope currently equipped with a commercial mid-resolution LISA spectrograph and CCD cameras from Shelyak Instruments. Our observations spread over a temporal baseline from 2021 December 14$^{\mathrm{th}}$ to 2023 January 12$^{\mathrm{th}}$, almost 13 months. The useful wavelength range covered was $\lambda \simeq$ 4000-8000 Å with a typical resolution of $\lambda/\Delta\lambda \simeq 1000$. The exposure time was split into 5 minutes intervals to be later median-combined in order to get rid of cosmic ray impacts. A total of 14 observing runs were performed. Data processing including bias, dark, flat field, spectra extraction and wavelength calibration based

[1] `https://gea.esac.esa.int/archive/`

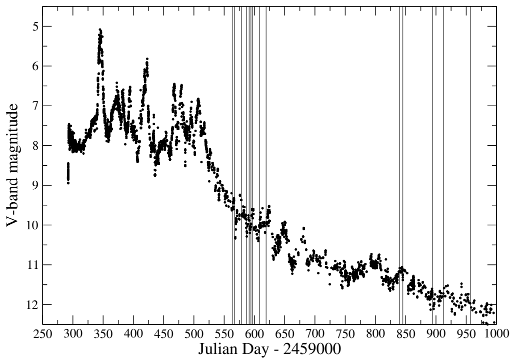

Fig. 1. AAVSO V-band light curve of V1405 Cas with vertical lines indicating the epochs of UJT spectroscopy.

on a Ne-Ar lamp was conducted using different tasks and scripts from the IRAF software package (Tody 1993). The detailed log of observations is listed in Table 1. Figure 1 shows the V-band observations of V1405 Cas collected by the American Association of Variable Star Observers[2] (AAVSO) with vertical lines marking the epochs of UJT monitoring. The total exposure time had to be increased as the nova progressively faded in the final observing runs.

Table 1. Log of spectroscopic observations.

Date (yyyymmdd)	Heliocentric Julian Day	Time after maximum (*) (d)	Exposure time
20211214	2459563.285	218	$3 \times 5^{\rm min}$
20211218	2459567.291	222	$3 \times 5^{\rm min}$
20211229	2459578.264	233	$3 \times 5^{\rm min}$
20220107	2459587.289	242	$3 \times 5^{\rm min}$
20220111	2459591.259	246	$3 \times 5^{\rm min}$
20220114	2459594.280	249	$3 \times 5^{\rm min}$
20220117	2459597.277	252	$3 \times 5^{\rm min}$
20220128	2459608.281	263	$3 \times 5^{\rm min}$
20220208	2459619.273	274	$5 \times 5^{\rm min}$
20220916	2459839.333	495	$3 \times 5^{\rm min}$
20220922	2459845.310	501	$3 \times 5^{\rm min}$
20221110	2459894.281	549	$5 \times 5^{\rm min}$
20221128	2459912.240	567	$5 \times 5^{\rm min}$
20230112	2459957.270	612	$5 \times 5^{\rm min}$

(*) The time of optical maximum is estimated as HJD 2459344.8 based on AAVSO data.

[2] https://www.aavso.org/

Essentially, we are reporting two different blocks of spectral observations separated by about seven months. The first block, top panel shown in Fig. 2, is dominated by permitted lines of H, He and Fe II. In contrast, the second block presented in the bottom panel of Fig. 2 clearly displays different forbidden lines expected to appear when the nova ejecta reaches the nebular phase. Tables 2 and 3 additionally contain the most relevant spectral features found in these two UJT data sets. Our identifications are based on the novae line lists by Williams (2012). Equivalent width (EW) and Full Width Half Maximum (FW) have been estimated using Gaussian fits and applying the deblending IRAF tools when needed. Their estimated uncertainties are about 10% and 5%, respectively.

2. Discussion

Our first block of spectroscopic follow-up of V1405 Cas started during the steady photometric decline of the nova (see light curve in Fig. 1), when permitted lines clearly dominated (see Fig. 2 top). Some P-Cygni profiles were evident at the beginning, particularly at the He I (4471 and 5876 Å) and He II (5412 Å) lines. The radial velocity of the absorption component was similar for all of them (-1700 ± 100 km s^{-1}) pointing to a common origin in the same expanding shell. The first spectrum on 2021 December 14th was obtained only one week after the emergence of high ionization lines was reported (Munari et al. 2021c). These mainly include He II 4686 Å and the Bowen blend[3], whose later evolution is commented below. Our second block of data (see Fig. 2 bottom) reveals spectra with a clear presence of forbidden lines typical of the nebular and post-nova phase. The transition between both regimes must have occurred at some point around mid-2022. In fact, Woodward et al. (2022) already reported on early August forbidden infrared lines of coronal emission. Similarly, the Valisa et al. (2023) spectral plots also confirm the enhancement of different forbidden lines as early as 2022 April/May.

2.1.The Bowen blend evolution

Figure 3 provides a detailed view of the emergence of high ionization conditions powered by photons from the central white dwarf. This fact was first reported by Munari et al. (2021c) when the ejecta was $\sim$ 200 day old. They witnessed the progressive development of Bowen blend and He II emissions, starting to become evident in their spectra at the beginning of 2021 November. The UJT spectra complementary show that these conditions prevailed months after their original detection, at least up to early 2022 February. This original impression could be later confirmed by inspecting the Valisa et al. (2023) dynamic plots.

According to Table 1 in Cunningham et al. (2015), the time needed to reach the breakout of the Strömgren sphere is mostly dependent on the white dwarf mass. Assuming typical nova shell parameters, to have the whole He atoms of the ejecta exposed to the ionizing flux as late as $\sim$ 200 d after the outburst event, only occurs for a mass close to the Chandrasekhar limit. This suggests that a high-mass white dwarf companion is harbored in this system.

[3] Centered at 4640 Å and mainly due to N III (4634-41 Å) blended with C III (4647-51 Å).

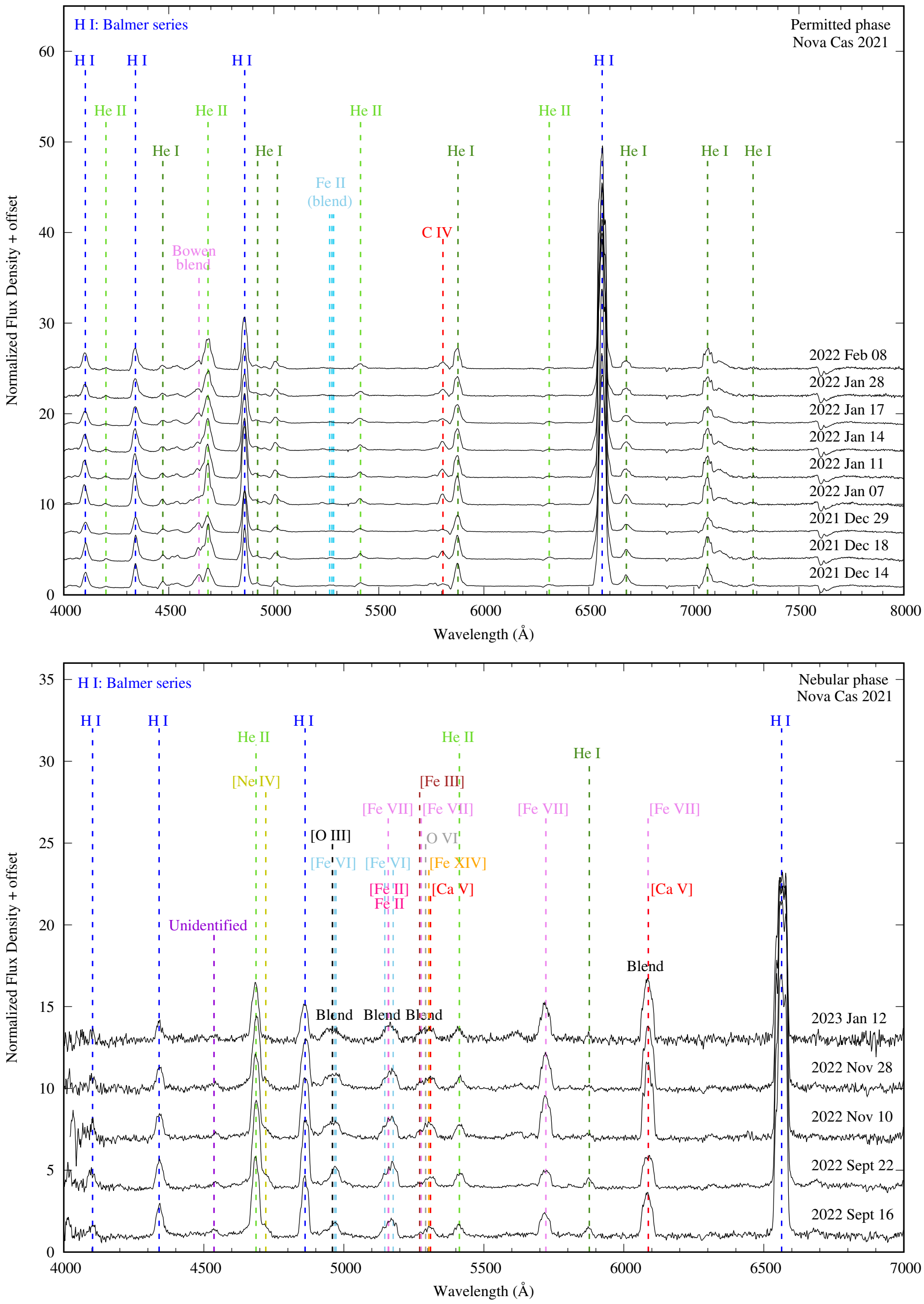

Fig. 2. Spectra of V1405 Cas obtained with the UJT covering almost 13 months of spectral evolution. The color code identifies the chemical species of the main emission lines. The top and bottom panels are separated by about seven months (permitted and nebular phases).

Table 2. V1405 Cas spectral line parameters in the permitted phase (EW and FW in Å).

Line Id.	Par.	2021 Dec 14	2021 Dec 18	2021 Dec 29	2022 Jan 07	2022 Jan 11	2022 Jan 14	2022 Jan 17	2022 Jan 28	2022 Feb 08
H I 4102	EW	−54	−54	−39	−61	−54	−53	−54	−43	−48
	FW	27	25	26	26	26	28	30	26	26
He II 4200	EW	−6	−9	−5	−8	−9	−10	−8	−8	−6
	FW	27	25	26	28	26	29	30	23	25
H I 4340	EW	−79	−87	−66	−119	−97	−97	−84	−80	−90
	FW	25	25	28	28	28	30	30	29	29
He I 4471	EW	−19*	−14	−16*	−17	−16	−16	−18	−18	−17
	FW	22	24	26	23	25	27	29	28	27
Bowen blend**	EW	−41	−33	−36	−18	−34	−44	−41	−27	−32
$\simeq$ 4643	FW	32	35	35	40	44	57	36	34	40
He II 4686	EW	−66	−89	−62	−96	−115	−107	−118	−101	−123
	FW	34	29	33	28	34	33	38	36	37
H I 4861	EW	−163	−179	−129	−198	−184	−161	−171	−137	−160
	FW	25	24	26	25	26	26	29	26	27
He I 4922	EW	−4	−3	−4	–	–	–	–	–	–
	FW	18	20	26						
He I 5016?	EW	−14	−19	−15	−24	−19	−21	−16	−21	−22
	FW	23	26	25	23	27	24	24	24	24
FeII 5265(48)	EW	−3	−3	−1	−1	–	–	−2	–	–
FeII 5276(49)	FW	30	23	30	17			23		
FeII 5284(41)										
(blended)										
He II 5412	EW	−12*	−15	−11*	−19	−18	−20	−19	−16	−21
	FW	32	31	32	33	34	36	38	34	39
C IV 5805	EW	−1	−20	−13	−30	−23	−23	−15	−28	−24
	FW	17	25	30	29	29	27	30	32	32
He I 5876	EW	−65*	−67	−66*	−84	−70	−71	−72	−83	−73
	FW	26	27	31	28	28	29	33	31	29
He II 6311	EW	−6	−7	−4	−6	−5	−3	−5	−4	−4
	FW	33	27	31	32	34	28	30	34	32
H I 6563	EW	−801	−992	−607	−1209	−936	−932	−886	−947	−1003
	FW	33	33	34	34	34	35	37	35	35
He I 6678	EW	−33	−24	−23	−31	−31	−26	−29	−26	−24
	FW	33	29	34	31	36	32	39	34	33
He I 7065	EW	−69*	−84	−66*	−72	−113	−90	−93	−100	−115
	FW	32	34	37	32	34	35	41	39	39
He I 7281	EW	−7	−8	–	–	–	–	–	–	–
	FW	32	32							

(*) With P-Cygni profile. (**) Due to N III (4634-41 Å) blended with C III (4647-51 Å).

2.2. The C IV line: repeated emergence and decay

The detection of C IV emission requires ionizing photons as energetic as 47.9 eV, i.e., significantly harder that those involved in the He II and Bowen blend lines. Being practically absent on 2021 December 14th, when high-ionization conditions were believed to be already established, the C IV 5805 Å feature remarkably emerged less than 4 days after (see Fig. 4). Later it faded and recovered again. Since early 2022 January to the end of the first block data, on early February, it remained present and well detected with no further fading signs. This suggests a long-term persistence of the ionizing flux.

Table 3. V1405 Cas spectral line parameters in the nebular phase (EW and FW in Å).

Line Id.	Par.	2022 Sep 16	2022 Sep 22	2022 Nov 10	2022 Nov 28	2023 Jan 12
H I 4102	EW	−29	−35	−15	−19	–
	FW	32	31	14	23	
H I 4340	EW	−60	−59	−51	−35	−31
	FW	29	28	28	24	25
Unid. 4536	EW	−8	−10	−7	−13	–
	FW	27	28	21	35	
He II 4686	EW	−124	−144	−142	−107	−104
	FW	27	28	28	27	28
[Ne IV] 4721	EW	−10	−12	−10	−5	–
	FW	19	20	20	13	
H I 4861	EW	−103	−114	−109	−84	−71
	FW	26	26	28	27	27
[O III] 4959	FW	−31	−35	−37	−39	−40
[Fe VI] 4967-72	EW	45	36	54	53	60
(blended)						
[Fe VI] 5146	EW	−59	−70	−63	−55	−42
[Fe VII] 5158	FW	46	46	45	45	43
[Fe II] 5159						
Fe II 5169(42)						
[Fe VI] 5176						
(blended)						
[Fe III] 5270	EW	−32	−27	−44	−36	−35
[Fe VII] 5276	FW	50	47	49	53	54
O VI 5292						
[Fe XIV] 5303						
[Ca V] 5309						
(blended)						
He II 5412	EW	−24	−26	−22	−20	−20
	FW	32	31	28	29	29
[Fe VII] 5721	EW	−43	−34	−78	−65	−82
	FW	33	33	31	31	35
He I 5876	EW	−14	−15	–	–	–
	FW	24	24			
[Fe VII] 6086	EW	−105	−87	−188	−155	−156
[Ca V] 6087	FW	35	37	33	34	35
(blended)						
H I 6563	EW	−665	−658	−630	−475	−452
	FW	35	35	37	37	37

Contrasting UJT data with the C IV trend in Valisa et al. (2023) confirms the observed behavior. This feature completely vanished later in the nebular phase.

2.3. The complex evolution of the H_α profile

Comparison of UJT H_α profiles with those detailed in Valisa et al. (2023) is very resemblant allowing for the different instrumental resolution.
During most of the permitted line phase, the strong H I 6563 Å or H_α emission feature remained single-peaked at the UJT resolution (Fig. 5, bottom). In contrast, the H_α profile during the nebular phase became strongly differentiated and at least four different components can be distinguished (Fig. 5,

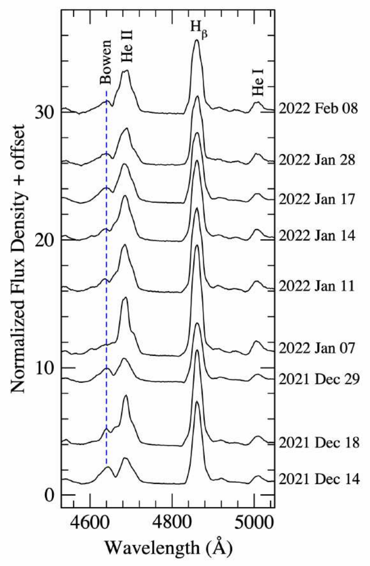

Fig. 3. Detailed profile evolution of the Bowen blend, He II and H_β region during the V1405 Cas light curve decay.

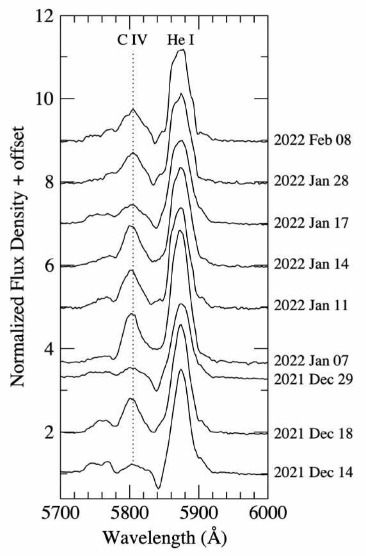

Fig. 4. Detailed profile evolution of the emission line C IV 5805 Å next to the He I 5876 Å feature during the V1405 Cas light curve decay.

top). Despite these changes, the FW measurements (Tables 2 and 3) did not experience strong variations and remained close to values equivalent to 1400-1500 km s^{-1}. The average heliocentric velocities of the proposed nebular H_α components corresponded to -830 ± 30, -250 ± 60, $+170 \pm 40$ and $+670 \pm 60$ km s^{-1}, respectively (dotted lines on top of Fig. 5). The fact that the profile of these features remains relatively stable in our final spectra up to 2023 January suggests that the mass ejection was already terminated. For classical novae, changes are expected in the shell structure only due to expansion effects. Lastly, it is worth to point out that our components are further resolved by Valisa et al. (2023) into several narrower ones with roughly similar Doppler shifts.

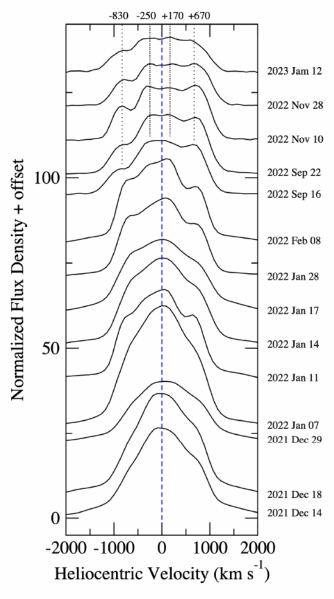

Fig. 5. Detailed profile evolution of the H_α emission line during the whole UJT data set. The horizontal axis shows heliocentric radial velocity in km s^{-1}. The blue dashed line corresponds to zero km s^{-1}, while the top dotted lines mark the main H_α components identified during the late nebular phase with radial velocities labelled on top.

2.4. Early hints of a neon nova

V1405 Cas turned out to belong to the subclass of neon novae following the detection of intense forbidden lines from different ions of this noble gas ([Ne III], [Ne IV] and [Ne V]) on 2022 November 27th spectra (Munari & Valisa 2022). The neon origin is usually traced back to the original white dwarf composition. As stated in the introduction, both Fe II and He/N class novae

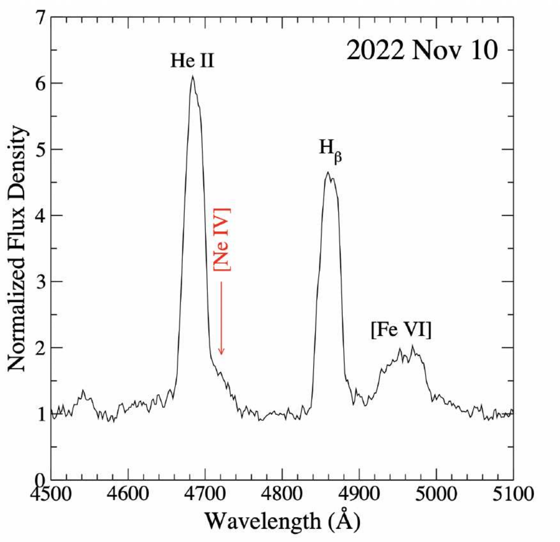

Fig. 6. Enlarged view of the UJT spectrum taken on 2022 November 10th where [Ne IV] 4721 Å emission is suspected.

in the nebular stage are known to evolve into the neon subclass, although this is not a frequent event: the estimated occurrence is about 30% of cases (Williams 1992). The UJT spectra do not cover the most intense neon lines. However, they do cover a [Ne IV] 4721 Å feature that was present and best seen on 2022 November 10th. This is illustrated in Fig. 6 where a strong excess appears blueward of the He II 4686 Å line, that was also pointed out by Munari & Valisa (2022) in their later spectra. Provided that the line identification is correct, the UJT detection would advance the neon classification by at least two weeks. The same feature is also visible in the Valisa et al. (2023) sequences suggesting an even longer one month advancement.

2.5. Estimating the mass of the ejecta

The reported spectra lack the detection of appropriate line ratios sensitive to the density and temperature of the ejecta from which a mass could be derived. Yet, we can attempt a crude guess based on plausible novae parameters. According to Snijders (1990), typical temperatures and electron densities for the ejected material in the nebular phase are approximately in the ranges $T_e \simeq (1-2)\times 10^4$ K and $N_e \simeq 10^{6.5} - 10^{8.5}$ cm^{-3}, respectively. The hydrogen mass of the ejecta can be estimated using the formula (Iijima & Esenoglu 2003; Iijima 2006):

$$m(\mathrm{H}/M_\odot) = \frac{D^2}{N_e} 8.3 \times 10^{11} I(\mathrm{H}_\beta), \tag{1}$$

where D is the distance in kpc, $I(\mathrm{H}_\beta)$ is the de-reddened intensity of the H I 4861 Å line, and the numerical coefficient is valid for $T_e \simeq 10^4$ K and $N_e \simeq 10^7$ cm^{-3}.

For the latest spectrum in Table 1, we obtained $I(\mathrm{H}_\beta) = 1.8 \times 10^{-11}$ erg s^{-1} cm^{-2} based on a calibration tied to the O-type standard star HD 192281. This flux significantly decayed since the first of our nebular spectrum, taken four months earlier, when $I(\mathrm{H}_\beta) = 7.0 \times 10^{-11}$ erg s^{-1} cm^{-2} was found. Together with $D = 1.7$ kpc, a plausible estimate of the hydrogen mass is

$$m(\mathrm{H}) = 1.2 \times 10^{-5}\ M_\odot \left[\frac{N_e}{10^7\ \mathrm{cm}^{-3}}\right]^{-1} \left[\frac{I(\mathrm{H}_\beta)}{5 \times 10^{-11}\mathrm{erg\ s}^{-1}\ \mathrm{cm}^{-2}}\right]. \qquad (2)$$

Correcting this mass for the He content of the ejecta is not an easy task because it requires an intensity ratio involving the He I 5876 line, very marginally detected at this late stage. Yet, we would crudely expect a 25 to 30% increase. The ejection of $\sim 10^{-5}\ M_\odot$ is comparable to outbursts in other nova systems.

Conclusions

We have reported optical spectroscopy over a year of the recent nova V1405 Cas, from the permitted line to the nebular phases. With our modest facilities at UJA, we managed to conduct an optical monitoring worth to be shared with the community in order to enrich the observational coverage of an event as remarkable as this nova. In particular, we provide identification of the most important emission lines and estimates of their main spectral parameters (FW and EW). In addition, different aspects of spectral evolution could also be followed in detail, such as:

1. the continuation of high ionization conditions (traced by Bowen blend and He II emissions) for several months after they were first reported in the literature. The timing of these features tentatively points to a massive white dwarf companion;
2. we witnessed the emergence, fading and re-emergence of the C IV emission line in a matter of days whose presence implies a significant hardening of the ionizing photon flux;
3. the H_α emission line developed a multi-component profile during the nebular phase. Its persistence indicates that, after early 2023, only expansion effects dominated the ejecta evolution;
4. a marginal detection of a [Ne V] feature suggests a minimum two week earlier classification of V1405 Cas as a neon nova;
5. assuming typical temperature and density parameters, an ejecta mass of $\sim 10^{-5}\ M_\odot$ is roughly estimated.

Comparison of UJT results with the Valisa et al. (2023) extensive spectral atlas of V1405 Cas remained always consistent and reassuring. As a final thought, we believe that the present work highlights the valuable role of small class telescopes when devoted to long-term monitoring purposes.

Acknowledgements. We acknowledge support by Agencia Estatal de Investigación of the Spanish Ministerio de Ciencia, Innovación y Universidades grant PID2019-105510GB-C32 / AEI / 10.13039 / 501100011033 and FEDER "Una manera de hacer Europa", as well as Programa Operativo FEDER 2014-2020 Consejería de Economía y Conocimiento de la Junta de Andalucía (Refs. A1123060E00010 and FQM-322). We also acknowledge with thanks the variable star observations from the AAVSO International Database contributed by observers worldwide and used in this research.

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