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Authors	MOLARO, Paolo, Izzo, L., MASON, Elena, Bonifacio, P., DELLA VALLE, Massimo
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Highly enriched ^7Be in the ejecta of Nova Sagittarii 2015 No. 2 (V5668 Sgr) and the Galactic ^7Li origin

P. Molaro,^{1★} L. Izzo,² E. Mason,¹ P. Bonifacio³ and M. Della Valle^{4,5}

¹INAF–Osservatorio Astronomico di Trieste, Via G.B. Tiepolo 11, I-34143 Trieste, Italy

²Instituto de Astrofísica de Andalucía (IAA-CSIC), Glorieta de la Astronomía s/n, E-18008 Granada, Spain

³GEPI, Observatoire de Paris, PSL Research University, CNRS, Univ Paris Diderot, Sorbonne Paris Cité, Place J. Janssen, F-92195 Meudon, France

⁴INAF–Osservatorio Astronomico di Napoli, Salita Moiarriello, 16, I-80131 Napoli, Italy

⁵International Center for Relativistic Astrophysics, Piazza della Repubblica 10, I-65122 Pescara, Italy

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ABSTRACT

We report on the evidence of highly blueshifted resonance lines of the singly ionized isotope of $^7\text{Be II}$ in high resolution UVES spectra of Nova Sagittarii 2015 No. 2 (V5668 Sgr). The resonance doublet lines $^7\text{Be II}$ at $\lambda\lambda 313.0583, 313.1228$ nm are clearly detected in several non-saturated and partially resolved high velocity components during the evolution of the outburst. The total absorption identified with Be II has an equivalent width much larger than all other elements and comparable to hydrogen. We estimate an atomic fraction $N(^7\text{Be})/N(\text{Ca}) \approx 53\text{--}69$ from unsaturated and resolved absorption components. The detection of ^7Be in several high velocity components shows that ^7Be has been freshly created in a thermonuclear runaway via the reaction $^3\text{He}(\alpha, \gamma)^7\text{Be}$ during the Nova explosion, as postulated by Arnould & Norgaard, however in much larger amounts than predicted by current models. $^7\text{Be II}$ decays to $^7\text{Li II}$ with a half-life of 53.22 d, comparable to the temporal span covered by the observations. The non-detection of $^7\text{Li I}$ requires that ^7Li remains ionized throughout our observations. The massive Be II ejecta result into a ^7Li production that is $\approx 4.7\text{--}4.9$ dex above the meteoritic abundance. If such a high production is common even in a small fraction (≈ 5 per cent) of Novae, they can make all the *stellar* ^7Li of the Milky Way.

Key words: nuclear reactions, nucleosynthesis, abundances – stars: individual: V5668 Sgr – novae, cataclysmic variables – Galaxy: evolution.

1 INTRODUCTION

^7Li is a unique element that shows a large variety of production processes. These include primordial nucleosynthesis, spallation processes by high energy cosmic rays in the interstellar medium, stellar flares in low mass stars, Cameron–Fowler mechanism in Asymptotic Giant Branch (AGB) stars and Novae, and neutrino induced nucleosynthesis in SNe explosions. Observations show that ^7Li has a constant abundance among metal-poor stars and begins to rise at $[\text{Fe}/\text{H}] \approx -1$ to reach the meteoritic value at solar metallicities (Rebolo, Beckman, & Molaro 1988) requiring a net ^7Li production (Romano et al. 1999). The rate of the Li increase favours AGB stars and Novae as the most significant *stellar* sources. Although ^7Li has been observed in AGB stars the observational evidence for Novae has only recently been found by Izzo et al. (2015) with the first detection of the $^7\text{Li } \lambda\lambda 6708$ line in the spectra of Nova Centauri 2013 (V1369 Cen) and by Tajitsu et al. (2015) with the first detection of

^7Be in the post-outburst spectra of the classical Nova Delphini 2013 (V339 Del).

Here, we report a study of the Be II by means of UVES observations of Nova Sagittarii 2015 No. 2 (V5668 Sgr). A spectrum from the High Dispersion Spectrograph of the Subaru Telescope taken at day 63 after maximum has been discussed by Tajitsu et al. (2016) who reported the presence of $^7\text{Be II}$ in this Nova, and also in V2944 Oph.

2 OBSERVATIONS

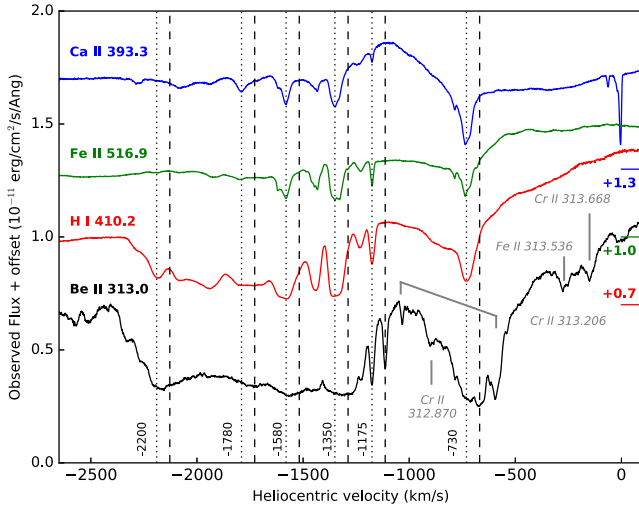
2.1 Evidence for $^7\text{Be II}$

Nova Sagittarii 2015 No. 2 was discovered by Seach (2015) on 2015 March 15 and reached the first maximum on March 21 at 04h 04m UT with a magnitude of $V = 4.3$. The Nova re-brightened several times and remained bright for about 80 d before declining due to dust formation. Soon after the discovery we started a DDT programme with the UVES spectrograph at the ESO-VLT. Several UVES spectra were obtained at +58, 63, 69, 73, 82 and 89 d from maximum as reported in Table 1. The settings with central

★ E-mail: molaro@oats.inaf.it

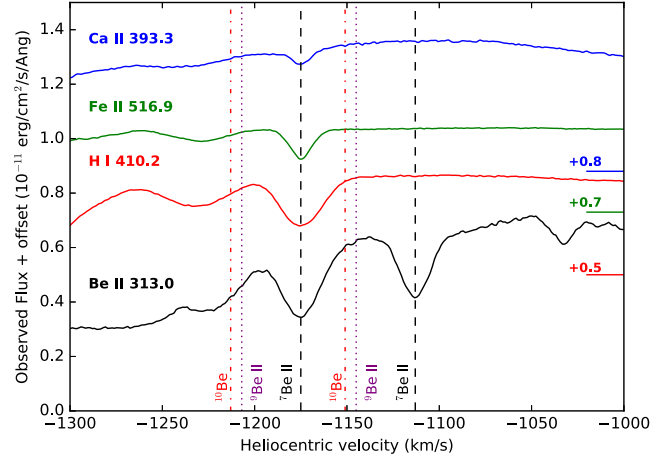
Table 1. Journal of the observations.

Date	UT	MJD	Day	346	437	564	760
2015	h m	57000	a.m.	s	s	s	s
05-19	08 49	161.36	58.7	400	2×150	2×100	2×150
05-24	05 49	166.24	63.6	2×400	2×150	4×100	2×150
05-30	03 20	172.14	69.5	400	100	9×7	3×10
06-03	05 18	176.22	73.6	400	100	9×7	3×7
06-12	05 25	185.23	82.6	400	60	9×7	2×10
06-19	01 29	192.06	89.4	2×602	2×60	22×15	3×15

**Figure 1.** Nova spectrum at day 58. The figure displays the spectrum in the vicinity of Fe I $\lambda\lambda 519.6$ (green line) H γ (red), Ca II K (blue) and $^7\text{Be II}$ (black) lines plotted on the velocity scale. The fluxes are scaled to provide roughly the same intensity shortwards the absorption. The velocity scale is adjusted to the $^7\text{Be II}$ $\lambda\lambda 313.0583$ nm line. The position of the main absorption components is shown with vertical dotted lines. The corresponding position of the expected $^7\text{Be II}$ $\lambda\lambda 313.1228$ nm line is shown by vertical dashed line.

wavelength of 346 nm (range 305–388 nm), 437 nm (375–499 nm), 564 nm (460–665 nm) and 760 nm (570–946 nm), were used, thus covering the full optical range from the atmospheric cutoff to the red edge of 946.0 nm with small gaps of ≈ 10 nm around the red central wavelengths. The resolving power was $R = \lambda/\delta\lambda \approx 80\,000$ for the blue arm and $\approx 120\,000$ for the red arm. Overlapping spectra have been combined for each epoch to maximize the signal to noise.

At early epochs the spectra of the Nova show several broad emission lines of neutral hydrogen and other permitted transitions of neutral or singly ionized species often accompanied by sharp and blueshifted multiple absorption components reaching blue edge velocities of ≈ -2300 km s $^{-1}$. Fig. 1 displays portions of the Nova spectrum of day 58 in the proximity of H γ , Ca II K, Fe II $\lambda\lambda 519.0$ and Be II $\lambda\lambda 313.0$ nm lines. These lines show several absorption components at heliocentric $v_{\text{rad}} \sim -730, -1175, -1350, -1580, -1780$ and -2200 km s $^{-1}$ with the more prominent ones marked with vertical black dotted lines in the figure. Ca II K shows also narrow absorption components at -4.3 and -62.9 km s $^{-1}$ velocities caused by intervening Galactic interstellar medium. At the wavelength of the Be II $\lambda\lambda 313.1$ nm doublet there is P-Cygni profile with a huge blueshifted absorption that Tajitsu et al. (2016) identified as ^7Be . In Fig. 2 we zoomed the component at -1175 km s $^{-1}$ which is seen only at this epoch and provides a robust identification. The two sharp absorption components (FWHM ≈ 0.19 Å) are separated

**Figure 2.** Zoom of Fig. 1 around the -1175 km s $^{-1}$ component. The $^7\text{Be II}$ $\lambda\lambda 313.0583, 313.1228$ nm are shown with a dashed line. The positions of the expected $^9\text{Be II}$ $\lambda\lambda 313.0442, 313.1067$ nm and $^{10}\text{Be II}$ $\lambda\lambda 313.0484, 313.1129$ nm are also shown.**Table 2.** Contaminants from Fe-peak elements in the range of the $^7\text{Be II}$ doublet measured in the spectrum of day 82.

Lines	λ_{lab} (Å)	$\log gf$	W (mÅ) –820	W (mÅ) –1900
Cr II (5)	3120.3691	0.120	16 ± 8	–
Cr II (5)	3124.973	–0.018	b	b
Cr II (5)	3128.700	–0.320	25 ± 7	b
Cr II (5)	3132.053	0.079	b	b
Fe II (82)	3135.360	–1.130	40 ± 7	104 ± 10
Cr II (5)	3136.681	–0.250	45 ± 8	51 ± 15
Fe II (82)	3144.751	–1.740	b	83 ± 10

by 0.654 Å which corresponds precisely to the separation of the $^7\text{Be II}$ resonance doublet of $\lambda\lambda 313.0583, 313.1228$ nm. Moreover, the component is perfectly aligned in radial velocity with the other species providing evidence that it is $^7\text{Be II}$ and not $^9\text{Be II}$ which has an isotopic shift of -15.4 km s $^{-1}$. The dips of each line of the $^7\text{Be II}$ doublet can be identified also at -730 km s $^{-1}$ in Fig. 1, but become hard to see in the flat bottoms of the other components. At velocities ≤ -1600 km s $^{-1}$ the absorption profile ascribable to Be follows mainly the hydrogen lines rather than the metallic lines which are very weak or absent. If based only on this spectrum the identification of this part of absorption with $^7\text{Be II}$ would therefore be controversial.

The bottoms of the strong lines in Fig. 1 are totally flat suggesting that the absorption is saturated but with the absorbing material only partially covering the background light source. The Balmer lines also show flat bottoms. At this epoch in correspondence of the $^7\text{Be II}$ the intensities are ~ 50 per cent but the intensity value varies with the day and the geometry of the outburst.

The $^7\text{Be II}$ absorption may be contaminated by the presence of other Fe-peak elements. Evidence is found for the presence of Cr II (5) multiplet. The Cr II $\lambda\lambda 313.2056$ nm line is observed resolved both in the $\sim -730, \sim -1175$ km s $^{-1}$ components. The Cr II (5) $\lambda\lambda 313.6680$ and 312.8699 nm and the Fe II (82) $\lambda\lambda 313.5360$ nm lines are now seen at -730 km s $^{-1}$. The Cr II $\lambda\lambda 312.4978$ nm line of the same multiplet (5) and with comparable intensity should therefore be present and contribute to the main absorption. Other lines show up on day 82 and are listed in Table 2.

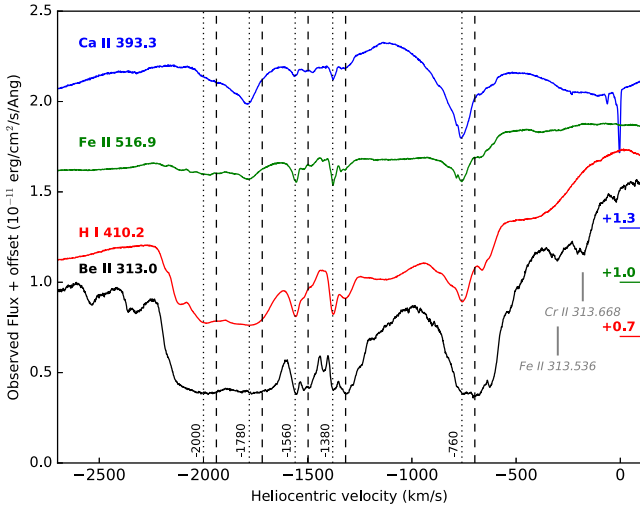


Figure 3. Same as Fig. 1 with the Nova spectrum of day 63. Legend as in Fig. 1. Note the presence of the partially resolved components of the ${}^7\text{Be}$ $\lambda\lambda 313.1228$ nm line for the components at velocities ≈ -1380 and -1560 km s $^{-1}$.

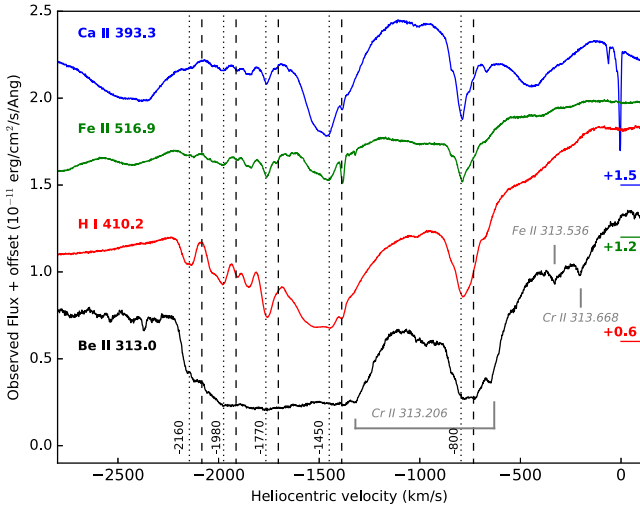


Figure 4. Same as Fig. 1 with the Nova spectrum at day 69. This observation is close to the one discussed in Tajitsu et al. (2016).

Fig. 3 displays portions of the Nova spectrum obtained on day 63. The components at velocities ≈ -1380 and -1560 km s $^{-1}$ become sharper and it is possible to identify the partially resolved component of the ${}^7\text{Be}$ $\lambda\lambda 313.1228$ nm line shown in the figure by vertical blue dashed lines. In addition, some absorption consistent with its presence can be observed in the -760 km s $^{-1}$ component as well as in all other lines. It is quite remarkable that while H γ shows some structure, ${}^7\text{Be}$ does not, and this is likely due to the presence of the doublet lines filling the inter-component velocity-space. Fig. 4 displays the spectrum obtained on day 69 which is very close to the spectrum analysed by Tajitsu et al. (2016). As it can be seen the narrow component identified by Tajitsu et al. (2016) as ${}^7\text{Be}$ $\lambda\lambda 313.1228$ nm is blended with the -1450 km s $^{-1}$ component of the Cr II $\lambda\lambda 313.2058$ nm. Fig. 5 displays portions of the spectrum obtained on day 73. At this epoch the high velocity components at ≈ -2000 km s $^{-1}$ weaken considerably in ${}^7\text{Be}$ revealing the presence of the ${}^7\text{Be}$ $\lambda\lambda 313.1228$ nm line in the components marked with a dashed blue line in the figure. To note

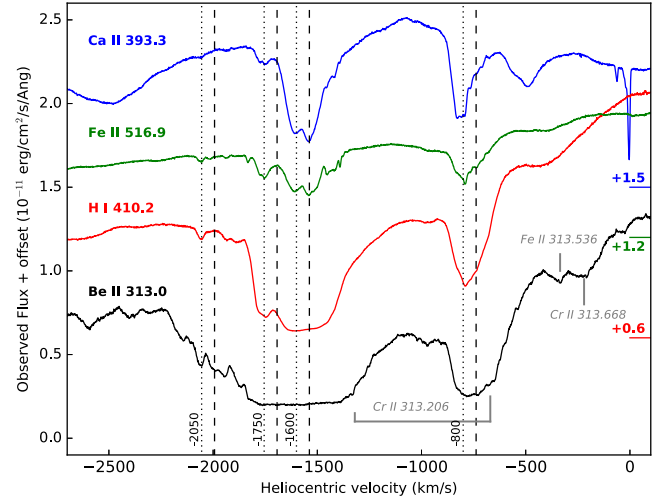


Figure 5. Same as Fig. 1 with the Nova spectrum at day 73. The ${}^7\text{Be}$ $\lambda\lambda 313.1228$ nm line is partially resolved in the component at velocities ≈ -2050 km s $^{-1}$.

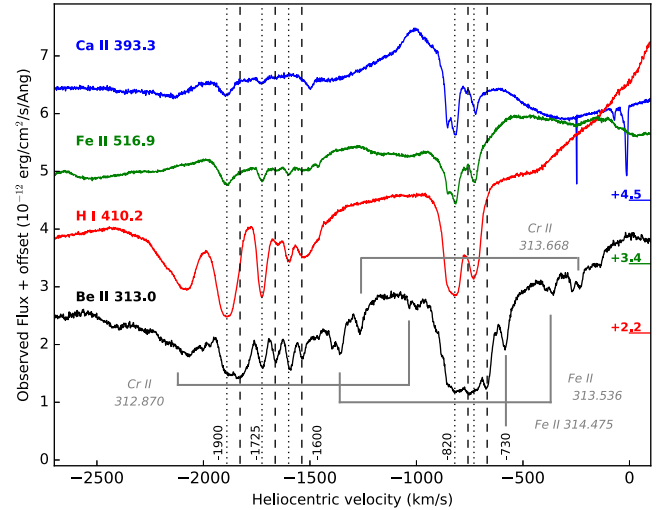


Figure 6. Same as Fig. 1 with the Nova spectrum at day 82. The ${}^7\text{Be}$ $\lambda\lambda 313.1228$ nm line is partially resolved in the two components which break up at velocities ≈ -820 km s $^{-1}$ and fully resolved in the components at velocities at ≈ -1600 and -1725 km s $^{-1}$ which were previously strongly saturated. Note the components at -1900 km s $^{-1}$ of the Cr II and Fe II which are now visible due to the ${}^7\text{Be}$ weakening.

that at this day the ${}^7\text{Be}$ $\lambda\lambda 313.1228$ nm line is partially resolved in the two components which break up at velocities ≈ -820 km s $^{-1}$ and is fully resolved in the components at velocities between ≈ -1600 and -1725 km s $^{-1}$ which were previously strongly saturated. After few days from this observation all the metallic components disappeared and therefore later observations are not considered here. Due to the weakening of the ${}^7\text{Be}$ on day 82 also the metallic contaminants due to iron-peak elements appear very clearly. The Cr II (5) $\lambda\lambda 313.6680$ nm and the Fe II (82) $\lambda\lambda 313.5360$ and 314.4751 nm lines are now seen at -1900 km s $^{-1}$ and should have been present also in the previous epochs but completely obscured by the strong

$^7\text{Be II}$ absorption. The $\text{Cr II (5)} \lambda\lambda 313.6680$ and 312.8699 nm and the $\text{Fe II (82)} \lambda\lambda 313.5360$ nm lines are now seen at -820 km s^{-1} . Scaling with the relative strengths of the other iron-peak elements we estimate that the combined contributions of these contaminants are ≈ 3.5 per cent of the total equivalent widths of the $^7\text{Be II}$ absorption.

2.2 ^7Be abundance

The abundance of ^7Be can be estimated by comparing the equivalent widths $W(^7\text{Be II})$ and $W(\text{Ca II K})$ for unsaturated and resolved lines, assuming that the covering factor of the absorbing expanding shell is constant with wavelength. Ca is not a Nova product and can be taken as a reference element. The more suitable components are the features of $^7\text{Be II}$ and the Ca II K lines observed at -1500 km s^{-1} on day 82. Though, we are aware that these abundances do not necessarily represent the abundances in the whole materials ejected.

Following Spitzer (1998) and Tajitsu et al. (2015) the ratio of column densities, N , can be written as

$$\frac{N(^7\text{Be II})}{N(\text{Ca II})} = 2.164 \times \frac{W(^7\text{Be II, Doublet})}{W(\text{Ca II, K})} \quad (1)$$

For the components at -1500 km s^{-1} on day 82 we measured $W(^7\text{Be II}) = (0.095 \pm 0.060) = 0.155 \text{ \AA}$ and the $W(\text{Ca II K}) = 0.019 \text{ \AA}$ which provide a column density ratio of $N(^7\text{Be II})/N(\text{Ca II}) = 17.7$. Assuming that most of ^7Be and Ca are in the singly ionized state as discussed in Tajitsu et al. (2016) these are also the relative elemental abundances. The presence of Na I in the blueshifted absorption line systems along with the presence of Ca I on day 58, as shown below, and the absence of doubly ionized iron-peak elements support this assumption. Since our measurement refers to day 82 after maximum and ^7Be decays to ^7Li via K-electron capture with a half-life of 53.22 d, the amount of ^7Be freshly produced by the Nova should have been ≈ 3 times larger which gives an atomic fraction $N(^7\text{Be})/N(\text{Ca})$ of ≈ 53 . We can determine the ^7Be abundance also for the component at -1175 km s^{-1} on day 58, which is fully resolved but slightly saturated. In this case we have $W(^7\text{Be II}) = (0.089 \pm 0.073) = 0.162 \text{ \AA}$ and the $W(\text{Ca II K}) = 0.011 \text{ \AA}$ which provides a $N(^7\text{Be II})/N(\text{Ca II}) = 31.9$. Considering that on day 58 the original value should have been a factor of 2.15 larger, we obtain an original atomic fraction $N(^7\text{Be})/N(\text{Ca})$ of ≈ 69 , which is quite consistent with the former value considering the uncertainties involved. Tajitsu et al. (2016) derived a $N(^7\text{Be II})/N(\text{Ca II}) = 8.1 \pm 2.0$ in the component at -786 km s^{-1} on day 63 without considering $^7\text{Be II}$ decay. Since this component is saturated, the derived abundance is a lower limit and therefore the two measurements are consistent with each other.

2.3 Nova ^7Be production

Thermonuclear production of ^7Be during the Nova explosions of hydrogen-rich layers containing some ^3He has been proposed by Arnould & Norgaard (1975) and Starrfield et al. (1978). Peak temperatures of 150 million K are reached in the burning regions and ^7Be is readily formed from the ^3He coming from the companion star via the reaction $^3\text{He}(\alpha, \gamma)^7\text{Be}$ (Hernanz et al. 1996). In this hot environment ^7Be can be also destroyed and it needs to be carried to cooler regions by convection on a time-scale shorter than the destruction time-scale as in the Cameron–Fowler mechanism (Cameron & Fowler 1971). The cooler regions are subsequently ejected and observed in absorption in the Nova outburst. Carbon and oxygen (CO) Novae destroy less ^3He with respect to oxygen

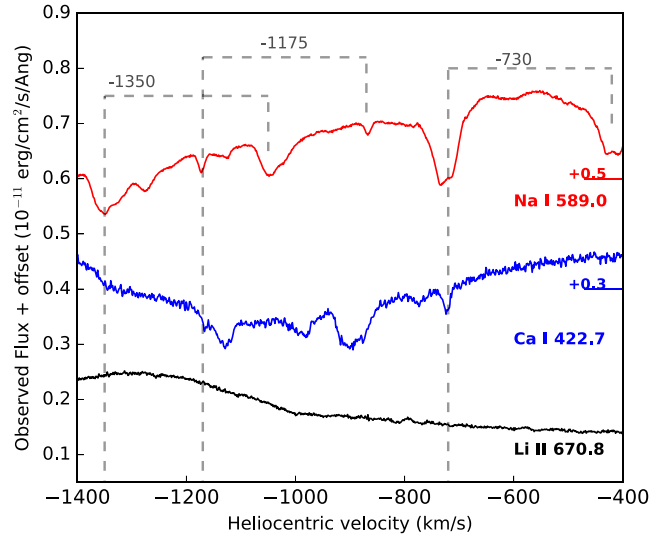


Figure 7. Nova spectrum at day 58 in the vicinity of $^7\text{Li I } \lambda\lambda 670.8$ nm (black line), Na I D doublet (red) and Ca I $\lambda\lambda 422.7$ nm (blue).

and neon (ONe) Novae, and therefore CO Novae have higher ^7Be yields (José & Hernanz 1998).

The detection of ^7Be in the post-outburst spectra of Nova Sagittarii 2015 shows that thermonuclear production of ^7Be is effectively taking place. The fact that ^7Be is detected at all velocities implies that all the absorption components are made of ejecta which have experienced thermonuclear runaway nucleosynthesis. However, the observed yields are larger by about one order of magnitude than predicted by the models of José & Hernanz (1998) and even more if compared with the models of Boffin et al. (1993). The number of freshly produced ^7Be atoms in Nova ejecta is necessarily lower than that of ^3He atoms in the accreted gas from the donor star or produced in situ as a result of the so called ^3He bump (Denissenkov et al. 2013). This implies that the fraction of ($^3\text{He}/\text{H}$) should be greater than 10^{-4} .

2.4 Nova ^7Li production

The ^7Be decays to ^7Li with a half-life of 53.22 d which is comparable with our temporal span. However, we do not detect counterparts of blueshifted absorption line systems of the $^7\text{Li I } \lambda\lambda 670.8$ nm in spite of the high signal-to-noise ratios of our spectra. Fig. 7 displays the spectrum on day 58 in the vicinity of $^7\text{Li I } \lambda\lambda 670.8$ nm, Na I D doublet and Ca I $\lambda\lambda 422.7$ nm lines. The other epochs are similar with the only difference that the trace Ca I disappears. We note however that while Ca I is non-present the Na I D lines are relatively strong and the complete absence of ^7Li is rather puzzling. It is interesting to report that these lines have been detected in the first three weeks spectra of Nova Centauri 2013 (Izzo et al. 2015) and that Izzo et al. (private communication) detected $^7\text{Li I } \lambda\lambda 670.8$ nm in spectra of V5668 Sgr taken on day 7. The non-detection of ^7Li in our observations implies that the ejected gas has a temperature high enough that almost all Li and Ca atoms are ionized. Normally Li is not detected in Novae outburst spectra and the unique Li I detection by Izzo et al. (2015) implies that the physical conditions in the ejecta permit the survival of neutral $^7\text{Li I}$ only in the very early stages. Since $^7\text{Be II}$ decays to $^7\text{Li II}$ the non-detection of $^7\text{Li I}$ in our epochs requires that ^7Li remains singly ionized while some Na I survives.

Since ${}^7\text{Be} = {}^7\text{Li}$ the $X({}^7\text{Be})/X(\text{Ca})$ fraction derived here corresponds to a ${}^7\text{Li}$ logarithmic overabundances of +4.7 dex with respect to the meteoritic value (Lodders, Palme, & Gail 2009), which is even higher than the overabundance of 4 dex obtained by Izzo et al. (2015) in Nova Centauri 2013. Theoretically the amount of ${}^7\text{Li}$ is a sensitive function of the conditions achieved in the outburst and from the initial ${}^3\text{He}$ of the companion star, and are expected to vary. The Novae in which ${}^7\text{Li}$ or ${}^7\text{Be}$ have been detected to date are all *slow* Novae characterized by $t_2 > 60^d$. However, it is quite remarkable that large ${}^7\text{Be}$ yields are observed in all three Novae where ${}^7\text{Be II}$ has been searched for. For a total ejected mass of $\approx 10^{-5} M_\odot$ the observed overproduction factor of V5668 Sgr implies a production of $M_{\text{Li}} \approx 7 \times 10^{-9} M_\odot$. The global Nova rate in the Galaxy is known within a factor of 2 (25–50 yr^{-1}) (della Valle & Livio 1994; Shafter 2016) and the *slow* Novae account for ≈ 10 per cent of the whole population (della Valle & Duerbeck 1993). However, a rate of 2 yr^{-1} of *slow* Nova events with the observed ${}^7\text{Li}$ overproduction in a Galaxy lifetime of $\approx 10^{10}$ yr is enough to produce $M_{\text{Li}} \approx 140 M_\odot$. This is comparable with the $M_{\text{Li}} \approx 150 M_\odot$ estimated to be present in the Milky Way inclusive of the $M_{\text{Li}} \approx 40 M_\odot$ produced in the big bang (Fields, Molaro, & Sarkar 2014). Thus, the *slow* Novae could indeed be the main factories of ${}^7\text{Li}$ in the Galaxy.

3 SUMMARY AND CONCLUSIONS

We have analysed UVES high resolution observations of V5668 covering six outburst phases from day 58 to day 89 from maximum. The evolution of the absorption offers clear evidence in support of the identification of ${}^7\text{Be II}$ by Tajitsu et al. (2016). In particular, the weakening of the ${}^7\text{Be II}$ absorptions at a late epoch shows that the iron-peak species are a minor contaminant. By means of unsaturated Be II components we derived an abundance of $N({}^7\text{Be})/N(\text{Ca}) \approx 53$ –69 when the ${}^7\text{Be}$ decay is taken into account. Assuming all the ${}^7\text{Be}$ goes into ${}^7\text{Li}$ this corresponds to a ${}^7\text{Li}$ overproduction of 4.7–4.9 dex over the solar-meteoritic value. We then argue that a rate of 2 yr^{-1} of such events in a Galaxy lifetime, i.e. only a small fraction of all Novae, could be responsible for the production of the whole ${}^7\text{Li}$ required from *stellar* sources.

We also notice that such a high ${}^7\text{Be}$ production should increase the probability of detecting the 478-keV γ -ray photons emitted in the ${}^7\text{Be}$ to ${}^7\text{Li}$ reaction which have been so far elusive despite several γ -ray searches.

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