Highly Enriched $^7$Be in the ejecta of Nova Sagittarii 2015 No. 2 (V5668 Sgr) and the Galactic $^7$Li origin

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ABSTRACT

We report on the evidence of highly blue-shifted resonance lines of the singly ionised isotope of $^7$Be\textsuperscript{ii} in high resolution UVES spectra of Nova Sagittarii 2015 No. 2 (V5668 Sgr). The resonance doublet lines $^7$Be\textsuperscript{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\textsuperscript{ii} has an equivalent width much larger than all other elements and comparable to hydrogen. We estimate an atomic fraction $N(^7\text{Be})/N(Ca) \approx 53-69$ from unsaturated and resolved absorption components. The detection of $^7$Be in several high velocity components shows that $^7$Be has been freshly created in a thermonuclear runaway via the reaction $^3$He($\alpha,\gamma$)\textsuperscript{7}Be during the Nova explosion, as postulated by Arnould & Norgaard (1975), however in much larger amounts than predicted by current models. $^7$Be\textsuperscript{ii} decays to $^7$Li\textsuperscript{ii} with a half-life of 53.22 days, comparable to the temporal span covered by the observations. The non detection of $^7$Li requires that $^7$Li remains ionised throughout our observations. The massive Be\textsuperscript{ii} ejecta result into a $^7$Li production that is $\approx 4.7-4.9$ dex above the meteoritic abundance. If such a high production is common even in a small fraction ($\approx 5\%$) of Novae, they can make all the stellar $^7$Li of the Milky Way.

Key words: stars: individual V5668 Sgr; stars: novae – nucleosynthesis, abundances; Galaxy: evolution – abundances

1 INTRODUCTION

$^7$Li 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 $^7$Li has a constant abundance among metal-poor stars and begins to rise at [Fe/H] $\approx -1$ to reach the meteoritic value at solar metallicities (Rebolo, Beckman & Molaro 1988) requiring a net $^7$Li production (Romano et al. 1999). The rate of the Li increase favours AGB stars and Novae as the most significant stellar sources. Although $^7$Li 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 $^7$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 $^7$Be in the post-outburst spectra of the classical Nova Delphini 2013 (V339 Del).

Here, we report a study of the Be\textsuperscript{ii} by means of UVES observations of Nova Sagitarii 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 $^7$Be\textsuperscript{ii} in this Nova, and also in V2944 Oph.

2 OBSERVATIONS

2.1 Evidence for $^7$Be\textsuperscript{ii}

Nova Sagitarii 2015 No. 2 was discovered by Seach (2015) on 15 March 2015 and reached the first maximum on 21 March
at 04h 04m UT with a magnitude of $V = 4.3$. The Nova re-brightened several times and remained bright for about 80 days before declining due to dust formation. Soon after the discovery we started a DDT program with the UVES spectrograph at the ESO-VLT. Several UVES spectra were obtained at +58, 63, 69, 73, 82 and 89 days from maximum as reported in Table 1. The settings with central 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 $\approx 10$ 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 maximise 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 ionised species often accompanied by sharp and blue-shifted multiple absorption components reaching blue edge velocities of $\approx -2300$ km s$^{-1}$. Figure 2 displays portions of the Nova spectrum of day 58 in the proximity of H$\gamma$, 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 $v_{\text{rad}} \sim -730, -1175, -1350, -1580, -1780 \text{ and } -2200$ 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 blue-shifted absorption that Tajitsu et al. (2016) identified as $^7$Be. 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 $\approx 0.19$ Å) are separated by 0.654 Å which corresponds precisely to the separation of the $^7$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 $^7$Be II and not $^9$Be II which has an isotopic shift of $-15.4$ km s$^{-1}$. The dips of each line of the $^7$Be II doublet can be identified also at $-730$ km s$^{-1}$ in Fig 2, but become hard to see in the flat bottoms of the other components. At velocities $\lesssim -1600$ km s$^{-1}$ the absorption profile ascribable to Be II 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 $^7$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 $^7$Be II the intensities are $\sim 50\%$ but the intensity value varies with the day and the geometry of the outburst.

The $^7$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 $\sim -730, -1175$ 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 $\sim -730$ 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 $^7$Be II $\lambda$313.1228 nm line for the components at velocities $\approx -1380$ 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 5 displays portions of the Nova spectrum obtained on day 63. The components at velocities $\approx -1380$ and $-1560$ km s$^{-1}$ become sharper and it is possible to identify the partially resolved component of the $^7$Be II $\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$\gamma$ shows some structure, $^7$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 63 which was 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 $^7$Be II 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 blue line in the figure. To note that at this day the $^7$Be II absorption spans wider velocities than H$\gamma$.

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

Figure 6. Same as Fig 1 with the Nova spectrum at day 82. The $^7$Be II 313.1228 nm line is partially resolved in the two components which break up at velocities $\approx -820$ km s$^{-1}$ and fully resolved in the components at velocities $\approx -1600$ 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 $^7$Be weakening.
nm lines are now seen at $-1900\ \text{km s}^{-1}$ and should have been present also in the previous epochs but completely obscured by the strong $^{7}\text{Be}\,\text{II}$ absorption. The $\text{Cr}\,\text{II}$ (5) $\lambda\lambda313.6680$ and $312.8699\ \text{nm}$ and the $\text{Fe}\,\text{II}$ (82) $\lambda\lambda313.5360\ \text{nm}$ lines are now seen at $-820\ \text{km s}^{-1}$. Scaling with the relative strengths of the other iron-peak elements we estimate that the combined contributions of these contaminants are $\approx 3.5\%$ of the total equivalent widths of the $^{7}\text{Be}\,\text{II}$ absorption.

### 2.2 $^{7}\text{Be}$ abundance

The abundance of $^{7}\text{Be}$ can be estimated by comparing the equivalent widths $W^{\prime}(^{7}\text{Be}\,\text{II})$ and $W^{\prime}(\text{Ca}\,\text{II}\,\text{K})$ 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 $^{7}\text{Be}\,\text{II}$ and the $\text{Ca}\,\text{II}\,\text{K}$ lines observed at $-1500\ \text{km s}^{-1}$ on day 82. Though, we are aware that these abundances do not necessarily represent the abundances in the whole materials ejected.

Following [Spitzer (1908)] and [Tajitsu et al. (2015)], the ratio of column densities, $N$, can be written as

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

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

Thermonuclear production of $^{7}\text{Be}$ during the Nova explosions of hydrogen-rich layers containing some $^{7}\text{Be}$ 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 $^{7}\text{Be}$ is readily formed from the $^{4}\text{He}$ coming from the companion star via the reaction $^{4}\text{He} + (\alpha, \gamma)^{7}\text{Be}$ ([Hernanz et al. 1996]). In this hot environment $^{7}\text{Be}$ 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 $^{7}\text{He}$ with respect to oxygen and neon (O, Ne) Novae, and therefore CO Novae have higher $^{7}\text{Be}$ yields ([José & Hernanz 1998]).

The detection of $^{7}\text{Be}$ in the post-outburst spectra of Nova Sagittarii 2015 shows that thermonuclear production of $^{7}\text{Be}$ is effectively taking place. The fact that $^{7}\text{Be}$ 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 $^{7}\text{Be}$ atoms in Nova ejecta is necessarily lower than that of $^{4}\text{He}$ atoms in the accreted gas from the donor star or produced in situ as a result of the so called $^{4}\text{He}$ bump ([Denissenkov et al. 2013]). This implies that the fraction of $(^{4}\text{He}/\text{H})$ should be greater than $10^{-4}$.

### 2.4 Nova $^{7}\text{Li}$ production

The $^{7}\text{Be}$ decays to $^{7}\text{Li}$ with a half-life of 53.22 days which is comparable with our temporal span. However, we do not detect counterparts of blue-shifted absorption line systems of the $^{7}\text{Li}$ $λ\lambda670.8\ \text{nm}$ in spite of the high signal-to-noise ratios of our spectra. Figure 7 displays the spectrum on day 58 in the vicinity of $^{7}\text{Li}$ $λ\lambda670.8\ \text{nm}$, Na D doublet and Ca $λ\lambda422.7\ \text{nm}$ lines. The other epochs are similar with
Table 2. Contaminants from Fe-peak elements in the range of the \(^{7}\text{Be}\) doublet measured in the spectrum of day 82.

| Lines     | \(\lambda_{\text{lab}}(\text{Å})\) | \(\log gf\) | \(W\) (mA) \(\approx -820\) | \(W\) (mA) \(\approx -1900\) |
|-----------|---------------------------------|-------------|-----------------------------|-----------------------------|
| Cr \(\text{ii}\) (5) | 3120.3691                      | 0.120       | 16: ± 8                     | -                           |
| Cr \(\text{ii}\) (5) | 3124.973                        | -0.018      | b                           | b                           |
| Cr \(\text{ii}\) (5) | 3128.700                        | -0.320      | 25 ± 7                      | b                           |
| Ca \(\text{ii}\) (5) | 3132.053                        | 0.079       | b                           | b                           |
| Fe \(\text{ii}\) (82) | 3135.360                        | -1.130      | 40 ± 7                      | 104 ± 10                    |
| Cr \(\text{ii}\) (5) | 3136.681                        | -0.250      | 45 ± 8                      | 51 ± 15                     |
| Fe \(\text{ii}\) (82) | 3144.751                        | -1.740      | b                           | 83 ± 10                     |

Table 2 contains contaminants from Fe-peak elements in the range of the \(^{7}\text{Be}\) doublet measured in the spectrum of day 82.

The only difference that the trace Ca \(\text{i}\) disappears. We note however that while Ca \(\text{i}\) is non present the Na\(1\)D lines are relatively strong and the complete absence of \(^{7}\text{Li}\) 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 (2016) detected \(^{7}\text{Li}\) \(\lambda\)670.8 nm in spectra of V5668 Sgr taken on day 7. The non detection of \(^{7}\text{Li}\) in our observations implies that the ejected gas has a temperature high enough that almost all Li and Ca atoms are ionised. Normally Li is not detected in Novae outburst spectra and the unique Li \(\text{i}\) detection by Izzo et al. (2015) implies that the physical conditions in the ejecta permit the survival of neutral \(^{7}\text{Li}\) only in the very early stages. Since \(^{7}\text{Be}\) decays to \(^{7}\text{Li}\) the non detection of \(^{7}\text{Li}\) in our epochs requires that \(^{7}\text{Li}\) remains singly ionised while some Na \(\text{i}\) survives.

Since \(^{7}\text{Be} = ^{7}\text{Li}\) the \(X(X)^{7}\text{Be}/X(Ca)\) fraction derived here corresponds to a \(^{7}\text{Li}\) logarithmic overabundances of \(+4.7\) dex with respect to the meteorite value (Lodders, Palme & Gail 2009), which is even higher than the over-abundance 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 \(^{7}\text{He}\) 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 characterised by \(t_{2} > 60\). However, it is quite remarkable that large \(^{7}\text{Be}\) yields are observed in all three Novae where \(^{7}\text{Be}\) 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 \(M_{\text{Li}} \approx 7 \cdot 10^{-9}M\odot\). The global Nova rate in the Galaxy is known within a factor two (25 – 50 yr \(^{-1}\)) (della Valle & Livio 1994, Shafter 2016), and the slow Novae account for \(\approx 10\)% 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 \(^{7}\text{Be}\) by Tajitsu et al. (2016). In particular, the weakening of the \(^{7}\text{Be}\) absorptions at a late epoch shows that the iron-peak species are a minor contaminant. By means of unsaturated \(^{7}\text{Be}\) components we derived an abundance of \(N(^{7}\text{Be})/N(Ca) \approx 53-69\) 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 \(\gamma\)-ray photons emitted in the \(^{7}\text{Be}\) to \(^{7}\text{Li}\) reaction which have been so far elusive despite several \(\gamma\)-ray searches.

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\(^{7}\text{Be in Nova Sgr2}\)