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Observations of ^{7}Be and ^{7}Li in classical novae

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Abstract. The abundance of lithium observed in very young stellar populations is few times larger than the primordial one estimated by recent Planck measurements. Since Lithium is easily destroyed in the stellar interiors, the search for astrophysical sources responsible for the observed lithium over-abundance was a challenge for decades. In this manuscript, we describe the results of an on-going survey dedicated to the study of nova outburst with high-resolution spectrographs at ESO/VLT, aimed at detecting beryllium-7. Our results represent a further confirmation of the occurrence of the thermonuclear runaway during nova explosions and imply that classical novae are one of the main factories of lithium in the Galaxy.

Key words. Stars: abundances – Galaxy: abundances – Stars: novae – ISM: abundances

1. Introduction

Lithium is one of the most fragile elements in the Universe. Due to its lowest binding energy per nucleon it is easily destroyed in almost any astrophysical process. Lithium is also the only "metal" formed during the Big Bang nucleosynthesis (BBN), due to the absence of a stable element formed by four protons and four neutrons: ^{8}Be is highly unstable and rapidly decays into two α-particles. However, the primordial abundance of lithium, as inferred from the observation of old Galactic halo stars, does not match with the expectations from the standard BBN scenario (Fields 2011): this problem is also known as the "Cosmological Lithium problem" (Cyburt et al. 2016; Coc & Vangioni 2017) and it is possibly ascribed to convective over-shooting occurring in stars during their pre-main sequence phase(Fu et al. 2015). In passing we note that different explanations can arise from new exotic physics in the early Universe (see e.g. Fields 2011; Yamazaki et al. 2017). On the other hand, Galactic younger stellar populations show an over-abundance of lithium in their spectra (see Lambert & Reddy 2004; Ramírez et al. 2012, and references therein), which implies the existence of currently active factories of lithium in the Galaxy (Romano et al. 2001). However, the yield required by all the possible astrophysical sources of lithium operating in the Milky Way are way higher than the ones inferred using observations and models for the stellar nucleosynthesis (Prantzos 2012; Grisoni et al. 2019).

The recent discovery of a considerable amount of ionized ^{7}Be observed in the spectra of bright classical novae (CN) (Tajitsu et al. 2015; Molaro et al. 2016) has caught in the spotlight the role of novae as possible main factories of lithium in the Galaxy. Thanks to the use of high-resolution spectrographs we were also capable to detect the resonance transition of neutral lithium in the early spectra of V1369 Cen (Izzo et al. 2015) and V906 Car (Molaro et al. 2019). But how lithium can be produced in this class of astrophysical sources ? CNe originate in the thermo-nuclear runaway (TNR, Starrfield et al. 1978) of matter accreted onto the surface of a white dwarf (WD), which is situated in a binary system with a late-type MS star or a red giant or sub-giant companion. The geometrical configuration of these systems and their evolutionary stages allow the secondary star to fill its Roche lobe and then matter escapes from the gravitational force and moves toward the primary WD through the Lagrangian L1 point. As the matter piles up on the WD surface, the temperature at the base of the accreted layer rises until the first nuclear reactions (pp-chain) ignite. At the same time, convection allows CNO elements from the interior of the WD to feed the CNO-cycle reaction, and this process paves the way to a rapid production of unstable β^+-isotopes, whose decay provides the energy to expand the outer layers eventually generating the nova phenomenon (for a more detailed review see Bode & Evans 2012). During the TNR, the presence of ^{3}He permits the production of the isotope ^{7}Be (Arnould & Norgaard 1975; Starrfield et al. 1978) via:

$$^3He(\alpha,\gamma)^7Be \tag{1}$$

that can be ejected into the ISM. Moreover, ^{7}Be decays only via the electron capture process, producing ionised lithium and the emission of a high-energy photon at 578 keV:

$$^7Be(e^-,\nu)^7Li \tag{2}$$

2. ^{7}Be and ^{7}Li observations

2.1. The detection of lithium in CNe

Signatures of lithium were largely searched in the spectra of CNe in the last 40 years but the lack of detection of the neutral transition visible at λ = 670.8 nm led only to upper limits on its abundance (Friedjung 1979; Della Valle et al. 2002). In the last years, we have started a survey using high-resolution spectrographs in order to study the narrow absorption lines observed in the early spectra of bright CNe, also reported as transient heavy element absorption (THEA, Williams et al. 2008). We got spectra of the CN V1369 Cen in late 2013 and in addition to the presence of about 300 THEA lines we also noticed the presence of Li I λ6708 at the expanding blue-shifted radial velocity of $v_{exp} = -550$ km/s, see also Fig. 1. This velocity was also observed for other low-ionisation features like Na ID, K I and Fe II. A detailed analysis led to the confirmation of the presence of neutral lithium in the ejecta of V1369 Cen (Izzo et al. 2015). This was the first identification of lithium in the ejecta of a CN and our analysis, using the Na ID and K I lines as reference, showed that the total amount of lithium expelled in this nova outburst inferred from the Li I resonance line was $M_{Li} \div 1 - 5 \times 10^{-10}$ $M_\odot$ consistently with the above reported upper limits. Assuming that all slow novae similar to V1369 Cen synthesised a similar amount of lithium during 10 Gyr and a Galactic nova rate of $\sim$ 20 novae/yr, we concluded that CNe contribute to a significant amount of lithium in the Milky Way (Izzo et al. 2015). In the following years, we detected traces of Li I only in other two novae, V5668 SGR (Izzo 2019) and V906 Car (Molaro et al. 2019), respectively.

2.2. Beryllium observations in CNe

The detection of the resonance doublet of ^{7}Be II in V339 Del was carried out for the first time by Tajitsu et al. (2015). In this nova, a considerable amount of ionised beryllium was observed over several days and the abundance ratio with respect to hydrogen was measured to be ^{7}Be/H $\sim 5\times 10^{-5}$ (Tajitsu et al. 2015). After the detec-

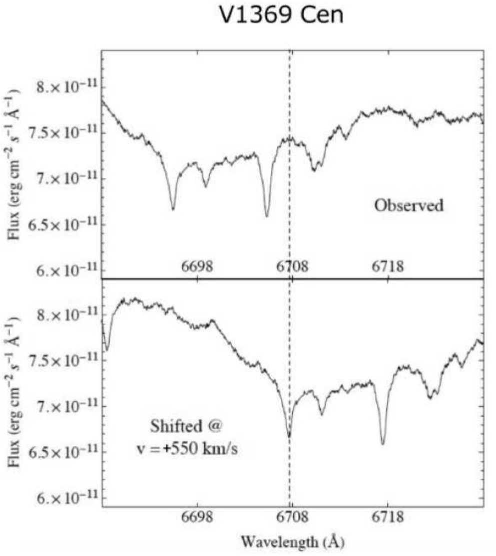

Fig. 1. The spectrum of V1369 Cen obtained six days after the discovery of the nova with FEROS at the 2.2m telescope located in La Silla (Chile). The upper panel shows thew observed spectrum while the lower panel shows the same spectrum corrected for a blue-shifted velocity of -550 km/s. The correction for the expanding velocity confirms the presence of Li I λ6708.

tion in V339 Del, we started to observe CNe with the ESO/VLT UVES spectrograph that provides a very high spectral resolution, useful for narrow features, in combination with a wide spectral range, from $\sim$ 3,000 Å to 10,000 Å. For some faint novae, we have also used X-shooter, a lower resolution echelle spectrograph that covers also the near infrared wavelength range up to 25,000 Å. During the four years of the program, we have observed eight novae, two of them in the Magellanic Cloud galaxies. A collaborator of us (P. Selvelli) has also started an archival effort to analyse CNe observed with the IUE satellite back in the '90s, and a first detection of ^{7}Be II in V838 Her was already published (Selvelli et al. 2018).

Observations of V5668 Sgr have allowed to carry out the first detection of beryllium with a ground based facility (VLT+UVES) (Molaro et al. 2016). We followed the evolution of the nova from day 56 after the discovery through the following $\sim$ 50 days. We observed broad P-Cygni profiles for the ^{7}Be II resonance doublet, characterised by two main component at different velocities, see also Fig. 2. This is a feature that we have observed in almost all the CNe in our sample. The absorptions were so strong that we could measure equivalent widths (EWs) for ^{7}Be II only in the spectrum of Day 83, when the wings of the absorptions did not show the broadening typical of saturation effects. We estimated the abundance of beryllium produced in the TNR using the Ca II H,K lines as term of comparison: if the optical depth along the line of sight is relatively small we can determine the relative element abundances using the ratio of the EW mediated by the oscillator strengths of the transitions considered. In the specific, we used the following formula:

$$\frac{N(^7BeII)}{N(CaII)} = \frac{gf_{CaII}}{gf_{^7BeII}} \frac{EW(^7BeII)}{EW(CaII)} \tag{3}$$

The final value for beryllium abundance must be still corrected for the amount of beryllium that has already decayed into lithium, given that the half-life time for the electron capture decay of ^{7}Be II into Li is about 53 days. Consequently, in each spectrum used for the abundance estimate we would miss a fraction of the total beryllium synthesised during the TNR, which is related to the epoch, from the initial TNR, of the same spectrum.

Assuming a solar abundance for calcium, we obtained a very large amount of lithium ($M_{Li} \sim 10^{-8}$ M$_\odot$) synthesised in V5668 Sgr and with this lithium yield we inferred that only a bunch of CNe like V5668 Sgr are enough to explain the higher than primordial abundance of lithium observed in young stellar populations (Molaro et al. 2016). We obtained similar results for V407Lup, another nova that we monitored the year following the V5668 Sgr observational campaign. V407 was a fast nova, characterised by a less massive ejecta than V5668 Sgr and a more massive primary WD; this was confirmed in the nebular spectrum obtained 155 days after the nova discovery when forbidden neon lines represented the brightest emission lines observed in the optical

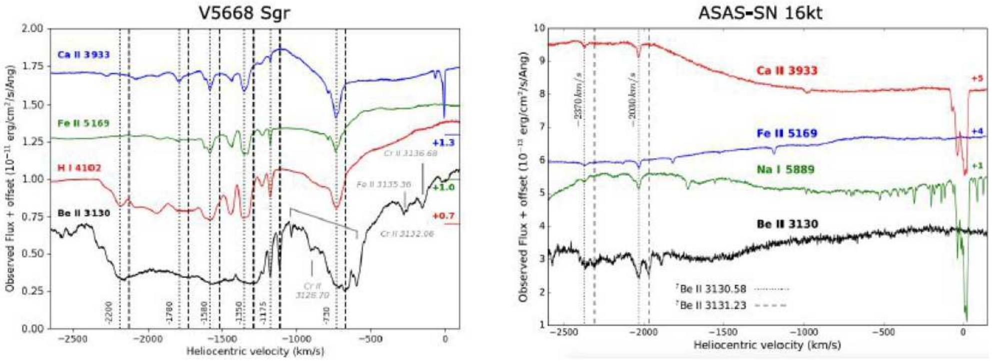

Fig. 2. (Left panel) The spectrum of V5668 Sgr obtained with UVES on Day 56 showing the presence of ^{7}Be II compared with other transitions like Fe II λ5169, Ca II λ3933 and Hδ. (Right panel) The spectrum of V407 Lup (ASASSN-16kt) obtained with UVES on Day 8 and showing the presence of ^{7}Be II compared with other transitions like Fe II λ5169, Ca II λ3933 and Na I 5889. Dashed and dotted line mark the multiple velocity components for the Be II doublet lines.

spectrum, an indication of an underlying ONe WD as the nova progenitor. The presence of ^{7}Be II was confirmed in the first spectrum obtained only eight days after the nova discovery, see Fig. 2. The abundance inferred from the line ratio methods using Ca II lines resulted to be lower ($M_{Li} \sim 3 - 5 \times 10^{-9}$ M$_{\odot}$) than the abundance observed in V5668 Sgr, but still consistent with other measurements (Izzo et al. 2018).

In the last years (2017-2018) we have observed with UVES the evolution of additional four bright novae: ASASSN-17hx, V357 Mus, V906 Car and FM Cir (Molaro et al. 2019). We were capable to observe the evolution of these CNe during their bright phases of the emission. We clearly detect ^{7}Be II in two of these CNe (namely V906 Car and V357 Mus) while the presence of ^{7}Be II in FM Cir is not uniquely clear, due to the presence of blended components from other elements like Cr II and Fe II. However, the most interesting result comes from the non-detection of beryllium in ASASSN-17hx in any of the spectra that we got for this nova, see Fig. 3. The light curve of ASASSN-17hx is, however, quite peculiar, being characterised by the presence of multiple maxima and by a very slow decline after the peak brightness. This evidence suggests the presence of a massive ejecta from a low massive progenitor WD, which is a solution in agreement with the most recent simulations of CN eruption (Starrfield et al. 2018).

The amount of beryllium inferred from the two CNe described above (V906 Car and V357 Mus) is in line with previous estimates obtained for othMolaro2019er novae.

In Table 1 it is reported the relative abundance of beryllium with respect to the hydrogen for the six novae studied so far for which we have detected the ^{7}Be II line. Five of these novae have a CO progenitor WD and only one has a ONe progenitor. We have also included an estimate for the t_2 parameter, which is the time that a nova takes to decay by 2 magnitudes from maximum light and can be considered a proxy for the progenitor mass, and then inversely related to the ejected matter (Livio 1992).

3. Conclusions

The total yield of lithium detected in the sample of novae presented in the previous section definitely confirms that CNe are one of the main factories of lithium in the Galaxy. Observations of the ONe nova V407 Lup show that novae are able to produce signif-

Table 1. The ^{7}Be/H (number) for the novae discussed in this manuscript and in the literature, corrected for the decay of ^{7}Be. The type column reports also CNe for which dust formation was reported. The t_2 value for V5668 Sgr was estimated after smoothing the light curve, given the presence of multiple "flares" in the brightest epochs. A more extended version of this table can be found in (Molaro et al. 2019).

Nova	Type	Epoch (days)	^{7}Be/H	t_2 (days)
V339 Del	CO	47	3.2×10^{-5}	10
V5668 Sgr	CO/dust	82	1.3×10^{-4}	~70
V2944 Oph	CO	80	1.6×10^{-5}	33
V407 Lup	ONe	8	6.2×10^{-5}	3
V357 Mus	CO/dust	35	1.5×10^{-5}	27
V906 Car	CO	80	2.2×10^{-5}	26

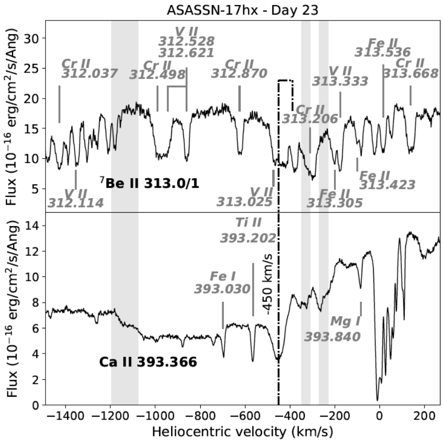

Fig. 3. The spectrum of ASASSN-17hx obtained 23 days after the discovery of the nova with UVES at the ESO/VLT. The upper panel shows the region centered on the ^{7}Be II λ3130.583 line while the lower panel is centered on the Ca II λ3933.66 line. The lack of beryllium components with the same velocities identified for the Ca II line is a clear indication of the lack (or a very low abundance) of beryllium in this nova. Note the presence of several low ionisation Fe-peak lines in correspondence of the expected P-Cygni Be II component.

icant amounts of lithium regardless of their rates of decline and progenitor WD. Recent numerical simulations dedicated to the study of the lithium abundance in the Milky Way and its main components, in particular for the thick and thin disc (Cescutti & Molaro 2019; Grisoni et al. 2019) give theoretical support to our observations. We generally have observed an amount of beryllium that is higher than the value expected from nova models (José & Hernanz 1998; Starrfield et al. 2018). In particular, the recent simulations performed by the group of Sumner Starrfield report an abundance of lithium that is $\sim$ 10 times lower than what we have inferred from our analysis. The origin of this discrepancy can not be unambiguously explained but one possibility can be found in the different abundance of lithium in the secondary stars: the process that triggers the formation of beryllium, and then lithium, is ignited by a considerable amount of ^{3}He, which is formed during the TNR but can be also accreted from the secondary. The dependence of lithium abundance from the secondary abundance is then something that does not depend directly from the progenitor WD and this evidence can be highlighted only from the analysis of a statistically significant sample of lithium novae. Nevertheless, Table 1 points out that the slowest nova in the sample that is characterized by the more massive ejecta, seems to have produced a larger amount of ^{7}Be mass with respect to faster novae, characterized by lighter ejected envelopes. At the same time, faster novae seem to show higher ^{7}Be/H number ratios, with the exception of V5668 Sgr.

The origin of the Li I resonance transition is still puzzling: it can not originate from the direct decay of ^{7}Be II, being that the Li I absorption is observed only in few novae and not at the same expanding velocities of the ^{7}Be II. This latter problem can found a possible solution in the "new paradigm" that was recently proposed after the analysis of few gamma-ray CNe (Mukai & Sokoloski 2019), where CNe are the result of a multi-phased ejection mechanism. On the other hand, the observations of CNe at high-energies can provide a definite confirmation for the synthesis of beryllium through the detection of the 478 keV emission line that forms during the electron capture process leading to the decay of beryllium into lithium. The most recent observations made with INTEGRAL have provided only upper limits to the flux of this line (Siegert et al. 2018) but the sensitivity of current detectors is so limited that they can detect this line only for novae at low distances (e.g. < 300 parsec). We are actually living a second "golden age" for the study of CNe and the future will be much brighter given the possibility of using advanced multi-wavelength detectors that will provide a more detailed picture on the role of CNe as chemical factories not only in the Milky Way but also in the most nearby systems.

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References

Arnould, M., Norgaard, H. 1975, A&A, 42, 55
Bode, M. F., Evans, A. 2012, Classical Novae (Cambridge Univ. Press, Cambridge, UK)
Cescutti, G., Molaro, P. 2019, MNRAS, 482, 4372
Coc, A., Vangioni, E. 2017, International Journal of Modern Physics E, 26, 1741002
Cyburt, R. H., et al. 2016, Reviews of Modern Physics, 88, 015004
Della Valle, M., et al. 2002, A&A, 390, 155
Fields, B. D. 2011, Annual Review of Nuclear and Particle Science, 61, 47
Friedjung, M. 1979, A&A, 77, 357
Fu, X., et al. 2015, MNRAS, 452, 3256
Grisoni, V., et al. 2019, MNRAS, 489, 3539
Izzo, L. 2019, in Southern Horizons in Time-Domain Astronomy, ed. R. E. Griffin (Cambridge Univ. Press, Cambridge, UK), IAU Symposium, 339, 61
Izzo, L., Della Valle, M., Mason E., et al. 2015, ApJ, 808, L14
Izzo, L., Molaro, P., Bonifacio P., et al. 2018, MNRAS, 478, 1601
José, J., Hernanz, M. 1998, ApJ, 494, 680
Lambert, D. L., Reddy, B. E. 2004, MNRAS, 349, 757
Livio, M. 1992, ApJ, 393, 516
Molaro, P., Izzo, L., Bonifacio, P., et al. 2019, arXiv e-prints, `arXiv:1912.13281`
Molaro, P., et al. 2016, MNRAS, 463, L117
Mukai, K., Sokoloski, J. L. 2019, Physics Today, 72, 38
Prantzos, N. 2012, A&A, 542, A67
Ramírez, I., et al. 2012, ApJ, 756, 46
Romano, D., Matteucci, F., Ventura, P., D'Antona, F. 2001, A&A, 374, 646
Selvelli, P., Molaro, P., Izzo, L. 2018, MNRAS, 481, 2261
Siegert, T., Coc, A., Delgado, L., et al. 2018, A&A, 615, A107
Starrfield, S., Bose, M., Iliadis, C., et al. 2018, American Astronomical Society Meeting Abstracts, 231, 358.11
Starrfield, S., et al. 1978, ApJ, 222, 600
Tajitsu, A., et al. 2015, Nature, 518, 381
Williams, R., et al. 2008, ApJ, 685, 451
Yamazaki, D. G., et al. 2017, International Journal of Modern Physics E, 26, 1741006