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Classical novae with CUBES

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Abstract Among the main science cases that have motivated the proposal of CUBES, a new high-resolution spectrograph for the Very Large Telescope at the European Southern Observatory, there is the study and the characterisation of the nucleosynthesis of beryllium. Classical novae have been proposed since the '70s as one of the main factories of lithium in the Galaxy, but this hypothesis has been demonstrated on empirical basis only recently thanks to the direct identification of lithium in V1369 Cen and through the observations of the resonance transition of ^{7}Be II, the ^{7}Li parent, at 313.0 nm in the near-UV range. CUBES is then the ideal instrument to quantify the amount of ^{7}Be and therefore of ^{7}Li produced by the different novae types hosted in the different components of the Milky Way and also in its nearby satellite galaxies. As important by-product of high resolution spectroscopic observa-

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tions obtained with CUBES, there are the study of the properties of nova ejecta abundances, the shocks evolution in novae and their connection with the high-energy emission observed in these transients, from satellites as Fermi and Swift.

Keywords nuclear reactions · nucleosynthesis · abundances – stars: novae

1 Introduction

Classical novae (CNe) originate in interacting binary systems composed by a primary white dwarf (WD) that accretes matter from a late-type main sequence, or a red giant companion [1]. The accreted gas piles up onto the WD surface until thermo-nuclear reactions ignite [2]. The following production of unstable e^+-isotopes provides the fuel for the expansion of the external layers into the interstellar medium and then contributing to its enrichment [3]. In the '70s, it was proposed that, during the thermo-nuclear runaway (TNR), CNe could form lithium through the formation of the ^{7}Be isotope from the ^{3}He (α,γ) ^{7}Be reaction [4,5]. This isotope decays indeed into ^{7}Li via electron capture with a half-life time decay of $\sim$ 53 days [6]. The study of the processes that lead to the production of lithium in the Universe, and its evolution, is one of the hot topics of modern astrophysics, both for cosmology [7] and for the chemical evolution of the Galaxy [8–11]. The present lithium abundance, A(Li)$\sim$3.3 [12], as measured from meteorites or from young T Tauri stars, is a factor of four larger than the BBN primordial value, A(Li)$\sim$2.7 [7] and one order of magnitude larger than the abundance observed in old metal-poor stars [13,14]. Then, a Galactic source is required to explain the observed over-abundance, and it is then crucial to look for the ^{7}Be/^{7}Li features in the early phase spectra of CNe to confirm them as lithium factories in our Galaxy.

2 The identification of ^{7}Be in nova spectra

The time-scale of a CN outburst mainly depends on the mass density of the ejecta and its expanding velocity [15], which in turn are a proxy for the underlying WD mass [16]. Based on the above information and on the time-scale of the beryllium decay, our search for ^{7}Be-^{7}Li features must focus on the epochs immediately after the maximum brightness of the nova outburst, when the ejecta is still cool and optically thick. A relatively high cadence monitoring will allow to identify the nova composition and its kinematics from the analysis of the evolution of P-Cygni absorption line profiles, originating from the nova ejecta emission. This timeline generally corresponds to 1-2 weeks after the outburst for very fast CNe, to two-three months for slow outbursts. However, despite CN spectra have been observed for almost a hundred years, it was only in recent times that we have been able to search for ^{7}Be/Li evidences in CN spectra, in particular in the near-UV range where the resonance line of the ^{7}Be II 313.0 nm is observed, thanks to the use of advanced high-resolution spectrographs, such as the proposed Cassegrain U-Band Efficient Spectrograph (CUBES) [17,18] for the Very Large Telescope (VLT) in Chile. The first identifications of ^{7}Be II in CN spectra have indeed been reported using specific spectrographs mounted on 8-meter class telescopes, and that are capable to observe the near-UV range, such as the High Dispersion Spectrograph (HDS) at the SUBARU telescope at Hawaii, US, and the Ultraviolet and Visual Echelle Spectrograph (UVES) currently operating at the VLT [19, 20].

A monitoring program is then necessary to quantify the Li yield from CNe. Since 2015 we have started a target-of-opportunity (ToO) program at the VLT to observe the outburst of bright novae with the UVES instrument [20]. A ToO program is necessary, given the transient nature of this class of astrophysical sources: we have been able to identify the P-Cygni absorptions for both the doublet components of the ^{7}Be II 313.0 nm feature in the early spectra of fast and slow novae [20–22], see as an example in Fig. 1 the recent detection in V6595 Sgr [23]. We have monitored the spectral evolution until the ^{7}Be features resulted unaffected by saturation effects. The ^{7}Be abundance is estimated by comparison with the resonance Ca II H,K lines. Calcium is not synthesised in the TNR and provides an estimate for the ^{7}Be, or ^{7}Li, synthesized in the TNR of $\log N(BeII)/N(HI) + 12 = 7.38 \pm 0.49$ [23]. Using these yields, chemical abundance simulations of the evolution of lithium in our Galaxy suggest that CNe can account for a large fraction of the lithium observed in the Milky Way [24,25,10,9]. However, the over-abundance of lithium estimated in CN outbursts are also in disagreement (by a factor of ~ 10 in N(Li)) with the expectations from theoretical simulations of CN explosions: while these still confirm the main role played by CNe as main factories of lithium in the Galaxy, at the same time they do not reproduce the observed lithium yield value using different nova models and accreted matter composition onto the primary WD [25]. On the other hand, recent and more accurate Galactic chemical evolution simulations that take into account the formation and evolution of binary systems giving rise to CNe explosions, are in agreement with the yield inferred from observations [26]. Consequently, more data, and of high quality, are still needed to: 1) increase the current statistics of events in the Galaxy and nearby systems (being currently composed of 12 Galactic and two SMC novae [23]), to infer a more accurate lithium yield by building a statistically-significant nova sample, and then solve the "tension" between the observational and the theoretical results; 2) to characterize the different CN progenitor populations in terms of their lithium yield (see also below); and 3) to verify if ionization effects and line saturation[27,28] can have an important role in the lithium yield estimate, thanks to a better signal-to-noise value (>> 50) in the 300-400 nm range; detailed analysis made with the 1-dim CLOUDY code have excluded this possibility in some events [23], but more detailed spectral synthesis models that takes into account 3-dim effects, non-local thermodynamic equilibrium and the effects of ejecta inhomogeneities must be used to observed spectra in order to provide a more accurate modelling and lithium abundance inference.

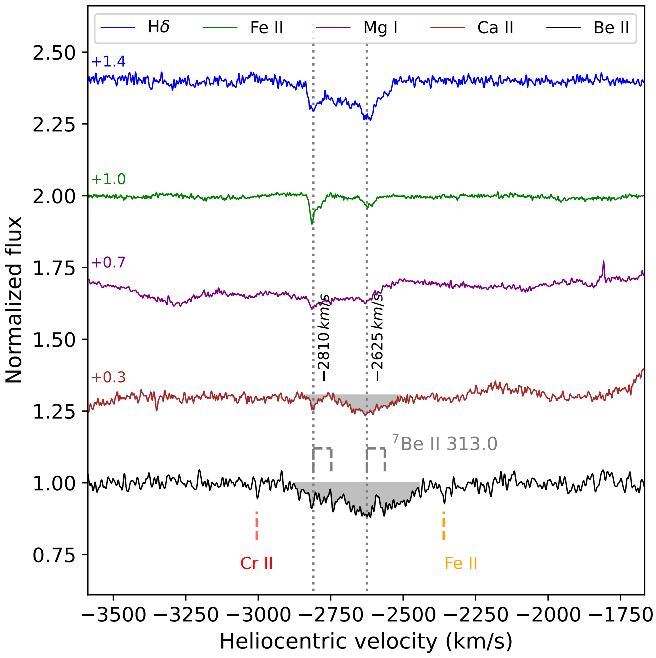

Fig. 1 The recent detection of ^{7}Be II in V6595 Sgr [23], compared with other absorption lines in the nova ejecta.

An important, and yet unexplored field, is also represented by the characterization of CN populations in the Milky Way. There is nowadays a clear evidence that CNe originates from two, or maybe more, progenitor populations: the main indication comes from the evidence that fast novae are more concentrated on the Galactic plane while slow novae are observed also at higher Galactic latitudes [15]. The speed class is mainly driven by the ejected mass [16], with fast novae characterised by smaller expelled masses, and then more massive progenitor WDs, than slow novae. This result could have important implications for the chemical enrichment of different regions of the MW: recent simulations suggest that CNe could be the main factories of lithium for the thin disk component of the Milky Way [9]. The identification of a massive ONe progenitor WD is generally associated with the presence of bright forbidden lines of neon, which are visible in the wavelength range 330-390 nm, which is available to CUBES. We still lack a more complete sample of Galactic novae at high spectral resolution to understand the properties of nova progenitors, if these can be ascribed to a different ejecta composition/metallicity, or to other properties [15], and their relationship with lithium production. All this can be accomplished with future near-UV spectrographs, such as CUBES.

The recent ^{7}Be detection in CNe observed in nearby local galaxies, such as the two Magellanic clouds [29] has also confirmed the important role of CNe as lithium factories in galaxies that are characterised by a metal poor stellar population and with an unresolved lithium enrichment problem [30]. CUBES at the VLT will definitely allow to investigate the near-UV spectral region for CNe in the nearby galaxies such as the Magellanic clouds (where CNe peak at $V \sim 11 - 12$ mag), and pushing our search to fainter events with $V \sim 16$ mag, given its more than> ten-fold flux sensitivity compared to UVES. We have indeed simulated the Day 1.6 spectrum of the recurrent nova RS Oph (Molaro et al. submitted), see also Fig. 2, using the CUBES exposure time calculator software [31], and the high-resolution mode, obtaining a signal-to-noise of $\sim$120 using an exposure time which is $\sim 1/10$ the one used for the UVES spectrum. The high spectral resolution ($R \sim$ 22,000, corresponding to a velocity resolution of $\sim$ 12 km/s) provided by CUBES will clearly allow us to identify and measure the properties of the ^{7}Be features in CNe, and disentangle the doublet components, which are separated by $\sim$ 62 km/s. Consequently, the lower spectral resolution compared with UVES does not limit our science goals, being high enough to distinguish narrow lines in the ejecta of CNe. This is clearly evident in our simulation of the Day 1.6 spectrum of RS Oph, which has been corrected for the telluric O3 Huggins bands [32]. To this purpose, we used the E2E CUBES simulator described in [31]. The results of our simulation are shown in Fig. 2, where it is clearly shown the potential of CUBES in detecting and reconstructing the line profile of the ^{7}Be II absorption feature, as well as to identify narrow metal lines during the early stages of a CN outburst. The wavelength coverage provided by CUBES is ideal for this purpose: so far, ^{7}Be abundance has been measured using Ca II H&K lines as reference, and both lines are visible in the wavelength range provided by CUBES. Last, while a flux calibration precision of less than 5% is required for late nebular epochs, when from the analysis of emission lines we will infer some physical properties of the ejecta like the abundance and ejected mass,, for the early phases it is not required, given that to estimate relative abundances we only need equivalent width measurements, which are not strictly dependent on the level of the flux calibration.

3 Further insights on nova phenomenology with CUBES.

An interesting by-product from the monitoring of CNe with the spectral resolution provided by CUBES is the characterisation of the abundance pattern derived from narrow absorption lines of heavy elements observed during the bright optically thick phases of CNe, also named THEA (transient heavy element absorptions - [33]). The study and the abundance characterisation of these features in the near-UV range can definitely shed light on their origin (if associated with the progenitor WD or from the secondary companion), their evolution within the first days/weeks of a nova outburst, how they relate with the new proposed paradigm for nova explosions [34], and finally to check if the components where these transitions take origin include lithium/beryllium.

Only a high-cadence follow-up program will permit to study the dynamics of the ejecta and its correlation with the high-energy radiation recently reported by gamma-ray detectors [35]. The energetic emission was found to be correlated with rebrightenings observed in the optical light curves as well as with the simultaneous appearance of additional higher velocity components in the spectra [36]. This evidence supported the proposal of a new scenario for the CN explosions, characterised by the presence of multiple ejecta components that interact with previously expelled gas, thus producing the observed shocked emission [34,37].

4 Conclusions

High-resolution spectrographs with near-UV capabilities opened a new era for the study of the TNR in CN. Multi-wavelength observations have provided evidence for shocks, aspherical ejecta and particle acceleration. The possibility to combine these observations with the high-resolution at optical and near-UV wavelengths with CUBES will be relevant in understanding the origin of the high-energy radiation and of the shocked emission. At the same time, CUBES will be one of the few spectrographs that will allow to study the abundance of the ^{7}Be II and therefore shed a definitive light on the role of CNe as main lithium factories in the MW and in the Local Group galaxies.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

1. M.F. Bode, A. Evans, *Classical Novae*, vol. 43 (2008)
2. J.S. Gallagher, S. Starrfield, ARA&A**16**, 171 (1978). DOI 10.1146/annurev.aa.16.090178.001131
3. R.D. Gehrz, J.W. Truran, R.E. Williams, S. Starrfield, PASP**110**, 3 (1998). DOI 10.1086/316107
4. M. Arnould, H. Norgaard, A&A**42**, 55 (1975)
5. S. Starrfield, J.W. Truran, W.M. Sparks, M. Arnould, ApJ**222**, 600 (1978). DOI 10.1086/156175
6. A.G.W. Cameron, W.A. Fowler, ApJ**164**, 111 (1971). DOI 10.1086/150821
7. B.D. Fields, P. Molaro, S. Sarkar, ArXiv e-prints (2014)

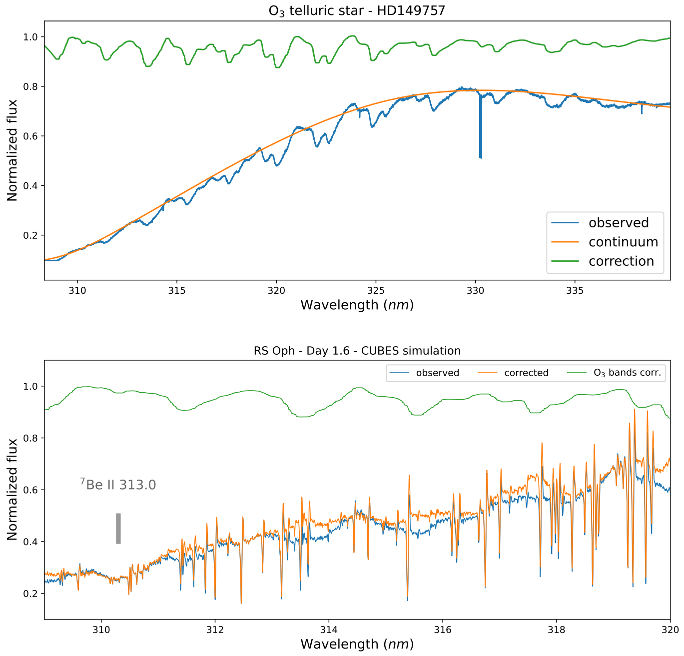

Fig. 2 (*Upper panel*) The spectrum of the Be star HD149757 as observed by CUBES (blue curve) using the dedicated E2E code [31], and used for the estimate of the O_3 correction (green curve). The orange curve corresponds to the stellar continuum used for the estimate of the O_3 bands. Narrow stellar/interstellar features have been opportunely excluded using a smoothing median filter on the final O_3 correction spectrum. (*Lower panel*) The simulated spectrum of the recurrent nova RS Oph on Day 1.6 as if it were observed by CUBES (blue curve). The original spectrum was observed with UVES, and it was given as input of the E2E code. The ^{7}Be II feature in the nova ejecta would have been clearly detected also with CUBES (gray mark), including several other narrower absorptions originating in the interaction of the nova ejecta with the secondary red giant wind (Molaro et al. submitted). The upper green curve corresponds to the telluric correction for the O_3 Huggins bands, derived from HD149757. The orange curve is the result of the correction for the Huggins bands from the simulated observed spectrum: note how the absorption feature associated with ^{7}Be II still persists in the corrected spectrum, while other "fake" absorptions disappear, being originated in O_3 telluric features. To test the quality of the CUBES simulations, we have measured a pseudo equivalent width for the ^{7}Be II feature of $pEW_{Be,C} = 1.043 \pm 0.133$ Å (SNR ~ 120 for a 3s exposure) while from UVES we got $pEW_{Be,U} = 1.065 \pm 0.086$ Å .

8. F. D'Antona, F. Matteucci, A&A**248**, 62 (1991)
9. G. Cescutti, P. Molaro, MNRAS**482**, 4372 (2019). DOI 10.1093/mnras/sty2967
10. D. Romano, L. Magrini, S. Randich, G. Casali, P. Bonifacio, R.D. Jeffries, F. Matteucci, E. Franciosini, L. Spina, G. Guiglion, C. Chiappini, A. Mucciarelli, P. Ventura, V. Grisoni, M. Bellazzini, T. Bensby, A. Bragaglia, P. de Laverny, A.J. Korn, S.L. Martell, G. Tautvaisiene, G. Carraro, A. Gonneau, P. Jofré, E. Pancino, R. Smiljanic, A. Vallenari, X. Fu, M.L. Gutiérrez Albarrán, F.M. Jiménez-Esteban, D. Montes, F. Damiani, M. Bergemann, C. Worley, arXiv e-prints arXiv:2106.11614 (2021)
11. F. Matteucci, A&A Rev.**29**(1), 5 (2021). DOI 10.1007/s00159-021-00133-8
12. K. Lodders, H. Palme, H.P. Gail, Landolt Börnstein **4B**, 712 (2009). DOI 10.1007/978-3-540-88055-4_34

13. F. Spite, M. Spite, A&A**115**, 357 (1982)
14. L. Sbordone, P. Bonifacio, E. Caffau, H.G. Ludwig, N.T. Behara, J.I. González Hernández, M. Steffen, R. Cayrel, B. Freytag, C. van't Veer, P. Molaro, B. Plez, T. Sivarani, M. Spite, F. Spite, T.C. Beers, N. Christlieb, P. François, V. Hill, A&A**522**, A26 (2010). DOI 10.1051/0004-6361/200913282
15. M. Della Valle, L. Izzo, A&A Rev.**28**(1), 3 (2020). DOI 10.1007/s00159-020-0124-6
16. M. Livio, ApJ**393**, 516 (1992). DOI 10.1086/171524
17. B. Barbuy, V. Bawden Macanhan, P. Bristow, B. Castilho, H. Dekker, B. Delabre, M. Diaz, C. Gneiding, F. Kerber, H. Kuntschner, G. La Mura, W. Maciel, J. Meléndez, L. Pasquini, C.B. Pereira, P. Petitjean, R. Reiss, C. Siqueira-Mello, R. Smiljanic, J. Vernet, Ap&SS**354**(1), 191 (2014). DOI 10.1007/s10509-014-2039-z
18. A. Zanutta, S. Cristiani, D. Atkinson, V. Baldini, A. Balestra, B. Barbuy, V.B.P. Macanhan, A. Calcines, G. Calderone, S. Case, B.V. Castilho, G. Cescutti, R. Cirami, I. Coretti, S. Covino, G. Cupani, V. De Caprio, H. Dekker, P. Di Marcantonio, V. D'Odorico, H. Ernandes, C. Evans, T. Feger, C. Feiz, M. Franchini, M. Genoni, C.D. Gneiding, M. Kałuszyński, M. Landoni, J. Lawrence, D. Lunney, C. Miller, K. Molaverdikhani, C. Opitom, G. Pariani, S. Piranomonte, A. Quirrenbach, E.M.A. Redaelli, M. Riva, D. Robertson, S. Rossi, F. Rothmaier, W. Seifert, R. Smiljanic, J. Stürmer, I. Stilz, A. Trost, O. Verducci, C. Waring, S. Watson, M. Wells, W. Xu, T. Zafar, S. Zorba, Experimental Astronomy (2022). DOI 10.1007/s10686-022-09837-w
19. A. Tajitsu, K. Sadakane, H. Naito, A. Arai, W. Aoki, Nature**518**, 381 (2015). DOI 10.1038/nature14161
20. P. Molaro, L. Izzo, E. Mason, P. Bonifacio, M. Della Valle, MNRAS**463**, L117 (2016). DOI 10.1093/mnrasl/slw169
21. L. Izzo, P. Molaro, P. Bonifacio, M. Della Valle, Z. Cano, A. de Ugarte Postigo, J.L. Prieto, C. Thöne, L. Vanzi, A. Zapata, D. Fernandez, MNRAS**478**, 1601 (2018). DOI 10.1093/mnras/sty435
22. P. Molaro, L. Izzo, P. Bonifacio, M. Hernanz, P. Selvelli, M. della Valle, MNRAS**492**(4), 4975 (2020). DOI 10.1093/mnras/stz3587
23. P. Molaro, L. Izzo, V. D'Odorico, E. Aydi, P. Bonifacio, G. Cescutti, E.J. Harvey, M. Hernanz, P. Selvelli, M. della Valle, MNRAS**509**(3), 3258 (2022). DOI 10.1093/mnras/stab3106
24. L. Izzo, M. Della Valle, E. Mason, F. Matteucci, D. Romano, L. Pasquini, L. Vanzi, A. Jordan, J.M. Fernandez, P. Bluhm, R. Brahm, N. Espinoza, R. Williams, ApJ**808**, L14 (2015). DOI 10.1088/2041-8205/808/1/L14
25. S. Starrfield, M. Bose, C. Iliadis, W.R. Hix, C.E. Woodward, R.M. Wagner, ApJ**895**(1), 70 (2020). DOI 10.3847/1538-4357/ab8d23
26. A.J. Kemp, A.I. Karakas, A.R. Casey, B. Côté, R.G. Izzard, Z. Osborn, ApJ**933**(2), L30 (2022). DOI 10.3847/2041-8213/ac7c72
27. N.N. Chugai, A.D. Kudryashov, Astronomy Letters **46**(2), 92 (2020). DOI 10.1134/S1063773720020036
28. S.N. Shore, I. De Gennaro Aquino, A&A**639**, L12 (2020). DOI 10.1051/0004-6361/202038599
29. L. Izzo, P. Molaro, G. Cescutti, E. Aydi, P. Selvelli, E. Harvey, A. Agnello, P. Bonifacio, M. Della Valle, E. Guido, M. Hernanz, MNRAS**510**(4), 5302 (2022). DOI 10.1093/mnras/stab3761
30. J.C. Howk, N. Lehner, B.D. Fields, G.J. Mathews, Nature**489**, 121 (2012). DOI 10.1038/nature11407
31. M. Genoni, M. Landoni, G. Cupani, M. Franchini, R. Cirami, A. Zanutta, C. Evans, P. Di Marcantonio, S. Cristiani, A. Trost, S. Zorba, Experimental Astronomy (2022). DOI 10.1007/s10686-022-09844-x
32. J. Schachter, PASP**103**, 457 (1991). DOI 10.1086/132842
33. R. Williams, E. Mason, M. Della Valle, A. Ederoclite, ApJ**685**(1), 451 (2008). DOI 10.1086/590056
34. K. Mukai, J.L. Sokoloski, Physics Today **72**(11), 38 (2019). DOI 10.1063/PT.3.4341
35. A. Franckowiak, P. Jean, M. Wood, C.C. Cheung, S. Buson, A&A**609**, A120 (2018). DOI 10.1051/0004-6361/201731516

36. E. Aydi, K.V. Sokolovsky, L. Chomiuk, E. Steinberg, K.L. Li, I. Vurm, B.D. Metzger, J. Strader, K. Mukai, O. Pejcha, K.J. Shen, G.A. Wade, R. Kuschnig, A.F.J. Moffat, H. Pablo, A. Pigulski, A. Popowicz, W. Weiss, K. Zwintz, L. Izzo, K.R. Pollard, G. Handler, S.D. Ryder, M.D. Filipović, R.Z.E. Alsaberi, P. Manojlović, R. Lopes de Oliveira, F.M. Walter, P.J. Vallely, D.A.H. Buckley, M.J.I. Brown, E.J. Harvey, A. Kawash, A. Kniazev, C.S. Kochanek, J. Linford, J. Mikolajewska, P. Molaro, M. Orio, K.L. Page, B.J. Shappee, J.L. Sokoloski, Nature Astronomy **4**, 776 (2020). DOI 10.1038/s41550-020-1070-y
37. E. Aydi, L. Chomiuk, L. Izzo, E.J. Harvey, J. Leahy-McGregor, J. Strader, D.A.H. Buckley, K.V. Sokolovsky, A. Kawash, C.S. Kochanek, J.D. Linford, B.D. Metzger, K. Mukai, M. Orio, B.J. Shappee, L. Shishkovsky, E. Steinberg, S.J. Swihart, J.L. Sokoloski, F.M. Walter, P.A. Woudt, ApJ**905**(1), 62 (2020). DOI 10.3847/1538-4357/abc3bb