The Astrophysical Journal, 907:70 (4pp), 2021 February 1 https://doi.org/10.3847/1538-4357/abd02e

Transient Formation of C_2 and CN in the Near-maximum Phase of Nova Cas 2020 (=V1391 Cas)

M. Fujii[1], A. Arai[2], and H. Kawakita[2]
[1] Fujii-Kurosaki Observatory, Okayama, Japan
[2] Koyama Astronomical Observatory, Kyoto-Sangyo University, Kyoto, Japan
Received 2020 August 25; revised 2020 November 5; accepted 2020 December 1; published 2021 February 1

Abstract

Nova Cas 2020 was a second example of a classical nova forming both C_2 and CN molecules during its near-maximum phase. The formation C_2 and CN is indicative of the carbon-rich (C/O > 1) gas envelope of the nova. Our low-resolution spectroscopic observations in the optical from UT 2020 July 31 to August 19 revealed the appearance and the disappearance of the molecular absorption bands of C_2 and CN in Nova Cas 2020. These molecules were present during ∼3 days only. Based on analysis of the C_2 Swan band profiles, C_2 (and probably CN also) formed at ∼5000 K in the nova envelope (see ∼8000 K for typical novae at their visual brightness maxima). Spectral evolution and the formation conditions of the molecules are similar to those of V2676 Oph, which is the first example of a C_2/CN-forming nova. We predict that a late-phase grain formation episode similar to that seen in V2676 Oph will occur in Nova Cas 2020.

Unified Astronomy Thesaurus concepts: Classical novae (251); Slow novae (1467); DQ Herculis stars (407)

Supporting material: data behind figure

1. Introduction

Nova Cas 2020 (=V1391 Cas) was discovered on UT 2020 July 27.930 by S. Korotkiy in the optical (at the unfiltered magnitude of 12.9) and identified as a classical nova by Sokolovsky et al. (2020a, 2020b). Sokolovsky et al. reported that the spectrum taken on UT 2020 July 29.025 was dominated by H I, Fe II, and Na I P-Cygni profiles and the absorption of the Hα P-Cygni profile was at a velocity of around $-850 \pm 100\,\mathrm{km\,s^{-1}}$. This nova is a typical "Fe II nova" according to the classification scheme reported by Williams (1992). Munari et al. (2020) reported the photometric and spectroscopic observations. Their spectrum taken on UT 2020 July 29.960 is dominated by a red continuum with minimal photospheric absorption lines. P-Cygni absorption was absent for all emission lines, except O I 7773 (for which the absorption is placed at $-385\,\mathrm{km\,s^{-1}}$ from the photocenter of the emission line). An average FWHM of the emission lines is about $500\,\mathrm{km\,s^{-1}}$. Munari et al. (2020) also reported that the emission in Na I and the P-Cygni absorption in Hα have gone, and He I has emerged in emission on UT 2020 July 29.960. The following spectroscopic observations from UT 2020 July 30.7 to August 11.9 were reported by Shore et al. (2020). Several blueshifted absorptions at low velocities by low ionization atomic species (e.g., Mg II λ4481, Ti II λ4764, and Si II λλ6347, 6371) were present on August 4–6. They pointed out the similarity in development of the spectra between Nova Cas 2020 and nova DN Gem in 1912 (McLaughlin 1965). Their spectroscopic observations are available from the ARAS Spectral Database (http://www.astrosurf.com/aras/Aras_DataBase/DataBase.htm). P-Cygni profiles of some species (e.g., O I 7773 and the Balmer lines) indicated expansion velocities of about $-200\,\mathrm{km\,s^{-1}}$ for the center of absorption and the line profiles that extended from $-500\,\mathrm{km\,s^{-1}}$ (in blue) to $+300\,\mathrm{km\,s^{-1}}$ (in red) in early August 2020.

Nova Cas 2020 became brighter slowly after its discovery and the nova reached visual brightness maximum around UT 2020 August 10–11 at ∼10.7 V-mag based on the reports to the AAVSO (Kafka 2020), as shown in Figure 1. After maximum, the nova became fainter and fell to ∼13 V-mag on August 17 (and then became brighter again and reached ∼11.5 V-mag on August 20).

We started low-resolution spectroscopic observations of Nova Cas 2020 in the optical wavelength region from UT 2020 July 31.73 to monitor the formation of diatomic molecules (C_2 and CN). Nagashima et al. (2014) observed the formation of both C_2 and CN in V2676 Oph for the first time in novae (only CN was observed in DQ Her in 1934; Martin 1989), and no other novae forming C_2/CN were found to date. We first detected the molecular absorption bands of C_2 and CN on UT 2020 August 12.71 (Fujii et al. 2020) a few days after the visual brightness maximum of the nova. Effective temperatures of pseudo-photosphere for typical novae (∼8000 K; Evans et al. 2005) are expected to be too high to form simple diatomic molecules. Nova Cas 2020 was cooler than typical novae at that time. We continued to observe the nova until August 19.78, then we had to stop our monitoring observations due to a trouble with the telescope control system.

2. Observations

Table 1 lists our observations monitoring the spectroscopic evolution of Nova Cas 2020 near visual maximum. We conducted the low-resolution spectroscopic observations using the 0.4 m telescope (f/10) with a low-resolution spectrograph FBSPEC-III ($R = \lambda/\Delta\lambda = 640$ at a wavelength of Hα, corresponding to a slit width of 5″) at Fujii-Kurosaki Observatory (FKO).

Figure 2 shows the spectral evolution of Nova Cas 2020. On UT 2020 August 10.72, as reported by Shore et al. (2020), the spectrum was dominated by the continuum and we could identify blueshifted absorption lines of neutral and low-ionized atomic species, such as C I, N I, O I, Si II, and Fe II, as shown in Figure 2. Our spectrum taken on UT 2020 August 12.71 clearly shows C_2 and CN absorption bands. The C_2 Swan bands and CN red-system bands could be identified (on the top of each panel, we also show the modeled spectra of molecular bands in the optically thin case). The C_2 Swan bands ($\Delta v = +1$, 0, -1)

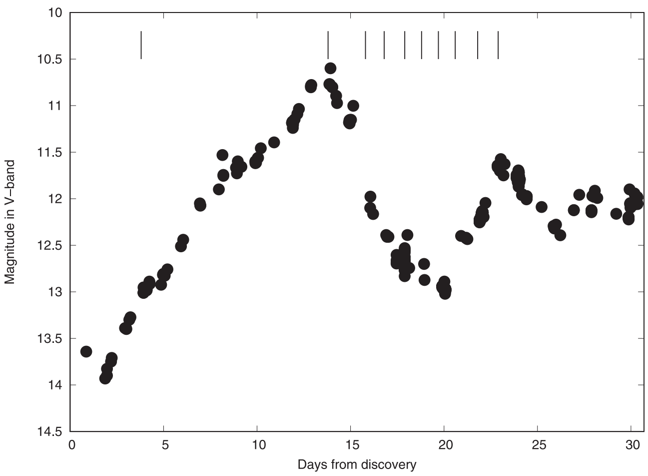

Figure 1. The V-band light curve of Nova Cas 2020 from the AAVSO database. Our observations at the Fujii–Kurosaki Observatory (FKO) cover the visual maximum of the nova. The vertical tick marks show the observing dates at FKO.

Table 1
Observations of Nova Cas 2020

Date (UT) star	t [days]	Airmass	Exp. time (min)	Standard Star
2020/07/31.73	3.80	1.19	70	HR8634
2020/08/10.72	13.8	1.18	120	HR8634
2020/08/12.71	15.8	1.19	90	HR8634
2020/08/13.73	16.8	1.18	120	HR8634
2020/08/14.79	17.9	1.21	80	HR8634
2020/08/15.69	18.8	1.19	120	HR8634
2020/08/16.66	19.7	1.22	120	HR8634
2020/08/17.53	20.6	1.59	150	HR7950
2020/08/18.76	21.8	1.18	150	HR8634
2020/08/19.78	22.9	1.21	114	HR8634

Note. Days from discovery: $t = 0$ for UT 2020 July 27.930 (JD2459058.43).

and the CN red-system bands ($\Delta v = +2$) were prominent (see also Figure 3, which is a comparison between Nova Cas 2020 and V2676 Oph). Those molecular absorption bands of C_2 and CN were also present on UT 2020 August 13.37 but not significant on UT 2020 August 14.79. They had almost vanished on UT 2020 August 15.69 as shown in Figure 2. After that, the nova showed the spectra usually seen in a typical Fe-II nova.

3. Discussion and Conclusions

We cannot see any molecular absorption bands in the low-resolution spectrum taken on UT 2020 August 11.90 (from the ARAS Spectral Database), almost one day before our detection of C_2 and CN molecules in the nova on UT 2020 August 12.71 (see Figure 2). Thus, the C_2 and CN rapidly formed between UT 2020 August 11.90 and 12.71 and almost vanished on UT 2020 August 15.69 in Nova Cas 2020. Those diatomic molecules could form and survive only for $\sim$3 days. The formation of C_2 and CN indicates the nova envelope gas was carbon-rich, $C/O > 1$ (Pontefract & Rawlings 2004). The absorption bands of C_2 and CN were also detected in the nova V2676 Oph and these molecular bands disappeared within $<\sim$7 days (Kawakita et al. 2015). Although the beginning of the molecular formation of both C_2 and CN was observed in

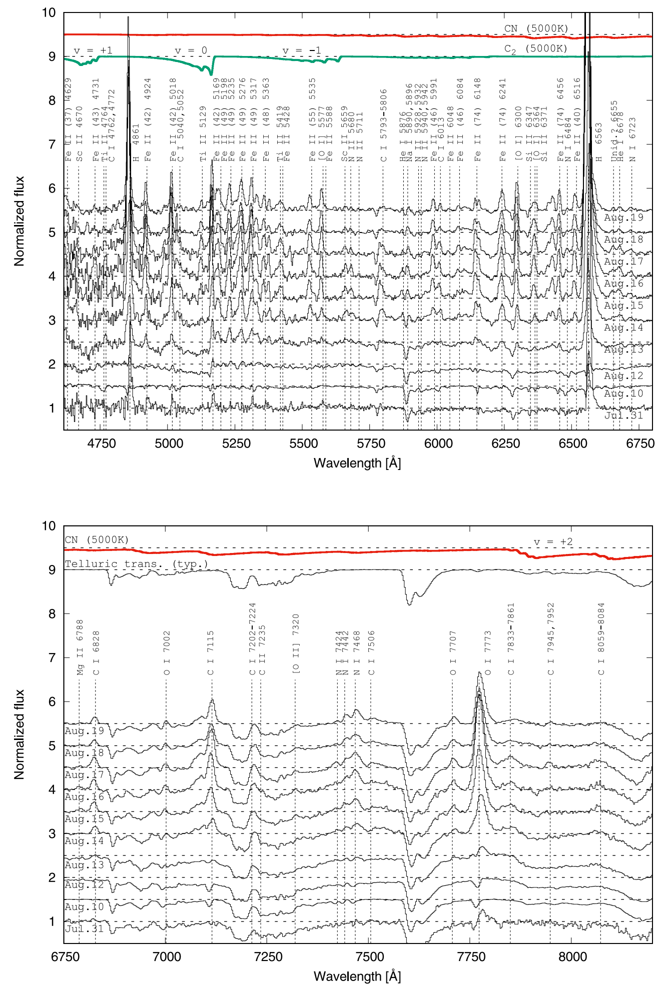

Figure 2. Normalized spectra of Nova Cas 2020. Upper panel shows the shorter wavelength range and lower panel shows the longer wavelength range. Modeled spectra of C_2 and CN molecules at an excitation temperature of 5000 K in the optically thin case, convolved with a typical spectral resolution, and a typical telluric absorption profile are shown on the top of each panel.

(The data used to create this figure are available.)

V2676 Oph for the first time, unfortunately the disappearance of the molecules was not observed in V2676 Oph. In Nova Cas 2020 we revealed the end of the molecular formation phase of nova for the first time. The residence times of these diatomic molecules in nova envelopes are consistent between V2676 Oph and Nova Cas 2020. We also note that DQ Her in 1934 (in which only CN formation was observed) showed the absorption of CN violet-system band during $\sim$1 week (Martin 1989). Molecular formation of C_2 and CN in nova envelopes seems to have a timescale $\sim$1 week or less.

Before the formation of C_2 and CN molecules, blueshifted absorption lines of neutral atomic species (e.g., C I $\lambda\lambda$4762, 4772, 5801, 6013, 7115, O I $\lambda\lambda$7002, 7773, and N I $\lambda\lambda$6484, 7424, 7442, 7468) were prominent in the spectrum on August 10.72, with a displacement of $-300 \pm 100\,\mathrm{km\,s^{-1}}$. The displacements are consistent with the expansion velocity estimated from the P-Cygni profile of Hα (i.e., the difference in wavelength between its emission peak and absorption minimum) on the same date, -300 to $-400\,\mathrm{km\,s^{-1}}$. These facts are indicative of the low ionization environment in the expanding nova pseudo-photosphere, and such an environment was favorable to molecular formation. A

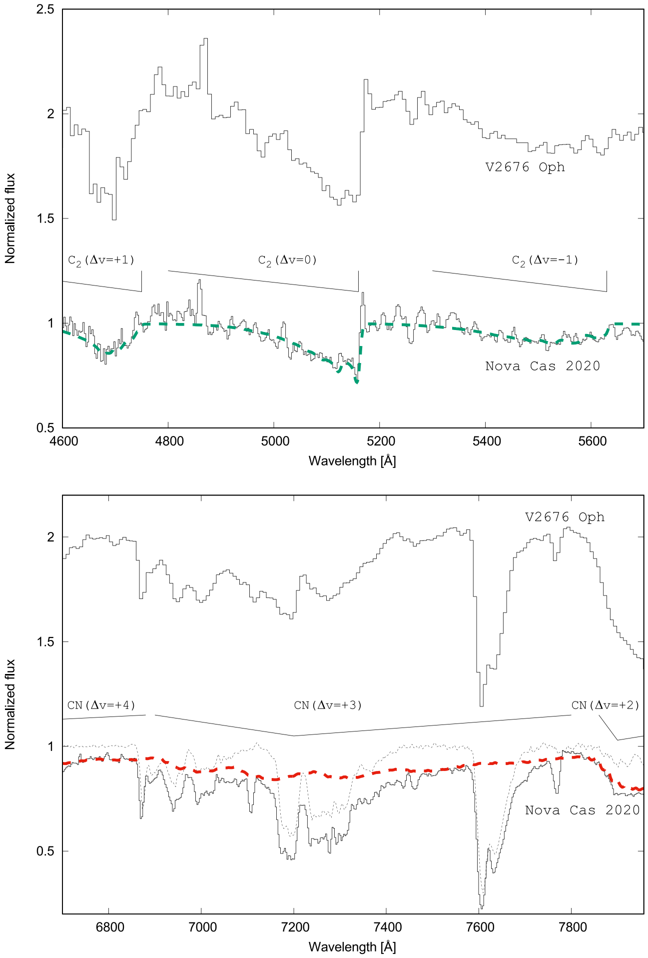

Figure 3. Comparison of normalized spectra between Nova Cas 2020 (on UT 2020 August 12.71) and V2676 Oph (taken from Nagashima et al. 2014, shifted with +1.0) for the C_2 Swan bands. Thick dashed lines in upper and lower panels are the synthesized spectra of C_2 and CN at an excitation temperature of 5000 K, respectively (see the Appendix). Thin dotted line in the lower panel is a telluric absorption spectrum estimated from the standard star observed on the same night. The C_2 Swan bands ($\Delta v = +1, 0, -1$) and the CN red-system bands ($\Delta v = +2$) were detected.

low ionization-degree environment was also observed in the envelope of V2676 Oph just before the molecular formation (Nagashima et al. 2014; Kawakita et al. 2015, 2016).

The expanding velocity of the nova ejecta was initially around -850 ± 100 km s^{-1} on July 29.025 and deaccelerated to -500 to -400 km s^{-1} on July 29.960, ~1 day after (Sokolovsky et al. 2020a; Munari et al. 2020). The velocity displacement of about -300 km s^{-1} was found not only for the neutral species (C I, O I, and N I) but also in low-ionized species such as Si II and Fe II in our spectrum on August 10.72. It was smaller than those in late July, but consistent with the velocities in early August reported by Shore et al. (2020). The nova envelope might deaccelerate toward the visual brightness maximum around August 10. Such behavior in the expansion velocity of Nova Cas 2020 is similar to that of V2676 Oph (Kawakita & Arai 2017), in which the expansion velocity deaccelerated before the molecular formation of C_2 and CN.

The spectral profiles of C_2 Swan bands ($\Delta v = +1, 0, -1$) recorded in our spectrum on UT 2020 August 12.71 are relatively free from contamination by atomic emission lines (especially of Fe II) and therefore we fit the profiles with a simple modeled spectrum. The Swan band absorption profiles can be explained by the synthesized absorption spectrum (based on the model concerning an optically thick "slab" of molecular gas above the photosphere; see the Appendix) for an excitation temperature of ~5000 K, as in the case of V2676 Oph (Kawakita et al. 2015, 2016). We overplotted the modeled profile of C_2 (in a thick dashed line) with the observed spectrum taken on UT 2020 August 12.71 in Figure 3. On the other hand, it is difficult to determine the excitation temperature of CN molecules although the synthesized spectrum of CN at 5000 K looks consistent with the observations. The diatomic molecules of C_2 and CN formed in the envelope of Nova Cas 2020 at around ~5000 K, the temperature at which nova V2676 Oph formed both C_2 and CN molecules (Kawakita et al. 2016). As suggested by theoretical studies, larger envelope masses would lead to larger maximum radii and lower effective temperatures of the nova pseudo-photosphere (Kato & Hachisu 2009). Kato & Hachisu (2009) also demonstrated that larger envelope masses at nova explosion basically correspond to lower masses of white dwarf (WD) of the nova. Thus, the formation of C_2 and CN at low temperatures in both Nova Cas 2020 and V2676 Oph might indicate that the WD masses of these novae are lower than typical novae (the mass of WD in V2676 Oph was estimated as ~0.6 solar mass; Kawakita & Arai 2017).

After UT 2020 August 12.71, emission lines of Fe II multiplets and H I Balmer lines became stronger. Furthermore, emission lines of He I (I.P. = 25.59 eV) at λλ5876, 6678 and of N II (I.P. = 29.60 eV) at λλ5680, 5711 were emerging compared to the emission lines of Fe II (I.P. = 16.20 eV) from August 12.71 to 16.66 as shown in Figure 2. Thus, the radiation field in the nova envelope became stronger and harder during this period. The molecules might be photodissociated by the strong UV radiation from the pseudo-photosphere of the nova (the dissociation energies are 8.63 eV and 7.75 eV for C_2 and CN).

In summary, Nova Cas 2020 was the second example of a C_2/CN-forming nova after V2676 Oph in 2012. These novae were cool enough to form simple diatomic molecules even during their near-maximum phase. From the viewpoint of observational properties, these novae are quite similar. Further observations of CO in the near-infrared wavelength region (routinely performed by infrared telescopes/instruments for other novae; e.g., Raj et al. 2015; Banerjee et al. 2016) will provide additional information about the molecular formation processes in nova envelopes. Recently, Russell et al. (2020) reported near-infrared spectra of Nova Cas 2020 on UT2020 August 17.64, in which atomic carbon emission lines and CO emission bands (both the fundamental and the first overtone bands) were prominent. Our spectrum did not show any hint of C_2 and CN absorption bands on the same date (Figure 2). The photodissociation limit wavelengths of C_2, CN, and CO are 1436, 1600, and 1118 Å, respectively. Thus, CO is more robust than C_2 and CN against UV radiation. Since the continuum absorption limit of C I is 1101 Å and this is close to the photodissociation limit wavelength of CO, the presence of abundant neutral carbon atoms in the nova envelope could reduce the UV radiation necessary for the photodissociation of CO, and might protect the CO molecules. The reduced UV radiation during the "iron curtain stage" of nova, related to the formation of simple diatomic molecules in the nova envelope, is also discussed elsewhere (e.g., Martin 1989; Evans & Rawlings 2008; Kawakita et al. 2015; Hauschildt 2008). The CO emission bands were also detected in V2676 Oph even ∼1 month after the C_2 and CN molecular absorption bands had vanished in the nova (Rudy et al. 2012).

More complicated molecules (like polycyclic aromatic hydrocarbon molecules) and finally dust grains will form in the nova envelope as in V2676 Oph (Kawakita et al. 2017). In order to make clear the evolution of nova ejecta materials from hot ionized atomic gas to warm grains through molecules, further near-infrared and mid-infrared observations in the near future are highly recommended.

The authors acknowledge with thanks the variable star observations from the AAVSO International Database contributed by observers worldwide and used in this research. This work was financially supported by MEXT under Grant-in-Aid for Scientific Research (C) 19K03933 (A. Arai). We thank the anonymous referee for the helpful comments that improved the manuscript.

Appendix

For the sake of simplicity, we modeled the molecular absorption bands recognized in the spectrum of Nova Cas 2020 by assuming the “slab” (as a layer of absorbing gas) containing diatomic molecules at a temperature above the photosphere (as a background light source). The transmittance of the absorbing layer above the photosphere can be written as;

$$\begin{aligned} T(\lambda) &= \exp(-\tau_\lambda) \times f_c + 1.0 \times (1 - f_c) \\ &= \{\exp(-\tau_\lambda) - 1\} \times f_c + 1.0, \end{aligned}$$

where τ_λ denotes an optical depth of the slab at a wavelength λ and f_c denotes a covering factor of the slab. The optical depth of each molecular species is proportional to the absorption coefficients calculated by using the PGOPHER program (Western 2017) with relevant molecular constants and Franck–Condon factors of C_2 and CN (Dwivedi et al. 1978; Brooke et al. 2013; Sneden et al. 2014) at a given excitation temperature. We assumed the isotopic ratio of carbon as $^{13}C/^{12}C \sim 0.6$ as reported by Russell et al. (2020).

ORCID iDs

A. Arai https://orcid.org/0000-0002-5756-067X
H. Kawakita https://orcid.org/0000-0003-2011-9159

References

Banerjee, D. P. K., Srivastava, M. K., Ashok, N. M., & Venkataraman, V. 2016, MNRAS, 455, L109
Brooke, J. S. A., Bernath, P. F., Schmidt, T. W., & Bacskay, G. B. 2013, JQSRT, 124, 11
Dwivedi, P. H., Branch, D., Fuffaker, J. N., & Bell, R. A. 1978, ApJS, 36, 573
Evans, A., & Rawlings, J. M. C. 2008, in Cambridge Astrophysics Series No. 43, ed. M. F. Bode & A. Evans (2nd ed.; Cambridge: Cambridge Univ. Press), 308
Evans, A., Tyne, V. H., Smith, O., et al. 2005, MNRAS, 360, 1483
Fujii, M., Arai, A., & Kawakita, H. 2020, ATel, 13941, 1
Hauschildt, P. H. 2008, in Cambridge Astrophysics Series No. 43, ed. M. F. Bode & A. Evans (2nd ed.; Cambridge: Cambridge Univ. Press), 102
Kafka, S. 2020, The American Association of Variable Star Observers (AAVSO), https://www.aavso.org
Kato, M., & Hachisu, I. 2009, ApJ, 699, 1293
Kawakita, H., & Arai, A. 2017, in Proc. The Golden Age of Cataclysmic Variables and Related Objects IV (Palermo, Italy)
Kawakita, H., Arai, A., & Fujii, M. 2016, PASJ, 68, 87
Kawakita, H., Fujii, M., Nagashima, M., et al. 2015, PASJ, 67, 17
Kawakita, H., Ootsubo, T., Arai, A., Shinnaka, Y., & Nagashima, M. 2017, AJ, 153, 74
Martin, P. G. 1989, in Classical Novae, ed. M. F. Bode & A. Evans (Evans, NY: Wiley), 93
McLaughlin, D. B. 1965, Publ. of the Observatory of the Univ. of Michigan, 9, 113
Munari, U., Siviero, A., Vagnozzi, A., Sokolovsky, K., & Aydi, E. 2020, ATel, 13905, 1
Nagashima, M., Arai, A., Kajikawa, T., et al. 2014, ApJL, 780, L26
Pontefract, M., & Rawlings, J. M. C. 2004, MNRAS, 347, 1294
Raj, A., Ashok, N. M., Rudy, R. J., et al. 2015, ApJ, 149, 136
Rudy, R. J., Russell, R. W., Sitko, M. L., et al. 2012, CBET, 3103, 1
Russell, R. W., Sitko, M. L., Rudy, R. J., et al. 2020, ATel, 13967, 1
Shore, S. N., Boussin, C., Boyd, D., et al. 2020, ATel, 13939, 1
Sneden, C., Lucatello, S., Ram, R. S., Brooke, J. S. A., & Bernath, P. 2014, ApJS, 214, 26
Sokolovsky, K., et al. 2020a, ATel, 13903, 1
Sokolovsky, K., et al. 2020b, ATel, 13904, 1
Western, C. M. 2017, JQSRT, 186, 221
Williams, R. E. 1992, AJ, 104, 725