Nova Ophiuchus 2017 as a Probe of 13C Nucleosynthesis and Carbon Monoxide Formation and Destruction in Classical Novae

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Abstract

We present a series of near-infrared spectra of Nova Ophiuchus 2017 in the K band that record the evolution of the first overtone CO emission in unprecedented detail. Starting from 11.7 days after maximum, when CO is first detected at great strength, the spectra track the CO emission to +25.6 days by which time it is found to have rapidly declined in strength by almost a factor of ~35. The cause for the rapid destruction of CO is examined in the framework of different mechanisms for CO destruction, namely, an increase in photoionizing flux, chemical pathways of destruction, or destruction by energetic nonthermal particles created in shocks. From LTE modeling of the CO emission, the $^{12}\text{C}/^{13}\text{C}$ ratio is determined to be 1.6 ± 0.3. This is consistent with the expected value of this parameter from nucleosynthesis theory for a nova eruption occurring on a low mass (~0.6 $M_\odot$) carbon–oxygen core white dwarf. The present $^{12}\text{C}/^{13}\text{C}$ estimate constitutes one of the most secure estimates of this ratio in a classical nova.

Key words: infrared: stars – novae, cataclysmic variables – stars: individual (Nova Ophiuchus 2017) – techniques: spectroscopic

1. Introduction

We present a series of near-infrared (NIR) spectra recording carbon monoxide (CO) emission from the classical nova (CN) Nova Ophiuchus 2017 that are analyzed with a two-fold motivation. The first is to make a robust estimate of the $^{13}\text{C}$ yield and compare it with expected values from theoretical nucleosynthesis models. The second aim is to record the evolution of the CO emission in the nova and thus advance our understanding of the formation and destruction processes of CO in nova winds. One of the striking predictions of nucleosynthesis theory of nova physics is that novae contribute almost all (or all) of the $^{13}\text{C}$ found in the Galaxy (Jose & Hernanz 1998). An additional sensational part of these predictions concerns the extent of the $^{13}\text{C}$ enrichment; namely, the $^{13}\text{C}$ generation in novae ejecta can be so extreme that the $^{12}\text{C}/^{13}\text{C}$ ratio can be smaller than unity (the solar value is ~90). The predicted novaere value of the $^{12}\text{C}/^{13}\text{C}$ ratio are, however, model dependent on the white dwarf (WD) mass, its core composition (whether it is composed of a carbon–oxygen or ONe core), and the extent of mixing of the accreted envelope with the WD surface material. The overabundance of $^{13}\text{C}$ in novae is a consequence of the following. The synthesis of $^{13}\text{C}$ commences once the thermonuclear runaway (TNR) is underway through the CNO cycle reaction $^{12}\text{C}(p,\gamma)^{13}\text{N}$. Hence, it follows that an initial higher content of $^{12}\text{C}$ would favor the synthesis of larger amounts of $^{13}\text{C}$. Thus $^{13}\text{C}$ enhancements are favored in CNes with carbon–oxygen core WDs when in addition there is substantial mixing between nova material and accreted material (henceforth CO stands for carbon monoxide).

The subsequent evolution of the $^{13}\text{C}$ production and destruction are through $^{13}\text{N}(\beta^+)^{13}\text{C}$ and $^{13}\text{C}(p,\gamma)^{14}\text{N}$ respectively. The $\beta^+$ unstable nuclei $^{13}\text{N}$, in the former reaction, is one of the most overabundant species produced at the peak temperatures of the TNR (Starrfield et al. 1972). Overproduction factors, relative to solar, in the models computed by Jose & Hernanz (1998) lie in the range 900–2500 for the different carbon–oxygen core models and in the range 400–900 for the ONe models.

To confirm the predictions for the $^{13}\text{C}$ yield in CNes, direct measurements may be done in two ways. The first is through isotopic analysis of presolar carbon-rich grains from meteoritic samples after establishing from other isotopic signatures that the grains under consideration have indeed originated in a nova outburst and not, for example, from an AGB star or a supernova. A second, more direct method, is through modeling the CO emission that a few novae exhibit early after their eruption. Modeling has so far been restricted only for the first overtone $\Delta\nu = 2$ bands, which lie between 2.29 and 2.5 μm. The fundamental band at 4.67 μm may also be used, but it is observationally challenging because of the strong thermal background in that region. A table is presented later that lists the predicted $^{12}\text{C}/^{13}\text{C}$ values from theoretical different models juxtaposed with observed values to enable a comparison between the two.

The second aspect we study is the formation and evolution of CO in the nova ejecta. There is generally a lack of observational data related to molecule formation in nova outflows. The first molecular species to be detected in the ejecta of a nova was CN, as seen in DQ Her (Wilson & Merrill 1935). At much later epochs, $H_2$ (2.122 μm) was detected in the DQ Her remnant (Evans 1991). Subsequently, with access to the mid-IR/FIR made possible through the advent of space observatories like Spitzer, many UIR bands have been observed and studied in detail (Evans & Gehrz 2012). CO emission in novae, specifically, is an extremely transient phenomenon; once it is formed it is rapidly destroyed. The typical timescale of the emission ranges from a few days to around two to three weeks, making it easy to escape detection. CO first overtone detections in novae are not too common—there are only 10 reported in all. Even more infrequent are


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multi-epoch observations during the emission phase. Of these, even less frequent are those with sufficient cadence to document the formation and destruction of the CO emission in detail. These last data having a good sampling are especially vital to enable a comparison with theoretical studies which predict the time evolution of the CO emission. In the present work we present a series of spectra, on a nearly daily cadence, that show the striking evolution of the CO emission in Nova Oph 2017. LTE modeling of the data is done to estimate the physical parameters of the CO gas: temperature, mass, velocity, and the $^{12}\text{C}/^{13}\text{C}$ ratio. We also pinpoint the mechanism that is likely responsible for the rapid destruction of the CO emission.

2. Nova Ophuchii 2017

Nova Oph was discovered by K. Itagaki (CBAT “Transient Object Follow-up Reports” at http://www.cbat.eps.harvard.edu) on 2017 May 08.7511 and spectroscopically confirmed to be a FeII nova by Williams & Darnley (2017) on 2017 May 11.15 UT (ATel 10366). Strader et al. (2017) pointed out that pre-discovery ASAS-SN records show that the nova was first detected at $V = 14.9$ on April 21.43 UT, 17 days before the discovery by K. Itagaki. The subsequent ASAS-SN light curve after April 21.43 shows substantial variability between $V \sim 14$ and $V \sim 16$ with maximum reaching on April 30.24 at $V = 14.1$. However, Strader et al. (2017) add the caveat that the peak is poorly defined because of large optical variability around maximum, which resembles the behavior seen in, e.g., the gamma-ray-detected nova V1369 Cen. We take April 30.14 as the reference point for the origin of time. Three days after discovery, NIR spectra were reported independently confirming the FeII class and also reporting first overtone CO emission from the nova (Joshi & Banerjee 2017). This was followed by a report on the commencement of dust formation around 2017 mid-June (Joshi et al. 2017).

3. Observations

NIR spectra in the 0.85–2.45 $\mu$m region were obtained at a resolution of $\sim$1000 using the Near Infrared Camera Spectrograph (NICS) deployed on the 1.2 m telescope of the Mount Abu Observatory, India. Since the observational procedures related to spectroscopy with NICS have been described in detail in several places (Banerjee et al. 2014; Joshi et al. 2015; Srivastava et al. 2016), we refer the reader to these works. Reduction and analysis of the spectra were done using a combination of IRAF and Python routines developed by us. In the present study, we use only the $K$-band spectra—the remaining $J$- and $H$-band spectroscopic data and $JHK_s$ photometry will be presented elsewhere. The log of the observations is given in Table 1.

### Table 1

| Date       | JD   | Days After Maximum | Int. Time (s) | Airmass Nova | Airmass Standard |
|------------|------|--------------------|---------------|--------------|------------------|
| 2017 May 11.93 | 2457885.43 | 11.69 | 380 | 1.60 | 1.54 |
| 2017 May 12.92 | 2457886.42 | 12.68 | 2280 | 1.57 | 1.52 |
| 2017 May 14.91 | 2457888.41 | 14.67 | 1520 | 1.57 | 1.53 |
| 2017 May 15.89 | 2457889.39 | 15.65 | 950 | 1.54 | 1.51 |
| 2017 May 16.92 | 2457890.42 | 16.68 | 1520 | 1.59 | 1.53 |
| 2017 May 17.97 | 2457891.47 | 17.73 | 2090 | 1.92 | 1.78 |
| 2017 May 18.89 | 2457892.39 | 18.65 | 1900 | 1.55 | 1.53 |
| 2017 May 19.85 | 2457893.35 | 19.61 | 1900 | 1.56 | 1.62 |
| 2017 May 20.84 | 2457894.34 | 20.60 | 2280 | 1.57 | 1.66 |
| 2017 May 25.84 | 2457898.46 | 25.60 | 3800 | 1.57 | 1.54 |

Note.

Standard star used was SAO 186061 (A0 type). Maximum was on April 30.24 = JD 2457873.74.

4. Results

4.1. The $^{12}\text{C}/^{13}\text{C}$ Ratio in Nova Oph 2017

The top panel of Figure 1 shows a representative spectrum of the novae between 0.8 and 2.5 $\mu$m. The spectrum is very typical of a FeII class of nova (or equivalently carbon–oxygen core nova), several spectra of which are shown in Banerjee & Ashok (2012). The lower panels of Figure 1 shows just the $K$ band displaying the rise and fall of the CO emission along with model fits whose parameters are given in Table 2. Model fits to the CO emission have been obtained assuming LTE populations for the rovibrational states and also assuming that the CO emission is optically thin. All the rovibration transitions of the first overtone band, up to $ν = 20$ and $J = 149$ are considered with Einstein $A$ coefficients for these transitions being taken from Goorvitch (1994). The model has been applied to several novae, namely, V2615 Oph (Das et al. 2009), V496 Sct (Raj et al. 2012), V5584 Sgr (Raj et al. 2015), and V5668 Sgr (Banerjee et al. 2016). Greater details on the model are given in Das et al. (2009). Only $^{12}\text{C}^{16}\text{O}$ and $^{13}\text{C}^{16}\text{O}$ are considered as contributing species to the CO emission; the contribution of other isotopologues, such as $^{12}\text{C}^{17}\text{O}$ and $^{14}\text{C}^{16}\text{O}$, is assumed to be negligible based on expected abundances of $^{17}\text{O}$, $^{14}\text{C}$, etc., in nova ejecta (Jose & Hernanz 1998).

Figure 2 shows the effect of varying the $^{12}\text{C}/^{13}\text{C}$ ratio on the fits to the CO emission. Although this illustration is shown for the spectrum of 12.9 May, similar results are obtained on the other days. The effect of varying the $^{13}\text{C}$ content is felt most in the 4-2 and 5-3 regions covering the third and forth $^{12}\text{CO}$ bands where the first two (2-0 and 3-1) bands of $^{13}\text{CO}$ starts contributing. In further redward bands, the $^{13}\text{C}$ effects are not as clearly seen because, longward of this, the S/N of the spectra sharply drops because of strong increasing telluric residuals, and shortward of this $^{13}\text{CO}$ has no emission. The $^{13}\text{C}$ ratio on the $JKH_s$ band is determined to be negligible based on expected abundances of $^{17}\text{O}$, $^{14}\text{C}$, etc., in nova ejecta (Jose & Hernanz 1998).
CI lines between 2.1156 and 2.1295 μm (Evans et al. 1996; Banerjee & Ashok 2012 and references therein; Srivastava 2015), both of which are marked in Figure 1. A strong CI 2.2906 μm feature seriously affects the fit of the 2-0 band as seen in the cases of V2274 Cyg (Rudy et al. 2003), V705 Cas (Evans et al. 1996), and V2165 Oph (Das et al. 2009). Fortunately, in this nova, the CI 2.2906 μm line is weak and hence its effect on the 2-0 band head is small. By allowing the temperature, velocity, and 12C/13C ratio to vary and using a chi-square minimization criterion for the goodness of the fit, we find that the best formal fit is obtained for a 12C/13C ratio of 1.6 ± 0.3. Even visual examination clearly establishes how the quality of the fits are sensitive to small changes in the 12C/13C ratio. This is one of the most secure estimates of the 12C/13C ratio with a few positives over some of the earlier estimates.

Figure 1. Top two panels show the complete spectra for +12.7 days and +19.6 days. A sharp decline in CO emission but minimal changes in the other lines are seen. The bottom six panels, all drawn to the same flux except when specified, show the rapid decline in the CO emission with time. Red = model fit; blue = adopted continuum; black = observed data.

These factors include the fact that (i) contamination of the CO emission with other atomic lines (e.g., CI 2.2906 μm) is minimal, (ii) the dependence of the model fits on a varying 12C/13C ratio is demonstrated clearly here in Figure 2, which we believe has not been done in earlier studies, and (iii) the data were obtained at higher spectral resolution compared to some of the other studies (e.g., R = 300 for the V2274 Cyg spectrum in Rudy et al. 2003). We compare our 12C/13C estimate with theoretical predictions for carbon–oxygen novae in Table 2. The comparison indicates that the 12C/13C ratio is consistent with the low values predicted from nucleosynthesis theory and specifically suggests that the nova eruption took place on a low-mass WD with \( M_{\text{WD}} \) close to \( 0.6 \, M_\odot \). Higher WD masses are not supported in this nova, and for that matter, in none of the other novae in Table 2. We find this thought
Table 2
CO Emission Parameters in NOph 2017; Details of All $\Delta v = 2$ CO Detections; Predicted Model $^{12}$C/$^{13}$C Values

| Date (days$^c$) | Temp. $^d$ | $M$(CO)$^d$ | Nova | Detection Epoch$^e$ (d) | Observed $^{12}$C/$^{13}$C | Reference | $M$$_{WD}$ ($M_\odot$) | Mixing Fraction | $^{12}$C/$^{13}$C | H$^f$ | JH | S |
|-----------------|------------|-------------|------|------------------------|-----------------------------|-----------|------------------------|-----------------|-----------------|-------|----|---|
| 11.93 May (+11.7 days) | 2600 | 1.4e-09 | NQ Vul | 19 | $\geq$3 | Ferland et al. (1979) | 0.6 | 0.5 | 2 | ... | 2.38 |
| 12.92 May (+12.7 days) | 2500 | 1.1e-09 | V842 Cen | 25 | $\sim$2.9 | Wichmann et al. (1991) | 0.8 | 0.25 | 0.4 | 0.41 | ... |
| 14.91 May (+14.7 days) | 2375 | 6.7e-10 | V705 Cas | 6 | $\geq$5 | Evans et al. (1996) | 0.8 | 0.5 | 0.6 | 0.48 | 1.22 |
| 15.89 May (+15.7 days) | 2450 | 5.0e-10 | V2274 Cyg | 17 | $\sim$1.2 | Rudy et al. (2003) | 1 | 0.25 | 0.5 | ... | ... |
| 16.92 May (+16.7 days) | 2550 | 4.5e-10 | V2615 Oph | 9 | $\geq$2 | Das et al. (2009) | 1 | 0.5 | 0.5 | 0.28 | 0.42 |
| 17.97 May (+17.7 days) | 2300 | 3.8e-10 | V5584 Sgr | 12 | ... | Raj et al. (2014) | 1.15 | 0.25 | 0.9 | 0.66 | ... |
| 18.89 May (+18.7 days) | 2450 | 2.9e-10 | V496 Sct | 19 | $\geq$1.5 | Raj et al. (2012), Rudy et al. (2009) | 1.15 | 0.5 | 0.7 | 0.50 | ... |
| 19.85 May (+19.6 days) | 2350 | 2.6e-10 | V2676 Oph | 37 | ... | Rudy et al. (2012a) | 1.15 | 0.75 | ... | 0.36 | ... |
| 20.84 May (+20.6 days) | 2400 | 2.1e-10 | V1724 Aql | 7 | ... | Rudy et al. (2012b) | 1.25 | 0.5 | ... | ... | 0.84 |
| 25.84 May (+25.6 days) | 2400 | 7.1e-11 | V5668 Sgr | 12 | $\sim$1.5 | Banerjee et al. (2016) | ... | ... | ... | ... | ... |

Notes.

$^a$ On all days, the velocity of the CO gas was found to be in the range $1000 \pm 100$ km s$^{-1}$; error on $T$ is $\pm 200$ K.

$^b$ For carbon–oxygen novae.

$^c$ $V_{max}$ on 2017 April 30.14.

$^d$ For distance $d = 1$ Kpc. For any other distance, mass scales as $d^2$.

$^e$ In terms of days after discovery.

$^f$ $H =$ Haencour et al. (2016); JH = Jose & Hernanz (1998); S = Starrfield et al. (1997).
provoking and perhaps even unusual that all $^{12}\text{C}/^{13}\text{C}$ determinations made so far have never shown a nova with a $^{12}\text{C}/^{13}\text{C}$ ratio less than unity, which is routinely expected from nucleosynthesis models. Does this mean that all CO producing novae have small masses ($\sim 0.6 \, M_\odot$) or is there some lacuna in the nucleosynthesis predictions. This issue needs the attention of theorists.

In this context, it should be added that Haenecour et al. (2016) have recently reported the in situ identification of two unique presolar graphite grains from the primitive meteorite LaPaz Icefield 031117. One of these grains (LAP-149) is extremely $^{13}\text{C}$-rich and $^{15}\text{N}$-poor with a $^{12}\text{C}/^{13}\text{C}$ ratio of $1.41 \pm 0.01$, which is one of the lowest values ever observed in a presolar grain. Although such low $^{12}\text{C}/^{13}\text{C}$ ratios can be produced in a few astronomical sources, namely born again AGB stars, J-type carbon stars, novae, and core-collapse Supernovae of Type II, Haenecour et al. (2016) rule out an origin in these other sources based on other isotopic signatures. The isotopic compositions of LAP-149 best match an origin in the ejecta of a low-mass CO nova. In particular, there is a very close match between the $^{12}\text{C}/^{13}\text{C}$ = 1.41 ± 0.01 and $^{14}\text{N}/^{15}\text{N}$ = 941 ± 81 values with those from nucleosynthesis predictions for a 0.6$M_\odot$ carbon–oxygen core WD predicted to have $^{12}\text{C}/^{13}\text{C}$ = 2 and $^{14}\text{N}/^{15}\text{N}$ = 979 respectively. They thus conclude that grain LAP-149 is the first putative nova grain that quantitatively best matches nova model predictions, providing the first strong evidence for graphite condensation in nova ejecta.

### 4.2. Evolution of the CO Emission

There are less than a handful of novae where the evolution of the CO has been witnessed in sufficient detail. V705 Cas presented a unique case wherein strong CO was seen in emission just 6 days after discovery (and 1 day before maximum!) making it the earliest CO detection. By day 26.5, the CO emission had waned and by day 45 it was below detection. Raj et al. (2012) documented the CO evolution in V496 Sct between +15 days to +21 days and saw a drastic drop in the emission strength during that time. The best sampled evolutionary history was recorded in the case of V2615 Oph (Das et al. 2009) who found the CO strongly in emission at +5 days after maximum. Subsequently, the CO emission remained in a saturated phase for a period of 7 days followed by a rapid decline in strength. Within a month of its first detection, the emission had faded below detection limits. The collective behavior of all the nova described above are in good agreement with the theoretical predictions of the Pontenfract & Rawlings (2004; henceforth PR2004) model discussed below for the evolution of CO.

As summarized in Das et al. (2009), the early theoretical studies of the chemistry of novae outflows were done by Rawlings (1988) in the form of pseudo-equilibrium chemical models of the pre-dust-formation epoch. These models required that the outer parts of the ejecta be dense and carbon be neutral for substantial molecule formation to occur. In a neutral carbon region, the carbon ionization continuum, which extends to less than 1102 Å, shields several molecular species against the dissociative UV flux from the central star. A modified version was subsequently presented by PR2004, which yielded a result that was a major point of departure from their earlier model. They found that contrary to the findings of their previous studies, the formation, evolution, and abundances of various molecular species was essentially not photon-dominated but rather controlled by neutral–neutral, ion–molecule, and other chemical reactions. For example, the initial primary loss routes for CO were through reactions with H and O+, while at later times the primary loss channels were reactions with N+. We show that this might apply in the case of Nova Oph 2017. A further significant result in PR2004 is the prediction of the evolution of the fractional CO abundance with time. It is seen that in both their C- or O-rich models, the CO abundance remains constant up to about 2 weeks after outburst, i.e., the CO is saturated with all the available oxygen or carbon, whichever has the lower abundance, being completely used up into forming CO. Following this, there is a sharp decline in the CO abundance by a factor of 1000 in \( \sim 27 \) days for the O-rich model and a decrease by a factor of 100 in \( \sim 16 \) days for the C-rich model. Essentially a very rapid destruction of CO is predicted that is observationally confirmed in the novae discussed above (V496 Sct, V705 Cas, and V2615 Oph).
Figure 3 shows the decline in the CO flux with time. As a proxy for the CO flux, we have measured the flux under the curve between 2.29 and 2.403 μm (i.e., regions including the 2-0, 3-1, 4-2, and 5-3 bands but excluding the noisy regions further redward). The rapid decline in the CO strength by a factor of \( \sim 33 \) in 14 days is quite remarkable entrenching further the fact that CO emission in novae is a very transitory phenomenon. In contrast, the strengths of Brγ and the Na I 2.2056, 2.2084 μm lines have remained fairly constant. The behavior of the latter lines is revealing about the possible cause for the rapid destruction of CO. Sodium has a first ionization potential (IP) of 5.139 eV; the lowest among those elements whose lines are seen in the NIR spectrum of novae (a comprehensive list of these lines is given in Das et al. 2008). It is easy to show from LTE calculations that at around 2500 K, only about 50% of Na remains neutral; by 3000 K almost 99% is ionized. This automatically implies that strong neutral Na I emission must originate from relatively cool zones, close to the temperature of \( \sim 1800 \) K, where the first dust condensates (carbon) are expected to form. These Na lines were thus proposed (Das et al. 2008) to be harbingers of imminent dust production in novae and observations of several dust forming novae have established this to be true. CO has a dissociation energy \( D(\text{CO}) = 11.1 \text{ eV} \), much larger than the first IP of Na I. It is therefore unlikely that the destruction of CO was caused by an increase in the UV photon flux from the central WD remnant; such an increase would have destroyed the Na I line emission too. There is supporting evidence that the temperature of the central source hardly changed during the time of the CO destruction. From the AAVSO database and also the SMARTS observations (http://www.astro.sunysb.edu/fwalter/SMARTS) the V-band magnitudes between 10 May and 25 were almost constant at \( \sim V = 15.1 \pm 0.15 \). This would imply very marginal changes in the WD temperature using the Bath & Shaviv (1976) empirical relation \( T = 15280 \times 10^{\Delta m/7.5} \text{ K} \) between the change in magnitude \( \Delta m \) and the WD temperature.

We explore whether CO could be destroyed by high energy nonthermal particles from shocks as has been proposed by Derdzinski et al. (2017). In their recent work on dust and CO formation in nova outflows, they proposed that dust formation could occur within the cool, dense shell formed behind shocks in a nova wind. The high densities \( (n_\text{e} \sim 10^{14} \text{ cm}^{-3}) \) due to radiative shock compression result in CO saturation and rapid dust nucleation. The detection of several gamma-ray emitting novae in the last 5 years has led to mounting evidence for the presence of extremely strong shocks in nova winds as parcels of outflowing matter collide with each other (Ackermann et al. 2014). Acceleration across these shocks can lead to particles with high energies (even up to the TeV range if \( \gamma \)-ray emission is to be explained). Derdzinski et al. (2017) propose that CO could be destroyed by such accelerated nonthermal particles. However, we believe that such nonthermal particles would be even more likely to ionize Na and destroy the neutral Na I emission that is seen to persist even as the CO emission declines sharply. If we eliminate photoionization and shocks as the routes for CO destruction in Nova Oph 2017, then the surviving mechanism is through chemical pathways as suggested by PR2004. While we cannot be certain of this, it may be reasonable to summarize that the unique data presented here could open new avenues for understanding the evolution of CO in CNe.

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