Strong CO$^+ \text{ and } N_2^+ \text{ Emission in Comet C/2016 R2 (Pan-STARRS)}$

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Abstract

We report on imaging and spectroscopic observations of comet C/2016 R2 (Pan-STARRS) obtained with the 0.8 m and 2.7 m telescopes of McDonald Observatory in 2017 November and December, respectively. The comet was at a heliocentric distance greater than 3 au during both sets of observations. The images showed a well-developed tail with properties that suggested it was an ion tail. The spectra confirmed that we were observing well-developed bands of CO$^+$ and N$_2^+$. The N$_2^+$ detection was unequivocally cometary and was one of the strongest bands of N$_2^+$ detected in a comet spectrum. We derived the ratio of these two ions and from that we were able to derive that N$_2$/CO = 0.15. This is the highest such ratio reported for a comet.

Key words: comets: individual (2016 R2) – molecular processes – protoplanetary disks

1. Introduction

Comets represent leftovers from the origins of the solar system and are an amalgam of various ices and dust. When perturbed into the inner solar system, they get heated and the ices sublime forming the coma and any tails. The most volatile species are sublimed first and are generally exhausted from near the surface leaving less volatile ices to sublime in subsequent solar passages. Spectra of comets consist of emissions from the sublimed ices, including neutrals and ions, along with a continuum of solar light reflected off the dust.

Comet C/2016 R2 (Pan-STARRS, hereafter R2) was discovered by the Pan-STARRS telescope on 2016 September 7. With an orbital period of $\sim$20,550 years and semimajor axis of $\sim$1500 au, this comet came from the Oort Cloud, but was not a dynamically new comet. Its perihelion distance will be at 2.6 au in 2018 May. In this Letter, we report on optical imaging and spectroscopic observations of this comet obtained at The University of Texas McDonald Observatory in 2017 November–December.

2. Observations

We imaged R2 using the narrowband Hale–Bopp comet filters (Farnham et al. 2000) on 2017 November 15 UT using the Prime Focus Corrector Camera on the 0.76 m telescope at McDonald Observatory. This camera has a 46 × 46 arcmin$^2$ field of view with 1.35 arcsec pixels. A log of observations is given in Table 1. Images were obtained with filters intended to isolate emissions of OH, CN, C$_2$, and two continuum regions in the blue and NUV. Figure 1 shows the images obtained with the CN and C$_2$ filters. Of note in this figure is the extremely well-developed tail seen in both filters but substantially stronger and more developed in the CN image.

It is rare to see a well-developed tail at such a large heliocentric distance. In addition, it is extremely unusual to see the tail more developed in the CN filter. Our first idea was that this was an ion tail rather than a dust tail, but even that is uncommon at such a large heliocentric distance. Consultation with others in the field also suggested that the tail must be ionic (D. Schleicher 2017, personal communication; T. Farnham 2017, personal communication; M. Knight 2017, personal communication). In order to confirm our hypothesis of ionic emission contaminating our narrowband imaging, we followed up the images with spectroscopy.

Spectra were obtained of R2 using the Tull 2DCoude spectograph (Tull et al. 1995) on the Harlan J. Smith 2.7 m telescope of McDonald Observatory on 2017 December 8–10 UT. Details of the observations are in Table 1. The spectograph was used with a 1.2 arcsec wide by 8 arcsec tall slit centered on the optocenter for all observations, yielding a resolving power ($R = \lambda/\Delta\lambda$) of 60,000. The brightness of R2 was around $V \sim 12.5$ total. It was immediately evident that this comet’s spectrum was different than most comets when we read out the first spectrum on December 8. Missing was the strong CN band at 3880 Å that is normally one of the strongest emission features observed in optical spectra of comets, and something we have observed with even slightly fainter comets when they are closer to the Sun. Missing also was any hint of the other usual molecules, C$_2$, C$_3$, CH, or NH$_2$. Instead there was a well-developed series of bands scattered from approximately 3700 Å to 5100 Å. Most of the bands either degraded to the red or were peaked near the center of the band. There was one band that degraded blueward near 3900 Å.

The majority of the detected strong bands can be attributed to CO$^+$. We detected the CO$^+$ (4, 0), (3, 0), (2, 0), (1, 0), (4, 2), (3, 2), (2, 1), and (1, 1) A $^2P_1/2–X^2\Sigma^+$ bands. Figure 2 shows the $^2P_{1/2}$ ladder of the CO$^+$ (2, 0) band, though we actually observed both ladders. As can be seen from the figure, the CO$^+$ bands are quite complex, with many perturbations and satellite lines. The wavelengths for these bands come from Kuo et al. (1986), Haridass et al. (1992), and Haridass et al. (2000).

The blue degrading band can be attributed to the B $^2\Sigma–X^2\Sigma$ (0, 0) band of N$_2^+$ with a bandhead at 3914 Å. Figure 3 shows this band with the P and R branches marked (since the band is a $\Sigma–\Sigma$ transition it does not have a Q branch). The wavelengths and structure of the band comes from Dick et al. (1978). In this figure, note that we see R-branch lines up through $J = 16$ (and quite possibly to $J = 18$). Note also, that the odd J-level R-branch lines are weaker than the even ones, as would be expected for this homonuclear molecule. There is also evidence for the lowest J-levels of the much weaker (0, 1) band with bandhead at 4278 Å.
When $N_2^+$ is observed in a cometary spectrum, it is often erroneously attributed to being from the comet; $N_2^+$ is excited in the Earth’s atmosphere, especially near dusk and dawn and it is the telluric lines that are most often what are detected. Cochran et al. (2000) derived very tight upper limits for $N_2^+$ for comets 122P/deVico and C/1995 O1 (Hale–Bopp). Other ionic species, including CO$^+$, were observed in these cometary spectra. This raises the question of why we believe that the $N_2^+$ seen in R2’s spectrum is cometary in nature. The evidence is actually quite strong. First, the comet was observed in the middle of the night, when we would not expect much telluric emission. Second, other comets observed on the same nights did not show this band at all. Third, the band was observed in all spectra on all three nights. Finally, the lines are precisely at the correct wavelength for the cometary Doppler shift and are not coincident with the telluric rest frame. This last statement relies on the high resolving power of the coudé spectra for certainty.

In addition to these clearly defined bands, we see evidence of the forbidden oxygen transitions of O $^1D$ and possibly O $^1S$. We also see some additional emission lines that we have yet to identify. However, we can eliminate emissions due to CO$_2^+$, CH$^+$, and H$_2$O$^+$.  

### Analysis and Implications

Since R2 cannot be on its first passage into the inner solar system, it is surprising to detect two such volatile species and nothing else. But these two species are interesting to observe as we expect preferentially for C to be bound into CO or CO$_2$ and N into N$_2$ when they formed in the outer solar system (Lewis & Prinn 1980; Charnley & Rodgers 2002; Mousis et al. 2012). With our identifications of the ions of these species, we can determine the $N_2$/CO ratio of the ices in this comet.

From the band intensity and some physical constants, one can compute the column density as

$$N = I_{\nu,\lambda}/g_{\nu,\lambda}^*,$$

where $N$ is the column density, $I_{\nu,\lambda}$ is the integrated band intensity, and $g_{\nu,\lambda}^*$ is the excitation factor. From this it follows that yields the ratio of the column density of $N_2^+/CO^+$. We measured the band intensity simply by marking a continuum and summing all of the flux above that continuum. For CO$^+$ we measured both ladders of the (2, 0) band separately and summed them. For $N_2^+$, we measured the whole P-branch and R(1)–R(5) together and then added in the additional flux contributions of R(6)–R(16). The $N_2^+$ and CO$^+$ (2, 0) bands are close in wavelength but they are still seven orders apart on the CCD and well off of the grating blaze. Thus, it is likely that the throughput is slightly different for the two orders. We did observe flux standards on each night. However, these two bands are at the wavelengths of the Balmer decrement in the A stars typically used for standards. Thus, there are no calibrations of this region. Instead, we used the solar spectrum from the daytime sky, obtained through the same spectrograph via a ground-glass port, in order to figure the relative flux of these orders when compared with the atlas of Kurucz et al. (1984). We determined we needed to increase the $N_2^+$ flux by a factor of 2.0 to have comparable throughput to the CO$^+$ order. The excitation factor used for CO$^+$ was $3.55 \times 10^{-3}$ photons s$^{-1}$ mol$^{-1}$ (Magnani & A’Hearn 1986). The excitation factor for $N_2^+$ was $7.00 \times 10^{-2}$ photons s$^{-1}$ mol$^{-1}$ (Lutz et al. 1993). Putting together these various factors, we found that $N_2^+/CO^+ = 0.15$.

Converting from the quantity of the ions to the quantity of the neutrals is dependent on our understanding of the photodestruction branching ratios that are not well understood. One possible source of CO is that some of it comes from dissociation of CO$_2$. However, in that case, we would expect to see CO$_2^+$ in our spectra and we definitely do not detect any. Thus, we assume all the CO$^+$ comes from the ionization of CO and convert our measured ratio of $N_2^+/CO^+$ to $N_2$/CO. Wyckoff & Theobald (1989) argued that one must multiply the ion ratio by two to derive the neutral ratio, while Lutz et al. (1993) argued that no such factor is necessary. The argument of Lutz et al. is consistent with the solar photoionization rates given in Table 3 of Huebner & Mukherjee (2015), so we adopted this argument. Thus, assuming that CO and $N_2$ are ionized in proportion to the amount of neutrals, this means that $N_2/CO = 0.15$.

Our measured ratio is much higher than the upper limits on this ratio found for deVico and Hale–Bopp using the same instrument and techniques (Cochran et al. 2000). Their limits ranged from $3 \times 10^{-4}$ for deVico to $6 \times 10^{-5}$ for Hale–Bopp. Indeed, it is much higher than other observations of $N_2^+/CO^+$, as listed in Table 3 of Cochran et al. Korsun et al. (2014) measured the $N_2^+/CO^+$ in comet C/2002 VQ94 (LINEAR), a comet active at >8 au, as 0.06. Feldman (2015) placed a 3σ upper limit on $N_2$/CO of 0.027 for comet C/2001 Q4 (NEAT) using FUSE observations. Ivanova et al. (2016) measured $N_2^+/CO^+$ as 0.013 for comet 29P/Schwassmann–Wachmann 1 at 5.25 au, though the $N_2^+$ feature is not well defined in these low-resolution spectra. Using a mass spectrometer on the Rosetta spacecraft in orbit with comet 67P/Churyumov–Gerasimenko, Rubin et al. (2015) measured an $N_2$/CO ratio of $5.7 \times 10^{-3}$. This is certainly the most robust measure of this ratio since it was measured in situ, though the closeness of

| Images | Log of Observations |
|--------|---------------------|
| Date   | $R_\mathrm{v}$ (au) | $\Delta$ (au) | Images per Filter |
| 2017 Nov 15 | 3.19 | 2.32 | 5 C2, 3 CN |

| Spectra | Date   | $R_\mathrm{v}$ (au) | $\Delta$ (au) | $\Delta$ (km s$^{-1}$) | Num. (30 minutes) |
|---------|--------|---------------------|----------------|----------------------|-------------------|
| 2017 Dec 8 | 3.06 | 2.10 | −10.48 | 1 |
| 2017 Dec 9 | 3.05 | 2.09 | −9.85 | 6 |
| 2017 Dec 10 | 3.05 | 2.09 | −9.21 | 6 |

Note. $^a$ Doppler shift in December ~0.13 Å.
these species in mass makes the measurement subject to model interpretation. Thus, comet R2 shows an $N_2/CO$ ratio at least a factor of 2 greater than any comet measured so far. Wierzchos & Womack (2017) reported on submillimeter observations of R2, including a detection of the CO $J = 2–1$ rotational line and a non-detection of the HCN $J = 3–2$ rotational transition. They conclude that this comet appears to be very CO-rich. We could potentially use the O($^1D$) 6300 Å lines as a proxy to determine the abundance of water. However, as CO can also contribute photons to this line, the derived water value would be suspect. Therefore, we leave detailed analysis of the O($^1D$) 6300 Å line in terms of the production of water for a future publication.

The ratio of $N_2/CO$ trapped in the cometary ices is not necessarily identical with the amount in the solar nebula. Owen & Bar-Nun (1995) used studies of deposition of gases into amorphous water ice in the laboratory to show that ices incorporated into comets at around 50 K would have $N_2/CO \approx 0.06$ if $N_2/CO \approx 1$ in the solar nebula. Our measurement of $N_2/CO$ is within a factor of 2 of their derived value, though ours is higher. Indeed, only some of the older photographic data related by C. Arpigny for Cochran et al. (2000) come close to the Owen and Bar-Nun prediction.

It must be noted that the ratio of species seen in the gas phase is not necessarily representative of the ratio of the ices in the nucleus. However, CO and N$_2$ are not terribly reactive with other species so chemical reactions probably do not alter this ratio much. It also means we do not expect to see the ratio change with heliocentric distance. Additionally, Bar-Nun et al. (1988) showed that CO and N$_2$ should be released in the same proportion as they exist in the ices.

Owen and Bar-Nun predicted that there would be higher values of $N_2/CO$ for dynamically new comets than for older comets. However, as pointed out earlier, R2 has a period of around 20,000 years and a semimajor axis of around 1500 au suggesting that it has been near the Sun prior to this apparition. Note that the comets with measured $N_2/CO$ ratios represent a variety of dynamical types, from Jupiter-family comets such as 67P and 29P, to dynamically new comets such as C/1940 R2 (Cunningham). There is no clear trend of the magnitude of this ratio with dynamical type.

Comet C/2016 R2 (Pan-STARRS) showed an unusual optical spectrum with strong CO$^+$ and N$_2^+$ emissions and none of the usual neutrals seen in most cometary spectra. This intriguing object showed the strongest and clearest N$_2^+$ emissions ever detected with modern digital spectra. Faced
with this unusual spectrum, we have alerted many members of the cometary community and they (and we) are requesting follow-up observations with a variety of instruments at all wavelengths in order to try to understand this unusual comet.

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Erratum: “Strong CO$^+$ and N$_2^+$ Emission in Comet C/2016 R2 (Pan-STARRS)”
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After publication of these observations, we discovered an error in our spreadsheet where we summed up the band intensities. Unfortunately, the flux in the P branch lines plus R(0) to R(5) got added in three times. As a result, we calculated a much higher N$_2^+$ band intensity than we should have. After correcting this error, we find that N$_2^+$/CO$^+$ = 0.06. By the arguments we included then N$_2$/CO = 0.06. This is more in keeping with the highest previous values detected and is consistent with the values of Owen & Bar-Nun (1995). However, our N$_2^+$ detection is the cleanest detection ever because it is digital and at high spectral resolution (see Figure 3 of the published article). Furthermore, we have continued monitoring this comet and still see N$_2^+$ and CO$^+$ but not more normal neutrals. The comet appears extremely CO-rich and depleted in many species.

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