New Horizons Upper Limits on O$_2$ in Pluto’s Present Day Atmosphere

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The New Horizons Atmospheres and Alice UV Spectrograph Teams

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Abstract

The surprising discovery by the Rosetta spacecraft of molecular oxygen (O$_2$) in the coma of comet 67P/Churyumov–Gerasimenko challenged our understanding of the inventory of this volatile species on and inside bodies from the Kuiper Belt. That discovery motivated our search for oxygen in the atmosphere of Kuiper Belt planet Pluto, because O$_2$ is volatile even at Pluto’s surface temperatures. During the New Horizons flyby of Pluto in 2015 July, the spacecraft probed the composition of Pluto’s atmosphere using a variety of observations, including an ultraviolet solar occultation observed by the Alice UV spectrograph. As described in these reports, absorption by molecular species in Pluto’s atmosphere yielded detections of N$_2$, as well as hydrocarbon species such as CH$_4$, C$_2$H$_2$, C$_2$H$_4$, and C$_2$H$_6$. Our work here further examines this data to search for UV absorption from molecular oxygen (O$_2$), which has a significant cross-section in the Alice spectrograph bandpass. We find no evidence for O$_2$ absorption and place an upper limit on the total amount of O$_2$ in Pluto’s atmosphere as a function of tangent height up to 700 km. In most of the atmosphere, this upper limit in line-of-sight abundance units is $\sim 3 \times 10^{-12}$ cm$^{-2}$, which, depending on tangent height, corresponds to a mixing ratio of $10^{-6}$ to $10^{-4}$, far lower than in comet 67P/CG.

Key words: planets and satellites: atmospheres – planets and satellites: individual (Pluto)

1. Introduction

In situ mass spectroscopy measurements aboard the Rosetta spacecraft at comet 67P/Churyumov–Gerasimenko (67P/CG) detected molecular oxygen (O$_2$), which represents the first detection of O$_2$ in a cometary coma (Bieler et al. 2015). Subsequently, FUV stellar occultation observations (Keeney et al. 2017) by the Rosetta Alice ultraviolet spectrograph (Stern et al. 2007) also detected O$_2$. The molecular oxygen in comet 67P/CG was found to be present at surprisingly high levels (several to several tens of percent relative to the line-of-sight column abundance of H$_2$O), suggesting that the O$_2$ is primordial, rather than the byproduct of coma chemistry, and therefore has likely been stored in the nucleus of the comet since its formation. O$_2$ has been found in atmospheres throughout the solar system, from terrestrial planets like Earth to icy moons such as Europa (Hall et al. 1995) and can also be found produced in the rings of Saturn (Johnson et al. 2006). However, comet 67P/CG originated in the distant reaches of the Kuiper Belt. Because such comets are theorized candidates for the building blocks of bodies like Pluto, this naturally motivates a search for molecular oxygen in the atmosphere of Pluto by making use of the data sets acquired by the New Horizons mission during its flyby in 2015 July.

One of the powerful tools for atmospheric study on the New Horizons spacecraft is the Alice extreme-/far-ultraviolet imaging spectograph (for a thorough instrument description, see Stern et al. 2008). This instrument has a bandpass of 52 to 187 nm, a wavelength region that is highly diagnostic for signatures of absorption by molecular species. Initial results from the analysis of a UV solar occultation of Pluto observed by this instrument yielded strong detections of both N$_2$ and CH$_4$, detections of minor hydrocarbon species such as C$_2$H$_2$, C$_2$H$_4$, and C$_2$H$_6$, as well as a measurement of the absorption by the haze that enshrouds the planet (Stern et al. 2015; Gladstone et al. 2016; Young et al. 2017). Because molecular oxygen also has significant absorption in this region of the UV (Ackerman et al. 1970; Brion & Tan 1979; Gibson et al. 1980), this work delves further into the New Horizons Alice occultation data set with the goal of detecting or constraining the abundance of O$_2$ in the atmosphere of Pluto. In Section 2, we compare the absorption of O$_2$ to other species detected in the UV solar occultation and set upper limits on O$_2$ line-of-sight column abundances as a function of tangent height. In Section 3, we discuss these results at Pluto within the context of Rosetta findings at comet 67P/CG. Finally, in Section 4, we consider possible explanations for the dramatic difference we observe in O$_2$ abundances, and suggest future observations that could improve our understanding of the prevalence of O$_2$ in the Kuiper Belt.

2. O$_2$ in the Ultraviolet

2.1. Comparison to Other UV Absorbing Species

Figure 1 compares the general features of the UV cross-section of O$_2$ with other species detected in Pluto’s atmosphere, including N$_2$, CO, and CH$_4$ along with its photochemical derivatives (C$_2$H$_2$, C$_2$H$_4$, C$_2$H$_6$). Disentangling the combined effects of absorption by these various species can be achieved due to their distinctly different cross-sections as a function of wavelength. References for these cross-sections are listed in Table 1.

Young et al. (2017, hereafter Y17) derived line-of-sight abundances of N$_2$, CH$_4$, C$_2$H$_2$, C$_2$H$_4$, C$_2$H$_6$, and a neutral-absorbing haze to match the observed Pluto occultation spectra.
at wavelengths from 55–65 nm and 100–185 nm. The results of Y17 provide our initial best-fit models for wavelength-dependent transmission at each level in the atmosphere. We note that N₂, the hydrocarbons, and haze together account for the bulk of all atmospheric absorption detected during the Alice ultraviolet solar occultation. Here, we reanalyze this same data set at the longer wavelength end in order to determine how much O₂ can be accommodated in a modeled atmosphere given the Alice detection limits.

As demonstrated in the top panel of Figure 2, which shows model results from Y17, followed in lower panels by modeled absorption due to O₂ fixed at 200 km altitude, we found that sensitivity to O₂ remains high despite the absorptions of other species. We tested three simple cases in which the mixing ratio of O₂ was fixed to a constant value with altitude, then calculated the effect on the atmospheric absorption in the UV, while keeping all other species abundances the same. This yielded an initial estimate of the maximum tolerable mixing ratio of O₂. More specifically, when using this approach, the Pluto solar occultation is sensitive to and clearly rules out absorption by O₂ at the ∼10⁻⁵ mixing ratio level or higher.

2.2. Vertical Profiles of Upper Limits on O₂ Abundance

We note, however, that constraints on O₂ abundances using this data set depend upon the tangent height of the observed spectra. Because a primary physical quantity measured by the occultation is the absorbing species line-of-sight (LOS) column abundance (cm⁻²), we also report the O₂ LOS abundance upper limits as a function of tangent height for both ingress and egress. During this part of our analysis, the contribution to UV absorption from O₂ was added as another free parameter in a simultaneous fit to the spectra, as done in Y17. The upper limit on LOS abundance of O₂ was then derived at each tangent height based on an optimized model spectral fit, briefly summarized here (see Y17 for a full description and discussion of the procedure). Starting at a tangent height of 2000 km altitude, spectra from each level in the atmosphere were iteratively fit down toward the surface. To retrieve the parameterized line-of-sight abundances from each spectrum, the spectrum from the previous level acted as an initial guess in a weighted Levenberg–Marquardt least-squares fit to minimize the weighted sum of squared residuals, or χ². The upper limits derived for LOS abundances of O₂ are shown in Figure 3.

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**Table 1**

| Species | Name        | Source                                      |
|---------|-------------|---------------------------------------------|
| N₂      | Nitrogen    | Shaw et al. (1992), Heays et al. (2011)     |
| CH₄     | Methane     | Lee et al. (2001), Kameta et al. (2002), Chen & Wu (2004) |
| CO      | Carbon Monoxide | Chan et al. (1993), Visser et al. (2009), Stark et al. (2014) |
| C₂H₆    | Ethane      | Kameta et al. (1996), Lee et al. (2001), Chen & Wu (2004) |
| C₂H₂    | Acetylene   | Nakayama & Watanabe (1964), Cooper et al. (1995), Wu et al. (2001) |
| C₂H₄    | Ethylene    | Cooper et al. (1995), Wu et al. (2004)      |
| O₂      | Oxygen      | Ackerman et al. (1970), Brion & Tan (1979), Gibson et al. (1980) |

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**Figure 1.** Absorption cross-section of O₂ in the ultraviolet compared to those of several other species found in the atmosphere of Pluto. Note that CO is represented by both low- and high-resolution cross-sections where available, with a transition region from low to high located at 90 nm; the other species have relatively lower-resolution cross-sections at the relevant temperatures. The sources for the cross-sections used in this work are compiled in Table 1.
In most of the upper atmosphere, the limit on the O₂ LOS column abundance is \( \sim 3 \times 10^{15} \text{ cm}^{-2} \). Depending on tangent height, this LOS abundance is generally equivalent to a constant mixing ratio model of \( 10^{-4} \) at 450 km, \( 10^{-5} \) at 250 km, and \( 10^{-6} \) at 150 km, becoming smaller as the tangent height decreases. This trend significantly weakens below 150 km, because the transmission of sunlight begins to approach zero at all wavelengths that are sensitive to O₂ absorption, and thus
additional O$_2$ absorption no longer has a significant effect on the model fit.

3. Pluto Compared to Comet 67P/CG

While the in situ results from the Rosetta mission at comet 67P/CG reported an O$_2$/H$_2$O ratio, it is far more useful at Pluto to compare the measured O$_2$/CO and O$_2$/N$_2$ ratios, because the temperatures in Pluto’s atmosphere are too cold for H$_2$O to remain in gas phase but are not too cold for CO or N$_2$ to remain in gas phase. The relative abundances of these species in the atmosphere of Pluto and the coma of comet 67P/CG may then shed light on the provenance of the O$_2$.

For comet 67P/CG, the O$_2$/CO ratio varied from about 0.1 to 1.0 (Bieler et al. 2015). At Pluto, the mixing ratio of CO has been most recently estimated from observations by ALMA to be $515 \pm 40$ ppm (Lellouch et al. 2017). Taken together with the upper limit from this work of $\sim 10^{-5}$ O$_2$ mixing ratio in Pluto’s entire atmospheric column, this implies a Pluto O$_2$/CO upper limit of $\sim 2 \times 10^{-2}$. This is 5–50 times lower than the O$_2$/CO ratio found in the coma of comet 67P/CG.

In the case of O$_2$/N$_2$ ratios, the difference is even more extreme. For comet 67P/CG, the O$_2$/N$_2$ ratio varied from about 20–100, with much more O$_2$ detected in outgassing from the comet than N$_2$. This is in stark contrast to Pluto’s atmosphere, which is dominated by N$_2$, and which has an upper limit O$_2$ mixing ratio relative to N$_2$ of $\sim 10^{-5}$.

4. Conclusions

We suggest several explanations for the relative lack of atmospheric O$_2$ on Pluto, which indicate that this warrants further study. First, it may be that comet 67P/CG is simply not typical of the material that went into the formation of Pluto. Alternatively, perhaps Pluto contains a similar inventory of primordial O$_2$, but it is not found in appreciable amounts in the present day atmosphere, i.e., it may be sequestered in the planet’s interior. Or as another alternative, O$_2$ inside Pluto may have been chemically converted into other oxygen-bearing species such as H$_2$O, CO, CO$_2$, or minerals, owing to the expected significantly different thermal and chemical evolution of Pluto, which is $\sim 10^9$ times as massive as comet 67P/CG.

In order to make further progress, we suggest that new observations are needed. Specifically, it is necessary to determine how typical the O$_2$ abundance in comet 67P/CG is for Kuiper Belt comets as a whole; Keeney et al. (2017) have shown that the O$_2$ in comet 67P/CG can also be detected by FUV stellar occultation techniques, opening the possibility that future observations with the Hubble Space Telescope or similarly capable future observatories could address this issue.

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