Pluto’s Ultraviolet Spectrum, Surface Reflectance, and Airglow Emissions

Andrew J. Steffl1 ©, Leslie A. Young3 ©, Darrell F. Strobel3 ©, Joshua A. Kammer3 ©, J. Scott Evans4 ©, Michael H. Stevens5 ©, Rebecca N. Schindhelm6, Joel Wm. Parker1 ©, S. Alan Stern1 ©, Harold A. Weaver7 ©, Catherine B. Olkin1 ©, Kimberly Ennico8 ©, Jay R. Cummings4 ©, G. Randall Gladstone3 11 ©, Thomas K. Greathouse3 ©, David P. Hinson9 ©, Kurt D. Retherford3 ©, Michael E. Summers10 ©, and Maarten Versteeg3 ©
1 Southwest Research Institute, 1050 Walnut Street, Suite 300, Boulder, CO 80302, USA; stef@boulder.swri.edu
2 The Johns Hopkins University, Baltimore, MD, USA
3 Southwest Research Institute, San Antonio, TX, USA
4 Computational Physics Incorporated, Springfield, VA, USA
5 Naval Research Laboratory, Washington, DC, USA
6 Ball Aerospace, Boulder, CO, USA
7 Johns Hopkins University, Applied Physics Laboratory, Laurel, MD, USA
8 NASA Ames Research Center, Moffett Field, CA, USA
9 SETI Institute, Mountain View, CA, USA
10 George Mason University, Fairfax, VA, USA
11 University of Texas at San Antonio, San Antonio, TX, USA
Received 2018 November 2; revised 2020 April 24; accepted 2020 April 24; published 2020 May 26

Abstract

During the New Horizons spacecraft’s encounter with Pluto, the Alice ultraviolet spectrograph conducted a series of observations that detected emissions from both the interplanetary medium (IPM) and Pluto. In the direction of Pluto, the IPM was found to be 133.4 ± 0.6 R at Ly14, 0.24 ± 0.02 R at Ly13, and <0.10 R at He1584 Å. We analyzed 3900 s of data obtained shortly before closest approach to Pluto and detect airglow emissions from H1, N1, N11, N2, and CO above the disk of Pluto. We find Pluto’s brightness at Ly14 to be 29.3 ± 1.9 R, in good agreement with preencounter estimates. The detection of the N11 multiplet at 1085 Å marks the first direct detection of ions in Pluto’s atmosphere. We do not detect any emissions from noble gases and place a 3σ upper limit of 0.14 R on the brightness of the Ar1 1048 Å line. We compare preencounter model predictions and predictions from our own airglow model, based on atmospheric profiles derived from the solar occultation observed by New Horizons, to the observed brightness of Pluto’s airglow. Although completely opaque at Ly14, Pluto’s atmosphere is optically thin at wavelengths longer than 1425 Å. Consequently, a significant amount of solar far-UV light reaches the surface, where it can participate in space weathering processes. From the brightness of sunlight reflected from Pluto, we find the surface has a reflectance factor (I/F) of 17% between 1400 and 1850 Å. We also report the first detection of a C3 hydrocarbon molecule, methacetylene, in absorption, at a column density of ~5 × 1015 cm−2, corresponding to a column-integrated mixing ratio of 1.6 × 10−6.

Unified Astronomy Thesaurus concepts: Pluto (1267); Spectrometers (1554); Ultraviolet astronomy (1736); Planetary atmospheres (1244); Planetary surfaces (2113)

1. Introduction

Pluto’s atmosphere was definitively discovered in 1988 by the technique of stellar occultation (Hubbard et al. 1988; Elliot et al. 1989), but its composition was unknown. The composition was subsequently deduced to be primarily N2 with trace amounts of CH4 and CO, based on detection of their ices on Pluto’s surface and their vapor pressures (Owen et al. 1993). Gaseous CH4 was later detected spectroscopically (Young et al. 1997; Lellouch et al. 2017). As of the launch of NASA’s New Horizons spacecraft in 2005, only upper limits had been placed on the amount of atmospheric CO (Bockelé-Morvan et al. 2001; Young et al. 2001). The first detections of gaseous CO were claimed in 2011 (Greaves et al. 2011; Lellouch et al. 2011), and high signal-to-noise ratio measurements of gaseous CO and HCN were made near in time to the New Horizons flyby with ALMA (Lellouch et al. 2017). Shortly after the New Horizons spacecraft’s closest approach to Pluto, the Alice instrument observed an occultation of the Sun by Pluto (Gladstone et al. 2016), while the Radio Science Experiment (REX) observed an occultation of Earth (Hinson et al. 2017). From the solar occultation, Alice detected absorption by N2, CH4, C2H2, C2H4, C2H6, and haze (Young et al. 2018). From the egress of the Earth occultation, which occurred over the Sputnik Planitia region, REX found that Pluto’s atmosphere was much colder (39 K at the surface, 65–68 K in the upper atmosphere) and more compact than expected prior to the flyby.

We report here observations of Pluto’s atmosphere and surface by the Alice far-ultraviolet (FUV) spectrograph onboard New Horizons, Stern (2008) just prior to its closest approach.

2. The Alice FUV Spectrograph

Alice is a lightweight (4.4 kg), low-power (4.4 W), imaging, FUV spectrograph (Stern et al. 2008). Sometimes referred to as “P-Alice” (for “PERSI-Alice,” a precursor instrument design, or “Pluto-Alice”), to distinguish it from its older sibling instrument on ESA’s Rosetta Spacecraft (Stern et al. 2007), it...
3. Airglow Observations and Processing

On approach to Pluto, Alice made numerous observations in search of airglow emissions. For our analysis, we selected data from just two separate airglow observations, PEAL_01_P-C_Airglow_Appr_3 and PEAL_01_PC_Airglow_Appr_4, hereafter Airglow3 and Airglow4. These particular observations were chosen because they are the closest, long-duration airglow observations of Pluto and thus, presumably, the most sensitive. Additionally, these observations have a favorable viewing geometry in which Alice is centered on Pluto, whose disk fills >98% of the FOV of the central row of the detector (row 16, zero-indexed). This minimizes the possibility of confusing emission from the interplanetary medium (IPM) with Plutogenic airglow emissions. The adjacent detector rows, 15 and 17, are centered at a tangent altitude of ∼890 km and cover a region from the surface to a tangent altitude of 1.6 Pluto radii. Figure 1, produced using the web-based GeoViz tool (Throop et al. 2009), illustrates the observing geometry during the Airglow3 and Airglow4 observations. The instrument footprint covers a significant fraction of Sputnik Planitia as well as regions poleward.

Data from the Airglow3 observation consist of ten 300 s histogram exposures obtained from 2015 July 14 03:11:26 to 2015 July 14 04:01:26 UTC. During these exposures, the distance to Pluto spanned 427,621–386,306 km, and the phase angle increased slightly from 16°90 to 17°09. We also selected six 150 s histogram exposures from the 18 exposures of the Airglow4 observation that covered a similar region on Pluto as Airglow3. These Airglow4 images were obtained from 2015 July 14 05:20:31 to 2015 July 14 05:35:31 UTC and spanned 320,976–308,588 km in distance and 17°51–17°60 in phase angle. To maximize the signal-to-noise ratio in the data, we coadded all 16 spectra. Observational details are shown in Table 1.

We apply the standard Alice data reduction techniques of dead time correction, stem pixel correction, and dark subtraction. These are described in more detail in the Appendix below. As discussed above, there is no photocathode coating on the MCP in the region around Lyα (1216 Å). This causes the extended wings of the line profile to appear to drop to zero, increase sharply around 60 Å from Lyα (where the CsI and KBr photocathode coatings begin), and then decrease gradually with further distance from the line center. Because Lyα emission line is so intrinsically bright, the extended wings of the line profile are comparable in intensity to the faint airglow emissions we are searching for—even several hundred anstroms away from the core of the line. Thus, careful removal of the scattered Lyα profile is required.

We created a Lyα template image by summing 38 hr of Alice observations (PC_AIRGLOW_DOY, where DOY is the day of year), made on approach to Pluto between 2015 May 29 (DOY 149) and 2015 June 18 (DOY 169). Owing to the large distance of New Horizons to Pluto (greater than 30 million km), no airglow emissions or sunlight reflected from Pluto were detected in these data and Pluto’s disk blocks out an insignificant fraction of the FOV. In half of these observations, Pluto was placed at the center of the box portion of the slit, and in the other half, Pluto was placed at the instrument boresight in the stem. No significant differences were seen between the two pointings. IPM emission lines were detected at Lyα (1216 Å) and Lyβ (1026 Å) but not at He I 584 Å. The observed brightness (or upper limit) of these lines is given in Table 2. The brightness of the IPM Lyα is ∼1.5× brighter than preencounter predictions (Gladstone et al. 2015).

Since interplanetary Lyβ emission is ∼500× fainter than Lyα emission, the extended wings of its line profile are not significant. To prevent the unintentional subtraction of the IPM Lyβ signal from the Pluto observations, we fit a Gaussian line profile with a linear background to the IPM spectrum around 1026 Å and subtract off the Gaussian component. The resulting template image contains only interplanetary Lyα and detector dark counts. We remove these dark counts by subtracting a composite “dark” image, obtained while the airglow aperture door was closed. The spectrum of these dark counts can be seen in the blue line of Figure 2. After subtracting the scaled dark image from the Pluto observations, we normalize the IPM Lyα template to the brightness of the Lyα emission in the Pluto data.
Due to the slight misalignment of the Alice detector and the optical axes of the spectrograph, emissions that are centered in a given detector row at short wavelengths will partially spill over onto the next lower detector row for wavelengths greater than \( \sim 1570 \) Å. We therefore extract the airglow spectrum from row 16 and add the spectrum of row 15 to it for \( \lambda > 1570 \) Å. The resulting uncalibrated spectrum of Pluto is shown in Figure 2.

![Figure 1](image1.png)

**Figure 1.** Observing geometry during the Airglow3 observation (left) and selected exposures from the Airglow4 observation (right). The projection of the Alice entrance slit onto the sky plane is outlined in blue. The approximately vertical, blue lines delineate the FOV of individual detector rows, with row 16 (zero indexed) lying on the disk of Pluto and rows 17 and 15 to the left and right of Pluto, respectively.

| Observational Quantity | Airglow3 | Airglow4 |
|-------------------------|----------|----------|
| Number of integrations  | 10       | 6        |
| Total integration time (s) | 3000    | 900      |
| Start time              | 2015 Jul 14 | 2015 Jul 14 |
| End time                | 2015 Jul 14 | 2015 Jul 14 |
| Distance to Pluto at start (km) | 427,600 | 386,300 |
| Distance to Pluto at end (km) | 321,000 | 308,600 |
| Pluto phase angle at start (°) | 16.90    | 17.09    |
| Pluto phase angle at end (°) | 17.51    | 17.60    |

| Species | Wavelength (Å) | Observed Intensity** (R) |
|---------|----------------|--------------------------|
| He I    | 584            | <0.10                    |
| H I     | 1026           | 0.24 ± 0.02              |
| H I     | 1216           | 133.4 ± 0.6              |

**Notes.**

a. \( \alpha = 18^h2^m38^s7^, \delta = -14^\circ37'37''2^).  
b. Quoted error bars are 1\( \sigma \), while the He I 584 Å upper limit is 3\( \sigma \).

D. Due to the slight misalignment of the Alice detector and the optical axes of the spectrograph, emissions that are centered in a given detector row at short wavelengths will partially spill over onto the next lower detector row for wavelengths greater than \( \sim 1570 \) Å. We therefore extract the airglow spectrum from row 16 and add the spectrum of row 15 to it for \( \lambda > 1570 \) Å. The resulting uncalibrated spectrum of Pluto is shown in Figure 2.

![Figure 2](image2.png)

**Figure 2.** Alice count rate spectra of Pluto and background sources. The spectra are extracted from detector row 16, except for wavelengths longer than 1570 Å, which also include row 15. This causes the apparent jump in background rates. The black curve shows the uncalibrated count rate spectrum from the sum of the Airglow3 and Airglow4 observations used in this analysis. The blue curve shows the dark count background produced by the detector when the airglow aperture door is closed, and the red curve shows the sum of the dark count spectrum and the IPM Ly\( \alpha \) profile, scaled to the level of Ly\( \alpha \) in the Airglow3 observations.

![Figure 2](image3.png)

**Figure 2.** We divide by the instrument’s effective area curve and by the solid angle of the sky as seen by a single detector row (0.3 spatial along the slit by 0.1 across it) to calibrate the spectrum in units of radiance.
4. Pluto’s Atmospheric Transmission and Surface Reflectance

The observed spectral radiance of Pluto over the Alice passband is shown in Figure 3. The central spectral feature is the Lyα airglow at 1216 Å. Since the disk of Pluto completely fills the FOV of the central row during this observation, there is no contribution from the IPM. Faint airglow emission features arising from molecular, atomic, and ionized species (e.g., N₂, C₂H₂, C₂H₄, N I, 1493 Å, and N II 1085 Å) are present in the spectrum and are discussed in Section 5 below.

At wavelengths greater than ~1500 Å, Pluto’s spectrum is dominated by sunlight passing through the atmosphere and reflecting off the surface. Scattering of sunlight by atmospheric haze particles 100–200 km above the surface may also contribute a small amount to the observed spectrum at these wavelengths. For our purposes, the reflected/scattered solar light serves as an additional source of background that potentially obscures fainter airglow emissions in this region of the spectrum. We therefore attempt to remove the solar contribution by constructing a simple model of Pluto’s atmospheric transmission and surface reflectance, based on the solar occultation profiles of Pluto’s atmosphere (Young et al. 2018).

4.1. Atmospheric Transmission

The ingress and egress solar occultation profiles reported by Young et al. (2018) are largely similar. To increase the signal-to-noise in our analysis, we averaged the two occultation profiles together and rebinned the data to 25 km vertical resolution. We used this profile to reproduce the results of Young et al. (2018). Pluto’s hazes are complex (Cheng et al. 2017; Zhang et al. 2017; Krasnopolsky 2020), and we do not attempt to derive a column density directly from the occultation profiles. Rather, following Young et al. (2018), we treat the haze as a spectrally neutral source of atmospheric opacity in our fits to the solar occultation transmission spectrum. For comparison with other atmospheric constituents, we assume a wavelength-independent haze cross section of 1 × 10⁻¹⁵ cm² Å⁻¹.

With the additional assumption of spherical symmetry (reasonable, given the similarity of the ingress and egress profiles), we can apply the Abel transform (Roble & Hays 1972) to derive local number density from line-of-sight abundances (column densities):

\[
n(r) = -\frac{1}{\pi} \int_r^\infty \frac{dN(r')}{dr'} dr',
\]

where \(n(r)\) is the number density of a given species at radial distance, \(r\), from Pluto and \(N(r')\) is the column density of that species at a tangent radius, \(r'\). The resulting atmospheric profiles are shown in Figure 4, which is broadly similar to Figure 17 of Young et al. (2018).

As shown in Figure 1, the Alice FOV covered a significant fraction of the disk of Pluto during the Airglow3 and Airglow4 observations and as such covers a large range of solar incidence and emission angles. Therefore, we divided the FOV of the central detector row (row 16, zero-indexed) into a grid of 31 × 11 lines of sight, separated by 0°01 (corresponding to a separation of roughly 70 km on Pluto’s surface) and calculated the atmospheric absorption and surface reflection along each line of sight. Averaged over the Alice FOV, the solar incidence angle is 36°2, while the average emission angle is 33°3. We integrate the atmospheric profiles shown in Figure 4 along the path from the Sun to the surface and then from the surface to Alice for each of the 341 lines of sight. The two-way atmospheric transmission, averaged over the Alice FOV, is shown in the top panel of Figure 5, while the one-way vertical atmospheric transmission is shown in the bottom panel (see Figure 12 of Young et al. 2018).

Pluto’s atmosphere is completely opaque at wavelengths below 1400 Å, largely due to absorption by methane (CH₄). However, the absorption cross section of methane decreases by more than four orders of magnitude between 1400 and 1500 Å, which results in the vertical optical depth of the atmosphere, \(\tau_\lambda\), being less than 1 for \(\lambda > 1425\) Å. Acetylene (C₂H₂) is the primary atmospheric absorber between 1430 and 1530 Å, while at wavelengths greater than 1530 Å, the atmospheric transmission is controlled by both haze particles and ethylene (C₂H₄).

As shown in the bottom panel of Figure 5, photons with \(\lambda > 1425\) Å readily pass through the atmosphere and interact.
observed spectral intensity in photons
acetylene
(atmospheric transmission. comparisons to other atmospheric constituents. Bottom: One-way vertical
over the Alice FOV. We include atmospheric absorption from methane
C2H2 (detailed properties of the haze are not modeled. Instead, the haze is assumed to
where
insolation when averaged over Pluto
s orbit, are darker and redder than the poles, which are brighter and more neutral in
color. They propose that this surface color distribution could be produced by the transport of volatiles away from the warmer
equator toward the colder poles. We suggest that in addition to
this mechanism, longer-wavelength FUV photons photolyze
tholins and haze particles on the surface, further reddening the
equatorial regions.

4.2. Pluto’s FUV Surface Reflectance

The reflectance factor, sometimes referred to as $I/F$, is defined as

$$I/F(\lambda) = \frac{\pi hc I(\lambda, \phi)r^2}{\mu_0 \Omega F_0(\lambda)},$$

where $h$ is Planck’s constant; $c$ is the speed of light; $I$ is the observed spectral intensity in photons s$^{-1}$ cm$^{-2}$ Å$^{-1}$ as a function of wavelength, $\lambda$, at a given solar phase angle, $\phi$; $r$ is the heliocentric distance of Pluto in astronomical units; $\mu_0$ is the cosine of the solar incidence angle, averaged over the FOV; $\Omega = 9.1 \times 10^{-6}$ sr is the solid angle subtended by a single row of the Alice detector; and $F_0$ is the solar flux at 1 au. After proper calibration, $I(\lambda, \phi)$ is what is actually measured by Alice. We use the same $F_0(\lambda)$ as in Young et al. (2018), which was assembled from SUMER reference spectra (Curdt et al. 2001) and observations from TIMED/SEE (Woods et al. 2005).

In the absence of an atmosphere and with a surface
reflectance factor of 100%, the spectral radiance of Pluto would be about an order of magnitude greater than what is
observed, as shown with the blue curve of Figure 6. Including
the two-way atmospheric transmission shown in Figure 5 reduces our model spectral radiance to about 6 $\times$ what is observed at long wavelengths. Combining this with a wavelength-independent surface reflectance factor of 17% yields a surprisingly good match to the observed radiance of Pluto at wavelengths greater than $\sim$1570 Å. Notably, the feature at 1657 Å appears to be entirely due to the reflected/scattered solar C I multiplet and not airglow emission from Pluto’s atmosphere.

Compared with other planetary surfaces, an FUV $I/F$ of 17% is relatively high. For example, comet 67P/Churyumov–Gerasimenko has an $I/F$ of just 1%–2% (Stern et al. 2015); Saturn’s moon, Phoebe, has a reflectance between 1% and 3% (Hendrix & Hansen 2008); while the Moon’s $I/F$ varies between 2% and 10% (Gladstone et al. 2012).

As discussed above, Pluto’s atmospheric haze was treated simply as a source of extinction. In reality, haze particles will both scatter and absorb sunlight. Therefore, the 17% surface $I/F$ value should really be thought of as an upper limit. Modeling the properties of Pluto’s atmospheric haze is well beyond the scope of this paper. However, as an end-member case, if we assume the haze particles are simple 0.2 μm spheres with a single scattering albedo of 0.55 at 1500 Å, Mie scattering theory predicts that the haze will be roughly half absorbing and half scattering and that the scattering should be roughly independent with wavelength over the Alice passband. If we then assume that as much sunlight is scattered back into our line of sight as out of it, a surface $I/F$ value of 13% is required to match the Alice observations. We suggest that a more detailed analysis of Pluto’s ultraviolet surface reflectance, properly accounting for atmospheric haze, is a fruitful area for subsequent work.
4.3. Methylacetylene

While the overall match between the Alice observations and our simple transmission/reflectance model is fairly good, as shown in Figure 6, our simple model predicts significantly more flux than is observed between 1535 and 1570 Å, resulting in an oversubtraction of the solar spectrum. This suggests that either the atmosphere or surface has one or more additional sources of opacity/absorption. However, FUV absorption features from solids tend to be very broad, on the order of hundreds of angstroms (Wagner et al. 1987). Likewise, we are not aware of any mechanism by which atmospheric haze can produce such relatively narrow absorption features. Thus, we favor the interpretation that one or more additional gaseous species are present in Pluto’s atmosphere at high enough column densities to significantly absorb sunlight passing through the atmosphere.

We examined the absorption cross sections of 32 additional atomic and molecular species that might plausibly be found in Pluto’s atmosphere (C, CH, CH₂, H₂O, C₂H₅, C₃H₆, C₃H₄, C₄H₆, H₂, H₂O, CO, CO₂, N₂, O, O₃, CO, N₂O, NH₃, CH₄, HCN, HCN, HNC, CO₂, N₂, O, O₂, O₃, OCS, PH₃, SO, and SO₂) and found that, among them, only methylacetylene (H₂C=C=CH₂ or propyne) has both a strong absorption band in this region and a lack of strong absorption bands at longer wavelengths, where no additional absorption is seen. Methylacetylene has been observed in the upper atmospheres of both Titan, where it can reach local mixing ratios of up to 10⁻³ (Li et al. 2015), and Jupiter, where it is part of an important chemical pathway in the production of acetylene (C₂H₂) (Gladstone et al. 1996). The Pluto photochemical model of Wong et al. (2017) predicts a methylacetylene column density of 2.5 × 10⁻¹⁵ cm⁻² along our two-path line of sight. Including methylacetylene in our model at twice this value (5 × 10⁻¹⁵ cm⁻²; corresponding to a column-integrated mixing ratio of 1.6 × 10⁻⁶) produces a significantly better fit around 1540 Å, as shown in Figure 6.

If absorption of reflected sunlight by methylacetylene is detectable in the airglow observations, it should also be evident in the solar occultation observed by Alice. Careful reexamination of the solar occultation profiles described by Young et al. (2018) over a range of tangent altitudes from 100 to 150 km shows a previously unnoticed absorption feature at 1540 Å, consistent with methylacetylene. Our preliminary reanalysis yields a methylacetylene column density of 1.5 × 10⁻¹⁵ cm⁻² along this line of sight. Since the analysis of the solar occultation observations involves only the transmission of sunlight through Pluto’s atmosphere and we directly measure the unocculted solar spectrum, we can exclude the possibilities that this feature is caused by something in Pluto’s surface reflectance spectrum or the solar spectrum itself. We therefore claim the first detection of a C₃-hydrocarbon in Pluto’s atmosphere and suggest that an additional, yet unidentified, atmospheric species is responsible for the apparent absorption features at 1530 and 1570 Å. The level of methylacetylene should provide an important constraint for future photochemical models of Pluto’s atmosphere.

5. Pluto’s Airglow Emissions

Pluto’s extreme ultraviolet (EUV) airglow spectrum is shown in Figure 7, and its FUV spectrum, after subtracting the reflected solar spectrum, is shown in Figure 8. (We loosely define the EUV region as wavelengths shorter than Lyα at 1216 Å and the FUV as longer than Lyα but shorter than 2000 Å.) Although the signal-to-noise ratio of the spectrum is relatively low throughout much of the bandpass (observed count rates are generally on the order of 1 count/pixel/100 s), faint emission features from H₁, N₂, N, and CO are detected at brightnesses of a few tens of a Rayleigh (10⁻⁶ photons s⁻¹ cm⁻² sr⁻¹). We discuss individual species in further detail in the subsections below.
To aid the identification of these features, we compare the observed airglow spectrum to a model spectrum produced by a version of the Atmospheric Ultraviolet Radiance Integrated Code (AURIC; Strickland et al. 1999; Stevens et al. 2011, 2015; Evans et al. 2015) adapted to Pluto. AURIC generates emission spectra from multiple species as a function of viewing direction. In particular, it calculates emissions from solar fluorescence, electron impact, photoionization, photodissociation, and recombination and then propagates these emissions through a radiative transfer model of the atmosphere of interest. We generate emission spectra over the 800–2000 Å bandpass. Since the Alice slit covers a significant fraction of the disk of Pluto, as discussed in Section 4.1, we average the model output over an evenly spaced grid of 341 lines of sight, separated by 0.01′ (~70 km projected on the surface). We start with the atmosphere of Young et al. (2018), as shown in Figure 4, and add CO at a surface mixing ratio of 5.0 × 10^{-4} (Lellouch et al. 2017), assuming that, like the rest of the atmosphere, it is in gravitational diffusive equilibrium.

AURIC produces synthetic spectra for molecular emission band systems and individual atomic species. For this paper, we did not vary the model’s input parameters in an attempt to fit the observed airglow spectrum in a fully self-consistent manner. Such work will be the subject of a future publication. However, recent analyses of the atmospheres of Mars and Titan using AURIC (Jain et al. 2015; Schneider et al. 2015; Stevens et al. 2015, 2017) have shown that weighting each of the individual component spectra can result in a markedly better match to the data. We use a multiple linear regression (MLR) algorithm to determine the weights for each component spectrum:

\[ S_{\text{final}}(\lambda) = \sum_{i} a_i S_i(\lambda) + a_2 S_2(\lambda) + \cdots + a_n S_n(\lambda), \]

where \( a_i \) are the weights for the individual component spectra, \( S_i(\lambda) \), for each molecular band system or atom produced by our AURIC model. Our MLR fit has five component spectra: the Lyman–Birge–Hopfield (LBH) and Vegard–Kaplan (VK) band systems of N\(_2\), the Fourth Positive (4PG) and Hopfield–Birge (HB) band systems of CO, and the emission multiplets of N I. The weights were simultaneously fit to the data over the following three bandpasses: 1100 Å < \( \lambda < 1200 \) Å, 1270 Å < \( \lambda < 1505 \) Å, and 1580 Å < \( \lambda < 1750 \) Å. The model intensities of these emissions, integrated over 800 Å < \( \lambda < 2000 \) Å, are given in Table 3.

Our model spectrum is a reasonably good match to the observations, as can be seen in Figures 7 and 8. All of the detectable emission features predicted by our model are either present in, or at least consistent with, the observed airglow spectrum. Conversely, there are no significant emission features predicted by our model that are clearly missing from the observed spectrum. On the other hand, there are several features in the observed spectrum that appear to be statistically significant but do not appear in our model. These are likely either instrumental artifacts or systematic effects of our data processing, and they are discussed in further detail in Section 5.7 below.

From the results of our AURIC model, we claim the detection (>4\( \sigma \) likelihood) of the N\(_2\) LBH bands, the CO 4PG bands, NI, and the N\(_2\) HB bands. With a 2\( \sigma \) level of confidence, we also plausibly detect emissions from the N\(_2\) VK bands, the brightest of which is predicted to be the (7,0) band at 1689. However, we advise caution in interpreting the CO HB bands as a (~2\( \sigma \)) “detection.” This band system in the EUV is quite faint (<0.2 R, integrated over the entire instrument bandpass), and while including it in the model does result in a statistically better fit, none of the predicted CO HB emissions (the brightest of which occur at 1151 and 1124 Å) are particularly compelling. We attempted to include the Birge–Hopfield-1 band system of N\(_2\) and Cameron band system of CO in our MLR model but found that these band systems were not sufficiently constrained by our data.

We detect airglow emissions from H I at both Ly\( \alpha \) and Ly\( \beta \) and derive the amount of hydrogen above the \( \tau = 1 \) altitude in Section 5.1 below. Although this is an important constraint, we cannot measure the vertical profile of hydrogen in Pluto’s atmosphere directly using the Alice data or from any other currently existing observations. Since hydrogen is produced and destroyed by a large number of reactions in Pluto’s atmosphere and developing a full photochemical model is well beyond the scope of this observational paper, we do not include it in our AURIC model atmosphere. As neither H nor H\(_2\) is a significant source of atmospheric opacity—at least for any physically reasonable amount of hydrogen—this omission does not affect the interpretation of other airglow spectral features.

In the EUV region of the spectrum, the airglow emission features are well separated (see Figure 7). To determine their brightness (or upper limits), we fit a Gaussian line profile plus a linear background to each feature. The width of the Gaussian profile was held constant to match the line function of the instrument for a filled slit (Stern et al. 2008). The area under the fitted Gaussian profile (or the 3\( \sigma \) uncertainty thereof, in the case of a nondetection) is given in Table 4, along with model predictions from Summers et al. (1997), Stern et al. (2008), Young et al. (2008), Stevens et al. (2013), Jain & Bhardwaj (2015), and our MLR-weighted AURIC model.

The situation is more complicated in the FUV, as Pluto’s atmosphere transitions from completely opaque for wave-lengths below 1400 Å to \( \tau < 1 \) for \( \lambda > 1540 \) Å. Sunlight, reflected from the surface, overwhelms the faint airglow emissions at wavelengths greater than ~1400 Å. Section 4 describes how we model the reflected sunlight and subtract it from the data. However, there appears to be an additional source of absorption in Pluto’s atmosphere between 1500 Å < \( \lambda < 1580 \) Å that is missing from our model. This results in an oversubtraction of the solar spectrum, as can clearly be seen in Figure 8. We therefore exclude this region from all subsequent analysis.

In addition, at the spectral resolution of Alice, emissions from the N\(_2\) LBH bands, the CO 4PG bands, N I, and the N\(_2\) VK bands (in blue, green, purple, and red, respectively) are significantly blended together. Since we cannot separate these components observationally and do not have full confidence—
at the level of individual spectral features—in the relative intensities predicted by our MLR model fit to the data, we report only the total brightness of each spectral feature.

5.1. Hydrogen

The bright emission line at Lyα (1216 Å) indicates that atomic hydrogen is present in Pluto’s upper atmosphere—a result of methane photochemistry. We find a Lyα brightness of 29.3 ± 1.9 R, which matches the preencounter predictions by Gladstone et al. (2015) that relied on the model atmosphere of Krasnopolsky & Cruikshank (1999). The H I Lyβ emission line at 1026 Å was also detected, although ~150× fainter than Lyα. Since the Lyα emission line is optically thick in Pluto’s atmosphere, we use the brightness, B (in units of Rayleighs), of the optically thin Lyβ line to estimate the hydrogen column density above the τ = 1 altitude:

\[ B = 10^{-6} g_{\text{H}} N, \]

where the “g-factor,” \( g_{\text{H}} \), is the number of radiative transitions per second per particle from quantum state \( k \) to state \( i \). Chamberlain & Hunten (1987) define the g-factor as

\[ g_{\text{H}} = \frac{\pi e^2}{m_e c^2} A_{ki} \sum_j P_j \pi F_{\odot} \frac{\lambda^2_{jk} f_{jk}}{r^2}, \]

where the subscript \( j \) in the sums on the right is necessary to account for all possible paths to/from the upper level, \( k \); \( r \) is the heliocentric distance, in astronomical unit; \( F_{\odot} \) is the incident solar flux (in photons s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\)) at 1 au (our \( F_{\odot} \) is identical to that described in detail by Young et al. 2018); \( A_{kj} \) is the Einstein “A” coefficient for the transition from state \( k \) to \( j \); \( f_{jk} \) is the oscillator strength for the upward transition from level \( j \) to level \( k \); and \( P_j \) accounts for the portioning of levels in the ground state, given temperature \( T \):

\[ P_j = (g_j + 1) e^{-E_j \tau} \sum_j (g_j + 1) e^{-E_j \tau}, \]

where \( g_j \) is the statistical weight of state \( j \). We find a g-factor for Lyβ of \( g_{1026} = 2.64 \times 10^{-9} \) photons s\(^{-1}\). This implies a hydrogen column density of \( N_{\text{H}} = 7.7 \pm 1.7 \times 10^{13} \) cm\(^{-2}\) and a line-of-sight mixing ratio of 8.1 ± 1.8 \times 10\(^{-5}\) above the \( \tau = 1 \) altitude of 490 km.

5.2. Argon

Resonant scattering of the EUV solar continuum by argon produces emission lines at 1048 and 1067 Å, well within the bandpass of Alice. Little is known about the relative abundance of argon in Pluto’s atmosphere or other objects in the Kuiper Belt. Early observations of the atmosphere of Saturn’s moon, Titan, by Voyager IRIS placed an upper limit on the mixing ratio of argon at 6% (Courtin et al. 1995). This led Summers et al. (1997) to include argon at a constant mixing ratio of 5% in their Pluto atmospheric models, resulting in a predicted brightness of the Ar I 1048 Å line of 0.3 R. More recently, Using the Krasnopolsky & Cruikshank (1999) “Model 2” atmospheric profile and an altitude-independent argon mixing

---

**Table 4**

| Species | Wavelength (Å) | Intensity* (R) | SSG97b | SSS08b | YSW08d | SEG13e | JB15f | This Work |
|--------|---------------|----------------|---------|---------|--------|--------|--------|-----------|
| He I   | 584           | <0.49          | ...     | ...     | ...    | ...    | ...    | ...       |
| N II   | 916           | <0.21          | 0.08    | 0.13    | 0.04   | 0.05   | ...    | ... 0.08  |
| N₂ CY(0,0) | 958          | <0.20          | 0.7     | 1.3     | 0.35   | 0.0    | ...    | 0.0       |
| N₂ CY(0,1) | 980          | 0.28 ± 0.08    | ...     | ...     | ...    | ...    | 0.2    | 0.4       |
| H I    | 1026          | 0.20 ± 0.04    | ...     | ...     | ...    | ...    | ...    | ...       |
| Ar I   | 1048          | <0.14          | 0.3     | 0.45    | 0.15   | 0.3    | ...    | 2 × 10\(^{-4}\) |
| N II   | 1067          | <0.21          | 0.3     | 0.35    | 0.15   | 0.3    | ...    | 2 × 10\(^{-4}\) |
| N I    | 1085          | 0.57 ± 0.14    | 0.4     | 0.6     | 0.2    | 0.2    | ...    | 0.30      |
| N I    | 1134          | 0.25 ± 0.09    | 0.2     | 0.9     | 0.1    | 0.1    | ...    | 0.15      |
| N I    | 1200          | 0.66 ± 0.64    | 1.2     | 5.4     | 0.6    | 0.7    | ...    | 1.3       |
| H I    | 1216          | 29.3 ± 1.9     | 37      | 28      | 18     | 41     | ...    | 30\(^{6}\) |
| N₂ LBH(4,0) | 1325         | 0.14 ± 0.10\(^{4}\) | ...     | ...     | 0.08   | 0.18   | 0.39   |           |
| N₂ LBH(3,0) | 1354         | 0.20 ± 0.11\(^{4}\) | ...     | ...     | 0.10   | 0.22   | 0.51   |           |
| N₂ LBH(2,0) | 1383         | 0.40 ± 0.13\(^{3}\) | ...     | ...     | 0.08   | 0.18   | 0.51   |           |
| N₂ LBH(1,1) | 1464         | 0.59 ± 0.21\(^{4}\) | ...     | ...     | ...    | 0.12   | 0.29   |           |
| N I    | 1493          | 0.63 ± 0.18\(^{3}\) | ...     | ...     | ...    | 0.23   | ...    | 0.68      |
| CO 4PG(0,1) | 1597         | 1.2 ± 0.4\(^{4}\)   | ...     | ...     | ...    | 0.0    | 2.0    | 1.2       |
| CO 4PG(0,2) | 1653         | 2.9 ± 0.9\(^{4}\)   | ...     | ...     | ...    | 0.0    | ...    | 1.0       |
| N₂ VK(7,0) | 1689         | 1.0 ± 0.7\(^{3}\)   | ...     | ...     | ...    | 0.21   | 0.72   |           |

**Notes.**

a Quoted error bars are 1σ, while the upper limits are 3σ.
b Summers et al. (1997).
c Stern et al. (2008).
d Young et al. (2008).
e Stevens et al. (2013).
f Jain & Bhardwaj (2015).
g In the absence of H in our AURIC model, we report here the value predicted by Gladstone et al. 2015.
h This spectral feature is a blend of multiple emission lines/bands. We report the total intensity of the feature, as determined by a Gaussian fit.
ratio of 5%, Stern et al. (2008) predicted 0.45 R, and more recently, Mousis et al. (2013) predicted a brightness of 1.3 R-levels that should be detectable by New Horizons’ Alice. However, subsequent in situ measurements of Titan’s atmosphere by the Huygens probe gas chromatograph mass spectrometer reduced the Voyager-era upper limit on the mixing ratio of argon by more than three orders of magnitude to just 3.39 ± 0.12 × 10⁻⁵ (Niemann et al. 2010). The ultraviolet spectrograph on Cassini, UVIS, also failed to detect any emission from argon at Titan (Stevens et al. 2011), calling into question whether Alice would detect argon emission at Pluto.

Preflyby models of Pluto’s atmosphere that predicted detectable argon emission lines generally assumed a relatively warm, well-mixed atmosphere. Instead, New Horizons found an atmosphere that is considerably colder (a peak temperature of 106 K at 25 km altitude, falling to a nearly constant temperature of 68 K in the upper atmosphere; Gladstone et al. 2016). At present, there are extreme discrepancies between various models of Pluto’s atmosphere. The model atmosphere of Young et al. (2018) has a very small eddy diffusion coefficient, resulting in an atmosphere with the well-mixed portion restricted to the planetary boundary layer (surface to 2 km). Above that, their atmosphere is in gravitational diffusive equilibrium. In contrast, the model atmosphere of Lupsay-Kuti et al. (2017) has a much larger eddy diffusion coefficient, such that argon does not diffusively separate until an altitude of approximately 400 km.

We do not detect either argon emission line in the Alice data. We place a 3σ upper limit of 0.14 R on the brightness of the Ar I 1048 Å line and 0.21 R on the Ar I 1067 Å line. At these wavelengths, methane is the primary source of atmospheric opacity. For a CH₄ absorption cross section of 3.2 × 10⁻¹⁷ cm² at 1048 Å ( Kameta et al. 2002; Chen & Wu 2004), an optical depth of τ = 1 is reached at a column density of N(CH₄) = 3.1 × 10¹⁶ cm⁻². Averaged over the FOV, this occurs at an altitude of 480 km above Pluto’s surface (Young et al. 2018).

The g-factor for the Ar I 1048 Å line at a heliocentric distance of 32.9 au is 7.6 × 10⁻¹¹ photons s⁻¹. Thus, to produce our 3σ upper limit of 0.14 R of Ar I 1048 Å requires an Ar column density of 1.8 × 10¹⁵ cm⁻² above the τ = 1 level. This is roughly 6% of the column of density of methane. For atmospheric models that use a small eddy diffusion coefficient (e.g., Strobel & Zhu 2017; Young et al. 2018), the Alice detection limit is not significant, because even if the density of argon and (molecular) nitrogen were equal at Pluto’s surface, one would still expect the brightness of the Ar I 1048 Å line to be ≲0.14 R. For atmospheric models with high eddy diffusion coefficients, such as Lupsay-Kuti et al. (2017), the Alice results could be more physically meaningful.

5.3. N I

Several multiplets from atomic nitrogen are present in the airglow spectrum. The brightest of these occurs in the FUV at 1493 Å, although this feature is blended with the CO 4PG (3,1) band and the N₂ LBH (3,3) band. The EUV multiplets at 1200 and 1134 Å are also significant. The observed N I 1200 Å multiplet is somewhat brighter than our AURIC model predicts. However, its proximity to the much brighter H I 1216 Å emission line (and resulting scattered light) results in a low signal-to-noise ratio for this multiplet. Although this emission feature appears to be real, it is only present at the 1σ level of significance.

5.4. N II

One of the brighter features in Pluto’s EUV airglow spectrum is the N II 1085 Å multiplet. This multiplet is produced primarily by the dissociative photoionization of molecular nitrogen by solar EUV and X-ray photons via excitation of the H band of N²⁺ (Samson et al. 1991; Bishop & Feldman 2003):

\[ \text{N}_2 + \lambda_{<340} \rightarrow \text{N}(^4S) + \text{N}^+2s2p^3(3D^0). \]

This N II 1085 Å multiplet was also detected at both Triton (Broadfoot et al. 1989) and Titan (Stevens et al. 2011). The detection here marks the first, and thus far only, detection of ions in Pluto’s atmosphere (although the in situ instruments SWAP and PEPSSI measured ions escaping from Pluto’s atmosphere Bagental et al. 2016). Although this multiplet provides a direct detection of ion production in Pluto’s upper atmosphere, because it is a consequence of the dissociation of N₂ rather than the excitation of an existing ion, it cannot be used as a diagnostic of the ambient ion density.

5.5. N₂

The emission feature at 980 Å is due to the N₂ Carroll–Yoshino (CY) c₂⁺ 1Σ⁺−XΣ⁺ᵣ (0,1) band—an electronic transition. Although the CY (0,0) band is strongly excited by photoelectrons and its emission was predicted by Young et al. (2008) and Stern et al. (2008), it was not detected. This is because the CY (0,0) band is optically thick and strongly self-absorbed. After multiple scattering, much of the energy is ultimately radiated away via the optically thin CY (0,1) band (Stevens et al. 1994; Stevens 2001). Both the Voyager UVS at Triton (Broadfoot et al. 1989) and the Cassini UVIS at Titan (Ajello et al. 2007; Stevens et al. 2011, 2013) detected the CY (0,1) band but not the CY (0,0) band. We adapt a multiple scattering model for the CY (0,Y’) bands used on Earth and Titan (Stevens et al. 1994; Stevens 2001) to the Pluto atmospheric profiles derived from the occultation results shown in Figure 4. Excitation rates for c₂’ were calculated from AURIC and used to initialize the model. The redistribution of photons to more optically thin bands is calculated at milliangstrom resolution over multiple scatterings and at all altitude layers. We find that the CY(0,0) band is optically thick and undetectable at Pluto. In contrast, the nadir viewing CY (0,1) emission is found to be 0.4 R, which is close to what is observed and included in Table 4.

In addition to the CY (0,1) band, emissions at several of the LBH (a²Πₐ−X²Σ⁺ᵣ) bands of N₂ are present in the spectrum at wavelengths greater than 1300 Å (see Figure 8). Among these, the LBH (4,0), (3,0), and (2,0) bands at 1325 Å, 1354 Å, and 1383 Å, respectively, are predicted to be the brightest. These features are present in the Pluto airglow spectrum, although at fairly low signal-to-noise levels. Many of the N₂ LBH bands overlap emissions from the CO 4PG bands.

The N₂ VK bands (A¹Σ⁺−X²Σ⁺ᵣ) should also be present and marginally detectable in the airglow spectrum of Pluto at wavelengths greater than 1600 Å. In the Alice bandpass, the brightest of these should be the (7,0) band at 1689 Å. There appears to be a weak emission feature at this location. Other
bands of the VK system are either too faint or too blended with other emissions to be clearly detected.

5.6. Carbon Monoxide

Just one month prior to the New Horizons flyby of Pluto, Lellouch et al. (2017) observed Pluto with the ALMA interferometer. They report the detection of CO in Pluto’s atmosphere at a mole fraction of $5.15 \pm 0.40$ ppm, that is, a surface mixing ratio of $\sim 5 \times 10^{-4}$. At this concentration, several of the bands of the CO 4PG system ($A^1\Pi - X^1\Sigma^+$) should be detectable by Alice, although they will be blended with the N$_2$ LBH, and VK bands. Almost all of the CO 4PG bands are optically thick, requiring careful modeling of radiative transfer effects to extract column density from the observed brightness. Due to the saturation of the bands of the CO 4PG, Alice is not very sensitive to changes in CO column density. For example, our modeling with AURIC suggests that doubling the surface mixing ratio of CO leads to only a $\sim 10\%$ increase in the brightest CO 4PG bands.

Given all of this, our model predicts the brightest CO emission features to be the (0,1), (0,2), (0,3), and (5,1) bands at 1597 Å, 1653 Å, 1712 Å, and 1435 Å, respectively, as shown in Figure 8. The first three of these bands are produced by the solar C IV 1548 Å emission line exciting the nearby CO (0,0) band at 1544 Å. Due to the large optical depth of the (0,0) band, much of this energy is radiated away via the (0,1), (0,2), and (0,3) bands. Similarly, the solar Si IV emission line at 1393.8 Å pumps the CO (5,0) band at 1391.1 Å, and because of optical depth effects, this energy is primarily radiated away through the (5,1) band at 1435 Å.

5.7. Other Features

None of the features below 920 Å are statistically significant. In particular, we do not detect any emission at He I 584 Å and place a $3\sigma$ upper limit of 0.49 R on the brightness of this emission line. Although there appears to be a $2\sigma$ significant emission feature at 736 Å, this is a known instrumental artifact (a Ly$\alpha$ ghost) and not emission from Ne I.

Between 1160 and 1180 Å, our airglow spectrum is significantly elevated above the background level. This feature is too wide to be due to a single emission line or band, and none of the species that have been detected in Pluto’s atmosphere emit significantly in this bandpass. Nor are we aware of any ions/atoms/molecules that might plausibly contribute to these putative emissions while producing no other detectable UV signature. We therefore believe this feature is likely an artifact of our data processing.

Similarly, there are several features in the FUV that appear to be significant at about the $2\sigma$ level yet do not correspond to the wavelength or predicted intensity of any known emissions. Examples include the feature at 1412 Å, which is both longward of the CO 4PG (6,1) band and shortward of the N$_2$ LBH (1,0) band, and the feature at 1449 Å, which could plausibly be the CO 4PG (3,0) band, except that our AURIC model predicts the (3,0) band should be undetectably faint.

There are several other potential features in Figure 8 at wavelengths greater than 1600 Å. Given the 1σ statistical error bars, several of these appear to be real. However, systematic errors introduced by our subtraction of the solar spectrum after modeling the atmospheric absorption and surface reflectance are likely much greater than the statistical uncertainty. We therefore urge caution in interpreting these features.

6. Spatial Distribution of Airglow Emissions

From the left-hand panel of Figure 1, the geometry of the Airglow3 observations is such that while the FOV of detector row 16 lies almost entirely on the disk of Pluto, rows 15 and 17 (zero-indexed) lie almost entirely off the limb, spanning a range of tangent altitudes from 0 to 1920 km (0.1–1.6 Pluto radii). No airglow emissions were detected in either of these rows. We suggest this is a consequence of gravitational diffusion and limb darkening. Methane (CH$_4$) is the dominant absorber below $\sim 1450$ Å. Because of its low molecular weight, it has a larger scale height than most other atmospheric species. As a result, there is considerably less of these heavier species between New Horizons and the $\tau = 1$ level in Pluto’s atmosphere along the tangential line of sight. For example, using the Young et al. (2018) atmospheric model, shown in Figure 4, the column density of N$_2$ above the $\tau = 1$ level at the LBH bands is $\sim 3.5 \times$ lower for rows 15 and 17 than it is for row 16. This decrease in apparent column density renders the already faint emission lines below our detection threshold.

7. Conclusions and Future Work

The main conclusions of our paper are as follows:

1. The brightness of IPM Ly$\alpha$ at a heliocentric distance of 32.5 au in the direction of Pluto ($\alpha = 18^h23^m38^s$, $\delta = -14^\circ37^\prime37^\prime$, $\lambda = 1435$ Å), as seen from the New Horizons spacecraft, is $133.4 \pm 0.6$ R. Ly$\beta$ has a brightness of $0.24 \pm 0.02$ R, and we place a $3\sigma$ upper limit of 0.10 R on the brightness of He I 584 Å.

2. Although Pluto’s atmosphere is completely opaque at Ly$\alpha$, it is optically thin ($\tau_c < 1$) for photons with $\lambda > 1425$ Å. These FUV photons can break molecular bonds and drive photolysis on the surface. We suggest this has important consequences for surface weathering and could explain why the areas on Pluto that receive the most sunlight, averaged over its orbit, are darker and redder than the poles.

3. Pluto’s surface reflectance between 1400 and 1850 Å is approximately wavelength independent with an $I/F$ of 0.17. This is the first measurement of Pluto’s reflectance in the FUV.

4. We detected a new species in Pluto’s atmosphere in absorption: methylacetylene (C$_3$H$_4$, or propyne). In our observations, methylacetylene has a column density of approximately $5 \times 10^{17}$ cm$^{-2}$, corresponding to a column-integrated mixing ratio of $1.6 \times 10^{-6}$. This could provide an important constraint for photochemical models of Pluto’s atmosphere.

5. We have detected airglow emissions from N$_2$, N I, N II, H I, and CO in Pluto’s upper atmosphere. Detected emissions range in brightness from a few tenths of a Rayleigh to $29.3 \pm 1.9$ R for Ly$\alpha$.

6. The discovery of the N II multiplet at 1085 Å is the first direct detection of ions in Pluto’s atmosphere. However, since this multiplet results from the prompt emission of N II after the dissociative photoionization of N$_2$, it is not diagnostic of ionospheric density.
We suggest several areas ripe for future work. First, we examined only the most promising subset of the Alice airglow observations, selected for their relatively long integration time and proximity to Pluto. Second, more of the solar spectrum is absorbed by Pluto’s atmosphere/surface between 1500 and 1580 Å than we can account for in our modeling. Following our discovery of methyllactene, we suggest that it is likely there are one or more additional minor species in Pluto’s atmosphere that have not yet been identified. Third, in our modeling, we have neglected the physics of Pluto’s haze particles, which are complex and likely to vary with altitude. A careful treatment of Pluto’s atmospheric haze is required to improve upon our upper limit of Pluto’s surface reflectance. Finally, although our atmospheric model produces a reasonable match to Pluto’s observed airglow spectrum, there is significant room for improvement. A careful treatment of the radiative transfer effects of emissions and absorption by multiple hydrocarbon species along the line of sight could yield a significantly better match to the observations.

Financial support for this work was provided by NASA’s New Horizons project via contracts NASW-02008 and NAS5-97271/TaskOrder30. We thank the New Horizons Mission team for making these observations possible. Werner Curdt provided the high-spectral-resolution solar models. We gratefully acknowledge the solar spectroscopic data available from the LASP Interactive Solar Irradiance Data Center (LISIRD) (http://lasp.colorado.edu/lisird/). Atmospheric profiles of C₃H₄ were kindly provided by M. L. Wong & Y. Yung (2017, private communication) based on their photochemical model (Wong et al. 2017). We thank Paul Feldman for constructive discussion and providing model spectra of the CO 4PG bands. We are grateful to the anonymous reviewer for helpful comments and the editorial staff for their understanding and accommodation of the delay between receipt of the reviewer’s comments and submission of the revised manuscript.

Facility: New Horizons.

Appendix
Data Reduction

In this appendix, we discuss the data reduction techniques described in Section 3 in more detail. The first data reduction step is to correct for the dead time of the detector, for each of the individual exposures. This correction is necessary because the detector electronics take a finite amount of time to process each detected count, during which the detector is “dead,” that is, it is insensitive to any additional counts. Thus, each detected count is weighted by a factor of 1/(1 − τC), where τ = 18 µs is the time constant of the electronics and C is the average count rate during the exposure (Stern et al. 2008).

After the dead time correction we then use the “stim pixels” to correct the location of the spectrum in data space (Stern et al. 2008). Unlike many classes of detectors such as charge-coupled devices (CCDs), the Alice detector does not have physical pixels. Instead, when an ultraviolet photon strikes the front surface of the MCP, it produces a photoelectron. As the front and back surfaces of the MCP are held at an electric potential of several thousand volts, the electron is accelerated into the pores of the MCP, where it strikes the walls, liberating more electrons. The resulting cascade produces a cloud of ~6 million electrons (~1 pC of charge) exiting the back surface of the MCP, which then strikes the readout anode. The detector electronics compares the times when the charge pulse is detected on one side of the readout anode to when the signal is detected on the other side of the anode, after traveling through a delay circuit. The difference in timing determines how the event is mapped from physical space on the readout anode to data space. Changes in temperature affect the resistivity of the readout anode, which, in turn, affects the relative timing of the charge pulses. Thus, an event that occurs at the same physical location can be mapped into a different location in data space, depending on temperature. To correct for this, the electronics produces artificial charge pulses at known physical locations on opposite sides of the detector, which allows for a linear correction to the apparent location of detected photons.

After applying the dead time correction factor and the stim pixel correction we coadd all the data and divide by the total exposure time of 3900 s. We then subtract a dark count rate image from the data. The dark count rate image was produced by summing Alice images acquired with the airglow aperture door closed and dividing by the total integration time. In total, 10,720 s of dark integration time was obtained during Active Checkout 8 in 2014 July and 10,800 s of dark integration time was acquired during the postencounter calibration campaign of 2016 July. Typical dark count rates are of the order of 0.004 counts s⁻¹ px⁻¹.

ORCID iDs
Andrew J. Steffl https://orcid.org/0000-0002-5358-392X
Leslie A. Young https://orcid.org/0000-0002-7547-3967
Darrell F. Strobel https://orcid.org/0000-0002-0944-8675
Joshua A. Kammer https://orcid.org/0000-0002-3441-3757
J. Scott Evans https://orcid.org/0000-0003-2025-5695
Michael H. Stevens https://orcid.org/0000-0003-1082-8955
Joel Wm. Parker https://orcid.org/0000-0002-3672-0603
S. Alan Stern https://orcid.org/0000-0001-5018-7537
Harold A. Weaver https://orcid.org/0000-0003-0951-7762
Catherine B. Olin https://orcid.org/0000-0002-5846-716X
Kimberly Ennico https://orcid.org/0000-0002-8847-8492
G. Randall Gladstone https://orcid.org/0000-0003-0606-072X
Thomas K. Greathouse https://orcid.org/0000-0001-6613-5731
David P. Hinson https://orcid.org/0000-0002-1620-4011
Kurt D. Retherford https://orcid.org/0000-0002-1939-6813
Michael E. Summers https://orcid.org/0000-0001-5986-8902
Maarten Versteeg https://orcid.org/0000-0002-2503-9492

References
Ajello, J. M., Stevens, M. H., Stewart, I., et al. 2007, GeoRL, 34, L24204
Baganoff, F., Horányi, M., McComas, D. J., et al. 2016, Sci, 351, aad9045
Bishop, J., & Feldman, P. D. 2003, IJGRA, 108, 1243
Bockelée-Morvan, D., Lellouch, E., Biver, N., et al. 2001, A&A, 377, 343
Broadfoot, A. L., Atreya, S. K., Bertaux, J. L., et al. 1989, Sci, 246, 1459
Chamberlain, J. W., & Hunten, D. M. 1987, Theory of Planetary Atmospheres.
An Introduction to Their Physics and Chemistry (Orlando, FL: Academic Press)
Chen, F. Z., & Wu, C. Y. R. 2004, JQSRT, 85, 195
Cheng, A. F., Summers, M. E., Gladstone, G. R., et al. 2017, Icar, 290, 112
Courtin, R., Gautier, D., & McKay, C. P. 1995, Icar, 114, 144
Curdt, W., Brekke, P., Feldman, U., et al. 2001, A&A, 375, 591
Elliot, J. L., Dunham, E. W., Bosh, A. S., et al. 1989, Icar, 77, 148
Evans, J. S., Stevens, M. H., Lumpe, J. D., et al. 2015, GeoRL, 42, 9040
Gladstone, G. R., Allen, M., & Yung, Y. L. 1996, Icar, 119, 1
