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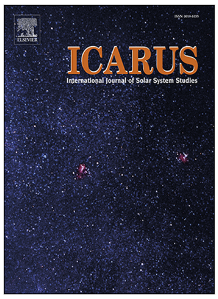

Constraints on Pluto's H and CH_4 profiles from New Horizons Alice Lyα observations

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Highlights

- Lyα emissions observed during the New Horizons flyby constrain the abundance profiles of H and CH_4 in Pluto's atmosphere
- These constraints indicate that the near-surface mixing ratio of methane is 0.4%, in agreement with solar occultation results
- The abundance levels of H and CH_4 in Pluto's upper atmosphere are very sensitive to small changes in Pluto's lower atmosphere

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Constraints on Pluto's H and CH_4 Profiles from New Horizons Alice Lyα Observations

G. Randall Gladstone [a,b], Joshua A. Kammer [a], Danica J. Adams [c], Yuk L. Yung [c], Wayne R. Pryor [d] Darrell F. Strobel [e] Leslie A. Young [f] Joel Wm. Parker [f] and S. Alan Stern [f]

[a] *Southwest Research Institute, San Antonio, TX 78238, United States*

[b] *The University of Texas at San Antonio, San Antonio, TX 78249, United States*

[c] *California Institute of Technology, Pasadena, CA 91125, United States*

[d] *Central Arizona College, Coolidge, AZ 85128, United States*

[e] *The Johns Hopkins University, Baltimore, MD, 21218, United States*

[f] *Southwest Research Institute, Boulder, CO 80302, United States*

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Email address: `rgladstone@swri.edu` (G. Randall Gladstone).

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Constraints on Pluto's Atmosphere Using Lyα

Please send Editorial Correspondence to:

G. Randall Gladstone

Southwest Research Institute

6220 Culebra Road

San Antonio, TX 78238, USA.

Email: rgladstone@swri.edu

Phone: (210) 522-3581

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ABSTRACT

The Alice spectrograph on New Horizons performed several far-ultraviolet (FUV) airglow observations during the July 2015 flyby of Pluto. One of these observations, named PColor2, was a short (226 s) scan across the dayside disk of Pluto from a range of $\sim 34,000$ km, at about 40 minutes prior to closest approach. The brightest observed FUV airglow signal at Pluto is the Lyman alpha (Lyα) emission line of atomic hydrogen, which arises primarily through the resonant scattering of solar Lyα by H atoms in the upper atmosphere, with a brightness of about 30 Rayleighs. Pluto appears dark against the much brighter ($\sim$ 100 Rayleigh) sky background; this sky background is likewise the result of resonantly scattered solar Lyα, in this case by H atoms in the interplanetary medium (IPM). Here we use an updated photochemical model and a resonance line radiative transfer model to perform detailed simulations of the Lyα emissions observed in the Alice PColor2 scan. The photochemical models show that H and CH_4 abundances in Pluto's upper atmosphere are a very strong function of the near-surface mixing ratio of CH_4, and could provide a useful way to remotely monitor seasonal climate variations in Pluto's lower atmosphere. The morphology of the PColor2 Lyα emissions provides constraints on the current abundance profiles of H atoms and CH_4 molecules in Pluto's atmosphere, and indicate that the globally averaged near-surface mixing ratio of CH_4 is currently close to 0.4%. This new result thus provides independent confirmation of one of the primary results from the solar occultation, also observed with the New Horizons Alice ultraviolet spectrograph.

Keywords: Pluto, atmosphere; Aeronomy; Ultraviolet observations;

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1 Introduction

Pluto's ultraviolet airglow line emissions are generally quite weak, with the exception of the HI Lyman alpha (Lyα) feature (Steffl et al., 2020). The two most important sources of Lyα emissions at Pluto are solar and interplanetary medium (IPM) Lyα; both sources are resonantly scattered by H atoms in Pluto's upper atmosphere, above the $\tau_{\rm abs} = 1$ level where absorption by methane becomes important (Gladstone et al., 2015). With a line width of only ~ 0.0004 nm, these very cold H atoms can only scatter a small fraction of the far broader (~ 0.1 nm) solar Lyα line; so that most of the solar Lyα photons photolyze methane, leading to the production of higher hydrocarbons, nitriles and haze particles in Pluto's atmosphere (Gladstone and Young, 2019). Likewise, scattering of the narrower (~ 0.006 nm) IPM line is also not very efficient, in this case because the typically large Doppler shift of the IPM line ($\sim \pm 0.009$ nm) moves it outside the scattering range of Pluto's ambient H atoms. Here we provide detailed simulations of a scan across the disk of Pluto by the Alice far-ultraviolet (FUV) spectrograph on the New Horizons spacecraft. The Alice scan occurred as a ride-along of the primary scan (designated PColor2 in the New Horizons observation plan) using the Multispectral Visible Imaging Camera (MVIC) instrument. The PColor2 observations are the highest spatial resolution observations of Pluto's disk that were made by the Alice spectrograph, and here we use the observed Lyα emissions to provide new constraints on the near-surface CH_4 mixing ratio and the vertical structure of Pluto's upper atmosphere, adding to those already described by Young et al. (2018).

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2 New Horizons Observations

The circumstances of the Alice PColor2 observation are provided in Fig. 1, which indicates the Alice field of view (FOV) and Pluto on the sky (in ecliptic coordinates) at the beginning and end of the scan. The New Horizons data that went into this study are available at the Atmospheres node of the Planetary Data System (e.g., at https://pds-atmospheres.nmsu.edu/data_and_services/-atmospheres_data/Horizons/alice.html). Pluto's distance from the Sun during the New Horizons flyby on 2015 July 14 was 32.91 AU, and the full-disk solar Lyα flux was 3.6×10^8 photons/cm^2/s (using TIMED-SEE L3A line irradiances, corrected for the 7.5° difference in the ecliptic longitudes of Pluto and Earth as seen from the Sun; values taken from http://lasp.colorado.edu/lisird/-data/timed_see_lines_l3a/). Inspection of solar Lyα fluxes during the $\pm$9 hours of the time corresponding to the PColor2 observation indicates the variability of a single measurement is quite large ($\sim$ 23%), and likely determines how accurately we can know what the actual solar flux was during PColor2. Predictions show that extinction of the solar Lyα line by the interplanetary medium is minimal, due to the near upstream location of Pluto (Gladstone et al., 2015), and is not accounted for in this study. The scan duration of the PColor2 observation was 226 s, at an angular rate of 0.060°/s, from 11:08:25 to 11:12:11, while the range of the New Horizons spacecraft to the center of Pluto decreased from $35,828$ to $32,972$ km, respectively, about 40 minutes before closest approach at 11:48:29 at a range of $13,674$ km. The Alice slit was centered on Pluto at 11:11:07, when the spacecraft range was 33,768 km.

The PColor2 Alice data were recorded in a time-tagged format known as "pixellist mode" (Stern et al., 2008), and the observed Lyα brightnesses are

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presented in Fig. 2. On the upper left, the normally-processed data are shown as a function of time for each row of the Alice slit; the upper right plot shows the same data plotted with projected distance from the center of Pluto at the epoch when the Alice slit was centered on the disk (11:11:07 UTC). This epoch was selected for presentation purposes only, i.e., so that the limb of Pluto is undistorted when overlaid on the data. Only rows 19-25, in the wide portion of the Alice slit (see Fig. 1), have relatively good signal-to-noise levels in the 1-second integrated time bins used here.

We use a novel artifice to increase the spatial resolution of these normally-processed data. Since no other emissions compete with the brightness of Lyα in the $110-132$ nm wavelength range plotted, we assume all detected photons have the Lyα wavelength of 121.567 nm. Any photons that are off-axis in the spectral direction are shifted in wavelength (for Alice, the shift is 10 nm/°), and we "adjust" the arrival time of each detected photon by the off-axis angle divided by the scan rate; this effectively repositions each off-axis Lyα photon to a time during the scan when it would have been detected if it were an on-axis Lyα photon. We also use the average signal far from Pluto (at times from Pluto center in the range -150 s to -70 s, and detector rows 18 through 24) to remove row-to-row instrumental brightness variations, as the IPM Lyα background is known to be slowly varying spatially (Gladstone et al., 2018). The adjusted brightnesses are shown in the lower two panels of Fig. 2; as for the normally-processed data, they are shown by relative scan time and Alice slit row number on the left, and by projected distance from the center of Pluto on the right. It is apparent from comparison of the upper and lower panels that this adjustment considerably improves the effective spatial resolution of the Alice instrument. We emphasize that this artifice is only possible because we

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can safely assume that, whatever their measured wavelength, all the photons detected by Alice in the $110 - 132$ nm wavelength range are actually off-axis Lyα photons.

3 Model Atmospheres

The background densities and temperature structure for our model Pluto atmosphere are based on Young et al. (2018), Hinson et al. (2017), and Wong et al. (2017), and are shown in Fig. 3. Along with the temperature and number densities of N_2, CH_4, and H as a function of altitude (and pressure), Fig. 3 also indicates the levels in the atmosphere at which unit opacity is reached for Lyα photons, for scattering at line center by H atoms (i.e., $\tau_{\mathrm{sca}} = 1$ near $z \sim 1000$ km) and absorption by CH_4 molecules (i.e., $\tau_{\mathrm{abs}} = 1$ near $z \sim 400$ km); the region between and above these two levels is where resonant scattering by H atoms occurs and is where the Lyα line arises on Pluto.

The IPM source of Lyα also scatters from H atoms in Pluto's atmosphere, but because this emission fills the sky it is difficult to calculate its brightness in detail. Following the method used in Gladstone et al. (2015) we estimate the on-disk brightness from this source peaks at 11.5 Rayleighs, and has an uncertainty of $\sim 25\%$.

In order to simulate the Alice data shown in Fig. 2, we have updated the photochemical scheme described by Wong et al. (2017) and generated a sequence of plausible model Pluto atmospheres in order to produce realistic H and CH_4 profiles to use in a radiative transfer code. Seven model atmospheres were produced assuming a range of near-surface methane mixing ratios from 0.04% to

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4%. It is important to note that these models are not entirely self-consistent, as they are each constrained to use the N_2 density profile and the temperature profile derived from the combined New Horizons radio and solar occultations (Hinson et al., 2017; Young et al., 2018). Truly self-consistent model atmospheres would solve the energy (temperature) and continuity (photochemistry) equations together, since methane plays an important role in heating and cooling the atmosphere. With the above caveat, the H and CH_4 number density profiles of these converged models, shown in Fig. 4, are used as inputs to a resonance line radiative transfer code that calculates both the solar Lyα emissions scattered by H atoms and the IPM Lyα background transmitted by CH_4 molecules in Pluto's atmosphere. Relevant opacity levels for the seven model atmospheres are provided in Table 1, which provides the altitudes for the unit line-center scattering opacity and unit absorption opacity, as well as the line-center scattering opacity at the unit absorption opacity level (seen to range from 40 to nearly 2000 among the 7 Cases in the last column of Table 1). The IPM Lyα emissions scattered by H atoms in Pluto's atmosphere are estimated using the method described by Gladstone et al. (2015).

We note that as we decrease the near-surface mixing ratio of CH_4 by a factor of 100 (from 4% to 0.04%) the response of the atmospheric methane and atomic hydrogen is quite non-linear, with CH_4 and H decreasing by nearly 6 orders of magnitude in the upper atmosphere. The reason is that, in the upper atmosphere, the abundance of CH_4 is limited by the supply that can be transported up from below, out of Pluto's stagnant lower atmosphere, and as the near-surface methane mixing ratio decreases, vertical transport is increasingly unable to compete with and compensate for the photochemical loss of these species.

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Proper modeling of the aerosol content of Pluto from Case 1 to Case 7 is beyond the scope of this paper. However, a scaling argument based on Gao et al. (2017) suggests that the aerosol extinction drops drastically from the CH_4-rich to the CH_4-poor case (D. J. Adams, private communication), implying that the CH_4-poor case could resemble Triton (Strobel and Zhu, 2017). This may be testable by stellar occultation studies as Pluto moves further away from the Sun in the next few decades.

4 Radiative Transfer Results

With a resonance line radiative transfer code (Gladstone et al., 2015), we have simulated the Lyα emissions of Pluto's airglow during the Alice PColor2 scan for each of the model atmospheres shown in Fig. 4. The model Lyα brightnesses for row 21 of the Alice spectrograph are shown in Fig. 5, along with the observed brightness at 1-second binning (and 5-second boxcar smoothing of the 1-second data), with 1σ error bars indicated. An apparent $\sim$ 14 s modulation in the row 21 brightness far from Pluto is probably due to random noise, as seen in the corresponding locations in the lower panels of Fig. 2 (faint UV stars would be expected to move through the 2°-wide box in $\sim$ 33 s). Since they ultimately depend only on the assumed near-surface mixing ratio of methane in Pluto's atmosphere, the family of models provide an effective "curve-of-growth" for the expected shape of Pluto's Lyα emissions during the PColor2 observation. Fig. 5 shows that a near-surface methane abundance of $f_{CH4} = 0.4\%$ clearly provides the best fit to the observations. For that model atmosphere (Case 5), we also show in Fig. 5 the contribution to the total brightness across the disk of Pluto calculated for resonantly scattered solar

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Lyα and transmitted IPM Lyα, and an estimate for the contribution from resonantly scattered IPM Lyα. We note that, in order to fit the measured Alice brightness profile, the simulation has to match both the steep falloff in the background Lyα, which is controlled by the methane profile, and the slight increase in brightness on the disk of Pluto from the terminator toward the sub-solar point, which is mostly controlled by the atomic hydrogen profile. The ability of the Case 5 model to match both these aspects of the observed brightness profile argues that the photochemistry (at least regarding H and CH_4) is reasonably accurate. Our best-fit near-surface methane mixing ratio of $f_{CH4} = 0.4\%$ is slightly larger, but in agreement with the methane abundance of $f_{CH4} = 0.28 - 0.35\%$ found by Young et al. (2018).

5 Summary

The Alice ultraviolet spectrograph on New Horizons was not designed to have high spatial resolution, but near Pluto closest approach, Lyα airglow emissions are found to be spatially resolved enough to provide useful constraints on atmospheric composition. These emissions result from a combination of resonantly scattered solar and IPM Lyα photons, in addition to the transmitted IPM background. By accounting for each of the sources and using sophisticated radiative transfer codes, we extract best-fit H (and CH_4) density profiles in Pluto's upper atmosphere, resulting in an independent estimate of Pluto's current near-surface methane abundance of $f_{CH4} = 0.4\%$. Although recent general circulation modeling indicates that the near-surface methane abundance should be quite spatially variable, (e.g., Forget et al. 2017; Bertrand et al. 2019), the value derived here represents a useful global average value for the near-surface methane abundance. Finally, photochemical modeling indicates that H and CH_4 abundances in the upper atmosphere are very sensitive to the average near-surface methane abundance, so that future remote sensing of Pluto's Lyα airglow emissions might provide a useful way to monitor seasonal climate changes in its lower atmosphere.

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Table 1

Model Pluto Atmosphere Lyα Opacity Details

Case	f_{CH4}†	$z(\tau_{abs} = 1)$ (km)	$z(\tau_{sca} = 1)$ (km)	$\tau_{sca}(\tau_{abs} = 1)$‡
1	0.04%	68.5	540.8	648.6
2	0.1%	160.3	717.9	1952.9
3	0.2%	268.2	912.9	1337.6
4	0.3%	347.2	1082.9	672.2
5	0.4%	419.0	1218.9	347.7
6	1%	696.2	1771.4	59.8
7	4%	1065.5	3088.6	39.9

†Near-surface methane mixing ratio. ‡Line-center scattering optical depth at the altitude of unit absorption optical depth.

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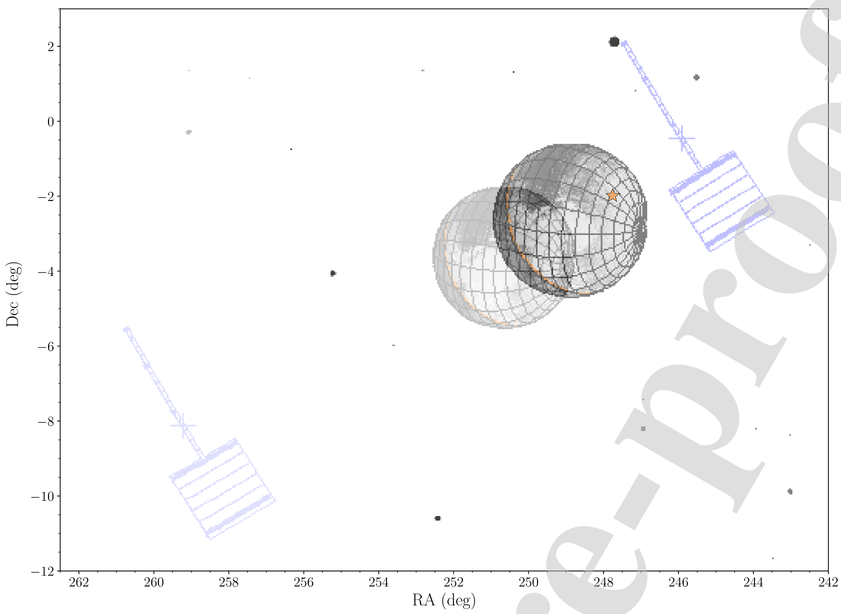

Fig. 1. The location, scale, and orientation on the sky of the New Horizons Alice slit with respect to Pluto is shown, in Right Ascension (RA) and Declination (Dec) coordinates, for the beginning (fainter,left) and end (darker, right) of the PColor2 scan observation. The terminator is indicated with an orange line, and the sub-solar position by an orange star. The scan duration was 226 s, at an angular rate of 0.060°/s, from 11:08:25 to 11:12:11 on 2015 July 14, while the range of the New Horizons spacecraft to the center of Pluto decreased from 35, 828 to 32, 972 km, about a half-hour before closest approach at 11:48:29 at a range of 13, 674 km. The Alice slit was centered on Pluto at 11:11:07, when the spacecraft range was 33,768 km.

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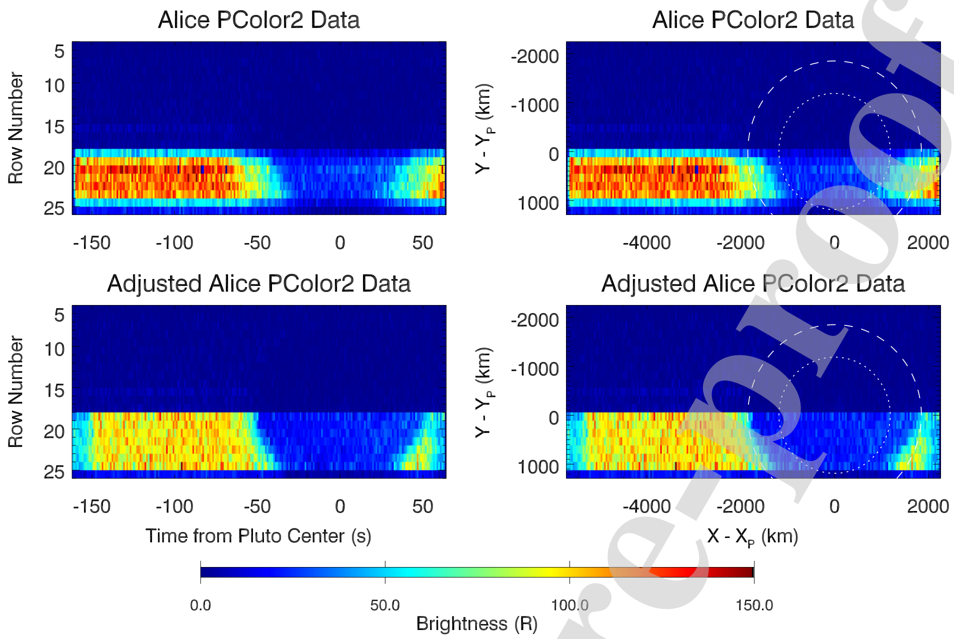

Fig. 2. The Alice PColor2 1-second integrated brightnesses for photons with wavelengths in the $110-132$ nm range, in which the Lyα line is the dominant emission. The upper two plots show the brightnesses (on the left) as a function of scan time (relative to the slit crossing of the center of Pluto at 11:11:07) and slit row number (Alice detector rows 5 through 25 are shown), and (on the right) as a function of distance from Pluto center, at the range when the Alice slit was centered on Pluto (33,768 km); the dotted circle is at Pluto's surface, the dashed circle is 500 km above the surface, near the $\tau_{\rm abs} = 1$ level for methane. The two lower plots show corresponding brightnesses after correcting for row to row sensitivity variations, and adjusting the time of arrival of each off-axis Lyα photon as if they were on-axis Lyα photons. See text for further details.

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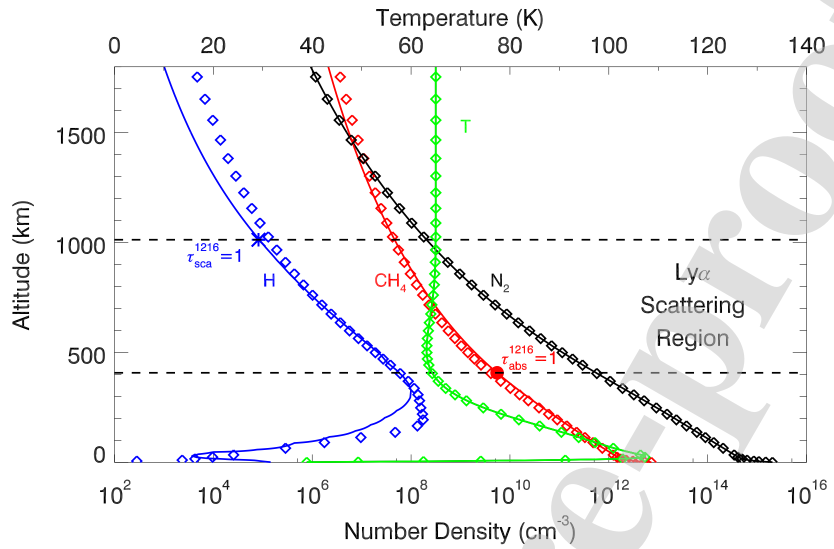

Fig. 3. Pluto model atmosphere, based on run F35 of Young et al. (2018), with temperature and the number densities of N_2, CH_4, plotted as a function of pressure and altitude. This model has a near-surface methane mixing ratio of $f_{CH4} = 0.35\%$. The H density from Wong et al. (2017), interpolated onto the Young et al. model using the vertical column density of methane, is also plotted. The altitude at which Lyα becomes optically thick at line center to resonance scattering by H atoms in Pluto's atmosphere, and the altitude at which Lyα becomes optically thick to absorption by CH_4 in Pluto's atmosphere are indicated by asterisks and filled circles, respectively, on the [H] and [CH_4] profiles. Overplotted for comparison (using open diamond symbols) are the corresponding values from our current photochemical model, which is an update of the Wong et al. model.

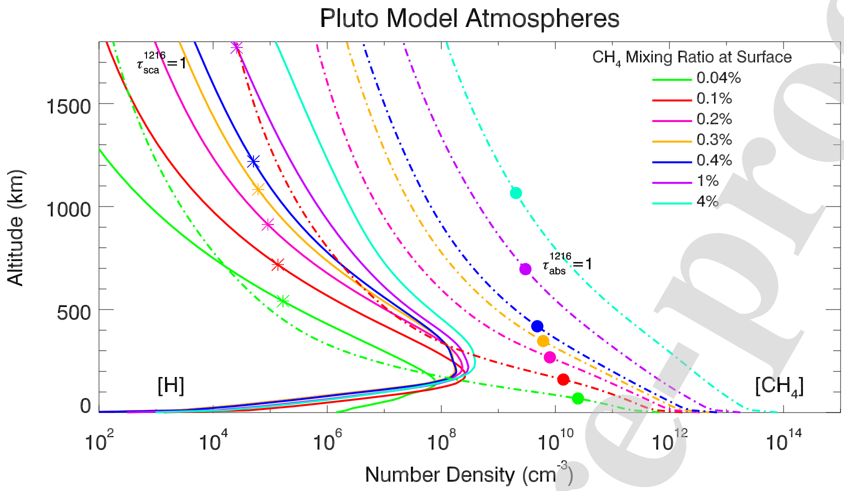

Fig. 4. Model Pluto atmospheres, with number densities of CH_4 (dot-dashed lines) and H (solid lines) plotted as a function of altitude. These models are for a range of near-surface methane mixing ratios, f_{CH4}, and are used in a resonance line radiative transfer code to simulate the Lyα brightness around Pluto in a "curve-of-growth" comparison with the Alice PColor2 scan results. As for Fig. 3, the altitudes at which Lyα becomes optically thick at line center to resonance scattering by H atoms in Pluto's atmosphere, and the altitudes at which Lyα becomes optically thick to absorption by CH_4 in Pluto's atmosphere are indicated by asterisks and filled circles, respectively, on the [H] and [CH_4] profiles.

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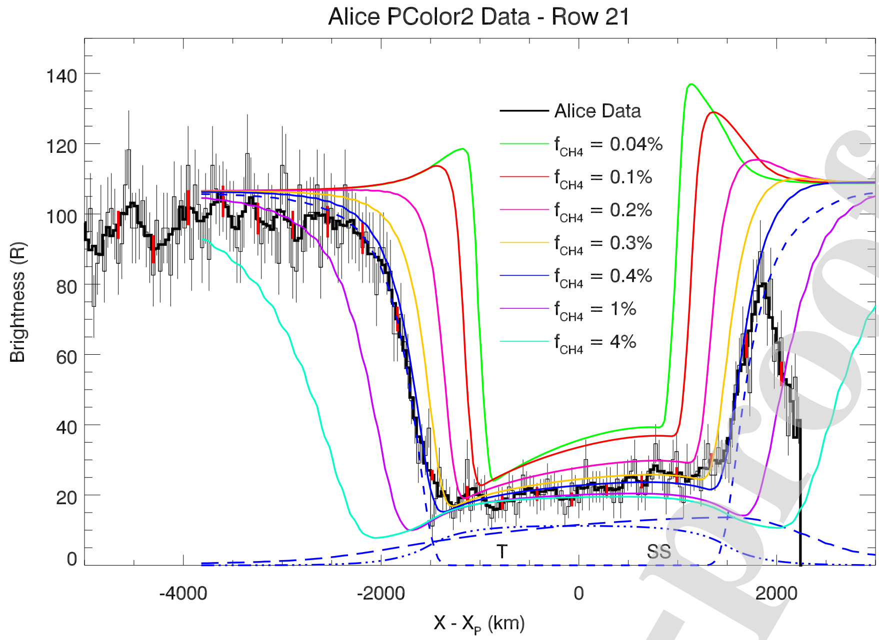

Fig. 5. Simulated PColor2 brightnesses (solid colored lines, using the model atmospheres of Fig. 4, for a range of near-surface CH_4 mixing ratios spanning two orders of magnitude), compared with Alice row 21 Lyα brightnesses measured across the disk of Pluto. The Alice data are shown with 1-second bins (thin black histogram), with a 5-second boxcar smoothing overlaid (thick black histogram). The sudden decrease in brightness at the right (at > 1800 km) is due to the ending of the MVIC scan of Pluto with which the Alice observations were riding along. The approximate locations of the row 21 terminator crossing and its point of closest proximity to the sub-solar location on Pluto are marked "T" and "SS", respectively. Of the various brightness models shown, the one corresponding a near-surface methane mixing ratio of $f_{CH4} = 0.4\%$ (blue curve) provides the best fit to the data. Each brightness model includes 1) solar Lyα that is resonantly scattered by H atoms in Pluto's atmosphere, 2) transmitted Lyα from the interplanetary medium background through Pluto's extended atmosphere after partial absorption by CH_4, and 3) an estimate of the contribution from interplanetary medium Lyα that is resonantly scattered by H atoms in Pluto's atmosphere; these contributions to the total brightness are shown for the $f_{CH4} = 0.4\%$ model by the long-dashed, short-dashed, and triple-dot-dashed blue lines, respectively.

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