ADVANCING EARTH AND SPACE SCIENCES

JGR Planets

RESEARCH ARTICLE

10.1029/2025JE009511

Feasibility of Optical Measurement of D/H Ratios of Cometary Comae Using a Small Ultraviolet Instrument

Y. Suzuki[1,2], K. Yoshioka[3,4], M. Taguchi[5], M. Kuwabara[5], A. Yamazaki[4], Y. Mitoh[4], S. Kameda[5], G. Murakami[1], N. de Oliveira[6], and I. Yoshikawa[3,4]

[1]Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA), Sagamihara, Japan, [2]Center for Space Physics, Boston University, Boston, MA, USA, [3]Graduate School of Frontier Sciences, The University of Tokyo, Kashiwa, Japan, [4]Graduate School of Science, The University of Tokyo, Tokyo, Japan, [5]Graduate School of Science, Rikkyo University, Tokyo, Japan, [6]Synchrotron SOLEIL, L'Orme des Merisiers, Saint-Aubin, France

Key Points:

- The absorption rate of Lyman-alpha radiation by a hydrogen absorption cell was experimentally measured
- Observational data of Comet Interceptor were simulated by combining a radiative transfer model and experimental results
- It was shown that cometary deuterium-to-hydrogen ratios can be determined using an ultra-small satellite-mounted optical system

Correspondence to:

Y. Suzuki,
suzuki.yudai@jaxa.jp

Citation:

Suzuki, Y., Yoshioka, K., Taguchi, M., Kuwabara, M., Yamazaki, A., Mitoh, Y., et al. (2026). Feasibility of optical measurement of D/H ratios of cometary comae using a small ultraviolet instrument. *Journal of Geophysical Research: Planets*, *131*, e2025JE009511. https://doi.org/10.1029/2025JE009511

Received 29 OCT 2025
Accepted 22 JUN 2026

Author Contributions:

Conceptualization: Y. Suzuki, K. Yoshioka
Data curation: Y. Suzuki, K. Yoshioka, M. Taguchi, M. Kuwabara, N. deOliveira
Formal analysis: Y. Suzuki
Funding acquisition: Y. Suzuki
Investigation: Y. Suzuki, K. Yoshioka, M. Taguchi, M. Kuwabara, A. Yamazaki, Y. Mitoh, S. Kameda, G. Murakami
Methodology: Y. Suzuki, K. Yoshioka, M. Taguchi, M. Kuwabara, A. Yamazaki, Y. Mitoh, G. Murakami
Project administration: K. Yoshioka, S. Kameda
Resources: Y. Suzuki, K. Yoshioka
Software: Y. Suzuki, N. deOliveira
Supervision: K. Yoshioka, I. Yoshikawa
Validation: Y. Suzuki
Visualization: Y. Suzuki
Writing – original draft: Y. Suzuki
Writing – review & editing: Y. Suzuki, K. Yoshioka, M. Taguchi, M. Kuwabara, A. Yamazaki, Y. Mitoh, S. Kameda, G. Murakami, N. deOliveira, I. Yoshikawa

Abstract

Comets are crucial objects of study for understanding the early solar system environment, including the origin of Earth's water. The Comet Interceptor (CI) mission is designed to perform a flyby of a long-period comet, and the Hydrogen Imager (HI) onboard will optically measure the deuterium-to-hydrogen (D/H) ratio. Optical measurement of D/H ratios requires high spectral resolution, which has often been achieved by large spectrometers. However, HI achieves this using small glass cells filled with hydrogen or deuterium gas called absorption cells. One challenge is that multiple scattering of Lyman-alpha (Ly-α) radiation in inner comae makes it difficult to accurately deduce hydrogen atom density from the observed Ly-α radiance. To address this challenge, here, we combined performance evaluation experiments of the absorption cell with a radiative transfer model to evaluate the feasibility of determining cometary D/H ratios using small telescopes mounted on ultra-small satellites. Through calculations of the signal-to-noise ratio for detecting deuterium Ly-α radiation assuming a 30-min observation in the CI's comet flyby, we verified that deuterium detection is feasible across a broad range of comets with the assumed parameter space. Furthermore, we confirmed that hydrogen atom density can be quantified with sufficient accuracy from Ly-α radiance observations by employing a radiative transfer model. These findings demonstrate that, even under the severe constraints of ultra-small satellites, optical measurement of cometary D/H ratios is feasible.

Plain Language Summary

Studying comets helps us learn about the early solar system and may also shed light on where Earth's water came from. The Comet Interceptor mission will carry out a close-up observation of a long-period comet. One of its instruments, the Hydrogen Imager, will measure the deuterium-to-hydrogen isotope ratio in the cometary thin atmosphere. In this study, we quantitatively examined whether that isotope ratio could be determined using a small telescope with a diameter of just a few centimeters on an ultra-small satellite. We first conducted a performance evaluation experiment on optical components. Then, we generated simulated data using a physical model of the cometary atmosphere. As a result, we found that it is possible to detect deuterium and accurately measure the hydrogen number density in the cometary atmosphere. Our findings are important not only for the Comet Interceptor mission but also for future observations using ultra-small satellites in general.

1. Introduction

Comets are among the most primordial objects in our solar system and serve as crucial windows into understanding the nature of planetesimals. It has been suggested that during periods of planetary migration, comets delivered significant amounts of water and other volatiles to planetary surfaces through impacts (e.g., Gomes et al., 2005). The deuterium-to-hydrogen (D/H) ratio has frequently been used as a diagnostic marker to determine the water deliverers to the Earth. Some short-period comets, such as 103P/Hartley 2 (Hartogh et al., 2011), exhibit D/H ratios close to Earth's seawater, while long-period comets, such as C/2001 Q4 (NEAT) (Weaver, 2008), tend to show higher D/H ratios. Although this trend broadly aligns with the idea that colder regions in molecular clouds exhibit higher D/H ratios (Ceccarelli et al., 2014), no clear correlation between orbital element and D/H ratio of each comet has been identified.

In recent years, it has become clear that the D/H ratio greatly varies depending on cometary activity, water sublimation rate from surfaces. Exploration of comet 67P/Churyumov-Gerasimenko by the Rosetta spacecraft revealed spatiotemporal variability in D/H ratios and it was suggested that dust activity in the coma may increase the D/H ratio (Mandt et al., 2024). Conversely, an inverse correlation between the D/H ratio and active fraction—the proportion of active areas on the nuclear surfaces—was observed, suggesting that water sublimated from extended sources may have lower D/H ratios (Lis et al., 2019). Suzuki et al. (2025) showed that multiple scattering of Lyman-alpha (Ly-α) photons within the comae causes a sharp increase in the D/H Ly-α radiance ratio near nuclei. Thus, while different mechanisms influencing cometary D/H ratios have been proposed, our current understanding remains insufficient to definitively connect these ratios to the origins of Earth's water. We need to clarify the physical phenomena occurring within the inner comae and systematically compare the D/H ratios of a larger sample of comets against their orbital elements, activities, and compositions.

Long-period comets are particularly valuable because they have less experience of approaching the Sun among comets and retain a higher proportion of primordial volatiles. Additionally, long-period comets often exhibit relatively high activities, making them ideal for studying the physical processes occurring within the comae. For close observation of a long-period comet, the Comet Interceptor (CI) mission (e.g., Jones et al., 2024) is designed. After launch, the spacecraft will be parked at the Sun-Earth Lagrange 2 (SEL2) point and approach a target comet when a comet with favorable conditions to be observed is identified. During the Encounter Phase, two probes will be released, approaching the nucleus within 1,000 km. One of these probes carries the Hydrogen Imager (HI; Yoshioka et al., 2024), observing the Ly-α radiance of the coma. During the Approach to Encounter Phase, HI will operate in the imaging mode to capture the two-dimensional spatial distribution of hydrogen Ly-α emissions. In the Encounter Phase, HI will switch to the light curve mode, reducing spatial resolution in order to increase temporal resolution by increasing data readout rate. HI employs a Cassegrain telescope and a detector which combines a micro-channel plate (MCP) with a resistive anode encoder.

One of the most critical tasks of HI within the CI mission is to determine the D/H ratio of the target comet. Hydrogen and deuterium atoms emit Ly-α rays at wavelengths of 121.567 and 121.534 nm, respectively. Thus, a spectral resolution better than 33 pm ($R > 4,000$) is required to optically measure the D/H ratio. The Imaging Ultraviolet Spectrograph (IUVS) onboard the Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft achieved such a high spectral resolution using a spectrometer weighing a total of 27 kg (McClintock et al., 2015). HI achieves this high resolution using small gas absorption cells (Figure 1a) instead of employing a large spectrometer. Absorption cells have been previously installed in optical instruments such as the Lyman-alpha photometer (Bertaux et al., 1978) onboard the Venera spacecraft, the Solar Wind Anisotropies (SWAN; Bertaux et al., 1995) camera onboard the Solar and Heliospheric Observatory (SOHO), and the Ultra Violet Spectrometer (UVS; Taguchi et al., 2000) onboard the Nozomi spacecraft, although none of them have ever measured cometary D/H ratios. HI is equipped with two absorption cells—one for hydrogen and the other for deuterium. Each cell is a glass container with a diameter of 35 mm and a length of 40 mm, filled with H_2 or D_2 molecular gas at pressures of approximately 10^2 Pa (Figure 1b). The cells are equipped with five filaments, including redundant ones. Filaments inside the cells are heated by external electrical power to thermally dissociate the molecular gas into atomic gas (Figure 1c). For example, deuterium cells absorb deuterium Ly-α emissions while remaining transparent to hydrogen Ly-α emissions, effectively acting as high spectral resolution filters. When the electrical power is switched on and off every few seconds during observations, the brightness of deuterium Ly-α can be evaluated by measuring the difference in the number of detected photons between the power-on and power-off states. The absorption efficiency depends on both the filament temperature and the target hydrogen temperature. Kuwabara et al. (2018) demonstrated that by varying the filament temperature, the hydrogen kinetic temperature of the targets can be estimated. Note that HI measures only the integrated brightness within specific wavelengths, while Figure 1 shows spectral examples.

As described above, we aim to use the CI/HI instrument—an ultra-small ultraviolet (UV) telescope—to optically measure a cometary D/H ratio. However, since the target comet will be selected post-launch, a general feasibility study based on current knowledge of comets is necessary. Here, we investigate the feasibility of these measurements by combining performance evaluations of CI/HI (Yoshioka et al., 2024) with a radiative transfer model in cometary comae (Suzuki et al., 2025), providing a quantitative discussion on the potential of ultra-small UV imagers for measuring cometary D/H ratios.

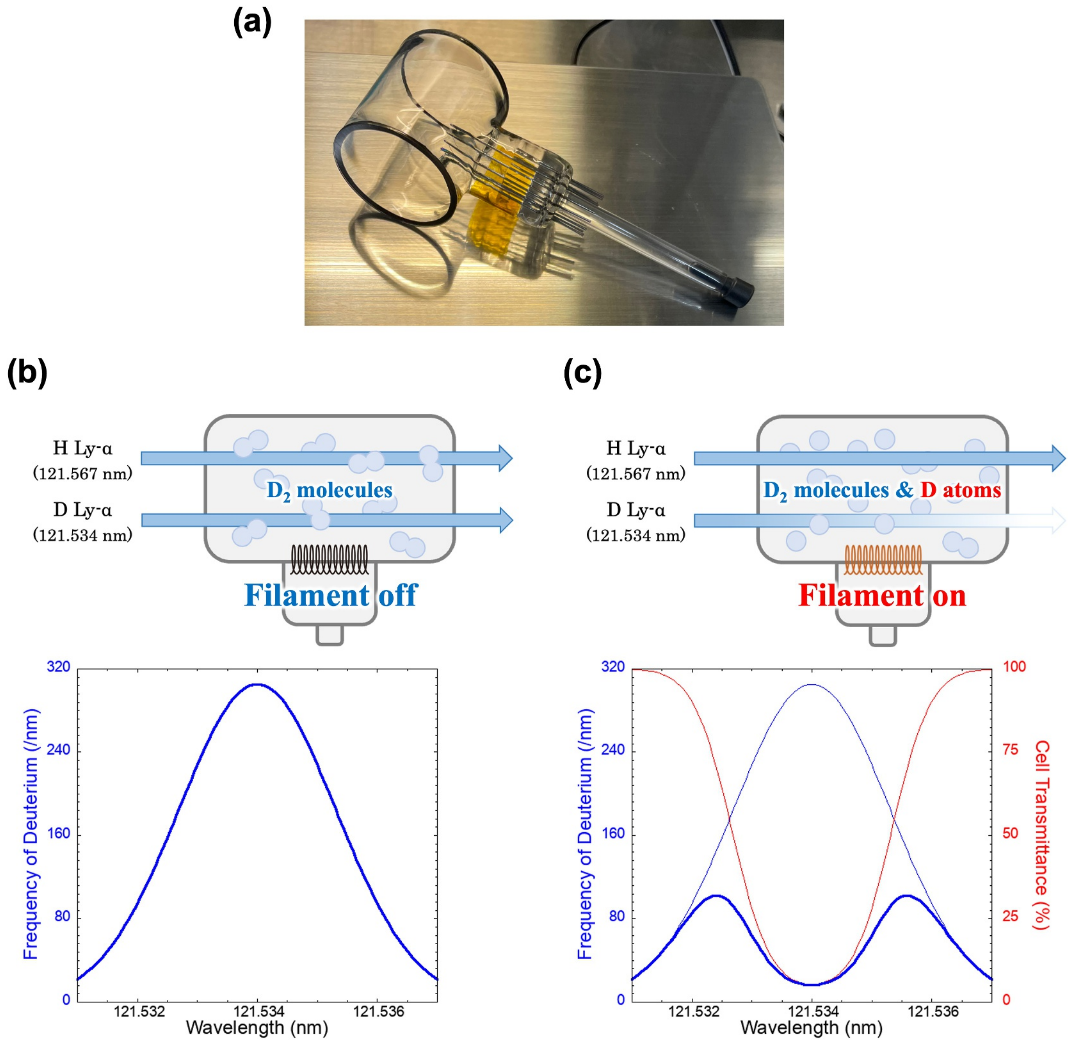

Figure 1. Image of the absorption cell used in this study (a), and schematic diagrams of the inside of the cell and the shapes of deuterium Ly-α spectra after passing through the cell with (b) and without (c) electrical power applied to the filament inside the cell. The thick blue line in (c) is the spectrum of the light transmitted through the cell, which is the product of the Ly-α spectrum of cometary hydrogen (thin blue line) and the transmittance spectrum of the absorption cell (red line).

2. Method

2.1. Performance Evaluation of Absorption Cells

To investigate the dependence of the absorption rate of the absorption cells on the filament and cometary hydrogen temperatures, we experimentally examined the UV transmittance spectrum of the absorption cells. Using the VUV beamline DESIRS (De Oliveira et al., 2016) at the SOLEIL synchrotron radiation facility, continuous UV radiation emitted by the synchrotron was directed into an absorption cell installed inside a vacuum chamber. The transmitted light spectrum was analyzed with a Fourier-transform spectrometer (FTS; De Oliveira et al., 2011) (Figure 2). The electrical power applied to the filament inside the absorption cell was controlled from outside the vacuum chamber. By varying the applied voltage, absorption spectra at different filament temperatures were obtained. The absorption cells were filled with either 300 Pa of hydrogen or deuterium molecular gas.

The transmission spectra obtained from the experiments were used to calculate the absorption rate of the absorption cell for comet-originated Ly-α radiation, assuming a single characteristic temperature for the cometary hydrogen. This calculation was performed using the following equation:

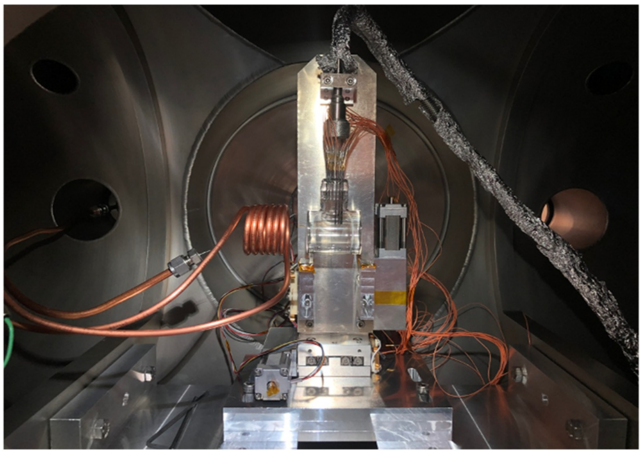

Figure 2. The experimental setup within the vacuum chamber. The absorption cell is placed at the center. Synchrotron light enters from the left, passes through the absorption cell, and is spectrally dispersed by the FTS placed on the right (not shown in the figure). The filament is connected to external electrodes for the application of electrical power.

$$r\left(T_{\mathrm{fil}}, T_{\mathrm{com}}\right) = \frac{\int \mathrm{d}\lambda\, A_{\mathrm{cell}}\left(T_{\mathrm{fil}}, \lambda\right) I_{\mathrm{com}}\left(T_{\mathrm{com}}, \lambda\right)}{\int \mathrm{d}\lambda\, I_{\mathrm{com}}\left(T_{\mathrm{com}}, \lambda\right)} \tag{1}$$

where λ, T_{fil}, and T_{com} represent the wavelength, temperature of the filament, and that of the cometary hydrogen, respectively. A_{cell} is a model transmission profile obtained by fitting the experimental transmission spectra with Equation 2 given in Kuwabara et al. (2018). I_{com} represents the radiance of the comet's Ly-α emission.

2.2. Generation of Simulated Data for CI/HI

First, we calculated the time variation of the Ly-α radiance observed during the comet flyby of the CI spacecraft. The hydrogen density profile was given by an analytical vectorial model (Festou et al., 1979), while the radiative transfer process of Ly-α within the coma was simulated using the Monte Carlo method (see Figure 8b of Suzuki et al. [2025]). Details of the models are provided in Festou et al. (1979), Richter et al. (2000), and Suzuki et al. (2025). In this study, we assumed that only H_2O and OH molecules act as parent molecules of hydrogen atoms. The D/H number density ratio within the coma was assumed to be constant, i.e., the number density of deuterium is proportional to that of hydrogen. Since the amount of deuterium is approximately 10^{-4} times that of hydrogen, the Ly-α emission from deuterium was assumed to be optically thin. The deuterium Ly-α radiance was calculated by multiplying the deuterium number density with the g-factor, which represents the resonance scattering emission efficiency. In reality, effects such as anisotropies in the hydrogen atom distribution caused by jets (e.g., Rubin et al., 2014) and absorption of Ly-α emission by dust may need to be taken into account. Although it is difficult to generalize these effects at the present stage, constructing a more realistic model using the Ly-α light curve obtained by HI during the flyby, together with dust measurements by other instruments, would lead to a more accurate determination of the D/H ratio.

Next, using the optical design of CI/HI and the results of performance evaluations of its components (Yoshioka et al., 2024 and Section 2.1 of this paper), the Ly-α radiance distribution of hydrogen and deuterium during the comet flyby was converted into the time variation of the detected photon count by CI/HI. Additionally, the standard deviation of shot noise—statistical fluctuations in the detected photon count—was calculated. As background sources of observed Ly-α emission, interplanetary hydrogen Ly-α at 700 R was also taken into account (Nakagawa et al., 2003), in addition to hydrogen atoms within the cometary coma. Dark and radiation noise levels were set at 1.0 and 5.0 cps/cm^2, corresponding respectively to 4.9 and 24.5 cps. The effective area of HI for 121.6 nm for the case with the cells switched off was 2.4×10^{-3} cm^2 (Yoshioka et al., 2024). During observations, the hydrogen absorption cell was kept off, while the deuterium absorption cell alternated between on and off every 5 s. This 5-s interval has been theoretically and experimentally confirmed to be highly feasible, taking into account the heating and cooling of the filament, and dissociation and recombination of hydrogen molecules. The detailed results demonstrating this performance are provided in Appendix A. While higher filament temperatures lead to higher absorption rates, they also reduce filament lifetimes. Therefore, the filament temperature was set to 1,800 K for this study. The temperatures of hydrogen and deuterium in the comet were assumed to be 7,000 and 3,500 K, respectively, while the temperature of interplanetary hydrogen was assumed to be 10,000 K. Consequently, the absorption rates of the cells for cometary hydrogen, cometary deuterium, and interplanetary hydrogen Ly-α were calculated to be 35%, 42%, and 30%, respectively. Regarding the assumption of a single thermal component for cometary gases, the thermal population is quantitatively dominant. Therefore, it is a reasonable first-order approximation to consider only the thermal component. Generally, in cometary comae near 1 au, H_2O is the dominant volatile species, making the thermal component derived from its photodissociation overwhelmingly dominant (e.g., Combi et al., 2004; Mumma & Charnley, 2011). Furthermore, non-thermal components exhibit a broadened spectral profile, which minimizes their contribution to both the absorption rate of the cells and the multiple scattering of the Ly-α emission. Consequently, the contamination from non-thermal populations is considered sufficiently small for the primary objective of this study, which is the quantification of the D/H ratio of water-derived hydrogen atoms.

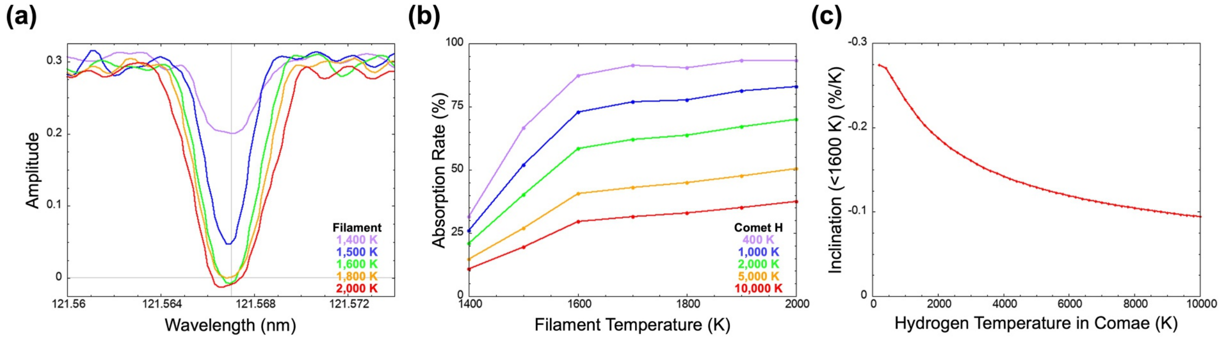

Figure 3. (a) Absorption spectra obtained by an experiment using a hydrogen absorption cell at the SOLEIL synchrotron. (b) The calculated absorption rates of the cell with respect to filament temperature and cometary hydrogen temperature. (c) Dependence of the slope of absorption rate against filament temperature (with filament temperature below 1,600 K) on cometary hydrogen temperature.

The flyby velocity is expected to be several tens of km/s, although the specific value will not be determined until the target comet and approach trajectory are confirmed. Here, the relative velocity of the spacecraft to the comet nucleus during the flyby was set to two possible values based on Jones et al. (2024): 30 and 70 km/s as the best and worst cases for our observation. The closest approach (CA) distance to the nucleus was assumed to be 1,000 km.

2.3. Detectability of Deuterium and Measurement Accuracy of Hydrogen Column Density

The simulated data from the previous section were integrated over 30 min centered around the time of the CA during the Comet Encounter Phase (15 min before and after the CA). The signal-to-noise (S/N) ratio for deuterium detection was calculated. For this, noise was defined as the standard deviation of shot noise, and the signal was defined as the difference in photon counts when the deuterium absorption cell was on versus off. Since the target comet will be determined after launch, the activity and D/H ratio of the target are currently unknown. Therefore, we need to calculate the S/N ratio over a wide parameter range. Previous observational results indicated that the D/H ratios of comets were approximately $(1-5)\times 10^{-4}$ (e.g., Altwegg et al., 2015; Clark et al., 2019), and the water production rates of long-period comets range from 10^{28} to 3×10^{30}/s (e.g., Combi et al., 2019). Thus, based on these results, we considered water production rates between $10^{27}-10^{31}$/s and D/H ratios between $10^{-4}-10^{-3}$ for our calculations. Since deuterium Ly-α is likely optically thin, the deuterium column density can be obtained by dividing the observed deuterium Ly-α radiance by the g-factor. When the hydrogen column density along the line of sight exceeds approximately $3\times 10^{12}/\mathrm{cm}^2$, hydrogen Ly-$\alpha$ becomes optically thick (Suzuki et al., 2025). Therefore, converting hydrogen Ly-α radiance into hydrogen column density requires a radiative transfer model. In this study, we used the model developed by Suzuki et al. (2025) to calculate the relation between Ly-α radiance and hydrogen column density for the CI/HI observational geometry. We computed the average and standard deviation of hydrogen column density for water production rates of $10^{27}-10^{31}$/s and hydrogen temperatures of $5,000-9,000$ K.

3. Results and Discussion

3.1. Absorption Rate of the Absorption Cell and Measurement Accuracy of Hydrogen Temperature in Cometary Comae

Absorption spectra of the absorption cell for various filament temperatures were obtained through the experiment (Figure 3a). As the filament temperature increased, the absorption spectra deepened. When the filament temperature reached 1,600 K, the absorption rate at the line center was nearly 100%. At even higher temperatures, the absorption width broadened. Assuming various temperatures for hydrogen in cometary comae and calculating the absorption rates using Equation 1, we found that higher filament temperatures and lower hydrogen temperatures in comae resulted in higher absorption rates (Figure 3b). For the filaments temperature above 1,600 K, the increase in absorption rate diminishes because of saturation of the absorption spectra. The slope of the absorption rate as a function of filament temperature depends on the temperature of the hydrogen in comae. The slope of the absorption rate against filament temperature below 1,600 K, calculated using the least squares method, is shown in Figure 3c. At filament temperatures below 1,600 K, the slope became gentler as the hydrogen temperature in

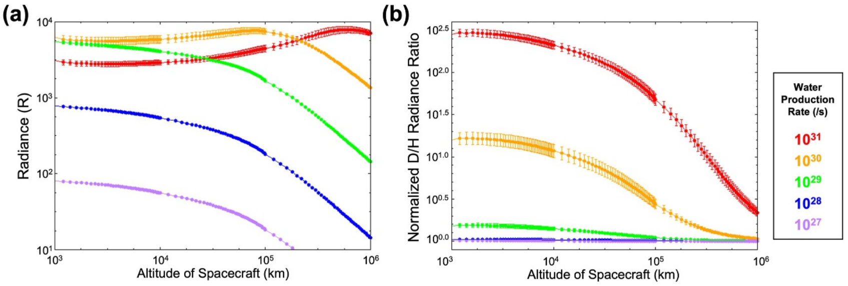

Figure 4. Relations between the distance from the nucleus and hydrogen Ly-α radiance (a) and the D/H Ly-α radiance ratio normalized by the D/H number density ratio (b) during CI's comet flyby. Since the activity of the target comet is unknown, the results are shown for water production rates of $10^{27} - 10^{31}$/s.

comae increased. Although the absolute absorption rate cannot be directly estimated from a single observation, the hydrogen temperature in the coma can be inferred from the slope of the absorption rate as the filament temperature changes. For example, if observational data have relative errors of 10% or 5% and measurements are repeated five times, the relative errors in the estimated hydrogen temperature, based on the slope below 1,600 K, are less than 30% or 16%, respectively. Note that each absorption cell in HI will be individually thermally controlled within a temperature range between +15°C and +55°C after launch, and thus the temperature of the cell body is not expected to affect the absorption rates.

3.2. Simulated Observation Data of CI/HI

Using the radiative transfer model developed by Suzuki et al. (2025), we calculated the Ly-α radiance profile expected to be observed by the observation of HI during the Comet Encounter Phase of CI (Figure 4a). The deuterium Ly-α radiance increases with proximity to the nucleus due to the increase in number density, while for comets with relatively high activity, the brightness of hydrogen grows at a lower rate due to multiple scattering effects. Consequently, the D/H Ly-α radiance ratio increases significantly (Figure 4b). An example of the time variation in the detected photon count is shown in Figure 5. In this simulation, the hydrogen absorption cell remains off, while the deuterium cell filament alternates between on and off every 5 s. Ideally, when the filament is on, deuterium Ly-α is absorbed and the detected photon count decreases, as shown by the black line in Figure 5. This difference in photon counts between the on and off states enables quantification of the deuterium Ly-α radiance. In practice, however, random errors caused by shot noise result in significantly scattered data, as represented by the red and blue points in Figure 5. It is necessary to integrate the detected photon count over a sufficient duration in the on and off states to reliably compare the photon counts.

3.3. Feasibility of the D/H Ratio Measurement

The S/N ratio for detecting deuterium was calculated by integrating the light curve obtained during the Comet Encounter Phase (Figure 6). Calculations were performed for comets with various water production rates and D/H ratios. Based on previous observations, the D/H ratios of long-period comets are expected to lie roughly between 1×10^{-4} and 5×10^{-4} (e.g., Altwegg et al., 2015; Clark et al., 2019), while their water production rates range from 10^{28} to 3×10^{30}/s (e.g., Combi et al., 2019). The regions enclosed by dotted lines in Figure 6 show this range for flyby velocities of 30 km/s (a) and 70 km/s (b). For comets with water production rates greater than 10^{29}/s, deuterium can be detected regardless of their D/H ratios. Additionally, for comets with water production rates below 10^{28}/s, deuterium can still be detected if their D/H ratios are relatively high. These results indicate that even small telescopes mounted on ultra-small satellites can detect deuterium in the comae of long-period comets. The region dominated by multiple scattering spans on the order of 10^4 km, and CI would traverse this region in a few minutes. Therefore, extending the integration time increases only the observation duration in optically thin regions, and this does not significantly improve the S/N ratio for deuterium detection. When the flyby velocity is slower, the observation time in the optically thick region increases, improving the S/N ratio by up to several times.

The hydrogen column density along the line of sight can be estimated from the number of photons detected when the deuterium cell is off. By utilizing a multiple scattering model, it is possible to derive the hydrogen column density from the observed Ly-α radiance, even in optically thick cases. Figure 7 shows the calculated averages and

10.1029/2025JE009511

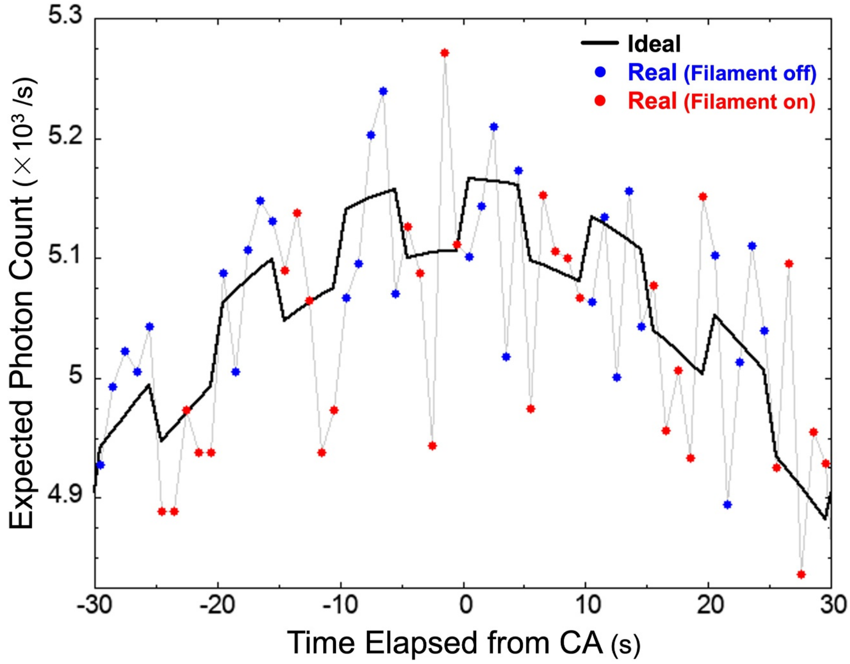

Figure 5. An example of simulated observational data. This calculation assumes a water production rate of 10^{31}/s and a D/H number density ratio of 3×10^{-4}. The black line represents an ideal light curve without considering noise. The gray line represents simulated data considering shot noise, with red points indicating filament-on conditions and blue points filament-off.

standard deviations of hydrogen column density, derived from observed hydrogen Ly-α radiance, for parameter ranges of water production rates of $10^{27} - 10^{31}$/s and temperatures of $5,000 - 9,000$ K. Even for the same column density along the line of sight, higher temperatures reduce the probability of mutual absorption of Ly-α photons due to larger relative velocities between atoms, making multiple scattering less effective and increasing the radiance. When the hydrogen temperature in the comet is assumed to be $5,000 - 9,000$ K based on past studies, the relative estimation error for hydrogen column density in the multiple scattering region is at worst 36% (Figure 7a). Furthermore, if, as shown in Section 3.1, the hydrogen temperature in the cometary coma could be constrained to $7,000 \pm 1,000$ K through observations during the Waiting at L2 or Approach to Encounter Phases, the error in column density derived from this measurement would improve to 20% at worst (Figure 7b). Furthermore, estimating the D/H ratio requires constraining the temperature of deuterium. While it is unrealistic to scan the *deuterium* temperature during the mission, previous high-resolution spectroscopic observations of comets have shown an empirical relationship where the effective temperature of *deuterium* is approximately half that of hydrogen (e.g., $T_H \sim 7,000$ K and $T_D \sim 3,500$ K; Weaver, 2008). By applying this relation, the temperature of *deuterium* can be reasonably constrained from the measured hydrogen temperature. This significantly reduces the uncertainty regarding the *deuterium* temperature, further suppressing the overall error in the derived D/H ratio.

With these constrained relative errors, it becomes possible to evaluate the D/H ratio in at least three categories of comets: Earth-like D/H ratios, high D/H ratios such as those found in comet 67P/Churyumov-Gerasimenko under specific conditions (Altwegg et al., 2015), and intermediate D/H ratios like comet 1P/Halley (Balsiger et al., 1995). Our results indicate that small telescopes mounted on ultra-small satellites are capable of measuring the D/H ratio of comets.

It should be noted that the present feasibility study assumes a severe operational constraint: a single fast flyby using an ultra-small, lightweight instrument. Due to the inability to measure the hydrogen temperature by changing the filament temperature during the flyby, and the limited number of detectable deuterium Ly-α photons, we must assume that the temperatures of hydrogen and deuterium, as well as the D/H ratio, are uniform and constant from the CA distance ($\sim 10^3$ km) up to the optically thick region ($\sim 10^5$ km). While the CI mission profile serves as a challenging "worst-case" scenario for small cameras, our results demonstrate that D/H ratio

10.1029/2025JE009511

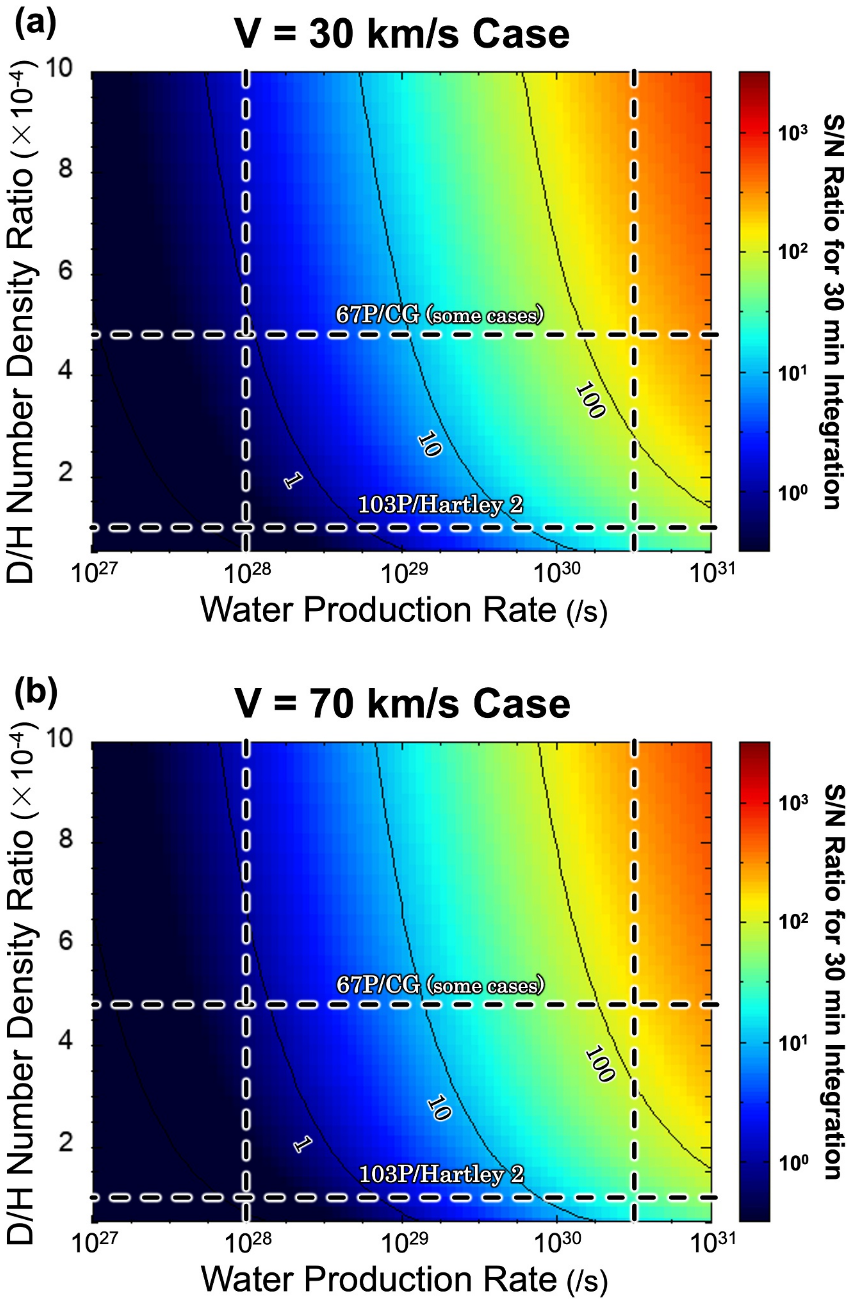

Figure 6. Predicted S/N ratio for deuterium detection in cometary comae with the spacecraft flyby velocities of 30 km/s (a) and 70 km/s (b). The horizontal and vertical axes represent the assumed water production rates and D/H ratios of comets, respectively, while the color map indicates the S/N ratio for deuterium detection under each parameter set.

measurements are viable even under such conditions. This implies that the proposed concept is highly scalable to a broader range of missions. For future missions requiring higher spatial and temporal resolutions, complementary approaches such as deploying large spacecraft equipped with echelle spectrographs or rendezvous missions that afford ample observation time to significantly improve the S/N ratio and enable advanced operations like filament temperature scanning even within the coma would be necessary.

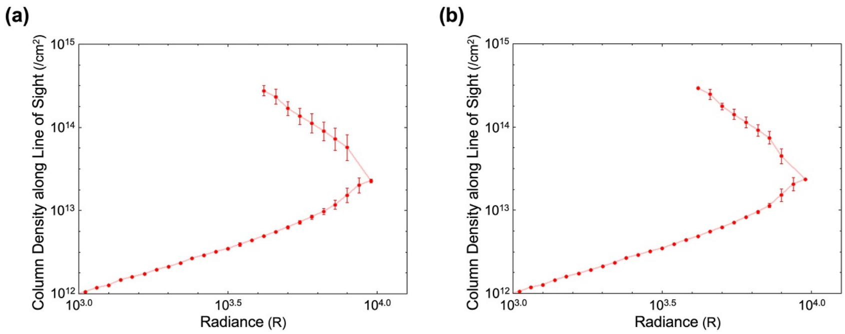

Figure 7. Relationship between observed hydrogen Ly-α radiance and derived hydrogen column density along the line of sight when cometary hydrogen temperatures are assumed to be $7,000 \pm 2,000$ K (a) and $7,000 \pm 1,000$ K (b), respectively. The x-axes show the observed hydrogen Ly-α radiance, and the y-axes represent the hydrogen column density derived from it. The error bars indicate the standard deviations caused by variations in water production rates and temperatures.

4. Conclusion

Comets are essential objects for understanding the early solar system environment. In particular, measuring the D/H ratio of comets is one of the critical keys to uncovering the formation environment of comets and the origin of water on Earth. CI/HI (Yoshioka et al., 2024) will optically measure the D/H ratio in the coma of a long-period comet during the flyby using an absorption cell. However, detecting deuterium with optical systems onboard ultra-small spacecraft with many constraints is challenging. Moreover, multiple scattering makes it difficult to estimate hydrogen atom density from Ly-α radiance observations. Since the target comet for the CI mission will not be determined until after launch, it is necessary to evaluate the feasibility of measuring the D/H ratio for comets with a wide parameter range.

In this study, we quantitatively investigated the feasibility of measuring the D/H ratio by combining two methods: developing a small gas cell filter and constructing a radiative transfer model. First, performance evaluation experiments for the absorption cell were conducted using the DESIRS beamline (De Oliveira et al., 2016) in the SOLEIL synchrotron. The absorption rate depends on both the temperature of the filament inside the cell and the hydrogen temperature of the cometary coma. Our results showed that when the observation conditions allow for five measurements with a relative error of 5%, for example, the hydrogen temperature of the cometary coma could be estimated with a relative error rate of 16% or less.

Subsequently, we used the radiative transfer model (Suzuki et al., 2025) to make simulated observation data of HI during the comet flyby. Ideally, the radiance of the deuterium Ly-α can be deduced from the difference in the detected count of photons when the deuterium absorption cell is switched on and off every few seconds. Although this difference may not be directly visible in the light curve in reality, it was found that the deuterium number density could be quantified for active comets with a water production rate of 10^{29}/s or higher, or for comets with relatively high D/H ratios. In addition, by using the radiative transfer model, the number density of hydrogen atoms could also be deduced with a relative error rate of 36% at worst even in optically thick cases. If we can constrain the hydrogen temperature to a range like $7,000 \pm 1,000$ K, it could be deduced with a relative error rate of better than 20%.

These results demonstrate that even with the stringent constraints of ultra-small satellites, CI/HI can provide scientifically meaningful measurements of cometary D/H ratios and hydrogen column densities. By extending the number of comets that can be sampled, this approach has the potential to systematically link cometary compositions to formation environments in the early solar system, offering critical constraints on the origin of water and the primordial building blocks of our planetary system. Furthermore, the trend of deep space exploration by ultra-small spacecraft gains momentum. Our findings highlight the potential of compact UV telescopes on small spacecraft to provide unique insights into planetary science, not only as a technological demonstration but also as a means to address fundamental questions about the solar system's formation and evolution.

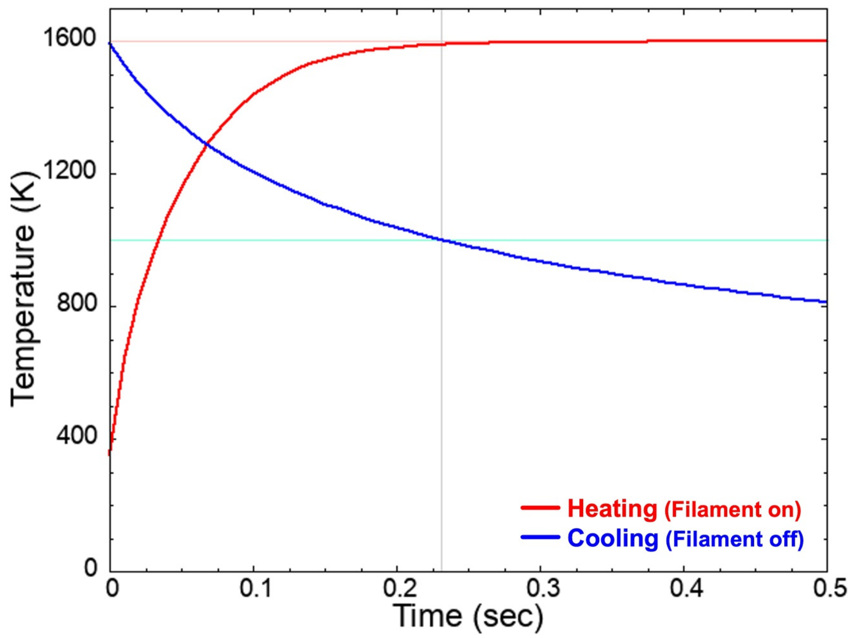

Figure A1. Variation in filament temperature over time after the applied voltage is turned on (red line) or off (blue line). The light red and blue horizontal lines show 1,600 and 1,000 K. After 0.23 s (gray vertical line), the filament temperature reaches 1,590 K when heating and 1,000 K when cooling.

Appendix A: Response Timescale of the Absorption Rate to Filament Voltage Switching

CI/HI will alternately switch the voltage applied to the filament in the deuterium cell on and off at a short interval during the Comet Encounter Phase. In such a high-cadence operation, the response of the cell's absorption rate to the voltage switching may be affected by thermal inertia of the filament and delay of dissociation and recombination of deuterium molecules. In this appendix, we first evaluate the theoretical response timescale of the absorption rate through numerical calculations. Subsequently, we present experimental results to validate the cell's performance. Our results demonstrate that the absorption cell is fully capable of responding to switching cycles on the order of several seconds.

First, we evaluate the time required for the filament temperature to reach a steady state. Assuming that the time required for thermal dissociation and recombination of deuterium molecules is short enough to be negligible, we calculated the time it takes for the filament temperature to reach a steady state.

The filament temperature as a function of time after voltage application was calculated using the following equation:

$$mC\frac{dT_f}{dt} = \frac{V^2}{R(T_f)} - A\varepsilon\sigma T_f^4 \tag{A1}$$

where T_f, m, and C are the filament temperature, mass of the filament, and heat capacity of tungsten. The first term on the right hand side represents the energy given to the filament due to power consumption, where V and R are the applied voltage and the filament resistance, respectively. The second term corresponds to the energy loss due to blackbody radiation, where A, ε, and σ are the surface area of the filament, the emissivity, and the Stefan-Boltzmann constant, respectively. Due to the low pressure of the enclosed deuterium gas (300 Pa), thermal conduction to the surrounding gas is negligible. Furthermore, thermal conduction from the filament ends to the lead wires is also ignored here. The filament temperature after the voltage is turned off can be calculated using the following equation by removing the first term from Equation A1:

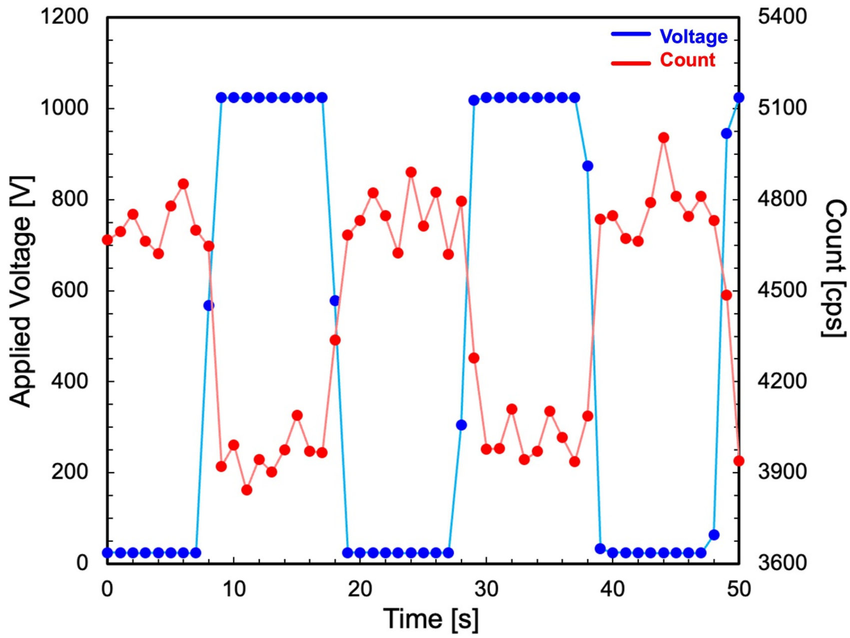

Figure A2. Variation in the voltage applied to the filament and the corresponding response of the transmitted radiance. Within the 1-s sampling interval after the voltage is applied to the filament, the absorption rate of the cell increases, resulting in a decrease in the transmitted radiance.

$$mC\frac{dT_f}{dt} = -A\varepsilon\sigma T_f^4 \tag{A2}$$

The calculated results of Equations A1 And A2 are shown in Figure A1 by the red and blue lines, respectively. The filament was found to reach $> 1,590$ K 0.23 s after the voltage was applied, and cooled down to $< 1,000$ K 0.23 s after the voltage was turned off. Both of these times are significantly shorter than the voltage switching times in our current plan for CI/HI.

Regarding the timescale of dissociation, the dissociation of deuterium molecules on a tungsten surface at temperatures above 1,500 K is determined by the collision frequency of gas molecules with the surface and the sticking coefficient. This dissociation process occurs almost instantaneously, on the order of microseconds to milliseconds. On the other hand, for recombination, atoms need to collide with the relatively cool walls of the cell to reform into molecules. Given that the thermal velocity of the atoms is several kilometers per second while the cell dimensions are only a few centimeters, the frequency of wall collisions is extremely high. The time required for recombination should be also estimated to be on the order of milliseconds. Thus, we concluded that the time required for the absorption rate variation could be ignored and the absorption rate of the cell during measurement can be considered constant.

While the above calculations suggest that the response time of the absorption rate to voltage switching is sufficiently short for CI/HI measurements, experimental validation is necessary to account for any other effects. To this end, we measured the variation in the intensity of the Ly-α emission transmitted through the absorption cell while switching the applied voltage on and off at short intervals. Although the switching interval used in this experiment was 10 s, as it was conducted prior to the finalization of the specific operation plan, this data set is sufficient for evaluating the response time discussed in this section.

As shown in Figure A2, the measured absorption rate responded to the voltage switching within the sampling interval of 1 s. While the temporal resolution of this specific experiment was limited to 1 s, the result is consistent with the calculated thermal response time of 0.23 s.

These results, both theoretical and experimental, demonstrate that the absorption cell is fully capable of following the 5-s switching cycle planned for the CI/HI observation, with a sufficient margin.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The data used to reproduce the results of this study are available at Suzuki (2025).

Acknowledgments

This work was supported by Grants-in-Aid for the Japan Society for the Promotion of Science (JSPS), Grant 22J15382, 22K21344, and 24KJ2224.

References

Altwegg, K., Balsiger, H., Bar-Nun, A., Berthelier, J. J., Bieler, A., Bochsler, P., et al. (2015). 67P/Churyumov-Gerasimenko, a Jupiter family comet with a high D/H ratio. *Science*, *347*(6220), 1261952. https://doi.org/10.1126/science.1261952

Balsiger, H., Altwegg, K., & Geiss, J. (1995). D/H and ^{18}O/^{16}O ratio in the hydronium ion and in neutral water from in situ ion measurements in comet Halley. *Journal of Geophysical Research*, *100*(A4), 5827–5834. https://doi.org/10.1029/94JA02936

Bertaux, J. L., Blamont, J., Marcelin, M., Kurt, V., Romanova, N., & Smirnov, A. (1978). Lyman-alpha observations of venera-9 and 10 I. The non-thermal hydrogen population in the exosphere of venus. *Planetary and Space Science*, *26*(9), 817–831. https://doi.org/10.1016/0032-0633(78)90105-8

Bertaux, J. L., Kyrölä, E., Quémerais, E., Pellinen, R., Lallement, R., Schmidt, W., et al. (1995). SWAN: A study of solar wind anisotropies on SOHO with Lyman alpha sky mapping. In B. Fleck, V. Domingo, & A. Poland (Eds.), *The SOHO Mission* (pp. 403–439). Springer Netherlands. https://doi.org/10.1007/978-94-009-0191-9_11

Ceccarelli, C., Caselli, P., Bockelee-Morvan, D., Mousis, O., Pizzarello, S., Robert, F., & Semenov, D. (2014). Deuterium fractionation: The ariadne's thread from the pre-collapse phase to meteorites and comets today. *Protostars and Planets VI*. https://doi.org/10.2458/azu_uapress_9780816531240-ch037

Clark, R. N., Brown, R. H., Cruikshank, D. P., & Swayze, G. A. (2019). Isotopic ratios of Saturn's rings and satellites: Implications for the origin of water and Phoebe. *Icarus*, *321*, 791–802. https://doi.org/10.1016/j.icarus.2018.11.029

Combi, M., Mäkinen, T., Bertaux, J.-L., Quémerais, E., & Ferron, S. (2019). A survey of water production in 61 comets from SOHO/SWAN observations of hydrogen Lyman-alpha: Twenty-one years 1996–2016. *Icarus*, *317*, 610–620. https://doi.org/10.1016/j.icarus.2018.08.031

Combi, M. R., Harris, W. M., & Smyth, W. H. (2004). Gas dynamics and kinetics in the cometary coma: Theory and observations. In *Comets II*.

De Oliveira, N., Joyeux, D., Roudjane, M., Gil, J.-F., Pilette, B., Archer, L., et al. (2016). The high-resolution absorption spectroscopy branch on the VUV beamline DESIRS at SOLEIL. *Journal of Synchrotron Radiation*, *23*(4), 887–900. https://doi.org/10.1107/S1600577516006135

De Oliveira, N., Roudjane, M., Joyeux, D., Phalippou, D., Rodier, J.-C., & Nahon, L. (2011). High-resolution broad-bandwidth Fourier-transform absorption spectroscopy in the VUV range down to 40 nm. *Nature Photonics*, *5*(3), 149–153. https://doi.org/10.1038/nphoton.2010.314

Festou, M., Jenkins, E. B., Barker, E. S., Upson, W. L., Ii, Drake, J. F., et al. (1979). Lyman-alpha observations of comet kobayashi-berger-milon (1975 IX) with copernicus. *The Astrophysical Journal*, *232*, 318. https://doi.org/10.1086/157291

Gomes, R., Levison, H. F., Tsiganis, K., & Morbidelli, A. (2005). Origin of the cataclysmic Late Heavy Bombardment period of the terrestrial planets. *Nature*, *435*(7041), 466–469. https://doi.org/10.1038/nature03676

Hartogh, P., Lis, D. C., Bockelée-Morvan, D., De Val-Borro, M., Biver, N., Küppers, M., et al. (2011). Ocean-like water in the Jupiter-family comet 103P/Hartley 2. *Nature*, *478*(7368), 218–220. https://doi.org/10.1038/nature10519

Jones, G. H., Snodgrass, C., Tubiana, C., Küppers, M., Kawakita, H., Lara, L. M., et al. (2024). The Comet Interceptor Mission. *Space Science Reviews*, *220*(1), 9. https://doi.org/10.1007/s11214-023-01035-0

Kuwabara, M., Taguchi, M., Yoshioka, K., Ishida, T., De Oliveira, N., Ito, K., et al. (2018). Evaluation of hydrogen absorption cells for observations of the planetary coronas. *Review of Scientific Instruments*, *89*(2), 023111. https://doi.org/10.1063/1.5007812

Lis, D. C., Bockelée-Morvan, D., Güsten, R., Biver, N., Stutzki, J., Delorme, Y., et al. (2019). Terrestrial deuterium-to-hydrogen ratio in water in hyperactive comets. *Astronomy & Astrophysics*, *625*, L5. https://doi.org/10.1051/0004-6361/201935554

Mandt, K. E., Lustig-Yaeger, J., Luspay-Kuti, A., Wurz, P., Bodewits, D., Fuselier, S. A., et al. (2024). A nearly terrestrial D/H for comet 67P/Churyumov-Gerasimenko. *Science Advances*, *10*(46), eadp2191. https://doi.org/10.1126/sciadv.adp2191

McClintock, W. E., Schneider, N. M., Holsclaw, G. M., Clarke, J. T., Hoskins, A. C., Stewart, I., et al. (2015). The imaging ultraviolet spectrograph (IUVS) for the MAVEN Mission. *Space Science Reviews*, *195*(1–4), 75–124. https://doi.org/10.1007/s11214-014-0098-7

Mumma, M. J., & Charnley, S. B. (2011). The chemical composition of Comets—emerging taxonomies and Natal Heritage. *Annual Review of Astronomy and Astrophysics*, *49*(1), 471–524. https://doi.org/10.1146/annurev-astro-081309-130811

Nakagawa, H., Fukunishi, H., Takahashi, Y., Watanabe, S., Taguchi, M., Bertaux, J.-L., et al. (2003). Solar cycle dependence of interplanetary Lyman α emission and solar wind anisotropies derived from NOZOMI/UVS and SOHO/SWAN observations. *Journal of Geophysical Research*, *108*(A10), 2003JA009882. https://doi.org/10.1029/2003JA009882

Richter, K., Combi, M. R., Keller, H. U., & Meier, R. R. (2000). Multiple scattering of hydrogen Ly α radiation in the coma of Comet Hyakutake (C/1996 B2). *The Astrophysical Journal*, *531*(1), 599–611. https://doi.org/10.1086/308433

Rubin, M., Combi, M. R., Daldorff, L. K. S., Gombosi, T. I., Hansen, K. C., Shou, Y., et al. (2014). Comet 1P/Halley multifluid mhd model for the *GIOTTO* fly-by. *The Astrophysical Journal*, *781*(2), 86. https://doi.org/10.1088/0004-637X/781/2/86

Suzuki, Y. (2025). Feasibility of optical measurement of d/h ratios of cometary comae using a small ultraviolet instrument. *Zenodo*. https://doi.org/10.5281/zenodo.17401631

Suzuki, Y., Yoshioka, K., Masunaga, K., Kawakita, H., Shinnaka, Y., Murakami, G., et al. (2025). Contribution of multiple scattering to the Lyman alpha radiance distribution in cometary comae. *Icarus*, *441*, 116720. https://doi.org/10.1016/j.icarus.2025.116720

Taguchi, M., Fukunishi, H., Watanabe, S., Okano, S., Takahashi, Y., & Kawahara, T. D. (2000). Ultraviolet imaging spectrometer (UVS) experiment on board the NOZOMI spacecraft: Instrumentation and initial results. *Earth Planets and Space*, *52*(1), 49–60. https://doi.org/10.1186/BF03351613

Weaver, H. A. (2008). Atomic deuterium emission and the D/H ratio in comets.

Yoshioka, K., Yamazaki, A., Mitoh, Y., Yoshikawa, I., Murakami, G., Suzuki, Y., et al. (2024). Small UV imager for hydrogen Lyman-alpha onboard ultra-small spacecraft. In J.-W. A. Den Herder, K. Nakazawa, & S. Nikzad (Eds.), *Space telescopes and instrumentation 2024: Ultraviolet to gamma ray* (p. 109). Yokohama. https://doi.org/10.1117/12.3018183