

Isotopic Signature of Organic Molecules from Beyond the Solar System: An Enriched Methane D/H Ratio in the Interstellar Object 3I/ATLAS

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Abstract

Interstellar objects are interlopers from other planetary systems, and their volatile compositions provide a glimpse into planet formation around their host star. We present near-infrared spectra of the coma of interstellar object 3I/ATLAS measured with the James Webb Space Telescope. Our results demonstrate an unexpectedly high $D/H = (3.31 \pm 0.34)\%$ for methane and represent an exceedingly rare detection of deuterated organic molecules in an interstellar object. This D/H ratio is a factor of 14 ± 2 higher than that measured in comet 67P/Churyumov-Gerasimenko by the Rosetta spacecraft, the only other comet for which CH_3D has been detected, yet the ratio of deuteration in methane compared with water is consistent for both comets within 1.2σ . The D/H ratio in methane is observationally unconstrained in extrasolar sources to date, but the enriched ratio in 3I/ATLAS is most similar to those measured in other organic molecules toward primitive environments. The high D/H ratios of water and methane in 3I/ATLAS are a natural consequence of formation in a high D/H elemental ratio environment as a result of locally cold conditions in the protoplanetary disk and prior interstellar cloud. Thus, 3I/ATLAS formed in an environment very different from that in which our Sun and planets originated.

Keywords: Interstellar Object 3I/ATLAS, Isotopic Ratios, Interstellar Medium

Preprint – In Review at Nature Astronomy: March 20, 2026

1 Introduction

Reconstructing the physics and chemistry of planet formation is a fundamental pursuit in astronomy. Dynamical simulations of accretion and orbital architecture, returned samples of comets and asteroids, analysis of meteorites, and remote sensing studies of the present day solar system have all helped to inform our understanding of planet formation around the Sun (e.g., [Sandford et al. 2006](#); [Gourier et al. 2008](#); [Duprat et al. 2010](#); [Levison et al. 2011](#); [Ito et al. 2022](#); [Miguel and Vazan 2023](#); [Biver et al. 2024b](#), and references therein). Yet revealing the interiors of protoplanetary disks around other young stars is challenging. Owing to significant opacity, the midplane

of the protoplanetary disk in extrasolar systems and the ice-phase chemistry occurring therein is generally not accessible via remote sensing (Sturm et al. 2024). Thus, astrochemical models inform the majority of our knowledge of these environments in other stellar systems. Given their provenance from our own protoplanetary disk mid-plane, the compositions of solar system comets serve as one of the few observational constraints on these models (Drozdovskaya et al. 2016; Willacy et al. 2022).

In this context, the recent discovery of comet-like objects passing through the solar system on hyperbolic, gravitationally unbound trajectories, namely 2I/Borisov and 3I/ATLAS, has opened up a new window into the chemistry of planet formation around other stars by delivering their contents to our own planetary system for analysis (Bailer-Jones et al. 2020; Lintott et al. 2022; Seligman et al. 2025). Studies of isotopic ratios in cometary molecules are particularly powerful tracers of formation conditions, as isotopic fractionation in elements such as H and C is favored in cold environments such as the interstellar medium and the outer protoplanetary disk. In particular, deuterium is enriched in water toward interstellar and proto-stellar environments, and organics such as CH₃OH and H₂CO show D/H ratios up to $\sim 10\%$ toward such sources (e.g., Jørgensen et al. 2018; Persson et al. 2018). Unfortunately, there is a severe paucity of CH₃D detections in extrasolar sources (e.g., Riaz and Thi 2022) and the deuteration of methane in primitive environments is observationally unconstrained. On the other hand, astrochemical modeling indicates that the higher exothermicity of the gas-phase ion-molecule exchange reaction $\text{CH}_3^+ + \text{HD} \rightleftharpoons \text{CH}_2\text{D}^+ + \text{H}_2$ (responsible for deuteration in organics) compared to the corresponding $\text{H}_3^+ + \text{HD} \rightleftharpoons \text{H}_2\text{D}^+ + \text{H}_2$ (responsible for deuteration in water) should enable methane to achieve considerably higher deuteration than water in primitive environments if it is formed by gas-phase reactions (Aikawa and Herbst 1999; Cleaves et al. 2016). Grain-surface reactions can also contribute to high deuterium abundances (Nagaoka et al. 2005).

Here we report analysis of molecular emission in the coma of the interstellar object 3I/ATLAS measured with the James Webb Space Telescope (JWST) NIRSpec Integral Field Unit (IFU) on UT 2025 December 22 and 23. The observations were obtained at a heliocentric distance (r_{H}) of 2.4 au while the object was at a distance (Δ_{JWST}) of 1.8 au from the telescope. Additional details of the observations are provided in Methods. Identifications of detected molecular vibrational bands are given in Extended Data. These observations detected ro-vibrational transitions of CH₄ and CH₃D along with nearby emission from CH₃OH, C₂H₆, H₂CO, H₂O, and CO. To date, CH₃D has only been detected in a single comet, 67P/Churyumov-Gerasimenko, through in-situ mass spectrometry measurements with the Rosetta spacecraft (Müller et al. 2022; Biver et al. 2024b). The detection of CH₃D and CH₄ in 3I/ATLAS provides a direct measure of the deuteration in alkanes at the time of planet formation in an extrasolar system.

2 Results

The object’s continuum photocenter was chosen to represent the nucleus position, from which spectra were extracted in a $1''.5$ diameter circular aperture (corresponding to a projected radial distance of ~ 980 km at the distance of 3I/ATLAS). The key parameters derived in this study are the production rate (Q , the number of molecules

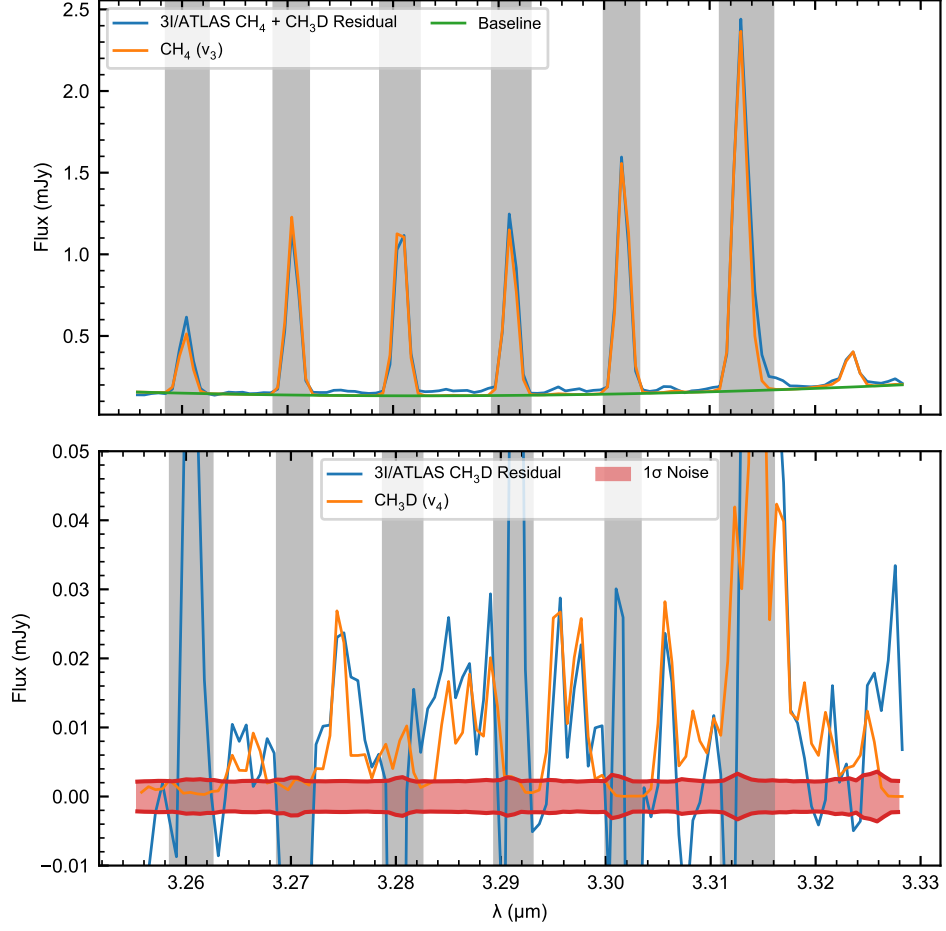


Fig. 1 **Upper Panel.** 3I/ATLAS $\text{CH}_4 + \text{CH}_3\text{D}$ residual spectrum, generated by extracting a spectrum in a $1''.5$ diameter aperture centered on the nucleus position and subtracting forward models of CH_3OH , H_2CO , C_2H_6 , and OH^* emission. The best-fit CH_4 model is overplotted. **Lower Panel.** 3I/ATLAS CH_3D residual spectrum generated by subtracting the best-fit CH_4 model and the spectral baseline from the upper panel. The best-fit CH_3D model and the 1σ instrumental noise envelope are also shown. The gray shaded regions denote the positions of CH_4 and blended CH_3D lines, which were masked when fitting CH_3D (see Methods).

subliming from the comet nucleus per second) and the rotational temperature (T_{rot} , K) for each detected species. These quantities were derived using molecular emission models and the Optimal Estimation Method implemented in the NASA Planetary Spectrum Generator (PSG; Villanueva et al. 2018), which includes a correction for any optical depth effects in the major species (see Villanueva et al. 2025, for further details).

Table 1 Molecular production rates and temperatures in 3I/ATLAS

Molecule	Q_x (10^{26} s^{-1})	T_{rot} (K)	$Q_x/Q(\text{CO})$ (%)	$Q_x/Q(\text{H}_2\text{O})$ (%)	$\langle Q_x/Q(\text{H}_2\text{O}) \rangle$ (%)
2025 December 22, G235H/F170LP					
H ₂ O	8.47 ± 0.05	23.3 ± 0.2	...	...	...
2025 December 23, G395H/F290LP					
CO	35.0 ± 0.2	42.3 ± 0.4	100	356 ± 5	5.2 ± 1.3
H ₂ O	9.82 ± 0.13	(23)	28.0 ± 0.4	100	...
CH ₃ OH	1.37 ± 0.04	34.4 ± 0.8	3.92 ± 0.09	13.7 ± 0.4	2.06 ± 0.20
H ₂ CO	0.039 ± 0.009	(34)	0.11 ± 0.03	0.40 ± 0.09	0.31 ± 0.06
CH ₄	1.90 ± 0.02	41.2 ± 0.5	5.43 ± 0.06	19.3 ± 0.4	0.78 ± 0.09
C ₂ H ₆	0.20 ± 0.02	(41)	0.58 ± 0.06	2.08 ± 0.21	0.55 ± 0.08
CH ₃ D	0.25 ± 0.03	(41)	0.72 ± 0.07	2.57 ± 0.25	...

Note — Q_x is the molecular production rate of each species. T_{rot} is the molecular rotational temperature. Values in parentheses are assumed. $\langle Q_x/Q(\text{H}_2\text{O}) \rangle$ are mean abundances with respect to H₂O among comets measured (Biver et al. 2024b; Dello Russo et al. 2016).

Isolating the CH₄ and CH₃D signal requires a careful treatment of any species with potentially blended signatures at the $R \sim 2700$ resolving power of the JWST NIR-Spec IFU. Among species previously detected in cometary atmospheres with strong transitions near those of methane (Biver et al. 2024b), these include CH₃OH, H₂CO, C₂H₆, NH₂, NH, CH₃CN, ¹³CH₄, and OH* (prompt emission, a vibrationally excited photodissociation product of H₂O which traces the production rate and spatial distribution of the latter; Bonev et al. 2006). We searched for all of these in the JWST spectra, yet only CH₃OH, H₂CO, and C₂H₆ were clearly detected.

We determined $Q(\text{CH}_3\text{OH})$ and $Q(\text{H}_2\text{CO})$ from modeling of isolated bands elsewhere in the JWST spectra. Despite a lack of clearly detected unblended lines of OH*, we conservatively included it in our models by setting $Q(\text{OH}^*) = Q(\text{H}_2\text{O})$ based on analysis of spectrally isolated H₂O emission. We then used these quantities to generate forward models of emission for CH₃OH, H₂CO, C₂H₆, and OH* expected near the position of the methane emission and subtracted them to generate a CH₄ and CH₃D residual spectrum of 3I/ATLAS. Figure 1 shows the resulting spectrum. Our retrieved production rates are summarized in Table 1.

Table 1 shows that CO was the most abundant molecule in 3I/ATLAS’s coma during our observations. Thus, we primarily calculated molecular abundances with respect to CO for all species in this study. H₂O is often the dominant coma molecule in comets measured at $r_{\text{H}} < 3$ au and is the standard compositional reference molecule in other comets (Biver et al. 2024b; Dello Russo et al. 2016), so we computed molecular abundances with respect to H₂O for ease of comparison. Our derived D/H ratio for methane is $(3.31 \pm 0.34)\%$.

3 Discussion

Aside from its high D/H ratio in methane, the volatile composition of 3I/ATLAS was in general super-enriched compared to water during our observations with respect to values found in solar system comets (Table 1; Dello Russo et al. 2016; Biver et al.

2024b). On the one hand, our measurements took place when the comet was at $r_H \sim 2.4$ au post-perihelion, and thus traversing the H_2O ice line. At these distances, H_2O sublimation becomes less vigorous as solar insolation attenuates, leaving CO and CO_2 to gradually overtake H_2O as the primary activity drivers. The analysis of these three species in Cordiner et al. (2026) is consistent with 3I/ATLAS’s transition from H_2O -to CO-dominated outgassing as it receded from the Sun. Since the majority of comet composition studies to date were undertaken interior to $r_H \sim 2$ au in H_2O -dominated comae (e.g., Biver et al. 2024b; Lippi et al. 2021; Dello Russo et al. 2016, and references therein), this caveat must be kept in mind. On the other hand, serial pre-perihelion ALMA measurements and IRAM 30-m measurements taken near perihelion of CH_3OH found that it was significantly enriched compared to solar system comets (Roth et al. 2026a; Biver et al. 2026), reinforcing the overall picture of 3I/ATLAS as an object enriched in trace volatiles.

Table 1 shows that there were significant differences in T_{rot} between the apolar and polar species. This may be explained in terms of differences in their rotational dipole moment and the increased radiative cooling efficiency of the latter (Bodewits et al. 2024). Table 1 also shows that our $Q(\text{CO})$ and $Q(\text{H}_2\text{O})$ values are nominally lower than those reported in Cordiner et al. (2026) for the same date. Their analysis was based on analysis of concentric, expanding azimuthally averaged annular spectra compared to our single nucleus-centered extracts, but the values are consistent within 2σ uncertainty. Our $Q(\text{CH}_4)$ is similarly lower (yet consistent within 2.3σ uncertainty) than reported in Belyakov et al. (2026) based on JWST MIRI observations four days later, although they postulated that $Q(\text{CH}_4)$ was variable in mid-late 2025 December.

3.1 Deuteration in Extrasolar Methane

Of the trace species detected, the most notable is CH_3D . It has proven extremely difficult to measure in solar system comets even with the most powerful ground- and space-based facilities. Aside from 3σ upper limits provided in a few bright comets ($\text{D}/\text{H} < (0.5 - 1)\%$; Gibb et al. 2012; Bonev et al. 2009; Kawakita et al. 2005), the only secure detection of CH_3D in a solar system comet was through in-situ mass spectroscopy of comet 67P/Churyumov-Gerasimenko (itself one of the most D-enriched solar comets found to date) performed by the Rosetta spacecraft (Müller et al. 2022; Biver et al. 2024b). Thus, this JWST study represents not only its rare detection in an interstellar object, but through remote sensing of a cometary atmosphere in general.

On the one hand, our D/H ratio of $(3.31 \pm 0.34)\%$ for methane is higher than that found for comet 67P/Churyumov-Gerasimenko, $(0.241 \pm 0.029)\%$, by a factor of 14 ± 2 . Yet the relative levels of deuteration measured for water and methane in the two comets provide greater insight. Müller et al. (2022) reported that the D/H ratio in methane was a factor of 4.8 ± 0.7 higher than that measured for water in 67P/Churyumov-Gerasimenko with Rosetta. We calculated the same quantity for 3I/ATLAS. Cordiner et al. (2026) measured a D/H ratio for water of $(0.95 \pm 0.06)\%$ and an enriched $^{12}\text{C}/^{13}\text{C}$ ratio for CO and CO_2 using the same JWST data analyzed in this work. These isotopic ratios were interpreted as evidence that 3I/ATLAS formed in an ancient stellar system in a low metallicity environment with the presence of intense star formation and a high cosmic ray ionization rate. Taken together, the D/H ratio

for methane in 3I/ATLAS is higher than water by a factor of 3.5 ± 0.4 . This ratio is consistent with the same value derived for 67P/Churyumov-Gerasimenko within 1.2σ . This level of agreement in deuteration between two objects with dramatic differences in their formation and evolutionary histories suggests a fundamental mechanism is at play.

CH_3D has been detected toward three proto-brown dwarfs (Riaz and Thi 2022), yet secure measurements can be found almost nowhere else outside of the solar system. However, CH_4 was not directly measured in these sources (it was inferred from CH_3D and the $\text{DCO}^+/\text{HCO}^+$ ratio), so the D/H ratio in methane is observationally unconstrained beyond the heliopause to date. Figure 2 shows a comparison of D/H ratios measured for methane and other organic molecules in solar system and extrasolar sources. Aside from comet 67P/Churyumov-Gerasimenko, the D/H ratio for methane has been measured for Venus, the giant planets, Titan, the dwarf planets Eris and Makemake, for organics in interplanetary dust particles (IDPs), carbonaceous meteorites, and ultra-carbonaceous Antarctic micrometeorites (UCAMMs; see Extended Data Table 3). The value in 3I/ATLAS is at least a factor of 1.4 higher than all of these, with the closest being $\text{D/H} = (1.5 \pm 0.5)\%$ for organic radicals in carbonaceous chondrite meteorite Orgueil (Gourier et al. 2008).

Beyond the solar system, the D/H ratio for methane in 3I/ATLAS is most similar to those found for other organic molecules, such as formaldehyde and methanol, in star-forming regions and protostars. In these regions, the D/H ratio for methanol exceeds that of water by a factor of ~ 10 (e.g., Taquet et al. 2019). This difference has been interpreted as reflecting the difference in the formation times of water and methanol on grain surfaces in the prestellar phase; that is, methanol formed later than water because deuterium fractionation increases with time in the low-temperature, prestellar phase (Ceccarelli et al. 2014). The high D/H ratio in methane compared to water in 3I/ATLAS may therefore be evidence of a difference in their formation times in its prestellar cloud. Indeed, CH_4 can be efficiently formed on grains by the hydrogenation of atomic C (Qasim et al. 2020).

With the complete lack of methane D/H ratios measured in primitive environments, this hypothesis is currently impossible to directly test observationally. In the absence of observational constraints, astrochemical models may provide insights. We note that to the best of our knowledge, the D/H ratios of icy species under low-metallicity environments (such as the origin system for 3I/ATLAS; Cordiner et al. 2026) have not yet been investigated by astrochemical models. Aikawa et al. (2012) modeled deuterium fractionation from the prestellar to protostellar core stage for water and many organic molecules, including methane and methanol. Although they were able to account for the $2 - 7\%$ D/H ratio for methanol measured in the inner regions of low-mass protostars with ALMA (Jørgensen et al. 2018; Taquet et al. 2019), the D/H ratio for methane in their models does not exceed $\sim 1\%$ at any stage.

In an alternative approach, Cleaves et al. (2016) explored whether protoplanetary disk chemistry alone can recreate the observed deuterium enrichment in solar system organics compared to water, identifying multiple potential contributors to enriched deuterium abundances. First, the higher volatility of CO (the precursor for organics) compared to O (the precursor for water) allows for a larger reservoir of feedstock for

organics formation in the disk. Next, the higher exothermicity of ion-molecule exchange reactions between $\text{CH}_3^+/\text{CH}_2\text{D}^+$ than between $\text{H}_3^+/\text{H}_2\text{D}^+$ enables deuterium fractionation to continue for longer and to involve a larger part of the disk for organics than for water.

Furthermore, the specific chemical formation pathways for each molecule is important. Methane is produced via more efficient gas-phase pathways throughout the disk along with grain-surface contributions in the outer (> 20 au) disk, whereas methanol is produced predominantly via less efficient grain-surface chemistry; thus, methane is able to achieve a significantly higher degree of deuteration than methanol. This is qualitatively consistent with IRAM 30-m measurements of 3I/ATLAS near perihelion, which found a 3σ upper limit on $\text{CH}_3\text{OD}/\text{CH}_3\text{OH} < 5.3\%$ (Biver et al. 2026). This upper limit rules out methanol deuteration in significant excess of our methane $\text{D}/\text{H} = (3.31 \pm 0.34)\%$ in 3I/ATLAS.

Finally, increased cosmic ray ionization rates resulted in even higher D/H ratios in organic species for the models of Cleeves et al. (2016). However, their models were ultimately unable to reproduce the D/H ratios of the most enriched solar system organics, such as the organic radicals in Orgueil, leaving them to postulate that additional deuteration in the pre/protostellar phase must be preserved into the disk phase.

Given the challenges in reproducing the level of methane deuteration in 3I/ATLAS through models in the literature to date, we estimated the $\text{CH}_3\text{D}/\text{CH}_4$ isotopic ratios in several sources using deuteration in cyclopropenylidene ($c\text{-C}_3\text{H}_2$), a small, cyclic molecule that is ubiquitous in the interstellar medium (see Methods). Our results suggest that the D/H ratios in methane in these environments may reach $\geq 4 - 7\%$.

Collectively, these observational and model results may provide a path to explain the exceptionally high D/H ratio in methane for 3I/ATLAS when considered alongside its high D/H ratio in water and high $^{12}\text{C}/^{13}\text{C}$ ratio in CO and CO_2 . Although its precise origin in the Milky Way is highly uncertain, dynamical studies have posited that 3I/ATLAS is between 3 – 11 Gyr old (Guo et al. 2025; Hopkins et al. 2025). Cordiner et al. (2026) provided additional constraints on its origins through its unusual isotopic abundances in water, CO, and CO_2 , hypothesizing that these required formation at very low temperatures in a low metallicity environment early in the Galaxy ($\sim 10 - 12$ Gyr ago) following a period of intense star formation. Such an environment would include a much higher cosmic ray ionization rate (by a factor of 100 based on their D/H ratio in water) than the local Galactic rate. This scenario provides all the necessary ingredients for achieving a very high D/H ratio in water compared to solar system objects, and in turn, an even higher ratio for methane.

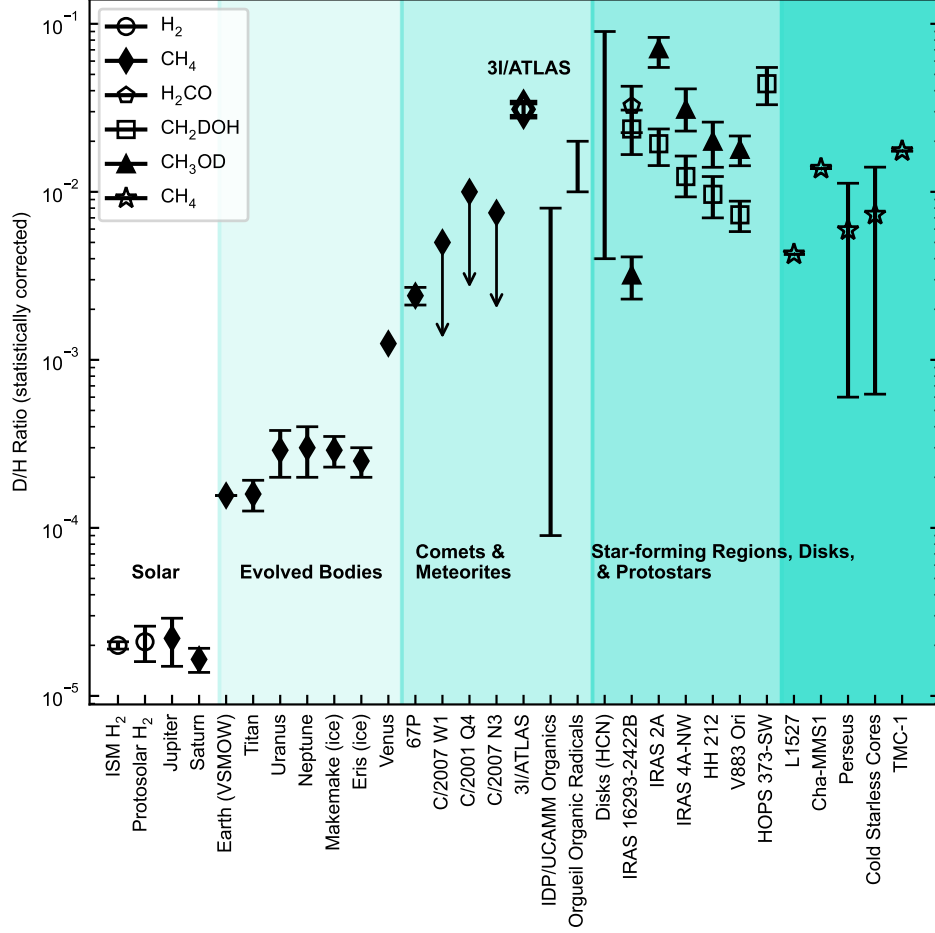


Fig. 2 D/H ratios in solar system and extrasolar sources. Ratios are for methane except when noted otherwise. Sources for which the D/H ratio in $c\text{-C}_3\text{H}_2$ was used to estimate the D/H in CH_4 are denoted with a $\star$. References and values for each object are given in Extended Data Table 3.

Methods

JWST Observations

Observations of 3I/ATLAS were carried out using the JWST NIRSpec IFU (Böker et al. 2022) on UT 2025 December 22 using the G235H/F1270LP grating (covering $\lambda = 1.66 - 3.05 \mu\text{m}$) and December 23 using the G395H/F290LP grating (covering $\lambda = 2.87 - 5.14 \mu\text{m}$) under General Observer program 5094. These gratings provide a spectral resolving power $\lambda/\Delta\lambda \sim 2700$. The comet’s observing geometry varied from $r_{\text{H}} = 2.37 - 2.42 \text{ au}$ and $\Delta_{\text{JWST}} = 1.79 - 1.80 \text{ au}$, with a solar phase angle $\phi = 22.7^\circ - 21.6^\circ$ and was tracked using JPL Horizons ephemeris orbit solution #42. A campaign to obtain accurate astrometry for and refine the ephemeris of 3I/ATLAS is detailed in Cordiner et al. (2026).

The G235H grating was executed with a single 642 s exposure beginning UT 2025-12-22 03:36, followed by $5 \times 700 \text{ s}$ exposures with G395H starting UT 2025-12-23 08:07. All observations used a four-point dither pattern. Background exposures with identical circumstances (exposure time, grating settings) were planned offset from the comet position by $300''$; however, two of the five background exposures for the G395H grating failed owing to background star issues, with follow-up attempts scheduled for later in 2026. Careful examination of the available background exposures did not reveal emission from any known interstellar infrared sources or zodiacal light, so analysis proceeded without background subtraction to maximize SNR. Exposures were processed using the JWST Pipeline version 1.20.2 with CRDS jwst_1464.pmap context files and aligned onto a common spatial-spectral axis using the Drizzle algorithm (Law et al. 2023).

Spectral Modeling

Cordiner et al. (2026) reported analysis of ALMA CO and HCN measurements in 3I/ATLAS carried out on 2025-Dec-22 between UT 07:32–08:36, as well as analysis of H₂O, CO, and CO₂ (along with their isotopologues) from the same JWST observations reported here. We adopted their relevant quantities (e.g., HDO/H₂O, gas expansion speeds) for the purposes of this analysis. Extended Data Table 1 provides a summary of the detected species and their ro-vibrational emission bands in this work.

We extracted and modeled spectra from a nucleus-centered $1''.5$ diameter aperture. Although the very central 1–2 spaxels are affected by the instrumental point-spread function (PSF), opacity effects are minimal within such an aperture at the low molecular production rates measured in this study. We used the jwstComet package (Roth 2026b), which provides for flexible spectral extraction from JWST IFU data cubes using functions from the astropy and photutils libraries, followed by automated interfacing with the NASA PSG API. The data cubes were converted from units of MJy sr^{−1} to Jy pixel^{−1}, then spectra were extracted from the data cubes using the photutils CircularAperture function and summed within the aperture using the aperture_photometry function (method = ‘subpixel’, subpixels = 10). Fluxes and 1σ noise on a per-spaxel basis were derived from the SCI and ERR extensions of the FITS files.

In the G395H grating, CO, CH₃OH, C₂H₆, H₂CO, CH₄, CH₃D, and H₂O were sampled simultaneously, while the G235H setting measured H₂O. In G395H, CO has strong emissions near 4.5 μ m, whereas H₂O has hot band emission throughout the 4 – 5 μ m region. Although this H₂O emission was sufficiently strong for measuring $Q(\text{H}_2\text{O})$, we could not retrieve a well-constrained rotational temperature. Instead the H₂O T_{rot} was determined from the G235H setting, then fixed when analyzing H₂O emission (and forward modeling OH*) in G395H.

We first worked to determine $Q(\text{CO})$ (relevant for setting the activity level in PSG) and $Q(\text{H}_2\text{O})$ (necessary for generating forward models of OH*) in the aforementioned aperture. Uncertainties on the retrieved parameters were obtained from the diagonal elements of the covariance matrix, scaled by the square root of the reduced χ^2 statistic, which includes uncertainties in the spectral baseline of the fit. All spectra were baseline subtracted using second or third-order polynomial fits. We used the lowest order polynomial baseline capable of reproducing the spectral shape and avoided higher-order polynomials to prevent introducing spurious features into the spectra. In all instances, we fit the spectral baseline simultaneously with the molecular emission, thereby incorporating uncertainties in the baseline fit into the uncertainties on each retrieved quantity (i.e., Q or T_{rot}). This baseline accounts for continuum emission from the dust and nucleus, as well as scattered sunlight and instrumental artifacts. Techniques employing simultaneous fitting of the continuum baseline and molecular emission models have been applied to decades of cometary infrared spectroscopy studies (e.g., DiSanti et al. 2003; Villanueva et al. 2011; Bonev et al. 2014; DiSanti et al. 2017; Roth et al. 2018; Faggi et al. 2019; Ejeta et al. 2024). We used a fixed spectral resolution element based on curves for dispersion as a function of wavelength provided by the Space Telescope Science Institute ¹.

As shown in Table 1, there are significant differences in T_{rot} between trace species, especially the apolar and polar species. However, the PSG only allows specification of a single T_{rot} during a retrieval; thus, it is not possible to model CO ($T_{\text{rot}} = 42$ K) and H₂O ($T_{\text{rot}} = 23$ K) in 3I/ATLAS during a single PSG simulation. This difficulty is most acute when modeling species whose strongest transitions are in spectrally crowded regions, such as CH₄, CH₃D, and C₂H₆. We therefore retrieved relevant quantities (Q or T_{rot}) for potentially confusing species (e.g., CH₃OH) from spectrally isolated bands whenever possible, then generated forward models of their emission to subtract away from species that are only available in spectrally crowded regions. We detail each of these instances below.

Following Cordiner et al. (2026), we set the gas expansion speed, v_{exp} , to 0.345 km s⁻¹ for CO and to 0.310 km s⁻¹ for all other species based on velocity resolved ALMA measurements of CO and HCN. We first retrieved $Q(\text{H}_2\text{O})$ and $T_{\text{rot}}(\text{H}_2\text{O})$ from the G235H setting on December 22. To determine $Q(\text{H}_2\text{O})$ from the G395H setting on December 23, we masked the strong nearby CO and OCS emission, fixed $T_{\text{rot}}(\text{H}_2\text{O}) = 23$ K, and analyzed H₂O emission between 4.45 – 5.1 μ m. Next we analyzed the CO emission, retrieving $Q(\text{CO})$ while allowing $T_{\text{rot}}(\text{CO})$ to freely vary. The retrieved values, including molecular production rates and rotational temperatures, are given in

¹<https://jwst-docs.stsci.edu/jwst-near-infrared-spectrograph/nirspec-instrumentation/nirspec-dispersers-and-filters#gsc.tab=0>

Table 1. Owing to a lack of spectrally isolated OH* emission lines clearly detected in our spectral regions of interest at the resolving power of JWST, we generated forward models of OH* by setting $Q(\text{OH}^*) = Q(\text{H}_2\text{O})$ in all subsequent steps.

Next, we retrieved $Q(\text{CH}_3\text{OH})$ and $T_{\text{rot}}(\text{CH}_3\text{OH})$ by fitting the ν_3 vibrational band near $3.5 \mu\text{m}$ simultaneously with $Q(\text{H}_2\text{CO})$ from the ν_1 and ν_5 bands near $3.6 \mu\text{m}$. Aside from several potentially blended OH* lines, these are spectrally isolated bands of each species which could be used to generate forward models when analyzing CH_4 , C_2H_6 , and CH_3D .

Owing to the proximity of the C_2H_6 ν_5 vibrational band to confusing emission from CH_3OH , H_2CO , and CH_4 , we took an iterative approach to its retrieval. The C_2H_6 ν_5 band does not emit appreciably at wavelengths shorter than $3.32 \mu\text{m}$, so we first worked to measure $Q(\text{CH}_4)$ by analyzing emission from $3.20 - 3.32 \mu\text{m}$. We generated forward models of CH_3OH (ν_2, ν_3, ν_9), H_2CO ($\nu_1 + \nu_6$), and OH* spectra at their respective rotational temperatures (34 K for CH_3OH and H_2CO and 23 K for OH*) and previously determined Q 's and subtracted them from our observed 3I/ATLAS spectrum.

We detected the CH_4 $R(0)$ through $R(8)$ transitions, the Q -branch, and several P -branch lines (although the latter becoming increasingly blended with CH_3OH and C_2H_6). Similar to challenges fitting CO_2 faced by [Cordiner et al. \(2026\)](#), we found that the higher- J CH_4 R -branch lines were not fit well by our radiative transfer models, likely owing to non-LTE effects at the very low temperatures and production rates in 3I/ATLAS during our observations. Namely, the higher- J lines depart from approximately LTE conditions more quickly than their lower- J counterparts. In turn, the PSG-produced baseline underneath the higher- J lines was skewed towards negative values. To test to what extent this may affect our fit, we fit a second order polynomial to the CH_4 extract before modeling the molecular line emission (Extended Data Figure 1). This model-independent baseline did not suffer from the same challenges near the higher- J lines, yet it clearly significantly overfits the baseline near the critically important trace emission between the towering CH_4 lines (especially the lower- J lines). Nevertheless, it is informative that we retrieve $Q(\text{CH}_4) = (1.99 \pm 0.03) \times 10^{26} \text{ s}^{-1}$ and $T_{\text{rot}}(\text{CH}_4) = 43.6 \pm 0.6 \text{ K}$.

We then returned to fitting the spectral baseline simultaneously with the CH_4 emission in the PSG, yet excluding the higher- J lines ($R(5) - R(8)$) from the fit (i.e., considering extracts with $\lambda > 3.255 \mu\text{m}$). This provided a significantly better baseline fit to the emission between the CH_4 lines and to the lower- J CH_4 lines themselves. Our retrieved values (Table 1) are in excellent agreement with the results from fitting all R -branch lines. Satisfied that restricting the number of CH_4 lines in our fit did not significantly affect the results, we proceeded to work to retrieve $Q(\text{C}_2\text{H}_6)$. We extended the spectral extract to cover wavelength ranges $\lambda = 3.255 - 3.38 \mu\text{m}$. This adequately covers the strong lines of the C_2H_6 ν_5 band but does not yet extend into the strongest features of the CH_3OH ν_9 band or other potential underlying solid-state features (e.g., polycyclic aromatic hydrocarbons; [Woodward et al. 2025](#)) at longer wavelengths. We fixed $Q(\text{CH}_4)$ and $T_{\text{rot}}(\text{C}_2\text{H}_6) = T_{\text{rot}}(\text{CH}_4)$ and retrieved $Q(\text{C}_2\text{H}_6)$, assuming that it followed the T_{rot} of the other apolar species.

Finally, we turned to fitting CH₃D, extracting a spectrum from $\lambda = 3.255 - 3.328$ μm and then subtracting the forward models of emission for CH₃OH, C₂H₆, H₂CO, CH₄, and OH* (Extended Data Figure 2). As shown in Figure 1, the CH₄ line fluxes are up to two orders of magnitude higher than the CH₃D line fluxes, yet the CH₃D features are clearly detected above the instrumental noise envelope. Given the dynamic range between the CH₄ and CH₃D lines, even slight mismatches between the observed and modeled CH₄ lines produce residuals that are comparably strong to the CH₃D lines themselves. Thus, we masked the positions of the CH₄ lines while retrieving CH₃D to prevent uncertainties in the CH₄ fit from propagating into the CH₃D retrieval. Furthermore, this masking removed strongly blended CH₃D features from the analysis, such as that near the 3.315 μm CH₄ *Q*-branch. We then fixed $T_{\text{rot}}(\text{CH}_3\text{D}) = T_{\text{rot}}(\text{CH}_4)$ and allowed $Q(\text{CH}_3\text{D})$ to vary as a free parameter. We tested the effects of varying the order of the polynomial spectral baseline from two to four, finding consistency regardless of our choice. Extended Data Table 2 provides a comparison of the derived molecular production rates, T_{rot} , and D/H ratio for methane as a function of polynomial baseline order. Our overall modeling process is shown in Extended Data Figure 2 and Extended Data Figure 3, including a total molecular emission model for the 3.3 μm region in 3I/ATLAS.

Estimating Methane D/H using *c*-C₃H₂

Here we detail our motivation and formalism for estimating the D/H ratio in CH₃D in primitive environments using the measured D/H ratio in hydrocarbons as a proxy. We discuss interstellar inheritance of pristine material that was fractionated during the star formation process as well as isotope chemistry in protoplanetary disks. We also address the viability of estimating the D/H ratio in methane through interstellar chemistry by examining observations of prestellar and protostellar cores.

In cold (~ 10 K) dense matter, H₃⁺ ions produced by cosmic rays can form H₂D⁺ and initiate deuterium fractionation in the exothermic ion-molecule exchange reaction (e.g., Millar et al. 1989)



where the rate of the endothermic reverse process depends on the ortho/para spin ratio of the hydrogen molecules (OPR=*o*-H₂/*p*-H₂); production of H₂D⁺ is inhibited by molecules in the higher-energy *o*-H₂ state. Gas-phase ion-molecule reactions involving H₂D⁺ subsequently lead to the incorporation of D atoms into interstellar molecules.

Late in the evolution of prestellar cores, significant depletion of CO molecules removes a major destruction pathway for molecular ions and H₂D⁺ ions can then react efficiently with HD to form D₂H⁺, which also reacts with HD to form D₃⁺ (Roberts et al. 2003). In this case, dissociative electron recombination reactions release more D atoms into the gas, elevating the atomic D/H ratio and leading to grain-surface chemistry producing high D/H ratios ($\sim 10^2 - 10^4 \times$ the cosmic ratio) and multiply-deuterated molecules (e.g., ND₃, D₂CO; Ceccarelli et al. 2014).

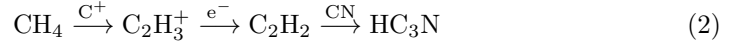
On grain surfaces, accreted carbon atoms provide the starting point for the formation of methane and its deuterated isotopologues through a series of H and D atom addition reactions, and so we may expect these fractionation characteristics to also

be evident. Models of deuterium fractionation in molecular clouds should therefore be required to self-consistently calculate the time-evolution of the ortho and para spin states of H_3^+ and H_2 , as well as those of H_2D^+ , D_2H^+ , and D_3^+ (Hugo et al. 2009; Sipilä et al. 2010). A further consequence of the time-dependence of H_2 spin conversion and CO depletion is that the ice mantle structure develops a D/H fractionation gradient: molecular D/H ratios are highest in the (late-forming) monolayers closest to the surface (Taquet et al. 2014).

Theoretical models of gas-grain deuterium fractionation in prestellar core and protostar formation that include all of these processes (Taquet et al. 2014; Furuya et al. 2016) can produce the range of $\text{HDO}/\text{H}_2\text{O}$ ratios found in interstellar ice mantles, hot corinos, and Solar System comets, as well as the ratio recently reported for 3I/ATLAS ($\approx 1\%$; Cordiner et al. 2026). Unfortunately, due to the absence of observed $\text{CH}_3\text{D}/\text{CH}_4$ ratios, few studies actually list the computed gas and ice phase ratios. An exception is that of Aikawa et al. (2012) who show that, during protostellar core formation, ice phase D/H ratios for methane lie in the range of $\approx 0.2\text{--}1\%$. However, as the models of Aikawa et al. (2012) neglected spin-state chemistry and mantle structure, these values should be taken with caution.

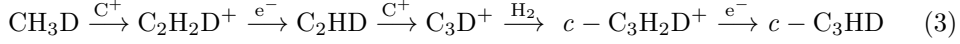
Calculations and observations of water deuteration support the view that cometary matter was inherited from the prestellar/protostellar phase of Solar System formation and not produced in situ (e.g., Furuya et al. 2017; Tobin et al. 2023). Additional support for this viewpoint comes from the high $\text{D}_2\text{O}/\text{HDO}$ ratio measured in comet 67P/Churyumov-Gerasimenko by Rosetta (Altwegg et al. 2017) as well as studies of protoplanetary disk chemistry. If cosmic rays were ineffective for ionizing the protosolar nebula (Dolginov and Stepinski 1994; Cleeves et al. 2013), ion-molecule chemistry would have been shut down and the water D/H ratios in comets and Earth’s oceans could not have been produced (Cleeves et al. 2014). For CH_4 deuterium fractionation, calculations which include cosmic-ray ionization rates below that commonly assumed for disks (e.g., Nomura et al. 2023), but where X-rays can also provide a source of ionization, only produce D/H for methane of $\approx 0.2\text{--}0.6\%$ (Cleeves et al. 2016). Hence, comparison with the D/H ratio in 3I/ATLAS of $(3.31 \pm 0.34)\%$ for methane suggests that, like water, its ices were inherited and not formed in its natal disk.

Observations of $\text{CH}_3\text{D}/\text{CH}_4$ isotopic ratios do not exist for star-forming environments due to the difficulty in detecting gaseous CH_3D . One exception is the tentative detection of CH_3D emission toward the protostar IRAS 04368+2557 in the L1527 molecular cloud (Sakai et al. 2012). This object belongs to a population of protostellar cores that exhibits a so-called warm carbon-chain chemistry (WCCC; Sakai and Yamamoto 2013) comprising of carbon-chain molecules and simple hydrocarbons usually found in cold molecular clouds. In such ‘lukewarm corinos’, elevated dust temperatures in the protostellar envelope, $T \sim 30$ K, allow methane (and CO) to evaporate from icy grain mantles and subsequently drive the observed gas-phase hydrocarbon chemistry, e.g. forming cyanoacetylene in the sequence



Although CH_4 has recently been detected in the L1527 ice mantles (Devaraj et al. 2026), CH_3D has not. This, and the difficulty in detecting gaseous CH_4 in cool material, as opposed to hot cores (Sakai et al. 2012), means that it is not possible to derive the $\text{CH}_3\text{D}/\text{CH}_4$ isotopic ratio in L1527, or indeed in any WCCC source. However, following Sakai et al. (2012), we can use hydrocarbon (i.e., $c\text{-C}_3\text{H}_2$) D/H ratios measured as a proxy for that in methane.

Cyclopropenylidene ($c\text{-C}_3\text{H}_2$) is small, cyclic molecule that is ubiquitous in the interstellar medium. Both it and its mono-deuterated form can be produced from CH_4 and CH_3D , e.g. through



(Millar et al. 2024). Defining $R(\text{XD})$ as the ratio of observed column densities $N(\text{XD})/N(\text{XH})$, we can estimate the D/H ratio for CH_3D as $R(c\text{-C}_3\text{HD})/4$. This estimate is based on the assumption that the evaporated $\text{CH}_3\text{D}/\text{CH}_4$ ratio is unaltered in the gas.

While deuteration by reaction (1) is suppressed at $T \gtrsim 30$ K, it can be maintained by (Millar et al. 1989)



which can then deuterate methane through



However, hot core calculations do show that the D/H ratios of ice molecules are unchanged on post-evaporation time-scales of $\sim 10^5$ years (Rodgers and Millar 1996).

As each of the two dissociative electron recombination steps in sequence (3) has an associated product channel which removes a D atom from the sequence, one has $R(c\text{-C}_3\text{HD}) < R(\text{CH}_3\text{D})$ with the reduction factor determined by the details of the product branching ratios. Hence, the estimates of the D/H ratio for methane made here should be considered as lower limits. From the $R(c\text{-C}_3\text{HD})$ values observed towards protostars we estimate D/H ratios for methane of 1.7% in L1527 (Sakai et al. 2009), 5.5% in Cha-MMS1 (Lis et al. 2025), and $\approx 0.25\text{-}4.5\%$ in a sample of 6 cores in Perseus (Ferrer Asensio et al. 2026).

Methane molecules formed on grain surfaces can also be continuously released into the gas by *reactive desorption* whereby the energy released in exothermic reactions (such as hydrogen atom addition) can overcome the surface binding energy of the product molecule (Brown and Charnley 1991; Cuppen et al. 2024). Thus, one can make an estimate of methane D/H ratios in cold (~ 10 K) starless/pre-stellar cores. Surveys of $c\text{-C}_3\text{HD}$ towards 27 such sources (Chantzos et al. 2018; Ferrer Asensio et al. 2026) yield D/H $\approx 0.25\text{-}5.6\%$. Only 3 sources match or exceed the ratio in 3I/ATLAS of D/H = $(3.31 \pm 0.34)\%$: two of the 8 protostellar cores, Cha-MMS1 and Core 326 in NGC1333, and one of the 27 cold cores, HH211. This suggests that D/H ratios for methane $\approx 4.5\text{-}5.5\%$ are possible in pre-cometary matter and in fact, based on the $R(c\text{-C}_3\text{HD})$ found in TMC-1 (Gratier et al. 2016), could be as high as 7%. As

these estimates are lower limits, even larger methane D/H ratios could be possible. Extended Data Table 3 provides values and references for D/H ratios towards sources detailed in Figure 2, including those estimated here.

To conclude, it is uncertain whether theoretical models of either star formation or disk chemistry can reproduce the methane D/H ratio in 3I/ATLAS's ices. This should ideally be confirmed by new chemical models. On the other hand, there is tentative evidence that interstellar/protostellar D/H ratios could match that of 3I/ATLAS.

Acknowledgments

This work is based on observations made with the NASA/ESA/CSA James Webb Space Telescope. The data were obtained from the Mikulski Archive for Space Telescopes at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-03127 for JWST. Analysis was supported via STScI grant JWST-GO-05094.001. We gratefully acknowledge the assistance of optical observers who submitted astrometric observations of 3I/ATLAS in the weeks leading up to our observations, to help refine the ephemeris position. In particular, we thank J. Chatelain, E. Gomez, S. Greenstreet, W. Hoogendam, C. Holt, H. W. Lin, T. Lister, T. Santana-Ros, L. Salazar Manzano, D. Seligman, Q. Ye and Q. Zhang. Supporting astrometric observations were obtained by the Comet Chasers school outreach program (<https://www.cometchasers.org/>), led by Helen Usher, which is funded by the UK Science and Technology Facilities Council (via the DeepSpace2DeepImpact Project), the Open University and Cardiff University. It accesses the LCOGT telescopes through the Schools Observatory/Faulkes Telescope Project (TSO2025A-00 DFET-The Schools' Observatory), which is partly funded by the Dill Faulkes Educational Trust, and through the LCO Global Sky Partners Programme (LCOEPO2023B-013). Observers included individuals and representatives from the following schools and clubs: E. Maciulis, A. Bankole, J. Bower, O. Roberts, participants on the British Astronomical Associations' Work Experience project 2025 from The Coopers Company & Coborn School; Upminster, UK; St Marys Catholic Primary School, Bridgend, UK; J. M. Perez Redondo & Students: A. Matea, L. Guilamet, A. Montoy, and A. Martin from Institut d'Alcarràs, Catalonia, Spain; Louis Cruis Astronomy Club, Brazil; Jelkovec High School, Zagreb, Croatia, and C. Wells at a British Astronomical Association event. This research has made use of NASA's Astrophysics Data System Bibliographic Services. This research has made use of data and/or services provided by the International Astronomical Union's Minor Planet Center. N.X.R., M.A.C., S.B.C. and S.N.M. were supported by the NASA Planetary Science Division Internal Scientist Funding Program through the Fundamental Laboratory Research work package (FLaRe). M.E.S. acknowledge support in part from UK Science and Technology Facilities Council (STFC) grant ST/X001253/1. D.F. conducted this research at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

- Data availability: All JWST data are available through the Mikulski Archive for Space Telescopes at the Space Telescope Science Institute under proposal ID #5094

Extended Data Table 1 Detected species and vibrational band identifications

Molecule	Vibration Band ID	λ (μm)
CO	ν_1	4.6
H ₂ O	$\nu_1 + \nu_3$	2.7
	$\nu_1 - \nu_2, \nu_3 - \nu_2$	4.5
CH ₃ OH	ν_3	3.5
	ν_2, ν_9	3.3 - 3.4
H ₂ CO	ν_1, ν_5	3.5
	$\nu_1 + \nu_6$	3.3
C ₂ H ₆	ν_5	3.35
CH ₄	ν_3	3.25
CH ₃ D	ν_4	3.25

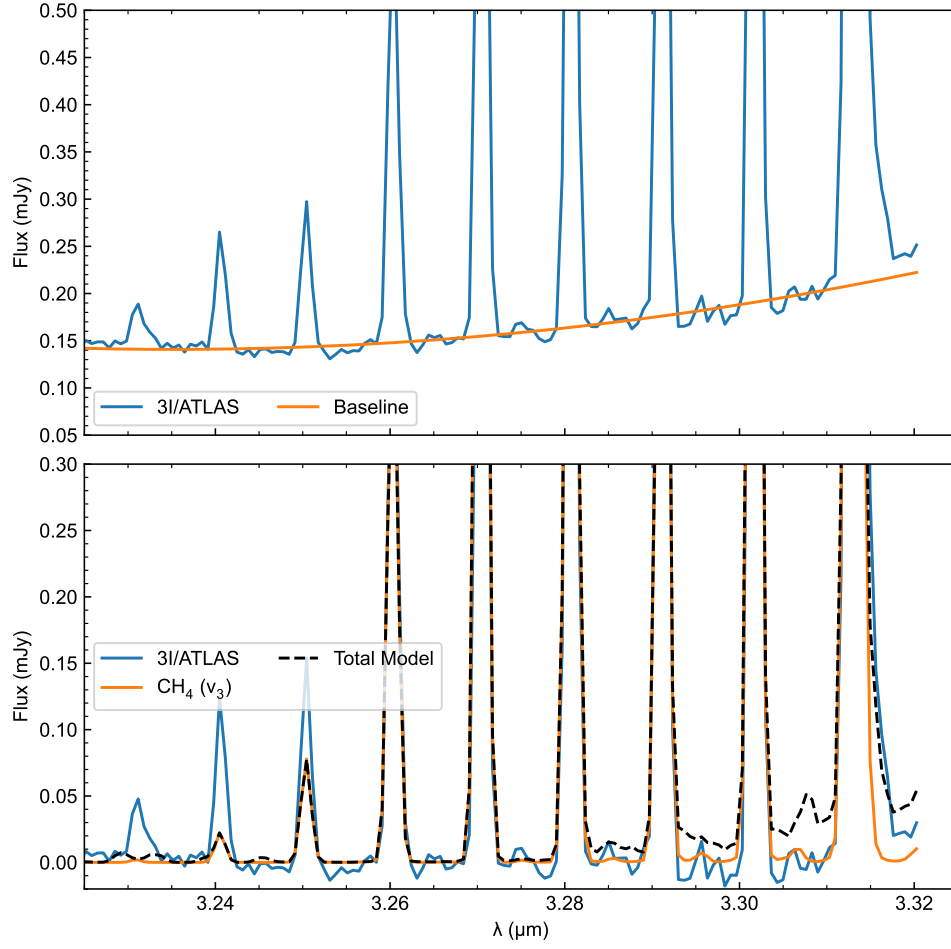
Extended Data Table 2 Methane molecular production rates in 3I/ATLAS vs. spectral baseline

Polynomial Order	$Q(\text{CH}_4)$ (10^{26} s^{-1})	$Q(\text{CH}_3\text{D})$ (10^{26} s^{-1})	T_{rot} (K)	D/H Ratio (%)
2	1.90 ± 0.02	0.25 ± 0.02	41.2 ± 0.5	3.31 ± 0.34
3	1.90 ± 0.02	0.25 ± 0.02	41.2 ± 0.5	3.38 ± 0.27
4	1.90 ± 0.02	0.26 ± 0.02	41.6 ± 0.5	3.45 ± 0.27

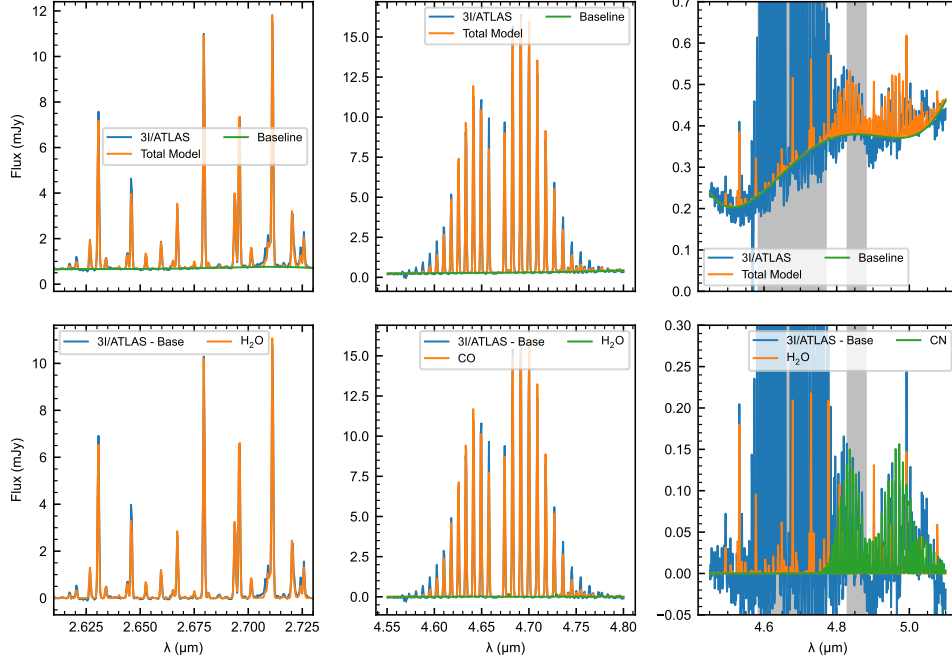
(<https://doi.org/10.17909/1jvn-1z72>). The data products are under a three month embargo.

- Code availability: The Planetary Spectrum Generator (Villanueva et al. 2025, 2018), used for modeling cometary infrared emission lines, is available at <https://psg.gsfc.nasa.gov/>. The jwstComet software (Roth 2026b), used for extracting spectra from JWST data cubes and interacting with the NASA PSG API, is available from <https://github.com/apertureSynthesis/jwstComet>. jwstComet makes use of the astropy (Astropy Collaboration et al. 2013, 2018, 2022), photutils (Bradley et al. 2025), and astroquery (Ginsburg et al. 2019) libraries.
- Author contributions: N. Roth performed the spectral extraction and modeling and led the manuscript writing. M. Cordiner calibrated the JWST data. M. Cordiner and G. Villanueva contributed to the data analysis methodology and independently checked the molecular retrievals. M. Micheli performed astrometric measurements. D. Farnocchia calculated the 3I/ATLAS orbit and ephemeris. S. Charnley developed the formalism for estimating CH₃D/CH₄ from $c\text{-C}_3\text{HD}/c\text{-C}_3\text{H}_2$ and helped interpret the isotopic ratios. All authors helped with the project design, data acquisition, interpretation of results, and editing of the manuscript.
- Competing Interests: The authors declare no competing interests.

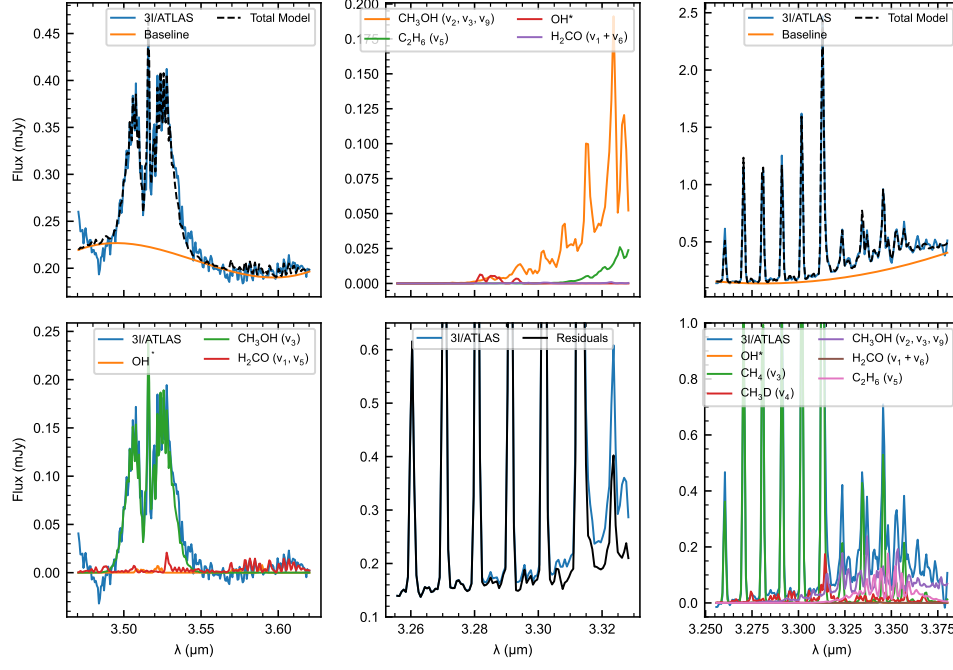
4 Extended Data



Extended Data Figure 1 Upper Panel. Observed 3I/ATLAS spectrum and second-order polynomial baseline, fit independently and before the fitting of PSG molecular emission models. **Lower Panel.** Best-fit PSG CH_4 model fit to the baseline-subtracted spectra, demonstrating that a baseline fitted separately from the emission models does not provide improvement to the fits of the higher- J CH_4 lines (and simultaneously degrades the fit near the lower- J lines), yet consistent $Q(\text{CH}_4)$ and $T_{\text{rot}}(\text{CH}_4)$ are retrieved when considering only the lower- J lines.



Extended Data Figure 2 Left Panels. Upper. 3I/ATLAS 2.7 μm H₂O spectrum on 2025 December 22 with best-fit model and spectral baseline overplotted. Lower. Baseline-subtracted 3I/ATLAS spectrum with best-fit individual molecular emission model(s) shown. **Middle Panels.** As in the left panels, but for CO on 2025 December 23. **Right Panels.** As in the left panels, but for H₂O and CN on 2025 December 23. The gray shaded regions show the strong CO and OCS emission masked when retrieving $Q(\text{H}_2\text{O})$.



Extended Data Figure 3 Left Panels. Upper. 3I/ATLAS CH_3OH and H_2CO spectrum on 2025 December 23 with best-fit model and spectral baseline overplotted. This was used to forward model both species when isolating C_2H_6 , CH_4 , and CH_3D . Lower. Baseline-subtracted 3I/ATLAS spectrum with best-fit individual molecular emission model(s) shown. **Middle Panels.** Upper. Forward modeled CH_3OH , C_2H_6 , H_2CO , and OH^* spectra used to generate a $\text{CH}_4 + \text{CH}_3\text{D}$ residual spectrum of 3I/ATLAS. Lower. Comparison of observed 3I/ATLAS spectrum with the $\text{CH}_4 + \text{CH}_3\text{D}$ residual spectrum generated after subtracting the forward models in the upper panel. **Right Panels.** Observed 3I/ATLAS $3.3 \mu\text{m}$ spectrum with total emission model and baseline overplotted. Bottom. Baseline-subtracted 3I/ATLAS spectrum with individual molecular emission models for all detected species shown.

Extended Data Table 3 D/H ratios in solar system and extrasolar sources

Object	Molecule	D/H Ratio	Reference
ISM	H ₂	$(2.0 \pm 0.1) \times 10^{-5}$	Prodanović et al. (2010)
Protosolar	H ₂	$(2.1 \pm 0.5) \times 10^{-5}$	Geiss and Gloeckler (1998)
Jupiter	CH ₄	$(2.2 \pm 0.7) \times 10^{-5}$	Lellouch et al. (2001)
Saturn	CH ₄	$(1.65 \pm 0.27) \times 10^{-5}$	Blake et al. (2021)
Earth	H ₂ O	1.56×10^{-4}	Marty (2012)
Titan	CH ₄	$(1.59 \pm 0.33) \times 10^{-4}$	Nixon et al. (2012)
Uranus	CH ₄	$(2.9 \pm 0.9) \times 10^{-4}$	Irwin et al. (2012)
Neptune	CH ₄	$(3 \pm 1) \times 10^{-4}$	Irwin et al. (2014)
Makemake (ice)	CH ₄	$(2.9 \pm 0.6) \times 10^{-4}$	Grundy et al. (2024)
Eris (ice)	CH ₄	$(2.5 \pm 0.5) \times 10^{-4}$	Grundy et al. (2024)
Venus	CH ₄	1.25×10^{-3}	Donahue and Hodges (1993)
67P/Churyumov-Gerasimenko	CH ₄	$(2.41 \pm 0.29) \times 10^{-4}$	Müller et al. (2022)
C/2007 W1	CH ₄	$< 5 \times 10^{-3} (3\sigma)$	Bonev et al. (2009)
C/2001 Q4	CH ₄	$< 1 \times 10^{-2} (3\sigma)$	Kawakita et al. (2005)
C/2007 N3	CH ₄	$< 7.5 \times 10^{-3} (3\sigma)$	Gibb et al. (2012)
3I/ATLAS	CH ₄	$(3.31 \pm 0.34) \times 10^{-2}$	This Work
IDP/UCAMM	Organics*	$9 \times 10^{-5} - 8 \times 10^{-3}$	Messenger (2000)
Orgueil	Organic Radicals	$(1.5 \pm 0.5) \times 10^{-2}$	Duprat et al. (2010)
Disks	HCN*	$4 \times 10^{-3} - 9 \times 10^{-2}$	Gourier et al. (2008)
			Öberg et al. (2012)
			Huang et al. (2017)
IRAS 16293-2422B	H ₂ CO	$(3.25 \pm 1.00) \times 10^{-2}$	Persson et al. (2018)
	CH ₂ DOH	$(2.37 \pm 0.70) \times 10^{-2}$	Jørgensen et al. (2018)
	CH ₃ OD	$(3.2 \pm 0.9) \times 10^{-3}$	Ilyushin et al. (2024)
IRAS 2A	CH ₂ DOH	$1.93^{+0.43}_{-0.50} \times 10^{-2}$	Taquet et al. (2019)
	CH ₃ OD	$7.10^{+1.20}_{-1.60} \times 10^{-2}$	Taquet et al. (2019)
IRAS 4A-NW	CH ₂ DOH	$1.23^{+0.40}_{-0.30} \times 10^{-2}$	Taquet et al. (2019)
	CH ₃ OD	$3.10^{+1.00}_{-0.80} \times 10^{-2}$	Taquet et al. (2019)
HH212	CH ₂ DOH	$(9.67 \pm 2.67) \times 10^{-3}$	Taquet et al. (2019)
	CH ₃ OD	$(2.00 \pm 0.60) \times 10^{-2}$	Taquet et al. (2019)
V883 Ori	CH ₂ DOH	$(7.30 \pm 1.50) \times 10^{-3}$	Zeng et al. (2025)
	CH ₃ OD	$(1.79 \pm 0.36) \times 10^{-2}$	Zeng et al. (2025)
HOPS 373-SW	CH ₂ DOH	$(4.4 \pm 1.1) \times 10^{-2}$	Lee et al. (2023)
L1527	CH ₄ *	0.42×10^{-2}	Sakai et al. (2009)
Cha-MMS1	CH ₄ *	1.40×10^{-2}	Lis et al. (2025)
Perseus	CH ₄ *	$(0.06 - 1.12) \times 10^{-2}$	Ferrer Asensio et al. (2026)
Cold Starless Cores	CH ₄ *	$(0.06 - 1.40) \times 10^{-2}$	Chantzios et al. (2018)
			Ferrer Asensio et al. (2026)
TMC-1	CH ₄ *	1.75×10^{-2}	Gratier et al. (2016)

Note — All D/H ratios are statistically corrected. The figures for organics in IDPs and UCAMMs, as well as for HCN in disks, are the ranges of values provided in the literature among multiple objects. Sources for which the D/H in $c\text{-C}_3\text{H}_2$ was used to estimate the D/H in CH₄ are noted with an * and the associated literature citations point to the publications reporting the D/H in $c\text{-C}_3\text{H}_2$.

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