National Aeronautics and Space Administration

FY23 Strategic Initiatives Research and Technology Development (SRTD)

Tracing Water from Interstellar Clouds to Ocean Worlds

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Strategic Focus Area: Tracing Water from Interstellar Clouds to Ocean Worlds | **Strategic Initiative Leader:** Paul F Goldsmith

Objectives: The objective of this initiative was to bridge the gap between interstellar and planetary chemistry and to promote JPL involvement in observations, instruments, and missions that address exciting scientific questions at this interface. The overarching scientific goal was to study the origin of the Earth's water in the context of inheritance from the protoplanetary disk, from which the Solar System formed, and to understand whether water in that disk was produced in situ or inherited from earlier phases. If the process operates universally, habitable planets like the Earth may be common in the Universe.

Background: Isotopic composition of cometary water provide important constraints on the origin of Earth's oceans. The deuterium-to-hydrogen ratio (D/H) of the inner Solar System (Asteroid belt) is well determined from measurements in meteorites. Comets are best tracers of the present day outer Solar System, because they have atmospheres that can be studied using remote sensing techniques. However, only 4 accurate space measurements of the D/H ratio in comets have been obtained over the past 35 years. Future JPL-led missions, such as the Astrophysics Probe PRIMA, will enable a statistical study comparing the isotopic composition the Oort cloud and Kuiper belt with that of the Asteroid belt is needed to test Solar System formation models combining chemistry and dynamics caused by giant planet migration.

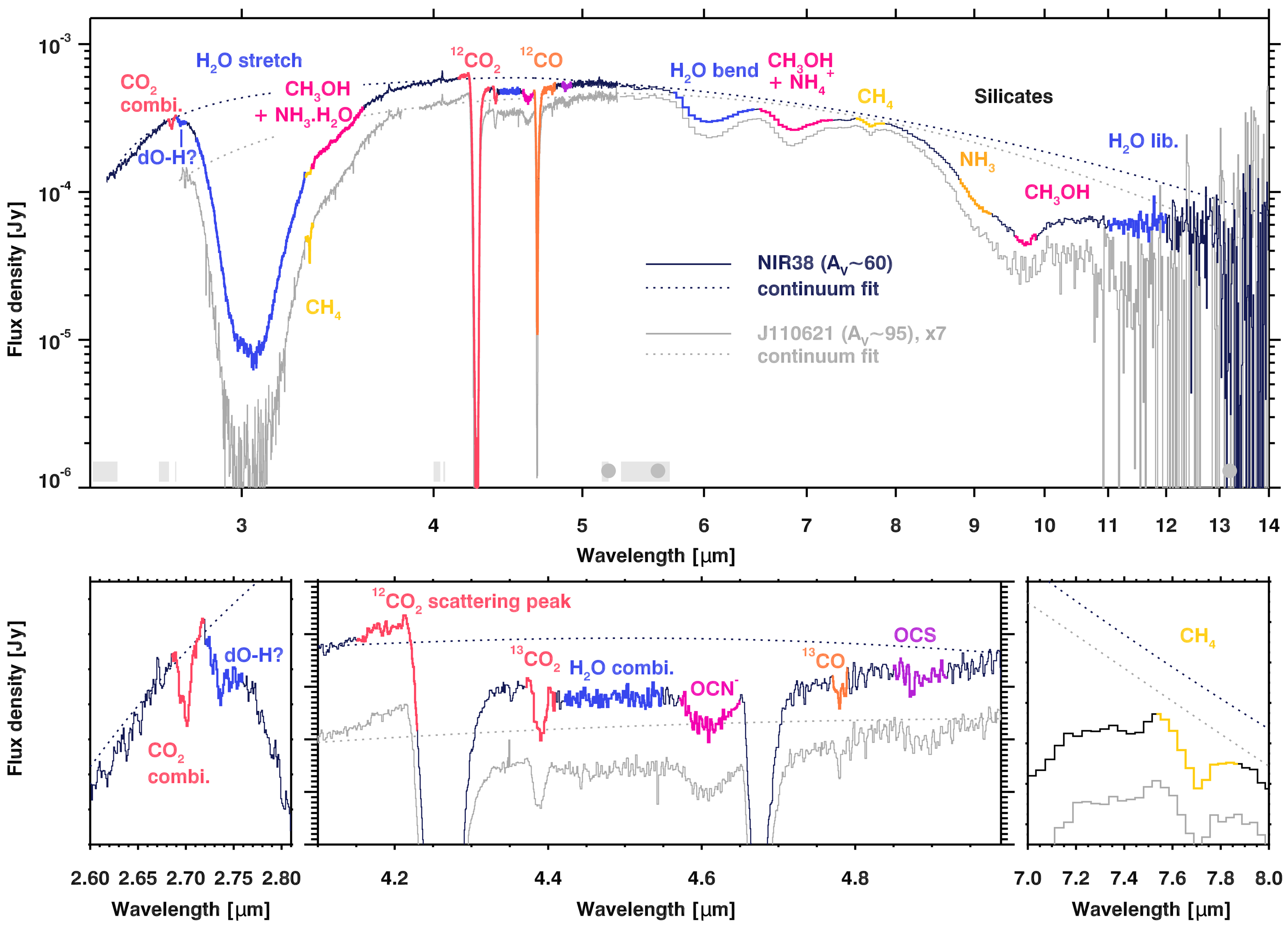

Figure 1. JWST NIRSpec and MIRI spectrum of ices toward 2 background stars in Chamaeleon (from publication [G]).

Significance/Benefits to JPL and NASA:
The *Herschel* Space Observatory, an ESA mission with a strong JPL involvement, gave an early indication of the importance of the observations of water and its isotopic variants in astrophysical and Solar System environments. JWST spectra now provide information about the water content and composition of interstellar ices. This Strategic Initiative puts JPL in a forefront position to lead new missions, develop new instruments, and to exploit a range of existing and upcoming facilities. It is directly related to JPL strategic quests "Understand how our Solar System formed and how it is evolving" and "Understand how life emerged on Earth and possibly elsewhere in our Solar System".

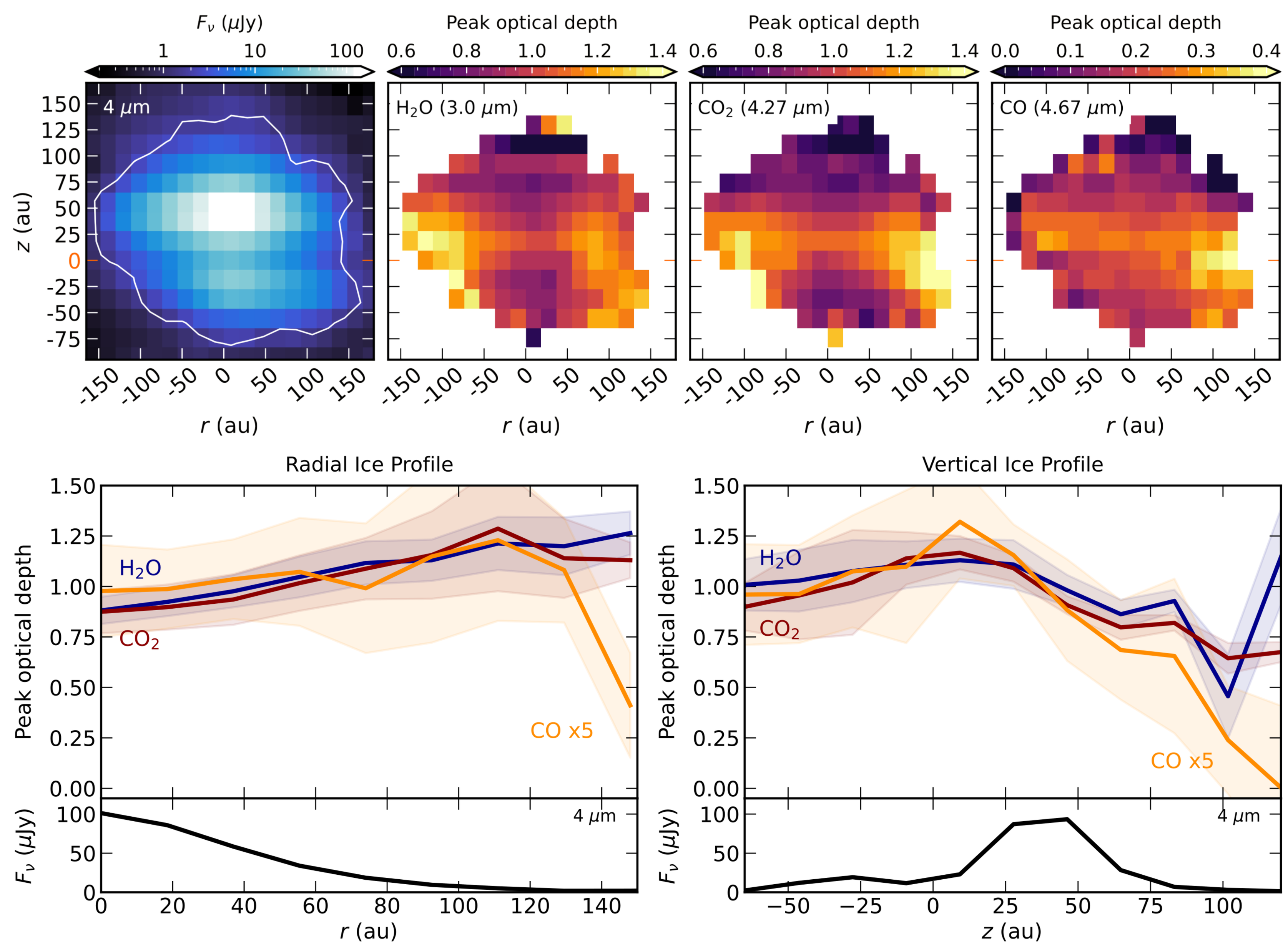

Figure 3. Spatial variations in the optical depth of the water, CO, and CO_2 ice features in the edge-on Class II disk HH 48 NE (publication [B]).

Approach and Results: PRIMA would provide D/H measurements in ~30 comets in a 5-year, 240 h per year GO program. Cometary lines are heavily spectrally diluted at the expected spectral resolution of the PRIMA direct detection spectrometer, R=4400(λ/112 μm). Through modeling, combined with past *Herschel*/PACS observations, we have demonstrated that neither the line-to- continuum ratio nor the line confusion are expected to be confounding factors for D/H measurements in comets with PRIMA.

In the interstellar medium, the majority of water present is in the form of ice mantles on dust grains. JWST now gives unparalleled access to IR bands of water ices. First NIRSpec and MIRI observations from the "Ice Age" ERS program show an incredible level of detail (Figure 1). These observations suggests that the formation of simple and complex molecules could begin early in water-rich environments. Furthermore, CHONS elements appear to be locked up in rocky or sooty materials. Solid state HDO is not detected.

An ice inventory of an edge-on Class II protoplanetary disk, HH48NE, was also studied (Figure 2). The low $^{12}CO_2/^{13}CO_2$ ratio of 14, compared with the local ISM value of 77, implies that the 12CO2 ice band is saturated, without the flux approaching zero. Spatial variations in the depth of strong ice features are smaller than a factor of 2, with no evidence for the presence of snow lines. This is explained by complex radiative transfer effects in the disk, where some photons from the background star can reach the observer directly, while others are multiply scattered, sampling the midplane ice.

Most cometary gases observed at radio wavelengths have yet to be imaged and their production/release mechanisms remain uncertain. ALMA mapped the coma of comet 46P/Wirtanen at an unprecedented spatial resolution of 25 km during its unusually close (0.1 au) apparition in 2018 December (publication [E]). Average kinetic temperature on the sunward side is shown to be significantly lower than on the anti-sunward side, explained by efficient adiabatic cooling on the sunward side. Spatial distribution of many species, including HCN, CH3OH, and CH3CN, is consistent with direct outgassing form, or very close to, the nucleus. However, molecules such as H2CO, CS, or HNC originate primarily in the distributed coma.

FY'23 Publications: [A] N. Biver, et al., *HDO in Comet 46P/Wirtanen with ALMA: Distribution Profile and D/H Ratio in Water*. A&A, in preparation (2023). [B] J.A. Sturm, et al.,A *Complete JWST Inventory of Protoplanetary Disk Ices: The Edge-On Disk HH 48 NE Seen with the Ice Age ERS Program*. A&A, submitted (2023). [C] L. Eining, et al., *Deep Learning Denoising by Dimension Reduction: Application to the ORION-B Line Cubes*. A&A, in press (2023; arXiv:2307.13009). [D] N.X. Roth, et al., *Molecular Outgassing in Centaur 29P/Schwassmann-Wachmann 1 During Its Exceptional 2021 Outburst: Coordinated Multi-Wavelength Observations using nFLASH at APEX and iSHELL at the NASA-IRTF*. Pl. Sc. J., in press (2023; arXiv:2304.14324). [E] M.A. Cordiner, et al., *Gas Sources in the Coma and Nucleus of Comet 46P/Wirtanen Using ALMA*. Ap. J., 953, 59 (2023). [F] H. Takemura, et al., *CARMA-NRO Orion Survey: Unbiased Survey of Dense Cores and Core Mass Function in Orion A*. Ap. J. Suppl., 264, 35 (2023). [G] M.K. McClure, et al., *An Ice Age JWST Inventory of Dense Molecular Cloud Ices*. Nature Astronomy (2023).

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