ATMOSPHERIC PARTICULATE CONTAMINATION AT URANUS

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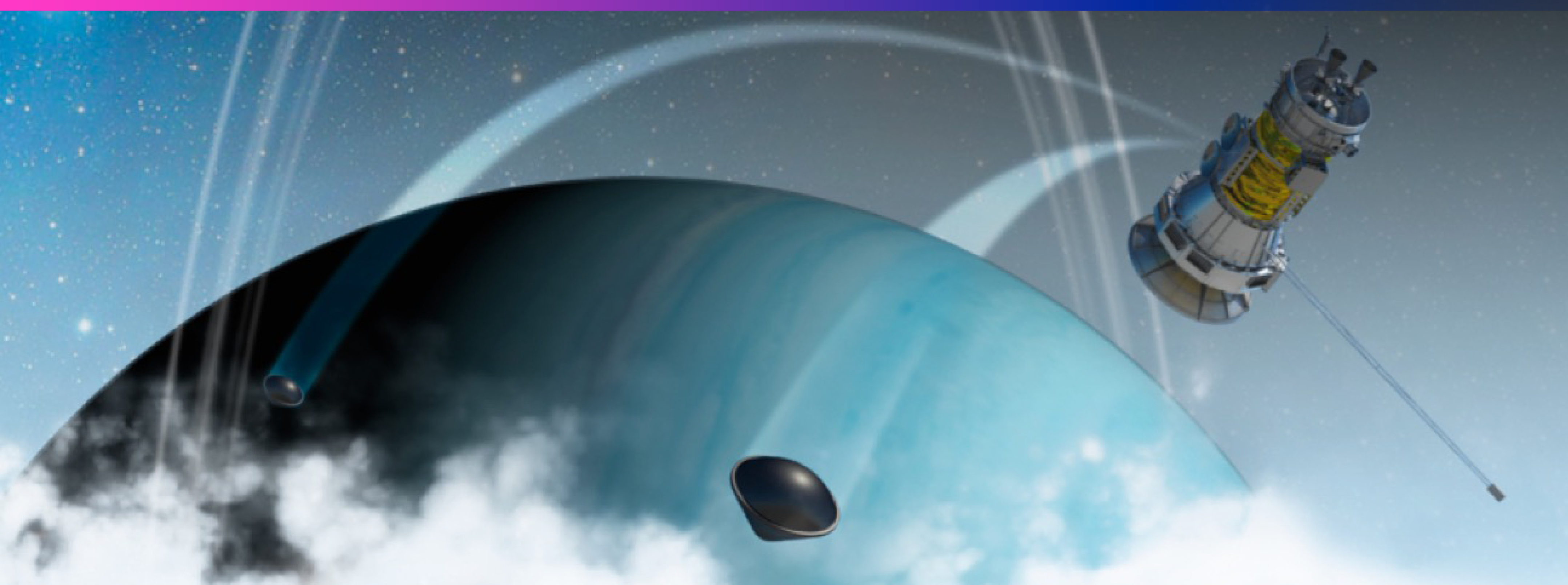

MOTIVATION

Entry probes need to know what to expect, in terms of atmospheric particles. These aerosols, in addition to their intrinsic scientific interest, could potentially block inlets needed for sampling by science instruments.

NASA and ESA are considering options for in situ science with atmospheric entry probes to the ice giants Uranus and Neptune. Nominal probe entry mass is in the 300-kg range, although a miniaturized secondary probe option is being studied in the 30-kg range (Sayanagi et al. 2017; see descent profile Fig. 1 at right). In all cases, compositional sampling would commence near the 100-mbar level at Uranus, after ejection of the heat shield and deployment of the descent parachute.

This presentation is a review of existing literature on the composition, mass loading, and vertical distribution of condensed material that the probe may encounter. Probe sample inlets should be heated to avoid potential buildup of particulate matter, which would block the flow of atmospheric gas into sensors of composition, pressure, ortho/para hydrogen ratio, etc.

TYPES OF AEROSOL ON URANUS

Three main types of aerosol are expected, based on observational and theoretical work to date (e.g., West et al. 1991; Pollack et al. 1987; Rages et al. 1991; Weidenschilling and Lewis 1973; de Pater et al. 1991). But our current understanding is quite incomplete. Definitive identification of particulate compositions (for all three classes) has not been achieved. We don't know the sizes of particles, or the variability in their properties with location, altitude, or time. The first atmospheric probe to Uranus (or Neptune) will greatly advance our knowledge of particulate distributions in the cold, carbon-rich atmospheres of the ice giants.

Hydrocarbon ices: In the stratosphere, solar UV photolyzes CH_4, leading to the production of volatile hydrocarbons with higher C/H ratios. These species diffuse from their production regions into colder levels where the ices of C_2H_2, C_2H_6, and C_4H_2 condense. Some studies have also considered condensation of C_3H_8, C_4H_{10}, C_6H_6, and C_6H_2.

Gunk: The hydrocarbon ices are thought to become polymerized due to irradiation from solar UV. The exact composition of the resulting gunk is not known. Solid-state photochemical processing may produce the traces of reddish (blue-absorbing) haze material, present in the troposphere at temperatures warm enough to sublimate the simple hydrocarbon ices.

Volatile ices: In the region accessible to probes under study (P ~ 0.5–10 bar), much thicker condensation clouds may form from volatile gases CH_4, NH_3, and H_2S. If large amounts of NH_3 are sequestered in the deeper H_2O liquid cloud, then the S/N ratio could exceed 1 in the probe-accessible region of the atmosphere, leading to NH_4SH and H_2S ices below the CH_4-ice cloud deck. Otherwise, NH_4SH and NH_3 ices would be found.

HYDROCARBON ICES

State of knowledge: There is considerable literature discussing hydrocarbon ices in ice giant atmospheres. This is partly because hydrocarbon reaction rates are well studied (although not always at the appropriate cold temperatures), due to industrial interest in combustion chemistry. As a result, photochemical modeling of methane-rich atmospheres (of giant planets and Titan) is at a high state of maturity, compared to observations.

Still, various models predict differing compositions and amounts of ices formed by photochemical processing of atmospheric methane. Table 1 lists hydrocarbon ices discussed in previous studies.

Distributions: Vertically, ice distributions are controlled by several factors: saturation vapor pressure functions, the temperature profile, eddy diffusion rates, photochemical gas pathways, production rates, and loss rates, and microphysical timescales. Studies of these factors independently, or in a comprehensive model, will be valuable pathways toward advancing our understanding of what ices might be present along an atmospheric probe's descent path.

With the strong seasonal variation of insolation at Uranus, and the controlling influence of solar UV on photochemical systems, it is likely that hydrocarbon ice distributions are spatially/temporally variable. The abundance of methane (the ultimate source of all the hydrocarbons) may also be spatially variable, although previous studies are not in complete agreement on the actual distributions (Yelle et al. 1989; Baines et al. 1998; Lellouch et al. 2015; de Kleer et al. 2015).

Probe inlet considerations: Typical probe entry profiles call for heat shield release at pressures of 100 mbar or more. This means that atmospheric sampling inlets will largely be free of contamination from the hydrocarbon ices, whose peak densities are at much lower pressures (Table 1). Still, these ices will precipitate into the troposphere, until they sublimate in the 600-mbar to 3-bar range (Rages et al. 1991). Ensuring inlets maintain a temperature above 100 K should thus be sufficient to keep them clear of hydrocarbon ice obstruction.

Table 1. Condensation regions for likely hydrocarbon ices in the stratosphere of Uranus.

Species	Condensation Range (mbar)	References
C_2H_2	2.5–14	Romani (1986); Courtin (2005); Moses et al. (2005); Pollack et al. (1987); Rages et al. (1991)
C_2H_6	10–100	Romani (1986); Courtin (2005); Moses et al. (2005); Pollack et al. (1987); Rages et al. (1991)
C_4H_2	0.1–2.5	Courtin (2005); Orton et al. (2014b); Moses et al. (2005); Pollack et al. (1987); Rages et al. (1991)
C_3H_8		Moses et al. (2005)
C_4H_{10}		Moses et al. (2005)
C_6H_6		Moses et al. (2005)
C_6H_2	0.05–0.5	Rages et al. (1991)

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"GUNK"

State of knowledge: Pollack et al. (1987) described a stratospheric aerosol cycle (Fig. 2), where ices of low order hydrocarbons (Table 1) may be polymerized by solar UV exposure, sediment downward, and eventually return to gas phase in the warmer troposphere. The observational evidence for this population of stable, reddish stratospheric particulates (Rages et al. 1991) is absorption seen at optical wavelengths in high-phase angle Voyager images (Pollack et al. 1987) and at UV wavelengths by the IUE satellite (Wagener et al. 1986; Cochran et al. 1990). The composition of these particles is not known in detail, and the overall opacity is very low. The total stratospheric haze optical depth is around 0.01 (West et al. 1991), with roughly evenly-divided mass of hydrocarbon ices and optical/UV-absorbing gunk (Rages et al. 1991).

The gunk discovery space: The very low optical depth of these UV-processed high-order hydrocarbon aerosols makes them very difficult to constrain from remote sensing. Yet scientific interest in them is large, due to the astrobiological connection to complex hydrocarbon formation in various solar system settings. Laboratory studies may represent the best option for advancing our knowledge of this haze population. Ice radiolysis studies are being done to investigate organic production on outer solar system surfaces, and to identify potential compositions of chromophore species in giant planet atmospheres, such as in conditions relevant to Jupiter's troposphere. Even colder experimental conditions are needed to better simulate the conditions of the ice giant stratospheres.

Probe inlet considerations: The evaporation of diacetylene (C_4H_2) and polymers would occur very deep in the Uranus atmosphere, at pressures of 3 bar or deeper. This means that even though the probe is protected by its heat shield as it traverses the source region of these materials in the stratosphere, they will precipitate and diffuse into the troposphere, representing a potential contamination source. Without more precise knowledge of the composition of these materials, we might speculate that inlets should be heated to at least the 5-bar temperature (130 K) in order to evaporate C_4H_2 and simple polymers.

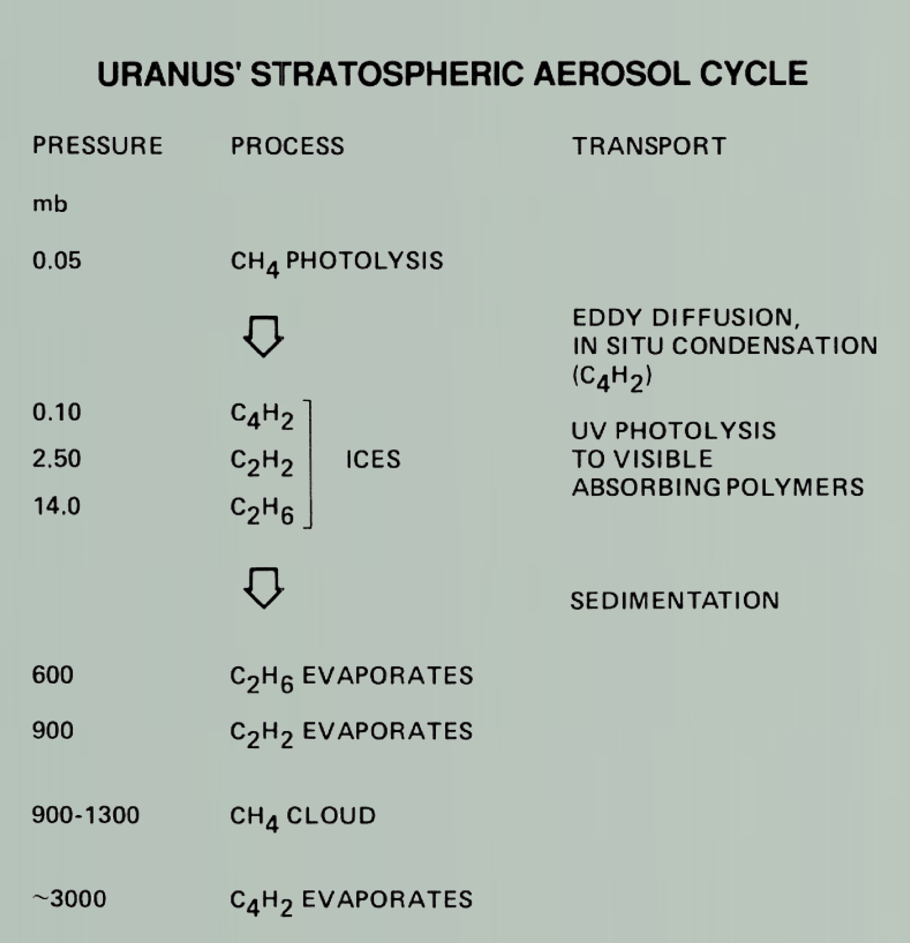

Figure 2: Schematic of the stratospheric aerosol cycle on Uranus. From Pollack et al. (1987). More recent work by Rages et al. (1991) and Moses et al. (2005) suggests that additional ices should be considered (see Table 1). Aromatic hydrocarbons, not considered here, could be an additional product of solid-state photolysis.

VOLATILE ICES

State of knowledge: In the troposphere, the upper cloud layer is composed of CH_4 ice, with discrete clouds of variable opacity and an extended haze of small CH_4 ice particles above it (e.g., Irwin et al. 2017). A 3-bar cloud layer lies beneath the CH_4 ice cloud (West et al. 1991). A solar sulfur/nitrogen (S/N) ratio would result in NH_3 ice clouds below the CH_4 ice cloud deck (Romani et al. 1989), corresponding to the H_2S-poor case in Fig. 3. But the microwave spectrum suggests much lower amounts of NH_3 gas opacity, which could mean that the S/N ratio is higher than 1 at the tens of bars pressure level, resulting in an NH_3-poor case with H_2S clouds underlying the CH_4 ice clouds (Spilker 1994, de Pater et al. 1991). Water plays a major role in determining the S/N ratio, as both NH_3 and H_2S dissolve into liquid water cloud droplets (Weidenschilling and Lewis 1973) at deeper levels that are inaccessible to direct probe measurement with current technology.

Volatile ice discovery space: There is need for advances in laboratory studies of the H_2O-NH_3-H_2S chemical system at outer planet conditions, atmospheric models of cloud chemistry including the role of dynamics and circulation, and resolved observations at wavelengths sensitive to CH_4, NH_3, and H_2S gas concentrations (e.g., Karkoschka and Tomasko 2009; de Pater et al. 2017).

Probe inlet considerations: Very high cloud densities require strong turbulence or strong updrafts (Ackerman and Marley 2001; Wong et al. 2015), both unlikely for Uranus. This argues against the need for extremely high inlet temperatures to burn off thick accumulations of cloud material. Inlet temperatures of 150 K or greater are probably sufficient to keep inlets clear, although a detailed study should be performed to compare accumulation and sublimation rates for a limiting case consistent with high-opacity CH_4 cloud regions (Irwin et al. 2017).

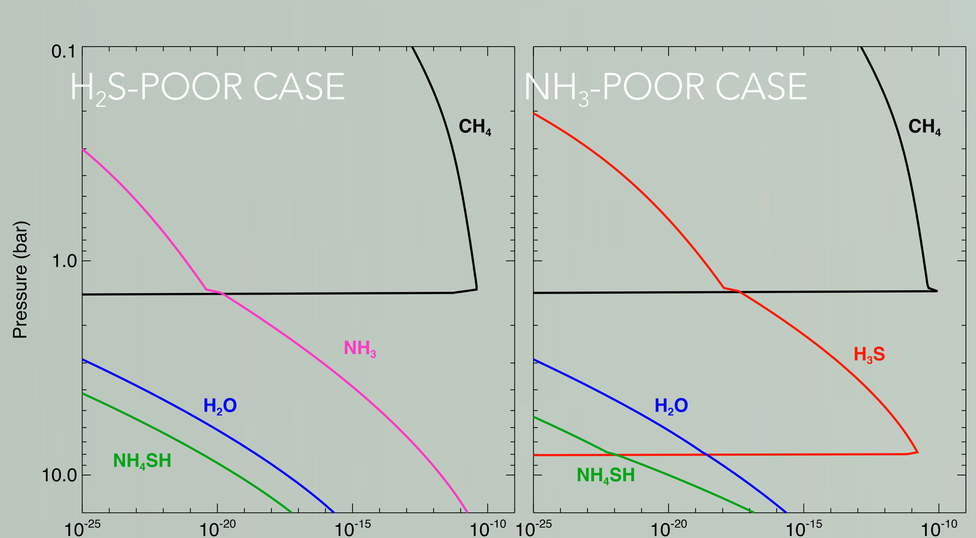

Figure 3: Two end-member cloud structures for Uranus: an H_2S-poor case (left) that would follow from a solar S/N ratio below the NH_4SH cloud and above the liquid H_2O cloud; and an NH_3-poor case (right) that is more consistent with microwave observations. Cloud density rates are calculated with the Wong et al. (2015) "fresh clouds" model; to obtain cloud densities, multiply the cloud density rate by the updraft speed.

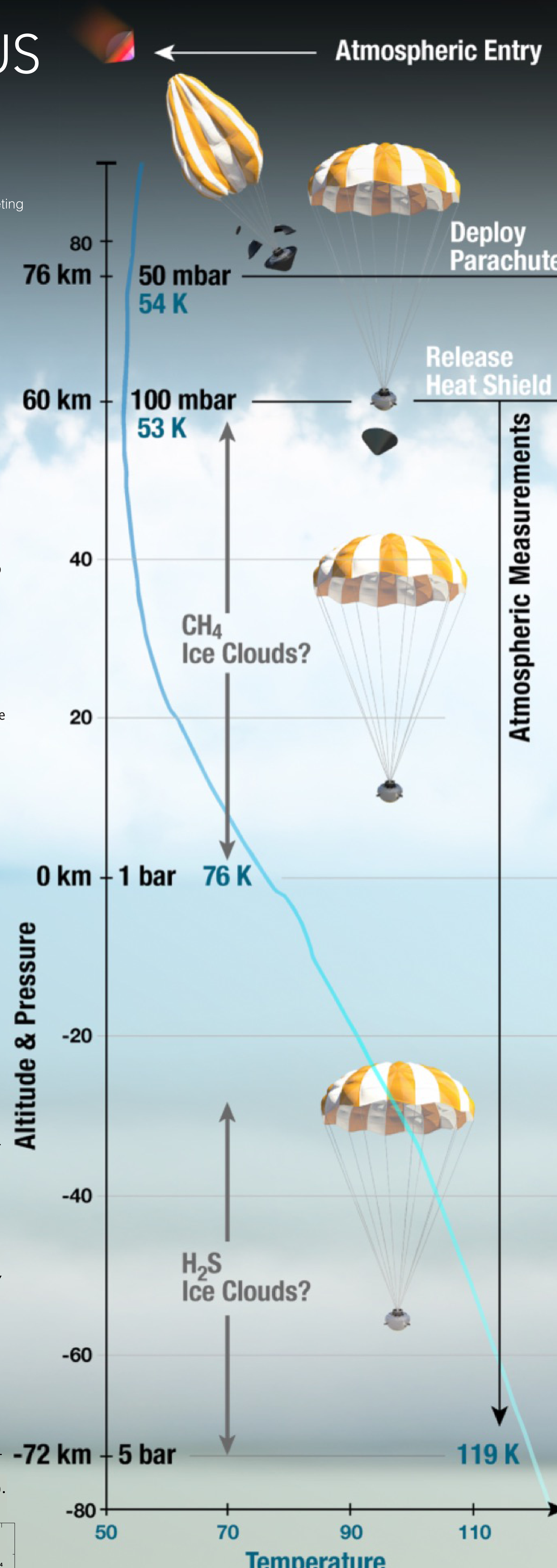

Figure 1: Descent profile for a Small Next-Generation Atmospheric Probe (SNAP) in the atmosphere of Uranus. Ice giant atmospheric probe mission planning requires an assessment of the potential hazard for inlet tubes from aerosol material that can clog the opening or interior gas flow channels. Active sampling would be limited to the troposphere (100 mbar and deeper), but aerosols formed higher in the stratosphere may precipitate and diffuse down into the probe region. The SNAP mission study is described in Sayanagi et al. (2017).

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