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# Planetary Atmospheric Science with ALMA

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**Abstract.**

The Atacama Large Millimeter Array will be one of the premier earth-based observatories for studying the atmospheres of nearly all solar system objects, including "almost airless" bodies such as Io and comets at moderate heliocentric distances as well as the more extensive atmospheres of both terrestrial and giant planets. Analysis of spatially resolved observations of pressure-broadened lines allows for three-dimensional mapping of temperature and species abundances, information that is often unattainable by other means. In addition, mapping the Doppler shift of line cores is a direct measure of the global atmospheric circulation. The high sensitivity and resolution provided by ALMA will allow precise atmospheric observations of the atmospheres of even small bodies such as Titan, Triton, and the Pluto-Charon system.

## 1. Introduction

Imaging spectroscopy at millimeter and submillimeter wavelengths provides a unique probe of planetary atmospheres. The observed line shape of a molecular transition is the product of the molecular abundance and atmospheric temperature profiles, and with suitable numerical algorithms, these vertical profiles can be retrieved. The versatility of ALMA will be important for planetary astronomy, since each target body has special characteristics in terms of size, sky motion, intensity, and width of spectral features. Planetary atmospheric science with ALMA can be described by the following broad primary goals:

- study the vertical temperature structure and abundances of molecular species, probing atmospheric chemistry and transport, through inversion of observed pressure-broadened lineshapes
- spatially resolve planetary disks down to $0.1''$ or less, to study the variation of temperature and species abundances with location and time

- directly study atmospheric dynamics at a variety of altitudes through measurement of Doppler shifts in line cores
- study cometary comae characteristics at many distances from their parent nuclei, probing transport and chemistry as a function of time and solar separations

ALMA will have superior sensitivity and imaging capabilities, coupled with a extremely broad spectrometer passband, allowing unprecedented exploration of the atmospheres of all the planets. ALMA will be able to spatially resolve nearly all planetary bodies (and many of their moons) save perhaps Pluto and Triton, allowing us to probe the three-dimensional structure of temperature and species abundances. In addition, the high sensitivity and rapid imaging ability of ALMA will allow direct detection of atmospheric winds through measurement of small (5–100 m/s) Doppler shifts of line cores.

We present state-of-the-art interferometer observations of Mars and Titan as examples of current array capability, providing a glimpse of the power that ALMA will bring us for studying planetary atmospheres.

## 2. Mars: Temperature and Water Abundance

The distribution of water vapor in the Martian atmosphere and surface is of particular interest to planetary researchers. Simultaneous 1.3 and 3 mm band observations in the HDO ($3_{12} - 2_{21}$) and CO (1–0) transitions in 1997 with the OVRO array. The combination of HDO and CO observations provide a measure of both the horizontal and vertical structure of temperature and water vapor in the Martian atmosphere. The integrated HDO emission is displayed in Figure 1. The moderate resolution (2.3") map shows that emission peaks at the Martian north pole and is clearly much stronger in the northern hemisphere. The presence of significantly more water vapor emission in the north at the time of the observations is consistent with the onset of sublimation of water deposits in the north polar cap during these Northern summer solstice observations. The latitudinal temperature structure determined from the CO observations is remarkably similar to that determined from Mariner and Viking data more than 20 years ago (Jakosky & Farmer 1982); absolute temperatures are approximately 15 K lower (c.f. Zurek et al. 1992).The global mean water vapor content above $\sim$5 km is significantly less than found during the Viking period (c.f. Jakosky & Haberle 1992). This result suggests that the atmosphere as a whole is ten times drier than during the Viking era, at least at altitudes above 5 km. ALMA will allow rapid imaging of many molecular species at spatial resolutions down to less than 100 *kilometers* (see $0.2''$ beam in image).

## 3. Titan: Vertical Profiles of Molecular Species

Understanding of the important chemical and dynamical processes on Titan relies on accurate observational data of the abundances of molecular species. In our ongoing campaign to study Titan's atmosphere, we observed rotational lines of key species at millimeter wavelengths using the OVRO Millimeter Array. An interferometer permits sideband isolation, allowing accurate line to continuum measurement of the very broad spectral lineshapes from Titan, a distinct advantage over observations made with single dish instruments.

We have observed the CO(1-0) line at 115.27 GHz, the HCN(1-0) lines at 88.63 GHz, and the $HC_3N$ (24-23) line at 218.32 GHz (Fig. 2). Carbon monoxide is uniformly distributed at 50+/-10 ppm from 60km to at least 200 km. We are insensitive to the CO abundance below 50 km, but our result is consistent with the original CO detection in Titan's troposphere (Lutz et al. 1983). The HCN line is best fit with a profile of 50 ppb at the HCN condensation altitude (near 90 km) and increasing to near 1 ppm at 300 km. This is the first detection of the condensation altitude, and is strong evidence that HCN and other hydrocarbons are condensing into liquid and "raining" out of the upper atmosphere. In contrast to CO and HCN, $HC_3N$ has a very narrow line, less than 1 MHz in width. This demands that $HC_3N$ be limited to altitudes higher than 325 km (50 microbar), best fit by a 10 ppb profile above that point.

Our future OVRO goals are to use the increased baseline length and the introduction of real-time atmospheric phase correction to resolve the disk of Titan ( 0.8") and measure spatial variations of nitrile species. Strong latitudinal variations of HCN, $HC_3N$, and $CH_3CN$ were measured during the Voyager fly-bys, and remain unexplained in photochemical models. It is of great interest to see if these variations persist today, and how they may change in the period preceding the arrival of the Cassini mission (and the Titan Huygens Probe). The construction of ALMA, with its high sensitivity, even at very high spatial resolution, will usher in a truly new era for the exploration of Titan's atmosphere.

## 4. ALMA and Planetary Science

Planetary atmospheres encompass a wide range of lineshapes and source sizes. We need to be able to observe tenuous atmospheres (e.g. Pluto, comets) where linewidths are thermal or velocity driven, moderate atmospheres (e.g. Mars, Titan, Venus) with moderate pressure broadening out to a few GHz, and giant planet atmospheres (e.g. Jupiter, Neptune) where observable pressure broadened lineshapes of $NH_3$ exceed 100 GHz or more. Target sizes range from less than $0.1''$ (Pluto, Charon, cometary nuclei) to $\sim 60''$ (Venus at closest approach), and cometary comae can extend for many arcminutes. In addition, molecular lineshapes are often weak features against the strong planetary continuum (e.g. HDO on Mars). The flexibility, sensitivity, resolution, and imaging capabilities of ALMA are well-suited to cover these diverse needs, and will provide an extraordinary instrument for planetary astronomy.

## References

Jakosky & Farmer 1982, JGR 87, 2999

Jakosky & Haberle 1992, in "Mars", ed. Kieffer et al. (Tucson: University of Arizona Press), 835

Lutz et al. 1983, Science 220, 1374

Zurek et al. 1992, in "Mars", ed. Kieffer et al. (Tucson: University of Arizona Press), 969

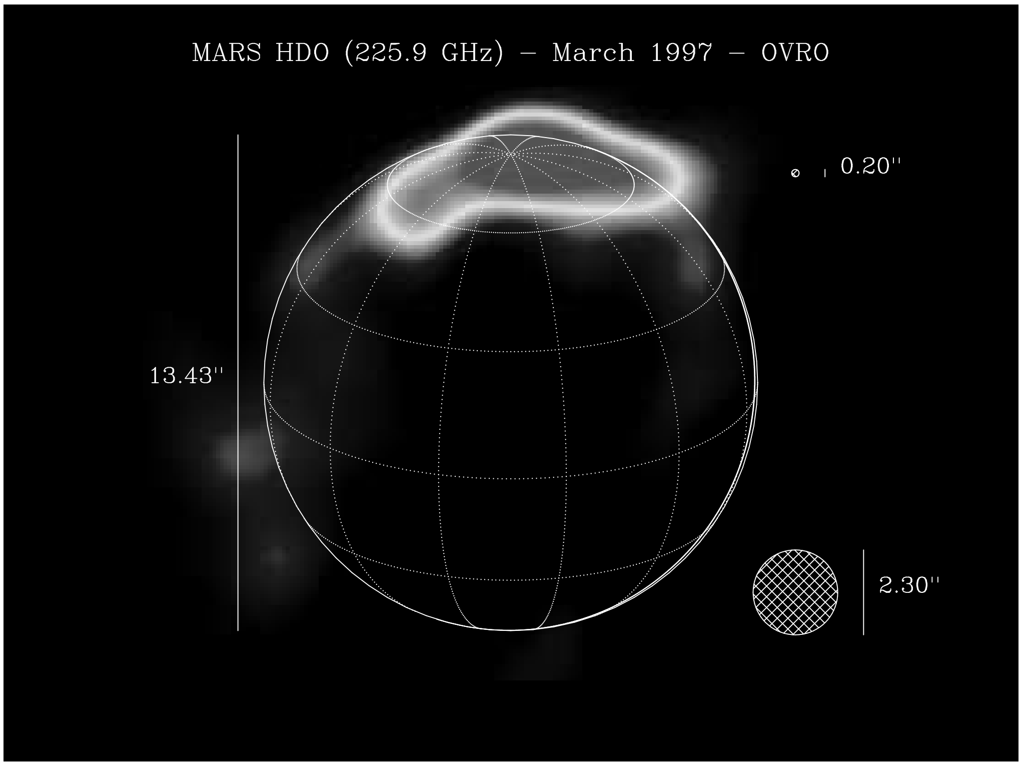


Figure 1. Integrated HDO (225.9 GHz) emission from Mars.

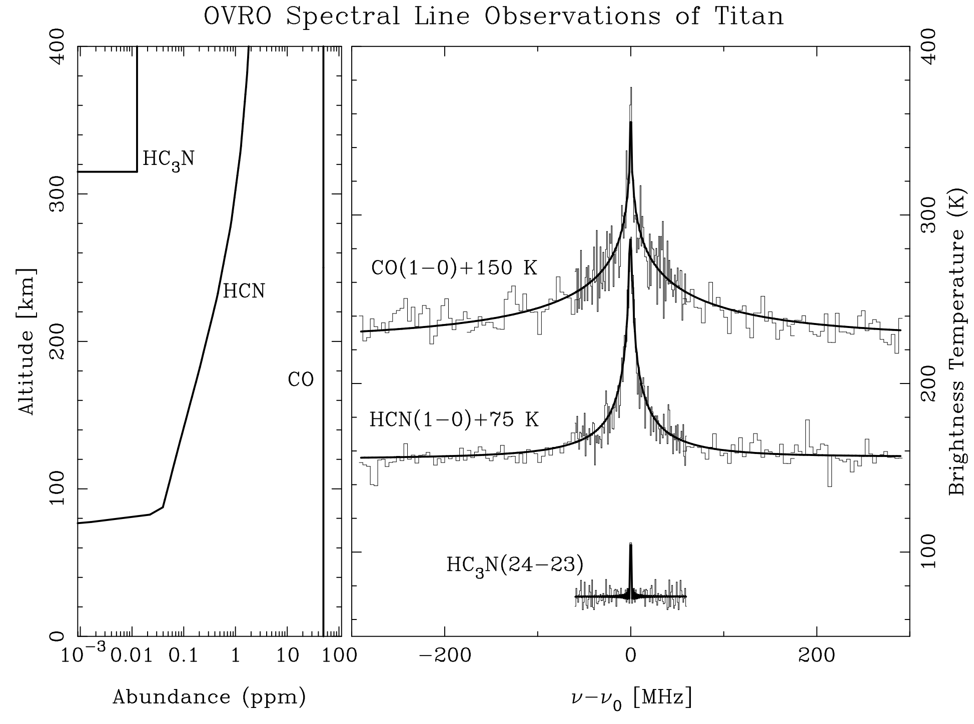


Figure 2. OVRO observations of molecular species in the atmosphere of Titan.