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In situ thermal conductivity measurements of Titan's lower atmosphere

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ABSTRACT

Thermal conductivity measurements, presented in this paper (Fig. 3), were made during the descent of the Huygens probe through the atmosphere of Titan below the altitude of 30 km. The measurements are broadly consistent with reference values derived from the composition, pressure and temperature profiles of the atmosphere; except in narrow altitude regions around 19 km and 11 km, where the measured thermal conductivity is lower than the reference by 1% and 2%, respectively. Only single data point exists at each of the two altitudes mentioned above; if true however, the result supports the case for existence for molecules heavier than nitrogen in these regions (such as: ethane, other primordial noble gases, carbon dioxide, and other hydrocarbon derivatives). The increasing thermal conductivity observed below 7 km altitude could be due to some liquid deposition during the descent; either due to condensation and/or due to passing through layers of fog/cloud containing liquid nitrogen–methane. Thermal conductivity measurements do not allow conclusions to be drawn about how such liquid may have entered the sensor, but an estimate of the cumulative liquid content encountered in the last 7 km is 0.6% by volume of the Titan's atmosphere sampled during descent.

1. Introduction

Titan's dense and extended atmosphere, retained by a small gravitational force equivalent to only a seventh of the Earth's gravity, has been and continues to be studied by various remote observation techniques. The Huygens probe (Lebreton et al., 2005) provided the first opportunity to make *in situ* measurements of Titan's atmosphere during its descent on 14th January 2005. The atmospheric composition of Titan was resolved during the Huygens descent by mass spectroscopy, a part of the GCMS instrument suite, whose results are described in Niemann et al. (2005), and complemented by infrared spectroscopy measurements in the wavelength range 840 to 1700 nm from the DISR instrument (Tomasko et al., 2005). The atmospheric structure of Titan, in terms of its vertical pressure, temperature and density profiles, were resolved by measurements from the HASI instrument suite (Fulchignoni et al., 2005). Given this background of accurate knowledge of Titan's atmosphere acquired from such high fidelity *in situ* measurements, the purpose of measuring a vertical thermal conductivity profile, rather than inferring from our present knowledge, seems to yield no extra information on Titan at first sight. However, none of the above measurements were able to distinguish the physical state of the atmosphere, in terms of how much liquid, if any, was encountered along the path of the probe's descent. Compositional measurements such as the mass/charge (m/z) ratio measurements of the ions from GCMS, or methane absorption bands in the IR spectra from DISR are unable to detect any liquid that may either be present in the form of 'methane rain on Titan' (Toon et al., 1988), or liquid accumulated from condensation.

In addition to complementing the above *in situ* measurements, thermal conductivity is a highly sensitive parameter to the physical state of the constituents; for instance, the ratio of liquid to gas thermal conductivity is >20 (NIST, 1993) in conditions similar to those found in Titan's atmosphere below 20 km (i.e. for a binary mix of 0.95 N_2–0.05 CH_4 (in mole fraction) at temperature of $\sim$80 K and pressure of $\sim 0.07 \times 10^6$ Pa). The thermal conductivity profile presented in this manuscript should contribute to the debate of some important, but as yet unresolved, issues pertaining to Titan, such as: the regions containing methane super saturation (Samuelson et al., 1997) and more recently, the inferred 'methane drizzle on Titan' (Tokano et al., 2006). Later in this paper, we estimate the mean molecular mass of Titan's atmosphere from the thermal conductivity measurements under the assumption that the constituents exist only in gaseous state.

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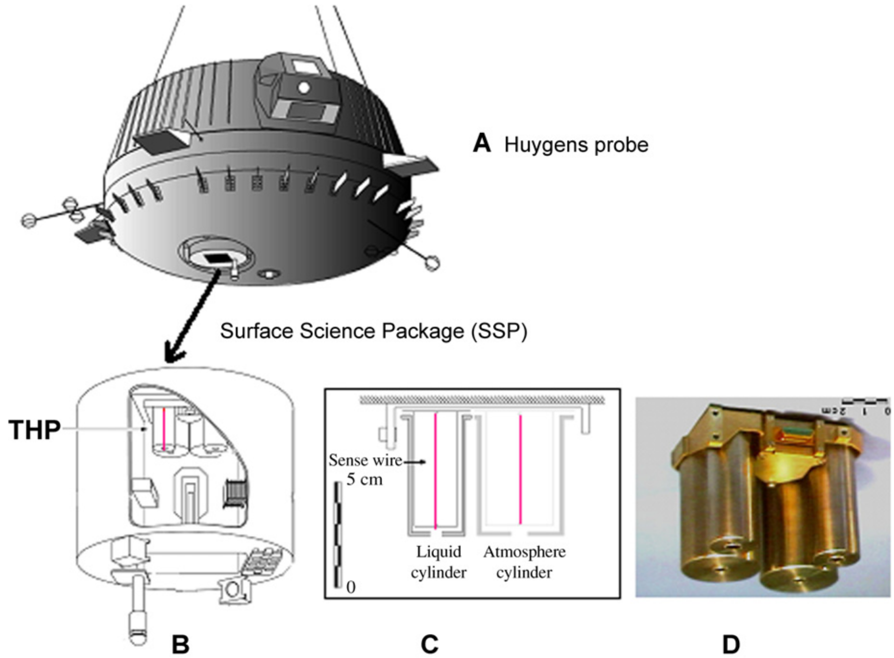

Fig. 1. Huygens probe (A) in descent configuration showing the atmosphere inlet via the SSP's instrument suite (B). The THP sensor is shown in detail in schematic (C) illustrating the active sensing element—a centrally suspended platinum wire, and photograph (D) showing the external cylinders enclosing each wire and limiting the fluid flow within each cell.

Thermal conductivity measurements were carried out by a dedicated thermal properties (THP) sensor, within the Surface Science Package (SSP) payload (Zarnecki et al., 2002). The THP sensor measures thermal conductivity by monitoring the heat flow between a heat source; a platinum wire enclosed by a cylinder in this case (see Fig. 1), and the surrounding medium; a fluid sample from Titan's atmosphere. The sensor operates on the principle of 'transient hot wire' (de Groot et al., 1974), whereby, changes in temperature (dT) relative to the initial temperature of the wire are recorded after applying a step heat input over a preset time interval (15 s in the case of THP during descent).

Details pertaining to the THP sensor in terms of its design, operation and the technique used to calculate thermal conductivity are described in Hathi et al. (2007).

Although the THP sensor started operating above 100 km altitude, the combination of measurement duration (15 s) and the low atmospheric pressure (<0.02 MPa), are deemed to be unsuitable conditions to allow sufficient heat exchange between the medium and the source, hence we present data below 30 km. Data from the Huygens mission and THP are being made available on NASA's PDS archive at the time of this publication for further analysis by the wider planetary science community.

2. Measurements

The process of calculating thermal conductivity, upon which the results in Fig. 3 are based, is described in Hathi et al. (2007). In summary, an initial estimate of thermal conductivity is obtained from a gradient of raw measurements (see 'Raw data' points in Fig. 2) and is used to generate a new temperature profile after applying various correction factors (see 'corrected data' points in Fig. 2). The iterative process generates a corrected data curve for each gradient calculation from raw data until the thermal conductivity values from the raw and corrected data sets converge. The method yields two values (minimum and maximum) at each altitude step; the actual thermal conductivity value may lie anywhere within the boundary defined by these minimum and maximum values.

The measurements presented here cover the last 30 km of the Huygens descent and vary in altitude resolution from 1 km per sample at higher altitudes, to 0.5 km. Under stable calibration conditions, the thermal conductivity calculations were accurate to within 1% for the three gaseous media: methane, ethane, and nitrogen. However, under descent conditions, where continuously changing pressure and internal–external temperature gradients determine gas flow rates through the THP sensor, the errors may be greater than the 1% encountered during calibration.

The errors (or the spread in values) in general decrease with decreasing altitude; in some regions the errors are well confined by a narrow range (see data around 11 to 10 km, and closer to surface below 5 km). The relatively large error bars in the upper atmosphere are due to poor convergence in the iterative method resulting from ill-confined residuals (see Fig. 2d) which in turn might be a result of the atmosphere sample within the measuring cell having a combination of either thermal gradients or a more turbulent gas flow. A constant eddy diffusion coefficient of 5000 cm^2/s has been estimated below 90 km (Barth and Toon, 2003) however, the eddy size of Titan's lower atmosphere is unknown and therefore it is not possible to compare turbulence length with those observed in high altitude THP measurements.

Data in Appendix A, summarised in Fig. 3 (below) describe Titan's vertical atmospheric structure in terms of its thermal conductivity. The measurements show a general trend of increasing thermal conductivity closer to the surface. The THP sensor measurements are time stamped, so the average altitude during a measurement can be correlated from the Huygens descent profile in Lebreton et al. (2005) (i.e. time–altitude profile).

The present analysis assumes that the gas sample in the THP sensor during a measurement is approximately similar to the external atmosphere sample (i.e. no gas flow lag between the THP sensor and the external atmosphere is considered). This assumption is based on the qualitative argument of increasing atmospheric pressure during the descent should result in some internal–external pressure differential ensuring that gas sample is similar to the external atmosphere sample.