EXPERIMENTAL CONSTRAINTS ON METHANE EVAPORATION AT THE LOW LATITUDES OF TITAN

A. Luspay-Kuti[1], V.F. Chevrier[1], F.C. Wasiak[1], L. A. Roe[1], W.D.D.P. Welivitiya[1], T. Cornet[2], S. Singh[1], E.G. Rivera-Valentin[3] [1]Arkansas Center for Space and Planetary Sciences (FELD 202 University of Arkansas, Fayetteville, AR 72701 USA; aluspayk@uark.edu), [2]Laboratoire de Planétologie et Géodynamique de Nantes, (UMR 6112, CNRS, OSUNA, 2 rue de la Houssiniére, Nantes, FRANCE), [3]Brown University (324 Brook St. Box 1846, Providence, RI 02912 USA)

Introduction: The surface of Titan exhibits a characteristic morphological dichotomy between the polar regions and their well developed lakes [1], and the equatorial regions characterized by vast dune fields [2] and fluvial channels [3]. Recent Cassini observations of a low latitude storm followed by extensive surface changes [4] show that liquid methane could currently shape the equatorial regions - a process also suggested by recent circulation models [5]. However, this process is mostly dependent on theoretical estimates of methane precipitation and evaporation rates [6, 7]. Here we report the first experimental simulations on the evaporation rate of liquid methane under simulated Titan conditions similar to those observed at the Huygens landing site [8]. We discuss the implications of our results on the evaporation process and stability of low latitude liquids on the surface of Titan.

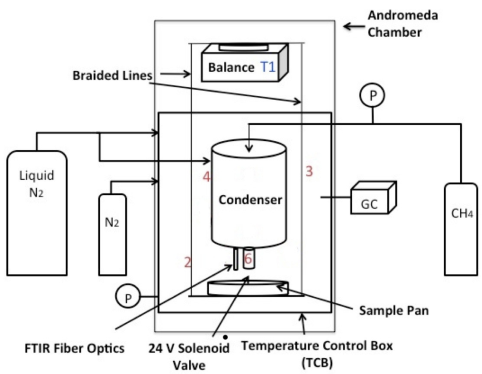

Figure 1: Schematic diagram of the Titan simulation facility and its various components. Numbers indicate the locations of K-type thermocouples. 'T1' is a T-type thermocouple used to monitor the temperature of the scale.

Methods: The experimental facility is specifically designed to simulate the surface environment of Titan [9]. Surface temperatures of 90-95 K are created by flowing liquid N_2 through coils within the Titan module, while a 1.5 bar atmosphere is maintained with pressurized N_2. Once the required temperature and pressure are achieved, we introduce methane into a condenser, then drain the liquid methane into a pan with a diameter of 15 cm (Fig. 1).

The mass loss of liquid methane over time, along with temperatures at various locations within the Titan module are continuously recorded. We use a gas chromatograph flame ionization detector to measure CH_4 concentration inside the chamber, from which we calculate the methane partial pressure, thus the relative humidity. We maintain a CH_4 mole fraction of $\sim 2\times10^{-2}$.

Results: Evaporation rates are calculated by first finding the linear portion in the mass vs. time curves (Fig. 2b) where the atmospheric temperature in the chamber remains below 95 K. A least-squares fit to the data is then performed in order to determine the evaporation rate for a given temperature range as the slope of the regression line with corresponding uncertainties to a 95% confidence interval. Based on various runs with the same experimental setup we determined an evaporation rate of $(3.1 \pm 0.6)\times10^{-4}$ kg s^{-1}m^{-2}.

Discussion: To apply the results for Titan, we use a theoretical approach based on the diffusion of lighter CH_4 molecules into a heavier N_2 atmosphere. Buoyancy is expected to affect evaporation and therefore modify simple diffusion. We use a modified mass flux equation originally developed for Martian ice [10]:

$$J = 0.17 D_{CH4/N2} \Delta\eta \left(\frac{\frac{\Delta\rho}{\rho_{surf}} g}{\nu^2} \right)^{\frac{1}{3}}, \qquad (1)$$

where $D_{CH4/N2}$ is the diffusion coefficient of CH_4 gas in N_2 , $\Delta\eta$ is the difference between the density of CH_4 above the liquid layer and the density of CH_4 in the ambient atmosphere, $\Delta\rho$ is the difference between the density of the ambient gas and the gas at the surface, g is the gravitational acceleration on Titan, and ν is the kinematic viscosity of CH_4.

Since our experiments are performed under Earth gravity, we correct for the difference in the gravity of Earth and Titan. From Eq. 1 we use a factor of $E_{Titan}/E_{Earth} = (g_{Titan}/g_{Earth})^{1/3}$. The resulting buoyancy driven evaporation rate applied for Titan is $(1.6\pm0.3)\times10^{-4}$ kg s^{-1}m^{-2}.

Due to the high solubility of N_2 in CH_4, we find that the sample liquid will not be pure CH_4, but rather a binary mixture of CH_4-N_2 with mole fractions of 0.84 and 0.16, respectively. This is in excellent agreement with results from Eq. 1 divided by the density of the binary mixture (J = 1.52 $\times 10^{-4}$ kg $s^{-1}m^{-2}$), suggesting that mass transfer in our experiments is largely controlled by the concentration difference in the simulated atmosphere and buoyancy-driven diffusion. At the same time, according to the model of [11], the daily average non-radiative fluxes on Titan are 20 times higher than previously thought [12], and are theoretically available for convective energy. However, we do not see any evidence for active convection in the chamber, only for passive convection in the form of buoyancy. Indeed, as shown in Figure 2 d and c, the temperature close to the pan remains cooler than in the ambient atmosphere of the chamber. Moreover, the temperature profiles remain very parallel and show an overall slight decreasing trend (Fig. 2c). These observations are indicative of heat conduction from the warmer upper gas downward into the liquid.

Using our experimentally determined evaporation rate, the areal coverage of the observed surface change and the elapsed time during a low latitude storm reported by [4] we estimated the maximum depth of the evaporated liquid resulting from the storm. We find the depth to be 2.4± 0.5 m and the maximum total mass $(5.4\pm1.2)\times10^{10}$ kg.

Conclusions: Based on the fact that Eq. 1 very closely matches the evaporation rate in the chamber we conclude that evaporation is predominantly diffusion-driven in the chamber, although we cannot exclude possible minor additional energy sources that could contribute to the evaporation. This is expected to play an important role on Titan as well, resulting in the significantly faster evaporation of the binary mixture than ternary liquids for purely energy controlled models.

Considering the significance of diffusion and buoyancy in our experiments and the effect of heat balance in the models, we propose that evaporation on Titan is most probably a combination of these effects, and so, should be taken into account in modeling in the future.

At the same time, the results of our experiments provide an upper bound to the evaporation of liquid CH_4 on Titan. Our results are within the model estimates of 0.5 - 15 mm hr^{-1}, thought to be required for the formation of fluvial features [13]. This implies that ponding, and even liquid flow may be possible depending on the local topography, in agreement with the presence of fluvial features and dunes in spite of the occasional heavy storm events.

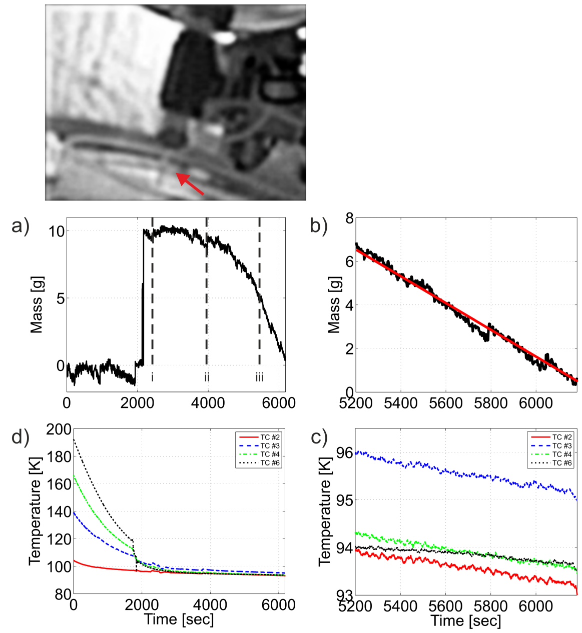

Figure 2: Example run of an evaporation experiment. Top left: Captured image of liquid CH_4 pouring out of the condenser through the solenoid valve (indicated by arrow). a) Mass vs. time throughout the run. The vertical lines indicate distinguished phases of the experiment. Between sections i and ii there is a plateau caused by ongoing heat transfer between the colder liquid and the warmer ambient atmosphere. ii-iii: non-steady state evaporation as the liquid and atmosphere equilibrate. b) Steady-state evaporation (Section iii in panel a)). The linear fit is marked by the red line. Bottom: Corresponding temperatures (d, c).

Acknowledgements:: This work was funded by NASA OPR #NNX10AE10G.

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