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How to interpret the temperature variability in Titan's upper atmosphere?

J. Cui (1,2,3)
(1) School of Atmospheric Sciences, Sun Yat-Sen University, Zhuhai, China, (2) Lunar and Planetary Science Laboratory, Macau University of Science and Technology, Macau, China, (3) Key Laboratory of Lunar and Deep Space Exploration, National Astronomical Observatories, Chinese Academy of Sciences, Beijing, China (cuijun7@mail.sysu.edu.cn / Fax: +86-0756-3668292)

Abstract

Over the past 12 years, the Cassini Ion Neutral Mass Spectrometer (INMS) observations have revealed a highly variable neutral temperature in Titan's upper atmosphere, with a mean temperature of 150 K but a variability of more than 70 K. No systematic horizontal or diurnal variations could be identified, and the observed temperature variability is more likely to be temporal in nature rather than spatial. At least three scenarios have been investigated so far to identify the driving force of the variable thermal structure, including the solar-driving scenario, the plasma-driven scenario, and the cooling-driving scenario. However, no scenario is able to interpret properly the observations.

1. Introduction

Over the past 12 years, the implementation of the Cassini-Huygens mission has greatly improved our understanding of Titan, the largest moon of Saturn and the only moon within the Solar System that possesses a permanent and extended atmosphere. As revealed by the Cassini Ion Neutral Mass Spectrometer (INMS) data, one of the intriguing characteristics identified in Titan's atmosphere is the large variability of more than 70 K in neutral temperature at altitudes above 1000 km (around a mean temperature of 150 K), which has sometimes been termed as the problem of energy crisis in Titan's upper atmosphere (e.g., Snowden & Yelle 2014 and references therein). This article is devoted to a description of such a problem and our continuous efforts towards understanding properly both the nature and the driving force of the observed temperature variability.

2. What is the nature of the observed temperature variability?

The first Cassini flyby with Titan, denoted as TA, revealed a neutral temperature of around 150 K in Titan's upper atmosphere (Waite et al. 2005, Yelle et al. 2006), which is consistent with the early Voyager observations made by the Ultraviolet Spectrometer (UVS) (Vervack et al. 2004). Later, a comparison between the TA and T5 flybys showed surprisingly that the nightside temperature is higher than the near-terminator temperature by more than 10 K (De La Haye et al. 2007). By combining the INMS data from 13 flybys covering exclusively Titan's northern hemisphere, both Mueller-Wodarg et al. (2008) and Cui et al. (2009) showed a tendency of decreasing neutral temperature from the equator towards the north pole, despite that no systematic diurnal variations could be identified. Finally, with the aid of 32 Titan flybys, Snowden et al. (2013) confirmed that any horizontal variations in neutral temperature, either meridional or diurnal, that had been previously reported were simply observational bias and the thermal structure of Titan's upper atmosphere appeared to be irregular and sporadic. The above observations suggest that the temperature variability is more likely to be temporal in nature rather than spatial. In such a scenario, the upper regions of Titan's atmosphere are more or less spatially uniform but expand or shrink as time evolves in response to certain externally driving forces. This scenario is also supported by the observation of H_2 density variability above Titan's exobase, which could only be reproduced by assuming an exbase density variability characterized by an infinitely large scale length (Cui et al. 2011). Since the scale length has to be finite, the above observation naturally implies that the exospheric density variability is likely temporal in nature.

The scenario of time-varying thermal structure in Titan's upper atmosphere led to the study of Westlake et al. (2011), who found that the mean temperature above 1000 km varied with the ambient plasma environment (especially in terms of the intensity of magnetospheric electron precipitation), being higher under plasma-sheet conditions as compared to lobe-like conditions (Rymer et al. 2009).

3. What is the driving force of the observed temperature variability?

The absence of any diurnal variation in neutral temperature (e.g., Snowden et al. 2013) clearly implies that the thermal structure of Titan's upper atmosphere cannot be solar-driven. This is also supported by the absence of correlation between neutral temperature and solar EUV flux (Snowden et al. 2013). In addition, Snowden & Yelle (2014) have predicted that with the variability in solar EUV flux over the period of Cassini observations, the temperature variability is no larger than 5 K, far insufficient to account for the observed variability.

The apparent correlation between neutral temperature and electron precipitation identified by Westlake et al. (2011) suggests that the thermal balance in Titan's upper atmosphere is likely plasma-driven. However, the typical heating/cooling timescale is about 10 Earth days (Snowden & Yelle 2014) whereas the duration for Cassini observations made in the vicinity of Titan during one Titan flyby is typically 10 minutes. The large difference in the above two timescales makes the accessing the significance of Westlake et al.'s correlation difficult (Snowden & Yelle 2014).

The seminal work of Yelle (1991) indicated that the thermal balance in Titan's upper atmosphere was strongly influenced by the abundance of the minor constituent, HCN, as the main coolant (through its rotational line emission) at altitudes above the homopause. In Cui et al. (2016), the so-called cooling-driven scenario was tested, showing that the neutral temperature could be different by more than 70 K at a similar level of $\sim 3\times10^{-4}$ in HCN mixing ratio. Therefore the variation in HCN abundance in Titan's upper atmosphere cannot account for the observed temperature variability either.

4. Conclusions and prospects

Over the past 12 years, the Cassini INMS observations have revealed a highly variable neutral temperature in Titan's upper atmosphere, with a mean temperature of 150 K but a variability of more than 70 K (e.g., De La Haye et al. 2007, Mueller-Wodarg et al. 2008, Westlake et al. 2011, Cui et al. 2011, Snowden et al. 2013). No systematic horizontal or diurnal variations could be identified, and the observed temperature variability is more likely to be temporal in nature rather than spatial (Cui et al. 2011). At least three scenarios have been investigated so far to identify the driving force of the variable thermal structure of Titan's upper atmosphere, including the solar-driving scenario, the plasma-driven scenario, and the cooling-driving scenario. However, no scenario is able to interpret properly the observations (e.g., Snowden & Yelle 2014, Cui et al. 2016).

There are other scenarios that have not been examined in detail. Extensive signatures of wave-like structures have been identified in the INMS data and characteristic values of basic wave parameters have been estimated (Cui et al. 2013, 2014). Therefore one of the scenarios likely responsible for the observed temperature variability is the wave-driven scenario in which the thermal structure of Titan's upper atmosphere is strongly modulated by the dissipation of waves of different modes (e.g., Matcheva & Strobel 1999, Hickey et al. 2000, Schubert et al. 2003).

Alternatively, it would also be interesting to examine rigorously the functional form and intensity of the missing energy source/sink in Titan's upper atmosphere for each flyby available. Such an examination has to be made with the aid of the observed N_2, CH_4 and HCN density profiles, which can be used to infer the solar heating rate, the HCN cooling rate, as well as the contribution from conductive heat flow. Comparing various energy source/sink terms would then allow the assessment of the detailed energetics in Titan's upper atmosphere and the derivation of any extra terms required to force thermal balance. Information on the vertical profile of solar heating efficiency appropriate for each individual flyby is crucial for such an examination.

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