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Preliminarily study of Saturn's upper atmosphere density by observing Cassini plunging via China's deep space station

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Abstract When the Cassini spacecraft finally plunged into the Saturnian atmosphere on 2017 September 15, China's deep space telescope pointed to Saturn to observe Cassini and study the Saturnian upper neutral atmosphere. In this first Chinese Saturnian radio science experiment, X band Doppler velocity radio science data between the deep space telescope and the Cassini spacecraft were obtained. After removing Saturnian and solar gravity effects, Earth rotation effect, the remaining Saturnian atmosphere drag information was retrieved in the Cassini final plunge progress. Saturn's upper neutral atmosphere mass density profile is approximately estimated based on atmosphere mass density derived principally by real orbit measurement data. Saturn's upper neutral atmosphere mass density from 76 000 km to 1400 km is estimated from the orbit measurement data, the mass density results are about from 1.4×10^{-15} kg cm^{-3} to 2.5×10^{-14} kg cm^{-3}.

Key words: Cassini — Saturn — Doppler velocity — neutral atmosphere mass density

1 INTRODUCTION

The Cassini spacecraft was used to study the Saturn system from 2004 until 2017. To protect two of Saturn's 62 moons from potential microbial contamination from Earth (Voosen 2017), Cassini plunged into Saturn's atmosphere on 2017 September 15. During Cassini's final plunge, it worked as an in situ entry spacecraft until it was destroyed by Saturn's great pressure and temperature. The final plunge orbit allowed Cassini to take its finest in situ measures of Saturn's atmosphere, and provided the best opportunity to study Saturn's atmosphere, such as atmosphere's composition, temperature, density, interactions with the Saturn rings (Edgington & Spilker 2016; Yelle et al. 2018; Hickey et al. 2018; Wahlund et al. 2018; Waite et al. 2018; Cravens et al. 2019; Persoon et al. 2019).

Saturn's atmosphere consists of various neutral molecules and their ionized gases, neutral gases often called a neutral atmosphere which is the subject of atmospheric drag effect to the spacecraft. There are several methods for obtaining the information of planetary atmosphere, such as optical measurements, in situ measurements, and neutral atmosphere derived from spacecraft orbit measurement or determination, and so on. The optical observation, like the ultraviolet and infrared spectrograph, are remote sensing measurements which are good at identifying the neutral compositions (Moore et al. 2004; Koskinen & Guerlet 2018). The only in-situ measurements of Saturn's neutral atmosphere are from the Cassini's Grand Finale orbits and specifically the Ion and Neutral Mass Spectrometer (INMS) instrument (Waite et al. 2006; Yelle et al. 2018). Compared to optical observation or in situ measurement by on board instruments, the method of planetary neutral atmosphere derived from spacecraft orbit measurement or determination can be also effective to obtain neutral atmosphere information (Hickey et al. 2018; Bruinsma & Biancale 2003; Jeon et al. 2011). This method depends on the principle of neutral atmosphere affecting spacecraft flight, giving the opposite force to the flying spacecraft, which can be utilized to derive neutral atmosphere density. The Cassini final plunge orbit was tailored for a radio science experiment (Voosen 2017), the high gain antenna (HGA) of Cassini pointed forward the Earth. Thus, Earth ground deep space radio telescope can effectively receive the downlink signal, monitor the Doppler velocity from the spacecraft's signal, which could be utilized to derive Saturn's upper neutral atmosphere.

In this work, we focus on Saturn's neutral atmosphere derived from Cassini's orbit measurement information. We introduce the atmosphere density measurement principle based on radio observation, the brief procedure of China's deep space telescope tracked and observed Cassini spacecraft during its final plunge into Saturn's atmosphere, and the result of Saturn's upper neutral atmosphere density estimation. China's deep space telescope named Jiamusi (JMS) participated in the final plunge observation. Firstly, Cassini downlink frequency information and observation plan were obtained in advance. Secondly, deep space telescope guide ephemeris was generated for Cassini observation. Thirdly, Cassini was tracked by China's deep space telescope, downlink radio signal was sampled and recorded by VLBI baseband terminal. Then, the Doppler measurement results were calculated from the recorded downlink signal. Fourthly, Cassini's acceleration on line of sight caused by Saturn's upper atmosphere was calculated, Cassini's post ephemeris (NASA 2018) was utilized to eliminate the other error impact effects. Finally, Saturn's upper neutral atmosphere density was approximately estimated from the residual acceleration information.

2 OBSERVATION PRINCIPLE AND EXPERIMENT

2.1 Atmosphere Mass Density Estimation Principle

Saturn's upper atmosphere density could be detected using the following calculation equation (Mehta et al. 2014; Jeon et al. 2011):

$$\boldsymbol{a}_{\mathrm{drag}} = -\frac{1}{2}\frac{\rho C_D A}{m} v^2 \frac{\boldsymbol{v}}{|\boldsymbol{v}|}\,, \tag{1}$$

where $\boldsymbol{a}_{\mathrm{drag}}$ is spacecraft acceleration due to atmosphere drag, ρ is the atmosphere mass density, $\boldsymbol{v}$ is the velocity of spacecraft relative to planet atmosphere, v is the velocity scalar, C_D is the atmosphere drag coefficient, A is the reference area of spacecraft, and m is the spacecraft's mass. In order to estimate Saturn's upper neutral atmosphere density, $\boldsymbol{v}$, $\boldsymbol{a}_{\mathrm{drag}}$, and A should be known in advance, especially $\boldsymbol{v}$ and $\boldsymbol{a}_{\mathrm{drag}}$.

The observation geometry of Cassini is shown in Figure 1. In the Cassini final plunging procedure, the uplink telescope was DSS43 in Canberra Deep Space Communication Complex, and DSS35 in Canberra Deep Space Communication Complex was the downlink telescope. Thus JMS deep space telescope can do Doppler measurement in three ways like DSS35 telescope.

In this paper, ρ is presumed that it has the same value in all direction. ρ will be derived on line of sight (LOS), the direction of spacecraft relative to the ground telescope. In order to obtain ρ, $\boldsymbol{a}^{\mathrm{los}}_{\mathrm{drag}}$ should be calculated first. When Cassini crossed Saturn's upper atmosphere step by step in the high latitude of Saturn, the main external force contained Saturnian gravity, solar gravity and Saturnian atmospheric drag, the other external forces were slight, which could be ignored, such as Cassini's solar pressure force, the other planets' gravity forces except for Saturn and solar. Equation (2) shows the main forces, where $\boldsymbol{F}^{\mathrm{los}}$ is the external force on line of sight, $\boldsymbol{F}^{\mathrm{los}}_{\mathrm{grav}}$ is the external force caused by Saturnian and solar gravity on line of sight, $\boldsymbol{F}^{\mathrm{los}}_{\mathrm{atm}}$ is the external force caused by Saturn's upper atmosphere on line of sight:

$$\boldsymbol{F}^{\mathrm{los}} = \boldsymbol{F}^{\mathrm{los}}_{\mathrm{grav}} + \boldsymbol{F}^{\mathrm{los}}_{\mathrm{atm}}\,. \tag{2}$$

$\boldsymbol{F}^{\mathrm{los}} = m\boldsymbol{a}^{\mathrm{los}}$, where $\boldsymbol{a}^{\mathrm{los}}$ is the total acceleration on line of sight, $\boldsymbol{F}^{\mathrm{los}}_{\mathrm{grav}} = m\boldsymbol{a}^{\mathrm{los}}_{\mathrm{grav}}$, where $\boldsymbol{a}^{\mathrm{los}}_{\mathrm{grav}}$ is total gravity acceleration on line of sight, $\boldsymbol{a}^{\mathrm{los}}_{\mathrm{drag}}$ is the atmosphere drag acceleration of spacecraft on line of sight, $\boldsymbol{F}^{\mathrm{los}}_{\mathrm{atm}} = m\boldsymbol{a}^{\mathrm{los}}_{\mathrm{drag}}$. Thus the following equation could be obtained. $\boldsymbol{a}^{\mathrm{los}}_{\mathrm{grav}}$ could be calculated utilizing Cassini post high accuracy ephemeris provided by JPL, which contains the gravity effects caused by Saturnian gravity and solar gravity. Meanwhile, IERS Conventions basic models (Petit & Luzum 2010) were utilized in acceleration calculation.

$$\boldsymbol{a}^{\mathrm{los}} = \boldsymbol{a}^{\mathrm{los}}_{\mathrm{grav}} + \boldsymbol{a}^{\mathrm{los}}_{\mathrm{drag}}\,. \tag{3}$$

The acceleration information is related to Cassini's external force, thus

$$\boldsymbol{a}^{\mathrm{los}} = \Delta\boldsymbol{v}^{\mathrm{los}}\,, \tag{4}$$

where $\Delta\boldsymbol{v}^{\mathrm{los}}$ is the difference of Doppler velocity on line of sight.

$$\Delta f_{\mathrm{dop}} = \frac{2\Delta\boldsymbol{v}^{\mathrm{los}}}{c} f_{\mathrm{up}} N\,. \tag{5}$$

According to three Doppler velocity measurement theory, $\Delta\boldsymbol{v}^{\mathrm{los}}$ could be calculated by Equation (5), where Δf_{dop} is the difference of Doppler frequency f_{dop}, which is obtained by deep space telescope observation. N is the turn-around ratio of spacecraft, f_{up} is the uplink carrier frequency.

Thus, the drag acceleration of the spacecraft $\boldsymbol{a}^{\mathrm{los}}_{\mathrm{drag}}$ could be estimated, then the neutral atmosphere mass density ρ could be approximately estimated:

$$\rho = -\frac{2m}{C_D A}\frac{\boldsymbol{a}^{\mathrm{los}}_{\mathrm{drag}}}{{v^{\mathrm{los}}}^2}\frac{|\boldsymbol{v}^{\mathrm{los}}|}{\boldsymbol{v}^{\mathrm{los}}}\,. \tag{6}$$

2.2 Observation Experiment

China's Deep Space Network (CDSN) construction was completed in 2016 (Dong et al. 2018). There are three deep space telescopes and two deep space data processing centers.

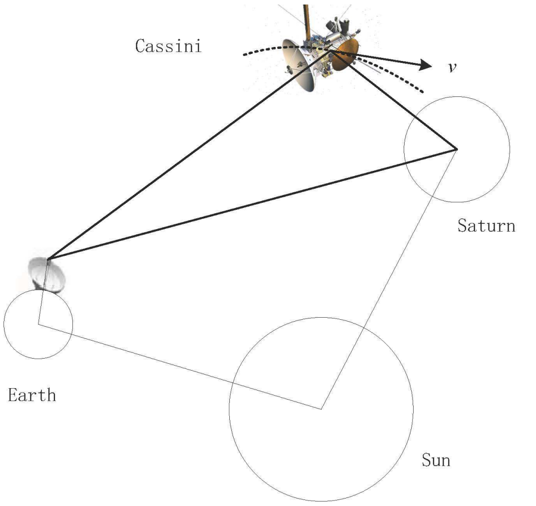

Fig. 1 The observation geometry of Cassini plunging into Saturn procedure.

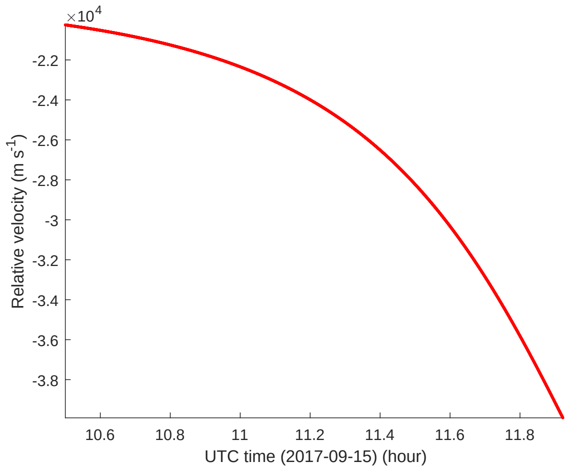

Fig. 2 The observation velocity of Cassini relative to JMS deep space telescope.

China's deep space telescope Jiamusi (JMS) with a diameter of 66 m, participated in the radio observation of the Cassini final plunge. Planetary ephemeris DE 435 was utilized (Folkner et al. 2016), telescope guide ephemeris of Cassini observation was generated utilizing the geometry relationship between Saturn and deep space telescope, since Saturn and Cassini were in the same telescope beam during the plunging process. X band was utilized for Cassini radio observation, Cassini sky frequency was 8429.938 MHz (Taylor et al. 2002), thus China's deep space telescope can track and observe Cassini downlink effective carrier signal.

The observation time was from 10:30 (UTC time) to 12:00 on 2017 September 15. VLBI baseband terminal in deep space telescope was utilized to sample and record Cassini's downlink carrier signal. Cassini's carrier frequency was estimated by Beijing Aerospace Control Center (BACC) measurement signal processing software. Because Cassini uplink carrier frequency was adapted by ramp model (Andersona & Schubertb 2010), ramp table was post obtained from NASA Planetary Data System (PDS) server (NASA 2018). Thus Doppler frequency between Cassini and JMS telescope was calculated, and Cassini's relative velocity was obtained. Figure 2 shows the observation velocity of Cassini by JMS deep space telescope from 10:30:00 to 11:55:21 (UTC time). The results show that the relative velocity between Cassini and JMS telescope varied intensely in the final plunge procedure, which was about from –20 km s^{-1} to –40 km s^{-1}. These observation results provided very useful information to study Saturn's upper neutral atmosphere.

In order to evaluate observation velocity accuracy based on JMS telescope, the observation velocity is compared to the calculation velocity based on Cassini post ephemeris, and the residual velocity is obtained. Meanwhile, the Cassini observation velocity based on DSS35 telescope is obtained from ODF data in PDS system (NASA 2018), and this velocity is also compared to Cassini post ephemeris. Thus, the residual velocity results are shown in Figure 3. It is shown that DSS35 velocity accuracy is a little better than JMS velocity accuracy, since the integration time of Doppler velocity measurement is 5 s in DSS35 according to ODF data, the accuracy is about 0.4 mm s^{-1} in 5 s integration time, while the integration time of Doppler velocity measurement is 1 s in JMS, the accuracy is about 2.1 mm s^{-1} in 1 s integration time. On the one hand, DSS35 and JMS residual velocity display approximately the same trend. On the other hand, the velocity accuracies both in DSS35 and JMS in the final plunge are obviously degenerated compared to the Cassini normal flying condition phase, especially the residual errors become large at the end of final plunge, shown in Figure 3. This is because the Cassini spacecraft had large dynamic movement in the final plunge causing measurement accuracy to become lower. But it can be concluded that JMS's observation velocity is reliable to derive Saturn's neutral atmosphere information.

3 SATURN NEUTRAL ATMOSPHERE DENSITY ESTIMATION RESULTS AND DISCUSSION

In order to calculate the density of Saturn's upper neutral atmosphere, according to Equation (1), the other parameters should be known in advance. In this paper, all the vector parameters, including the speed of the spacecraft, the drag acceleration of the spacecraft, are expressed on line of sight. The reference area is the projected area on line of sight.

The following steps are for calculating Saturn's upper neutral atmosphere density.

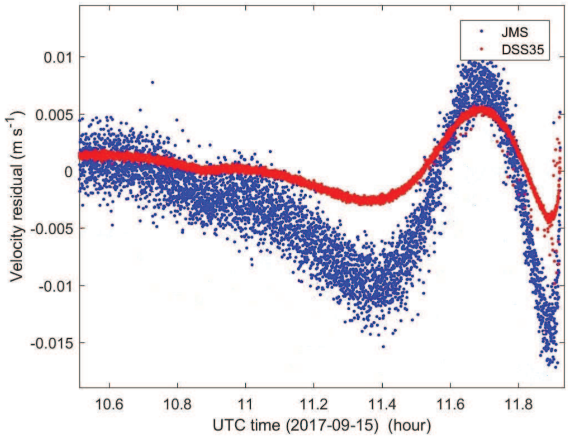

Fig. 3 DSS35 and JMS telescope velocity measurement accuracy in the final plunge.

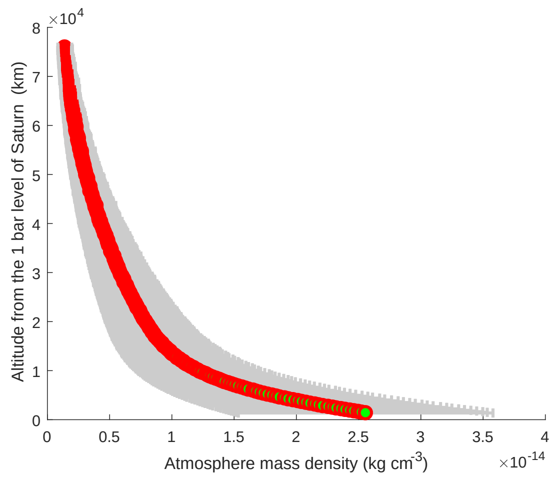

Fig. 4 Saturn's upper atmosphere mass density results obtained by JMS telescope.

Step 1, calculating the drag acceleration caused by Saturn's upper neutral atmosphere.

The drag acceleration of the spacecraft is caused by the force of Saturn's upper neutral atmosphere. In order to obtain drag acceleration, the total acceleration on line of sight and the gravity acceleration caused by Saturn and the Sun on line of sight are calculated. The total acceleration results are calculated from Cassini's final ephemeris, and the gravity acceleration results were calculated from Saturn's gravity field (Anderson & Schubert 2007; Kong et al. 2018; Iess et al. 2019), Saturn and the Sun's ephemeris. The gravitational coefficients J2, J4, and J6 are utilized in this paper. From the above derivation process in Section 2.1, the drag acceleration caused by Saturn's upper neutral atmosphere can be obtained.

Step 2, the projected area is approximately calculated. Since Cassini spacecraft stands more than 6.7 meters high and is more than 4 meters wide (Liechty 2006). For comparison, the projected area of the Cassini Titan-A flyby was calculated to be 18.46 m^2, and the projected area of the Titan-5 flyby was 19.08 m^2 (Liechty 2006), the projected area of Cassini flyby E21 was 18.6 m^2 (Lorenz & Burk 2018). In this paper, the projected area is approximately fixed as the mean projected area of the above three projected area to 18.71 m^2 in the final plunge progress, which ignore the spacecraft flying attitude affection. It assumes that Cassini's shape is cylinder, with the height 6.7 meters, the diameter 4 meters, thus Cassini's max projected area is 26.8 m^2, Cassini's min projected area is 12.56 m^2. The uncertainty is approximately 40%, when the projected area is setup 18.71 m^2.

Step 3, the drag coefficient is fixed to 2.1 in this paper, which has been confirmed to be very reasonable (Liechty 2006).

Step 4, Saturn's upper neutral atmosphere mass density is calculated. Saturn's upper neutral atmosphere mass density is calculated from JMS telescope observation data. The mass of Cassini was setup to 2150 kilogram (wikipedia[1]). The mass density estimation results of Saturn's neutral atmosphere are shown in Figure 4. The red marks are the estimation results, the gray lines express the estimation error uncertainty. The mass density profile obtained from observing the final plunge shows that Saturn's neutral atmosphere density estimation results are from 1.4×10^{-15} kg cm^{-3} to 2.5×10^{-14} kg cm^{-3} when the altitude between Cassini and the 1 bar level of Saturn is from 76 000 km to 1400 km, the mean mass density is about 7.2×10^{-15} kg cm^{-3} with 1σ uncertainty 40%.

Since Saturn's neutral atmosphere has unexpected heavy neutral molecules except for H2, HD, and He (Yelle et al. 2018; Cravens et al. 2019; Waite et al. 2018), this paper just gives the atmosphere mass density results derived from Cassini orbit measurement data, not the atmosphere number density results for each neutral molecule. The projected area not considering Cassini's flying altitude is one of the major error sources for Saturn's neutral atmosphere mass density estimation. The low-order gravity field coefficient of Saturn may also cause some estimation errors. This paper gives another technique different from in situ measurement and remote sensing measurement (Vervack & Moses 2015; Waite et al. 2018; Yelle et al. 2018), to obtain useful information of Saturn's neutral atmosphere density. Although the method and results of indirectly obtaining atmosphere mass density are different from the in situ measurement of Saturn's atmosphere, this method is reasonable, and the orbit measurement data of the line of sight Doppler which has been phase-locked to the frequency standard given by active hydrogen atomic clocks at deep space tracking stations is reliable. There are two possible reasons for this discrepancy between the in situ measurement by INMS and the indirect measurement which de-

[1] *https://en.wikipedia.org/wiki/CassiniCHuygens*

rived from spacecraft orbit information. (1) Some simplified model or data are utilized in the paper, for example the projected area of Cassini spacecraft is fixed, the drag coefficient is fixed to 2.1, Cassini's solar pressure force is ignored, the other planets' gravity forces except for Saturn and solar radiation pressure is ignored. These models or data's uncertainty produce a little effect on the final atmosphere density estimation results. (2) Cassini's velocity relative to Saturn in the final plunge is much larger in the final plunge. Shown in Figure 3 in this paper, it indicates that both DSS35 and JMS orbit measurement accuracy is lower than normal spacecraft flying procedure. There is a slightly obvious and large oscillation in the orbit determination residual errors in both DSS35 and JMS results shown in Figure 3, the max velocity measurement residual error on line of sight is larger than 1 cm s^{-1}. We believe that both DSS35 and JMS observation data are precise, this oscillation should to be derived from spacecraft orbit determination by NASA (NASA 2018), which may be caused by Saturn's atmosphere unknown effects, or may be caused by the force of Cassini firing the thruster regularly in the final plunge. Maybe the paper's estimated value of Saturn's upper neutral atmosphere mass density could be stated as an upper limit compared to the in situ measurement.

4 CONCLUSIONS

During the final plunge of Saturn, China's deep space telescope tracked Cassini and obtained its Doppler velocity successfully. The observation here is identical to the observation of NASA deep space network. Based on the Doppler velocity observation obtained by China's deep space telescope, a method for atmospheric density estimation was developed and used to approximately derive the mass density profile of Saturn's upper neutral atmosphere. The results show that Saturn's neutral atmosphere density is from 1.4×10^{-15} kg cm^{-3} to 2.5×10^{-14} kg cm^{-3} with the uncertainty 40%, when the altitude between Cassini and the 1 bar level of Saturn is from 76 000 km to 1400 km. The mean mass density is about 7.2×10^{-15} kg cm^{-3}. This paper provides the referable and useful method and results for studying Saturn's upper neutral atmosphere density.

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