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Enceladus Plume Density from Cassini Spacecraft Attitude Control Data

Ralph D. Lorenz^{a,*} and Thomas A. Burk^b

^aSpace Exploration Sector, Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, MD 20723, USA.

^bCassini Spacecraft Operations Office, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

Abstract

The plumes of Enceladus are of interest both as a geophysical phenomenon, and as an astrobiological opportunity for sampling internal material. Here we report measurements of the total mass density (gas plus dust, a combination not reported before except in the engineering literature) deduced from telemetry of Cassini's Attitude and Articulation Control System (AACS), as the spacecraft's thrusters or reaction wheels worked to maintain the desired attitude in the presence of gas drag torques during close flybys. The drag torque shows good agreement with the water vapor density measured by other instruments during the E5 encounter, but indicates a rather higher mass density on other passes (E3,E14), possibly indicating variations in gas composition and/or gas:dust ratio. The spacecraft appears to have intercepted about 0.2 grams of material, on flyby E21 in October 2015 indicating a peak mass density of $\sim 5.5 \times 10^{-11} \text{ kg m}^{-3}$, the highest of all the flybys measured (E3,E5,E7,E9,E14,E21).

1. Introduction

Although not as sensitive to low gas density as a dedicated science instrument, the exquisite performance of Cassini's attitude sensing and control systems allow a completely independent determination of plume mass density in close flybys. Further, since no individual instrument measures all components of the plume at once (e.g. the dust analyzer has a minimum threshold dust particle size, and a limited area that gives a statistical upper limit to the particle sizes counted, while the INMS operates only up to 100 Da and must be configured to measure either ions or neutrals, but not both, at any instant), the total mass density is of interest in combination with other data. It is furthermore the property of immediate relevance in planning future missions, insofar as that (as with Cassini) the drag torques may be a factor limiting the lowest altitude that can be safely probed during a flyby, as for plume encounter missions at other worlds (e.g. Lorenz, 2015).

*Corresponding author. Tel. +1 443 778 2903 Fax. +1 443 778 8939, Ralph.lorenz@jhuapl.edu.

2. Plume Density Measurement

Cassini is a three-axis controlled spacecraft (e.g. Lorenz, 2017) designed to maintain a specified pointing profile during encounters with target objects in the Saturnian system to point instruments, to direct its antenna to Earth for communication, or to avoid deleterious environmental effects such as solar heating on instrument radiators. The commanded profile in inertial space is followed by the Attitude and Articulation Control System (AACS) using inputs from an inertial reference unit and/or a star tracker, and is effected either by reaction wheel assemblies ('RWA control') or for cases where strong external torques exist or rapid slewing is required, by a reaction control system using hydrazine thrusters ('RCS control'). In either case, the AACS engineering telemetry contains information (e.g. reaction wheel speeds, or thruster firings) from which external torques can be estimated. The dominant torque during close Titan flybys is that due to atmospheric drag, and AACS data have been used to reconstruct Titan atmospheric densities (e.g. Sarani, 2007). Similar techniques have recently been used by Venus Express to measure atmospheric densities at that planet (Persson, 2015).

Although flybys through Enceladus' plumes are rather brief, the scientific interest in sampling the plumes has driven some flybys to pass through dense enough regions that drag torques are significant, demanding modeling of the plume density in order to be sure that effective attitude control could be maintained (Sarani, 2010) and permitting reconstruction of the plume density after the fact (Lee et al. 2010, 2013). Although those efforts were described in the engineering literature, the resultant plume density measurements may be of scientific interest and are reported again here (table 1), together with the determination of the E21 plume density which is new. These results serve as a constraint on models of the plume and a comparison with other measurements (such as INMS), as well as informing estimates of the dust:gas ratio.

The full retrieval methodology is described in detail in the papers cited above, although is conceptually rather simple. The spacecraft is a complex shape, whose cross-section normal to the relative gas flow is not coincident with its center of mass. Thus the atmospheric drag force also creates a torque. Knowing the torque from the attitude reconstruction (usually a more sensitive exercise than measuring the drag effect on the spacecraft trajectory) it is possible to derive the density from equation (1) :

$$T_{atm} = \frac{1}{2} C_D \rho A V^2 (\vec{CP} - \vec{CM}) \times \hat{V} \quad (1)$$

where T_{atm} is the atmospheric torque, C_D is a dimensionless drag coefficient, ρ the retrieved mass density, V and $\hat{V}$ denoting the magnitude and unit vector of the gas velocity relative to the spacecraft : A is the cross-sectional area projected in the direction $\hat{V}$. The term in parentheses is the center-of-pressure offset from the center of mass, i.e. the moment arm of the drag force. In this instance, $A=18.6 \text{ m}^2$, and in the $\{X,Y,Z\}$ axes of the spacecraft frame (see supplementary information for definitions), the moment arm is $\{-0.0728, 0.838, -0.386\}$ meters, with spacecraft velocity 8.49 km/s .

The results of this determination for the E21 flyby (in which a hydrogen abundance was recently reported for the plume – Waite et al., 2017) are shown in figure 1. Uncertainties in the retrieved densities include the finite precision of the torque measurement itself and of knowledge of the spacecraft center of mass (recall that the spacecraft has large propellant tanks, and the distribution of propellant mass within is not completely known). These factors contribute to the difference between the retrieved densities using the Z-axis angular momentum history and those derived from the Y-axis.

It is assumed in this exercise that the velocity of the incident plume flow in the spacecraft frame is simply the negative of the spacecraft velocity vector relative to Enceladus' center of mass. For very fast flybys this is fairly accurate, but is less so for E21, where the spacecraft velocity is only a factor of ~5 larger than the plume gas velocity. The spacecraft area is reasonably well-known, although some instrument positions and thermal blanket configurations and mutual shadowing effects may not be perfectly accounted for. Finally, the drag coefficient, which encapsulates the physics of impact and subsequent re-emission of incident particles (molecules or dust grains and ejecta) is assigned the typical spacecraft aerodynamics value of 2.2 (a value of 2.0 would be classical Newtonian drag, wherein the molecule impacts and sticks or is re-emitted with negligible velocity: in practice the re-emission of molecules from the warm spacecraft surfaces enhances the momentum somewhat, as is also the case for ejecta from dust impacts). Taking these factors together, and noting that the speed distribution and impact physics of dust (ice) grains will be rather different from the gas, the retrieved peak density is probably accurate to rather better than 30%. We may note that the difference between modeled and AACS-retrieved plume densities in (E3,E5,E7,E9,E14 – Lee et al., 2013) was always less than 21%, with an average of ~10%.

3. Results and Discussion

The Cassini AACS has maintained the desired pointing throughout its Enceladus flybys. Integration of the density curve in figure 1 with the area and velocity indicates that the spacecraft encountered about 190 milligrams of material. It is not possible to determine how much of this was gas versus dust : this ratio will vary with position in the plume in any case. As discussed by Lee et al. (2013), previous retrieved densities have been in good agreement with predicted densities, based on a simple geometric model.

We may, however, compare with previous in-situ measurements of gas density made by the Ion and Neutral Mass Spectrometer, which has been a prime instrument at many Enceladus encounters (e.g. Waite et al., 2008; 2017). In fact, however, the retrieval of gas densities from INMS counts is nontrivial, and INMS measurement of Titan atmosphere densities were for many years discrepant with AACS retrievals and other data until a full account of gas and ion transport within the INMS instrument was developed in a sophisticated model (e.g. Teolis et al., 2017). The problem at Enceladus is possibly even more challenging, in that the dominant gas species, water vapor (Waite et al., 2006) may interact more with the walls of the instrument than does molecular nitrogen which dominates at Titan. Nonetheless, a couple of densities have been reported by Teolis et al. (2010), those for the E3 and E5 encounters (see table 1). Their gas densities are reported with an uncertainty of 1% or better,

but we may note that the retrievals depend on a conversion efficiency whose estimated value changes by a factor of >2 between flybys; the accuracy of that efficiency estimation is not clear.

It is seen that the E5 determination of total density of about 11 is in good agreement with the ~ 10 for gas only determined by the INMS (both values in units of 10^{-12} kg/m³). The E3 AACS value of ~ 5 is a factor of ~ 2 – 3 higher than INMS – a higher dust:gas ratio may have been responsible, but it should be noted that the lower absolute density makes the AACS determination rather more uncertain than typical.

INMS total gas densities have not been reported for other flybys as yet, although Perry et al. (2015) do indicate CO₂ densities inferred from mass 44 counts. CO₂ represents 0.3–0.8% by volume of the plume gas, and so a total gas density can be guessed by scaling this value by 120–330. Adopting 330 yields a value that agrees well with the water vapor number from Teolis et al. (2010) for E3, but a factor 2 different for E5, highlighting the challenges of INMS data analysis, and the utility of independent density measures, as in the present paper. Perry et al. (2015) report mass 44 counts for E7 and E14, which we scale up by 330 in the table.

In all cases, the AACS density (the ‘effective density’ producing torque is after all the quantity of interest for mission design and safety considerations) is larger than the INMS-derived value by a factor of 2–3. Some component of this may be dust : dust:gas mass ratios of unity are not implausible (e.g. Waite et al., 2006; Lorenz, 2016) which would account for a factor of 2 difference. Further difference may be due to errors in one or both determinations, in gas composition of the plume (e.g. CO₂:H₂O ratio) or differences in dust:gas ratio.

4. Conclusions

We have reported density measurements of the Enceladus plume using Cassini engineering data which provide an independent measure of the total (gas and dust) material encountered. Comparison with other data in general shows good agreement, and suggests possible variations in plume gas composition or dust:gas ratio.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

(a) the raw reported quantity, namely the spacecraft angular momentum reported at a 4-s cadence (Z-axis only shown here). Relative errors are probably better than 10%. (b) the derivative of angular momentum, minus any commanded torques (here none), is the torque, here attributed entirely to gas drag. (c) The derived atmospheric density – solid line is that derived from the Z-axis torque, the dashed line from the less well-determined Y-axis torque.

The difference between the two curves gives some indication of the retrieval precision, of the order of 30% of the peak value.

Table 1.

Plume density retrievals from AACS and INMS – see text for discussion of uncertainties. Notes 1 . AACS density from Lee et al. (2013). 2. INMS density from Teolis et al. (2010). 3. INMS density deduced from Perry et al. (2015) mass 44 counts, assuming CO₂ volume mixing ratio of 0.3% (Waite et al., 2017). INMS density from water number density in Dong et al. (2011). 5. INMS density from Teolis et al. (2017). Hyphen indicates that densities have not yet been reported.

Flyby	Date	C/A Altitude (km)	C/A Latitude (°S)	C/A Longitude (°W)	Flyby Speed (km/s)	AACS Peak Density (10 ⁻¹² kg/m ³)	INMS Peak Density (10 ⁻¹² kg/m ³)	Note
E-3	12 March 2008	48	20	135	14.41	5.6	2.3 (1.9)	1,2,(3)
E-5	9 October 2008	29	28	97	17.73	11.2	10 (22)	1,2,(3)
E-7	2 November 2009	103	82	159	7.74	31.1	24.6 (9)	1,4,(3)
E-9	28 April 2011	103	89	147	6.51	34.7	-	1
E-14	1 October 2011	9	90	128	7.44	47.0	13.2 (25)	1,5,(3)
E-21	28 October 2015	49	87.5	71	8.49	45–55	-	This Work