Constraining Enceladus Plume Structure and Variability from Cassini INMS and UVIS observations

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Ion Neutral Mass Spectrometer (INMS) data from three Cassini spacecraft low altitude (99, 74, 74 km) flybys through the Enceladus plume (Table 1), reveal detail of the neutral gas density and distribution along the spacecraft trajectory, enabling resolution of individual gas jets and tiger stripe sources within the broad plume [1,2]. Here we use these INMS data, together with two (Table 1) Ultraviolet Spectrograph (UVIS) solar and stellar occultation meaurements of the plume's gas column density, to (1) constrain the properties (locations, magnitudes and gas velocity) of the plume surface sources, and (2) extrapolate the three-dimensional structure of the plume, including the diffuse plume and individual tiger stripe sources.

Table 1. INMS (UVIS) flyby (occultation) times and true anomalies (180 deg is Enceladus apoapsis).

Event	Time (UTC)	Date	
UVIS 1	06:01:17.45	18-May	2010
UVIS 2	17:07:20.800	24-Oct	2007
E7	07:41:57.678	2-Nov	2009
E14	13:52:25.714	1-Oct	2011
E17	18:30:09.18	27-Mar	2012
E18	14:01:37.806	14-Apr	2012

To model the plume, we approximated the gas thermal velocity distribution as a drifted Maxwellian via an analytical expression that depends on the source(s) rate, location and Mach [3]. The expression can be quickly evaluated along the Cassini trajectories, enabling rapid iteration through plume parameter space, i.e., source positions, rate, Mach numbers, and jet pointing directions. We consider two possible plume components: (1) a source continuously distributed along the tiger stripes with Mach number as a free parameter and source rate an increasing function of tiger stripe temperature (measured by CIRS), and (2) multiple jets originating from points along the tiger stripes, with jet-specific source rates, Mach numbers, and pointing directions. Optionally we can apply a Mach number distribution to the continuous or jet source, as may be appropriate for gas emerging from a fissure with a distribution of flow velocity (e.g. slower near the walls).

The question of whether the plume sources, as seen in Cassini ISS imaging data, should be interpreted in terms of discrete jets distributed along the tiger strike, or rather a continuous curtain-like emission, has recently become a major focus of discussion in the literature [4,5]. While ISS is sensitive to the plume dust, the dust is presumably entrained in the vapor flow, and thereby propelled from the surface fissures into space by the escaping vapor. Accordingly, the INMS and UVIS plume vapor measurements can provide an additional constraint on the nature of the gas sources, and can thereby help to determine the relative contributions of curtains and jets. In Figs. 1-2 we compare our model fits to the INMS CO_2 density and UVIS H_2O column density measurements under a model consisting (1) of the 98 jets discussed by [4], and (2) a continuous curtain emission as proposed by [5]. In model (1) we use jets with the same source locations and directions as identified by [4]. We (i) consider mach 2-4 jets, and (ii) vary the strengths of the jets with our computational modeling tool. With model (2) we also vary the strength of the emission along the tiger stripes, but in this model we consider a continuous emission along the tiger stripes directed normally to the surface. The models typically yield multiple solutions, corresponding to reductions/enhancements in different combinations of jets, or different vapor source distributions along the tiger stripes. As shown in Figs. 1-2 the fit to the INMS densities and to the UVIS column densities appears slightly better for jets which capture specific peaks missed by the curtain models.

We find evidence of local scale time variability in the plume sources along the tiger stripes and, using the jets [4] as the modeling constraint, we could, in some cases, identify specific jets which had changed between flybys. The modeling algorithm analyzes all possible model fits to the each of the INMS flybys and UVIS occultation, including all likely combinations of jet intensities or (in the curtain model) tiger stripe emission profiles which fit the data. From these solutions we reconstruct the most probable strength, and margin of error, of each jet. As shown in Fig. 3, the individual jets appear to fluctuate sometimes drastically between flybys, but some flybys exhibit generally elevated activity. The variability of each jet was unpredictable, and showed no discernible correlation to the normalized number of jet sightings in ISS images as reported by Porco et al. 2014 [4] or to predictions of tidal stress models of the compressive/tensional forces as a function of position along the tiger stripes and tiger stripe orientation. However, our results for the total plume source rate show a similar dependence on Enceladus orbital position mean anomaly to that indicated by Cassini VIMS data [6] as shown in Fig. 3, with the total plume source rate, i.e., summed over all jets, elevated near Enceladus apoapsis, as expected. Therefore, while a pattern of variation in specific jets cannot presently be discerned (probably due to details in the geometry of individual fissures beyond detectability), the overall level of jet activity and total plume intensity exhibits the anticipated dependence on mean anomaly (Fig. 4), thereby providing the first confirmation of the VIMS result on the basis on INMS and UVIS based plume modeling.

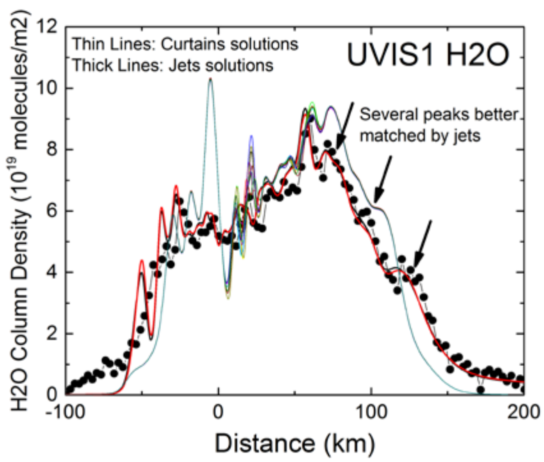

Figure 1. Enceladus plume water vapor column density measurement from the UVIS 2010 solar occultation (dotted line), plotted versus distance across the plume along the occultation line of sight minimum ray height. Thin lines: modeling solutions for the curtains case. Thick lines: Solutions for the [4] jets.

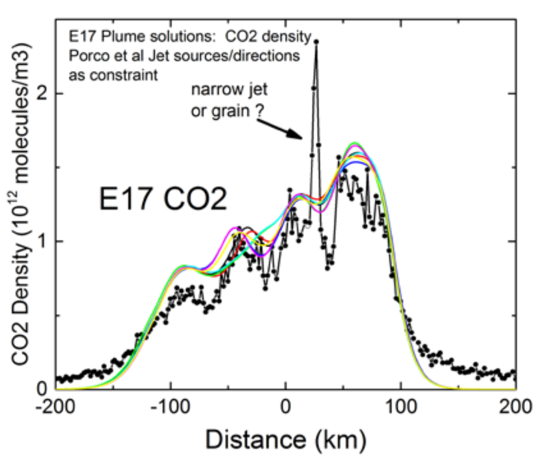

Figure 2. INMS CO2 density measurement (Dotted line) vs distance from closest approach along the E17 flyby trajectory, showing peaks suggestive of discrete plume sources. Lines: Solutions with [4] jets as the constraint.

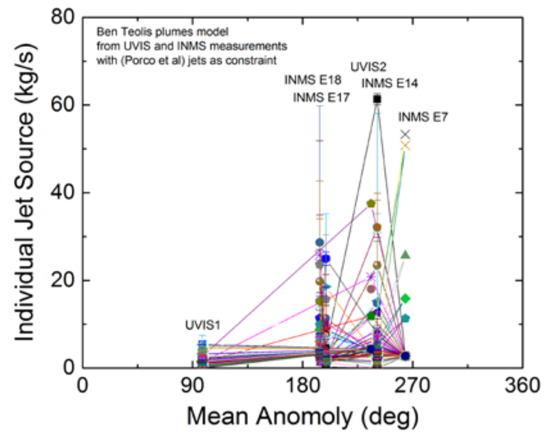

Figure 3. Estimated jet source strengths from the plume modeling versus Enceladus mean anomaly for the UVIS occultations and E7, 14, 17 and 18 flybys, using the Porco et al. 2013 [4] jets as the constraint. The error bars represent the variability between solutions. Individual jets are unpredictable but overall activity is maximal near apoapsis.

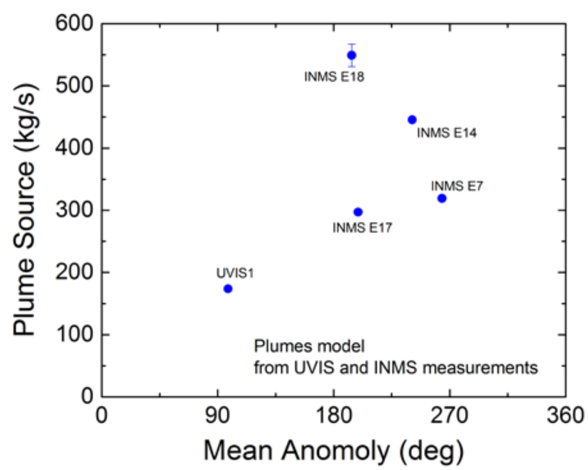

Figure 4. Estimated plume total mass source rate versus Enceladus orbital posi-tion. While the plume exhibits significant variation between flybys, the overall trend is consistent with a more-intense plume near 180 deg (apoapsis), consistent with the trend identified in Cassini VIMS data [6].

References: [1] Perry, M. E., et al (2015), *Icarus*, 257, 136. [2] Hurley et al. (2015) *JGR*, 120, 1763. [3]Dong, Y., et al (2011), *JGR*, 116, A10294. [4] Porco et al (2014), *ApJ*, 148, 45. [5] Spitale, J. N., et al (2015), *Nature*, 521, 57. [6] Hedman et al (2013), *Nature*, 500, 182.