DIRECT MEASUREMENT OF THE VELOCITY OF THE ENCELADUS VAPOR PLUMES. Mark E. Perry[1], Benjamin D. Teolis[2], Jacob Grimes[2], Greg P. Miller[2], Dana M. Hurley[1], J. Hunter Waite, Jr.[2], Rebecca S. Perryman[2], Ralph L. McNutt, Jr.[1], [1]The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA. [2]Southwest Research Institute, San Antonio, TX 78228, USA.

Introduction: The velocity distribution of the neutrals that comprise Enceladus' vapor plumes is a fundamental property of the plumes and the conditions at the source. (See Spencer and Nimmo 2013 [1] for an overview of Enceladus and its plumes.) Unfortunately, most observations can only provide estimate the neutral velocities based on indirect measurements and assumptions. One such class of measurements is the one containing most of the data from the Cassini Ion and Neutral Mass Spectrometer (INMS), which has made multiple *in situ* measurements of the plumes. When operating in its Closed Source Neutral (CSN) mode, INMS obtains the density of the plumes along Cassini's track [2, 3], but neither these measurements nor Cassini's Ultraviolet Imaging Spectrometer (UVIS) measurements of column density during occultations [4] provide the molecular velocities. Without these velocities, for example, conversions of the observed density to the mass loss of the emitted vapor requires assumptions such as the temperature of the vapor.

During four encounters between November 2009 and October 2015 (Table 1), the INMS operated in its Open Source Neutral Beam (OSNB) mode. Although 500 times less sensitive than the CSN mode, the OSNB mode has two advantages: 1) it can measure the velocities of the neutrals, and 2) it can measure reactive neutrals that might be affected by contact with the walls of the INMS CSN inlet system. Although the velocity data from OSNB measurements are somewhat coarse, they provide insight into the speed distribution of H_2O molecules within and surrounding the plumes.

Flyby	Min alt	Location relative to plume
E8	1,600km	In a high-velocity jet
E11	2,300km	Slower, broader velocities
E16	100km	Far from south pole region
E21	49km	Deep in plume; multiple scans

Table 1. Enceladus encounters with OSNB measurements. Except for E21, Cassini rotated during each encounter and the compensation velocity (V_{COMP}) was fixed. During E21, pointing was fixed at 3° relative to Cassini's flight path and V_{COMP} was varied to obtain velocity scans.

Data analysis: In the OSNB mode, the velocity of the neutrals measured by INMS are determined by the angle of the INMS boresight, which sets the direction of the molecules, and the INMS compensation velocity parameter (V_{COMP}), which sets the speed of the molecules. The vector addition of this velocity, which is the neutrals' velocity relative to Cassini, with Cassini's flyby velocity provides the velocity of the neutrals relative to Enceladus (Fig 1). During E8, E11, and E16, V_{COMP} was fixed, but Cassini rotated so that INMS fortuitously scanned the velocity of neutrals arriving from Enceladus. Cassini's rotation produced a single velocity scan, where the measured molecules were approximately radial from Enceladus with speeds increasing from 0 to 3 km/s. E21 operations were different: Cassini's attitude was fixed and V_{COMP} was scanned throughout the encounter to purposely sample the velocity distribution of the plume multiple times.

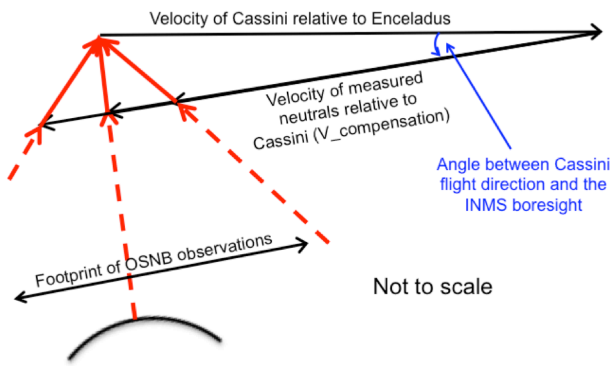

Fig. 1. Diagram showing the geometry for OSNB observations far from Enceladus such as those during E8, E11, and E16. When the INMS compensation velocity is set to the middle-length black arrow, INMS will accept ions within a range of speeds indicated by the longer and shorter black arrows. The solid red arrows indicate the velocity (speed and direction) of the measured ions relative to Enceladus.

For each OSNB measurement, INMS accepts molecules with a range of speeds and a range of angles. For H_2O at the velocities of the encounters with Enceladus, the speed resolution is ±300 to ±600 m/s and the angular resolution is ±2° to ±3° [5]. Ground calibration experiments and instrument modeling are being conducted to confirm and refine these values. For E8, E11, and E16, the measurement ranges translate to an uncertainty in the speed of approximately ±0.3 km/s. The angular resolution of the measured molecules was sufficient to identify Enceladus as the source of the molecules. During E21, the proximity to Enceladus elevates the importance of the angle of the measured neutrals, and any velocity-space dependence of the neutral density is convolved with the spatial dependence as Cassini traveled through the plumes and observed neutrals approaching from both in front and from behind Cassini.

Results: The H_2O neutrals measured during E8 had a Mach-4 distribution centered on 1.2 km/s with a width of ±300 m/s, which corresponds to a temperature of

65K (Figure 2). The Mach-4 result is consistent with the width of dense, high-velocity jets as deduced from UVIS occultation data [4]. As shown in Fig. 3, all of the E8 OSNB measurements were within range of the source marked "V," one of the originally identified strong sources [6]. An interpretation of these results is that the velocity distribution derived from E8 is for the dense, high-velocity sources.

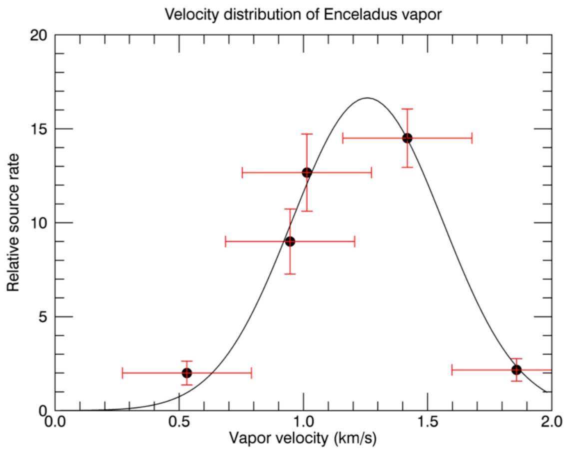

Fig. 2. A drifted Maxwellian distribution fit to the E8 OSNB measurements of neutral velocity. The distribution has a bulk velocity of 1.25±0.1 km/s and a width of ±300 m/s.

During the E11 encounter, OSNB measurements were farther from the tiger stripes and farther from the influence of the strongest sources. The E11 measurements showed a bulk velocity of 750 m/s with a width

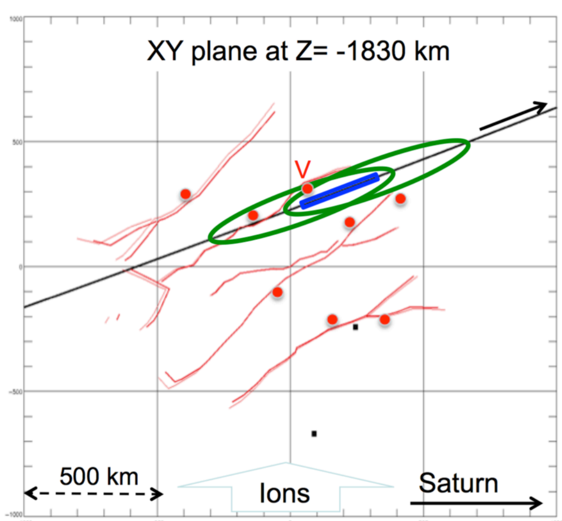

Fig. 3. Geometry of the E8 encounter. Red lines are projections (emissions normal to surface) of the tiger stripes onto the plane of the E8 trajectory (black line). Red dots are location of the original 8 sources. Blue bar is the location of the OSNB measurements. Green ovals show the reach of OSNB mode for high-Mach sources. INMS is in the core of source V emissions for the all the OSNB measurements.

of ±430 m/s. This slower, broader distribution of velocities may represent the more-diffuse emissions that comprise most of the plume. This interpretation is bolstered by modeling of INMS data from the early encounters, E3 and E5, which showed similar velocities [7] and by recent modeling that suggests that the diffuse sources distributed along the tiger stripes may be the dominant source of water vapor [8].

Instead of the single scan of velocities obtained in E8, E11, and E16, the INMS observations for E21 were designed for multiple scans. Figure 4 shows the aggregate of the three scans performed during the time when INMS was in the densest region of the plumes, near close approach. The plot shows the speed distribution in one dimension, along the track of Cassini (the scans only varied the along-track velocity). At ±400 m/s, the width of the distribution is nearly identical to that measured during E16 and is further indication of the primary velocity distribution. However, these are preliminary results that may be adjusted when the data are fully reduced. For example, the width of the distribution is convolved with the range of speeds accepted for each INMS measurement, and that range is similar to the width of the observed distribution. The measurements

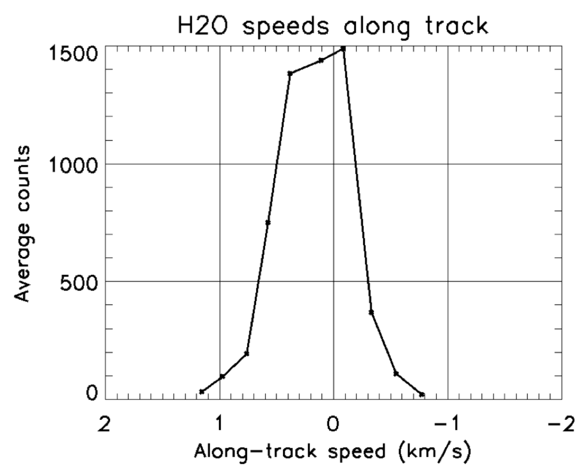

Fig. 4. The E21 velocity distribution for H_2O during the six seconds centered on the time of closest approach. The plot shows the along-track velocity; positive velocities are looking forward (the neutrals are approaching Cassini from the front). The width is ±400 m/s.

are also gathered at different locations and therefore subject to the spatial variations created by separate sources which may be strong jets or diffuse emissions. Modeling efforts are underway to aid in assessing the effect of these factors.

References: [1] Spencer J. R. and Nimmo F. (2013) *Annu. Rev. Earth Planet Sci., 41*, 693. [2] Teolis B. D. et al. (2010) *JGR, 114,* A09222.. [3] Perry et al. (2015) *Icarus, 257*, 139. [4] Hansen et al. (2011) *GRL, 38,* L11202. [5] Waite J. H. et al. (2004) *SSR, 114*, 113 [6] Spitale and Porco (2007) *Nature, 449*, 695. [7] Smith et al. (2010) *JGR, 115*, A10252. [8] Hurley et al. (2015) *JGR, 120*, 1763.