INMS MEASUREMENTS OF ENCELADUS PLUME DENSITY. Mark E. Perry[1], Benjamin D. Teolis[2], Brian A. Magee[2], J. Hunter Waite, Jr.[2], Timothy G. Brockwell[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: During six encounters between early 2008 and late 2013, the Cassini Ion and Neutral Mass Spectrometer (INMS) made *in situ* measurements deep within the plumes of Enceladus, the Saturn moon that emits at least 200 kg/s of water vapor from its south-polar region [e.g., 1,2]. Throughout each encounter, INMS measurements show density variations that reflect the conditions at the source of the vapor, where high-velocity jets and slower, more-diffuse gasses are released from a probable subterranean ocean [3,4]. Spatial variations in vapor density were first quantified by UVIS measurements of column density [5]. However, INMS data are unique in their ability to sample and investigate the local density variations.

Density calculations: Teolis et al., 2010 [6] analyzed the first two INMS plume data sets deep within the plume, and described the approach for dealing with two complications of INMS data at Enceladus: an instrument effect that causes time-distortion of the INMS measurements of H_2O, which comprises at least 90% of the plume; and the spurious measurements caused by ice grains entering the INMS aperture. The first effect, non-volatile molecules adhering to the walls of the INMS inlet system, results in H_2O measurements that do not reflect rapid density variations. In contrast, INMS responds to volatiles species in a fraction of an Integration Period (IP), which is the temporal resolution of INMS [7]. Therefore, we use volatiles to track changes in density. CO_2, with a mass of 44 u, and N_2 (or CO) at 28 u are the two most abundant volatiles.

An ice grain entering INMS's Closed Source Neutral (CSN) aperture while INMS is measuring a volatile species causes a high count or spike for that single measurement. Spikes mask the gas density, cloud interpretation of INMS measurements, and add uncertainty. Since the resident time for volatiles in the INMS CSN inlet system is so short, the grain only affects the measurement of volatiles for one IP.

The size of ice grains spans the range from molecular clusters to several microns in radius. Only grains that cause counts rates much larger than the neighboring measurements are clearly identified. The existence of other grains causes two types of ambiguity in the INMS measurement: small spikes may be misinterpreted as local increases in vapor density, and rapid density variations may be misinterpreted as grain spikes. At lower gas densities, smaller spikes are detectible; at peak densities, only the largest spikes are unambiguous.

INMS measurements can also be affected by high velocities. At speeds greater than 10 km/s, larger organic molecules may dissociate, creating smaller molecules that are misinterpreted as vapor constituents. With encounter velocities greater than 14 km/s, both E3 and E5 showed more carbon-group molecules than the later, slower encounters. The enhancement of molecules below 100 u indicates that molecules with masses of 100 u or more exist in the plume and dissociate on impact with the CSN inlet. This has a drastic effect on minor-species composition but less on the density structure of the plumes as derived from the major volatiles.

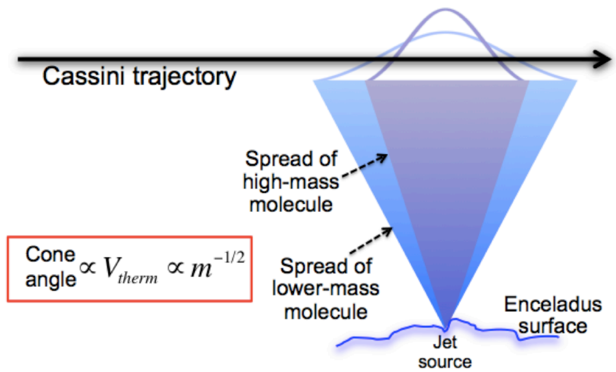

Fig. 1. Diagram of the mass-dependent behavior of high-velocity molecules emitted by the jets. All molecules are emitted at the same supersonic velocity and all in thermal equilibrium at the time they are emitted. The cone angle or spreading of the molecules depends on mass and causes differences in spatial composition that are measured by INMS.

Another consideration in interpreting INMS measurements is a characteristic of the plume that complicates direct conversion of volatile density to the bulk density. This characteristic produces INMS measurements that show variations in the fractional abundance of volatiles. Although changes in source composition are possible, the mass-dependent behavior of molecules in high-velocity jets can produce the observed variations. Molecules emitted from jets have bulk velocities that are several times the thermal velocity, and the cone angle or spreading of the molecules depends on their thermal velocity, which is inversely proportional to the square root of the mass (Fig. 1). Lower masses have wider spreading cones—the molecules are less collimated—and produce less-peaked densities. These differences are substantial and measureable: water vapor, at 18 u, spreads 60% faster than CO_2 at 44-u.

Modeling confirms that mass-dependent thermal velocity can create the compositional differences observed by INMS. Model results show that the ratio of 44 u to 28 u densities can differ by a factor of two and that measured composition depends on jet angle, location, temperature, and altitude. Models of volatile densities provide a means to determine H_2O density and produces constraints on the vapor source parameters.

Results: During E3 and E5, Cassini traveled from north to south, and was embedded in the plumes once entering them ~1 Enceladus radius (R_E) from the south pole. This geometry minimizes the mass-dependent effects, as is evident in the INMS measurements, which show similar behavior and structure for all volatiles. For these two encounters, the volatiles accurately represent the time-dependent density for all species, including H_2O.

For the other four encounters, E7, E14, E17, and E18, Cassini passed at low altitude (<100 km) across the plumes, and INMS measurements of volatiles do not translate directly to H_2O density. This is particularly obvious in E14 (Figure 2), where the two densest volatiles, at 28 u and 44 u, have density profiles that differ by more than a factor of two in relative abundance. Since H_2O density depends on the model used to simulate the outflow of the jets, H_2O densities are the topic of additional research and not provided here.

Based on ground [7] and flight calibration at Titan [8], each INMS count during E7, E14, E17, and E18, corresponds to 2,100 molecules/cm^3 for the 28-u mass channel and 1,500 molecules/cm^3 for the 44 u channel. Calibration uncertainty is 15%. For E3 and E5, which had higher velocities, the calibration is 890 and 660 molecules/cm^3 for 28-u and 44-u channels, respectively. Since high-velocity measurements are modified by fragmentation products of molecules with masses greater than 100 u, counts may be increase by a factor of two to five above the counts corresponding to the actual 28-u and 44-u densities [9].

Ice grains contribute the greatest uncertainty in deducing plume structure or density variations. An ice grain can increase an INMS measurement from 1 to 10,000 counts. When the increase is more than 40%, it can usually be identified by comparison with neighboring measurements and is excised from the data.

Discussion: INMS data at Enceladus contain a wealth of information, but they to not immediately reveal the bulk density or the density variations in the most abundant species, H_2O, whose response in INMS is distorted by wall interactions in the inlet system. However, INMS measurements of volatiles do show structure, which can be used to infer properties of the vapor source, particularly the high-velocity jets. Those source properties can then be used to model the H_2O density and the bulk density of the plume.

INMS measurements of the plume show evidence of compositional variability both between encounters and within encounters. E14 has the most variability, a factor-of-four variation in the ratio of 28-u and 44-u counts. These clear differences in density are expected for the high-Mach outflow and are due to mass-dependent thermal velocities of the emitted molecules.

The mass-dependent densities in the jets complicate translation of volatile measurements to H_2O density, but this mass dependence also provides additional insight into the source properties. Indeed, the ratios may provide essential data on the location of a supersonic jet. With a single mass, we cannot differentiate between measurements in a weak jet from those at the edge of a jet. With two masses, a higher ratio of the more-massive species indicates greater penetration into the core of the jet and a lower ratio indicates a jet-edge measurement. Source composition differences are possible, but they are not necessary to explain the INMS measurements.

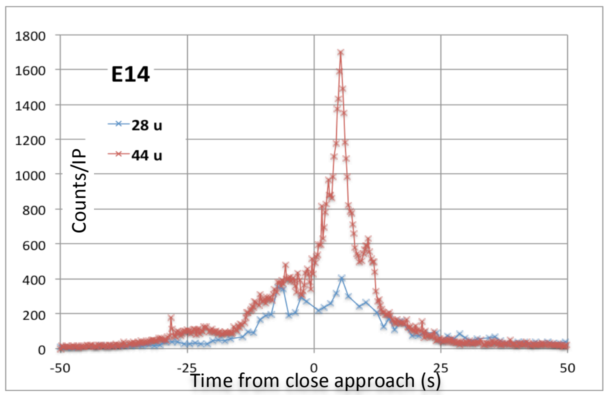

Fig. 2. Profiles for the E14 Enceladus encounters. The plots contain count rates (cnts/IP) for species with masses of 28 u and 44 u. Measurements that were contaminated have been removed, leaving gaps in the data record. To improve spatial resolution for the last three encounters, CO_2 at 44 u was collected at several times the rate of the 28-u measurements.

The relative uncertainty in structure due to spikes is substantial, and interferes with the desire to draw definite conclusions about source rate, location, angle, velocity, and variability of the jets. We can use the size-frequency distribution of the ice grains to characterize the ice-grain uncertainty. We estimate the likelihood that an ice grain is sufficiently large to affect the INMS measurement but insufficient to be clearly identified as a spike. This work in ongoing.

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