FAR ULTRAVIOLET OBSERVATIONS OF ICY SATELLITE ATMOSPHERES AND PLUMES. C. J. Hansen[1] and A. R. Hendrix[1], [1]Jet Propulsion Laboratory, Mail stop 169-237, 4800 Oak Grove Dr., Pasadena, CA 91109; candice.j.hansen@jpl.nasa.gov.

Introduction: The potential for investigating the atmospheres and eruptive activity of icy satellites at far ultraviolet wavelengths has been demonstrated by the Cassini Ultraviolet Imaging Spectrograph (UVIS). UVIS has observed the oxygen atmosphere of Europa, determined upper limits for the potential oxygen atmosphere of Rhea, and constrained volatile activity of Phoebe. The biggest scientific payoff was the UVIS investigation of Enceladus' water vapor plume. The spatial dimension of the Cassini UVIS FUV channel adds the capability to map emissions, which often enhances the data interpretation.

Techniques: We have used two primary methods to study gases associated with icy satellites: long integration observations of gas emissions, and stellar occultations. In the FUV there are useful emission lines for common important gases such as oxygen (130.4 and 135.6 nm) and nitrogen (114.3 and 149.3 nm). Stellar occultation observations offer the opportunity to detect the broader absorptions of molecules such as water vapor, CO, CO_2, and O_2.

The Cassini UVIS has 4 channels: an extreme ultraviolet spectrograph (EUV), a far ultraviolet spectrograph (FUV), a Hydrogen-Deuterium Absorption Cell, and a High Speed Photometer (HSP). The UVIS FUV channel uses a 2 dimensional microchannel plate detector to cover 1024 spectral channels, spanning 111.5 to 190.0 nm, by 64 ~1 mrad spatial pixels. The EUV channel also uses a microchannel plate for similar simultaneous collection of spatial and spectral data. The wavelength range of the EUV channel is 55 to 110 nm. The HSP is sensitive to the same wavelength range as the FUV. The HSP is read out every 2 or 8 msec [1].

Specific Investigations: Cassini has observed all of Saturn's major icy satellites. Additionally, Io and Europa data were acquired as Cassini flew past Jupiter.

Sputtered Atmospheres - Europa. Europa has a thin O_2 atmosphere sputtered from its water ice surface. Discovered by HST [2] the predominance of 135.6 over 130.4 emission was indicative of O_2 as the primary constituent. The 130.4 emission feature is a multiplet, and is excited by resonant solar scattering and electrons. The 135.6 feature is also a multiplet, but is a forbidden transition, excited only by electron impact dissociation. The ratio of the two is indicative of whether the oxygen is atomic or molecular.

UVIS found that in addition to the bound molecular oxygen atmosphere there is atomic oxygen extending further out. The spatial dimension of the data allowed us to separate the contribution of atomic oxygen of Io's torus from atomic oxygen associated with Europa [3].

Sputtered Atmospheres - Rhea. Rhea is the largest of Saturn's icy moons, and the only one massive enough to potentially have a gravitationally bound atmosphere [4]. We selected 10 data sets to investigate whether spectral features indicative of the presence of an oxygen atmosphere could be detected. These were all observations with a typical duration of 90 min and stationary pointing. The data was calibrated and flat-fielded after summing over time. We then summed eight spectral pixels containing the 130.4 nm multiplet and eight spectral pixels containing the 135.6 nm multiplet. Eight spectral pixels between the two features were summed to use for background determination and subtracted from each of the oxygen feature sums. Signal above background was then plotted for the 130.4 spectral band and the 135.6 spectral band vs. UVIS spatial pixel to look for a morphologic association of oxygen with Rhea.

Although there are oxygen emission features in the data we believe these are associated only with the oxygen permeating Saturn's system [5], not with Rhea. The signal levels are consistent with the system oxygen, and there is no morphological indication that the oxygen is bound to Rhea.

We have calculated an upper limit to the oxygen from the UVIS detection threshold [6]. UVIS sensitivity at 130.4 nm is 3.4 counts/sec-kRayleigh. For a 90 min duration observation the detection threshold at 130.4 nm is 2.72 Rayleighs or (1/4pi)*2.72 x 10^6 photons/cm^2-sec-ster. Solar scattering constrains the amount of atomic oxygen that is detectable (the probability for electron excitation is far lower). The probability for solar photon scattering (g-val) at Saturn is 1.8 x 10^{-7} / sec. Column density can be calculated from I = [O] * l *g-val where l is the path length. The upper limit atomic oxygen column density is then [O]= 2.72 x 10^6 /(1.8 x 10^{-7}) = 1.5 x 10^{13} cm^{-2}. Similarly the upper limit for molecular oxygen column density is determined by the signal due to electron impact dissociation probability. UVIS sensitivity at 1356 is similarly 3.4 counts/sec-kRayleigh, thus required signal is again 2.72 Rayleighs for a positive detection. For emission due to electron impact dissociation, I= $[O_2]$*[e-]*k*l. For an electron density of 5/cm^3 and k = 3.5 x 10^{-9} cm^3/sec at 20 eV, $[O_2]$ = 2.72 x 10^6 / (5 x 3.5 x 10^{-9}) = 1.6 x 10^{14} cm^{-2} [6].

Phoebe Volatile Activity. The possibility that Phoebe could have formed originally in the outer solar system motivated us to look for evidence of volatile activity analogous to Chiron. Total integration time on Phoebe was 10.3 hours. The spectrum shows no evidence of oxygen, nitrogen or carbon monoxide emissions that would be anticipted if volatile activity were present. Upper limits to oxygen and C abundance were calculated as above [7].

Enceladus' Plume. Two stellar occultations were observed during two close Cassini passes by Enceladus. The first showed no indication of the presence of an atmosphere. The second showed the clear absorption signature of a gas on ingress but not egress. This was the initial evidence that Enceladus has a regionally confined plume rather than a globally distributed atmosphere. The absorbing gas was identified to be water vapor and the column density was determined at different altitudes corresponding to the track of the star. Simple assumptions with regard to the velocity (we assumed thermal velocity at a temperature of 145 K) and spatial distribution allowed the flux of water from Enceladus to be computed [8]. As Cassini approached Saturn we observed atomic oxygen filling the system [5]. The source was a mystery until the discovery of the plume of water vapor spewing from Enceladus. The calculation of the flux of water from Enceladus showed that this is an adequate amount to maintain the oxygen in the system against losses. Conversely, observations of the oxygen in the system can be used as a proxy for monitoring Enceladus' levels of eruptive activity. Data analysis shows that the number density of system oxygen has changed, occasionally dramatically [5].

More sophisticated modeling of the plume, validated by comparison to the vertical distribution of water vapor determined from the stellar occultation data, verified the flux numbers. The velocity that best matched the data was 300 to 500 m/sec which implies that the source is venting from some depth beneath the surface, inconsistent with simple sublimation of a surface source [9].

A new stellar occultation observation will be acquired in October 2007, shown in Figure 1. The geometry of the occultation will carry the star approximately parallel to Enceladus' limb, through the jets of gas coming from the tiger stripes that blend to become Enceladus' plume. The UVIS HSP will be used to detect fluctuations in density, which will help to determine the ability of the gas to loft solid particulates of ice.

Escaping gases. Stellar occultations and emission feature profiles can be used to derive the profile of a gas escaping from Saturn's icy moons, such as hydrogen. Hydrogen emission feature profiles were reported on in 2005, however results were tentative [10]. The profiles are being updated with the new UVIS flat field calibration. We will also report on the acquisition and analysis of new stellar occultation data from Tethys, Dione and Rhea.

References:

[1] Esposito, L. et al (2004) *SSR, 115:299-361*. [2] Hall, D. T. et al (1995) *Nature* 373:677-679. [3] Hansen, C. J., D. Shemansky and A. Hendrix (2005) *Icarus* 176:305-315. [4] Saur, J. and D. Strobel (2005) *Astrophys. J.*, 620:L115-L118. [5] Esposito, L., *et al* (2005) *Science* 307:1251-1255. [6] Jones, G. et al (2007) submitted to *Nature*. [7] Hendrix, A. R. and C. J. Hansen (2007) submitted to *Icarus*. [8] Hansen, C. J. *et al* (2006) *Science* 311:1422-1424. [9] Tian, F. *et al* (2007) *Icarus*, in press. [10] Hendrix, A. R. and C. J. Hansen (2005) *BAAS* 37:706.

Acknowledgements: This work was partially supported by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautic and Space Administration.

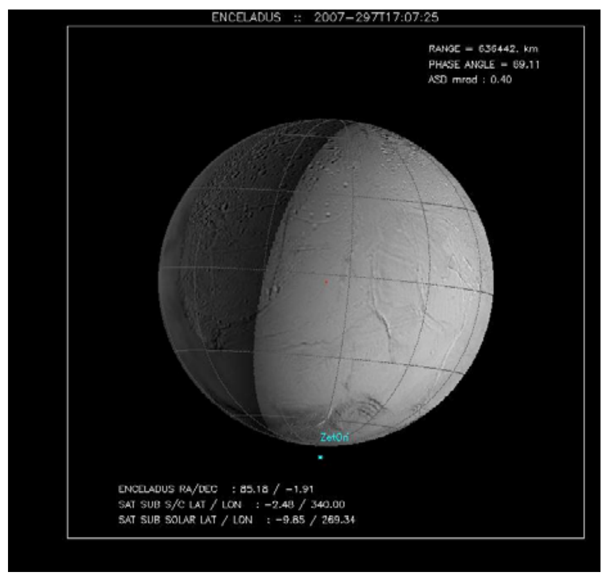

Figure 1. The geometry of this occultation will carry the UVIS field of view horizontally through Enceladus' plume, which may allow us to detect individual gas jets coming from the tiger stripes.