

# Detection of Exospheric $O_2^+$ at Saturn's Moon Dione

R.L.Tokar<sup>1</sup>, R.E.Johnson<sup>2</sup>, M.F.Thomsen<sup>1</sup>, E.C. Sittler<sup>3</sup>, A.J. Coates<sup>4</sup>, R.J. Wilson<sup>5</sup>, F.J. Crary<sup>6</sup>,  
D.T. Young<sup>6</sup>, G.H. Jones<sup>4,7</sup>

<sup>1</sup>Space Science and Applications, Los Alamos National Laboratory, Los Alamos, NM 87545  
([rlt@lanl.gov](mailto:rlt@lanl.gov))

<sup>2</sup>University of Virginia, Charlottesville, VA

<sup>3</sup>NASA, Goddard Space Flight Center, Greenbelt, MD

<sup>4</sup>Mullard Space Science Laboratory, University College London, UK

<sup>5</sup>University of Colorado, Boulder, CO

<sup>6</sup>Southwest Research Institute, San Antonio, TX

<sup>7</sup>The Centre for Planetary Sciences at UCL/Birkbeck, UK

## Abstract

During a close pass of Cassini through the plasma wake of Saturn's moon Dione on April 7, 2010 the Cassini Plasma Spectrometer (CAPS) detected molecular oxygen ions ( $O_2^+$ ) on pick up ring velocity distributions, thus providing the first in situ detection of a neutral exosphere surrounding the icy moon. The density of  $O_2^+$  determined from the CAPS data ranges from 0.01 to 0.09 /cm<sup>3</sup> and is used to estimate the exosphere  $O_2$  radial column density, obtaining the range 0.9 to  $7 \times 10^{11}$ /cm<sup>2</sup>. CAPS was unable to directly detect pick up  $H_2O^+$  from the exosphere but the observations can be used to set an upper limit to their density of ~10 times the  $O_2^+$  density.

## Introduction

Saturn's moon Dione (radius ~ 560 km) is in an approximately circular orbit at a radial distance from Saturn of about 6.3 Saturn radii ( $R_S = 60,268$  km), outside the orbits of Enceladus ( $R=3.9 R_S$ ) and Tethys ( $R=4.9 R_S$ ) and inside Rhea ( $R=8.7 R_S$ ). Dione is one of Saturn's icy moons, with a surface dominated by water ice [*Fink et al.*, 1976]. It's orbital speed is about 10 km/s, so that the proton and water group ( $O^+$ ,  $OH^+$ ,  $H_2O^+$ , and  $H_3O^+$ ) plasma in Saturn's inner

magnetosphere, with speed comparable to the rigid corotation speed at Dione's orbit (~62 km/s), overtakes the moon. This plasma impacts and is absorbed by Dione's surface creating a plasma void region (a wake) extended in the direction of Dione's orbital velocity and possibly a neutral exosphere via radiolysis and sputtering. To date there have been two flybys of Dione by Cassini, on Oct 11, 2005 an upstream flyby (D1) and on April 7, 2010 a wake flyby (D2), both at altitudes of about 500 km. In this study, the in situ detection of  $O_2^+$  pick-up ions by the Cassini plasma spectrometer (CAPS) (*Young et al.*, [2004]) during D2 is reported. (No similar pick-up was detected by CAPS during the D1 flyby due to the unfavorable upstream geometry.) The pick-up ions are produced when neutrals in the exosphere are ionized primarily via charge exchange, with electron impact and photo ionization also contributing. The newly produced pick-up ions are swept downstream in Saturn's magnetic field. The observations confirm the existence of a sputter-produced neutral exosphere at Dione with associated mass-loading and are consistent with CAPS observations of enhanced plasma production near Dione's orbit (*Tokar et al.* [2008]). In addition, recent magnetohydrodynamic modeling of the D1 magnetic field signature measured during D1 suggested the presence of a neutral exosphere (*Simon et al.* [2011]), albeit one with much higher density than that inferred here.

During the Pioneer and Voyager Saturn flybys, all far from Dione, unexplained correlations of Saturn's plasma properties, kilometric radiation, and ion cyclotron emission with Dione's orbital distance and period were noted (*Frank et al.* [1980], *Kurth et al.* [1981], *Smith and Tsuratani* [1983], *Barbosa* [1992]) In 1997, using the Hubble Space Telescope, *Noll et al.* [1997] reported the detection of ozone ( $O_3$ ) in Dione's surface water ice, indicating concentrations of trapped molecular oxygen ( $O_2$ ). The  $O_2$  and  $O_3$  are thought to be produced primarily by surface radiolysis, a process (e.g. see *Johnson and Sittler* [1990]) recently identified by Cassini

at the moon Rhea (*Teolis et al.* [2010]). In preparation for the Cassini mission, *Sittler et al.* [2004] modeled a possible sputter-produced exosphere at Dione and suggested the existence of an exosphere could be inferred by CAPS via detection of pick-up ions during wake flybys, a prediction confirmed in this paper. Following *Sittler et al.*, *Saur and Strobel* [2005] also modeled a possible exosphere at Dione and the strength of Dione's interaction with the magnetospheric plasma, predicting the associated mass-loading. More recently, *Johnson et al.* [2008] used the average CAPS plasma data to calculate new sputtering rates for the icy satellites that included the temperature dependent contribution from radiolytic decomposition of ice resulting in the production of O<sub>2</sub>.

### **Cassini Plasma Spectrometer Observations**

Figures 1 and 2 illustrate the Cassini trajectory and CAPS ion measurements during the Dione 2 encounter, with Figure 3 illustrating the CAPS electron observations. In the Dione frame of reference a coordinate system is defined with +x in the direction of nominal plasma corotation, +y toward Saturn, and the z axis completing a right-handed system. Referring to the top panel of Figure 1, Cassini moves from left to right (at 8.4 km/s with respect to Dione) with position in the x-y plane shown as the blue line. The approximately corotating plasma in Saturn's magnetosphere flows from the bottom to the top in the +x direction, creating the geometric wake. The z coordinate of Cassini is approximately zero throughout the encounter, as shown in the z-y trajectory in the top panel of Figure 2. Therefore, during the Dione 2 encounter Cassini passes directly through the wake void region and near the equatorial plane, with closest approach to Dione at 05:16:11.

The CAPS ion observations are discussed first, followed by the electron observations. During the encounter the 8 detectors of the CAPS ion mass spectrometer (IMS) were at a fixed look direction, sampling different ion pitch angles. Typically the CAPS actuator (*Young et al.*

[2004]) is held fixed during the relatively fast moon encounters with CAPS anodes each sampling different ion gyro plane phases or pitch angles. In the bottom panel of Figure 1, measurements from IMS anode 4 are shown, which during D2 sensed ion flow approximately in the +x corotation direction. Similarly, the bottom panel of Figure 2 illustrates measurements from IMS anode 1 which detected ions flowing southward (-z) along the magnetic field direction during this encounter. The color-coded ion count rate for both anodes is plotted as a function of time (4s resolution) over the energy per charge range of about 1 eV to 46 keV. Before the encounter, from about 05:11:00 to at least 05:14:00 UT, the bottom panels of Figures 1 and 2 illustrate typical thermal plasma, consisting of  $H^+$ ,  $H_2^+$  and water group ions, nearly corotating at these radial distances. CAPS thermal plasma moments yield an ion flow speed in the azimuthal corotation direction with value  $39 \pm 6$  km/s with respect to Dione, or  $\sim 79\%$  of perfect corotation. Note that because CAPS is not actuating no information is available on the radial flow velocity during the encounter. Within the geometric wake both ion detector count rates are small, indicative of a plasma void region. Ion acceleration into the wake from the northern wake boundary is evident in the anode 1 data (Fig 2) with a typical signature of ambipolar diffusion (e.g. see *Samir et al.* [1983]). At later times after leaving the wake the ion data show the characteristic signature of ion injection events (e.g. *Hill et al.*, [2005]) leading to a complex plasma environment.

Figure 3 illustrates electron measurements from the CAPS electron spectrometer (ELS) during the encounter, with anode 5 in the bottom panel illustrating the usual low energy plasma population in Saturn's dynamic magnetosphere at this distance ( $<10$ eV). This plasma is disturbed by plasma wake effects at Dione (05:14:40-05:18:20), and also, throughout the interval, by superimposed injection events (*Hill et al.* [2005]). The injection events are present both before closest approach (e.g. 05:12 and 05:12:50) and afterwards (e.g., an extended event 05:19-05:20,

and an extended event which appears to be superposed on the wake signature itself between 05:17:40-05:18:00). The events before closest approach resemble remote injections while at later times they resemble local injections (*Burch et al.* [2005], *Hill et al.* [2005], *Rymer et al.* [2009]). The wake signature as seen by ELS consists of a population depleted in flux, but rising in energy to  $\sim 30$  eV, as well as a population which persists for the whole wake period (05:14:40-05:18:20) with a maximum energy  $\sim 400$  eV. Electron pitch angle data (not shown) reveal a refilling of the plasma wake behind Dione by electrons with up to a few hundred eV. Clearly, the ELS signature indicates a complex combination of wake effects and dynamic magnetospheric effects including injection events. In addition, data from anode 3 (top panel Fig 3) show a remarkably narrow (in energy) and long-lived feature in the wake region between  $\sim 05:15:30$  and 05:17, which has an energy of  $\sim 600$  eV, intensifies with time, increases a little in energy and eventually apparently merges with an injection signature. It is possible that this feature corresponds to negative pickup ions as observed at Rhea (*Teolis et al.*, [2010]), complementary with the positive pickup ions we report before closest approach, but further analysis is required to confirm this. In particular it is difficult to rule out the role of injection events in producing this population, which will be the subject of a separate study.

Of primary importance here are the ion measurements from IMS anode 4 just before and while entering the geometric wake region (Figure 1). Recall this anode is sensing flow predominantly in the corotation direction perpendicular to the magnetic field. It is expected that a newly born ion out of a Dione exosphere will be picked up by Saturn's magnetic field and swept away, with a typical trajectory shown by the red curve in the top panel of Figure 1. This trajectory is plotted at 2s intervals for an  $O_2^+$  ion picked up into a bulk flow along  $+x$  of 39 km/s (with respect to Dione) and a uniform magnetic field of 75 nT in the  $-z$  direction (*Khurana et al.* [2008]). Be-

cause this is a low altitude wake pass, freshly produced ions are most likely on a ring velocity space distribution (*Sittler et al.* [2004]) and CAPS anode 4, viewing mainly perpendicular to the magnetic field direction, should detect them as a “bump” in the count rate at energies greater than the main water group ions. (It is also possible that the ions could be non gyrotropic “streams”, although CAPS has no measurements at various ion gyrophases.) As illustrated in Figure 4, such a signature is observed by CAPS in four slices of IMS ion counting data versus energy per charge measured in the region just before entering the wake void (green shaded region on the Cassini trajectory, top panel Figure 1). The arrows in Figure 4 point out the bump in the spectra, attributed here to the presence of freshly-produced pick-up ions.

Figure 5 expands on the results in Figure 4, showing in the top panel average CAPS IMS ion counts versus energy for anode 4 at early times well away from Dione (05:11:15 to 05:11:27 UT, see Fig 1) and, in the bottom panel, the average of the 4 spectra in Figure 4. In the top panel the green curve is a fit to the water group core using a Maxwellian velocity distribution. Note the high energy tail (produced by hot  $H^+$  and  $W^+$ , determined by CAPS time of flight data not shown here) between about 1 and a few keV. It is, not surprisingly, not well fit by the Maxwellian but is not a “bump” like those seen in Figure 4. For the average spectrum (bottom panel) fits are shown consisting of  $H^+$  (red dashed),  $H_2^+$  (red),  $W^+$  (green), and the sum (blue) is shown. Also illustrated are the nominal positions in energy of  $H_2O^+$  and  $O_2^+$  ring distributions for the average core flow speed of 39 km/s. From the *Sittler et al.* [2004] study, the dominant freshly-produced ion from a Dione exosphere would be  $H_2O^+$ , with minor ions also created including  $O_2^+$ . The conclusion from this result is that the bump measured at higher energies is most likely  $O_2^+$  pick-up ions and that  $H_2O^+$  pick-up ions if present would be difficult to observe within the high count water group core. This result holds over the azimuthal flow speed range measured by CAPS near

Dione of  $39 \pm 6$  km/s (in the Dione frame). For this range of speeds, a relatively cold  $O_2^+$  ring, expected for new pick-up ions, has a midpoint energy near the CAPS 1.02 keV energy channel with a range for these flow speeds of 724 eV to 1.45 keV. On the other hand, cold pick-up  $H_2O^+$  has the midpoint energy near the 609 eV channel, as shown in Figure 5, with a range from 430 to 725 eV, well below the energies measured for the bump. These results are a strong indication that the bumps in the CAPS spectra are due to  $O_2^+$  pick up ions.

## Discussion

The CAPS ion counts at the  $O_2^+$  ring energy (Figures 4 and 5) can be used to provide a rough estimate of the  $O_2^+$  pick-up ion density. This result can in turn be used to test the modeling of the proposed  $O_2$  atmosphere. Our pick-up ion density estimate is rough primarily because of the large uncertainty in the velocity space distribution of these ions. The estimate is calculated for uniform ring and shell velocity space distributions and the temperature for both is chosen as 10 eV, reasonable given the energy spread of the bump shown in Figure 5. For the estimate of  $O_2^+$  density, the measured CAPS counts at 1.02 keV, corrected for background, are attributed entirely to  $O_2^+$  and used to calculate a representative phase space density for this ion. Assuming uniform density, this is multiplied by the volume of velocity space for a ring or shell to obtain number density. The phase space density is  $f_i = C / (v^4 G \varepsilon \Delta t)$ , with  $C$  the ion counts at the peak of the bump (1.02 keV) corrected for background,  $v$  the speed of an  $O_2^+$  ion with energy 1.02 keV,  $G = 7.44 \times 10^{-4} \text{ cm}^2$ , the CAPS geometric factor at this energy,  $\varepsilon = 0.46$ , the detection efficiency for  $O_2^+$ , and  $\Delta t = 54.7$  ms, the sample time. The volume of the ring in velocity space is  $V = (2\pi V_{\text{ring}})(\pi v_{\text{th}}^2)$  where  $V_{\text{ring}} = 39$  km/s is the ring radius and  $v_{\text{th}}$  is the thermal speed of the ring  $O_2^+$  ions assuming  $T = 10$  eV. A similar expression is used for the volume of a shell. The results

of this are summarized in Table 1, with the density of  $O_2^+$  ranging from  $0.01 \pm 0.001 \text{ cm}^{-3}$  for a ring and  $0.09 \pm 0.01 \text{ cm}^{-3}$  for a shell. The result for the ring is the most probable of these two, given the close proximity of Cassini to the source region (see Figure 1) and that the ring may only be partially filled, i.e. non-gyrotropic or streams of ions, as observed by CAPS at Rhea (*Teolis et al.* [20110]). As for the possible presence of  $H_2O^+$  pick-up, the CAPS results can be used to estimate an upper limit density by calculating the  $H_2O^+$  density needed to produce 100 counts in CAPS IMS. This level of counts is a rough threshold above which the ring distribution would be observable within the high count  $W^+$  core. This calculation yields an upper limit density of  $H_2O^+$  pick up ions about 5 to 10 times higher than that for  $O_2^+$  on either ring or shell velocity distributions.

In anticipation of Cassini encounters with Dione, *Sittler et al.* [2004] estimated pick-up ion densities near Dione, in particular expectations for a wake pass like D2. Using estimates of the plasma properties at Saturn from Voyager, they obtained pick-up densities  $\sim 0.07 O_2^+/\text{cm}^3$  and  $\sim 0.8 H_2O^+/\text{cm}^3$  for the D2 geometry, remarkably consistent with the estimates presented here. Their results were calculated using a net sputter flux of  $9.6 \times 10^{25} H_2O/s$  with a source rate for  $O_2$  that was 10% of the  $H_2O$  source rate. That estimate, based on the assumption of a significant sputtering contribution from energetic  $O^+$ , is fortuitously close to a recent estimate based on the CAPS thermal plasma data (*Johnson et al.* [2008]). The corresponding source rate of  $O_2$  from plasma induced decomposition of ice, which is sensitive to the surface temperature, is also close to the assumed 10% of the  $H_2O$  source rate. (Assuming a mean surface temperature  $\sim 87K$ , and using the activation energy in Johnson et al. [2008], the result is  $\sim 7\%$ .) The ionization rate used is also reasonably close to the Voyager estimate but the description of their atmosphere was simplified as the ejected  $O_2$  has an escape fraction,  $f_s \sim 0.36$  for the assumed ejecta speed distribution

for O<sub>2</sub>. Therefore, most O<sub>2</sub> returns to the surface, is transiently absorbed, and is re-emitted thermally accommodated to the average surface temperature as discussed earlier for Rhea (*Teolis et al.* [2010]) and Europa (*Johnson et al.* [2009]). Therefore, the O<sub>2</sub> that does not escape accumulates until the loss rate, due to escape, ionization and dissociation, equals the source rate. Noting that the ballistic lifetime for O<sub>2</sub> is ~ 2000sec whereas the lifetimes against ionization and dissociation are ~10<sup>6</sup> -10<sup>7</sup>s, the oxygen is cycled through the atmosphere many times prior to its destruction.

The dependence of the density, n, vs. radial distance, r, of this ballistic thermal atmosphere using a mean surface temperature of 87K with Jeans parameter (gravitational escape energy/ kT) ~5.6, is also quite close to that in Fig. 1a in *Sittler et al.* [2004]. Because the accumulation of pick-up ions along the fluid element is dominated by pick-up where the neutral density is largest, (i.e. when the element is closest to Dione's surface) we can use the ratio between the calculated pick-up ion density, ~ 0.07/cm<sup>3</sup> and the neutral density at the surface, n<sub>o</sub> ~2 x10<sup>4</sup>/cm<sup>3</sup>. However, the calculated pick-up ion density for the model atmosphere was estimated assuming a small gyroradius: i.e., treating the ions motion as a fluid. In a recent paper, *Hartle and Sittler* [2007] accounted for the ratio of the ion gyroradius, ~180km, to the scale height, ~100km, to correct the pick-up ion density estimates. Using their Fig.6 the density would be a factor of ~ 1/2 smaller. Therefore, we scale our results using 2(2x10<sup>4</sup>/0.07) ~ 6x10<sup>5</sup> for the ratio of surface O<sub>2</sub> density to O<sub>2</sub><sup>+</sup> pick-up ion density for a Cassini wake pass. Based on our range of pick-up ion densities (0.01-0.09 O<sub>2</sub><sup>+</sup>/cm<sup>3</sup>) and assuming the same total ionization rate (~2x10<sup>7</sup>/s), Dione's O<sub>2</sub> atmosphere has a surface density in the range n<sub>o</sub> ~0.6 - 5 x10<sup>4</sup>/cm<sup>3</sup>. This would be a rough lower bound if the fluid elements detected did not sample down to the physical surface. Using these densities, a rough estimate of the O<sub>2</sub> radial column density ~0.9 - 7 x 10<sup>11</sup>/cm<sup>2</sup>, is of the

order of that found at Rhea (*Teolis et al.* [2010]) but much smaller than the recent estimate for Dione using D1 magnetometer data (*Simon et al.* [2011]).

There are uncertainties in this calculation, not only in the density of the  $O_2^+$  pick-up ions but also the location and structure of the detected fluid elements and the fact that the local ionization rates can differ from that in the background gas. More importantly, the surface temperature is not uniform with significant day-night and equator-pole differences ranging from  $\sim 50$ -90K (*Howett et al.* [2010]). This affects the production, escape, redistribution and, possibly, the burial of  $O_2$  across the surface, allowing for the possibility of build up in the regolith in the colder regions. The radiation chemistry involved has been reviewed recently (*Johnson* [2011]). These issues will be dealt with in subsequent, more detailed modeling. However, what is not uncertain is we report here the first in situ detection of a component of Dione's thin sputter produced atmosphere by collecting the pick-up ions. Since the pick-up ion density is directly related to the atmospheric densities, we have also obtained a rough estimate of the atmospheric  $O_2$  density. This is consistent with the earlier observations of oxygen products trapped in the surface ice and places Dione in a category with Europa, Ganymede, Rhea and Saturn's main rings all of which have oxygen atmospheres. Finally, we note that the Cassini ion neutral mass spectrometer (INMS) team has reported the detection of an  $O_2$  exosphere at Dione during the D3 encounter on Dec 12, 2011 [*B.D. Teolis*, private communication], subsequent to the submission of this paper. CAPS was not operational during the D3 encounter.

## Acknowledgements

The authors wish to thank Krishan Khurana for helpful conversations regarding the Cassini Dione observations. The work of U.S. co-authors was supported by JPL contracts 1243218 with Southwest Research Institute. We acknowledge support of the CAPS ELS operations and software team by the UK Science and Technology Facilities Council (STFC, to 2010) and by ESA via UK Space Agency (from 2011), and support of CAPS-ELS science by STFC. GHJ is supported by an STFC Advanced Fellowship. Cassini is managed by the Jet Propulsion Laboratory for NASA.

## References

- Barbosa, D.D., Theory and observations of electromagnetic ion cyclotron waves in Saturn's inner magnetosphere, *J. Geophys. Res.*, vol. 98, No. A6, pgs 9345-9350, 1 June 1992.
- Burch, J.L., et al., Properties of local plasma injections in Saturn's magnetosphere, *Geophys. Res. Letts.*, vol. 32, L14S10, doi:10.1029/2005GL022611, 2005.
- Fink, U. et al., Infrared spectra of the satellites of Saturn: identification of water ice on Iapetus, Rhea, Dione, and Tethys, *Astrophys. J.*, 207: L63-L67, 1 July 1976.
- Frank, L.A. et al., Plasmas in Saturn's magnetosphere, *J. Geophys. Res.*, vol. 85, no. A11, pgs. 5695-5708, 1 Nov. 1980.
- Hartle, R.E. and E. C. Sittler Jr. Pickup ion phase space distributions: Effects of atmospheric spatial gradients 112, A07104, doi:10.1029/2006JA012157, 2007
- Hill, T.W. et al., Evidence for rotationally driven plasma transport in Saturn's magnetosphere, *Geophys. Res. Letts.*, vol. 32, L14S10, doi:10.1029/2005GL022620, 2005.
- Howett, C.J.A. et al., Thermal inertia and bolometric Bond albedo values for Mimas, Enceladus, Tethys, Dione, Rhea and Iapetus as derived from Cassini/CIRS measurements. *Icarus* 206, 573–593, 2010.
- Johnson, R.E. and E.C. Sittler, Jr., Sputter-produced plasma as a measure of satellite surface composition: the Cassini mission, *Geophys. Res. Letts.*, vol 17, no. 10, pgs 1629-1632, Sept, 1990.
- Johnson, R.E. et al., "Sputtering of Ice Grains and Icy Satellites in Saturn's Inner Magnetosphere", *Planet & Space Sciences*, 56, 1238-1243 (2008).

Johnson, R.E. et al., "Composition and Detection of Europa's Sputter-Induced Atmosphere", Chapter in *Europa*, Eds. R. Pappalardo et al. pp507-527, 2009.

Johnson, R.E., "Photolysis and Radiolysis of Water Ice", Chapter 10 in *Physics and Chemistry at Low Temperatures*, L. Khriachtchev (Ed.) , *World Scientific*, Singapore, Published by *Pan Stanford Publishing Pte. Ltd.* pp297-339 , 2011.

Khurana, K.K., C.T. Russell, M.K. Dougherty, Magnetic portraits of Tethys and Rhea, *Icarus*, 193, pgs 465-474, 2008.

Kurth, W.S., D.A. Gurnett and F.L. Scarf, Control of Saturn's kilometric radiation by Dione, *Nature*, vol 292, pgs 742-745, 20 August 1981.

Martens, H. R. et al., Observations of molecular oxygen ions in Saturn's inner magnetosphere, *Geophys. Res. Letts.*, vol. 35, L20103, doi:10.1029/2008GL035433, 2008

Noll, K.S. et al., Detection of ozone on Saturn's satellites Rhea and Dione, *Nature*, vol 388, pgs 45-47, 3 July 1997.

Rymer, A.M. et al., Cassini evidence for rapid interchange transport at Saturn, *Planetary and Space Science*, doi:10.1016/j.pss.2009.04.010

Samir, U. et al., The expansion of plasma into a vacuum: basic phenomena and processes and applications to space plasma physics, *Rev. Geophys. and Sp. Phys.*, vol 21, no. 7 pgs 1631-1646, August, 1983.

Saur, J. and D.F. Strobel, Atmospheres and plasma interactions at Saturn's largest inner icy satellites, *Astrophys. J.*, 620; L115-L118, 20 Feb. 2005.

Simon, S. et al. "Magnetic signatures of a tenuous atmosphere at Dione", *Geophys. Res. Letts.*, 38, L15102, doi:10.1029/2011GL048454.

Smith E.J. and B.T. Tsuratani, Saturn's magnetosphere: observations of ion cyclotron waves near the Dione L shell, *J. Geophys. Res.*, vol. 88, no A10, pgs 7831-7836, 1 Oct. 1983.

Sittler, E.C. et al., Pickup ions at Dione and Enceladus: Cassini plasma spectrometer simulations, *J. Geophys. Res.*, vol. 109, A01214, doi:10.1029/2002JA009647, 2004.

Teolis, B.D. et al., Cassini finds an oxygen-carbon dioxide atmosphere at Saturn's icy moon Rhea, *Science*, 10.1126/science.1198366, 25 Nov. 2010.

Tokar, R.L. et al., The interaction of the atmosphere of Enceladus with Saturn's plasma, *Science*, 311, pg 1409, 10 March 2006.

Tokar, R.L. et al., Cassini detection of water-group pick-up ions in the Enceladus torus, *Geophys. Res. Letts.*, 35, L14202, doi:10.1029/2008GL034749, 2008.

Young, D.T. et al., Cassini plasma spectrometer investigation, *Space Sci. Rev.*, 114, 1-112, 2004

Figure 1: Bottom panel is CAPS ion count rate at 4s resolution as a function of time and energy per charge. The measurements are for anode 4 of CAPS, sensing flow predominantly in the corotation direction. The top panel shows the Cassini trajectory during D2 and Dione's geometric wake, with a sample pick-up  $O_2^+$  ion trajectory in the ambient flow plotted at 2s resolution. The pick up ions are detected by CAPS just before entering the wake, in the green shaded region on the trajectory.

Figure 2: Similar to Fig. 1 but illustrating ion data from anode 1 of CAPS which senses flow along the magnetic field direction. This anode detects the plasma wake void region as well as refilling along the magnetic field.

Figure 3: CAPS electron spectrometer observations during the D2 encounter. See text for details.

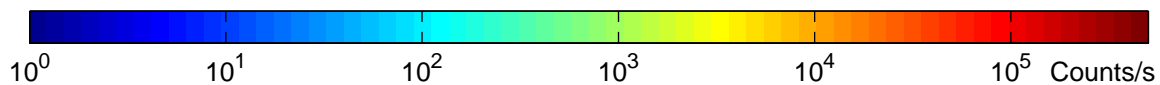
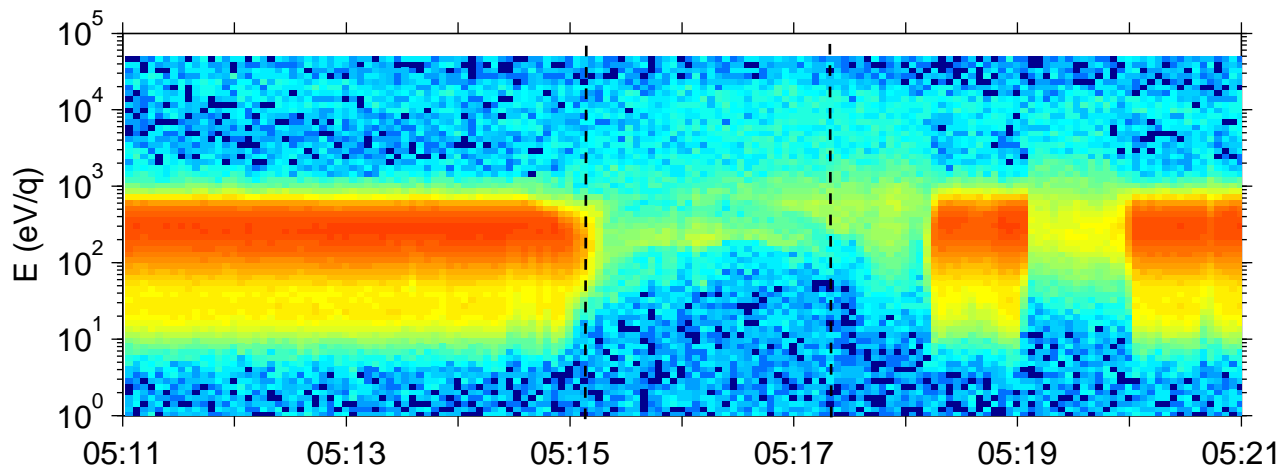
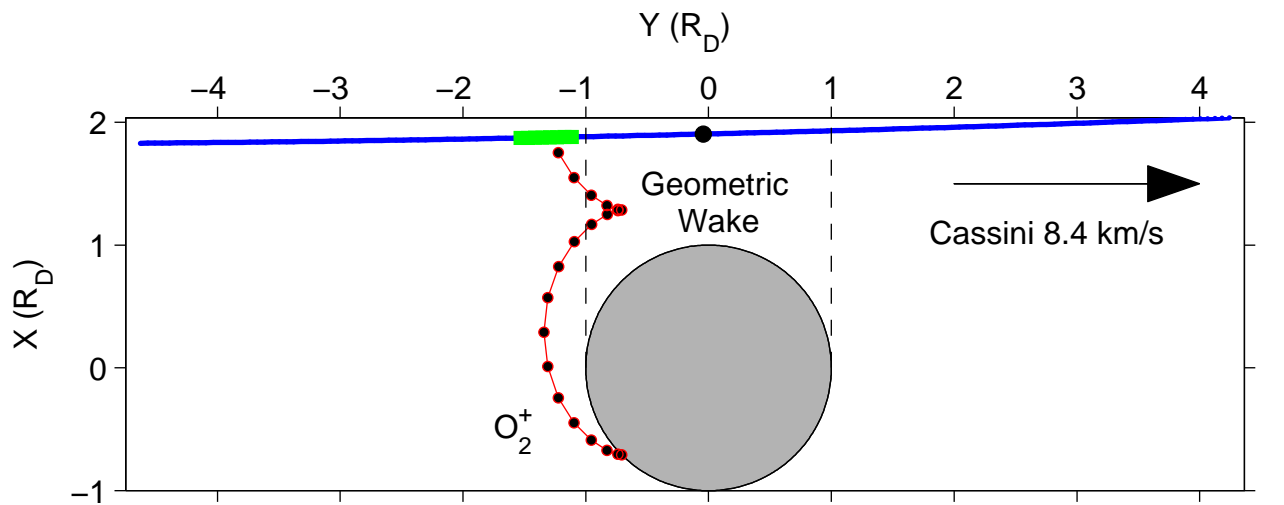
Figure 4: CAPS anode 4 spectra separated by 4 s and just outside the wake. Arrows point out the bump in counts attributed to the freshly produced pick up ions. This figure illustrates that the pick-up ion signature attributed to  $O_2^+$  persists over multiple CAPS spectra for at least 32 s.

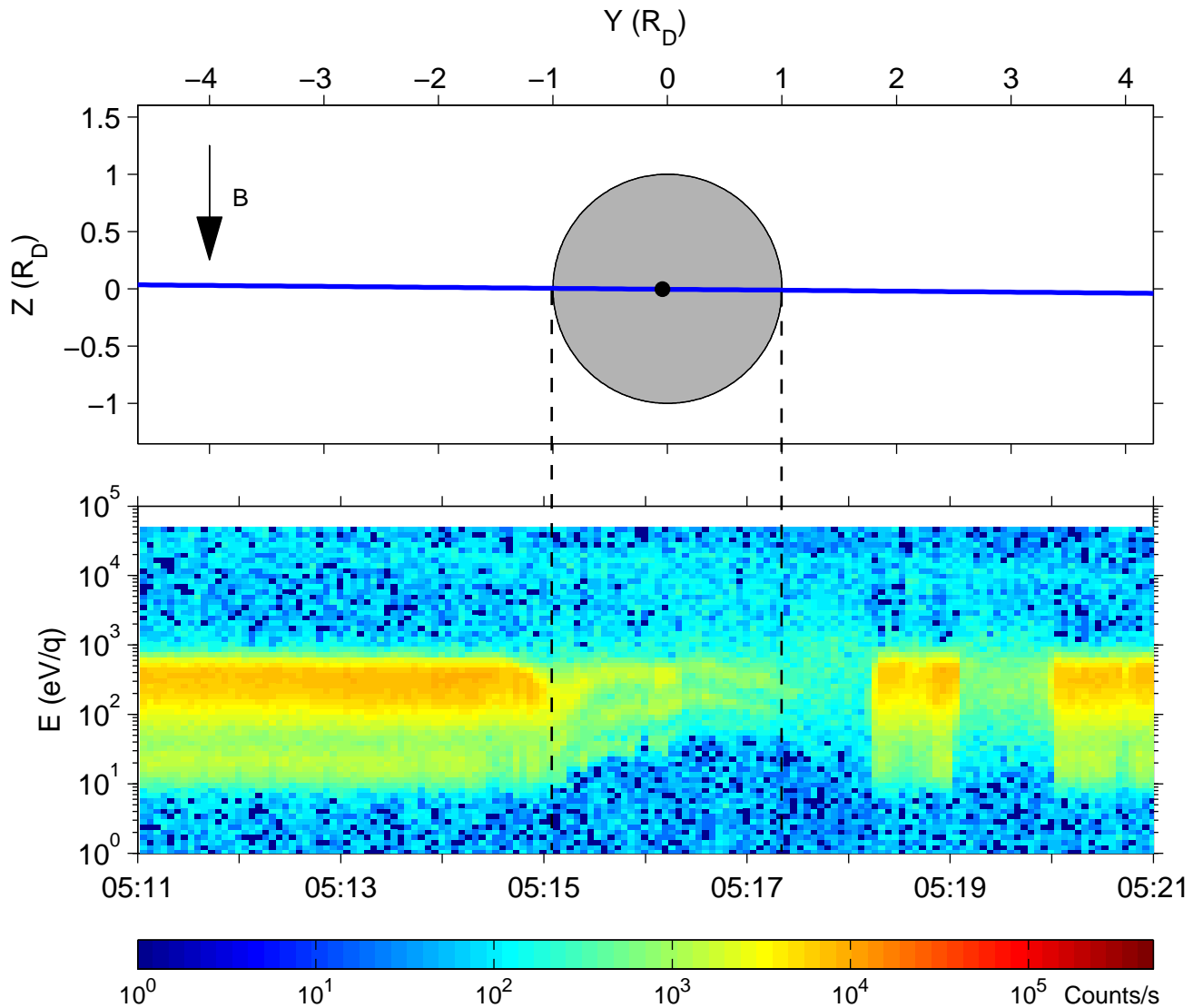
Figure 5: This figure shows CAPS average ion counts measured by anode 4 (black circles) far from Dione (top) and close to the moon's wake (bottom). In addition, ion counts are simulated for both  $O_2^+$  and  $H_2O^+$  pick-up ion rings for the nominal plasma flow, indicating good agreement of the observed pick-up ion energy with the simulated  $O_2^+$  pick-up ion energy.

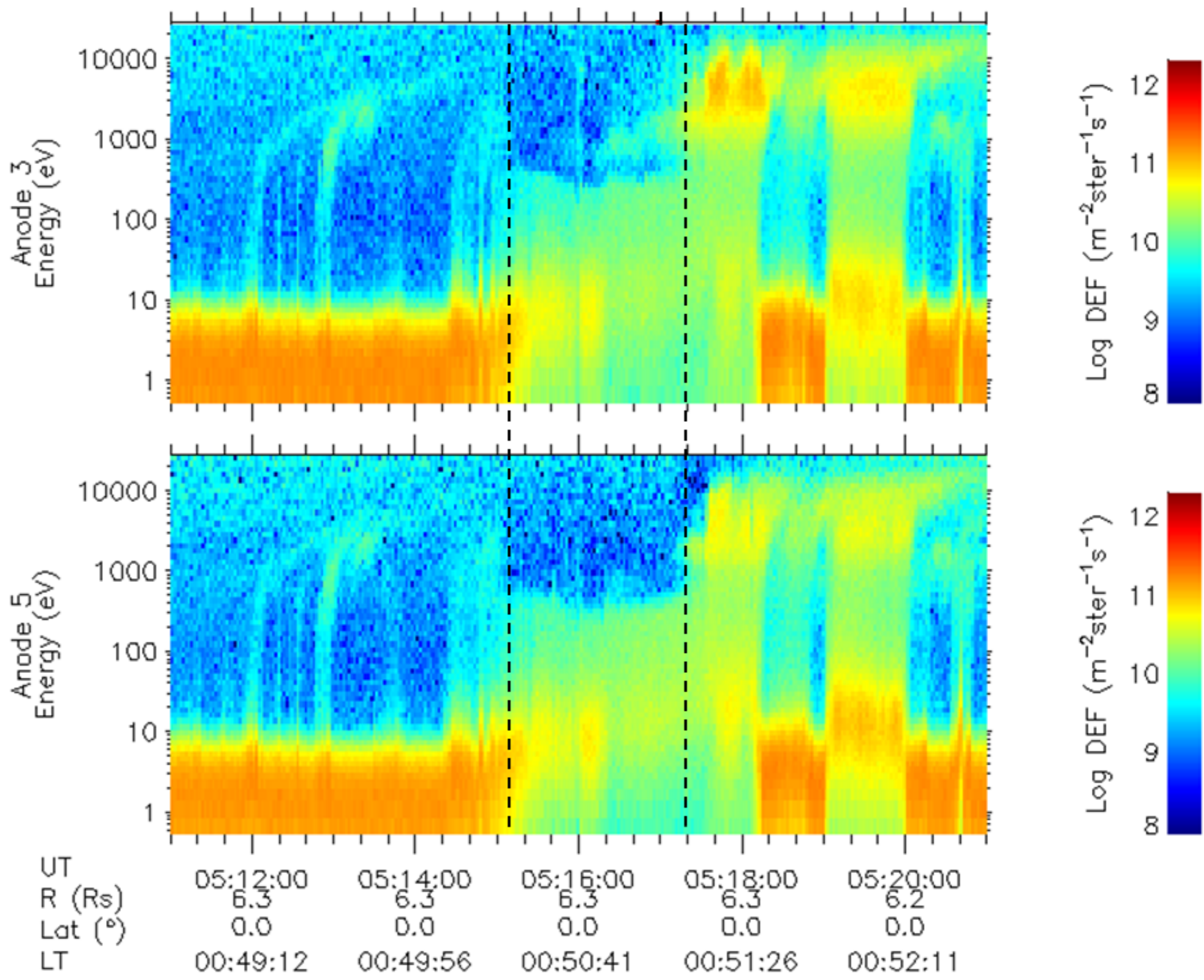
**Table 1**

Time (UT)	Counts (1.02 keV)	Background (10 to 46 keV)	O2+, f ( $s^3/cm^6$ )	O2+, N (ring) ( $cm^{-3}$ )	O2+, N (shell) ( $cm^{-3}$ )
05:14:31	38	6.0	$4.7 \times 10^{-22}$	0.011	0.099
05:14:35	31	4.6	$3.9 \times 10^{-22}$	0.009	0.082
05:14:39	30	5.2	$3.5 \times 10^{-22}$	0.008	0.074
05:14:43	37	5.7	$4.6 \times 10^{-22}$	0.011	0.097

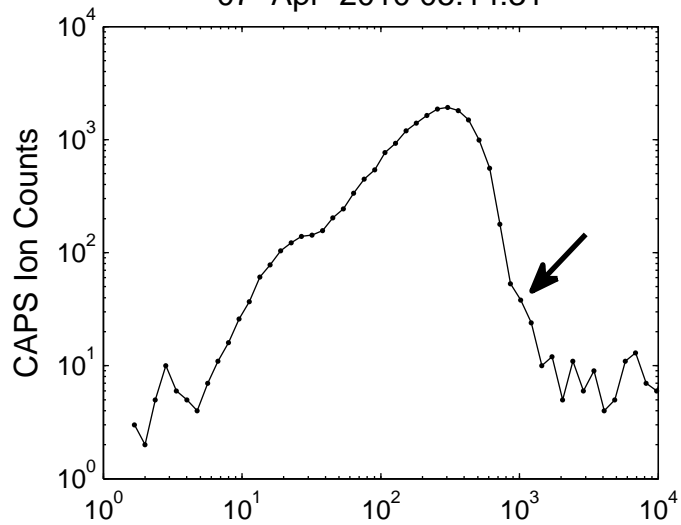
Table 1: Summary of analysis of CAPS pick-up ion counts to extract  $O_2^+$  density for the four ion energy spectra shown in Figure 4. The fourth column is ion phase space density for the peak of the ion bump assuming these counts are solely due to  $O_2^+$ . The last two columns give the resulting ion density for ring and shell velocity space distributions.



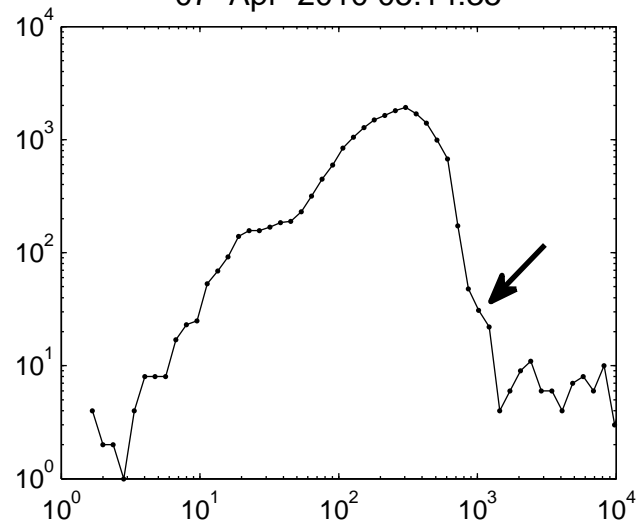




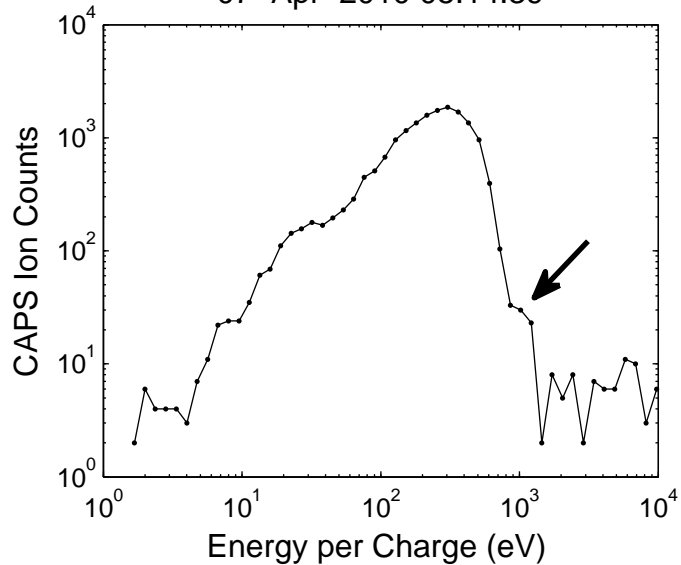
07-Apr-2010 05:14:31



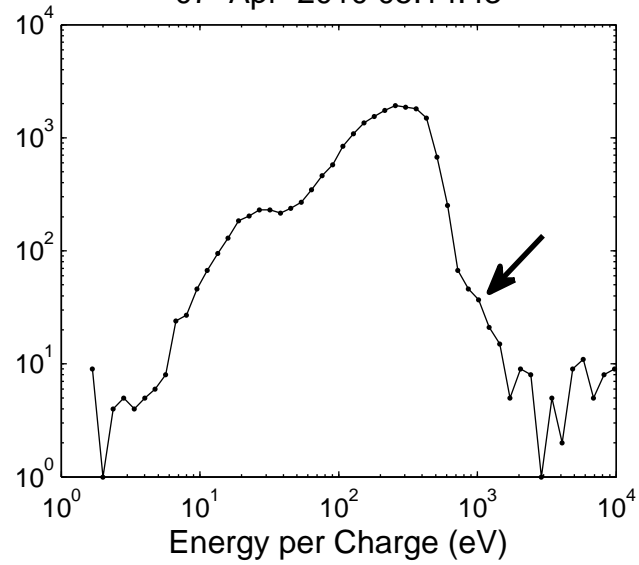
07-Apr-2010 05:14:35



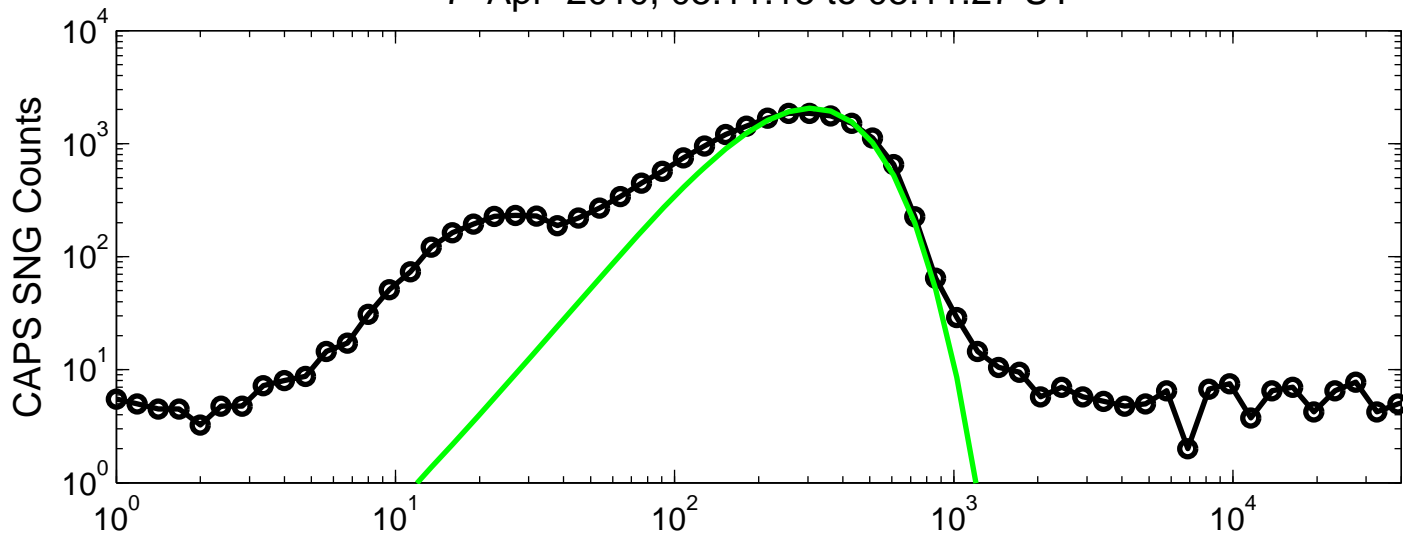
07-Apr-2010 05:14:39



07-Apr-2010 05:14:43



7-Apr-2010, 05:11:15 to 05:11:27 UT



7-Apr-2010, 05:14:31 to 05:14:43 UT

