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# Discrete classification and electron energy spectra of Titan's varied magnetospheric environment

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[1] We analyse combined electron spectra across the dynamic range of both Cassini electron sensors in order to characterise the background plasma environment near Titan for 54 Cassini-Titan encounters as of May 2009. We characterise the encounters into four broad types: Plasma sheet, Lobe-like, Magnetosheath and Bimodal. Despite many encounters occurring close to the magnetopause only two encounters to date were predominantly in the magnetosheath (T32 and T42). Bimodal encounters contain two distinct electron populations, the low energy component of the bi-modal populations is apparently associated with local water group products. Additionally, a hot lobe-like environment is also occasionally observed and is suggestively linked to increased local pick-up. We find that 34 of 54 encounters analysed are associated with one of these groups while the remaining encounters exhibit a combination of these environments. We provide typical electron properties and spectra for each plasma regime and list the encounters appropriate to each. **Citation:** Rymer, A. M., H. T. Smith, A. Wellbrock, A. J. Coates, and D. T. Young (2009), Discrete classification and electron energy spectra of Titan's varied magnetospheric environment, *Geophys. Res. Lett.*, *36*, L15109, doi:10.1029/2009GL039427.

## 1. Introduction

[2] Titan's nitrogen dominated atmosphere is the most dense of any moon in the solar system and this fascinating environment is an important target of the current Cassini mission at Saturn. It was initially believed that Titan would be the most significant source of neutral nitrogen particles in Saturn's magnetosphere [*Barbosa*, 1987; *Ip*, 1992; *Smith et al.*, 2004]. With Cassini's arrival at Saturn in 2004 one of the first surprising discoveries was that this was far from being the case and that in fact the bulk of Saturn's neutral particles are provided by the tiny moon Enceladus.

[3] Accurate models of Titan atmospheric structure, chemistry, formation and loss rely on accurate knowledge of the local plasma environment as a source of energy to the system as well as possibly introducing variability in atmospheric interactions. For example the fifth Cassini-Titan encounter (T5) has been researched in detail. In particular, *Cravens et al.* [2009] show the existence of a strong night side ionosphere during this encounter. Our analysis shows that the T5 encounter occurred in a particularly hot and dense electron 'plasma sheet' environment which we will show is not typical for the plasma environment near Titan. Similarly T18 occurred in a particularly low density 'lobe-like' environment which might partially explain the low levels of energetic particle atmospheric penetration reported by *Smith et al.* [2009].

[4] Large scale variability of the plasma environment near Titan is quite well understood as predominantly the result of three well documented properties of the magnetosphere, 1) variable solar wind pressure which expands and compresses the magnetosphere which can result in Titan being inside/outside the magnetopause [*Arridge et al.*, 2006; *Bertucci et al.*, 2008]; 2) day/night asymmetry resulting in a thicker and typically more dense plasma sheet at the dayside than the night side [*Sergis et al.*, 2009] and 3) periodic motion of the plasma sheet causing it to 'flap', or move up and down relative to the equatorial plane, and hence to Titan's orbit [e.g., *Carbary and Krimigis*, 1982; *Carbary et al.*, 2007; *Coates et al.*, 2007; *Arridge et al.*, 2008]. The latter affect is a consequence of the well documented and still unexplained observation that many magnetospheric phenomena at Saturn are organised by the Saturn rotation rate, despite Saturn having its dipole and spin axis almost precisely aligned.

[5] With the completion of 54 Cassini Titan encounters at the time of writing we now have enough data to examine Titan encounters on a statistical basis. Our goal is to examine the electron environments observed during these encounters and determine if these environments can be separated into a small group of categories in order to facilitate better understanding and modelling of Titan and its interaction with Saturn's magnetosphere.

## 2. Instrumentation

[6] We have focussed this study on the electron environment because electron-impact interactions with Titan's atmosphere and ionosphere are important near Titan and, due to their high thermal speed with respect to the local magnetospheric flow speed, are well sampled irrespective of spacecraft pointing. In the subsequent analysis, we use in-situ Cassini data from the CAPS Electron Spectrometer (ELS) [*Linder et al.*, 1998; *Young et al.*, 2004] and the MIMI Low Energy Magnetospheric Measurements System (LEMMS) [*Krimigis et al.*, 2004] to produce the first calibrated combined electron spectra across the dynamic range of both instruments near Titan. CAPS-ELS measures the incident energy and direction of electrons across the energy range 0.6 eV to 28 keV, with instantaneous spatial coverage of 160° by 5° provided by a fan of eight anodes and a potential maximum spatial coverage of 160° by 208° in approximately

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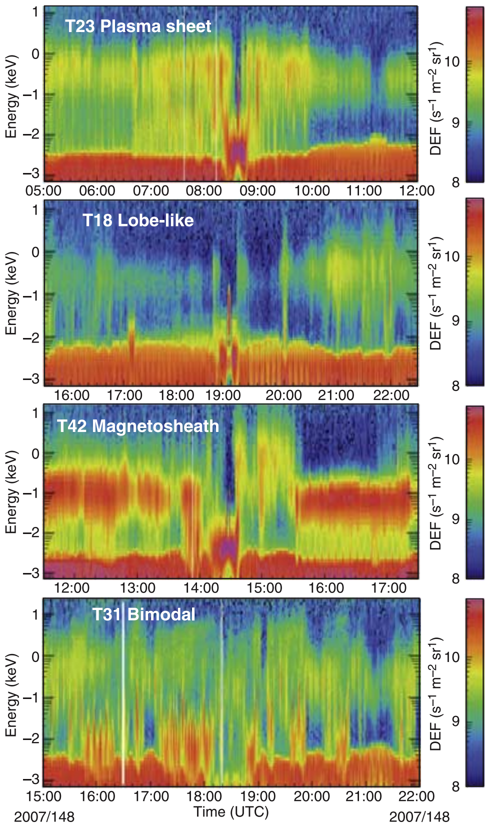

**Figure 1.** Electron energy-time spectrograms (∼±3 hours of closest approach to Titan) showing examples of the four different categories of electron background observed during Cassini-Titan encounters along with their associated Titan encounter number.

3.5 minutes, provided by a scanning platform. In flight calibration of the CAPS-ELS is described by *Lewis et al.* [2008]. MIMI-LEMMS measures the incident energy and direction of electrons across the range 15 keV to 5 MeV in two oppositely oriented telescopes. In compiling the combined electron spectra (shown later in Figure 2) we use an anode near the centre of the ELS fan and time periods where both ELS and LEMMS are measuring the same pitch angles.

## 3. Plasma Environment Categorisation

[7] In Figure 1 we show four energy-time spectrograms of electron energy flux (Differential Energy Flux, DEF, $cm^{-2}$ $sec^{-1}$ $steradian^{-1}$) measured by the CAPS-ELS. Each plot shows ∼6 hours of data, within 3 hours either side of Cassini's closest approach to Titan. The electron population below ∼ 10 eV at the bottom of each plot consists of photoelectrons, which are electrons emitted from spacecraft surfaces due to the photoelectric effect. There are two low-energy electron populations affecting s/c charge: photoelectrons generated by s/c surfaces and ambient ionospheric electrons. The balance of currents from these populations largely determines s/c potential. Commonly (away from very dense plasma environments and not in solar eclipse) there are more electrons flowing off than on to Cassini causing the spacecraft to carry a small positive charge – this charge allows sufficiently low energy photoelectrons to be attracted back the spacecraft and detected by the ELS sensor [*Rymer*, 2004]. At the approximate centre of each plot is closest approach to Titan (indicated by the apparent discontinuity in the spectrum). Near Titan the ionospheric electron population can be sufficiently dense to cause more electrons to flow onto Cassini from Titan's ionosphere than flow off the spacecraft through the photoelectric effect, giving the spacecraft a net negative charge. This results in the low energy photoelectrons accelerating away from the spacecraft causing the characteristic photoelectron population to vanish. The goal of this paper is to characterise the background plasma environment so we focus our research outside of the Titan ionospheric interaction region.

[8] After compiling all available electron energy-time spectrograms for 54 Titan encounters from October 2004 to May 2009 we determined that over half of the encounters are broadly associated with one of four categories. We have labelled these categories as: 1. Plasma sheet, 2. Lobe-like, 3. Magnetosheath and 4. Bimodal. Although our nomenclature for category 2. is not completely accurate, we use the term 'lobe-like' because the hot tenuous nature of the Earth's lobe regions is similar to these low density regions near Titan.

[9] The categories are defined as follows:

[10] 1. Plasma sheet encounters, (example: T23, DOY 13 2007). This region is characterized by a relatively high energy and density electron environment with peak energy between 120 and 600 eV and the flux at peak energy between $3.5 \times 10^5$ and $1.2 \times 10^6$ $cm^{-2}$ $s^{-1}$ $sr^{-1}$. This region exhibits little bi-modality.

[11] 2. Lobe-like encounters, (example: T18, DOY 266 2006). This region is characterized by a relatively high energy but a lower density electron environment with an energy peak at approximately the same or slightly higher energy than plasma sheet populations (between 150 and 820 eV) and typically an order of magnitude lower flux at these peak energies than the plasma sheet proper, between $5.3 \times 10^4$ and $2.4 \times 10^5$ $cm^{-2}$ $s^{-1}$ $sr^{-1}$. This region also exhibits little bi-modality.

[12] 3. Magnetosheath encounters, (example: T32, DOY 164 2007). This region occurs outside the magnetopause in shock heated solar wind plasma with electron populations characterised by lower energy (a few hundred eV), high flux electrons (peak flux of $\sim 1 \times 10^6$ $cm^{-2}$ $s^{-1}$ $sr^{-1}$ at around 50 eV). This region does not exhibit bi-modality.

[13] 4. Bi-modal plasma background, (example: T31, DOY 148 2007). This region contains easily identifiable and fairly sustained occurrences of bi-modal electron populations and is often highly variable. The peak energy of the more energetic bi-modal component ranges from 200 eV to 3.4 keV (similar to or higher than typical plasma sheet or lobe-like energies) with flux at the peak energy between $9.0 \times 10^4$ and $2.4 \times 10^5$ $cm^{-2}$ $s^{-1}$ $sr^{-1}$. The peak energy of the less energetic bi-modal component ranges between 5.3 eV and 16.3 eV with the flux at peak energies between $5.7 \times 10^5$ and $1.6 \times 10^6$ $cm^{-2}$ $s^{-1}$ $sr^{-1}$.

[14] The 'bi-modal' category is a particularly interesting category because it contains two very different superposed electron populations. The more energetic population appears to be either plasma sheet or lobe-like electrons

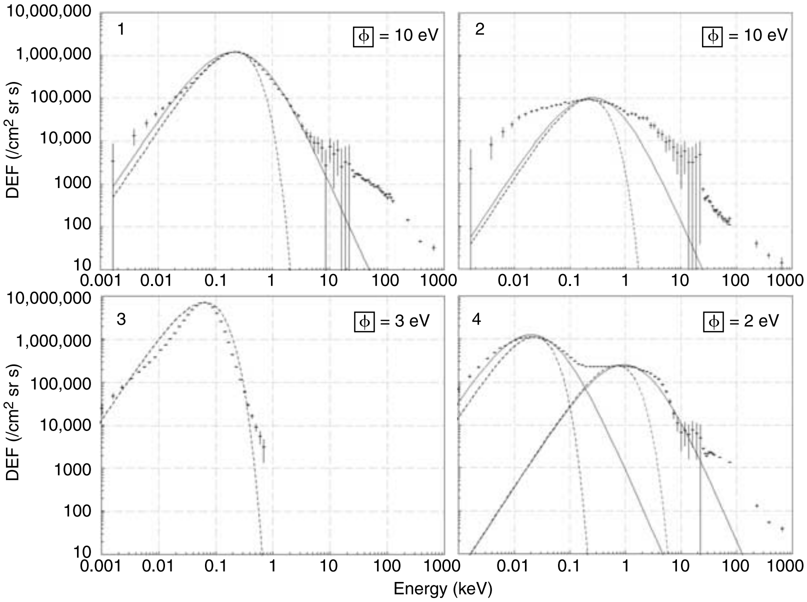

**Figure 2.** Example combined CAPS-MIMI electron differential energy flux versus energy spectra for the four regions identified. (top left) An example plasma sheet spectra observed during T13. (top right) A low density lobe-like population observed during T8. (bottom left) A magnetosheath spectra from T32. (bottom right) A bi-modal example spectra observed during T31. Dashed and solid lines are Maxwellian and kappa fits to the data, respectively. The spacecraft potential correction (Φ) applied to each spectra is indicated in the top right hand corner.

while the less energetic but more dense population looks a lot like a local electron pick-up population, such as is observed throughout the inner magnetosphere and associated with local pick-up from the distributed neutral cloud [*Rymer et al.*, 2007; *Sittler et al.*, 2008; *Wilson et al.*, 2008]. An electron produced at zero energy (say) will be almost immediately 'picked-up' in Saturn's corotating electric field which near 20 Rs provides only a few tenths of eV to the electron, even assuming rigid corotation. The time taken for a 0.1 eV electron population to equilibrate through Coulomb collisions with 350 eV electrons or 1 keV protons with density of 0.11 cm$^{-3}$ is implausibly long to explain the observed cold electron temperature ($10^5$ and $10^4$ hours respectively). The total excess energy from the photolysis of hydrogen (~4 eV) is also less than the observed cold electron energy. This leads us to speculate that they might be associated with photo-ionisation of heavier ions for which the total excess energy can be a few 10s of eV. CAPS ion data during T31 shows evidence of water group particles. Water group particles originate from the inner magnetosphere, primarily from Enceladus, and not from Titan. A cursory look at the ion data for the other 'bi-modal' encounters also indicates the presence of water group. We therefore speculate that the cold electron component observed near Titan is associated with local pick-up from water group neutrals redistributed from the inner magnetosphere.

[15] In addition to these clear categories we have also provided a 'Mixed' category in which we list the encounters that did not occur solely in one of the four plasma environments identified and an 'Unclassified' category in which plasma distributions not included in any of our categories are observed occasionally, but not throughout. For example a high energy electron distribution (peaking around and above 10 keV with electron flux at the peak of few times $10^4$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$) is occasionally observed during Titan encounters. Since no encounter occurs exclusively in this type of environment we have not designated it as a separate category. We note that most of the encounters in the 'Unclassified' category show evidence of both very high energy electrons and the cold 'pick-up' population – perhaps indicative of additional ionisation energy being provided by sporadic energetic electron distributions.

[16] Figure 2 shows examples of combined CAPS-MIMI electron differential energy flux (DEF) versus energy spectra for each category. The data have been corrected for spacecraft potential following the method of *Johnstone et al.* [1997] and the penetrating background has been removed from the CAPS data following the method of *Arridge et al.* [2009]. Figure 2 (top left) shows an example plasma sheet spectra observed during T13 from 19:00 to 19:10 UT DOY120 2006; Figure 2 (top right) shows a typical low density lobe-like population observed during T8 from 03:00 to 03:10 UT DOY301 2005; Figure 2 (bottom left) shows a magnetosheath spectra observed during T32 from 19:00 to 19:10 UT DOY164 2007 and Figure 2 (bottom right) shows an example of a bi-modal electron spectra observed during T31 from 17:30 to 17:40 UT DOY148 2007. The approximate boundary between CAPS and MIMI is at 20 keV, the discontinuity in the lobe-like and magnetosheath spectra at this energy can be understood as the CAPS-ELS signal falling below its instrument background levels at the higher end of its energy range while the LEMMS signal is still above its instrument background level. This illustrates a fundamental sensitivity difference between the two instruments. Long dashed and solid lines are Maxwellian and kappa fits to the data, respectively. The parameters of these fits are listed in Table 1.

[17] We note that the lobe-like distribution is not well fit by either a kappa or a Maxwellian distribution and that it is

**Table 1.** Summary of Fit Parameters From Figure 2

| | Maxwellian | | Kappa | | |
|---|---|---|---|---|---|
| Region | n (cm$^{-3}$) | T (eV) | n (cm$^{-3}$) | T (eV) | Kappa |
| a) Plasma sheet | 0.039 | 112 | 0.050 | 130 | 4 |
| b) Lobe-like | 0.003 | 112 | 0.004 | 150 | 4 |
| c) Magnetosheath | 0.435 | 31 | n/a | n/a | n/a |
| d) Bi-modal (cold, hot) | 0.112, 0.004 | 12, 350 | 0.170, 0.005 | 12, 570 | 4, 4 |

not possible to fit the higher energy tails of the distributions using this method.

## 4. Results

[18] The majority of Titan encounters occur in an environment similar to one or a combination of the electron spectra shown in Figure 2. In Table 2 we provide the categorisation of the encounters. Where an encounter

**Table 2.** Magnetospheric Environment Categorisation During Titan Encounters as Identified From CAPS-ELS and MIMI-LEMMS Electron Spectra[a]

| | 1 Plasma Sheet | 2 Lobe-like | 3 M'sheath | 4 Bimodal | 5 Mixed | 6 Unclassified | Saturn Local Time (digital hours) |
|---|---|---|---|---|---|---|---|
| TA | X | | | | | | 11.00 |
| TB | | | | | 1, 2 | | 10.47 |
| T3 | | X$^{1,4}$ | | | | | 10.33 |
| T4 | | X$^{1}$ | | | | | 5.27 |
| T5 | X | | | | | | 5.27 |
| T6 | | | | | 2, 4 | | 5.00 |
| T8 | | X | | | | | 9.27 |
| T9 | X | | | | | | 3.00 |
| T10 | | X | | | | | 8.47 |
| T11 | X | | | | | | 1.13 |
| T12 | | | | | 1, 2 | | 6.40 |
| T13 | X | | | | | | 23.13 |
| T14 | | X$^{4,2}$ | | | | | 4.40 |
| T15 | X$^{4}$ | | | | | | 21.20 |
| T16 | | | | | | X$^{1}$ | 2.40 |
| T17 | | | | | | X$^{4}$ | 2.27 |
| T18 | | X | | | | | 2.27 |
| T19 | X$^{4,6}$ | | | | | | 2.20 |
| T20 | | | | | 1, 2 | | 2.13 |
| T21 | | | | | 1, 2 | | 2.00 |
| T22 | | | | | 1, 3, 2, 1 | | 1.93 |
| T23 | X$^{4}$ | | | | | | 1.93 |
| T24 | | | | | 1, 2 | | 1.87 |
| T25 | | | | | | X | 13.80 |
| T26 | | | | X$^{1}$ | | | 13.80 |
| T27 | | | | | | X$^{4}$ | 13.73 |
| T28 | | | | | 2, 4, 6 | | 13.67 |
| T29 | X$^{3}$ | | | | | | 13.67 |
| T30 | | | | | 2, 4, 6 | | 13.60 |
| T31 | | | | X$^{1}$ | | | 13.60 |
| T32 | | | X$^{1}$ | | | | 13.53 |
| T33 | X$^{4}$ | | | | | | 13.53 |
| T34 | X$^{4}$ | | | | | | 18.80 |
| T35 | | | | | | X$^{4}$ | 11.53 |
| T36 | X$^{4,3}$ | | | | | | 11.47 |
| T37 | | | | | | X$^{4}$ | 11.40 |
| T38 | | | | | | X$^{4}$ | 11.40 |
| T39 | X$^{3}$ | | | | | | 11.33 |
| T40 | | | | X$^{1,2,6}$ | | | 11.33 |
| T41 | | X | | | | | 11.20 |
| T42 | | | X$^{1}$ | | | | 11.13 |
| T43 | | X$^{4}$ | | | | | 11.00 |
| T44 | X | | | | | | 10.93 |
| T45 | | | | | | X$^{4}$ | 11.00 |
| T46 | | | | X$^{2}$ | | | 10.50 |
| T47 | | | | X$^{2,6}$ | | | 10.50 |
| T48 | | | | | | X$^{4}$ | 10.50 |
| T49 | X | | | | | | 10.40 |
| T50 | | | | | 4, 1, 6 | | 10.20 |
| T51 | X$^{4,6}$ | | | | | | 10.00 |
| T52 | X$^{4}$ | | | | | | 22.00 |
| T53 | X | | | | | | 22.00 |
| T54 | | | | | 2, 1 | | 22.00 |
| T55 | X$^{4}$ | | | | | | 22.00 |
| total | 19 | 8 | 2 | 5 | 11 | 9 | |

[a] The final column shows the local time of each encounter, where 12 hours is at noon (sunward) and 0 hours is midnight (in the tail).

(±~3 hours from closest approach) is clearly associated with one region we have placed an 'X' in the appropriate category. If there are brief occurrences of other plasma types we indicate this with a superscript number, for example '$X^1$' associates the encounter with the region indicated with an 'X' but also exhibiting brief occurrences of type '1' plasma (i.e., plasma sheet-like conditions). The fifth column contains encounters that clearly transition from one environment to another with the regions occurring during the encounter indicated with the region number. For example '1, 2' in the 'mixed' column indicates that the encounter was split between plasma sheet and lobe-like environments. The sixth column is 'unclassified' referring to encounters that typically contain elements of the above regions, but also contain electron spectra which are difficult to classify. The final column shows the local time of each encounter, where 12 hours is noon (sunward) and 0 hours is midnight (in the tail).

[19] Our analysis indicates that 34 of the 54 Cassini Titan encounters analysed can be mainly associated with one of our four environment categories, with 19 plasma sheet encounters, 8 encounters in what we have referred to as a lobe-like region, 2 encounters that were predominantly in the magnetosheath and 5 encounters consisting of predominantly bi-modal electron signatures.

## 5. Conclusions and Discussion

[20] We have produced the first calibrated combined electron spectra across the dynamic range of both Cassini electron sensors near Titan in order to assess the different electron plasma environments near Titan. After analyzing electron data from 54 Titan encounters, we have identified four plasma environments which are often observed at 20 Rs during Cassini-Titan encounters as: 1. Plasma sheet: higher flux and energy. 2. Lobe-like: lower flux and higher energy. 3. Magnetosheath: higher flux and lower energy. 4. Bimodal: superposed high and low energy electron populations.

[21] We note that the less energetic, dense part of the bi-modal populations looks a lot like a local electron pick-up population, such as is observed throughout the inner magnetosphere and associated with local pick-up from the distributed neutral cloud [*Rymer et al.*, 2007; *Sittler et al.*, 2008; *Wilson et al.*, 2008]. CAPS ion data during T31 shows evidence of water group particles. Since water group particles originate from the inner magnetosphere, primarily from Enceladus, and not from Titan we speculate that the cold electron component observed near Titan is associated with local pick-up from water group neutrals redistributed from the inner magnetosphere. Further this cold electron component is frequently, while more sporadically, observed during most of the 'Unclassified' encounters and are associated with periods of very hot electrons – which might provide extra ionisation energy near Titan periodically, they might, for example, be associated with large scale energetic particle injections occasionally observed near Titan's orbit by the MIMI energetic neutral camera [*Carbary et al.*, 2007]. Confirmation of whether the lower energy bi-modal electron populations (as in T31) are associated with water-group ions and explanation of the observed cold electron component temperature are interesting areas for future research.

[22] We provide examples of Cassini electron spectra for each of the above environments as well as a classification for each of the first 54 Cassini-Titan encounters where data was available. We find that 34 of the encounters can be associated with one of our 4 categories: 1. Plasma sheet: TA, T5, T9, T11, T13, T15, T19, T23, T29, T33, T34, T36, T39, T44, T49, T51, T52, T53, T55. 2. Lobe-like: T3, T4, T8, T10, T14, T18, T41 and T43. 3. Magnetosheath: T32, T42. 4. Bi-modal: T26, T31, T40, T46 and T47.

[23] Of the remaining 20 encounters 11 occur during a mixture of these plasma types (as indicated on column 5 of Table 1) while 9 occur during periods of plasma spectra not represented by any of our categories that are difficult to categorise for reasons listed earlier.

[24] Titan encounters are mostly in the plasma sheet category. Titan encounters in the magnetosheath are rare despite numerous Cassini-Titan flybys near noon. Intervals of sheath type plasma were seen during several encounters (T22, T29, T32, T36, T39) however encounters T32 [e.g., *Bertucci et al.*, 2008] and T42 are the only encounters to date that are predominantly close to or in the magnetosheath. Given that over half of these encounters occurred within two hours of noon (29 out of the 54 encounters considered) this might be evidence that increased plasma pressure due to plasma loading from Titan could locally 'hold-off', or radially extend, the magnetopause boundary as suggested by *Wei et al.* [2009]. However, we also note that solar activity has been rather low during the observed portion of the Cassini tour so it is possible that Titan may be exposed more often to the magnetosheath as solar activity increases and pushes the magnetosheath Saturn-ward. There seems to be a tendency for the 'unclassified' encounters to occur post noon and so might be associated with a more disturbed dusk flank region of the magnetosphere.

[25] These results will support more accurate Cassini modelling and form a basis for more thorough categorisation incorporating ion data and magnetic field data. Such studies are required to resolve many of the apparent inconsistencies between predictions and observations of Titan and its interactions with the surrounding plasma environment.

[26] **Acknowledgments.** The authors would like to thank Norbert Krupp for use of MIMI-LEMMS data. We thank the many individuals at JPL and NASA who have contributed to making the Cassini project an outstanding success. This work was supported by NASA-JPL contract NAS5-97271 between the NASA Goddard Space Flight Center and Johns Hopkins University for the MIMI investigation and by NASA-JPL contract 1243218 for the CAPS program at the Southwest Research Institute. CAPS data analysis at Mullard Space Science Laboratory is supported by the UK Science and Technology Facilities Council.

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