Heavy ions, temperatures and winds in Titan's ionosphere: Combined Cassini CAPS and INMS observations


Southwest Research Institute, 6220 Culebra Rd. San Antonio, TX 78229, USA

A R T I C L E   I N F O

Article info
Received 5 December 2008
Received in revised form 1 September 2009
Accepted 7 September 2009
Available online 22 September 2009

Keywords:
Titan
Ionosphere
Heavy ions
Ionospheric winds
Ion temperature

A B S T R A C T

Multiple Titan encounters by the Cassini spacecraft have shown that ion chemistry in Titan's upper atmosphere is much more complex than previously thought. As well as showing a great variety of species present below 100 amu, they also include the detection of negative ions and of large abundances of ions above 100 amu. Here, we use data from two Cassini instruments, the Cassini plasma spectrometer's ion beam sensor (CAPS/IBS) and the ion and neutral mass spectrometer (INMS) during fourteen Cassini encounters with Titan's upper atmosphere. By simultaneous analysis of the combined data, we are able to determine the ion temperature, one component of the wind speed and spacecraft potential. Using these derived quantities, we are also able to extend the analysis of CAPS/IBS data to quantify the abundance of ions above 100 amu and to statistically estimate their composition.

1. Introduction

Titan's ionosphere was first detected by radio occultation in 1980 (Bird et al., 1997) and has been extensively studied through theoretical models of ionospheric chemistry (Fox and Yelle, 1997; Wilson and Atreya, 2003, and references therein; Krasnopolsky, 2009) and of solar and magnetospheric energy input (Cravens et al., 2004; Keller et al., 1992). Since October, 2004, the Cassini spacecraft has made repeated, in situ measurements of Titan's ionosphere (Wahlund et al., 2005; Waite et al., 2005, Cravens et al., 2006). These measurements have revealed complex chemistry with species at nearly all masses below 100 amu but with a strong tendency to form “clumps” or “families” of species. These “families” have similar masses and are separated from each other by approximately 12 amu, suggesting each represents species with progressively more carbon or nitrogen atoms (Waite et al., 2005; Cravens et al., 2006; Vuitton et al., 2007). In addition, negative ions ranging up to thousands of atomic mass unit and heavy positive ions with masses up to 350 amu have been detected (Waite et al., 2007; Coates et al. 2007). These very heavy ions may represent the early stages of condensation and haze particle formation.

In this paper we use the combined data from the Cassini plasma spectrometer's ion beam sensor (CAPS/IBS) and the ion and neutral mass spectrometer (INMS) to determine those properties of Titan's ionosphere, which cannot be directly constrained by either instrument alone. First, we compare the simultaneous measurements of both sensors, measuring the same ionospheric species below 100 amu. The two instruments use different techniques and display different sensitivities to ion temperature, wind speed and spacecraft potential. Using the INMS-determined densities and fitting the CAPS/IBS spectra, we determine these properties. Using these results, we are then able to quantify the abundance of ions more massive than 100 amu (which are not sampled by INMS) and place constraints on the chemistry of these heavy ions.

2. Observations

The data used in the present analysis were collected on 14 of Cassini's Titan encounters. These include all encounters during the Cassini prime mission encounters during which simultaneous INMS and CAPS–IBS data were available. Table 1 lists the name, time, date and geometry of these encounters. Half of these encounters (T16, T23, T25, T28, T29, T30 and T39) used a spacecraft orientation suitable for synthetic aperture radar imaging of Titan's surface. In these cases, the INMS data are only available at and near closest approach. The other encounters used an orientation optimized for INMS observations and obtained full vertical profiles from 1300 to 1650 km, above the exobase, down to closest approach altitudes of 950–1050 km.
Counts are accumulated for 31 ms. Transmitted ions are then counted using a secondary electron analyzer, which selects ions of a specific mass to charge ratio. They then pass through a radiofrequency quadrapole mass analyzer. For a given mass, the voltages are adjusted to sequentially measure the flux ions as a function of their kinetic energy per charge. The IBS sensor is not, per se, a mass spectrometer; it measures the flux of ions as a function of their kinetic energy per charge and direction. However, its high-resolution energy spectra may be used to determine ion mass in sufficiently cold (high Mach number) plasmas. The CAPS instrument also contains a time-of-flight ion mass spectrometer, but this very sensitive instrument saturates in the dense plasma of Titan’s ionosphere. Therefore, we confine our analysis to the IBS data.

The IBS measures the flux of ions within one of the three long (150°), narrow (1.4°) angular passbands and within a 1.7% wide range of energies (Young et al., 2005). The fields of view are tilted 30° with respect to each other, to provide information on the direction of ion beams (Bame et al., 1978). In the present analysis, only two of these three detectors are used, since the third has displayed an angular response, which is significantly different from that of the other two. Over 2 s, the energy sampled is stepped through 255 adjacent energy ranges. In the case of the Titan observations discussed here, this produces energy spectra from 3 to 207 eV. At the same time, the sensor is rotated back and forth in order to scan back and forth across the direction of the ion beam. In the case of Titan encounters, a range of 28° in one direction is scanned once every 52 s. At the center of this range (along the spacecraft—X axis), all IBS detectors and the INMS open source field of view overlap.

### 3. Modeling of IBS response

In the case of a cold, supersonic ion beam, where the flow speed is much larger than the root mean square thermal velocity, the IBS energy spectra are equivalent to low resolution mass...
spectra. To first order, the peak flux from a given species, \( x \), occurs at an energy \( E_x = m_x w^2 / 2 + 8kT \), where \( m_x \) is the mass of the species, \( w \) the flow speed and \( T \) the temperature. The width of the peak is approximately equal to the thermal velocity. Thus, when \( m_x w^2 / 2 \gg 8kT \), the energy at which the peak appears provides a measure of the mass of the species producing the peak. Thus, the energy spectra are effectively mass spectra with a resolution of \( M/\Delta M \sim w/(2kT m_x)^{1/2} \). During Titan encounters, the flow speed is approximately 6 km/s. If the ion temperature were 150 K (typical of values calculated below), the effective mass resolution of IBS would be 30 at 28 amu. At higher masses or lower temperatures, the effective resolution is limited to \(< 60 \) by the 1.7% energy resolution of the sensor. As a result, species with similar masses (e.g. HCNH\(^+\) and C\(_2\)H\(_5\)\(^+\)) cannot be resolved in the IBS spectra.

For a quantitative comparison of the IBS and INMS measurements, we adopt a more rigorous model of the response of IBS to a single species in a Maxwellian distribution. A relatively complex treatment of the response is required, since the ion flux is spread over several energy bins and is partially outside the sensor’s angular field of view. The resulting corrections are mass, flow speed and temperature-dependent, and are necessary for an accurate, combined analysis of IBS and INMS data.

In modeling the instrument response, we assume that the instrument’s sensitivity is given by an effective area, which is zero outside each energy/angle passband and constant within each passband. The flux is then given by the integral of differential particle flux over the passband. A more rigorous, but computationally impractical approach would be to convolve the differential energy flux with the full energy–angle response of the instrument. The approximation adopted here is generally within 20% of the more rigorous calculation. Assuming the species to be singly charged and when looking directly into the direction of ion flow, the flux from a single species, \( x \), measured by the sensor is given by

\[
F_{i,x} = \int_{v_{i,0}}^{v_{i,1}} dv \int_{-\theta}^{\theta} d\theta \int_{-\gamma}^{\gamma} v^3 \cos \theta d\phi \frac{n_x}{\pi^{1/2}} a_x^{1/2} e^{-(v-w)^2/a_x^2} \]

where \( F_i \) is the flux at energy step \( i \) (centered on an energy of \( E_i \)), \( v_{i,0} \) and \( v_{i,1} \) are the velocities corresponding to the minimum and maximum energies observed at step \( i \), \( \Phi_{sc} \) is the spacecraft potential, \( n_x \) is the ion density, \( w \) is the flow speed and \( a_x \) is the root mean square thermal velocity of the ions, \( T \) their temperature and \( m_x \) the mass of that species. The numerical factors represent the energy and angular width of the IBS sensor’s passbands. Eq. (1) assumes full sensitivity within the sensor’s passband and zero sensitivity outside it. In practice, the response is more complex. Assuming \( a_x \ll w \), this simplifies to

\[
F_{i,x} = \frac{n}{2\sqrt{\pi}} \text{Erf} \left( \frac{v_{i,0} + v_{i,1} \tan 0.7}{2a_x} \right) \left\{ a_x \left( e^{-(v_{i,0} - w)^2/a_x^2} - e^{-(v_{i,1} - w)^2/a_x^2} \right) \right\} + w \sqrt{\pi} \left[ \text{Erf} \left( \frac{v_{i,0} - w}{a_x} \right) - \text{Erf} \left( \frac{v_{i,1} - w}{a_x} \right) \right] \]

The total flux observed, in the presence of multiple ion species, is simply the linear sum of fluxes from each, individual species, \( F_i = \sum F_{i,x} \).

In principal, a similar, temperature-dependent correction should be applied to INMS data, since some fraction of the ion flux could be outside their 3° field of view. We do not, however, attempt to introduce such a correction in our analysis. As noted, below, out analysis requires accurate knowledge of the ion abundance within each of the seven mass groups, but is not sensitive to the absolute densities of each species. The effects of such a correction on abundance within a group is greatest at the lower masses and even in these cases, only introduces approximately a 5% error in the relative abundance.

4. Combined analysis of IBS and INMS spectra

IBS data from both detectors are selected by first finding energy sweeps, which are local maxima of total ion fluxes, summed over all energies. These sweeps are those that occur when the sensor is pointed in, or very nearly in, the direction of the ion flow. An IBS spectrum is then compiled from the maximum observed flux for each energy bin collected over five spectra centered on the bin containing the peak total flux. This ensures that, energy by energy steps, the measurement is made while looking directly into the flow direction. Since the energy steps are sampled sequentially, the first step of a sweep is sampled 2 s, and 2° of the actuator motion, before the last. This can cause the steps at the end of one sweep, and those at the beginning of the next, to be the samples taken while looking
closest to the flow direction. In addition, at the lower masses, the spacecraft potential may deflect the ion trajectories by a few degrees, causing the desired look direction to differ slightly for these species. By taking a maximum of five sweeps, centered on the sweep with peak total flux, we assure that each energy step was measured while looking into the flow direction and that Eq. (1) is valid. During the observations used in this analysis, CAPS actuated over a 28° range, centered on the expected ram direction. Given its large (150°) field of view in the other direction, the flow could be as much as 14° off the ram direction without compromising our assumption of looking into the ram direction. A flow 14° off the ram direction would result from a 1.5 km/s cross-track wind. The corresponding INMS ion spectrum is calculated by taking the mean of observed INMS ion measurements collected within 10 s of the IBS flux spectrum. The data where the INMS angle of attack is beyond 5° of the ram direction are filtered out.

Having collected simultaneous INMS and IBS spectra, we fit the IBS energy spectra using the INMS-measured densities by iteratively minimizing $\chi^2$. In each spectrum, each of the seven groups of ions (e.g. 15–20, 22–32 amu, etc.) are fit separately, using Eq. (2) and summing over all ion species observed by the INMS. At each iteration of the fitting process, the INMS densities are adjusted based on sensitivity as a function of the spacecraft potential.

The free parameters are ion temperature, an effective spacecraft potential and a relative sensitivity correction. The ion temperature primarily affects the width of the model peaks, the degree to which the peaks from individual species within a group merge together, and the amplitude of the peak (since the flux, integrated over the peak, is only a weak function of the temperature). The effective spacecraft potential combines the effects of the true spacecraft potential and the wind speed in the direction of the spacecraft’s velocity.

$$\Phi = \Phi_{sc} + \frac{m_e}{e}(w_{sc}w_{wind} + w_{wind}^2/2) = \Phi_{sc} + \frac{m_w}{e}w_{wind}$$

The primary effect of this parameter is to shift the location and spacing of the energy peaks. Note that the IBS energy spectra are only sensitive to the component of the wind speed in the direction of the spacecraft’s motion. In addition, the wind speed measured in this way is the sum of the neutral wind speed and the ion drift relative to the neutrals. Below the exobase, the ion drift is expected to be small, but at higher altitudes a significant fraction of the calculated speed may be due to ion drift. The cross-track component of the wind would shift the direction of the peak flux, but not its energy. Spacecraft potential can also have this effect, and unlike the related shift in particle energy, the shift in direction is a complex function of the spacecraft’s shape and photo-electron sheath. As a result, we do not attempt to use directional information to compute the cross-track wind speed. Although the INMS densities are corrected for the fit spacecraft potential, we do not include any, similar correction for winds. Based on the INMS calibration data, the <260 m/s along-track winds would have a negligible effect. Cross-track winds of a similar magnitude would result in a 10–20% underestimate of densities. Since we cannot determine this cross-track component, we cannot correct for this resulting in a small but unavoidable additional uncertainty. The final fit parameter is the relative sensitivity factors of two instruments, a constant multiplicative factor changing the amplitude of the model peak. The INMS and the IBS sensors are not absolutely inter-calibrated, so an arbitrary correction factor is

Fig. 2. Example comparison of an INMS, CAPS–IBS and fit spectrum. The INMS spectrum from the T26 encounter, at 1025 km of the ingress leg, is shown above. Below, the CAPS–IBS spectrum from the same time and the best fit model spectrum using the INMS densities as input.
included as a free parameter in the fits. Our use of the INMS data relies on the relative abundance of ions rather than the absolute density. By including a scaling factor as one of our fit parameters we avoid sensitivity to the absolute accuracy of the instrument. This correction factor does not affect any of our other results, since the other fit parameters (temperature, spacecraft potential, and along-track wind speed) depend on the shape and the location of peaks, not their amplitude. The derived heavy ion abundances, below, rely on the temperature, potential and wind speed, but do not use the amplitude correction generated by these fits.

After fitting each group separately, temperature is calculated by averaging each group’s best fit values. The spacecraft potential and wind are calculated by fitting the effective potential of each group to Eq. (3). Fig. 1 shows an example of wind speed calculated from fitting the mass-dependent effective potential.

Due to the nature of the model and fitting regime, a human user is necessary to oversee the proper execution of each fit. A graphical interface has been developed for the fitting process that gives a human user the necessary control to define each ion group, set reasonable initial values for each fit parameter, and verify the accuracy of the resultant fit. Human error is mitigated by testing suspect fits with different input parameters, and dismissing erroneous fits entirely.

5. Results

Fig. 2 shows an example of the INMS and the IBS spectra and the results of this fitting process, while Fig. 3 shows a series of fits as a function of altitude. The fits only extend up to 100 amu. The process depends on the INMS density as an input and the INMS only measures density up to 100 amu. Overall there is an excellent agreement between the two data sets. Fig. 4 shows examples of the resulting fit parameters (spacecraft potential, ion temperature, and along-track wind speed) for ingress and egress of the T17 and the T26 encounters.

5.1. Spacecraft potential

The model fits are very sensitive to the spacecraft potential at the location of the CAPS and the INMS sensors, which affect both the location of energy peaks in IBS spectra and an important correction to the INMS sensitivity. Further, once derived by the present analysis, the results may be used to improve the absolute calibration of the INMS data.

Most flybys fit within a general structure is characterized by increasing the spacecraft potential from $-2 \text{V}$ near 1500 km to $-0.5 \text{eV}$ near 1000 km with a few notable exceptions. The spacecraft potential resulting from these fits have been compared to those determined independently by the RPWS Langmuir probe. Fig. 5 shows the IBS/INMS derived values and the Langmuir probe measurements. Other than a small constant DC offset of order 0.25 V these data are in good agreement. An offset of a fraction of a volt is reasonable and probably due to a non-uniform spacecraft potential. The Langmuir probe is mounted on a different part of the spacecraft, is on a 1.5 m boom and was carefully coated with titanium nitride, which allows precise measurements of the spacecraft’s potential relative to the surrounding plasma (Gurnett et al., 2005). The INMS and the CAPS instruments, on the other hand, are co-located and covered by conductive, carbon-impregnated Kapton thermal blankets (Young et al., 2005). This insures that the CAPS and the INMS instruments are equipotential, but the differences from the Langmuir probe could easily result in the observed 0.25 V difference. These comparisons are very encouraging because they provide a method of validating our results and by extension our application of the fit model. Mean precision of the fit spacecraft potentials is found to be $0.035 \text{eV}$.

5.2. INMS–IBS sensitivity correction

A majority of fits result in a mass-dependent sensitivity correction, increasing with mass in a logarithmic fashion. This phenomenon is yet to be understood completely but does represent a clear and reliable trend. It was found to be necessary to use a different sensitivity factor for each of the IBS detectors. This parameter is then the lone value calculated for each individual IBS detectors, which is not surprising given the age of the channel electron multipliers and possible slight shifts in gain. Other sources of a mass-dependent sensitivity include the detection efficiency, which may be a function of the mass, the
Fig. 4. Panels a–d: spacecraft potential derived from combined INMS–IBS fits for the T17 ingress (a), T17 egress (b), T26 ingress (c) and T26 egress (d). The potential measured by the RPWS–LP is shown as squares. Panels e–h, derived ion temperature from the same encounters. Panels i–l, derived along-track wind speed for the same encounters.
somewhat idealized instrument which went into Eq. (1), corrections to the INMS data to account for the fraction of particles outside its field of view due to temperature or wind speed, and the effects of cross-track winds (which cannot be included since these winds are not measured).

5.3. Ion temperature

Fig. 6a shows the derived ion temperatures as a function of altitude for all spectra. Fitted ion temperatures typically vary between 100 and 200 K and generally have large uncertainties. The model spectra are not especially sensitive to the temperature: For temperatures over ~100 K, the peaks from individual species are merged, as is seen in the data. Beyond that, the temperature (in combination with the relative abundances of the species in a group) acts to broaden the merged peaks and causes subtle differences in the peak shapes. This has a far less significant effect on $\chi^2$ than the peak locations or amplitudes. Typical uncertainties in temperature are between 20 and 30 K.

Despite these uncertainties, some clear trends are evident when the data from several encounters are considered together. In Fig. 6, there is an overall trend of increasing temperature with altitude from ~125 K at 1100 km to ~200 K at 1600 km. We find that the best linear fit to the ion temperatures above 1200 km is $(110 \pm 3 K) + (0.26 \pm 0.02 \text{K/km}) (z-1200 \text{ km})$. This is in contrast to observations of the neutral atmosphere at these altitudes, which indicate more constant temperatures between 145 and 160 K (Vervack et al., 2004; Shemansky et al., 2005; De La Haye et al., 2007) or temperatures which decrease with altitude (Müller-Wodarg et al., 2008). This indicates a decoupling of ion and neutral temperatures, due to decrease in the density and collision frequency. Ion heating is also implied. This heating could be due to any one of the several processes and may involve the interaction between Titan’s ionosphere and the magnetospheric plasma of Saturn (Rosenqvist et al., 2009, and references therein).

Below 1100 km, there is a suggestion of higher temperatures at lower altitudes. At these altitudes, the best linear fit is $(133 \pm 3 K) - (0.12 \pm 0.03 \text{K/km}) (z-1100 \text{ km})$. The empirical, INMS-based model of Müller-Wodarg et al. (2008) shows neutral temperatures structure below 1100 km, which depends on latitude, but no local time or solar zenith angle were noted in this analysis. The uncertainty in our derived ion temperatures requires that the use of all available points detect decreasing temperature with altitude below 1100 km. The available data are insufficient to quantitatively assess this trend as a function of the local time and longitude.

A series of five encounters also shows a clear, if unsurprising, trend in the derived ion temperature. As indicated in Table 1, the T26, T28, T29, T30 and T32 encounters were nearly identical in all respects (longitude, and local time with respect to both Titan and Saturn) except for their latitude, which increased from 31.7° at a closest approach to 84.5° near the northern (winter) pole. For measurements between 950 and 1050 km, the ion temperature falls monotonically from 186 K at 31.7° to 128 K near the northern (winter) pole. A similar trend in neutral temperatures was also noted by Müller-Wodarg et al. (2008). Other trends and correlations with local time, latitude or longitude are not obvious due to the uncertainty and the limited number of samples within the four-dimensional parameter space.

5.4. Ion winds

The presence of ion winds is clear in the combined analysis of the INMS and the IBS spectra. The energy of higher mass peaks does not match their predicted locations without including ion winds along the spacecraft track. These disagreements are systematic and well-modeled by the inclusion of winds. Wind speeds are commonly calculated to be in the range of 100 m/s with the highest values reaching up to 260 m/s. The average precision of this parameter is approximately ±10 m/s.
Note that wind speeds and along-track directions are calculated based on the best available, reconstructed spacecraft ephemeris and in a frame at rest with respect to, and rotating with, Titan.

These results are difficult to compare with other estimates of winds at these altitudes. Only one component of the wind is measured. That component is not the same from encounter to encounter, and IBS is rarely oriented to sample a purely zonal or meridional component. In magnitude, however, our results are on par with an estimate of $245 \pm 50 \text{ m/s}$ (Müller-Wodarg et al., 2006) and up to $150 \text{ m/s}$ (Müller-Wodarg et al., 2008) for neutral winds at these altitudes and of neutral winds up to $160 \text{ m/s}$ in the lower atmosphere (Flasar et al., 2005).

6. Heavy ions above 100 amu

The preceding analysis examined the properties of ions with masses below 100 amu, that is, those ions in the INMS range. However, the CAPS–IBS sensor covers energies up to $207 \text{ eV}$ in these scans, corresponding to the ram energy of a 1080 amu ion. In the IBS spectra, ions at energies corresponding to 100–200 amu appear below approximately 1200 km and become the dominant ion species below 1000 km (Waite et al., 2007). At lower altitudes, ions with masses above 200 amu are also observed, although their density is low and the spectra do not indicate any clear peaks at particular masses. Using the spacecraft potential and wind derived from comparing INMS and IBS data, the IBS data above 100 amu can now be analyzed to accurately describe the heavy ion population above INMS mass range capabilities.

6.1. Estimates of heavy ion properties

We first interpolated the IBS energy bins of spectra taken below 1200 km to 1 amu mass bins using the fit-determined spacecraft potential and wind. A peak determination scheme was then applied such that a mass bin was identified as a peak if its flux was above the noise and was also the bin containing the highest flux within 1 eV. For this peak-identification analysis, the mass range was capped at 200 amu due to the decrease in effective mass resolution of IBS data. The error in determining the peak mass was set to the error in the fit spacecraft potential. A total of 130 spectra were analyzed in this fashion producing a large database of peaks. This database of peak locations was then examined and exhibited clearly static groupings. A percent occurrence chart (Fig. 7) was produced by determining what percentage of the analyzed spectra showed a peak within 1 sigma of each mass bin. For example, in the mass range labeled 4 in Fig. 6, a peak between 135 and 147 amu was observed in 95% of the 130 spectra analyzed. In 31% of these spectra, this peak occurred at 141 amu, in 25% of these spectra, at 140 amu, etc. While the percent occurrence cannot be used directly as a mass spectrum, it is useful for determining the properties of the high mass ions.

In addition to the identification of persistent peaks above 100 amu, the CAPS–IBS data can also be used to estimate total ion densities. Each energy step in the ion spectrum is assumed to correspond to a mass equal to $m=2E/w^2$, where $w$ is the spacecraft velocity, and using the spacecraft potential and wind speed derived from the INMS–IBS comparisons. Eq. (2) is inverted, using the derived ion temperature, to give the relative density of ions associated with that energy bin. These relative densities were then normalized by the sum over all bins, to give the abundance of ions within each bin. This normalization cancels out uncertainties in absolute calibration of the IBS sensor. Summing by all energy bins above 18.75 eV gives the abundance of ions heavier than 100 amu. Fig. 8 shows an example of this abundance of these heavy ions as a function of altitude, for all analyzed spectra. Densities of all ions and all ions over 100 amu are calculated, as described in the text, using the spacecraft potential, ion temperature and along-track ion wind speed derived from the combined INMS–IBS fit, and the abundance of heavy ions is calculated from the ratio.

![Fig. 7. The percent occurrence calculated for each mass bin from 100 to 200 amu as described above. Total percent occurrence for each apparent group is shown in box above the peak.](image)

![Fig. 8. The abundance of heavy (> 100 amu) ions as a function of altitude, for all analyzed spectra. Densities of all ions and all ions over 100 amu are calculated, as described in the text, using the spacecraft potential, ion temperature and along-track ion wind speed derived from the combined INMS–IBS fit, and the abundance of heavy ions is calculated from the ratio.](image)
6.2. Heavy ion chemistry

The structure of the percent occurrence plot (Fig. 7) shows seven distinct groups each of which contains a narrow region of highly probable peaks. The spacing between the peak percent occurrences is 12–14 amu, suggesting that the ions consist of carbon and nitrogen compounds. From the ion data obtained below 100 amu, it is clear that the most likely ions are hydrocarbons and hydrocarbon–nitrile combinations (Waite et al., 2007; Vuitton et al., 2006; Vuitton et al., 2007). Waite et al. (2007) suggested that the high mass ions contained naphthalene, anthracene derivatives and an anthracene dimer. Naphthalene (C10H8+), anthracene (C14H10+), and naphthalene (C10H6+) would occur around masses 128 and 178. Naphthalene is in a high percent occurrence group (seen in 79% of the spectra). Anthracene is within the least frequently seen group, present in only 30.8% of the spectra, but its mass is the most commonly observed peak within that group.

Methods for producing high mass ions include ion-neutral reactions and homogeneous chemical reactions followed by proton capture or ionization and condensation. Ion-neutral reactions for the production of high mass ions have been considered through polycyclic aromatic hydrocarbon (PAH) polymerization in which either acetylene or hydrogen cyanide combines with phenyl radicals (C6H5+) to build multi-ringed structures have been considered by Bauschlicher et al. (2002) and Ricca et al. (2001). The prevailing methods for neutral production are acetylene polymers, nitrile polymers, PAHs and aliphatic (straight chain) and aromatic copolymers (Wilson and Atreya, 2003). The measured ion densities obtained show that the rate of condensation is one-tenth of the ion-neutral chemical process (Waite et al., 2007). Table 2 shows the more probable, 100–200 amu ions produced by these methods. When compared to the probability of occurrence as a peak in the IBS data, it is clear that the most likely pathway is through ion-neutral reactions that produce PAHs.

7. Conclusions

We have developed a novel technique to combine the data from an ion mass spectrometer and an electrostatic analyzer energy spectrometer. Using this technique and the data from the Cassini INMS and CAPS/IBS spectrometers, we have determined ionospheric temperatures and wind speeds, as well as the spacecraft potential, and derived properties of heavy ions above the 100 amu limit of the INMS instrument. The data used come from 14 Titan encounters, and include all the Cassini prime mission encounters where suitable data from both instruments are available.

Ion temperature were found to vary from 90 to 255 K. Taking all encounters together, there is a trend of increase in temperature with altitude, from approximately 120 K at 1200 km to 225 K at

Table 2
Possible ion species within each of the peak group shown in Fig. 7.

<table>
<thead>
<tr>
<th>GROUP</th>
<th>ACRYLIC POLYMERS</th>
<th>ACRYLIC COPOLYMERS</th>
<th>ALIPHATIC COMPOUNDS</th>
<th>NITRILE POLYMERS</th>
<th>ALIPHATIC COMPOUNDS</th>
<th>NITRILE AROMATIC COMPOUNDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>104 (C4N2)</td>
<td>100 (C3H3N)</td>
<td>105 (C2H3N4)</td>
<td>122 (C6H3)</td>
<td>119 (C3H4)</td>
<td>104 (C3H4N)</td>
</tr>
<tr>
<td>2</td>
<td>112 (C5H2)</td>
<td>110 (C4H2)</td>
<td>131 (C3H3N)</td>
<td>129 (C6H2)</td>
<td>128 (C3H3N)</td>
<td>129-130 (C6H4N)</td>
</tr>
<tr>
<td>3</td>
<td>130 (C4H2)</td>
<td>122 (C3H3N)</td>
<td>124 (C4H2)</td>
<td>129 (C6H2)</td>
<td>128 (C3H3N)</td>
<td>129-130 (C6H4N)</td>
</tr>
<tr>
<td>4</td>
<td>146 (C2H4)</td>
<td>134 (C3H3N)</td>
<td>146 (C2H4)</td>
<td>134-136 (C4H4)</td>
<td>153 (C6H4N)</td>
<td>156 (C6H6N)</td>
</tr>
<tr>
<td>5</td>
<td>156 (C3H3N)</td>
<td>157 (C4H2)</td>
<td>156 (C3H3N)</td>
<td>155 (C6H2)</td>
<td>153 (C6H4N)</td>
<td>156 (C6H6N)</td>
</tr>
<tr>
<td>6</td>
<td>170 (C3H3N)</td>
<td>160 (C3H3N)</td>
<td>170 (C3H3N)</td>
<td>165 (C6H6N)</td>
<td>165 (C6H6N)</td>
<td></td>
</tr>
</tbody>
</table>

Each species is color coded with the with the frequency at which a peak was observed at that ion’s mass. It is clear from this analysis that the peaks are most frequently seen at the masses of aromatic hydrocarbons and not aliphatic compounds.
1600 km. Temperatures between 950 and 1200 km are either constant, or show a weak decrease with altitude.

The comparison between CAPS/IBS and INMS spectra show clear evidence of strong ionospheric winds. Although only one component of the wind speed is measured, and that component varies from encounter to encounter, winds of approximately 100 m/s are observed on most encounters. The full range of wind speeds measured varies from 28 m/s (essentially zero within measurement error) to as much as 230 m/s.

Heavy ion, with masses over 100 amu, have been detected in the CAPS/IBS data (Waite et al., 2007). Our inter-instrument comparison allows us to quantify these results. These show that heavy ions are ubiquitous below 1200 km and often represent the dominant ion species below 1000 km. Although the exact mass of these species cannot be determined, the locations of persistent peaks are consistent with polycyclic aromatic hydrocarbons produced by the more efficient chemical processes in Titan’s upper atmosphere.

PAHs have been proposed as the link between the gaseous compounds and the organic aerosols (tholins) found lower in Titan's haze (Waite et al., 2007). The most well-known aromatic hydrocarbon is benzene, which has been identified in Titan's upper atmosphere at a mole fraction of a few times $10^{-6}$ (Waite et al., 2005). Our analysis indicates that two and three ring PAHs are present in Titan's upper atmosphere at altitudes above 950 km.

**Acknowledgements**

We thank the support of the Cassini CAPS and INMS operations teams, NASA/JPL contract 959930 with SwRI for financial support of the CAPS investigation and 1283095 for financial support of the teams, NASA/JPL contract 959930 with SwRI for financial support of the CAPS investigation and 1283095 for financial support of the INMS investigation. The authors thank J.-E. Wahlund for providing support of the Cassini CAPS and INMS operations teams, NASA/JPL contract 959930 with SwRI for financial support of the CAPS investigation and 1283095 for financial support of the INMS investigation. The authors thank J.-E. Wahlund for providing

**References**


