Composition and chemistry of Titan’s thermosphere and ionosphere

BY V. VUITTON1,2,*, R. V. YELLE2 AND P. LAVVAS2

1 Laboratoire de Planétologie de Grenoble, CNRS, 38041 Grenoble, France
2 Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721-0092, USA

Titan has long been known to harbour the richest atmospheric chemistry in the Solar System. Until recently, it had been believed that complex hydrocarbons and nitriles were produced through neutral chemistry that would eventually lead to the formation of micrometre sized organic aerosols. However, recent measurements by the Cassini spacecraft are drastically changing our understanding of Titan’s chemistry. The Ion and Neutral Mass Spectrometer (INMS) and the Cassini Plasma Spectrometer (CAPS) revealed an extraordinary complex ionospheric composition. INMS detected roughly 50 positive ions with \( m/z < 100 \) and a density higher than 0.1 cm\(^{-3}\). CAPS provided evidence for heavy (up to 350 amu) positively and negatively charged (up to 4000 amu) ions. These observations all indicate that Titan’s ionospheric chemistry is incredibly complex and that molecular growth starts in the upper atmosphere rather than at lower altitude. Here, we review the recent progress made on ionospheric chemistry. The presence of heavy neutrals in the upper atmosphere has been inferred as a direct consequence of the presence of complex positive ions. Benzene (C\(_6\)H\(_6\)) is created by ion chemistry at high altitudes and its main photolysis product, the phenyl radical (C\(_6\)H\(_5\)), is at the origin of the formation of aromatic species at lower altitude.

Keywords: Titan; atmospheres; composition; ionospheres

1. Introduction

Titan has long been known to harbour the richest atmospheric chemistry in the Solar System that culminates in the generation of thick haze layers. Far ultraviolet solar radiation dissociates the major neutral species (nitrogen and methane) in the upper atmosphere and produces primary species such as HCN, C\(_2\)H\(_2\) and C\(_2\)H\(_4\) (Yung et al. 1984; Wilson & Atreya 2004). The first photochemical models investigating aerosol formation found a maximum production at approximately
200 km through neutral chemistry involving complex hydrocarbons and nitriles (Lebonnois et al. 2002; Wilson & Atreya 2003). However, this result was in disagreement with microphysical models that required a production above 400 km in order to fit the geometric albedo (McKay et al. 2001).

It came as a surprise then, if not a shock, that Cassini instruments revealed some very complex molecules in Titan’s upper thermosphere and ionosphere. The Ion and Neutral Mass Spectrometer (INMS) and the Cassini Plasma Spectrometer (CAPS) performed the first composition measurements of Titan’s upper atmosphere. They revealed an extraordinarily complex ionospheric composition. INMS detected roughly 50 positive ions with $m/z<100$ and a density higher than 0.1 cm$^{-3}$ (Cravens et al. 2006; Vuitton et al. 2006, 2007). CAPS provided evidence for heavy (up to 350 amu) positively and negatively charged (up to 4000 amu) ions (Coates et al. 2007; Waite et al. 2007). These species are probably the first intermediates in the formation of even larger molecules. As a consequence, they affect the composition of the bulk atmosphere, the composition and optical properties of the aerosols and the flux of condensable material to the surface.

Based on INMS results, we present here a brief review of the complex chemistry in Titan’s thermosphere and ionosphere and further describe its larger role in chemical cycles. In §2, we show how modelling the ion composition constrains the density of minor neutral constituents. The species identified with this technique include a variety of aromatics, (cyano-) polyynes, nitriles, imines and ammonia. We compare the results to the predictions of the most recent photochemical models. We review formation mechanisms and highlight needs for new experimental and theoretical data.

In §3, we focus on benzene distribution and production. We show how the response of the INMS closed-source neutral (CSN) at $m/z=77$ and 78 can be understood as a combination of atmospheric C$_6$H$_6$ and a recombination of C$_6$H$_5$ radicals with H atoms on the walls of the instrument. We explain that the benzene and phenyl densities required to fit the data are consistent with the results of a state-of-the-art photochemical model. The model shows that benzene is efficiently produced by ion chemistry in the upper atmosphere. However, benzene is quickly photolysed and phenyl radicals (C$_6$H$_5$), the main photodissociation products, are approximately three times as abundant as benzene in the upper atmosphere. Loss of benzene occurs primarily through the reaction of phenyl with other radicals, producing more complex aromatic species. Section 4 presents some concluding thoughts.

2. Complex hydrocarbons and nitrogen-bearing species in the ionosphere

(a) A variety of ions and their associated neutrals

Figure 1 shows the average ion spectrum in the 1027–1200 km region measured by INMS during the outbound of the T5 encounter (Vuitton et al. 2007). At the closest approach (C/A), the spacecraft was at latitude of 74° N, the solar zenith angle at this location was 127° and the encounter occurred in darkness. The mass spectrum of Titan’s ionosphere is quite complex. There are 45 peaks between $m/z=1$ and 99, with a mass periodicity of 12 amu. The detection threshold is approximately 0.3 cm$^{-3}$.
Photochemical models (Ip 1990; Keller et al. 1992, 1998; Banaszkiewicz et al. 2000; Wilson & Atreya 2004) provide some insight into the chemistry and composition of Titan's ionosphere. Solar EUV photons, photoelectrons and Saturnian magnetospheric electrons ionize the major neutral species (nitrogen and methane) to produce N\textsuperscript{+}, CH\textsuperscript{+}, NH\textsuperscript{+}, HCNH\textsuperscript{+}, NH\textsubscript{2}N\textsuperscript{+}, HCN\textsuperscript{+}, C\textsubscript{2}H\textsuperscript{+}, C\textsubscript{3}H\textsuperscript{+}, C\textsubscript{4}H\textsuperscript{+}, CH\textsubscript{2}\textsubscript{NH\textsuperscript{+}}, C\textsubscript{3}H\textsubscript{7}\textsuperscript{+}, C\textsubscript{6}H\textsubscript{5}NH\textsuperscript{+}, C\textsubscript{7}H\textsubscript{7}\textsuperscript{+}, C\textsubscript{6}H\textsubscript{7}\textsuperscript{+}, C\textsubscript{5}H\textsubscript{7}\textsuperscript{+}, C\textsubscript{4}H\textsubscript{5}\textsuperscript{+}, C\textsubscript{6}H\textsubscript{3}\textsuperscript{+}, C\textsubscript{5}H\textsubscript{5}\textsuperscript{+}, C\textsubscript{5}H\textsubscript{7}\textsuperscript{+}, C\textsubscript{4}H\textsubscript{3}\textsuperscript{+}, C\textsubscript{6}H\textsubscript{5}\textsuperscript{+}, C\textsubscript{7}H\textsubscript{5}\textsuperscript{+}, C\textsubscript{6}H\textsubscript{7}\textsuperscript{+}, C\textsubscript{5}H\textsubscript{5}\textsuperscript{+}, C\textsubscript{6}H\textsubscript{3}\textsuperscript{+}, C\textsubscript{2}H\textsubscript{7}\textsuperscript{+}, C\textsubscript{2}H\textsubscript{5}\textsuperscript{+}, C\textsubscript{3}H\textsubscript{3}\textsuperscript{+}, C\textsubscript{3}H\textsubscript{4}\textsuperscript{+}, C\textsubscript{3}H\textsubscript{5}\textsuperscript{+}, C\textsubscript{2}H\textsubscript{5}\textsuperscript{+}, C\textsubscript{2}H\textsubscript{3}\textsuperscript{+}, C\textsubscript{5}H\textsubscript{3}\textsuperscript{+}, CH\textsubscript{3}\textsuperscript{+}, C\textsubscript{2}H\textsubscript{3}\textsuperscript{+}, CH\textsubscript{2}\textsuperscript{+}, NH\textsubscript{2}\textsuperscript{+}, C\textsubscript{2}H\textsubscript{2}\textsuperscript{+}, CH\textsubscript{4}\textsuperscript{+} and CH\textsuperscript{+} ions (Gan et al. 1992). Ion–neutral chemistry converts these ions to higher mass products. As in any reducing environment, ionization flows from species whose parent neutrals have smaller proton affinities (PA) to species whose parent neutrals have larger PA (Fox & Yelle 1997). Because proton exchange reactions drive the chemistry, the most abundant ions are essentially protonated neutrals (closed-shell ions). It follows that the ionospheric composition is a function of the neutral composition weighted by the PA of these neutrals.

With this approach, Vuitton et al. (2006, 2007) attributed many ions to nitrogen-bearing species that were not expected by pre-Cassini models. Moreover, by coupling a simple chemical model with the measured densities of ions, they determined the abundance of many minor neutrals, abundance that cannot be retrieved by any other technique. The mole fractions of 6 hydrocarbons and 10 nitrogen-bearing species are listed in table 1. These species include the most complex molecules identified so far on Titan.

Figure 1. INMS measurements and the ion chemistry model output (from Vuitton et al. 2007). The data points show the INMS mass spectrum measured on 16 April 2005 (T5 flyby), averaged between the altitudes of 1027 and 1200 km. The dashed line connects the data points. Error bars are included with the points but are smaller than the symbol size for larger densities. They represent the uncertainty due to counting statistics. A systematic error of approximately 20% due to calibration uncertainties is not included. The solid line represents the modelled spectrum with densities of selected neutral species tuned to reproduce the observations.

Photochemical models (Ip 1990; Keller et al. 1992, 1998; Banaszkiewicz et al. 2000; Wilson & Atreya 2004) provide some insight into the chemistry and composition of Titan’s ionosphere. Solar EUV photons, photoelectrons and Saturnian magnetospheric electrons ionize the major neutral species (nitrogen and methane) to produce N\textsuperscript{+}, N\textsuperscript{+}, CH\textsuperscript{+}, CH\textsuperscript{3+}, CH\textsuperscript{2+} and CH\textsuperscript{+} ions (Gan et al. 1992). Ion–neutral chemistry converts these ions to higher mass products. As in any reducing environment, ionization flows from species whose parent neutrals have smaller proton affinities (PA) to species whose parent neutrals have larger PA (Fox & Yelle 1997). Because proton exchange reactions drive the chemistry, the most abundant ions are essentially protonated neutrals (closed-shell ions). It follows that the ionospheric composition is a function of the neutral composition weighted by the PA of these neutrals.

With this approach, Vuitton et al. (2006, 2007) attributed many ions to nitrogen-bearing species that were not expected by pre-Cassini models. Moreover, by coupling a simple chemical model with the measured densities of ions, they determined the abundance of many minor neutrals, abundance that cannot be retrieved by any other technique. The mole fractions of 6 hydrocarbons and 10 nitrogen-bearing species are listed in table 1. These species include the most complex molecules identified so far on Titan.
Table 1. Neutral mole fractions in Titan’s upper atmosphere. (The mole fractions are determined from INMS ion measurements obtained on the Cassini T5 flyby at 74° N and 1100 km. The neutral mole fractions of selected compounds computed by the photochemical models of Wilson & Atreya (2004) and Lavvas et al. (2008a) are listed as well.)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>C2H4</td>
<td>$1 \times 10^{-3}$</td>
<td>$1 \times 10^{-3}$</td>
<td>$5 \times 10^{-4}$</td>
</tr>
<tr>
<td>C2H2</td>
<td>$1 \times 10^{-5}$</td>
<td>$2 \times 10^{-6}$</td>
<td>$1 \times 10^{-6}$</td>
</tr>
<tr>
<td>C2H2</td>
<td>$1 \times 10^{-7}$</td>
<td>$1 \times 10^{-8}$</td>
<td>$3 \times 10^{-9}$</td>
</tr>
<tr>
<td>C2H6</td>
<td>$3 \times 10^{-6}$</td>
<td>$1 \times 10^{-10}$</td>
<td>$6 \times 10^{-10}$</td>
</tr>
<tr>
<td>C2H8</td>
<td>$2 \times 10^{-7}$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>C3H2</td>
<td>$2 \times 10^{-7}$</td>
<td>$5 \times 10^{-11}$</td>
<td>—</td>
</tr>
<tr>
<td>HCN</td>
<td>$2 \times 10^{-4}$</td>
<td>$9 \times 10^{-4}$</td>
<td>$9 \times 10^{-4}$</td>
</tr>
<tr>
<td>CH3CN</td>
<td>$3 \times 10^{-6}$</td>
<td>$1 \times 10^{-5}$</td>
<td>$1 \times 10^{-5}$</td>
</tr>
<tr>
<td>C2H3CN</td>
<td>$1 \times 10^{-5}$</td>
<td>$1 \times 10^{-6}$</td>
<td>$4 \times 10^{-6}$</td>
</tr>
<tr>
<td>C2H5CN</td>
<td>$5 \times 10^{-7}$</td>
<td>—</td>
<td>$2 \times 10^{-8}$</td>
</tr>
<tr>
<td>HC3N</td>
<td>$4 \times 10^{-5}$</td>
<td>$2 \times 10^{-6}$</td>
<td>$4 \times 10^{-6}$</td>
</tr>
<tr>
<td>HC5N</td>
<td>$1 \times 10^{-6}$</td>
<td>—</td>
<td>$2 \times 10^{-8}$</td>
</tr>
<tr>
<td>NH3</td>
<td>$7 \times 10^{-6}$</td>
<td>$4 \times 10^{-8}$</td>
<td>$2 \times 10^{-7}$</td>
</tr>
<tr>
<td>CH3NH</td>
<td>$1 \times 10^{-5}$</td>
<td>—</td>
<td>$6 \times 10^{-5}$</td>
</tr>
<tr>
<td>C2H7N</td>
<td>$3 \times 10^{-7}$</td>
<td>—</td>
<td>$6 \times 10^{-7}$</td>
</tr>
<tr>
<td>CH3NH2</td>
<td>$&lt;10^{-8}$</td>
<td>—</td>
<td>$5 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

*aValues for solar minimum conditions.

(b) Formation pathways of minor neutrals

Photochemical models expected the presence in Titan’s upper atmosphere of some of the species identified by INMS, as shown in Table 1. These species include (cyano-) polyynes, HCN, CH3CN (Yung et al. 1984; Toublanc et al. 1995; Banaszkiewicz et al. 2000) and in more recent models, C6H6, C2H3CN, NH3, CH2NH, CH3NH2 and C2H5N as well (Wilson & Atreya 2004; Lavvas et al. 2008b). The predictions of neutral mole fractions by photochemical models can be compared with the mole fractions inferred from INMS ion spectra in order to get some constraints on neutral formation pathways. However, spatial (latitude, longitude) as well as temporal (local time, season, solar cycle) variations can be large and observational as well as chemical uncertainties in both neutral (Hébrard et al. 2006, 2007) and ion (Carrasco et al. 2007) chemistry are important. As a consequence, it is unrealistic to aim for a ‘perfect’ agreement between models and observations. However, we consider that any discrepancy of more than one order of magnitude between both datasets has to be interpreted as a misrepresentation of the chemistry of the associated species. In the following, we focus on the recent results obtained for amine and imine species. The profiles resulting from the model of Lavvas et al. (2008a) are compared with the INMS densities in figure 2.

In the model of Wilson & Atreya (2004), the production of NH3 in the thermosphere occurs via initial formation of NH4+ and its subsequent electron recombination to NH3. However, this process is slow and the model underestimates
the NH₃ abundance inferred by INMS by two orders of magnitude. Lavvas et al. (2008a) obtain approximately 10 times as much NH₃ by including production of ethylenimine (C₂H₅N) through

\[ \text{N}^2(\text{D}) + \text{C}_2\text{H}_6 \rightarrow \text{C}_2\text{H}_5\text{N} + \text{H}, \]

followed by its photolysis to NH₃. The corresponding mole fraction of C₂H₅N is 5 × 10⁻⁶, about one order of magnitude larger than the INMS value, suggesting that the production of NH₃ from this pathway is overestimated. However, chemical loss pathways are not considered in the model and it is possible that including them would bring the C₂H₅N density into agreement with the observations. In any case, another source of NH₃ is required. Heterogeneous chemistry at the surface of aerosol particles might be the key.

In both models of Lavvas et al. (2008a) and Wilson & Atreya (2004), CH₃NH₂ is mainly produced by

\[ \text{NH}_2 + \text{CH}_3 + \text{M} \rightarrow \text{CH}_3\text{NH}_2 + \text{M}. \]

The associated mole fraction at 1100 km is 3 × 10⁻¹⁰ and 3 × 10⁻¹¹ in good agreement with the upper limit of 10⁻⁸ inferred from the INMS spectrum.

The evolution of CH₂NH has recently been followed in the photochemical model of Lavvas et al. (2008a) for the first time. In these calculations, CH₂NH is mainly produced by

\[ \text{N}^2(\text{D}) + \text{CH}_4 \rightarrow \text{CH}_2\text{NH} + \text{H} \]

and

\[ \text{CH}_3\text{NH}_2 + \text{hv} \rightarrow \text{CH}_2\text{NH} + 2\text{H}. \]

The calculated abundance is only slightly larger (by a factor of a few) than the one retrieved by the INMS measurements (Vuitton et al. 2007), suggesting that the production processes for CH₂NH are now fairly well understood. However,
kinetic and spectroscopic data about the (photo-) chemical loss processes of CH$_2$NH are lacking and all reaction rates had to be estimated. In order to come to a clear conclusion, new laboratory measurements regarding the reactivity of CH$_2$NH are needed.

3. Distribution and formation of benzene

(a) Benzene distribution

Figure 3a, b shows low altitudes INMS CSN spectra from the inbound and outbound legs of T16 (Vuitton et al. 2008). The spectra show a clear signal in the $m/z=62$–63 and $m/z=73$–79 regions that is interpreted as evidence for benzene based on the INMS calibration (Cui et al. submitted). This attribution is supported by a simple diffusive equilibrium model for a species of mass 78 amu, which provides an excellent fit to the $m/z=78$ inbound data from 1350 to 950 km. This model assumes a constant temperature determined from analysis of the N$_2$ density distribution (Müller-Wodarg et al. 2008). In addition to the benzene features, the outbound T16 spectrum, shown in figure 3b, has sizeable peaks at $m/z=91$–92. The molecular weight suggests the chemical formula is C$_7$H$_8$ and the feature is well fit by an INMS calibration spectrum for toluene.

The benzene and toluene signals peak approximately 20 s after C/A rather than at C/A (Vuitton et al. 2008). This time dependence is quite peculiar. The densities for all species in Titan’s upper atmosphere decrease exponentially with altitude and the temporal response of the INMS is extremely fast (tens of microseconds), implying that the measured signal should increase with time up...
to C/A and decrease thereafter. For example, measurements of ethane (C$_2$H$_6$) at $m/z$=30 during T16 have a maximum at C/A and are fairly symmetric about this time.

The anomalous time behaviour of the signals is attributed to an internal process in the instrument rather than a property of the atmosphere. It is unlikely that the asymmetry around C/A is caused by large horizontal variations in the atmosphere. First, there is no evidence that the time shift varies from pass to pass, as would be expected if it were due to horizontal variations. Second, horizontal variations would have to be extremely large to cause the observed asymmetry, inconsistent with the observed density variations between passes.

The CSN operational mode uses an enhancement chamber in front of the mass spectrometer that concentrates atmospheric molecules resulting in higher sensitivity (Waite et al. 2005). Radical recombination on chamber walls is a common phenomenon in spaceflight mass spectrometers (Hedin et al. 1973; Kasprzak et al. 1980). Photochemical calculations show that H, CH$_3$ and C$_6$H$_5$ radicals have a large abundance in Titan’s upper atmosphere and it follows that benzene and toluene are produced partly by radical recombination on the walls of the INMS closed source. This hypothesis explains the presence of both C$_6$H$_6$ and C$_7$H$_8$ because these are the products produced by reaction of the main radicals in the upper atmosphere. It explains the time delay observed for these species because the surface chemistry should require a significant amount of time.

The results of the empirical surface chemistry model for the production of C$_6$H$_6$ described in Vuitton et al. (2008) are shown in figure 4. The model gives a correlation of the gas density in the chamber, i.e. the density measured by the INMS
detection system, with the ambient atmospheric density of benzene. The benzene density in the closed-source chamber is determined by the instantaneous balance between outflow from the entrance aperture to the chamber and the combination of the flow of benzene into the chamber from Titan’s atmosphere and desorption of benzene from the chamber walls. The desorption rate of benzene is assumed to be proportional to the triple product of phenyl surface density, atomic hydrogen surface density and the inverse of an empirical time constant. The C₆H₅ and C₆H₆ densities are adjusted to fit the data, but the H and CH₃ are held fixed at the values predicted by a photochemical model for the atmosphere described in §3b. The time constant corresponds to the rate of diffusion over the surface of the chamber and the intrinsic reaction rate for the adsorbed C₆H₅ and H. However, knowledge of surface chemistry for these radicals is too uncertain to permit determination of the chemical time constants from first principles, so they are treated as empirical parameters determined through fits of the model to the T16 data.

A chemical time constant of 15 s for H + C₆H₅ provides the best fit to the data. The required direct gaseous source of C₆H₆, shown as the dashed line in figure 4, corresponds to a density of 2.5x10⁴ cm⁻³ or a mole fraction of 1.3x10⁻⁶ at an altitude of 950 km. The signal-to-noise ratio of the toluene signal is too low to meaningfully constrain its density. However, the time constant that we determined for H + C₆H₅ is adequate to fit the signal at m/z=92, suggesting that toluene is mostly produced by surface chemistry as well.

The INMS is really measuring the sum of benzene and phenyl and the density of phenyl in Titan’s atmosphere is roughly trice as much as that of benzene. The wall reaction hypothesis helps to reconcile the photochemical models with the measured C₆H₆ signal because, as discussed in §3b, the phenyl abundance in the upper atmosphere is predicted to be larger than the benzene abundance. The required production rate of benzene is significantly reduced compared with what is required if it were to be assumed that the signal were due to benzene alone.

(b) Benzene formation

Photochemical models (Wilson et al. 2003; Wilson & Atreya 2004; Lebonnois 2005; Lavvas et al. 2008a) find that the primary benzene production channel is the following three-body reaction:

\[ C_3H_3 + C_3H_3 + M \rightarrow C_6H_6 + M. \]

This reaction can account for the observed benzene density of a few ppm in the lower stratosphere (Coustenis et al. 2007), but is extremely inefficient at the low densities in Titan’s thermosphere. As a consequence, the models of Wilson & Atreya (2004) and Lavvas et al. (2008a) fail to predict the large benzene mole fractions observed in the thermosphere. In the model of Lebonnois (2005), benzene reaches a thermospheric abundance similar to that measured by INMS. However, this is an artefact caused by the lack of efficient chemical loss for C₆H₅, the main photodissociation product of benzene. As a consequence, the most probable fate of C₆H₅ is to re-form benzene by reaction with H atoms and benzene accumulates in the atmosphere. Clearly, the fact that the abundance of benzene in the thermosphere is larger than in the stratosphere indicates that an efficient chemical pathway to synthesize benzene at high altitude is required.
Laboratory simulations of Titan’s chemistry can provide clues on benzene formation pathways. Imanaka & Smith (2007) investigated the formation of complex species from a N$_2$/CH$_4$ gas mixture as a function of irradiation wavelengths from 50 to 150 nm. The formation of benzene is observed at wavelengths less than 80 nm, which corresponds to the photoionization threshold of N$_2$. This indicates that the benzene in this system is probably synthesized by ion chemistry. Benzene has also been observed on Jupiter (Kim et al. 1985). Under high-latitude conditions where precipitation of energetic electrons is important, benzene is produced through successive ion–neutral reactions followed by electron recombination of C$_6$H$_7^+$ (Wong et al. 2003). In their study dedicated to the mechanisms for the formation of benzene in the atmosphere of Titan, Wilson et al. (2003) also considered ion–neutral reactions and found that electron recombination of C$_6$H$_7^+$ controls the benzene production in the upper atmosphere. However, the production rate is too low to account for the observed benzene abundance in the thermosphere (Wilson & Atreya 2004).

After INMS revealed the richness of Titan’s ion composition (Cravens et al. 2006; Vuitton et al. 2006), and in particular showed that protonated benzene, i.e. C$_6$H$_7^+$, is a significant ion (Vuitton et al. 2007), Vuitton et al. (2008) reinvestigated Titan’s benzene chemistry. They first calculated the benzene production rate in the upper atmosphere with a dayside ionospheric model and used it as an input in a photochemical model for hydrocarbon chemistry. They extended considerably the chemical network considered in previous ion and neutral chemistry models and used density, temperature and eddy diffusion profiles recently constrained by the Cassini observations (Müller-Wodarg et al. 2008; Yelle et al. 2008).

On the dayside, N$_2$ and CH$_4$ are rapidly photoionized and C$_6$H$_7^+$ is efficiently produced by ion chemistry reactions (Waite et al. 2007; Vuitton et al. 2008). C$_6$H$_7^+$ is mostly produced by

$$C_6H_5^+ + C_2H_4 \rightarrow C_6H_7^+ + C_2H_2$$

and

$$C_6H_5^+ + H_2 \rightarrow C_6H_7^+ + h\nu.$$  

C$_6$H$_5^+$ comes primarily from

$$C_4H_2^+ + C_2H_4 \rightarrow C_6H_5^+ + H.$$  

C$_4$H$_2^+$ at m/z=50 is a major ion in the INMS spectrum but none of the ion–molecule reactions present in the model efficiently produce C$_4$H$_2^+$. Fragmentation of heavier ions could possibly produce C$_4$H$_2^+$, but the lack of experimental constraints precludes from including such reactions in the model. As a consequence, the C$_4$H$_2^+$ production rate is scaled in order to get a forced agreement between observed and calculated C$_4$H$_2^+$ densities. Benzene is finally produced by electron recombination of C$_6$H$_7^+$:

$$C_6H_7^+ + e^- \rightarrow C_6H_6 + H.$$  

The globally averaged column-integrated production rate of benzene from ion–neutral chemistry is approximately 10$^7$ cm$^{-2}$ s$^{-1}$, referred to the surface. This calculated ionospheric production rate is sufficient to produce large benzene densities in Titan’s upper atmosphere, of the same order as those measured by the INMS.
Photolysis, the main loss for benzene, peaks at approximately 900 km (Vuitton et al. 2008). As shown in figure 5, the density of phenyl, the main photodissociation product, is roughly thrice as much as that of benzene, consistent with the INMS observations. Once formed, C₆H₅ diffuses downward and is involved in reactions with CH₃, C₂H₃ and C₂H₅ radicals that are responsible for the rapid decrease in benzene mole fraction below 900 km shown in figure 5. These radical reactions, which had never been considered before, are responsible for the conversion of benzene to heavier aromatics in the 350–800 km region, with a total production rate of approximately 10⁷ cm⁻² s⁻¹. Benzene photolysis involves a transient benzene that, as the pressure increases, becomes efficiently deactivated by collisions with N₂ to form again benzene:

\[
C₆H₆ + h\nu \rightarrow C₆H₆(S_{0}^*) \rightarrow C₆H₅ + H.
\]

\[
\downarrow N₂
\]

\[
C₆H₆
\]

Its stabilization lifetime becomes comparable with its dissociation lifetime at a density of 10¹⁵ cm⁻³ (approx. 350 km). Thus, in the lower atmosphere, stabilization of the transient state is a crucial process. Moreover, at 350 km, the recombination of H and C₆H₅ becomes equal to the photolysis rate and destruction of C₆H₆ by photolysis stops. Below 300 km, C₆H₆ is created by

---

Figure 5. Modelled neutral vertical profiles and comparison with observations (from Vuitton et al. 2008). C₆Hₓ refers to a combination of the benzene and phenyl abundances, as explained in the text. The observed C₆H₆ mole fraction in the stratosphere was retrieved by CIRS at 15°S (Coustenis et al. 2007). Data points represent averages over 12 Titan passes of the C₆H₆ density measured by INMS. Error bars include statistic uncertainties but not calibration uncertainties. ‘Aromatics’ refers to heavy aromatic species that are not tracked in the model.

**Phil. Trans. R. Soc. A** (2009)
recombination of C\textsubscript{2}H\textsubscript{3} and C\textsubscript{4}H\textsubscript{3}, and C\textsubscript{3}H\textsubscript{3}, producing a low-altitude peak in C\textsubscript{6}H\textsubscript{6} density. These reactions contribute to most of the benzene formation via neutral chemistry, with a total integrated production rate of approximately 4×10\textsuperscript{6} cm\textsuperscript{-2} s\textsuperscript{-1}. The mole fraction in the lower stratosphere is approximately 30 ppb, as shown in figure 5, which is consistent with that inferred from mid-IR spectroscopy (CIRS).

4. Conclusions

(i) The INMS provides for the first time some information about the chemical composition of Titan’s upper atmosphere. The inversion of the ion spectra reveals the presence of the most complex neutrals ever detected on Titan: aromatics, (cyano-) polyynes, nitriles, ammonia and one imine. Modelling of the time dependence along the spacecraft trajectory of the CSN data allows the retrieval of the density of the phenyl radical (C\textsubscript{6}H\textsubscript{5}) and its parent molecule, benzene (C\textsubscript{6}H\textsubscript{6}).

(ii) Benzene is efficiently produced in the upper atmosphere via ion–neutral reactions followed by electron recombination of C\textsubscript{6}H\textsubscript{7}\textsuperscript{+}. The globally integrated production rate of benzene in the ionosphere is approximately 10\textsuperscript{7} cm\textsuperscript{-2} s\textsuperscript{-1}, of the same order of magnitude as the neutral production rate of approximately 4×10\textsuperscript{6} cm\textsuperscript{-2} s\textsuperscript{-1}. This production rate is sufficient to reproduce the benzene mole fraction at 950 km of 1.3×10\textsuperscript{-6} measured by INMS.

(iii) Following benzene photolysis, the phenyl radical is quickly converted to heavier aromatics through reactions with other radicals. The total production rate of aromatics is approximately 10\textsuperscript{7} cm\textsuperscript{-2} s\textsuperscript{-1} or 10\textsuperscript{-15} g cm\textsuperscript{-2} s\textsuperscript{-1} and the total benzene condensation rate is approximately 10 per cent of this value. If such a deposition rate has been maintained over the age of the Solar System, an average layer of 3 m of solid aromatic material must be present on the surface of Titan, modifying its appearance and composition. However, according to the model of the history of Titan’s interior from Tobie et al. (2006), CH\textsubscript{4} outgassing may have been episodic and, as a consequence, the total organic production rate may be lower.

(iv) By analysing the optical properties of the detached haze layer observed at 520 km in Titan’s mesosphere, Lavvas et al. (submitted) retrieve a mass flux of haze particles (approx. 2×10\textsuperscript{-14} g cm\textsuperscript{-2} s\textsuperscript{-1}) approximately equal to the mass flux required to explain the main haze layer. This is the first quantitative evidence that thermospheric chemistry is the main source of haze on Titan. This recent progress opened some questions that are not yet answered. As an example: can ionospheric chemistry be quantitatively linked to the production of the haze? How? Models need to implement these new data, and answer this.

We want to emphasize that there is a need for identification of the products of C\textsubscript{6}H\textsubscript{7}\textsuperscript{+} + e\textsuperscript{−} as well as rates and products for ion reactions involving more complex hydrocarbons and nitrogen-bearing species. Low pressure and temperature rates for reactions of H, CH\textsubscript{3}, C\textsubscript{2}H\textsubscript{3}, C\textsubscript{3}H\textsubscript{3} and C\textsubscript{6}H\textsubscript{5} and discrimination of the different
isomers in the C$_3$H$_3$ recombination reaction are required. Products branching ratios at shorter wavelength for benzene and other aromatics as well as studies of the reactivity of the transient state involved in benzene photodissociation would also be very useful. Finally, the production of C$_4$H$_7^+$, which is not at all understood, and forced in order to reproduce this ion abundance, is an essential open question, given the importance of this ion in the ionospheric production pathway of benzene.

We thank T. Cravens, R. Thissen, O. Dutuit, A. Somogyi, H. Imanaka and M. Smith for their useful discussion of Titan chemistry and the Cassini and INMS operation teams. This research has been supported by NASA grant NAG5-12699 to the University of Arizona and by the Cassini–Huygens project.

References


*Phil. Trans. R. Soc. A* (2009)


