Electrical properties of ions in the atmosphere of Titan

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Abstract. The Permittivity, Wave and Altimetry (PWA) package on the Huygens probe measured atmospheric electrical activity during its 14 January 2005 descent into Titan's atmosphere. Electrical mobilities of positive ions have been estimated using a combination of predictions of mass from the available chemical models, and the atmospheric properties measured by Huygens. Disc-shaped relaxation probes were used on the PWA to measure air conductivity. In this paper we present the extension of an inversion technique, originally developed to extract ion mobility information from cylindrical relaxation probe data, to the disc geometry. The maximum distance from which typical positive ion species are influenced by the electric field of the relaxation probe in Titan's troposphere and stratosphere is calculated, and found to be ~10μm. However, loss of positive ion data from the Huygens probe prevents the application of the new technique. Based on the Huygens data, evidence for, and possible characteristics of, a global electric circuit on Titan are also discussed.

1. Introduction

Saturn's largest moon, Titan, has one of the most substantial atmospheres in the Solar System, and is thought to be similar in composition to that of pre-biotic Earth [1]. It is primarily composed of molecular nitrogen with ~6% methane [2]. The pressure and temperature range on Titan allows methane to exist in three physical states, suggesting a possible methane cycle, analogous to the terrestrial water cycle, with methane rain [3]. The European Space Agency's Huygens probe on the Cassini mission took the first *in situ* measurements in 2005. Measurements made by Huygens included searching for lightning, which has been implicated in the origins of life [4], the atmospheric composition and structure, and other electrical properties, such as the air conductivity profile, caused by the existence of atmospheric ions and/or electrons.

The Huygens Atmospheric Structure Instrument (HASI) contained the Permittivity, Wave and Altimetry (PWA) package, which consisted of six electrodes, of which four were mutual impedance probes, capable of measuring atmospheric conductivity between 10^{-11} and 10^{-7} Sm^{-1} [5]. The other two were disc-shaped relaxation probes (RP) to measure conductivity between 10^{-15} and 10^{-11} Sm^{-1} [5]. The

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operating principle of a relaxation probe is to apply, and then disconnect, a voltage to a conductor. The probe, which is then effectively floating, exchanges charge with the atmosphere and the voltage on it decays quasi-exponentially, from which, as will be described in Section 3, air conductivity and ion properties can be calculated.

1.1. Ions on Titan

Ions are produced in all atmospheres by cosmic rays. On Titan, additional sources of atmospheric ions include the decay of surface radioactive isotopes, solar UV radiation and electrons from Saturn's magnetosphere. Solar UV and magnetospheric electrons are dominant in the upper atmosphere, but negligible compared to cosmic ray ionisation below 600km [6]. The contribution from radioisotopes, by terrestrial analogy, is likely to be small outside the planetary boundary layer. In the absence of free electrons, air conductivity, σ, depends on the number concentration $n_{\pm}$ of positive or negative ions and their electric mobility, μ, and is given as

$$\sigma_{\pm} = e \int_{\mu_{\min}}^{\mu_{\max}} \mu_{\pm} n_{\pm}(\mu) d\mu \qquad 1,$$

where e is the charge of the electron.

The mobility of an ion is its drift velocity in a unit electric field and is affected by the physical properties of both the ion, its size, density, and charge (for the nm size particles discussed in this paper, only a single charge is relevant) and the ambient gas (principally, temperature and pressure) [7]. The number of ions with different mobilities, the ion mobility spectrum, is closely related to the mass spectrum, and the integral under the ion mobility spectrum gives the ionic air conductivity (1). Ion mobility spectra can be used to understand the atmospheric composition, global electric circuit [2][8] and transport of charged particles.

In this paper we predict the mobility of positive ions in Titan's lower atmosphere (Section 2) and describe a new approach to extract ion mobility from Huygens measurements (Section 3). Air conductivity, which arises from ion (or electron) concentration and mobility, is an important part of the global circuit concept. In a global electric circuit, thunderstorms or other discharges generate a potential difference between a conductive upper atmosphere and surface. Away from these "disturbed weather" regions, there is a slow drift current of ions or electrons through the weakly conducting atmosphere. Huygens provided the first *in situ* extraterrestrial atmospheric electrostatic measurements, and is therefore well placed to investigate the suggestion that global circuits could exist on other planets [2]. In the final part of this paper, evidence for a global electric circuit on Titan is discussed to put the microphysical work into context.

2. Predicting Titan ion mobility from chemical models

Chemical models have estimated ion composition based on laboratory simulations and the limited pre-Huygens observations [1]. The mobility of predicted chemical species can be calculated from their mass, if the properties of the ambient gas are known. The mass-mobility relationship used must be reliable for small ions (diameter <2nm), where the ion size is comparable to molecules in the ambient gas. Here we apply the Tammet [10] relationship to calculate ion mobility, with an updated empirical factor [11]. Due to uncertainty over electrophilic species in Titan's atmosphere, the predictions only consider positive ions. Molina-Cuberos [6] has produced the most comprehensive theoretical model for positive ion chemistry in Titan's lower atmosphere, from which ion mobilities have been estimated using Tammet's model[10] and atmospheric properties measured by the HASI [9] (Figure 1).

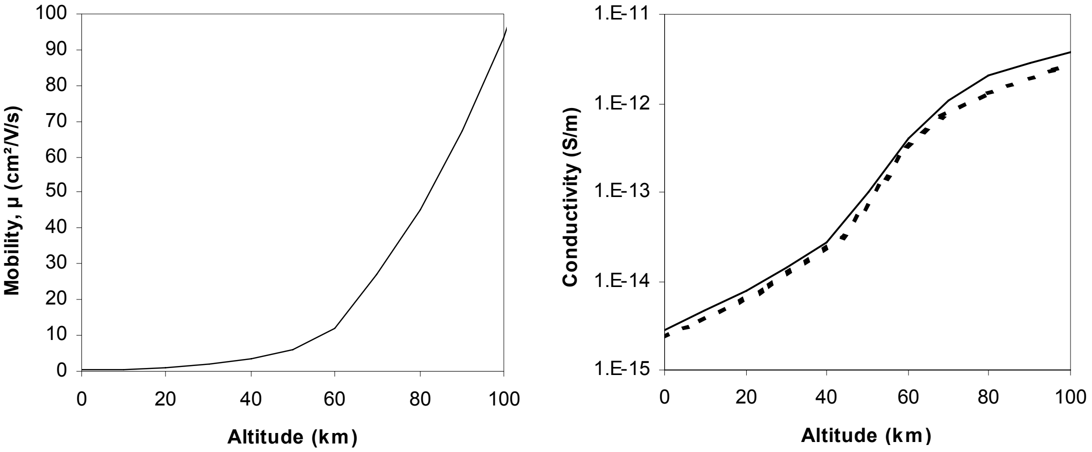

Figure 1. Variation in Titan positive ion properties with altitude (a) Predicted mean mobility (b) Predicted positive conductivity, compared to the model in [6] (dotted line). The discrepancy between the two conductivity profiles can be explained by the small differences in the measured temperature and pressure [9] to those used in [6] which were predicted from pre-Huygens models.

Ion mobility increases slowly with height as atmospheric pressure decreases. In the stratosphere (~45km), the temperature increases [9], which further increases the mobility. The decreased conductivity below 80 km is due to attenuation of cosmic rays in the lower atmosphere, reducing the ion production rate. Despite their lower mass (average ~57amu), ions on Titan generally have a lower mobility than ions on Earth (average ~100-200amu), due to the lower atmospheric temperatures which makes the ions less energetic, and the higher pressure which limits their mean free path. Typical Titan ions have μ~0.1 $cm^2V^{-1}s^{-1}$ at the surface compared to ~1 $cm^2V^{-1}s^{-1}$ on Earth. Loss of data from the Huygens probe [12] has prevented direct verification of Figure 1b.

3. Deriving ion mobility spectra from the Huygens Relaxtion Probe data

Ions in Earth's atmosphere are conventionally measured using an aspirated capacitor (or "Gerdien condenser"), consisting of two cylindrical coaxial electrodes along which air is passed. If a bias voltage is applied to the outer electrode, charged particles are deflected towards the inner electrode. Conductivity is measured through either the change in potential after the bias voltage is removed, (relaxation mode), or the ion current generated if the bias voltage is continuously applied (current mode) [13]. In the relaxation mode, high-impedance connections ensure that the collecting electrodes are floating after the bias voltage is disconnected, and conductivity σ is determined from the rate of voltage decay of the RP, where τ is the exponential time constant.

$$\sigma \approx \frac{\varepsilon_0}{\tau} \qquad 2.$$

A critical mobility, μ_c, is defined as the minimum mobility of ion contributing to the measurement, obtained by equating the distance moved by ions in the air flow through the instrument, to the radial distance they travel towards a collecting electrode [7]. If k is a geometrical constant, u the flow rate through the capacitor and V the bias voltage, μ_c is given by

$$\mu_c = \frac{ku}{V} \qquad 3.$$

It is clear that, in the relaxation mode, the critical mobility varies during the measurement as the voltage decays. The resulting variation in ion species contributing to the decay can be used to extract ion mobility spectra. This "Relaxation Potential Inversion Method" (RPIM) has been exploited for the cylindrical configuration [14] but has not been used with other geometries. In order to apply RPIM to the Huygens PWA voltage decays, the variation of ion mobility with electric field must first be defined for a floating conducting disc like the Huygens RP, following the technique developed for cylindrical geometry [7]. This is described below.

3.1.1. Derivation of a "critical mobility" for a disc-shaped Relaxation Probe

Critical mobility for any RP is derived by considering a "collection time" t_c for an ion of mobility μ assuming it moves an incremental distance in an electric field E given by $dr = \mu E dt$ [7]. For a disc, t_c for an ion to move from a perpendicular distance z towards an RP is

$$t_c = \frac{1}{\mu}\int_0^z \frac{dz}{E_z} \tag*{4,}$$

where E_z is the electric field [7]. For a floating conducting disc of radius R, Gauss's Law can be used to derive E_z

$$E_z = \frac{4V}{\pi R}\left(1 - \frac{z}{\sqrt{z^2 + R^2}}\right) \tag*{5.}$$

Combining (4) and (5) gives a collection time t_c

$$t_c = \frac{\pi R}{4\mu V}\int_0^z \frac{dz}{\left(1 - \frac{z}{\sqrt{z^2 + R^2}}\right)} \tag*{6.}$$

During t_c, the RP moving at a fall speed u falls a distance ut_c. If $ut_c < z$, then all the ions approaching the disc will be collected. Rearranging (6) and including the components of the RP tilt and tip angles θ and ϕ gives a "minimum mobility" μ_m of ion that can be collected at a bias voltage V at a perpendicular distance z from the RP,

$$\mu_m = \frac{\pi u}{8V\cos\theta\cos\phi}\int_0^z \frac{dz}{\left(1 - \frac{z}{\sqrt{z^2 + R^2}}\right)} \tag*{7}$$

where the integral term is

$$\int_0^z \frac{dz}{\left(1 - \frac{z}{\sqrt{z^2 + R^2}}\right)} = Z - \frac{R^3}{3R^2} + \frac{\left(z^2 + R^2\right)^{3/2}}{3R^2} + \frac{z^3}{3R^2} \tag*{8.}$$

The expression for μ_m for the disc-shaped RP (7) is similar to the critical mobility for a cylindrical condenser (3); it is proportional to u/V with a geometric constant. The difference between the two geometries is that the enclosed cylinder defines a distance over which ions are collected, whereas for the disc a "critical distance" has to be defined (i.e. a distance z over which the integration in (7) is to be performed). Critical distance indicates the region of influence of the probe, from which all ions with $\mu \geq \bar{\mu}$ (average ion mobility) will be collected. Critical distance has been calculated for Titan's lower atmosphere by equating Huygens' fall speed with the typical ion drift time towards the electrodes, Table 1. Critical distance is small, of order microns, because of the combination of Titan's ions moving very slowly in its dense, cold atmosphere, and Huygens' rapid fall rate. It increases with altitude due to the non-linear increase in ion mobility described in Section 2.

Table 1 Critical distance for an ion of mass 57amu (predicted average positive ion mass) at five altitudes. Probe descent speed is from [15], pressure and temperature from [12].

Altitude (km)	Probe descent speed (ms^{-1})	Mobility of a 57amu ion ($cm^2V^{-1}s^{-1}$)	"Critical distance" (μm)
0	4	0.1	<<1
20	7	0.5	1.5
40	13	2.8	5
60	25	13	11
80	47	46	19

In principle, the concept of critical distance allows the RPIM to be applied to extract ion mobility spectra from voltage decays from a disc-shaped probe as in [14]. However, in practice, other effects, such as air flow, may be more significant on these small length scales. Additionally, the free electrons in Titan's atmosphere [16] mean that sheath effects have to be considered for the negative RP data. Positive ion data was lost from Huygens [12], which makes it impossible to apply the RPIM to test the predictions made in Section 2. It is not possible, therefore, to apply the RPIM to the Huygens relaxation probe data until sheath effects from free electrons are better understood.

4. Titan global electric circuit

The model of a global electric circuit (GEC) was first suggested by C.T.R. Wilson [8]. On Earth, thunderstorms and shower clouds charge up the ionosphere with respect to the ground, and an ionic drift current moving in the electric field between the ionosphere and surface closes the circuit. Recently, the idea of a GEC has been applied to other planets, in particular Mars [17], but also across the Solar System [2]. For Titan, several of the basic criteria for a global circuit, as defined in [2], have already been fulfilled, for example, the existence of polar atmospheric molecules, mobile charged particles and a conductive upper layer. Other aspects of a possible Titan global circuit will be briefly discussed below in the light of the Huygens observations: the mechanism returning charge to ground (Section 4.1) and the important parameter air conductivity, and its ratio to the surface conductivity (Section 4.2).

4.1. "Disturbed weather"

A global circuit needs to have both charge separation, and discharges or precipitation, to maintain the surface-ionosphere electric field. Models predict that Titan cloud-to-ground lightning could occur from collisional cloud charging [18]. The type, frequency and intensity of any electrical discharges are unknown.

Lightning on Titan may be rare due to the lack of solar radiation to initiate convective activity. However, the existence of precipitation, both from violent convective storms [19], and drizzle from stratiform methane-nitrogen clouds [3] seems likely. Terrestrial clouds readily become charged even in relatively quiescent conditions [20], and precipitation carrying this charge can contribute to the global circuit [22]. If the analogy to Earth's hydrological system can be extended, the precipitation current could provide an important global charge exchange mechanism in the Titan environment, if electrical discharges are infrequent or weak. Further work is needed to assess the probable charging mechanisms for the cloud types observed and expected on Titan.

4.2. Air and surface conductivity

Huygens has measured the conductivity of the Titan surface to be $4x10^{-10}Sm^{-1}$ [21]. This seems relatively insulating with respect to the air, since the measured conductivity due to electrons, which will dominate over any positive ion conductivity, between 0-60km is 10^{-10}-10^{-9}Sm^{-1} [16]. The ratio of surface conductivity to atmospheric conductivity is not as large as on Earth, but the possible observation of a Schumann-like resonance suggests that there could be a sufficiently conductive layer to establish a resonant cavity [21].

5. Conclusions

The Relaxation Potential Inversion Method for extracting mobility information from relaxation of a cylindrical condenser has been extended to a disc-shaped probe. Unfortunately the combination of the existence of free electrons and the loss of positive ion data has prevented the RPIM being applied in an extraterrestrial atmosphere. There is scope to use it in the future to voltage decays obtained during testing of the Huygens RP in the terrestrial atmosphere.

The direct evidence from Huygens supports the existence of a global electric circuit on Titan, in which it can be expected that precipitation charge exchange, as on Earth, plays an important role.

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