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On the origin of Titan's nitrogen

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Abstract

The enigma of the dense nitrogen atmosphere persists even after over ten years of scrutiny through the eyes of the Cassini-Huygens mission. However, recent measurements of the nitrogen composition of the comet 67P Churyumov-Gerasimenko (67P) by the ROSINA instrument onboard the Rosetta spacecraft provide new information that may be of importance in determining the volatile building blocks of Titan's atmosphere. We use these constraints to demonstrate that more than adequate amounts of nitrogen (in the form of both ammonia and molecular nitrogen) can be delivered by cometary-like icy planetesimals (CLIPs) and we discuss potential scenarios for the subsequent evolution that lead to the present day atmosphere as characterized by Cassini-Huygens.

1. Introduction

The Gas Chromatograph Mass Spectrometer (GCMS) onboard Huygens and the Cassini Orbiter Ion Neutral Mass Spectrometer both measured the bulk composition [1,2] including the noble gas ^{36}Ar, which was found to be surprisingly low in concentration as compared to solar abundances – 2.1 x 10^{-7} molar mixing ratio. The ^{36}Ar deficiency led [1,3] to conclude that the source of Titan's nitrogen was not primordial N_2, but instead was created by photochemical conversion of NH_3 [4]. It also presented a dilemma as to nature of the inventory of the original volatile compliment delivered to Titan during the accretionary process and how extensively these accreting volatiles may have been processed in the early Saturnian sub-nebula. Here we review the results from the ROSINA observations of N_2 in 67P [6] to derive the amount of N_2 that can supplied to Titan by Comet-Like Icy Planetesimals (CLIPs). Furthermore, we scale this relative to previously measured values of NH_3 and CO from comet Hale Bopp to quantitatively derive the amount of NH_3 and N_2 delivered by CLIPs to Titan. We show that the N_2 and delivered is more than sufficient to explain the present day reservoir.

2. 67P implications for Titan's nitrogen

By assuming that water makes up 50% of present day Titan we can infer the probable volatile content of early Titan from CLIPs. Titan's atmospheric nitrogen has two possible sources. Nitrogen could have simply been delivered to Titan in N_2 form during its formation and then outgassed from the satellite's interior after the core overturn epoch. This assumption is justified by the potentially large N_2/CO ratio measured in 67P (0.16-1.7% [5]), which, based on the CO/H_2O ratio (12-23% [6]) measured in comet Hale Bopp give a N_2/H_2O ratio in the 2-39 x 10^{-4} range. Hale Bopp is chosen for this scaling due to its presumed pristine composition, since this was its first pass through the heating that occurs when comets pass through the inner solar system. Scaled to the mass of water ice trapped in Titan, the N_2/H_2O ratio implies that the amount of nitrogen present in this form can be substantially larger than the present atmospheric mass of N_2.

Titan's nitrogen could also originate from the conversion of primordial NH_3 into N_2 via photochemistry and/or shock chemistry. Based on the NH_3/H_2O ratio measured in comet Hale-Bopp (0.7%, [6]), we find that the if NH_3 was the source of the nitrogen in the present day Titan's atmosphere then there is 35 times more nitrogen than is presently observed in Titan's atmosphere and if cometary N_2 (at the levels measured in 67P) was the primary source of present day nitrogen the scale factor from the amount of N_2 delivered to present day abundances ranges from 2 to 47.

3. Two possible sources for Titan's atmospheric nitrogen

The origin of the atmospheric nitrogen must be explained in the context of how the formation strategy unfolds. Two end members can be defined based on the energetics of the accretion processes. With minimal differentiation we can imagine that one end member is a slushy ice layer that has outgassed it's CO, CH_4, and N_2. In the case of this end member a scenario is realized with at least two problems: How to get rid of the CO and how to explain the present day isotopic ratio of nitrogen? The latter concern is based on present day observations where N_2 at Titan has at $^{14}N/^{15}N$ ratio of 165 [1] whereas in the Saturn atmosphere a value of ~500 [7], which is more compatible with Jupiter and the solar wind [8]. Resolving the isotopic dichotomoy has been previously explained through a scenario where the N_2 in Titan's atmosphere is formed from cometary NH_3 with a $^{14}N/^{15}N$ ratio near 130 [9,10].

The counter end member for the primordial atmosphere originates from a warm accretion process that leaves Titan with a global water ocean where the volatiles are partitioned between the atmosphere and the ocean according to their solubility and vapor pressure. In this case the CO_2 CH_3OH, CH_2O, H_2S and NH_3 are highly soluble and largely confined to the ocean. The starting atmosphere volatile content is then primarily CO, CH_4, and N_2 with small amounts of H_2O and NH_3. Photochemistry acts on this atmosphere to provide a means of isotopically equilibrating N_2 and NH_3. This isotopic-exchange photochemistry occurs in a manner similar to the chemical reactions between atomic and molecular nitrogen in molecular clouds when CO is present to produce OH which reforms molecular nitrogen from odd nitrogen [11,12]. In this case the optimum mixing model to obtain a nitrogen isotopic ratio near today's levels suggests that 90% of the original nitrogen is in the form of NH_3 and 10% as N_2 and that the NH_3 is largely in solution in the ocean and the N_2 is in the atmosphere, but that photochemistry mediated by NH_3 vapor and OH produced from CO and H_2O has fully equilibriated the isotopic ratio between the two nitrogen species. Such values for N_2 leave us with a factor of three excess in atmospheric nitrogen that must be loss from impacts during the formation phase or from atmospheric escape over geological time.

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