



Non-thermal atmospheric escape of sulfur and oxygen on Io driven by photochemistry and atmospheric sputtering

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Introduction

Io, the innermost of Jupiter's four Galilean satellites, processes a unique SO₂-dominated atmosphere comprising sulfides, oxides (such as SO, S, O₂, and O), and other minor alkali and chlorine compounds [1]. In general, three mechanisms are responsible for the generation of an atmosphere on Io, including active volcanism, frost sublimation, and surface sputtering, of which the former two are more important [2]. Both the active volcanism arising from Jupiter's powerful tidal forces and the SO₂ frost sublimation from Io's surface release large amounts of gases to replenish the tenuous atmosphere of Io, triggering a rich and complicated photochemical network, which may be a significant source of photochemical escape on Io [3-4]. Meanwhile, Io suffers from intense ion bombardment from Jupiter's magnetosphere [5]. This constant atmospheric erosion by energetic ion precipitation, referred to as atmospheric sputtering, also serves as an important mechanism of Io's atmospheric escape.

Aims

With the aid of constantly accumulated understandings of Io's space environment and atmospheric photochemistry, as well as the updated laboratory measurements [6], we evaluate the non-thermal escape of sulfur and oxygen on Io driven by both photochemistry and atmospheric sputtering [7]. A comprehensive review of the atmospheric escape process on Io is also provided.

Methods

The sputtering yield and escape probability are introduced to evaluate the escape intensity driven by the above two mechanisms. A one-dimensional Test Particle Monte Carlo (TPMC) Monte Carlo model is constructed to track the energy degradation of incident energetic ions and atmospheric recoils from which the sputtering yields and escape probabilities of different atmospheric species are determined. Different plasma populations (S⁺⁺ and O⁺) and atmospheric conditions are compared, including high-density volcanic and low-density quiet atmospheric states, in which various chemical channels (photodissociation, neutral-neutral, ion-neutral, and dissociative recombination reactions) are considered. The background atmosphere and ionosphere are adapted from previous photochemical models of [3] and [4].

Results and Conclusions

Our calculations suggest a total escape rate of 3×10^{29} atom s^{-1} driven by atmospheric sputtering on Io, and SO_2 is the dominant sputtered species. The photochemical escape rates are $(1.1-2.0) \times 10^{27}$ s^{-1} for total O and $(1.5-6.7) \times 10^{26}$ s^{-1} for total S, occurring mainly in the atomic form. Further investigations reveal that (1) S^{++} is the most efficient species for atmospheric sputtering on Io and sputtering yields increase substantially with increasing incident ion mass, energy, and incidence angle; (2) The photochemical escape rates vary extensively with the atmospheric conditions, especially in terms of the intensity of volcanic eruption, resulting in the chemical escape rate increases by up to a factor of five. Photochemistry is the most chemical escape channel. (3) By comparing multiple escape mechanisms including thermal escape (Jeans escape) and non-thermal escape, we conclude that atmospheric sputtering is the dominant mechanism driving atmosphere escape at Io. Photochemical escape outweighs Jeans escape for both atomic O and S for the quiet atmosphere scenario, while for the volcanic scenario, it is likely important for atomic S only.

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