Dust ablation on the giant planets: Consequences for stratospheric photochemistry

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ABSTRACT

Ablation of interplanetary dust supplies oxygen to the upper atmospheres of Jupiter, Saturn, Uranus, and Neptune. Using recent dynamical model predictions for the dust influx rates to the giant planets (Poppe et al., 2016), we calculate the ablation profiles and investigate the subsequent coupled oxygen–hydrocarbon neutral photochemistry in the stratospheres of these planets. We find that dust grains from the Edgeworth–Kuiper Belt, Jupiter-family comets, and Oort-cloud comets supply an effective oxygen influx rate of $1.0^{+2.2}_{-0.7} \times 10^7$ O atoms cm^{-2} s^{-1} to Jupiter, $7.4^{+16}_{-5.1} \times 10^4$ cm^{-2} s^{-1} to Saturn, $8.9^{+19}_{-6.1} \times 10^4$ cm^{-2} s^{-1} to Uranus, and $7.5^{+16}_{-5.1} \times 10^5$ cm^{-2} s^{-1} to Neptune. The fate of the ablated oxygen depends in part on the molecular/atomic form of the initially delivered products, and on the altitude at which it was deposited. The dominant stratospheric products are CO, H_2O, and CO_2, which are relatively stable photochemically. Model-data comparisons suggest that interplanetary dust grains deliver an important component of the external oxygen to Jupiter and Uranus but fall far short of the amount needed to explain the CO abundance currently seen in the middle stratospheres of Saturn and Neptune. Our results are consistent with the theory that all of the giant planets have experienced large cometary impacts within the last few hundred years. Our results also suggest that the low background H_2O abundance in Jupiter's stratosphere is indicative of effective conversion of meteoric oxygen to CO during or immediately after the ablation process — photochemistry alone cannot efficiently convert the H_2O into CO on the giant planets.

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1. Introduction

Small interplanetary dust grains are continually showering down into the atmospheres of solar-system planets. This dust originates from the disruption and outgassing of comets, from impacts and collisions between objects of various sizes (particularly from mutual collisions within the asteroid belt and Edgeworth–Kuiper belt), from particles ejected from active plumes on satellites such as Io, Enceladus, and Triton, and from interstellar dust particles streaming into the solar system. Beyond Jupiter's orbit, the main progenitors are the Edgeworth–Kuiper belt, long-period Oort-cloud comets, and short-period Jupiter-family and Halley-type comets (e.g., Stern, 1996; Yamamoto and Mukai, 1998; Landgraf et al., 2002; Poppe, 2015; 2016), and the particles likely contain ices, along with silicate and organic material. As the dust grains spiral in through the outer solar system, they are affected by gravity from the Sun and planets, solar wind and Poynting–Robertson

drag, stellar radiation pressure, and collisions (e.g., Burns et al., 1979; Gustafson, 1994; Horanyi, 1996; Liou and Zook, 1997).

Poppe (2016) recently developed a comprehensive model for the dynamical evolution and density distribution of dust grains in the outer solar system. The model considers the dominant interplanetary dust sources for the outer solar system described above, and includes the relevant physics for the dynamical and collisional evolution of the grains. *In situ* spacecraft measurements from the *New Horizons* Student Dust Counter, the *Galileo* Dust Detection System, and the *Pioneer 10* meteoroid detector are used to constrain the model. One important byproduct of the Poppe (2016) model is a prediction of the total mass influx rate of dust grains to the giant planets.

Gravitational focusing by the planets will cause the incoming dust particles to enter the upper atmospheres of Jupiter, Saturn, Uranus, and Neptune at high velocities (Poppe, 2016), leading to full or partial ablation of the grains (Moses, 1992; 1997; 2001; Pryor et al., 1994; Moses et al., 2000b; Kim et al., 2001). This ablation introduces gas-phase metals and water to the thermospheres and stratospheres of these planets; such species would

otherwise not be present in the upper atmosphere because of condensation and sequestering of the intrinsic water and metals in the deeper troposphere. The unablated or recondensed refractory component provides a source of high-altitude haze and condensation nuclei that can facilitate condensation of stratospheric hydrocarbons (Moses et al., 1992) and can alter atmospheric radiative and scattering properties (e.g., Rizk and Hunten, 1990; Pryor et al., 1994; Moses et al., 1995). The ablated metals and water can affect the chemistry and structure of the ionosphere (e.g., Connerney and Waite, 1984; Connerney, 1986; Majeed and McConnell, 1991; Cravens, 1994; Lyons, 1995; Moses and Bass, 2000; Kim et al., 2001; Grebowsky et al., 2002; Moore et al., 2004; Molina-Cuberos et al., 2008), while water and the other oxygen species can affect the neutral photochemistry and aerosol structure in the stratosphere (e.g., Moses, 1992; Moses et al., 2000b; 2005; Ollivier et al., 2000).

Sublimation from H_2O, CO, and CO_2 ices in the grains as they are heated during atmospheric entry releases these molecules directly into the atmosphere, while thermochemical reactions within the meteor trail, energetic collisions with atmospheric molecules, or subsequent photochemical interactions within the stratosphere can further process the oxygen-bearing component. For example, the ablated water can be photolyzed by ultraviolet radiation from the Sun to produce hydroxyl radicals (OH), which can react with methane photochemical products to produce CO (e.g., Prather et al., 1978; Strobel and Yung, 1979; Moses et al., 2000b; 2005; Ollivier et al., 2000), potentially diminishing the abundance of unsaturated hydrocarbon molecules such as C_2H_2 and C_2H_4 in the process (e.g., Moses et al., 2000b). The H_2O introduced from the icy component of the grains will condense at relatively high altitudes on all the giant planets, affecting the stratospheric aerosol structure and properties, while the CO_2 will condense on colder Uranus and Neptune.

Although CO has been observed in giant-planet stratospheres and is a major end product of the chemistry of the ablated vapor (see Sections 3.2–3.6), it is the most volatile of the major oxygen-bearing species on the giant planets and is not expected to condense. Stratospheric CO has additional potential sources, both external and internal to the giant planets, such as large cometary impacts and/or thermochemical quenching and convective transport from the deep troposphere (Prinn and Barshay, 1977; Fegley and Lodders, 1994; Lodders and Fegley, 2002; Bézard et al., 2002; Lellouch et al., 2002; Lellouch et al., 2005; 2006; 2010; Visscher and Fegley, 2005; Visscher et al., 2010b; Hesman et al., 2007; Cavalié et al., 2008b; 2009; 2010; 2013; 2014; 2017; Luszcz-Cook and de Pater, 2013; Wang et al., 2015; 2016); water and carbon dioxide can also be delivered from cometary impacts (e.g., Lellouch, 1996; Lellouch et al., 2002). Accurately predicting the fate of the oxygen from interplanetary dust sources therefore has important implications for the bulk elemental oxygen abundance on the giant planets, the strength of convective mixing from the deep atmosphere, and the impact rates of large comets in the outer solar system. These implications, combined with the recent improved predictions for the incoming dust fluxes to Jupiter, Saturn, Uranus, and Neptune (Poppe, 2016) and new constraints on the abundance of stratospheric oxygen species from *Spitzer* and *Herschel* observations (Meadows et al., 2008; Lellouch et al., 2010; Fletcher et al., 2012; Cavalié et al., 2013; 2014; Orton et al., 2014a; 2014b), motivate us to theoretically track the fate of the volatiles released from the ablation of interplanetary dust on the giant planets.

To determine how the dust-delivered oxygen affects stratospheric photochemistry on the outer planets, we first run an ablation code (see Moses, 1992; 1997) with the interplanetary dust fluxes, mass distributions, and velocity distributions from the Poppe (2016) dynamical model as input. After making assumptions about the bulk composition of the grains based on cometary dust and nucleus compositions (Greenberg and Li, 1999; Lisse et al.,

2006; 2007), we then use the ablation model to calculate the mass loss and vapor release as a function of altitude from the incoming grains (see Section 3.1). The resulting gas production rate profiles from the ablation process are then included as a source of oxygen species to stratospheric photochemical models (e.g., Moses et al., 2000b; 2005; 2015) that consider coupled hydrocarbon–oxygen chemistry (see Sections 3.2–3.5). In Sections 3.2–3.5, we compare the photochemical model results with observations and discuss the implications with respect to the origin of the observed oxygen species on each planet, and in Section 4 we discuss the likely importance of thermochemistry and high-energy collisions during the meteor phase in securing the high inferred CO/H_2O ratio in the stratospheres of these planets.

2. Theoretical model description

Two main theoretical models are used for these calculations. The first is the meteoroid ablation code described in Moses (1992), with updates from Moses (1997). The second is the Caltech/JPL one-dimensional (1D) KINETICS photochemical model developed by Yuk Yung and Mark Allen (e.g., Allen et al., 1981; Yung et al., 1984), most recently updated for the giant planets by Moses et al. (2015).

The physics of meteoroid ablation has been understood for decades, at least in an idealized sense (e.g., Öpik, 1958). The interplanetary dust grains being considered here are typically much smaller than the mean free path of the atmosphere in the region in which they ablate, which puts the physics in the free-molecular-flow regime. Under such conditions, the incoming grains collide directly with individual air molecules, leading to deceleration and heating of the grains. The heating is offset by radiative and evaporative cooling and by the change in internal energy of the grains. As in Moses (1992) and Moses (1997), we assume the incoming grains are solid compact spheres (and remain spherical throughout their flight), have a uniform composition, are heated uniformly throughout their volume, and are not affected by sputtering, fragmentation, or thermal diffusion within the solid. For more sophisticated treatments, see Vondrak et al. (2008).

The physics in this case is reduced to a set of four coupled differential equations that track the evolution of an incoming dust grain's mass, velocity, temperature, and position within the atmosphere see Eqs. (1)–(4) in Moses, 1992. We assume that the entry angle is 45° and remains constant throughout the particle's flight. The grains are assumed to be composed of either pure water ice, "silicates", or "organics", with the incoming dust mass flux being divided such that 26% of the grains are silicate, 32% are refractory organic, and 42% are ices, based roughly on their corresponding mass fractions within cometary nuclei and dust (Greenberg and Li, 1999). The water ice and silicate material properties are taken from Moses (1992) (and references therein), except for the vapor pressures, which follow the recommendations of Moses (1997). For the organic grains, which were not considered by Moses (1992; 1997), we take the material properties somewhat arbitrarily from benzo(a)pyrene ($C_{20}H_{12}$), as a refractory organic that has a vaporization temperature in the appropriate 400–600 K range. The vapor pressure of the representative organic material is $\log_{10} p(\text{atm}) = 9.110 - 7100/T(\text{K})$ (Murray et al., 1974), with an assumed bulk density of 1.24 g cm^{-3}, an assumed latent heat of sublimation of 118 kJ/mol, and an assumed specific heat of 254.8 J mol^{-1} K^{-1} (Roux et al., 2008). For the purposes of converting mass loss into the amount of organic vapor "molecules" injected into the atmosphere, we assume a mean molecular mass of 77 amu for the organic vapor (e.g., a single C_6H_5 organic ring), although the exact choice is unimportant, as the organic vapor is ignored in the subsequent photochemical calculations because the carbon released is a small fraction of the carbon already in the atmosphere.