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A Sublimation-driven Exospheric Model of Ceres

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ABSTRACT

After Vesta, the NASA Dawn spacecraft will visit the dwarf planet Ceres to carry out in-depth observations of its surface morphology and mineralogical composition in 2015. One of the important questions is whether Ceres has any outgassing activity that would lead to the formation of a thin atmosphere. The recent detection of water vapor emitted from localized source regions by Herschel (Küppers et al., 2014) has only underscored this point. If the localized outgassing activity observed by Herschel is totally switched off, could a sizable surface-bounded exosphere still be maintained by other source mechanisms? Our preliminary assessment is that chemical sputtering via solar wind interaction and meteoroid impact are probably not adequate because of the large injection speed of the gas at production relative to the surface escape velocity of Ceres. One potential source is a low-level outgassing effect from its subsurface due to thermal sublimation with a production rate of the order of 10^{24} molecules s^{-1} as first considered by Fanale and Salvail (1989). If the water plumes are active, the fall-back of some of the water vapor onto Ceres' surface would provide an additional global source of water molecules on the surface with a production rate of about 10^{25} molecules s^{-1}. In this work, different scenarios of building up a tenuous exosphere by ballistic transport and the eventual recycling of the water molecules to the polar cold trap are described. It turns out that a large fraction of the exospheric water could be transferred to the polar caps area as originally envisaged for the lunar polar ice storage.

1. Introduction

Watson et al. (1961); Watson et al., (1963) and Arnold (1979) theorized that the polar craters in permanent shadow could serve as a cold trap of water ice and other volatiles. Later works by Hodges (1991) and Butler (1997) examined the process of global transport of water molecules to the storage zones. There are a number of potential sources according to these authors, namely, cometary impact, interplanetary dust bombardment, chemical sputtering of solar wind hydrogen, and outgassing. The recent impact experiment of the LCROSS mission at the Cabeus crater on the Lunar South pole showed the presence of water ice with a relative abundance of about 5.6 ± 2.9% by mass [Colaprete et al. 2010]. This important result validated the theoretical ideas on the existence of buried ice. An interesting question in this context is whether sub-lunar-sized objects like Ceres with a mean radius of $R = 476.2$ km [Thomas et al., 2005] might possess similar cold traps in the polar regions. A'Hearn and Feldman (1992] reported a marginal (3σ) detection of OH (0,0) emission at 308 nm in the vicinity of the north pole of Ceres from IUE observations. The derived water production rate was about 1.4×10^{26} molecules s^{-1}. Recent measurements using the UVES (Ultraviolet and Visual Echelle Spectrograph) of the Very Large Telescope yielded an upper limit of 7×10^{25} molecules s^{-1} [Rousselot et al., 2011]. The most recent detection of water vapor cloud emitted from Ceres by Herschel (Küppers et al., 2014) suggested that the peak production rate could be about 2×10^{26} molecules s^{-1}. But the signature of such water cloud was found to be variable, sometimes there and sometimes simply missing. The surface escape velocity of 0.52 km s^{-1} could only keep up to 10% of the emitted gas from leaving Ceres according to the calculation of Kueppers et al. (2014). It is therefore clear that the atmosphere of Ceres should be quite tenuous.

In Section 2, we will discuss different possible source mechanisms (including the water plumes) and make an assessment of their relative importance. In Section 3, the principal formulation of the thermal model calculation for the diurnal variation of the surface temperature

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and the ballistic transport of gas molecules will be given. The numerical results from the Monte Carlo simulations will be described in Section 4 which is to be followed by a summary and discussion in Section 5.

2. Source mechanisms

Basically there are a number of possible source mechanisms of water molecules and other volatile species at planetary bodies without an atmosphere, namely, solar wind interaction, magnetospheric charged particle sputtering, photon-stimulated desorption (PSD), micrometeoroid bombardment, UV photon sputtering and, finally, thermal sublimation either directly from ice-covered surface or from subsurface ice as was first studied by Fanale and Salvail (1989). Last but not the least, the possible existence of vapor plumes from subsurface liquid water as in the case of the gas plume of Enceladus (Porco et al., 2006) or cryogenic volcanism such as what was observed on the surface of Triton (Soderblom et al., 1990). Though not very likely, these must be born in mind after the Herschel discovery (Kueppers et al., 2014). The first four effects have been found to be important in producing sodium-rich exospheric systems of the Moon and Mercury [Potter and Morgan, 1997; Killen and Ip, 1999; Killen et al., 2007; Wang et al., 2011]. For icy objects like the Jovian satellites, Ganymede and Europa, and the Saturnian satellites, Iapetus and Rhea, UV photosputtering and surface thermal sublimation would also become significant sources. In the case of Ceres, we will only focus on three main processes: solar wind interaction, meteoroid impact, and thermal sublimation because magnetospheric particle sputtering and photosputtering are not applicable if there is no globally exposed ice on the surface.

2.1. Solar wind interaction

In the following, we give some assessment on the viability of the solar wind source for Ceres. Zeller et al. (1966) and Zeller and Ronca (1967) reported the conversion of trapped hydrogen atoms to OH and H_2O in silicate lattices from proton irradiation for which the OH signature is detected spectroscopically. More recently, in the context of the sodium exosphere of Mercury, Potter (1995) proposed that surface processing of the absorbed solar wind hydrogen atoms via reactions like $2H+NaSiO_3 \rightarrow H_2O+SiO_2+Na$ could be effective in producing water molecules on the lunar and planetary surfaces. The detection of the OH signature in minerals on the lunar surface by the M3 instrument of the Chandrayaan-1 mission [Clark, 2009; Pieters et al. 2009] has thus given a spur to this idea, even though subsequent laboratory simulation experiments have not been conclusive. That is, while Managadzea et al. (2011) claimed to have observed the signature of water production by impinging (protons) in the laboratory experiments, Burke et al. (2011) did not obtain similar result.

Under the assumption that Ceres does not have a global magnetic dipole field and its bulk electrical conductivity is small as indicated by laboratory measurements of meteoritic materials (Brecher et al., 1975), Ceres should be a good absorber of the solar wind protons just like the Moon [See Wang et al., 2011]. In this case, chemical sputtering effect as postulated by Potter (1995) might indeed take place. The amount of water molecules generated by solar wind implantation could be estimated by using an average solar wind flux of $\sim 3\times10^{12}$ protons-$m^{-2}s^{-1}$ at 1 AU heliocentric distance. The upper limit for the production rate of H_2O via chemical sputtering (Q) is therefore given by the corresponding absorption coefficient γ and the projected area of Ceres with respect to the solar wind A_c; we have $Q=\gamma f A_c/{R_H}^2$, which is $\sim 1.4\times10^{23} H_2O\ s^{-1}$ at $R_H\sim$ 2.8 AU if γ is of order unity. Note that Wieser et al. (2009) detected the reflection of solar wind protons as neutral hydrogen atoms from the lunar surface according to their Chandrayaan-1 measurements. The flux of the reflected hydrogen atoms was measured to be about 20% of the original solar wind flux thus suggesting γ to be about 0.2. The production rate of water molecules via solar wind chemical sputtering is therefore about $Q\sim 2.8\times10^{22}$ molecules s^{-1} which is far below the upper limit obtained by Rousselot et al. (2011).

Since H_2O molecules require photon-stimulated desorption to eject them from the lattices (see McGrath et al., 1986; Wang and Ip 2011), the emission velocity ($\sim$0.72–0.78 km/s, see Thrower et al., 2008) could be high enough that only a small fraction would be retained. Solar wind interaction is therefore not an important source of water on Ceres.

2.2. Micrometeoroid bombardment

Another possible source of water on Ceres is micrometeoroid bombardment. Unlike the Moon which is very dry, Ceres is basically water-rich in its surface materials, and interior composition could contain as much as 25% of water (McCord and Ch, 2005; Thomas et al., 2005; Rivkin et al. 2011). It is therefore likely that a large amount of water vapor could be generated by impact. However, one important issue is that the impact vapor should have high temperature (3000–5000 K) (Wiens et al., 1997; Milillo et al., 2005; Domingue et al., 2007) so that most of the gas in the expanding plume would escape from Ceres, since the surface escape velocity is 0.52 km/s (calculated by the mentioned parameters).

2.3. Subsurface outgassing

From the above consideration, one remaining possible source mechanism is thermal sublimation. In its thermal evolution, Ceres might have once contained liquid water in its interior (Jones, 1988; McCord and Ch, 2005). Fanale and Salvail (1989) examined the stability of water ice at different depths below the surface of Ceres over the age of the solar system. Their thermal sublimation model is that of percolation of water gas through a dust mantle overlying an ice layer (See also Schorghofer 2008; Prialnik and Rosenberg 2009). They found that water ice could exist at 1–10 m depth, in latitude higher than 40°, whereas the stability zone would be located below 10–100 m for lower latitudes. The subsurface penetration of the thermal wave would maintain a certain level of outgassing process with $Q\sim 10^{24}\ H_2O\ s^{-1}$ (Fanale and Salvail (1989)). The scenario is therefore to have a distributed source of water molecules across the surface of Ceres with emission velocity ($\sim$0.48 km/s) determined by the local temperature ($\sim$200 K). They will carry out ballistic motion from place to place until being lost to either photodissociation or condensation in cold traps. In the next section, we will examine the ballistic transport of the water molecules generated by the putative underground ice layers.

2.4. Localized source regions

The Herschel detection of water vapor clouds at Ceres raised the question of their origin. As discussed by Kueppers et al. (2014), possible mechanisms could include sublimation of water ice on the surface exposed by impact cratering events, or some form of active outgassing from a surface source region. According to a comparison of the submillimeter water absorption line profiles with numerical models, Kueppers et al. (2014) found that the emission speed ranged between 0.3 and 0.7 km s^{-1} such that about 3% of the water molecules would directly fall back on Ceres' surface because of its gravitational pull and about 7% would impinge on the surface because of collisional effect. Under this