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Scenarios of atmospheric mass evolution on Mars influenced by asteroid and comet impacts since the late Noachian

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ABSTRACT

Early in its history, Mars probably had a denser atmosphere and higher surface temperatures to sustain the presence of stable liquid water or saline solution at the surface. Impacts by asteroids and comets could affect the atmospheric evolution of a planet, by removing part of its atmosphere and by delivering into it material and volatiles. In this study we investigate the atmospheric loss and delivery of volatiles between the end of the Noachian and present, with the help of a semi-analytic model. Our results suggest that impacts alone can hardly remove a significant amount of atmospheric mass over this period. Contribution of additional factors such as outgassing and non-thermal escape processes cannot explain neither the presence of surface pressure larger than few hundreds of mbars 3.9 Gyr ago, unless parameter values outside of their expected range are considered. Based on extreme case scenarios, maximum surface pressures at the end of the Noachian, could be as much as 0.25 bar or 1.9 bar, with and without CO_2 storage into carbonate reservoirs, respectively.

1. Introduction

Mars' climate may have been different during this period allowing stable liquid water on the surface long enough for alteration and geological changes. The environmental conditions (for the presence of stable liquid water) of early Mars depend on several parameters including atmospheric mass and composition, orbital properties, solar luminosity, as well as exchange processes between the atmospheric and subsurface reservoirs.

Geological evidence found on Mars suggest the past existence of liquid water on its surface, particularly at the end of the Noachian (about 3.8–3.9 Gyr ago) (see, for example, Baker, 2001). The climate conditions of the planet may have been different during this period with higher surface pressures that allowed stable liquid water on the surface. Mars' climate may have been different during this period allowing stable liquid water on the surface long enough for alteration and geological changes. The environmental conditions (for the presence of stable liquid water) of early Mars depend on several parameters including atmospheric mass and composition, orbital properties, solar luminosity, as well as exchange processes between the atmospheric and subsurface reservoirs]. Measurements of isotopic composition of atmospheric CO_2 from the surface of Mars suggest that a significant amount of carbon has escaped the Martian atmosphere over the last 4 Gyr (Mahaffy et al., 2013; Webster et al., 2013). Studies based on carbonates outcrops (Niles et al., 2010; Van Berk et al., 2012) or based on ancient impact craters (Kite et al., 2013) imply a pressure range between 0.5 and 2 bar at the end of Noachian period.

The surface pressure during the Noachian period can be estimated using models that takes into account various mechanisms of atmospheric escape and delivery (i.e. Brain and Jakosky, 1998; Haberle et al., 1994; Lammer et al., 2013; Manning et al., 2009). These mechanisms include, solar wind escape (also called non-thermal escape) (Chasseféire and Leblanc, 2011; Chasseféire et al., 2007; Lundin et al., 2007), erosion due to solar radiation (thermal escape) (Erkaev et al., 2013; Lundin et al., 2007; Tian et al., 2009), impacts (Ahrens, 1993; Cameron, 1983), volcanic outgassing (Grott et al., 2011; Morschhauser et al., 2011) and storage of CO_2 into carbonates reservoirs (Haberle et al., 1994). No large carbonate reservoirs have been detected on Mars yet (Bibring et al., 2005; Chevrier et al., 2007), however, traces of carbonates on the surface (Bandfield et al., 2003; Morris et al., 2010), or in Martian meteorites (Bridges et al., 2001) suggest that sequestration of CO_2 into carbonate reservoirs could have taken place throughout the Noachian, Hesperian, and Amazonian periods (Lammer et al., 2013; Niles et al., 2010). Among these mechanisms, we focus on atmospheric loss and volatile delivery by impacts. The main objective is to model atmospheric evolution due to impacts in order to estimate the range of possible surface pressures that could exist on Mars, at the end of the Noachian, 3.9 Gyr ago.

Impacts could have affected in particular early atmospheric evolution of terrestrial planets (for example, de Niem et al., 2012;

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Pham et al., 2011; Shuvalov et al., 2013). Impact erosion of the atmosphere is suggested to be more efficient for Mars compared to Venus and Earth, because of its smaller size and gravity (Pham et al., 2011; Vickery, 1990). Following an impact, the quantity of escaped atmosphere, as well as impactor and target materials can be estimated using numerical simulations by hydrodynamical codes, also called hydrocodes, where equations of motion and state are solved numerically using tabulated equations of state for the pressure (see, for example, Pierazzo and Collins, 2003). The major challenges of the numerical codes are appropriate equations of state from solid state to vaporized state, for materials at very high pressures and temperatures, and a proper modeling of vapor cloud expansion in the presence of a dense atmosphere. Studies on the atmospheric loss and delivery due to impacts differ sometimes by orders of magnitude, mainly due to different equation of state and dynamical models used (Hamano and Abe, 2010; Melosh and Vickery, 1989; Newman et al., 1999; Shuvalov, 2009; Shuvalov and Artemieva, 2001; Svetsov, 2007; Vickery and Melosh, 1990). The hydrocode simulations designed to simulate a single impact are not suitable to study the cumulative effect of impact erosion and delivery in the long term due to their extremely high computation costs. Instead, empirical approximations based on hydrocode simulations have been used to estimate atmospheric evolution (for example, Hamano and Abe, 2010; Manning et al., 2006; Melosh and Vickery, 1989; Pham et al., 2009, 2011; Shuvalov, 2009; Svetsov, 2007; Vickery and Melosh, 1990). The model we use in this study is similar to the semi-analytical model presented in Pham et al. (2009, 2011). Compared to previous studies, the atmospheric delivery and erosion contains additional terms and revised parameters (see Section 2.2). The model allows comparison between different hydrocode results and computes atmospheric mass evolution upon impacts with much less calculation time in comparison to other analytical models. In addition, different delivery and lost mechanisms including volcanic outgassing and non-thermal escape can be taken into account to study various atmospheric evolution scenarios.

The paper is organized as follows: Section 2 presents the impact erosion and delivery model we use to compute atmospheric mass evolution. Surface pressure evolution upon impacts is calculated, for the last four billions of years, in Section 3. We present two scenarios of atmospheric mass evolution on Mars in Section 4, in which additional erosion and delivery mechanisms such as atmospheric escape due to solar wind, volcanism as well as carbonate weathering are also considered.

2. Impact erosion and delivery model

2.1. *Flux of projectiles*

The efficiency of impacts to remove atmosphere or deliver volatiles depends on the quantity a single impact can remove or deliver volatile, as a function of its mass and velocity, but also of the number of impacts that strike the planet over the age of the solar system. Impact cratering forms the most ubiquitous geological process affecting all planetary bodies in the solar system. Hence, asteroidal and cometary impacts could have significantly affected the atmospheric mass evolution. Since there are no cratering record data older than $\sim$ 4.1 Gyr, the exact initial impact flux and its evolution over the age of solar system has been long debated. Concerning the evolution of the impact flux, there are different competing theories in the literature. *Exponential decaying flux* suggests that the impact flux declined exponentially with time since the formation of the solar system (Hartmann and Neukum, 2001; Neukum et al., 2001; Neukum and Wise, 1976; Werner, 2008), whereas the *Late heavy bombardment*, postulates the existence of a spike in the impact flux on the terrestrial planets about 3.8–3.9 billion years ago, that lasted between 20 and 200 Myr (Ryder, 2002; Strom et al., 2005; Tera et al., 1974; Wetherill, 1975). The *"sawtooth" Late heavy bombardment* hypothesis (Morbidelli et al., 2012) proposes that impact bombardment declined exponentially with time, like in the exponential decrease hypothesis. A sudden increase of bombardment rate that affected the terrestrial planets occurred around 4.0–4.1 Gyr ago and, before it, the impact rate could be far lower than the one extrapolated by the exponential decrease hypothesis. The peak in the bombardment rate might have been triggered by a migration of an old main belt asteroid population, the E-belt asteroids, which existed between 1.7 and 2.1 AU (see Bottke et al., 2012).

To quantify effects of asteroids and comets on atmospheric mass evolution, we choose to use an exponential decaying impact flux that is applied from 4.1 Gyr ago, approximate age of the onset of the geological record, to present. This hypothesis is consistent with both the exponential decaying flux as well as the sawtooth Late Heavy Bombardment hypothesis over this time period. The impactor flux can be expressed analytically, based on crater chronology data (Hartmann and Neukum, 2001; Neukum et al., 2001; Neukum and Wise, 1976), and by converting crater diameter into impactor mass (for example, Chyba et al., 1994; Ivanov, 2001). Using the cratering chronology of Ivanov (2001) for Mars and crater diameter to impactor mass formula conversion, we obtain the flux of impactors with mass greater than m:

$$\frac{\partial N_{cum}(>m,t)}{\partial t} = A\left[1+Be^{\lambda(4.6-t)}\right]m^{-b}, \tag{1}$$

where A, B and b are constants given in Table 1 and t, given in Gyr, corresponds to the age of the planet.

Parameter b is the spectral slope representing the impactor mass distribution. Cratering chronology from (Ivanov, 2001) yields $b = 0.5$ for craters larger than 1 km of diameter which is similar to the estimation of Melosh and Vickery (1989); $b = 0.47$. The value of b tends to be larger for small craters (lower than 1–4 km of diameter) (see, for example, Ivanov, 2001; Neukum et al., 2001) and Zahnle (1993) suggests b between 0.5 and 1. Among the plausible values for b, here we consider only $b = 0.5$ which corresponds to impact craters with diameters larger than 1 responsible for most of the impact erosion.

2.2. *Equations of atmospheric mass evolution upon impacts*

The net rate of change of atmospheric mass $M_{atm}(t)$ upon impacts is expressed as the difference between the atmospheric erosion and delivery rates:

$$\frac{dM_{atm}(t)}{dt} = \sum_k \mu_k \left(\frac{dM_{del,k}(t)}{dt} - \frac{dM_{esc,k}(t)}{dt}\right). \tag{2}$$

Each impactor type, k, i.e. asteroids ($k=1$), short-period (SP) comets ($k=2$) and long-period (LP) comets ($k=3$), differ by their respective composition and mean impact velocity. In the above equation, μ_k is the fraction of the impactor type k in the impact

Table 1
Impactors flux coefficients defined by Eq. (1). The values are derived from cratering chronology model of Ivanov (2001).

Coefficient	Value
A (km^{-2} Gyr^{-1} kg^{b})	8.04
B	4.50e−10
λ (Gyr^{-1})	6.93
b	0.50