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Molecular oxygen formation from irradiation of ice grains in the protosolar nebula

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Abstract

Molecular oxygen has been detected in the coma of comet 67P/Churyumov–Gerasimenko with abundances in the 1–10% range by the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis-Double Focusing Mass Spectrometer instrument (ROSINA) on board the Rosetta spacecraft. These observations suggest that O_2 was incorporated in the grains precursors of comets when they were in low-density environments such as the interstellar medium. Here, we investigate the possibility that O_2 was produced in the protosolar nebula when cometary grains were lifted toward its upper layers and dragged down over a large number of cycles, due to turbulent mixing.

1. Introduction

Molecular oxygen has been detected in the coma of comet 67P/Churyumov–Gerasimenko (67P/C-G) with abundances in the 1–10% range by the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis-Double Focusing Mass Spectrometer instrument on board the Rosetta spacecraft [1]. To account for this observation, it has been recently shown that the radiolysis of icy grains is not fast enough in the protosolar nebula (PSN) to create sufficient amounts of O_2 over its lifetime [2]. It has been then proposed that 67P/C-G agglomerated from icy grains originating from ISM instead of condensing in the protosolar nebula because low-density environments such as molecular clouds allow the radiolysis to work in an efficient manner [2]. Here, we investigate the alternative possibility that the icy grains condensed in the protosolar nebula midplane before their agglomeration by comets. Due to turbulent mixing, these grains were lifted toward the upper layers of the disk and dragged them down over a large number of cycles [3]. In our model, these grains spend a non-negligible fraction of their lifetime in the disk's upper regions, where the irradiation is strong.

2. Model

To mimic the vertical motion of particles, we used a simple description of the PSN structure [4, 5] and the transport module of particles described in [6]. Our calculations have been performed at a distance of 30 AU from the Sun. Once the trajectories of particles have been determined, we used the approach of [7] to compute the energy rate received from cosmic rays irradiation by water molecules as a function of the column density of the gas.

3. Results

As illustrated by Figure 1, turbulence plays an important role in the motion of small dust grains that are well coupled to the gas. Micron-sized grains initially settled in the midplane are entrained by turbulent eddies and diffuse radially and vertically with an effective viscosity roughly equal to that of the gas for such small particles [5]. Consequently, solid particles follow a Gaussian distribution in the vertical direction. The scale height of dust (corresponding to the standard deviation of the distribution) is a fraction of the gas scale height, this fraction being larger and possibly equal to the gas scale height in the cases of small grains and higher degrees of turbulence. Figure 2 represents the vertical distribution of 1 cm particles computed with our transport/disk model, assuming a coefficient of turbulent viscosity $\alpha = 10^{-3}$. Figure 3 shows the evolution of the O_2/H_2O ratio in 1 cm particles as a function of time. The resulting abundance of oxygen is at best four orders of magnitude lower than the one observed by the Rosetta spacecraft.

4. Discussion

Our preliminary computations suggest that, even if a significant fraction of the icy particles has been lifted toward the upper layers of the disk over several hun-

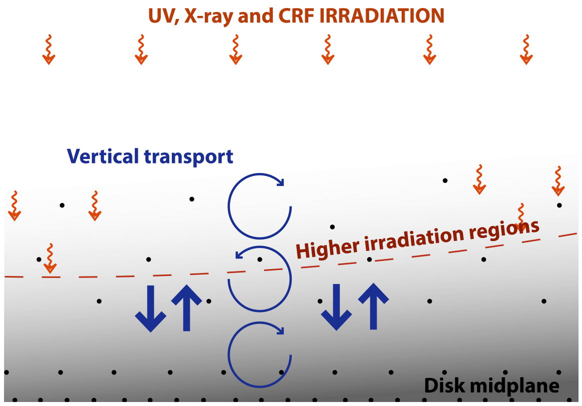

Figure 1: Illustration of the vertical transport of small icy grains toward disk regions where they are efficiently irradiated (see [3]). Dust is concentrated in the midplane of the disk due to gravitational settling and gas drag. However, turbulent eddies lift the icy grains toward the upper regions and also drag them down because the direction of the velocity is random and consistent during a timescale comparable to the local keplerian period.

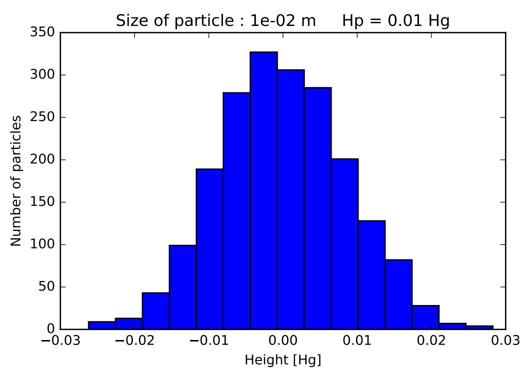

Figure 2: Vertical distribution of 10^{-2} m particles at 30 AU in the PSN.

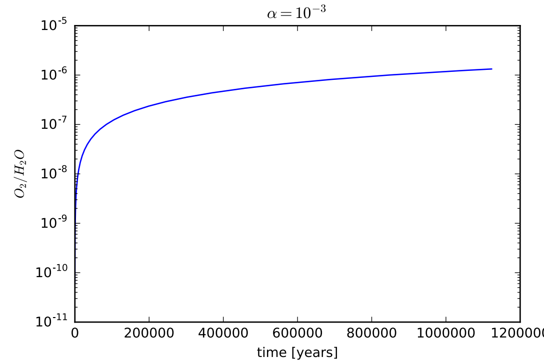

Figure 3: Abundance of O_2 relative to H_2O in 1 cm particles as a function of time. The O_2 abundance reaches a plateau at $\sim$0.8 Myr.

dred thousands years during the PSN evolution, the amount of O_2 created via radiolysis cannot account for the Rosetta observations. However, only simulations of the vertical transport of 10^{-2} m particles with a unique α value have been investigated. To provide a more robust conclusion, we need to investigate the full domain of plausible α values as well as different sizes of particles in the 10^{-6}–10^{-2} m range.

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