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Implications of evaporative cooling by H_2 for 1I/‘Oumuamua

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ABSTRACT

The first interstellar object observed in our solar system, 1I/‘Oumuamua, exhibited several peculiar properties, including extreme elongation and non-gravitational acceleration. Bergner & Seligman (2023) proposed that evaporation of trapped H_2 created by cosmic rays (CRs) can explain the non-gravitational acceleration. However, their calculation of surface temperature ignored the crucial cooling effect of evaporating H_2. By taking into account the cooling by H_2 evaporation, we show that the surface temperature of H_2-water ice is lower than the temperature obtained by Bergner & Seligman (2023) by a factor of 9. As a result, the thermal speed of outgassing H_2 is decreased by a factor of 3, which requires that all H_2 from water ice is dissociated by CRs in the interstellar medium, making the model untenable as an explanation for the properties of 1I/‘Oumuamua. Moreover, the lower surface temperature also influences the thermal annealing of water ice, a key process that is appealed to by Bergner & Seligman (2023) as a mechanism to release H_2.

Keywords: asteroids: individual (1I/2017 U1 (‘Oumuamua)) — meteorites, meteors, meteoroids

1. INTRODUCTION

The detection of the first interstellar object, 1I/‘Oumuamua by the Pan-STARRS survey (Bacci et al. 2017) implies an abundant population of similar interstellar objects (Meech et al. 2017; Do et al. 2018). An elongated shape of semi-axes $\sim 230\,\mathrm{m}\times 35\,\mathrm{m}$ is estimated from light-curve modeling (Jewitt et al. 2017). The extreme axial ratio of $\gtrsim 5:1$ implied by ‘Oumuamua’s lightcurve is mysterious (Fraser et al. 2018; Gaidos et al. 2017).

Several authors (Bannister et al. 2017; Gaidos 2017) suggested that ‘Oumuamua is a contact binary, while others speculated that the bizarre shape might be the result of violent processes, such as collisions during planet formation. Domokos et al. (2017) suggested that the elongated shape might arise from ablation induced by interstellar dust, and Hoang et al. (2018) suggested that it could originate from rotational disruption of the original body by mechanical torques. Sugiura et al. (2019) suggested that the extreme elongation might arise from planetesimal collisions. The latest proposal involved tidal disruption of a larger parent object close to a dwarf star (Zhang & Lin 2020), but this mechanism is challenged by the preference for a disk-like shape implied by ‘Oumuamua’s lightcurve (Mashchenko 2019).

The detection of non-gravitational acceleration in the trajectory of ‘Oumuamua is another pecularity (Micheli et al. 2018). The authors suggested that cometary activity such as outgassing of volatiles could explain the acceleration excess. Interestingly, no cometary activity of carbon-based molecules was found by deep observations with the Spitzer space telescope (Trilling et al. 2018) and Gemini North telescope (Drahus et al. 2018). Bialy & Loeb (2018) explained the acceleration anomaly by means of radiation pressure acting on a thin lightsail, and other authors (Moro-Martin 2019; Luu et al. 2020; Sekanina 2019) suggested a porous object. Fitzsimmons et al. (2018) proposed that an icy object of unusual composition might survive its interstellar journey. Previously, Füglistaler & Pfenniger (2018) suggested that ‘Oumuamua might be composed of H_2. However, Rafikov (2018) argued that the level of outgassing needed to produce the acceleration excess would rapidly change the rotation period of ‘Oumuamua, in conflict with the observational data.

Hydrogen ice was suggested by Seligman & Laughlin (2020) to explain ‘Oumuamua’s excess acceleration and unusual shape. Their modeling implied that the object is ~ 100 Myr old. Assuming a speed of $30\,\mathrm{km\,s^{-1}}$, they suggested that the object was produced in a Giant Molecular Cloud (GMC) at a distance of ~ 5 kpc.

However, their study did not consider the destruction of H_2 ice in the interstellar medium (ISM), through evaporation by sunlight. Hoang & Loeb (2020) showed that H_2 iceberg could not survive the journey as it would be heated and destroyed by starlight from the GMC birthsite to the solar system. Recent studies by Jackson & Desch (2021); Desch & Jackson (2021) have proposed that 'Oumuamua is a fragment of N_2 ice since an object of this type is more likely to survive the interstellar journey owing to a much lower sublimation rate.

Bergner & Seligman (2023) proposed that the cosmic-ray (CR) bombardment can dissociate water in the water ice comet and create H_2 which are trapped within the CR track under the surface. When 'Oumuamua approaches the Sun, solar radiation heating can cause the thermal annealing, which results in the reorganization of the water ice matrix so that H_2 can evaporate from the surface. They found that the surface temperature of 'Oumuamua can reach above ~ 140 K for its heliocentric distance below 3 au (see their figure 3), which is enough for thermal annealing and evaporation of H_2. The observed acceleration of 1I/'Oumuamua (Micheli et al. 2018) can be explained if at least a third of all the water dissociated by CR impact into molecular hydrogen within the iceberg. The surface temperature of the object is a crucial parameter for the release of H_2 trapped within the water ice matrix. However, the treatment in Bergner & Seligman (2023) ignored the effect of H_2 evaporative cooling. Here, we calculate the surface temperature by taking into account the evaporative cooling.

In Section 2, we discuss the heating and cooling mechanisms of the body surface and calculate the surface temperature. Our conclusions are presented in Section 3.

2. SURFACE TEMPERATURE

2.1. *Heating and radiative cooling*

Heating by starlight and solar radiation raises the surface temperature of the H_2-water ice. The local interstellar radiation field is assumed to have the same spectrum as the interstellar radiation field (ISRF) in the solar neighborhood (Mathis et al. 1983) with a total radiation energy density of $u_{\rm MMP} \approx 8.64\times10^{-13}\,{\rm erg\,cm^{-3}}$. We normalize the strength of the local radiation field by the dimensionless parameter, U, so that the local energy density is $u_{\rm rad} = Uu_{\rm MMP}$. For simplicity, we assume a spherical object shape in our derivations, but the results can be easily generalized to other shapes.

Let p be the albedo of the object surface. The heating rate due to absorption of isotropic interstellar radiation and solar radiation is given by,

$$\frac{dE_{\rm abs}}{dt} = \pi R^2 c\left[Uu_{\rm MMP} + \frac{L_{\odot}}{4\pi cd^2}\right](1-p)\epsilon_{\star}, \quad (1)$$

where $\epsilon_{\star}$ is the surface emissivity averaged over the background radiation spectrum, and d is the distance from the Sun (Hoang & Loeb 2020).

In principle, the object can be heated by collisions with ambient gas (Hoang & Loeb 2020), but this process is subdominant in the solar system.

The cooling rate by thermal emission is given by,

$$\frac{dE_{\rm emiss}}{dt} = 4\pi R^2 \epsilon_T \sigma T^4, \quad (2)$$

where $\epsilon_T = \int d\nu \epsilon(\nu) B_\nu(T)/\int d\nu B_\nu(T)$ is the bolometric emissivity, integrated over all radiation frequencies, ν.

2.2. *Thermal sublimation and evaporative cooling*

The binding energy of H_2 to water ice is $E_b/k \sim 500\,{\rm K}$ (Sandford & Allamandola 1993), equivalent to $E_b({\rm H_2}) \approx 0.05\,{\rm eV}$. H_2 can sublimate when the surface temperature is sufficient such that the thermal energy exceeds the binding energy. The characteristic timescale for the evaporation of an H_2 molecule from a surface of temperature $T_{\rm ice}$ is

$$\tau_{\rm sub} = \nu_0^{-1}\exp\left(\frac{E_b}{kT_{\rm ice}}\right), \quad (3)$$

where ν_0 is the characteristic oscillation frequency of the H_2 lattice (Watson & Salpeter 1972). We adopt $\nu_0 = 10^{12}\,{\rm s^{-1}}$ for H_2 ice (Hegyi & Olive 1986; Sandford & Allamandola 1993).

Evaporating H_2 molecules carry away heat from the surface and cause evaporative cooling (Watson & Salpeter 1972; Hoang et al. 2015). Let f(H_2) be the ratio of H_2 to water on the ice surface. Following Hoang & Loeb (2020), the cooling rate by evaporation of H_2 and water is given by,

$$\frac{dE_{\rm evap}}{dt} = \frac{E_b dN_{\rm mol}}{dt} = \frac{E_b N_s}{\tau_{\rm sub}(T_{\rm ice})}, \quad (4)$$

where $dN_{\rm mol}/dt$ is the evaporation rate, namely, the number of molecules evaporating per unit time, and $N_s = 4\pi R^2 f(H_2)/r_s^2$ is the number of surface sites with $r_s = 10$ Å being the average size of the H_2 surface site (Sandford & Allamandola 1993). Here, we neglect the cooling by water because of its much higher sublimation temperature.

2.3. *Equilibrium surface temperature*

The energy balance between surface heating and cooling is described by

$$\frac{dE_{\rm abs}}{dt} = \frac{dE_{\rm emiss}}{dt} + \frac{dE_{\rm evap}}{dt}. \tag{5}$$

Using Equations (1), (2) and (4, one obtains

$$\pi R^2 c\left[U u_{\rm MMP} + \frac{L_{\odot}}{4\pi c d^2}\right](1-p)\epsilon_{\star} = 4\pi R^2 \epsilon_T \sigma T^4 + \frac{E_b N_s}{\tau_{\rm sub}(T_{\rm ice})}. \tag{6}$$

For our numerical calculations, we adopt the typical albedo value of $p = 0.1$ and the interstellar radiation strength of $U = 1$. The radius of the object is assumed to be $R = 1000$ m, and $\epsilon_T = \epsilon_{\star} = 1$.

Figure 1 (left panel) shows the heating and cooling rates when ‘Oumuamua is located at 1.4 au from the Sun. Evaporative cooling is dominant over radiative cooling at the temperature above 20 K. Therefore, the effect of evaporative cooling by H_2 cannot be ignored as in Bergner & Seligman (2023) and must be considered for calculations of the surface temperature.

We numerically solve Equation (6) for the surface equilibrium temperatures for the different distances from the Sun. The right panel of Figure 1 compares the realistic surface temperatures when the evaporating cooling is taken into account with the results without evaporative cooling for the different ratio of H_2 to water (f(H_2). For the case without evaporative cooling, our obtained temperature is comparable to those obtained in Bergner & Seligman (2023) (see their figure 3). With evaporative cooling, the surface temperature increases slightly with increasing f(H_2) for the considered range. As shown, the realistic temperature is significantly lower than the temperature obtained when ignoring the evaporative cooling, by a factor of 9.

3. DISCUSSION AND CONCLUSIONS

More than 5 years after the discovery of 1I/‘Oumuamua, many peculiar properties of it are still hotly debated. Bergner & Seligman (2023) proposed that evaporation of trapped H_2 created by cosmic rays (CRs) by sunlight can explain the non-gravitational acceleration. However, their calculations of surface temperature disregard the cooling effect by evaporating H_2. Here we found that the evaporative cooling is much more efficient than radiative cooling at temperatures above 20 K (see Figure 1, left panel). By taking into account the evaporative cooling by H_2 evaporation, our results (see Figure 1, right panel) show that the surface temperatures of H_2-water ice are lower by a factor of 9 than the temperature obtained by Bergner & Seligman (2023) (see their figure 3). Therefore, the thermal speed of outgassing H_2 is decreased by a factor of 3. As a result, the thermal speed of outgassing H_2 is decreased by a factor of 3, requiring that all H_2 was made from water ice is produced by CRs in the interstellar medium. That is a constraint which is unlikely to be satisfied as it necessitates an oxygen iceberg. Given this constraint, the requirement for a surface layer that is made of pure molecular hydrogen will not survive the journey through interstellar space as a result of heating by starlight (Hoang & Loeb 2020).

Moreover, the lower surface temperature also influences the thermal annealing of water ice, a key process that is appealed to by Bergner & Seligman (2023) to release H_2.

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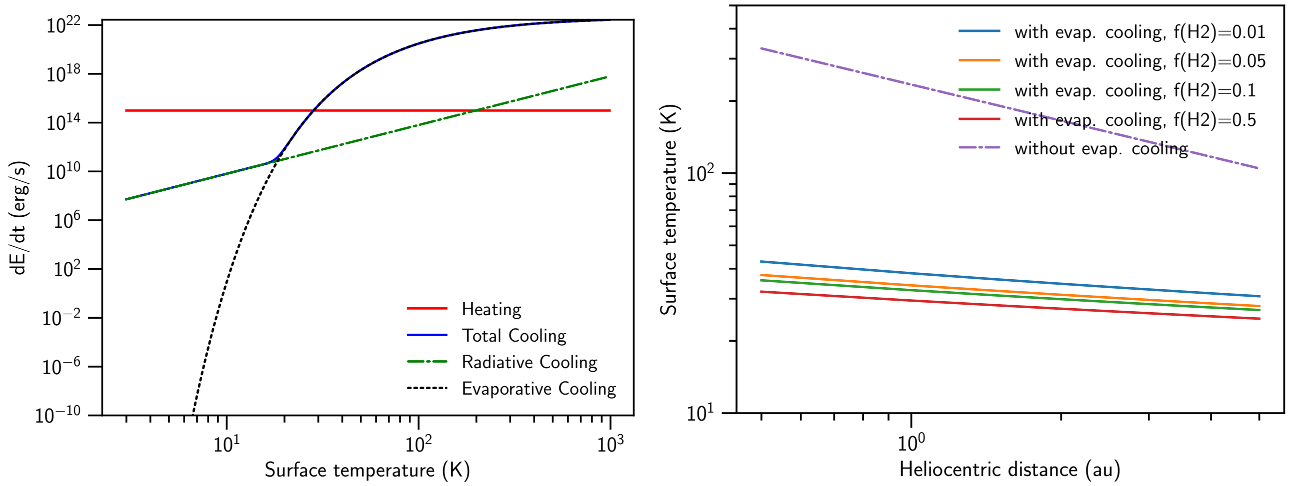

Figure 1. Left panel: comparison of heating and cooling rates when the object is located at 1.4 times the Earth separation from the sun. Evaporative cooling by H_2 is dominant over radiative cooling. The intersection of heating and total cooling determines the equilibrium surface temperature. Right panel: surface temperature at different distances, calculated for the case with (solid lines) and without (dashed-dotted line) evaporative cooling. Different ratio of H_2 to water is assumed. Evaporative cooling by H_2 decreases significantly the surface temperature compared to the case without evaporative cooling (dashed-dotted line).

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