Matters arising

Accelerating 'Oumuamua with H_2 is challenging

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The interstellar object 1I/2017 U1 'Oumuamua (hereafter 'Oumuamua) was non-gravitationally accelerated when it flew past the Sun. Bergner and Seligman[1] proposed that this acceleration is caused by thermal outgassing of molecular hydrogen (H_2) that was formed by galactic cosmic-ray (GCR) radiolysis of water (H_2O) ice during 'Oumuamua's interstellar travel. However, modelling, laboratory and theoretical results show that it is unlikely that sufficient H_2 can be produced in 'Oumuamua to accelerate it if the object largely consisted of H_2O ice. This implies that there must be another or additional driver of 'Oumuamua acceleration or the object has a very unusual ice composition and is substantially older (>500 Myr) than postulated.

To reproduce observations, Bergner and Seligman[1] invoke H_2:H_2O ratios of 0.3–0.4, implying a radiolysis yield of 23–28% H_2:$H_2O_{initial}$. The first issue arises when the amount of H_2 produced during 'Oumuamua's lifetime is calculated. Although its age is uncertain, Bergner and Seligman[1] state that 'Oumuamua is about 100 Myr old. With this information, the H_2 yield for an 'Oumuamua-like object can be determined by calculating the GCR dose rate into H_2O and combining this with experimentally determined H_2 production rates (Supplementary Information). This calculation results in an upper limit of the H_2 yield, as neither H_2 destruction nor a network of competing chemical reactions are taken into account.

Figure 1a shows the H_2:$H_2O_{initial}$ yield in percentage for a range of H_2 production rates and average radiation doses. At the largest experimentally determined H_2 production rate[2] (1.5×10^{-2} eV^{-1}) and 100-Myr irradiation at the shallow depth of 10 cm, the H_2 yield is ≤8% (see intersect between H_2 formation rate and the 100-Myr radiation dose in Fig. 1a). Deeper in the object, the yield is lower and integrated over the top 10 m it is ≤5.8% (Fig. 1b). Although insufficient H_2 is produced in 100 Myr, 'Oumuamua could be substantially older. The calculation shows that in 500 Myr of GCR irradiation, a maximum H_2 yield of about 25% can be obtained. As this is the largest experimentally determined H_2 production rate in low-temperature ice, the actual rate can be lower. Consequently, for a more average H_2 formation rate of 7.0×10^{-3} eV^{-1}, it takes 1,000 Myr for 'Oumuamua's subsurface ice to obtain sufficient H_2 (Fig. 1c). The difficulty in producing sufficient H_2 is underlined by the model results of ref. 3, which found a H_2 yield of about 55% over the top 10 m of cometary ice after 4.5 Gyr of irradiation by GCRs. By scaling with time, this means H_2 yields of 12% and 1.2% for 1,000 Myr and 100 Myr of irradiation, respectively.

Even for a much older object, it is questionable whether high (about 25%) H_2 yields can be achieved by radiolysis of H_2O-rich ice. All the radiolysis experiments cited in Bergner and Seligman[1] present maximum H_2 yields of around 5% (refs. 4–7; see also Supplementary Table 1). These experiments show that the systems reach, or are close to reaching, a steady state, meaning that H_2 production has levelled off and no additional H_2 is produced at longer irradiation times. This behaviour is also seen for oxygen-bearing H_2O radiolysis products, such as hydrogen peroxide (H_2O_2), which are easier to investigate in the laboratory. For example, when reproducing the experimental H_2O radiolysis data of ref. 8 with an astrochemical model, ref. 9 found that H_2 production levelled off at a maximum yield of ≤2% H_2:H_2O.

Only one study in the literature has found a much higher H_2 yield of 35% (ref. 2), but there are several indicators that this value is not applicable to the GCR-irradiated subsurface H_2O ice of 'Oumuamua. First, this experiment makes use of ultraviolet photons to irradiate ice and produce H_2, which will not be relevant at depths greater than about 1 μm. Photolysis can give higher yields than radiolysis[10], so care needs to be taken in adopting the photolysis yields to a radiolysis scenario. Second, the ice used in ref. 2 is a mixture of H_2O:CH_3OH:NH_3:CO ice at a 100:50:1:1 ratio. Methanol (CH_3OH) ice abundances in interstellar clouds and in comets are generally 5–10% with respect to H_2O, with outliers up to 30% (ref. 11). If 'Oumuamua has a highly unusual ice composition of hydrogen-rich molecules (for example, CH_3OH) and was irradiated for a long enough duration (>500 Myr), this may result in a sufficiently high H_2 yield.

Another question is what happens to H_2 that is trapped in H_2O ice. Experiments in ref. 12 showed that H_2-enriched porous-amorphous H_2O-ice films irradiated with 100 KeV protons lose up to 65–75% H_2. This effect has been ascribed to pore collapse in the H_2O-ice films, which is relevant to the type of ice that 'Oumuamua is suggested to consist of[1]. Assuming this process is efficient down to about 10 m depth—meaning that after pore collapse and H_2 expulsion, the liberated H_2 can be lost to space and does not linger, or freezes out again in the subsurface—two out of three produced H_2 molecules will be lost and consequently it will take three times longer to achieve a sufficiently large yield.

When the H_2:H_2O yield is lowered by a factor of four to five to match experimental data, most of the models presented in Bergner and Seligman[1] do not generate sufficient acceleration to explain 'Oumuamua's behaviour. One notable exception exists for the model that uses the highest temperature of $T_{H2} = 140$ K and largest H_2O-ice-to-dust ratio of $X_{H2O:dust} = 3$. In this case, a H_2 abundance of up to a factor 4.6 lower could still be sufficient to accelerate 'Oumuamua. However, H_2O-ice-to-dust ratios measured in Solar System comets are found to be smaller than unity, as is the case with the most thoroughly investigated comet 67P/Churyumov–Gerasimenko, where this ratio is about 0.4 (ref. 13). The combination of several model parameters that are significant outliers compared with what is generally observed makes it unlikely that this model is realistic.

In conclusion, radiolysis of H_2O ice is unlikely to generate sufficient H_2 to accelerate 'Oumuamua, even at longer irradiation timescales than the postulated 100 Myr. If 'Oumuamua has an unusual ice composition

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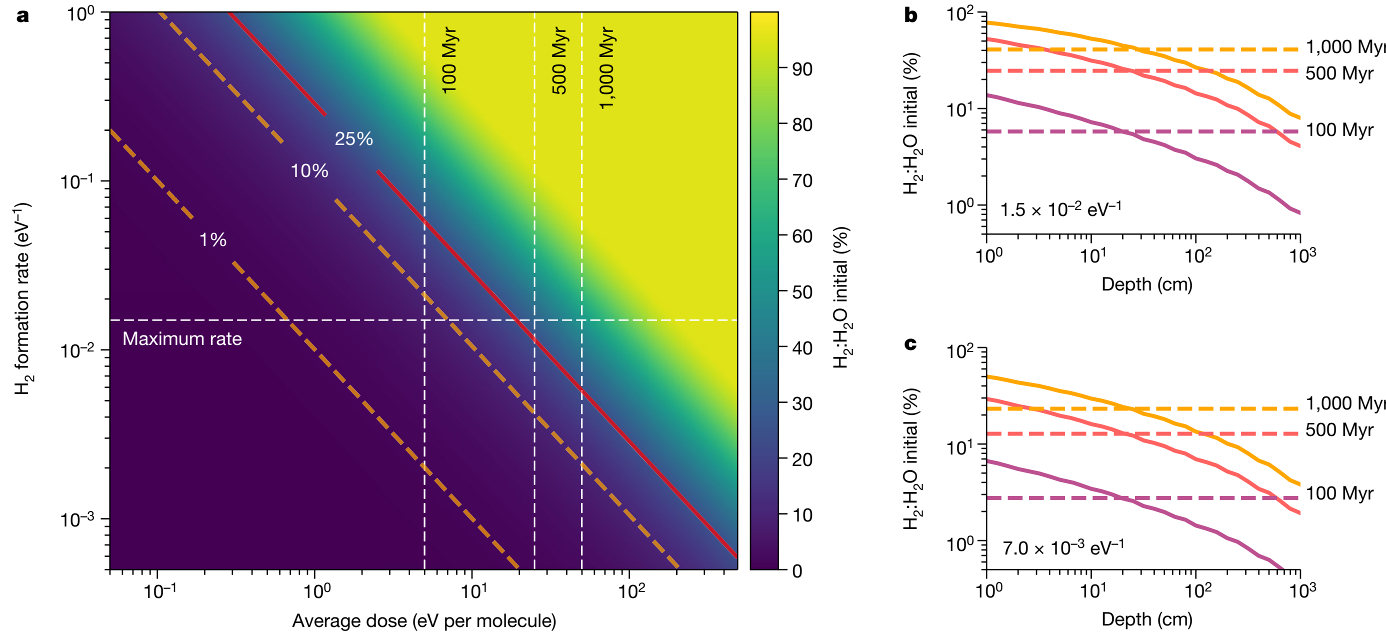

Fig. 1 | The H_2:$H_2O_{initial}$ yield for a H_2O-ice-dominated object irradiated by GCRs. a, H_2 yield for different formation rates and radiation doses. The orange dashed and red solid lines indicate yields of 1%, 10% and 25%, as indicated. The white horizontal dashed line indicates the largest experimentally determined H_2 formation rate[2] and the white vertical dashed lines indicate the dose received at 10 cm depth after 100 Myr, 500 Myr and 1,000 Myr of irradiation. **b**, H_2 yield after 100 Myr, 500 Myr and 1,000 Myr of irradiation at 1–1,000 cm depth for a H_2 formation rate of 1.5×10^{-2} eV^{-1}. The dashed horizontal lines indicate the average H_2 yield over 10 m and are found to be 5.8%, 24.6% and 40.9%, respectively. **c**, The same as in **b**, but for a H_2 formation rate of 7.0×10^{-3} eV^{-1} resulting in average H_2 yields of 2.8%, 12.8% and 23.2%, respectively.

(for example, highly methanol rich) and was irradiated for substantially longer timescales (that is, >500 Myr), this might result in a sufficiently large H_2 yield to accelerate ʻOumuamua.

Data availability

The datasets generated during and/or analysed during the current study are available from the author on reasonable request.

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Additional information
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Reply to: Accelerating ‘Oumuamua with H_2 is challenging

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REPLYING TO: N. F. W. Ligterink *Nature* https://doi.org/10.1038/s41586-023-06697-y (2023).

In the accompanying Comment[1], Ligterink claims that it is challenging to explain 1I/‘Oumuamua’s non-gravitational acceleration with molecular hydrogen (H_2), primarily due to insufficient formation of H_2 by galactic cosmic-ray (GCR) processing of a pure-water (H_2O) body. The article underscores important considerations, including the age of the body and the uncertainties with adopting an appropriate H_2 yield for this scenario. Nonetheless, the model presented in our paper[2] remains a valid explanation for ‘Oumuamua’s non-gravitational acceleration. In the following, we address Ligterink’s various argument themes.

Ligterink claims that the radiolytic production of H_2 cannot produce the non-gravitational acceleration of 1I/‘Oumuamua because it is difficult to produce sufficient H_2 within a 100-Myr lifetime via cosmic-ray exposure. It is important to highlight that the suggested 100-Myr dynamical age of 1I/‘Oumuamua is only a rough estimate and purely statistical in nature. Kinematically, it has been demonstrated that it is likely that 1I/‘Oumuamua was comoving with the Carina and Columba stellar associations during the time period that they were forming. However, this does not prove co-formation, and the authors are indeed very cautious on this point[3].

The dynamical age of an interstellar object can only be roughly estimated from its incoming kinematics[3]. Given the uncertainties in the stellar dynamics data and the statistical nature of extrapolating the age from the kinematics, the individual ages of interstellar objects are not well constrained. For more details, see the discussion in the recent paper on interstellar interlopers (section 5.2 in ref. 4): “The strongest conclusion is that 1I/‘Oumuamua is likely to have spent less time in interstellar space than 2I/Borisov”.

In Ligterink’s fig. 1, it is clear that somewhat older objects can achieve H_2:H_2O ratios in the low tens of per cent when assuming experimentally measured yields[1].

Ligterink also argues that—even for an older body—it is “questionable” that H_2 yields >10% can be achieved. For comparison, in our study[2], we tested conversion yields of 23–28%. First, it is critical to note that for some parameter combinations explored by in our study[2], the body contains factors of a few times more H_2 than is necessary to explain the magnitude of non-gravitational acceleration. For instance, H_2 excesses up to about 3.5× and about 4.5× are seen in fig. 1a,c of our paper[2]. Therefore, the model is still viable even with a significantly lower H_2 yield than the values adopted for the parameter study in our paper[2]. Also, as pointed out[2], if H_2O sublimation is active, then this would further reduce the H_2 content necessary to explain the non-gravitational acceleration.

In any case, we now outline why H_2 yields above 5–10% are plausible. Ligterink asserts that the peak H_2 yield of about 5% seen in some radiolysis experiments[5–7] represents an intrinsic maximum value due to a steady state being reached. However, from an inspection of the growth curves in these studies, it is not clear that H_2 (or D_2) yields have reached a steady state at the highest energy doses. We have compiled the yield data from these studies in Fig. 1: there is no reason to conclude that “no additional H_2 is produced at longer irradiation times”. Clearly, more experiments with longer timescales and energy doses are necessary before a maximum yield can be determined.

It is also important to recognize that chemical systems cannot be assumed to behave identically between laboratory and astrophysical environments. For instance, the ices in a cometary body are metres to kilometres thick instead of (sub-)micrometres. Moreover, the energy doses are deposited over more than millions of years instead of several hours. Naturally, the quantitative details of ice chemistry may differ between these two environments. To reiterate our previous point, it is clear that additional experimental efforts are necessary to explore trends in H_2O radiolysis for, for example, thicker ices and over longer timescales. However, the extant experimental data do not convincingly prove that higher H_2 yields cannot occur in astrophysical settings.

Reference 8 found a higher H_2 yield of about 35% in experiments involving photolysis of ice mixtures, well above the values tested in our study[2]. Ligterink states that ice photolysis is sometimes more efficient than radiolysis, with the implication that a photolysis yield of 35% H_2:H_2O is higher than what could be achieved for ‘Oumuamua. In fact, studies comparing photolysis versus radiolysis of H_2O ice mixtures show that the formation and destruction yields per unit energy are generally consistent within the uncertainties[9,10]. Ligterink also suggests that the high H_2 yield could be due to the high content of methanol (CH_3OH) in the experiments of ref. 8. As also noted by Ligterink, it is certainly possible that ‘Oumuamua had a CH_3OH-rich composition. Indeed, the interstellar object 2I/Borisov had a very different CO:H_2O ratio compared with typical Solar System comets (about 1 versus about 0.05, respectively)[11–13].

Ligterink also argues that H_2 may be lost from the ice due to pore collapse during H_2O irradiation. However, it is highly speculative to assume that a bulk desorption process observed in thin (roughly sub-micrometre) ices will be active down to depths of many metres. In other words, although pore collapse may occur deep within an icy planetesimal, it is not clear that this would lead to H_2 loss from the body. Moreover, in other experiments, irradiation of H_2O ices has actually been shown to induce amorphization of the ice mantle, rather than causing pore collapse[14,15]. Given these considerable uncertainties, there is not at present cause to favour radiation-induced H_2 loss.

The models in our study[2] with an ice-to-dust ratio of 3 can explain the non-gravitational acceleration of ‘Oumuamua given much lower H_2:H_2O ratios (up to about 4.5×) than what was assumed in the original parameter study. There is, therefore, no tension between these models and a purported maximum H_2 yield <10%. Ligterink argues that an ice-to-dust ratio >1 is unlikely, with reference to the ratio of 0.4 found

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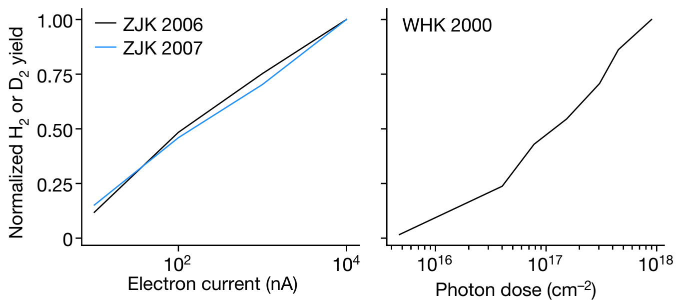

Fig. 1 | H_2 and D_2 growth curves from H_2O or D_2O ice electrolysis or photolysis. These data are taken from table 6 in ref. 6 (ZJK 2006) and table 1 in ref. 7 (ZJK 2007), and from fig. 8 in ref. 5 (WHK 2000). Yields are normalized for clarity; note that a steady state at the highest energy doses is not apparent.

in comet 67P/Churyumov–Gerasimenko. In fact, ice-to-dust ratios remotely inferred for different comets vary considerably: the quantity $Q(\mathrm{OH})/Af\rho$, a remote proxy for the H_2O-to-dust ratio, varies by over an order of magnitude at a given heliocentric distance[16], and 67P is on the low end of inferred ice-to-dust ratios[17,18]. Moreover, literature estimates of the ice-to-dust ratio of 67P vary despite the large amount of in situ data[19]. High ice-to-dust ratios are therefore not excluded based on current observations of Solar System comets.

Dust-poor comets are also known to exist in the Solar System, such as 2P/Encke[20]. Moreover, refs. 21–23 reported significant non-radial non-gravitational accelerations on seven photometrically inactive near-Earth objects. The magnitudes and directions of these accelerations are inconsistent with being caused by thermal effects such as radiation pressure or the Yarkovsky effect. Therefore, these authors concluded that these objects were plausibly sublimating volatiles with little dust production. Specifically, the 'dark comet' (523599) 2003 RM shows an 11% chance of originating from the Jupiter family region[24]. High ice-to-dust ratios are not unprecedented within the Solar System small bodies, and would additionally be in accord with the non-detection of a dust coma for 'Oumuamua.

We agree that when modelling the behaviour of 'Oumuamua, it is important to consider factors such as its age and received energy dose, as well as the ice-phase H_2 formation rate and possible maximum yields. Ultimately, the model presented in our paper[2] can explain 'Oumuamua's non-gravitational acceleration with assumptions for the age, composition and H_2 content of the body that are compatible with existing experimental and observational constraints.

Data availability

All data are taken from the previously published articles referenced in the text.

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Additional information

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