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Study on the Origin of the Earth's Water

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Abstract:

Planet Earth holds a comparatively abundant of liquid water. The only astronomical object which sustains liquid water on its surface is the solar system. This study will commence with introducing the use of analysing the isotropic and chemical composition when considering the potential source of water on Earth. The analysis of these compositions allows a level of constraint when considering the ultimate question of the origin of water on Earth. Subsequently, the study will review two different candidates potentially responsible for the source of the water on earth: comets and carbonaceous chondrites with their key supporting evidence. The review continues with a discussion of the present challenges, mainly focused on the controversies between the two scenarios based on their water delivery scenario. Due to the insufficient data on the comets in the solar system, and the existing uncertainty on the research of the Earth's interior, both scenarios are possible to bring water to the Earth if further corrections of their model can be done in the future. Furthermore, the study will discuss the future initiatives of the next generation researching directions.

Keywords: Origin of water, comets, carbonaceous chondrites.

1. Introduction

The search for Extra-terrestrial Intelligence (SETI) has been drawing attention since the last century, not only on scientific research but also on social media. To study the existence of other life forms even aliens require a full understanding of the origin of life on Earth before searching for any signs of life. Unraveling the mystery of the origin of life plays an important role in various fields, especially in planetary science and astrobiology.

Before developing any search projects associated with life on exoplanets, it is necessary to first think about water, in particular liquid water. All life forms, to maintain their activity, have to perform several essential organic reactions that require water such as cellular respiration. There is no scientific reason that life on exoplanets cannot exist and perform their organic reaction in other solvents, as long as the solvents can support material exchange. Besides, for these reactions to take place on a planet, the planet must have a relatively rich amount of hydrogen, carbon, oxygen, and sulfur molecules, combined with an energy source to initiate and maintain the reaction. Thanks to what has been studied from the Miller–Urey experiment, it is very likely that these molecules could form the common organic compounds that made life. Those conditions may not be universal as planet Earth is the only place in the universe where life has been found and studied. It would be interesting to study how exactly life was formed from the random collision of these organic compounds as it is a statistically low possibility event for those molecules to form even a single bacterium, however, that would be another fascinating topic beyond the research of the author. To date, the ongoing origin of water studies mainly focuses on comparing and hence fitting the isotropic composition of the extra-terrestrial material with the current ocean data of the Earth. Because of the existing quantity of data, for both Earth and the extra-terrestrial material, the constraint on the existing candidates remains at a relatively low precision. This raises difficulty when eliminating some hypothesized events which may seems unlikely to happen in the history of Earth.

This report is organized as follows: In section 2, some background information will be given, which is related to chemistry, physics, and astronomy. This background will help provide evidence or constraint for the existing hypothesis which has the potential to explain the origin of water. In section 3, two potential candidates for earth water delivery will be introduced with the most notable chemical evidence that has been found related to their scenario. In section 4, the existing challenges to the two mentioned scenarios will be discussed. In section 5, the author will provide a summary of the key findings and discuss potential next directions for research. The constraints and introduced two potential candidates are described: Comets and Carbonaceous Chondrites.

The current supporting evidence and major problems for both hypotheses are described. The future research direction of the candidates is summarised and another potential solution to the origin of water is introduced.

2. Constraints

When explaining how a large quantity of water has been delivered to the earth, the constraints of the existing hypothesis come mainly from two measurements: the isotropic composition and the geochemical composition. The isotropic ratio of key elements such as hydrogen and oxygen can give an interpretation of where the water-delivering material has been formed [1]. The geochemical constraints, however, limit the period of when the material has landed on Earth by analysing the core-mantle composition of the early Earth [2]. By combing information about when and where the mystery of how the water has been delivered to the earth can be unveiled.

2.1 Deuterium/Hydrogen (D/H) ratio

One key constraint on the origin of Earth's water is the deuterium/hydrogen (D/H) abundance ratio. The study history of the D/H ratio may be traced back to the year 1948 when Ralph Asher Alpher used Big Bang nucleosynthesis to explain how heavier elements are created out of the light elements in his dissertation [3]. Since 1974, it has been realised that no post-Big Bang process can produce a large portion of deuterium rather than destroy it [4]. The uniqueness of deuterium makes it not only a perfect Baryon meter but also an indicator of whether liquid water has existed on a specific planet. In 1998, the D/H ratio of earth water was estimated to be $150\,ppm$ [5]. The latest D/H ratio is determined with higher precision to be $155.76 \pm 0.05\,ppm$ [6]. Worth mentioning, that this value is close to the D/H ratio for water-rich carbonaceous chondrite meteorites [7-9]. This makes carbonaceous chondrite a strong candidate for water delivery to Earth to a certain extent and will be explained in more detail in Section 3.2.

2.2 Planet Formation

In the standard model of the protosolar nebula, the temperature of the terrestrial planet-forming zone has been long considered too high for water to exist. Therefore, as shown in Figure 1, when the Earth was formed by accretion, most material should be dry.

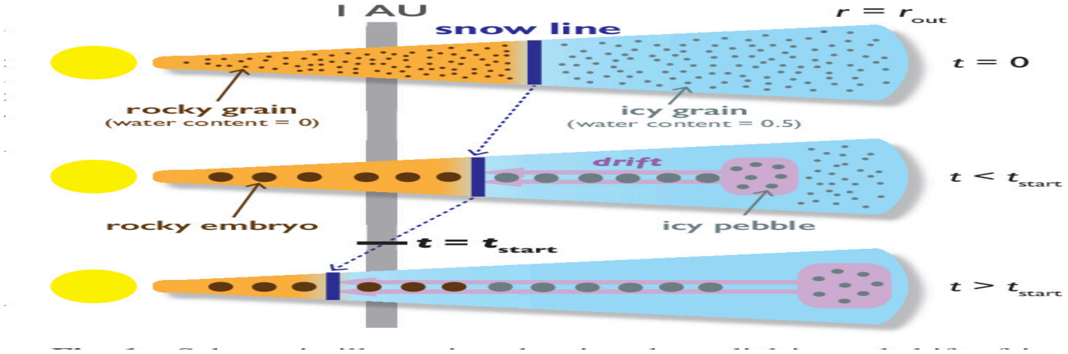

Fig. 1 Schematic representation of the protoplanetary disk, where r represents the heliocentric distance. 1AU has been illustrated for comparison [10].

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According to this model, the present-day water should only be delivered at later stages by some external mechanisms after the planet is formed. Besides this standard model, various mechanisms have been suggested, allowing the gaining of water from local sources explaining how the planetesimal could eventually form a water-rich terrestrial planet. However, those mechanisms face difficulties in different ways so will not be introduced in this report.

3. Potential Candidates

As shown in Figure 2, from the data have been collected from different meteorite types, a clear increasing trend of water mass fraction has been observed as the heliocentric distance increases. Therefore, when considering the potential water source of the earth, the water-rich bodies seem likely to be formed beyond the inner asteroid belt.

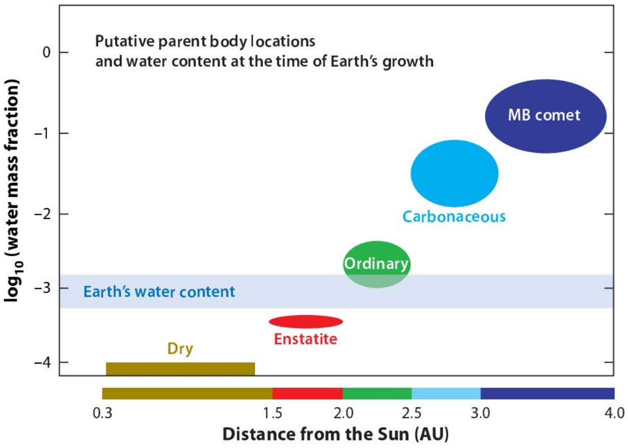

Fig. 2 Schematic representation of the level of moisturisation is expected at different heliocentric distances. Types of asteroidal and comet material have been labeled at their corresponding distances. The total water content of the earth is not estimated to high precision, so illustrated as a range for comparison. Ordinary chondrites, Carbonaceous chondrites, and MB (Main Belt) Comets appear to hold a higher water mass fraction compared to the Earth [11].

3.1 Comets

Comets have been suggested as a potential source of water for the Earth given their icy and volatile-rich structure in the solar system. However, comets hold a large variation range of the D/H ratio. Before the year 2000, their mean value of the D/H ratio was calculated to be approximately twice that of the terrestrial planets [12]. The reason for this value may be that the data was mostly taken from the Oort cloud or Halley-type comet [13]. From the data that have been measured in the years 2011 and 2013, two Jupiter-family comets (JFCs) have a D/H ratio close to the terrestrial planets [14, 15]. The variation of this D/H ratio is often interpreted as an indicator reflecting their spatial coordinate when they were formed. However, in the year 2015, another JFC was pointed to have a D/H ratio of almost three times terrestrial planets, which may lower the reliability of this interpretation [16]. Nevertheless, one recent study suggested that comets may still be a potential source of Earth water as they pointed out that there could be mechanisms changing the isotropic properties of the comet [17].

3.2 Carbonaceous Chondrites

The value of ocean D/H value on earth is very close to the mean D/H ratio of water-rich carbonaceous chondrites. Besides, the CM (Mighei-like) and the CI (Ivuna-like) groups can have ~3-22% of water and other organic compounds [18]. Those properties suggest that carbonaceous chondrites or similar material could be a potential source of earth water. However, when compared to the Earth, the oxygen isotope ratio of carbonaceous chondrite material does not match the Earth [19, 20]. Instead, it is closer to Enstatite chondrites, which is a material drier than the Earth, so cannot be the source of water, but perhaps the source of oxygen and even other elements (Fig. 3) [21, 22].

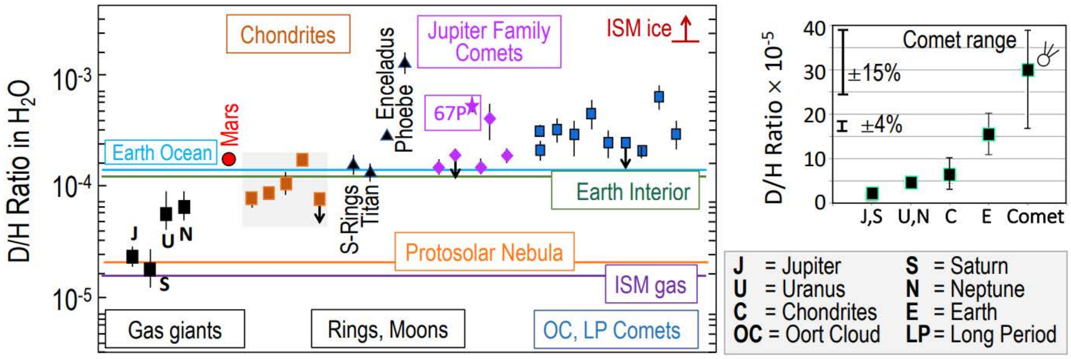

Fig. 3 Schematic representation of the D/H ratio of different solar system objects. Both Carbonaceous Chondrites and Jupiter Family Comets hold similar D/H values of the Earth. However, the D/H value alone cannot provide further information on the origin of water, the other isotropic and chemical composition profiles can provide further constraints [23].

4. Discussion

4.1 Current Challenges and Future Initiatives of Cometary Delivery

Despite all geochemical constraints, the biggest challenge that may eliminate the possibility of the comet being the primary source may come from the statistical constraint.

Based on past work in 2000, the probability which comets outside the asteroid belt hit the Earth has been estimated to be 1×10^{-6}, and the total mass of the comet-like bodies in the solar system are estimated to be $50M_{Earth}$ [24, 13]. Combining both pieces of information, comets can potentially carry $5\times10^{-5}M_{Earth}$ of water in mass. However, from what have been estimated, the earth should have contained at least $2.8\times10^{-4}M_{Earth}$ of water, which implies that the quantity of water delivered in the past should have exceed this value to shape the present earth [25]. By comparing the order of magnitude, if there are no other assumptions, the conclusion can already be given: Comets may only contribute to a small proportion of the earth's water. Nevertheless, until today, the total count of known comets is 3963 [26]. Therefore, as there are estimated to exist one trillion comet-like materials in the solar system, it is still promising to make corrections to the previous result once a larger quantity of comet data has been obtained in the future. Besides, one recent research has shown that there may exist a correlation between the cometary activity and its D/H ratio [17]. It suggests that if only the D/H ratio is considered, it is likely that there exist other mechanisms that may provide D/H fingerprints similar to the Earth, which raises new possibilities.

4.2 Carbonaceous Chondrites

As mentioned above, carbonaceous chondrites hold a terrestrial D/H ratio, which makes them partially satisfy the isotropic composition. However, the inconsistency in the oxygen isotope ratio and other volatile element abundance suggests that carbonaceous chondrites cannot contribute to significant amounts of water to the earth's ocean. Studies have shown carbonaceous chondrites will only contribute to approximately ~2% of the Earth's mass [20]. However, there are some levels of controversy around this result, mainly related to some elements such as Nitrogen. According to the inventory, some elements in the Earth's interior appear to be lost by an order of magnitude [20]. This may indicate that some dynamical event may have happened in the past and changed the isotropic fingerprint of the Earth's interior, or a larger sampling quantity may be needed.

4.3 The Grand Tack Scenario

As mentioned above, both comet and carbonaceous chondrites seem unlikely to provide large quantities of water to the earth according to the current research. It may be likely that other mechanisms have happened, such as planet migration. The Grand Tack scenario has the potential to explain multiple unsolved problems in the solar system. A kind of the Grand Tack scenario uses a set of computational simulations to study the potential dynamics of the asteroids under the condition that Jupiter and Saturn undergo a set of migrations. The results of the simulations have shown that the water-rich materials from beyond the asteroid belt region can get scatted by the turbulence caused by the migration of the gas giants, and eventually reach the terrestrial planet region. However, in the case where the earth accretes sufficient water, Mars, according to the simulations, would be at least 5 times larger than its actual size. Numerous constraints have been set to avoid the problem, other models such as the low-mass asteroid belt model have been developed, but they are less related

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to the delivering process of water, so they will not be discussed in detail. Nevertheless, dynamical models similar to the Grand Tack scenario may bring further corrections or even new possibilities when considering the origin of water on Earth, such as the historical event that may have happened and changed the composition of the earth as mentioned in section 4.2.

5. Conclusion

In summary, based on the discussion of two different potential candidates for earth's water source both hypotheses of cometary delivery and carbonaceous chondrites delivery exhibit problems when matching either the isotropic ratio or the chemical composition to the earth's ocean. Furthermore, studies have shown in both scenarios, the comets and carbonaceous chondrites will only contribute to a small proportion of earth water. Nevertheless, cometary water delivery may remain promising as there is still much comet data to be collected, especially further than the outer asteroid belt. Besides, this conclusion may also indicate the need for an alternative candidate responsible for the origin of water on Earth, or even a planet-migration mechanism, such as the Grand Tack scenario or similar scenarios. Data with higher reliability of the water on Earth will be essential for the validation of the existing water delivery hypothesis.

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