Alex Ogden
Department of Physics
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ORIGIN OF EARTH'S WATER

Durham University

N-body simulations are used to evaluate whether Earth's water was delivered by collisions with water-rich planetesimals from beyond the frost line during planetary formation. It is found that this model produces realistic solar systems and this mechanism is likely a major source of Earth's water.

INTRODUCTION

The origin of Earth's water persists as a crucial unsolved problem in physics. It has vast implications about the conditions in the early solar system, the mechanisms governing planetary formation and the abundance of wet, habitable exoplanets.

Since water can only exist as ice in the cold outer solar system (beyond the frost line): we know that the planetesimals which eventually became terrestrial planets were very dry(1). There must therefore be some mechanism that delivers water to Earth via bodies from outside the frost line. One proposed model is that gravitational interactions with Jupiter caused water-rich planetesimals to 'deplete' and migrate towards the inner solar system(2). This projectuses N-body simulations of a primordial solar system to evaluate the likelihood of this depletion scenario.

ALGORITHM

The leapfrog algorithm was chosen for this simulation since it is computationally efficient for large numbers of bodies. To evolve the system for each body, the next position (n+1) is calculated using the position at current step (n) and the velocity from the half-step between them (n+1/2). The half step velocity is calculated using the previous half step velocity (n-1/2), the body's mass (M), the total gravitational force (F) and the timestep (dt).

$$\mathbf{v}_{n+1/2} = \mathbf{v}_{n-1/2} + \frac{\mathbf{F}}{M}dt \tag{1}$$

$$\mathbf{r}_{n+1} = \mathbf{r}_n + \mathbf{v}_{n+1/2}\,dt \tag{2}$$

Timestep must be chosen carefully. When bodies are close together, large forces arise. Timesteps that are too large do not have a sufficient resolution to model this and causes bodies to get ejected from the system. Timesteps that are too small make the code slow and inefficient. A timestep of 5 days was found to be appropriate on these scales for 10^6 total steps.

INITIAL CONDITIONS

In the early solar system, small grains of material formed from the solar nebula via accretion slowly grow to become planetesimals. These simulations model the interactions of 20 planetesimals as they collide to form rocky planets, Jupiter and the Sun have already formed. If the depletion model is correct then we expect to see water-rich bodies collide with the inner bodies and produce a system analogous to the real solar system.

Realistic collisions are computationally expensive and have been approximated as inelastic mergers, making a new body at the centre of mass. The close distances involved in a real collision would require a tiny timestep. Instead, bodies collide when they are within a threshold distance from each other. A threshold distance of 100 radii was found to be appropriate.

PLANET DISTRIBUTIONS

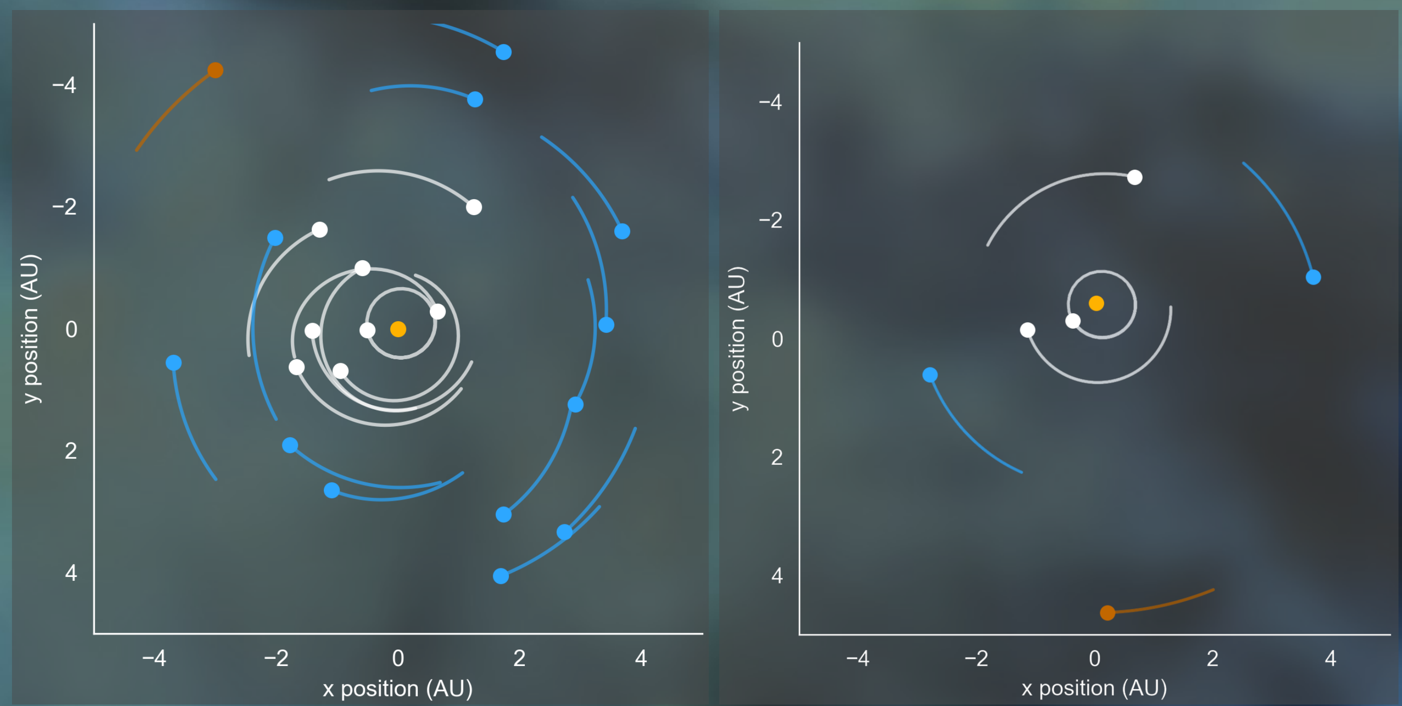

Fig 1: Sample simulation of 20 planetesimals (velocity variance of 0.01) becoming an analogue of today's solar system after 14,000 years (with 250 day trails). The Sun is yellow at the origin and Jupiter is orange. The dry bodies initially within 2 AU are white and the wet bodies beyond the frost line (between 2 and 4.5 AU) are blue.

In all simulations, the planetesimals formed a stable and reasonable solar system with 6 or less rocky planets very quickly (in under 10^5 years). 10% of simulations produced at least one water-rich planet with similar mass and orbital radius to earth although most were lighter and further away. In future, a more powerful computer may be able to implement this method with a smaller timescale and produce an improved system over a more realistic timescale.

WATER AND D/H RATIO

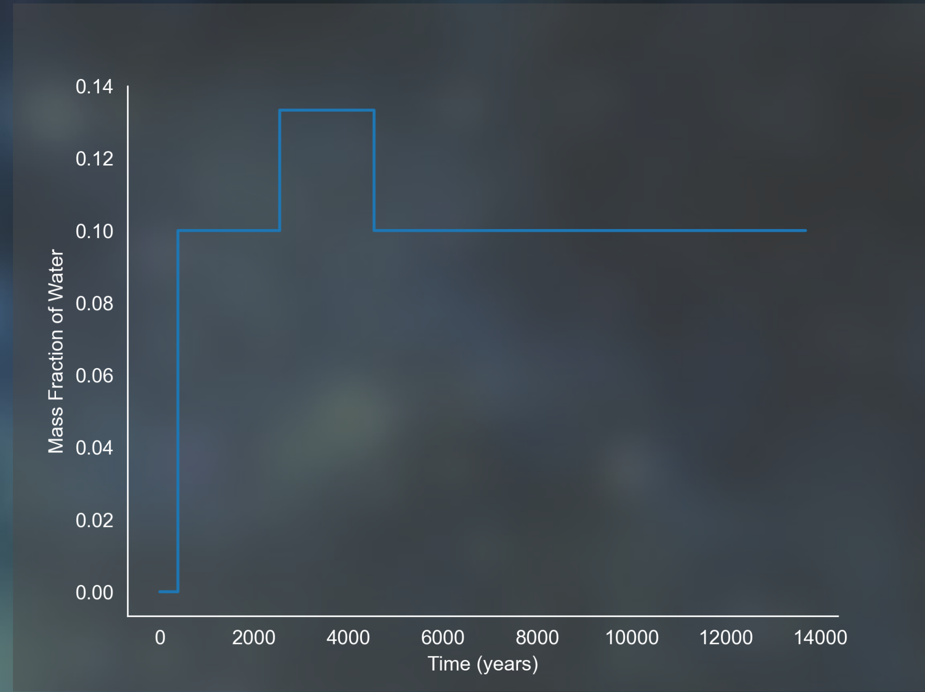

Fig 2: The fraction of water (by mass) contained within the outermost initially dry planet in the final state of Fig 1. The planet begins dry, however after 2 collisions with migrating wet bodies reaches 14% water. A further dry collision results in 10% of the planet's mass as water.

The simulations all demonstrated wet bodies migrating inwards and that this is significantly more likely than the reverse. The wet planetesimals had the same water mass (20%) and Deuterium/Hydrogen (D/H) ratio (140±10 ppm)(3) as Carbonaceous Chondrites (CCs), a primordial water-rich species of asteroid. The wet planets often had ~1% water, much greater than Earth's 0.02%. The D/H ratio of the wet planets was similar to that of the CCs and Earth (149±3 ppm). This implies that the delivery of water by CC-like material is likely a major source of Earth's water although the early solar system likely had fewer CC-like planetesimals than simulated.

CONCLUSIONS AND FUTURE WORK

The depletion scenario is a realistic water delivery mechanism in the early solar system as it produces planets with reasonable water and orbital distributions. This will be further investigated by fine tuning initial conditions and optimising the code to work over longer timescales. Other models will also be investigated such as the 'Late Veneer Scenario' where Earth's water is delivered by Kuiper belt comets.

REFERENCES

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