Water on Earth*

Where Did it Come From?

Biman Nath

The question of the origin of water on Earth has been a puzzle since long. The standard scenario that comets have deposited water here over eons has many loopholes, and some recent results have put a question mark on this. Instead, asteroids have become the favorite candidates for ferrying the water. At the same time, other discoveries seem to hint towards a large reservoir of water inside Earth.

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1. Introduction

What makes our planet the most special in the whole solar system is the fact that it has liquid water. The amount of water on Earth ($\sim 1.4 \times 10^{21}$ kg) may be a tiny fraction ($\sim 0.02\%$) of the total Earth mass, but the special features of water molecules, such as its polar nature, bestow it with all those properties that makes it essential for life. The question of life on Earth is, therefore, intimately connected to that of water on Earth. In this context, there is a substantial amount of water here. About 71% of the Earth's surface is covered with water. One may be naturally tempted to ask, where has it all come from? Has the water been here on Earth since the planet was born? Or has it been added later? If so, how and when did it happen?

Let us consider the first possibility: Water has been present on Earth from the very beginning. Comparing the water content of Venus or Mars with that of the Earth does not help us confirm or refute this hypothesis. This is because the evolution of the planets have been different leading to the observed difference in the

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present-day water content in these planets. The question whether Mars had water in the past and how much, is still not settled. The condition of temperature and pressure on Venus is unsuitable for liquid water on its surface, and it may also have lost a lot of water since the beginning.

However, there is one measurement which puts a question mark on the 'from the beginning' hypothesis. The abundance of deuterium[1], holds some clue to the origin of water on Earth. Deuterium also forms water-like compounds, D_2O and HDO, a mixture of which is usually referred to as 'heavy water', and one can measure the relative abundance of such heavy water in a sample of water. The relative abundance D/H on Earth is roughly $(149 \pm 3) \times 10^{-6}$; in other words, roughly one hydrogen atom among a million is in the form of deuterium. In comparison, the present-day D/H ratio in Venus is about 100 times larger. It may have been due to some sort of selective loss of H atoms relative to D, during the photodissociation of water molecules at the top of Venetian atmosphere. But it still points out a significant difference between water on Earth and Venus.

[1] An isotope of hydrogen with a neutron in its nucleus that hydrogen does not have.

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2. Did Comets Bring Water to Earth?

This discrepancy clearly begs for an explanation in terms of an outside agent for supplying water to the Earth. Perhaps from the outer reaches of the solar system where gas giants are, and where water may not have evaporated away, unlike the inner rocky planets.

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Box 1. Oceans on the Earth

Consider a spherical comet of radius 4 km. With an average cometary mass density of 600 kg m^{-3}, its mass is 1.6×10^{14} kg. When it comes near the Earth–Moon system, its kinetic energy is $\sim 2.5 \times 10^{23}$ J. Suppose one such comet hits the lunar surface. The impact will heat the lunar rocks to about 3500 K and vapourise them. Suppose it creates a crater of depth 10 km. Assuming that the rocks are made of silicates, with molecular weight $\sim$ 30 times the mass of a proton, and with mean solid density $\sim$ 2000 kg m^{-3}, then (ignoring the latent heat of melting and vaporising the rocks) equating the kinetic energy of the comet to the total thermal energy of the vaporized rocks, the size of the crater comes out to be roughly 50 km.

There are about 10 such craters of this size on the Moon, in the relatively clean mare regions, during the past 3 billion years or so. The corresponding number of impacts on Earth will be larger, firstly because of its bigger size and secondly its gravity. Ignoring gravity, the ratio 3.7 between the radii of the Earth and Moon implies that the Earth has been hit by roughly $10 \times (3.7)^2 \sim 140$ comets of 4 km radii.

But there are more number of smaller comets than big ones. Comets have a mass distribution that says that the ratio of the number of comets with mass m_1 and m_2 is $(m_1/m_2)^{-3}$. The radii of the comets range between $\sim$ 0.2–4 km. From these two ingredients, and the estimate of cometary impacts of size 4 km on Earth, one can estimate the total mass of comets that impacted the Earth, which comes to $\sim 1.8 \times 10^{20}$ kg (the intrepid reader is encouraged to work it out and confirm) . So if the comets mostly contained frozen ice, then the comets could have supplied 10% of the total amount of water on Earth.

(See also Exercise 5 in Chapter 6 of Dan Maoz's *Astrophysics in a Nutshell*).

comets. Taking a cue from the crater history on the Moon, one can estimate the frequency of comets of different sizes and the total amount of water that may have been deposited on the Earth. It turns out that a significant portion of Earth's oceans can indeed be accounted for in this way (a simplified version of Christopher Chyba's suggestion in 1987 is described in *Box* 1).

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Astronomers believe that there was a period, soon after the formation of the Moon, when the Earth and Moon were hit by asteroids and comets called the 'late heavy bombardment era'. It is thought that this period started around 4.1 billion years ago and lasted for about 300 million years.

However, recent measurements of D/H ratios in some comets, from the observations of spectral lines from water vapor that is given off by comets as they approach the Sun have put a dent on this hypothesis that was popular in the 1990s. The D/H ratios in comets Halley, Hyakutake, and Hale–Bopp have been measured to be $(310 \pm 40) \times 10^{-6}$, which is roughly twice the value on Earth. This was confirmed by the Rosetta mission that landed on comet 67P/Churyumov–Gerasimenko in 2014 and examined its surface. This implies that not more than half the total amount of water in our oceans could have come from the comets.

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Interestingly, the D/H ratio in a class of meteorites, known as carbonaceous chondrites, have been found to be very similar to that of seawater. These rocky planetesimals are fragments of carbon and water-rich asteroids that move around in the region between Mars and Jupiter, and they do contain a non-negligible amount of water (up to 20% by weight). These chondrites often contain tiny fragments of opal, which requires water to form, which is another indication that they contain water.

There is circumstantial support for this idea from the study of ice on the Moon. Recent space missions have discovered a substantial amount of ice in the polar regions of the Moon. The D/H ratio in lunar ice is found to be similar to that of seawater, and, therefore, the origin of water/ice on Earth and Moon is most likely to be similar. In 2016, a group of astronomers [1] estimated that carbon-rich chondrites could have supplied a major portion of the lunar ice, shortly after the origin of the Moon, perhaps for about 200 million years after its birth. The time estimate is based on their studies on the differentiation of lunar magma (denser parts sank below) after its birth. Since the Moon does not have plate tectonics, the lunar magma retained its 'memory', so to speak, from the era when the ice had been deposited. There is yet another piece of evidence in support of the meteorite hypothesis. A study of xenon from deep within the Earth's mantle in the volcanic Eifel region in Germany in 2016 has shown that its isotopic ratios (between ^{130}Xe, ^{128}Xe and some lighter isotopes) resemble that of meteorites. Since this xenon is mixed with carbon dioxide-rich mineral spring gas, meteors may be responsible for other volatile elements trapped in the Earth's mantle, such as

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water, carbon, etc. (The xenon in the atmosphere has a different isotopic signature and has probably come from some other sources.)

3. Water Before the Late Heavy Bombardment Era

But this hypothesis also has its share of problems. Some astronomers do not believe that the lunar craters are the result of impacts of objects from the asteroid belt. According to them [3], the size and frequency of these fragments do not match those of the lunar craters, and they should have created more and bigger craters than observed. They indicate a different source for lunar craters, such as the debris from an impact on Mars that created the large Borealis basin on it. This basin, which covers two-fifths of the Martian surface, is believed to have been formed due to a giant impact on Mars, which could have also formed its moons – Deimos and Phobos. The debris from this impact may have been the reason behind most of the ancient lunar craters. If this is true, then the late heavy bombardment era may not have been so 'heavily bombarded' after all, and might have been over sooner than thought. In that case, the mechanism of ferrying water to the Earth or Moon by meteors also becomes doubtful.

When astronomers recently studied the distribution of ice in the polar regions of the Moon, they noticed [4] that the largest concentration of ice is not where the poles are, but about 200 km away from the two poles. According to them, these two places mark the original locations of lunar poles, and the rotation axis of the Moon has tilted by about 6° since then. They believe that an internal change in the density structure, perhaps to do with heating of the inner Moon below the Procellarum region, changed the moment of inertia and tilted the axis. This incident most likely happened billions of years ago, and this in turn implies that the polar ice has been there since ancient times.

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On one hand, the line of thought that ocean water, or a portion of it, has been on the Earth since the beginning has got a recent boost from theoretical calculations by a team of astrophysicists

[5]. It is generally believed that the radiation from the nascent Sun during the formation period of planets would have increased the D/H ratio in water, by a rather complicated chain of processes. However, they considered the fate of interstellar ice in the solar nebula during the formation of the Sun and the planets, because interstellar ice and the regions around protostars seem to show a large D/H ratio, like that found in comets. According to their detailed calculations, a small fraction of water molecules could have survived, and some portion of seawater (of order 10%) could be from interstellar ice.

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On the other hand, some recent geological discoveries have also been pointing towards an ancient reservoir of water on the Earth. Geologists have known about a group of basalts from Baffin island in northern Canada that shows a high value of the isotope ratio ^{3}He/^{4}He, indicative of the presence of primordial helium. Further, from the abundance of lead, the result of radioactive decay of uranium and thorium, it was shown in 2010 that the part of the mantle that melted to form the Baffin island basalts formed around 4.5 billion years ago, within about 100 million years of the formation of the Earth. Such oceanic islands form from the rising of plumes of mantle rising from very deep, perhaps near the core-mantle boundary. These rising plumes contain some amount of water trapped inside 'inclusions'. Recently, geologists have measured the D/H ratio in these inclusions and found it to be similar to the values found in the solar wind [6]. This discovery, therefore, tells that the water came quite early to the Earth, and this ancient water may be buried deep inside the Earth.

There is another piece of indirect evidence that points towards the early existence of water on Earth. In the Jack Hills region of Western Australia, scientists have found many pieces of zircon that contain traces of organic carbon. This fossil has recently been dated to be 4.1 billion years old [7]. This means that life in some form existed on Earth within 500 million years of the origin of Earth, before the standard period of late heavy bombardment era. This also implies the existence of water on Earth back then.

4. Deep Inside the Earth

Another tantalizing recent discovery hints towards a hidden reservoir of water inside the Earth. The clue comes from a tiny piece of diamond that was discovered in the Mato Grosso region of Brazil in 2008, among the pebbles on the shallow regions of a river. Geologists from the University of Alberta, Canada, were looking for a different mineral, but they bought the strange looking piece (5 mm in size) from the local people, thinking they would examine it later. Then they found that this piece contains an impurity – an interesting mineral called ringwoodite [8]. Back in the 1950s, geologist Ted Ringwood conjectured that in the transition region between the upper and lower mantle, at a depth of roughly 500 km (extending to about 150 km), there exists olivine-type material which crystallizes at high temperature and pressure. Olivine is essentially magnesium iron silicates, and similar minerals are called olivines. Later, when scientists discovered a blue olivine-type crystal in meteorites formed due to high temperature and pressure, they christened it ringwoodite.

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The interesting aspect of ringwoodite is that it contains a substantial portion of water (1.5%), more than other minerals. And if it forms at a depth of about 500 km inside the Earth, it is possible that there could be a hidden reservoir of water down there.

There is an indirect evidence for such a hypothesis. Geologists use the data of the propagation of seismic waves in order to determine the inner structure of the Earth. Different types of seismic waves propagate differently through different layers, and so they arrive at various detectors (located at different distances from the epicentre) at different times. The time differences can be used to map the inner structure. Scientists recently used an array of 2000 seismometers across the USA to find that the seismic velocity abruptly dropped at the transition zone between 400–600 km depth, which they interpreted as a sign of this region containing water.

At the same time, researchers worked on ringwoodite in the laboratory, subjecting it to pressure and temperature of the transition zone. The mineral contains water as a part of its molecular structure. But when the temperature and pressure is increased, the crystal can get dehydrated. So they surmised that when this mineral in the transition region sinks down to the lower mantle, it melts by giving away water – a process known as dehydration melting.

If this is true, and the transition region contains even 1% water by mass, then the total amount of 'water' down there would amount to three times the total mass of water in the oceans. But of course, this is not 'water' in liquid form, but trapped inside the molecular structure of olivines. (Although one is reminded of Jules Verne's *Journey to the Centre of the Earth*, which had descriptions of underground sea, and even beaches, but that is not what geologists have discovered.) The burning question of the day now is whether this reservoir of water has anything to do with the birth of oceans, and how is it related to the water cycle we have learned in school – the cycle of evaporation of seawater to clouds and precipitation back to the surface.

Suggested Reading

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