Aquarian Comets: the Origin of the Oceans

When comets such as Hale-Bopp pass close to the Earth they bring clues to the origins of the solar system; and like all great travellers they tell stories of lost worlds before heading off again to distant places. But comets might have brought much more than tales. They might have brought the right conditions for the origin of life itself

In an edited version of a talk given at Uppsala University, Sweden in May **Hans Rickman** describes how comets might have brought the oceans from distant parts of the solar system and, opposite, a brief report of the latest on the theory

This picture of comet Hale-Bopp was taken on 27 March 1997 at Landeryds observatory, Linköping, Sweden, using Elite Kodak II film, speed 400 ASA, with 58 mm objective and 60 seconds exposure time (Lennart Samuelsson)

"Consider me, standing in front of a table, as being the Sun (or the protosun). The surface of the table is a small part of a much larger disk, with the real size of the planetary system, or rather the solar nebula. It is composed of gas and very small solid particles. Anyone sitting around the table may be considered as markers of different parts of the solar nebula, from which the planets Saturn, Jupiter, the Earth *etc* arose. The nebula, and therefore also you and me because we are built from it, consists basically of the same type of material or combination of elements. However, there are important differences and they depend upon the temperature at different places in the nebula. Examples are the Earth at 700°C, an asteroid at 200°C, Jupiter at -50°C and Saturn at -100°C.

Why do I give such high temperatures, much higher than today at the corresponding sites? The rotating disk is an enormous engine in which gas streams are hitting each other, merging and slowing down if they have different speeds. The disk nebula is not rotating as a solid body like a wheel, but like a whirlpool with different angular velocities at different distances from the centre just as with our planets. The period for Mercury is only 88 days but Saturn needs nearly 30 years for one revolution.

The gas in the nebula spirals slowly toward the centre, the protosun. The protosun becomes heavier and its temperature rises as potential energy is converted into kinetic energy. In this collecting engine there is no efficient cooling so the temperature rises to high values. Finally the gas where I stand is hot enough to start fusion reactions in which hydrogen atoms are combined into helium. Our star is born, 4.6 billion years ago.

Important clues about the past history of our solar system come from meteorites, falling to the ground from time to time. Most of them consist of a mixture of particles from the solar nebula. However, different mixtures of materials are found. These depend on chemical reactions at different temperatures in the solar nebula. Some of the meteorites found on Earth can only have been formed at even higher temperatures than 200°C and others were solidified at lower temperatures. Most meteorites today come from the asteroid belt, in which a certain separation is observed so that asteroids containing the 'hotter' materials occupy its inner part and those hosting lower temperature condensates dominate the outer parts.

The particulate material in the early solar nebula slowly aggregated and formed the planets. Asteroids are relics of that process. At the place where the Earth was formed, the material consisted of a hotter assemblage of rock and metal than in the asteroid belt. Such stones do not contain any water – the meteorites coming from the inner part of the asteroid belt also do not contain water but the colder asteroids from the outer parts of the belt do contain some water.

It is doubtful if there was any water vapour at the place in the solar nebula where the Earth formed. Perhaps nearly all the oxygen of the solid phase was bound to metals and silicon oxides, and the rest mainly in gaseous carbon monoxide. Perhaps most of the carbon was fixed in that carbon monoxide – a very volatile substance which the Earth had no chance to collect. Only very small amounts of carbon were included in the solid bodies in the form of silicon carbide and microscopic diamonds. And when I say 'perhaps', it is most likely an unnecessary caution. All the evidence supports these state-

But Theory Rolls On

When Rickman gave this talk in May the astrophysics community was coming to believe that comets had brought most of the water in the oceans. But then along came results that said otherwise. The deuterium to hydrogen ratio (D/H), *ie* ratio of heavy to normal water, in the water in comets does not match that in ocean-water.

"There are now three comets for which D/H measurements have been made: Halley, Hyakutake and Hale-Bopp," says Chris Chyba at the Lunar and Planetary Laboratory in Arizona. "All three are Oort cloud comets, not Kuiper belt comets. All three show D/H ratios about twice that of Earth's oceans. On the face of it this suggests less than half of Earth's ocean-water is due to comets. Most could be due to asteroids, some of which (judging from carbonaceous meteorites) have Earth-like D/H ratios."

And it is still possible that among the trillion or so comets not yet observed there are some with an Earth-like D/H ratio. More measurements on comets, especially Kuiper belt ones, should give a clearer picture. While it is probable that comets did bring water, the recent findings now leave astrophysicists looking for a second larger source.

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The planets were built gradually. During the final stage, relatively big protoplanets collided violently. If some of these terrestrial embryos came from more distant sites and therefore may have contained some water, that water most probably was lost due to the shock heating and evaporation at the collision. The conclusion is that the newly born Earth, some 4.5 billion years ago, was dry and sterile and very much depleted in water.

The late arrival of water

So, from where have all the oceans come? And what about the carbon in limestones as well as other carbonates in all living organisms? These two questions are brought together in the following question: "How did life on Earth start?" RNA and DNA, basic frameworks of life, are organic compounds where both carbon and nitrogen are important constituents. In fact, the amino acids, of which RNA and DNA are built, are largely made of these elements. If the Earth had not got an extra supply of carbon and nitrogen it would be difficult to understand how those molecules, so important for life, could have been produced in such abundance that life itself could start. Also, liquid water is considered to be a necessary condition for the environment of life – perhaps not for its origin, but certainly for its further development. The following is a good answer to these questions.

From the zone of the solar nebula where the planet Jupiter was formed and further out, the temperature was so low that ice was included in the solid material. (Oxygen is a very common element in the cosmos, and hydrogen is the most common one.) So, a large amount of H_2O and, at low temperatures, lots of ice were formed. What happens when there is a lot of ice as the material is gathering into ever larger bodies? They become very icy all the way from Jupiter through the other giant planets out to Pluto and the comets.

In a situation where all bodies are built from smaller particles forming larger entities, the comets represent a type of preliminary stage to the giant planets. If we assume such a building principle and calculate the amount of time that would be needed to form a giant planet, we find that the time scale is for Saturn 150×10^6 years, Uranus 400×10^6 years and Neptune 800×10^6 years.

So, in order to build Uranus and Neptune, which largely consist of H_2O, several hundred million years were needed. During that period a lot of comets were thrown around. Calculating the total amount of H_2O ice in such comets and a reasonable percentage of them hitting the Earth, we get (or even exceed) the amount of water that we now have in the oceans.

The water on the Earth may largely have come from comets [*see But Theory Rolls On*]. So what about the carbon and the nitrogen? The comets contain a large amount of organic compounds and these are rich in carbon and nitrogen. RNA is not present as far as we know, and amino acids are still not observed, but certainly there is a large amount of relatively complex organic molecules.

Comets as seeds of life

From a biological point of view, the central question is how the first self-replicating molecules arose. We do not know the composition of the early atmosphere of the Earth. We have long assumed that it was rich in methane and ammonia, *ie* simple hydrides of carbon and nitrogen, and experiments have shown that thunderstorms and lightning discharges might actually have produced enough amino acids from methane and ammonia. But we now know that comets contain very little of these compounds, and most scientists favour an early atmosphere dominated by carbon dioxide. We are therefore justified in seeking a solution based on the comets and their hydrocarbons.

We know that the comets are very fragile. They break up even due to very weak forces. So when comets hit the Earth it is usually only small fragments that enter our atmosphere. Each year we see meteor showers, *eg* the Perseids in August. These incoming particles are only comet trash. We have never experienced a comet nucleus hitting the Earth (thank the Heavens). The impact of a full-scale comet nucleus would cause an explosion that would probably destroy all the organics of the comet. But when comets enter the atmosphere in tiny fragments, their hydrocarbons may survive. We do not know how life on Earth started, but hundreds of millions of years of comet rain would have given plenty of opportunities.

In a million years we might have Chiron here – a comet considered to be the most dangerous object in the solar system

As you might expect from something sent from the Heavens, comets can not only bring life, but take it away. Cometary impactors are not always small. Occasionally in the distant past icy bodies of many kilometres in diameter have hit the Earth. Just look at the Moon (it was in orbit around the Earth already 4.5 billion years ago). Nothing is left of the early lunar surface: it has been destroyed and covered by craters.

The present surface of the Moon records events from about four billion years ago. The most easily recognisable structures are the young lunar maria (dark areas), which formed as giant basins nearly four billion years ago and were filled with up-flowing lava a few hundred million years later. These basins resulted from a series of large bodies hitting the Moon, and they mark the end of a heavy bombardment that lasted for half a billion years.

If giant impacts have produced basins on the Moon, it is hardly likely that the Earth escaped a similar bombardment. Unfortunately, all markings on the Earth's surface from that time are lost. In fact, the oceans may have already existed at the time of the heavy bombardment. What effects would a giant impact then cause on the Earth? Large amounts of rock would be vapourized and reach a temperature of several thousand degrees and a pressure of 100 atmospheres. Due to the high temperature all the water in the oceans would have boiled off within a few months, causing an extra pressure of 300 atmospheres of hot water vapour. The ground would have a temperature of 1200°C and consist of rock-melt. Within 1000 years the temperature would have fallen to a level where rain could start to fall. Heavy rainfall during 2000 years would then have brought the oceans back.

It seems quite safe to say that if life existed before such a collision, all of it would have died. The oldest fossils are 3.5 billion years old (with some evidence of life even 3.8 billion years ago). It thus seems that the start of life somehow was not very unprobable, as it appeared when the planet was still young. It is even possible that several ocean-vapourizing impacts killed existing life forms preceding the present life. If the role of the comets was to bring basic possibilities for life to the Earth, they also may have caused the end of existing life.

Comets have continued to hit the Earth, though less frequently than during the heavy bombardment. Some scientists have claimed that these comets continued to bring life to Earth, but this seems unlikely.

On the other hand, there is a consensus that comets may still bring death to our planet. We have to consider that comets come in all possible sizes, from small particles to large comet nuclei. Nobody has ever been killed by a meteor, nor by a bolide or fire ball (a bolide is associated with an explosion in the atmosphere). But even if these are unusual, some of them are very violent.

Around midsummer of 1908 such an explosion occurred some 7 km above the ground in the Tunguska region in Siberia. No crater was formed, but the forest was felled by a shock hitting from above. In terms of explosive power it was equivalent to a bomb of a few tens of Megatons. Nobody was killed (to my knowledge), mainly because the area was nearly deserted. Such explosions occur about once every few hundred years. It is not unlikely that a densely populated area will be hit at some point. Still, this would be a local disaster as long as the exploding body is only some hundreds of meters in diameter.

But once in several hundred thousand years a kilometre-sized body will hit the Earth. It will cause a crater with a diameter more than 10 km but the formation of the crater is not the most serious hazard. More important are the extended forest fires and the particles, including soot, splashed into the stratosphere. These would trigger a climate change involving the entire Earth and cause casualties of several million people or possibly much more. The impactors in question may be comets or asteroids. The largest individuals of this population, hitting the Earth only once per 100 million years, are the most dangerous ones.

We do not know if it was an asteroid or a comet that hit the Earth 65 million years ago, causing the 200 km big Chicxulub crater on the coast of the Yucatan peninsula in southern Mexico. But most likely this event played a central role in the extinction of the dinosaurs and many other living species. And several other biological mass extinctions also appear to be related to very large impacts.

Remember that Homo sapiens have been on this planet for only a few million years. We have not been around long enough to be seriously exposed to the risk of such a big impact. That risk, from a statistical point of view, may not be very imminent if we look a million years ahead. But of course no one knows when the next collision will come. Within a million years we might have Chiron here.

Chiron is a comet considered to be the most dangerous object in the solar system. It currently has an orbit between those of Saturn and Uranus, but this is unstable and so may become Earth-crossing. The risk for a collision with Chiron is perhaps less than one in a million. But if it would happen, our civilisation would become extinct under a thick atmosphere of vapourized rock. A hundred-meter depth of ocean would evaporate. The heat-shock would sterilise everything down to a depth of 50 m over the entire Earth. Life could only survive at great depths in the oceans or in very deep caves.

We are in the hands of the comets. We should not turn our back on them. But we should go on studying them independently of whether such research will give us knowledge enough to eventually protect us.

This talk was translated by Lennart Samuelsson of Linköping University, Sweden. Hans Rickman is an assistant professor at the Astronomical Observatory, Uppsala University, Sweden.

Further reading

Comets and the Origin and Evolution of Life, eds. **P.J. Thomas, C.F. Chyba, C.P. McKay,** Springer-Verlag, New York 1997