Solar wind origin of terrestrial water

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Abstract

The origin of the Earth water reserves during the evolution of the planet is one of the big miracles in geophysics. Common explanations are storage of water in the Earth mantle at a time when the crust had not yet formed and depositing of water by comets during the time of late heavy bombardement. Both explanations have different problems - especially when comparing with the evolution of Mars and Venus. Here we discuss the possible role of hydrogen collected from the solar wind by the early Earth magnetosphere. While the water production by solar wind capture is very small today it may have been significant during the first billion years after planetary formation because solar wind was much stronger at that time and Earth magnetospheric configuration may have been different. We estimate that the contribution of solar wind hydrogen to the Earth water reserves can be up to 10% when we assume a that the Earth dipole acted as a collector and early solar wind was 1000 times stronger than today. We can not even exclude that solar wind hydrogen was the main contributor to Earth water reserves

1 Introduction

Water is one of the essential ingredients for the evolution of life on a planet. Among the terrestrial planets Earth is unique in its amount of water - stored in its oceans. Still no commonly accepted theory exists on the origin of this water (see for example *Williams* [2007]). According to current models of the formation of our planet Earth formed from the solar nebula about 4.54 billion years ago and its surface remained in a hot fluid magma state for the next 400 million years. In a geological explanation of the origin of water this early magma contained enough hydrogen and oxygen to cause an outgassing of water when the crust of Earth cooled down [*Williams*, 2007].

An astronomical explanation invokes the import of water from comets during the time of late heavy bombardment about 4.1 to 3.8 billion years ago. Both explanations do not agree with the recent discovery of zirconium minerals indicating fluid water on the Earth surface about 4.4 billion years ago [Wilde et al., 2001]. Another problem of both explanations is that - if these explanations hold - both Mars and Venus should harbor amounts of water comparable to Earth which they obviously do not do at present time. A common explanation for this is that Mars and Venus had a similar atmospheric composition after the formation of the planets but have suffered from atmospheric erosion by solar radiation more than Earth [Lammer et al., 2008]. One main reason for the difference in erosion in this explanation is the protection of Earth by its magnetic field. While in the models of atmospheric erosion the ablation of unprotected atmospheres by solar wind impact is regarded as an important factor it has so far not been considered how strong the import of solar wind hydrogen into a large magnetosphere can be. In this short article we will elucidate this factor on the evolution of terrestrial water reserves.

2 Intrusion of protons into the magnetosphere

The effect of a magnetosphere on the solar wind flow is manifold. In the configuration of the Earth magnetosphere as we see it today the magnetic poles are rather close to the rotation axis and do never point parallel to the direction of the solar wind. In this case the magnetosphere acts as a shield but part of the solar wind flux is deflected towards the magnetic poles where particles can penetrate to low altitudes along the field lines. Measurements of the penetrating proton flux have been collected by Hardy et al. [1989] who report mean fluxes of the order of 10²⁴ protons/s penetrating over one pole for current mean solar wind conditions with a variation of one order of magnitude. It is important to note that the total proton flux is linearly dependent on the solar wind intensity and the size of the polar cusp directed towards the sun which can be much larger than a planetary diameter. Another effect which may be important is the storage of solar wind protons in the magnetospheric tail. Part of these protons can also penetrate to low altitudes in magnetospheric storms. Hardy et al. [1989] already realized that these protons can be a significant source of hydrogen at altitudes above 300km. If we now assume that an early planetary atmosphere was rich in carbon-dioxide and oxygen from photo-dissociation the penetrating hydrogen may produce a significant amount of water.

For Venus this collection of protons through a large magnetic cusp never happened since Venus has no internal magnetic field. For Mars we know that the planet had an early magnetic field that probably lasted for several hundred million years. In our model this time span may have been long enough to collect the amount of water which we still see today in the Martian water-ice reserves.

3 Early solar wind intensity

The current solar wind has a mean flow velocity of about 400km/s and an intensity of about 1.0/cm³ at Earth corresponding to a flux intensity of $F = n \times v = 4 \times 10^7 / \text{cm}^2 \text{s}$. The amount of protons impinging on the total magnotospheric cross-section with a diameter of about 10 Earth radii is $F \times A = 5 \times 10^{27} \text{/s}$, where $A = 100 \pi R_E^2 = 1.3 \times 10^{20} \text{cm}^2$. Taking the results of *Hardy et al.* [1989] this means that at current conditions only about 0.1% of the total impinging flux reaches the Earth atmosphere. Taking the proton mass of $m_p = 1.7 \times 10^{-27} \text{kg}$ the current proton mass import is only about $M=0.001\times m_p\times F\times A=0.01$ kg/s. If any two protons react with free oxygen this corresponds to about 0.08kg/s of water or about 2500 tons/year. The total water content of the Earth atmosphere is about 2×10^{13} tons, of the oceans 1.4×10^{18} tons. This means at current solar wind level and magnetospheric configuration the solar proton import can just refill the atmospheric water content over a time span of the age of the solar system. Observations of sun-like stars show that the particle flux from early sun may have been up to 1000 times stronger than the current solar wind for a period of 500-1000 million years after the formation of the solar system (see for example the review by Lammer et al. [2008]).

4 Early Earth magnetic field

While many models of the early Earth predict a lower magnetic field intensity of the Earth, recent observations show that a significant Earth magnetic field existed at least 3.5 billion years old [Tarduno et al., 2010]. If we now assume that the Earth magnetic field configuration was multipolar or its cusp directed more towards the sun the magnetosphere may have acted as a solar wind collector and not as a shield. Taking a cusp cross section of 1 Earth radius in such a geometry would result in a proton flux of $F \times A = 5 \times 10^{25}/\text{s}$ for current solar wind intensity and $F \times A = 5 \times 10^{28}/\text{s}$ for strong early solar wind corresponding to 2×10^8 tons of water per year. Over a time span of 1 billion years the solar proton influx then may have contributed up to 10% of the total Earth water reserves. If we assume that the early Earth magnetic field was even stronger and its cusp directed towards the Sun one can even reach a higher estimate. Since this is only an order of magnitude estimate we can not even exclude that solar wind hydrogen was the main contributor to the Earth water reserves.

5 Deuterium content of planetary waters

The relative deuterium content of planetary water reserves is usually taken as indicator for the amount of lighter hydrogen atoms which have been escaping from the atmospheres over the age of the solar system (see for example [Greenwood et al., 2008] for recent Martian deuterium observations). The current deuterium/hydrogen ratios are 0.015% for Earth, 0.08% for Mars, and 2.0% for Venus, but 0.002% for the solar wind and 0.031% for the few comets where measurements have been possible [Lammer et al., 2008]. If the original deuterium ratio of the Earth water reserves was similar to the cometary one the influx of solar wind protons could explain the lower ratio observed on Earth today.

6 Discussion and conclusions

We have shown that the influx of solar wind protons into the Earth atmosphere may be a significant source of water during the early evolution of the solar system if the Earth magnetosphere acted as a solar wind collector. While for planets without a magnetosphere, like Mars and Venus, the escape of hydrogen and oxygen is usually regarded as higher than the proton influx, this is not so clear for Earth. Only recently *Engwall et al.* [2009] reported that the current hydrogen outflow may be 10^{26} protons/s - significantly higher than the inflow observed by *Hardy et al.* [1989]. But this must not hold for early solar system conditions. Also for other solar system bodies with magnetospheres, for example moons of the outer planets, the collection of ions through magnetospheric cusps may be an important source of atmospheric particles.

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