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EARTH'S HABITABLE LOOP: WATER, ATMOSPHERIC STRUCTURE, THE GEOMAGNETIC FIELD AND PLATE TECTONICS

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Complex and intelligent life developed on Earth because it has retained sufficient water, primarily in liquid form, for several billion years. The loss of Earth's water to outer space is limited by a cold trap at the top of its thick troposphere. Earth maintains a thick troposphere because the dipolar geomagnetic field deflects the solar wind, preventing ionized particles from heating the upper atmosphere and lowering the tropopause. Earth's magnetic field is sustained by the dynamo action of convective motions within the outer core, which require a large flux of heat from core to mantle. Plate-tectonics, which provides the required rate of planetary cooling over billions of years, requires the presence of liquid water to make the plates ductile and to lubricate the plate boundaries. The sustained, coupled interaction of liquid water, atmospheric structure, the geomagnetic field and plate tectonics forms a feedback-loop which maintains Earth's long-term habitability.

Keywords: Earth's habitability; geomagnetic field; plate tectonics; solar wind; upper atmosphere; water

It is generally agreed that the key factor in the habitability of Earth is the presence of liquid water on and near the surface. This requires the delivery of a suitable inventory of water as Earth formed, retention of nearly all that inventory for several billion years and climate stability such that much of the water remains liquid. A key factor in the retention of Earth's inventory of water, and a necessary prerequisite for the development of intelligent life, is the sustained maintenance of a feedback loop involving liquid water, atmospheric structure, the geomagnetic field and plate tectonics.

Water is lost from Earth (at a current rate about 1 mm/Ma) primarily by photo-dissociation of water molecules within the stratosphere, followed by escape of

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hydrogen to outer space. The loss rate is limited by the cold trap at the top of the troposphere, where the mean temperature is roughly $-50°$C. This temperature is set by the effective mean height of the tropopause ($\sim$10 km), coupled with an adiabatic lapse rate of $-6.5°\mathrm{C\ km}^{-1}$ and a mean surface temperature of 15°C. Throughout Earth history, the surface temperature has been sufficiently low and the troposphere has been sufficiently thick that very little water reached the stratosphere and the rate of water loss remained small.

The thickness of the troposphere is limited by heating within the upper atmosphere, due principally to the absorption of solar UV radiation by ozone. This heating is relatively weak and occurs at high altitude, giving a thick troposphere and an effective cold trap for water. If a stronger source of heating were present, the troposphere would be thinner and the tropopause would be warmer, making the cold trap less effective and increasing the rate of water loss.

In fact, a stronger source of heating is available: ionized particles carried by the solar wind. However, virtually all of these particles are prevented from reaching the atmosphere by the geomagnetic field. If the geomagnetic field were significantly weaker or were predominantly non-dipolar (as likely occurs during reversals), energetic ions from the solar wind would reach into the upper atmosphere, providing a significant source of heating that would thin the troposphere and permit a much greater rate of loss of water from the planet by both thermal and non-thermal processes, particularly early in solar-system history when the solar wind was much stronger (DeHant et al. 2007, Kulikov et al. 2006, 2007, Lundin et al. 2007). Surprisingly little attention has been paid to this water-loss mechanism for Earth, likely because it is hypothetical. However, mechanisms such as photochemical escape, pick-up ion sputtering and solar-wind scouring have been investigated in connection with water and atmospheric loss on Venus and Mars (Kulikov et al. 2006, 2007, Lundin et al. 2007). In particular, Chassefière (1997) noted that in the case of Venus "... a terrestrial-type ocean was completely lost in $\sim$10 million years ..." during the solar T-Tauri phase, because that planet lacked a magnetic field. The important point is that Earth has retained its inventory of water because the geomagnetic field has kept the solar wind at bay throughout most — if not all — of Earth history.

It is known from paleomagnetism that Earth has possessed a strong dipolar magnetic field for at least the past 3.5 Ga. No paleomagnetic record of the field exists prior to that time because no rocks have been preserved from that interval of Earth history. However, given that the amount of power available to the geodynamo, which sustains the geomagnetic field, was significantly greater early in Earth history (associated with a larger cooling rate), it is quite reasonable to assume that Earth always has had a strong, dipolar field.

The geomagnetic field is the result of dynamo action of fluid motions within Earth's liquid outer core. These motions stir the liquid outer core vigorously, maintaining it in a state very close to adiabatic. The metallic outer core is a good conductor of heat and the flux of heat that is conducted down the adiabatic thermal gradient in the core and transferred to the mantle ($\sim$3.8 terawatts (Stacey and Loper 2007)) is roughly 1/10 of the surface flux. This heat loss is the 'cost of doing

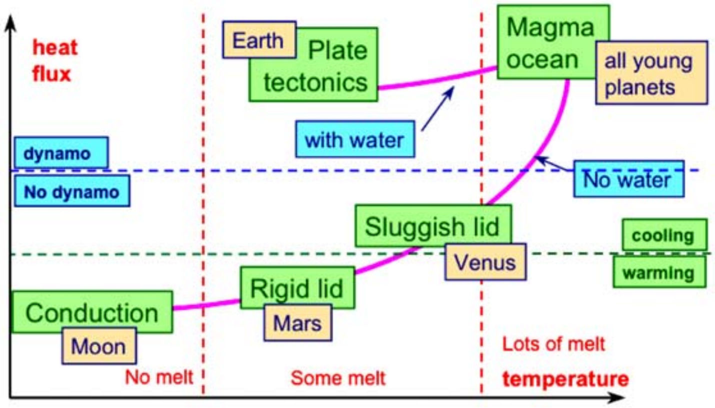

Fig. 1. A schematic plot of planetary heat flux versus temperature, showing a branch having lower flux in the absence of water and a plate-tectonic branch, with water, having higher flux. Our solar system currently provides examples of all modes of cooling, save the magma-ocean mode. Planets having heat flux smaller than the rate of radioactive heating will become warmer with time. Large heat flux is necessary for dynamo action and preservation of water

business' for the geodynamo; if the rate of core heat loss were to fall below this value, the dynamo very likely would cease to operate.

Sources of heat within the core include primordial heat released during planetary accretion and core formation, radioactive heating and latent heat and compositional separation as the inner core grows, together with the release of gravitational potential energy as the core cools and contracts. Including all these sources, the effective specific heat of the core is about 1700 J kg^{-1} K^{-1} (Loper 2007). With the core having a mass of 1.94 10^{24} kg, the conductive heat loss could have been provided by the core having cooled less than 200 K over its lifetime. While this is a modest drop in temperature compared with the potential temperature of the core ($\sim$3800 K), the rate of cooling is in fact quite rapid, given that the core is encased in a poorly conducting silicate mantle.

The heat flux from the core must be removed by mantle convection, which also serves to carry primordial and radioactive heat from the mantle to the surface. Of the five possible modes of planetary cooling, three (conduction, rigid-lid convection, sluggish-lid convection) are incapable of conveying heat to the surface sufficiently rapidly to sustain dynamo action in the core. On the other hand, the magma- or mush-ocean mode of convection cools the planet rapidly and cannot persist for longer than several Myr (Zahnle et al. 2007). Only plate tectonics provides a sustained large flux of heat to the planetary surface; see Fig. 1, which has been adapted from Sleep et al. (2000) and is similar to Fig. 2 by van Thienen (2007). It follows that a planetary dynamo requires plate tectonics. There is strong evidence that Mars had a dynamo and plate tectonics early in its history, but soon lost both (DeHant et al. 2007, Nimmo and Stevenson 2000).

The most likely reason that plate tectonics ceased on Mars is the loss of liquid water which is essential for plate tectonics. Water penetrates cracks within the oceanic crust, primarily near spreading centers, forming hydrated minerals, partic-

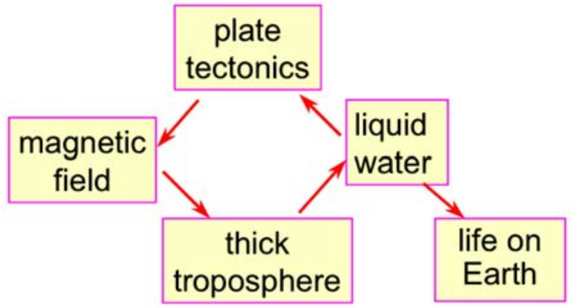

Fig. 2. An illustration of the relationships among water, atmospheric structure, geomagnetic field and plate tectonics, forming a habitable loop. Liquid water is necessary for the plate tectonic mode to operate, plate tectonics permits the sustained large planetary heat flux necessary for the operation of the geodynamo and the existence of the dipolar magnetic field over most of Earth history. This field shields the atmosphere from solar-wind heating, preserving Earth's inventory of water

ularly lawsonite and serpentine (Williams and Hemley 2001). These minerals make the oceanic lithosphere more ductile, permitting plates to bend rather than break at subduction zones (Conrad and Hager 1999). If the plates were to break, slab pull would not be transmitted to the horizontal portion of the plate and plate tectonics would cease. In addition, subducted hydrated minerals convey water to depths of 100 to 200 km (Franck and Bounama 2001), where they decompose upon heating, releasing water which lubricates the slip zone between the subducting and non-subducting plates. Without this effect, the plates would lock up and plate tectonics would cease (Regenauer-Lieb et al. 2001). If in the future the plate-tectonic mode cannot be sustained, Earth may adopt the sluggish-lid mode of convection, similar to Venus, or even the rigid-lid mode, similar to Mars. In either case, the dynamo would cease and the geomagnetic field would rapidly decay.

To summarize, preservation of water requires a thick troposphere, a strong magnetic field is necessary to prevent solar-wind heating from thinning the troposphere, the magnetic field requires a large heat flux from the planet, this large flux can only be sustained by plate tectonics and plate tectonics requires the presence of liquid water. These dependencies form Earth's habitable loop, necessary to sustain life, as illustrated in Fig. 2.

The ideas presented in this paper are necessarily somewhat speculative, as much of the research required for firm substantiation remains to be completed. Key questions to be addressed include: What would the thermal structure of Earth's atmosphere be if the geomagnetic field were absent? How would this structure depend on the strength, variability and character of the solar wind? How rapidly would Earth be losing water now if the geomagnetic field were absent? If Earth had not had a magnetic field during the Sun's T-Tauri phase, how much water would have been lost? How sensitive is the longevity of the plate tectonic mode to the size of a planet and its initial inventory of radioactive elements and of water? How long is the plate-tectonic mode expected to last on Earth, and what would be its mode of failure?

In addition to clarifying the operation of Earth as a habitat for life, answers to these questions will illuminate the prevalence of life-sustaining planets elsewhere within our galaxy. In recent years it has become clear (e.g., see Ward and Brownlee 2000, Burger 2003) that Earth, rather than being a typical planet orbiting an ordinary star within our galaxy, is in fact a very special place which has remained habitable for the billions of years required for the evolution of intelligent life. Maintenance of a habitable loop may be an essential ingredient in the long-term survival of life on Earth and possibly on other — as yet undiscovered — planets.

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