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A PROPOSAL FOR CLIMATE STABILITY ON H₂-GREENHOUSE PLANETS

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Abstract

A terrestrial planet in an orbit far outside of the standard habitable zone could maintain surface liquid water as a result of H₂–H₂ collision-induced absorption by a thick H₂ atmosphere. Without a stabilizing climate feedback, however, habitability would be accidental and likely brief. In this letter I propose stabilizing climate feedbacks for such a planet that require only that biological functions have an optimal temperature and operate less efficiently at other temperatures. For example, on a planet with a net source of H₂ from its interior, H₂-consuming life (such as methanogens) could establish a stable climate. If a positive perturbation is added to the equilibrium temperature, H₂ consumption by life will increase (cooling the planet) until the equilibrium climate is reestablished. The potential existence of such feedbacks makes H₂-warmed planets more attractive astrobiological targets.

Keywords

astrobiology; planets and satellites: atmospheres

1. INTRODUCTION

The traditional definition of planetary habitability is the ability of a planet to maintain liquid water at its surface. For a planet to be of astrobiological interest, it must maintain habitability for timescales relevant for biological macroevolution (at least tens of millions of years). Earth has been able to maintain habitable conditions for most of the last four billion years despite the solar flux increasing by about 50% over that period (Sagan & Mullen 1972). A possible explanation for this is the silicate-weathering feedback, which would regulate the atmospheric CO₂ in such a way as to maintain habitable conditions as other forcings, such as solar flux, varied (Walker et al. 1981). The silicate-weathering feedback is also essential for the standard habitable zone. The standard habitable zone is defined as the circumstellar region where an Earth-like planet (having both land and ocean, volcanism, and a predominantly N₂–CO₂–H₂O atmosphere) could maintain habitable conditions, assuming the functioning of the silicate-weathering feedback (Kasting et al. 1993).

Recent work has pointed out that planets outside of the standard habitable zone with thick H₂ atmospheres could maintain surface liquid water due to the greenhouse effect of H₂–H₂ collision-induced absorption (Stevenson 1999; Pierrehumbert & Gaidos 2011). This is noteworthy because many terrestrial planets larger than Earth (super-Earths) have been

detected, and calculations suggest that they could retain an H₂ atmosphere (against escape to space) for billions of years. Potential biosignatures on this type of planet have already been investigated (Seager et al. 2013). The habitability of such a planet, however, would be transient or accidental in the absence of some stabilizing feedback (Wordsworth 2012), rendering such planets significantly less interesting places to search for life.

Wordsworth (2012) notes that the reducing atmosphere of an H₂-greenhouse planet would produce pre-biotic compounds that would favor the origin of life and speculates that this life could evolve mechanisms to regulate the H₂ pressure and maintain habitable surface conditions. This is in contrast with Pierrehumbert & Gaidos (2011), who write that the evolution of life on an H₂-greenhouse planet would likely lead to the consumption of H₂ and the destruction of the atmosphere (and habitability). A factor that could affect this conclusion of Pierrehumbert & Gaidos (2011) is that it seems likely that the destruction of H₂, which supports the conditions that allow life, by life itself would inherently be self-limiting. The arguments in this letter will be built around this idea.

The purpose of this letter is to propose specific biological feedbacks that could maintain habitable conditions on a planet with an H₂-dominated atmosphere and greenhouse warming provided primarily by H₂-H₂ collision-induced absorption. Such feedbacks would allow the habitable zone for this type of planet to extend to very large distances from its host star, greatly expanding the list of attractive candidates for biosignature searches. This work is speculative, yet I think worthwhile because I approach it by making a minimum of reasonable assumptions and following them to their logical conclusion. I will begin by outlining the critical assumptions made in this letter (Section 2). Next I will show how a stabilizing feedback would work on planets with a net source of H₂ from the interior to the atmosphere (Section 3) and on planets with a net loss of H₂ to space (Section 4). Finally, I will discuss these results (Section 5) and conclude (Section 6).

2. IMPORTANT ASSUMPTIONS

The most important assumption I will make is that biological processes are temperature-dependent such that there is a maximum rate of functioning at some temperature (and consequently functioning decreases at temperatures above or below this temperature, Figure 1). This assumption describes the behavior of many terrestrial biological systems, and it is difficult to think of a realistic biological system that would not obey it. An illustrative functional form that describes this type of temperature dependence is

$$F(T) = F_0 \frac{(T - T_1)[(T_2 - T_1) - (T - T_1)]}{(T_2 - T_1)^2}, \quad 1$$

where $F(T)$ is the rate of functioning (which will correspond to production or destruction of H₂ in this letter), F_0 is a base functioning rate dependent on factors such as nutrient availability, T_1 is the minimum temperature for the biological function, and T_2 is the maximum temperature for the biological function. I will assume that the biological function does not operate outside of the temperature range $T_1 \leq T \leq T_2$.

I will also assume that we are considering planets distant enough from their host star that they have a very low emission temperature (60 K or lower). In such cases H_2 is optically thick near the radiating temperature, and other greenhouse gases such as CO_2 , CH_4 , and H_2O are effectively not present at that atmospheric pressure because their vapor pressure is too low (Pierrehumbert & Gaidos 2011). These gases therefore cannot affect the outgoing longwave radiation. It is a reasonable approximation to take the adiabatic lapse rate as independent of these minor constituents, so that H_2 is the only greenhouse gas relevant for determining the surface temperature.

3. PLANETS WITH A NET HYDROGEN SOURCE FROM THE INTERIOR

I will first consider planets with a net source of hydrogen from their interior, either from direct outgassing or as a result of serpentinization. One example would be an Earth-like planet with a large hydrogen envelope in interstellar space (Stevenson 1999). If such a planet has the right amount of H_2 for liquid water on its surface, then life can evolve on it. One likely option is that methanogenic life (henceforth methanogens) will take advantage of available H_2 through a reaction such as

consuming H_2 in the process. The CO_2 in Equation (2) could be outgassed from the interior if it is relatively oxidized, or it could be left over from formation. It is also possible that life could reduce some element other than carbon to obtain energy. What is important is that H_2 is consumed during the process. If we assume that these methanogens function with a temperature dependence given by Equation (1), then we can write the following equation for the time derivative of the hydrogen pressure

$$\frac{dp_{H_2}}{dt} = P_0 - 4L_0 \frac{(T - T_1)[(T_2 - T_1) - (T - T_1)]}{(T_2 - T_1)^2} \quad 3$$

where P_0 is the background source rate of H_2 from the interior, and L_0 is the scale of H_2 consumption by methanogens, which is dependent on factors such as nutrient availability. I have inserted the factor of four in Equation (3) for later mathematical convenience.

The assumption that H_2 is the only greenhouse gas that affects outgoing longwave radiation (Pierrehumbert & Gaidos 2011) leads to an equation yielding the mean surface temperature as a function of the H_2 pressure. Following the fit to radiative calculations given in Wordsworth (2012), I will use the following equation:

$$\frac{1}{4}(1 - \alpha)S_0 + F_{\text{geo}} = ap_{H_2}^{-1}T^4, \quad 4$$

where T is the planetary surface temperature, α is the planetary albedo, S_0 is the stellar constant, F_{geo} is the geothermal heat flux, and a is a constant that is defined slightly differently here than in Wordsworth (2012). For an Earth-gravity planet, $a = 7.3 \times 10^{-9} \text{ W m}^{-2} \text{ K}^{-4} \text{ Pa}$. The exponent of p_{H_2} in Equation (4) is actually slightly different from negative one. I approximate it as negative one because doing so simplifies the mathematics and does not change the qualitative behavior of the system. I assume that the planetary albedo is constant, which also does not change the qualitative behavior of the system since increasing p_{H_2} leads to significantly more greenhouse warming than it increases Rayleigh scattering (Wordsworth 2012), particularly for planets in distant orbits.

Let us define $F = \frac{1}{4}(1 - \alpha)S_0 + F_{\text{geo}}$ and assume that F is constant on the timescale of biological adjustment of H_2 (we will revisit this assumption in Section 5). We can then linearize Equation (4) around T_1 and take the time derivative to find that

$$4aT_1^3 \frac{dT}{dt} = F \frac{dp_{\text{H}_2}}{dt}, \quad 5$$

when $T \approx T_1$. By combining Equations (3) and (5), defining a nondimensional temperature $\phi = \frac{T - T_1}{T_2 - T_1}$, defining a nondimensional time $\tau = t \frac{L_0 F}{4aT_1^3(T_2 - T_1)}$, and defining a

nondimensional hydrogen outgassing rate $\beta = \frac{P_0}{L_0}$, we find the following nondimensional equation for surface temperature of the planet

$$\frac{d\phi}{d\tau} = \beta - 4\phi(1 - \phi). \quad 6$$

When $\beta < 1$, Equation (6) has two steady-state solutions (fixed points, Figure 2). The solution with $\phi < 0.5$ is stable and the solution with $\phi > 0.5$ is unstable. The stable solution is associated with the increase in methanogenic H_2 consumption with temperature at low temperatures (Figure 1). If some perturbation increases the planetary temperature from its equilibrium value, methanogens consume H_2 more efficiently (reducing the greenhouse effect and cooling the planet) and decrease the temperature back to its stable steady-state value. By this mechanism an H_2 -greenhouse planet with a net source of hydrogen from its interior can maintain climate stability against changes in the stellar flux or geothermal heat flux on geological timescales if methanogens have evolved on it. If β is increased above one, a bifurcation occurs and the system no longer has any fixed points. Instead, the temperature increases indefinitely. This corresponds to a hydrogen outgassing rate so high that methanogens cannot consume H_2 fast enough to allow a stable steady-state climate. Such a situation could perhaps be due to nutrient limitation of the methanogen population.

4. PLANETS WITH NET HYDROGEN LOSS TO SPACE

Let us now consider a planet with a net loss of hydrogen to space. One example might be a distant H₂-greenhouse planet orbiting an active young star. Let us assume that as the surface conditions evolve on our hypothetical planet as a result of H₂ loss to space, habitable conditions are reached, and life evolves (Wordsworth 2012). Some H₂-greenhouse planets could have enough photosynthetically active radiation reach their surface to sustain photosynthesis (Pierrehumbert & Gaidos 2011). Let us assume that a biosphere evolves on the planet that is capable of producing biomass through photosynthesis that releases H₂ as a byproduct. The following reaction is one example of this type of photosynthesis

where “CH₂O” likely represents more complex organic molecules on which carbon has a net oxidation state of zero. On this reduced planet photosynthesis would use solar energy to oxidize carbon and produce biomass. It is also possible that methanogens would evolve that would consume H₂ through Equation (2) or by running Equation (7) backwards (a reducing kind of respiration) to obtain energy by reducing organic carbon, leading to cycling between H₂ production and destruction. We can think of Equation (7) as either the only relevant reaction, or we can imagine that it is the net effect of photosynthesis, methanogenic H₂ consumption, and either the burial or other disposal of organic matter. Since we are considering a habitable planet, it is reasonable to assume that there is abundant H₂O on the surface. I will assume that CH₄ is obtained from the planetary interior through outgassing, or potentially through serpentinization reactions if CO₂ is preferentially outgassed (Oze 2005). The latter process uses H₂ to create CH₄, so for the feedback I will describe to function it would have to create an overabundance of CH₄ which Equation (7) could then convert back to H₂ as needed.

Following similar logic to that in Section 3, including assuming that biological production of H₂ by Equation (7) has temperature dependence given by Equation (1), we can derive the following equation for the time derivative of the hydrogen pressure on such a planet

$$\frac{dp_{\text{H}_2}}{dt} = 4P_0 \frac{(T - T_1)[(T_2 - T_1) - (T - T_1)]}{(T_2 - T_1)^2} - L_0, \quad 8$$

where L_0 is the net loss of H₂ to space unrelated to biological H₂ production and P_0 is the scale of biological H₂ production. L_0 is increased by thermal and hydrodynamic escape to space, large meteorite impacts that knock some atmosphere off the planet, and solar wind. L_0 is decreased by fluxes of H₂ from the interior to the atmosphere as a result of direct outgassing and serpentinization. I will assume that L_0 does not depend on surface temperature.

We can combine Equation (8) with Equation (5) and nondimensionalize to find

$$\frac{d\phi}{d\tau} = 4\phi(1 - \phi) - \gamma, \quad 9$$

Where $\phi = \frac{T - T_1}{T_2 - T_1}$ is again the nondimensional temperature, $\tau = t \frac{P_0 F}{4aT_1^3(T_2 - T_1)}$ is the nondimensional time, and $\gamma = \frac{L_0}{P_0}$ nondimensional loss rate of hydrogen to space.

For $\gamma < 1$ the system has two fixed points (Figure 3). The fixed point with $\phi > 0.5$ is stable, which means that if the planet occupies this fixed point and is perturbed away from it, it will tend to return to its original temperature. This stable fixed point is associated with the loss of efficiency of biological H_2 production at higher temperatures (Equation (1)). If the planet occupies this fixed point and some perturbation leads to an increase in surface temperature, the biological production of H_2 will decrease, which will decrease the H_2 pressure (Equation (8)) and therefore decrease the surface temperature back toward its starting point (Equation (4)). As long as the net loss of hydrogen to space is low enough ($\gamma < 1$), the planet will be stable against secular perturbations (e.g., increases in stellar flux) and random perturbations (e.g., random changes in outgassing that lead to changes in L_0) as long as they are small enough that the system is not perturbed beyond its unstable fixed point. If, however, the net loss of hydrogen to space becomes too large ($\gamma > 1$), the system has no fixed points (Figure 3) and the atmosphere simply collapses as a result of H_2 escape to space, leading to permanent loss of habitability. This could result from either nutrient limitation of biological capacity, or an excessively high base rate of H_2 loss to space.

5. DISCUSSION

The model I have derived here assumes that biological functions can adjust H_2 faster than the 10^8 – 10^9 year timescale that stellar and geothermal heat fluxes change. We will now examine this assumption. For a planet with a net hydrogen source from the interior (Section 3), the adjustment timescale is $\frac{4aT_1^3(T_2 - T_1)}{L_0 F}$. Let us assume that biological consumption of

H_2 is on the same scale as the interior flux ($L_0 \approx P_0$) and set the hydrogen outgassing rate to a reasonable value of $10^{10} H_2$ molecules $cm^{-2} s^{-1}$ (Haqq-Misra et al. 2011), or $3 \times 10^{-12} Pa s^{-1}$ for Earth's gravity. Let us also assume that the solar plus geothermal heat flux input (F) is on the order of $1 W m^{-2}$, $T_1 = 300 K$, and $T_2 - T_1 = 100 K$. With these assumptions, we arrive at a timescale of $\approx 10^6$ years, or a couple orders of magnitude smaller than the timescale of changes in the forcings.

The feedbacks discussed in this letter clearly will not work for every H_2 -greenhouse planet. Among other issues, for some planets the chemistry will not be correct, and for others there will be limited amounts of necessary nutrients for biological functions. This is analogous to the habitability of terrestrial planets in the Solar System, only one of which appears to possess stabilizing feedbacks capable of maintaining a habitable climate over long time periods. Nevertheless, it is significant that stabilizing climate feedbacks on an H_2 -

greenhouse planet result naturally merely from assuming the existence of life processes that either consume or produce H_2 at a rate that has a maximum as a function of temperature.

The key to detecting a stabilizing climate feedback on a planet with an H_2 -greenhouse planet would be to measure the H_2 surface pressure (a difficult task) and compare it to what would be necessary to maintain a habitable surface temperature. If a single planet were found with the correct amount of H_2 and some sort of biosignature (Seager et al. 2013), this would be weak evidence that a stabilizing climate feedback could exist on that planet. Alternatively, if it is eventually found that an unexpectedly large number of H_2 -greenhouse planets orbiting far from their stars have the right amount of H_2 to support habitable surface conditions, a statistical argument could be made that some sort of climate-stabilizing feedback (potentially related to the ones described here) exists on those planets.

An interesting possibility is that an H_2 -greenhouse planet might actually exhibit both forms of climate stability discussed in this letter over its lifetime. For example, a planet might receive a high XUV flux from its star early in its life, causing significant H_2 escape to space, and maintain climate stability through H_2 production by life (Section 4). Later as the star becomes less active, there might be a net source of H_2 to the atmosphere from the interior, and the planet might maintain climate stability through H_2 production by life (Section 3).

I have neglected many processes in this letter. This is appropriate in a letter that proposes a simple idea about a system for which there are currently few constraints. Nevertheless, it might be interesting to extend this work including consideration of the effects of clouds and the effects of minor constituent gases on the atmospheric temperature profile. Another issue that could be considered is how atmospheric chemistry would affect the feedbacks described here (e.g., Batalha et al. 2015), although at distant orbits photochemical effects would be minimal. Finally, more work could be done on biological issues such as the specific nutrients that might be important to life on an H_2 -greenhouse planet and how entropic waste would be dealt with.

6. CONCLUSIONS

I have shown that stabilizing climate feedbacks on H_2 -greenhouse planets in distant orbits result from the simple assumption of the existence of biological processes that either consume or produce H_2 at a rate that has a maximum as a function of temperature. Since this assumption is not restrictive, it is possible that such planets could remain habitable on geological timescales, making them more attractive candidates for biosignature searches. I hope this work encourages more thought on stabilizing feedbacks for the climate of distant planets with habitable conditions supported by H_2 atmospheres.

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Figure 1.

These are example curves of normalized biological functioning (e.g., production or destruction of H_2) as a function of planetary surface temperature. The solid curve shows the relation plotted in Equation (1), which is symmetric around the temperature of maximum biological functioning. The dotted curve represents an alternative temperature dependence of biological functioning in which the decrease in efficiency at high temperatures is steeper than the increase in efficiency at low temperatures. In this letter I use the symmetric curve because it simplifies the mathematics, but the asymmetric curve is more realistic in many cases and will yield qualitatively similar results.

Figure 2.

Diagrams showing the nondimensional rate of change of temperature ($\frac{d\phi}{d\tau}$) of an H_2 -greenhouse planet with a net source of hydrogen from its interior as a function of the nondimensional temperature (ϕ) for two different values of the nondimensional hydrogen outgassing rate (β). Arrows along the $\frac{d\phi}{d\tau} = 0$ line indicate the flow direction of ϕ , as determined by the sign of $\frac{d\phi}{d\tau}$. Circles where $\frac{d\phi}{d\tau}$ intersects zero for $\phi < 1$ (in the top panel) are fixed points, and represent temperatures where the climate achieves an equilibrium. The open circle is an unstable fixed point, and the filled circle is a stable fixed point. The climate returns to the stable fixed point when it is perturbed away from it. If β is increased above one (bottom panel), a bifurcation occurs and the system no longer has any fixed points. If the asymmetric biological temperature dependence curve from Figure 1 were used, the qualitative behavior would be the same, but the stable and unstable fixed points would not be symmetric around $\phi = 0.5$.

Figure 3.

Diagrams showing the nondimensional rate of change of temperature ($\frac{d\phi}{d\tau}$) of an H_2 -greenhouse planet with net loss of hydrogen to space as a function of the nondimensional temperature (ϕ) for two different values of the nondimensional loss rate of hydrogen to space (γ). Arrows along the $\frac{d\phi}{d\tau} = 0$ line indicate the flow direction of ϕ , as determined by the sign of $\frac{d\phi}{d\tau}$. Circles where $d\phi/d\tau$ intersects zero for $\beta < 1$ (in the top panel) are fixed points, and represent temperatures where the climate achieves an equilibrium. The open circle is an unstable fixed point, and the filled circle is a stable fixed point. The climate returns to the stable fixed point when it is perturbed away from it. If γ is increased above one (bottom panel), a bifurcation occurs and the system no longer has any fixed points. If the asymmetric biological temperature dependence curve from Figure 1 were used, the qualitative behavior

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