Hydrogen Greenhouse Planets beyond the Habitable Zone

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ABSTRACT

We show that collision-induced absorption allows molecular hydrogen to act as an indescribable greenhouse gas, and that bars or tens of bars of primordial H$_2$-He mixtures can maintain surface temperatures above the freezing point of water well beyond the “classical” habitable zone defined for CO$_2$ greenhouse atmospheres. Using a 1-D radiative-convective model we find that 40 bars of pure H$_2$ on a 3 Earth-mass planet can maintain a surface temperature of 280K out to 1.5AU from an early-type M dwarf star and 10 AU from a G type star. Neglecting the effects of clouds and of gaseous absorbers besides H$_2$, the flux at the surface would be sufficient for photosynthesis by cyanobacteria (in the G star case) or anoxogenic phototrophs (in the M star case). We argue that primordial atmospheres of one to several hundred bars of H$_2$-He are possible, and use a model of hydrogen escape to show that such atmospheres are likely to persist further than 1.5 AU from M stars, and 2 AU from G stars, assuming these planets have protecting magnetic fields. We predict that the microlensing planet OGLE-05-390L could have retained a H$_2$-He atmosphere and be habitable at ~2.6 AU from its host M star.

Subject headings: astrobiology — planetary systems

1. Introduction

In the circumstellar habitable zone (HZ), an Earth-like planet has surface temperatures permissive of liquid water (Hart 1979). The HZ is typically calculated assuming an H$_2$O-CO$_2$ greenhouse atmosphere. At its inner edge, elevated water vapor leads to a runaway greenhouse state; at the outer edge, CO$_2$ condenses onto the surface. The HZ of the Sun is presently 0.95-2 AU but is much more compact around less-luminous M dwarfs (Kasting et al. 1993). Most reported Earth-size exoplanets are well starward of the HZ because the Doppler and transit detection techniques are biased towards planets on close-in orbits (Gaidos et al. 2007). The Kepler mission can detect Earth-size planets in the HZ of solar-type stars (Koch et al. 2010; Borucki et al. 2011) but these cannot be confirmed by Doppler. In contrast, the microlensing technique, in which a planet around a foreground gravitational lensing star breaks the circular symmetry of the geometry and produces a transient peak in the light curve of an amplified background star, is sensitive to planets with projected separations near the Einstein radius of their host star, e.g. ~3.5 AU for a solar mass. Surveys have found planets as small as 3M$_\oplus$ (Bennett et al. 2008) and projected separations of 0.7-5 AU (Sumi et al. 2010). Most microlensing-detected planets orbit M dwarf stars as these dominate the stellar population. The Einstein radius of these stars is well outside the classical HZ (Sumi et al. 2010; Kubas et al. 2010) but
coincides with the “ice line” where Neptune-mass or icy super-Earth planets may form (Gould et al. 2010; Mann et al. 2011).

The effective temperatures of microlensing planets around M stars will be below the condensation temperature of all gases except for H\(_2\) and He. These mono- and di-atomic gases lack the bending and rotational modes that impart features to the infrared absorption spectra of more complex molecules. At high pressure, however, collisions cause H\(_2\) molecules to possess transient dipole moments and induced absorption. The resulting greenhouse effect can considerably warm the surface. Stevenson (1999) conjectured that “free-floating” planets with thick H\(_2\)-He atmospheres might maintain clement conditions without benefit of stellar radiation. Around a star, an H\(_2\)-He atmosphere might admit visible light to the surface; these planets could, in principle, host photosynthetic life.

We demonstrate that H\(_2\) and He alone can maintain surface temperatures above the freezing point of water on Earth- to super-Earth-mass planets beyond the HZ. In §2 we describe calculations of a radiative-convective atmosphere and its transmission of light; results are given in §3. In §4 we estimate the amount of H\(_2\) gas that a planet may accrete from its nascent disk, and the amount lost back to space. Finally, we discuss the effects of other gases and a candidate H\(_2\) greenhouse planet detected by microlensing (§5).

2. Calculation of radiative fluxes and surface temperature

Surface temperatures were computed using a one-dimensional radiative-convective model. For pure H\(_2\) and H\(_2\)-He atmospheres, the infrared opacity due to collision-induced absorption is from Borysow (2002). (Effects of additional greenhouse gases are discussed in §5.) Thermal infrared fluxes for any given temperature profile were computed using the integral form of the solution to the non-scattering Schwarzschild equations, while the planetary albedo and absorption profile of incoming stellar radiation were computed using a two-stream scattering code including the effects of continuum absorption and Rayleigh scattering. The incoming stellar flux was modeled as blackbodies at 3500 and 6000 K for M and G stars, respectively. The calculations were independently performed in wavenumber bands of width 10 cm\(^{-1}\) over 10-16490 cm\(^{-1}\). The atmosphere was assumed not to absorb at higher wavenumbers (λ < 606 nm), although Rayleigh scattering of incoming stellar radiation was still considered. Continuum absorption is a smooth function of wavenumber, obviating the need for a statistical model within each band. Convection was modeled by adjustment to the adiabat appropriate for a dry H\(_2\)-He composition (but see §3). The adiabat was computed using the ideal gas equation of state with constant specific heat.

In selected cases up to 10 bar surface pressure \(p_s\), the full radiative-convective model was time-stepped to equilibrium. The atmosphere was found to consist of a deep convective troposphere capped by a nearly isothermal stratosphere. Absorption of incoming stellar radiation slightly warms the stratosphere, but does not create an Earth-like temperature inversion because the pressure-dependence of absorption means that most absorption of stellar radiation and heating occurs at low altitude or at the surface. The tropopause occurs at a pressure level of ≤170 mbar, producing an optically thin stratosphere that has little effect on infrared cooling to space. For \(p_s = 1\) bar, the formation of the stratosphere cools the surface by only 3 K relative to a calculation in which the entire temperature profile is adiabatic. The slight effect becomes even less consequential as \(p_s\) and the infrared optical thickness of the atmosphere increases (Pierrehumbert 2010, Chapter 4). Therefore, we used the computationally efficient ”all troposphere” approximation, in which the temperature profile is set to the adiabat corresponding to an assumed surface temperature \(T_g\).

The radiation code calculates the corresponding infrared flux to space \(OLR(T_g, p_s)\) (Outgoing Longwave Radiation), and planetary albedo \(\alpha(T_g, p_s)\). \(T_g\) is obtained from the balance

\[
OLR(T_g, p_s) = \frac{1}{4}(1 - \alpha(T_g, p_s))L
\]

where \(L\) is the stellar constant evaluated at the planet’s orbit (the analogue of Earth’s Solar constant \(L_\odot\)).
3. Climate model results

3.1. Minimum surface pressure to maintain surface liquid water

We present results for a 3M⊕ rocky planet with surface gravity \( g = 17 \text{ m s}^{-2} \) \citep{seager2007}. Gravity enters the calculation of OLR only in the combination \( p_s^2/g \); the results can be applied approximately to other values of \( g \) by scaling \( p_s \). Scaled results will diverge slightly from the correct values because Rayleigh scattering depends on \( p_s/g \), whence albedo scales differently from OLR.

Figure 1 (left panel) illustrates the energy balance for a pure H\(_2\) atmosphere. OLR computed with the all-troposphere approximation is shown as a function of \( p_s \) for different values of \( T_g \), together with curves of absorbed stellar radiation for G and M star cases with stellar constants \( L = 40 \text{ W m}^{-2} \) and \( L = 80 \text{ W m}^{-2} \). Equilibria are represented by the intersections between OLR curves and absorbed stellar radiation curves. The absorbed stellar radiation decreases more rapidly with \( p_s \) for G stars than for M stars because the greater shortwave radiation in the former case leads to more Rayleigh scattering, whereas the latter is dominated by absorption. For \( L = 40 \text{ W m}^{-2} \) (somewhat less than Jupiter’s insolation) \( p_s = 10 \) bar is sufficient to maintain a surface temperature of 280 K about a G star; around an M star, only 7 bars is required.

Figure 1 (right panel) also shows the minimum \( p_s \) required to maintain \( T_g = 280 \text{ K} \) as a function of the orbital distance. We use 280 K as a criterion because an ocean world whose global mean temperature is too near freezing is likely to enter a “snowball” state \citep{pierrehumbert2011}. The required pressure is higher around M stars because more greenhouse effect is needed to compensate for the lower luminosity. For an early M-type star with luminosity 1.3% of the Sun, 100 bars of H\(_2\) maintains liquid surface water out to 2.4 AU; around a G star, these conditions persist to 15 AU. Cases requiring > 20 bars are speculative because the maintenance of a deep convective troposphere, when so little stellar radiation reaches the surface, is sensitive to small admixtures of strongly shortwave-absorbing constituents.

Our results are not appreciably affected by the formation of a stratosphere. The stratosphere in these atmospheres is essentially transparent to incoming stellar radiation and heated mainly by absorption of upwelling infrared radiation. As expected for a gas with frequency-dependent absorptivity, the stratospheric temperature is somewhat (few K) below the grey-gas skin temperature \( T_{\text{eff}} \), where \( \sigma T_{\text{eff}}^4 = \text{OLR} = \frac{1}{4}(1 - \alpha)L \) \citep{pierrehumbert2010}, Chapter 4).

3.2. Photosynthetic Active Radiation at the Surface

Starlight is a potential energy source for life, so we consider whether the stellar flux reaching the surface is sufficient to sustain photosynthesis. Most terrestrial photosynthetic organisms use light in the \( \lambda = 400 - 700 \text{ nm} \) range. The flux to sustain half maximum growth rate for many cyanobacteria is \( \sim 1 \text{ W m}^{-2} \) \citep{carr1982,tilzer1987}, and an anoxygenic green sulfur bacterium can use a flux of \( 3 \times 10^{-3} \text{ Wm}^{-2} \) \citep{manske2005}. Planets on more distant orbits experience less stellar irradiation and require a thicker atmosphere to maintain surface liquid water, which reduce transmission of light to the surface. For a pure H\(_2\) atmosphere, transmission in photosynthetically active radiation (PAR) is limited by Rayleigh scattering and differs slightly for M vs. G star spectra. The main difference is that G stars have higher luminosity, requiring less atmosphere to maintain liquid water at a given orbital distance, and a higher proportion of their output is PAR. Figure 2 shows surface PAR at the substellar point as a function of orbital distance for a minimum pure H\(_2\) atmosphere to maintain 280 K. Hydrogen greenhouse planets as far as 10 AU from a G star or 1 AU from an M star could sustain cyanobacteria-like life; distances of tens of AU or several AU, respectively, still permit organisms like anoxygenic phototrophs.

4. Origin and Loss of H-He Atmospheres

A body whose Bondi radius (at which gravitational potential energy equals gas enthalpy) exceeds its physical radius will accumulate gas from any surrounding disk. The critical mass is less than a lunar mass and protoplanets may acquire primordial atmospheres of H\(_2\) and He, as well as gases released by impacts \citep{stevenson1982}. Earth-mass planets will not experience runaway gas accretion and transformation into
gas giants (Mizuno 1981). The atmospheres of accreting Earth-mass planets will probably be optically thick and possess an outer radiative zone (Rafikov 2006). If the gas opacity is supplied by heavy elements and is pressure-independent, the atmosphere mass is inversely proportional to the accretion luminosity (Stevenson 1982; Ikoma & Genda 2006; Rafikov 2006). In the “high accretion rate” case (planetesimals are strongly damped by gas drag), the surface pressure will be $1.2a^{1.5}(M_p/M_\oplus)$ bar, where $a$ is the orbital semimajor axis in AU and $M_p$ is the planet mass.

We examine EUV-driven escape of atomic H from the escape rate is not limited by H$_2$ dissociation. The exobase temperature is adjusted until the correct value of $n$ at the homopause is reached. Cooling from the escape of H at the exobase, the adiabatic upward motion of gas in the atmosphere to maintain steady-state, and the collision-induced opacity of H$_2$ (Borysow et al. 1997; Borysow 2002) are included. We use a thermal conductivity $k \approx 0.0027 T^{0.73}$ W m$^{-1}$ K$^{-1}$ based on Allison & Smith (1971). We adopt $g_{EUV} = 1.5 \times 10^{-4}$ W m$^{-2}$ at 1 AU from a 4.5 Gyr-old G star (Watson et al. 1981). This is the current solar incident EUV flux of $1.67 \times 10^{-3}$ W m$^{-2}$ for $\lambda < 900\AA$ (Hinteregger et al. 1981; Del Zanna et al. 2010) times a 30% heating efficiency (Watson et al. 1981). EUV is scaled to different ages and M stars assuming proportionality to soft X-ray flux (Penz et al. 2008; Penz & Micela 2008).

At sufficiently high EUV flux, the atmosphere expands to the scale of the planet, gravity at the
exobase decreases, no steady-state solution to the temperature profile exists, and \( \lambda < 2.8 \). We presume this to correspond to hydrodynamic escape, fix the temperature structure at its last state consistent with Jeans escape, and use the energy-limited escape rate (Equation 3). Additional \( \text{H}_2 \) may escape as a result of interaction with the stellar wind (Lammer et al. 2007).

We calculate total atmospheric lost by 4.5 Gyr for planets around G and M dwarf stars (Figure 3). Significant atmospheric loss usually ceases by \( \sim 2 \) Gyr. Planets around M dwarfs, with their lower X-ray luminosities, can retain their \( \text{H}_2 \) atmosphere close to the star. However, these stars, especially those of mid- to late-M spectral type, may vary greatly in their EUV flux (Reiners & Basri 2008; Browning et al. 2010).

5. Discussion

Effects of other gases: The addition of \( \text{He} \) to the pure \( \text{H}_2 \) atmospheres considered above would warm the surface by somewhat less than the effect of adding the same number of \( \text{H}_2 \) molecules, because the 
CIA coefficients for \( \text{H}_2-\text{He} \) collision are generally weaker than those for \( \text{H}_2-\text{H}_2 \) (Borysow et al. 1988), and because \( \text{He}-\text{He} \) collisions do not contribute. Addition of \( \text{He} \) also makes the adiabat steeper and the surface warmer relative to the pure \( \text{H}_2 \) case, but for a 10\% \( \text{He} \) concentration the extra warming is no more than 1 K.

The warming provided by the \( \text{H}_2 \) greenhouse permits other greenhouse gases to be stable against complete condensation, notably \( \text{CO}_2, \text{H}_2\text{O}, \text{NH}_3 \) and \( \text{CH}_4 \). For the distant orbits of interest in this Letter, the effective radiating temperature occurs in the upper troposphere, and is \( \sim 60 \) K for a planet 2 AU from an M star. The low saturation vapor pressure at this temperature confines the gases to lower altitudes, where they add little to the greenhouse effect. Even at 100 K the saturation vapor pressures of \( \text{CO}_2, \text{H}_2\text{O}, \text{NH}_3 \) are all \( <0.02 \) Pa. \( \text{CH}_4 \) with a vapor pressure of 0.338 bar at 100 K, is most likely to exert a modest additional warming effect.

The condensible gases also affect climate through latent heat release, which makes the adiabat less steep and reduces the surface temperature. Because of the heat capacity of the thick \( \text{H}_2 \) atmosphere, the effect on the adiabat is slight, amounting to, for example, a 3 K surface cooling for an \( \text{H}_2\text{O} \) saturated atmosphere in 5 bars of \( \text{H}_2 \). It is much less for thicker atmospheres. Instead, the main effect of condensible constituents would be to form tropospheric clouds, which would increase the albedo and hence increase the \( \text{H}_2 \) pressure needed to maintain habitability. A quantitative treatment of clouds is outside the scope of this Letter.

Cold cases: Two “super-Earth”-mass planets detected by microlensing are plotted in Figure 3. MOA-2007-BLG-192L orbits \( \sim 0.7 \) AU from a very late-type M dwarf. It has an effective temperature of 40-50 K, below the condensation temperature of all gases except \( \text{H}_2 \) and \( \text{He} \), although \( \text{N}_2 \) or \( \text{CO} \) might be volatilized at the substellar point of a synchronously rotating planet (Kubas et al. 2010). We predict that any primordial hydrogen atmosphere has been lost by EUV-driven hydrodynamic escape carrying \( \text{He} \) and other light volatiles with it. In contrast, more massive OGLE-05-390L, which orbits \( \sim 2.6 \) AU from a mid M-type star but has a similar effective temperature (Ehrenreich et al. 2006), may retain a primordial hydrogen atmosphere. This planet could potentially sustain liquid water at its surface, and may represent potentially ocean-bearing planets to be revealed by future microlensing surveys (Beaulieu et al. 2008; Bennett et al. 2010).

All planets smaller than Neptune detected by Kepler or Doppler orbit within the zone where hydrogen escape is predicted to be efficient. Gliese 581d (\( \geq 6 \)M\( \text{\oplus} \), 0.2 AU) is in this category; though it may lie within the classic HZ (Wordsworth et al. 2010; von Paris et al. 2010; Hu & Ding 2011). Larger, transiting planets such as GJ 436b (22 M\( \text{\oplus} \)) have retained a low molecular-weight envelope despite their proximity to their parent stars, perhaps due to their high gravity and migration from further out in the primordial nebula. Should the Kepler mission be extended (\( \sim 6 \) yr), planets at 1.5-2 AU, the inner boundary where a hydrogen atmosphere is retained (Figure 3), could be confirmed with 3 transits. Measuring mass would be at the limit of current Doppler technology (radial velocity amplitude \( \leq 1 \) m s\(^{-1}\)), but spectra obtained during transits might reveal any \( \text{H}_2 \)-rich atmosphere.

The effects of life: These habitable worlds may
nurture the seeds of their own destruction, on account of the chemical disequilibrium between an H₂-dominated atmosphere and (we presume) a comparatively oxidizing silicate mantle. If the planet’s tectonics supports CO₂ outgassing as is the case for Earth, then methanogens could deplete the H₂ atmosphere by combining it with CO₂ to produce CH₄. The O₂ produced by cyanobacteria would similarly consume H₂ and convert the atmosphere to organic carbon and water. Either case would eventually cause a freeze-out of the atmosphere, in the absence of some biotic or abiotic process that regenerates H₂.

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REFERENCES

Allison, A. C., & Smith, F. J. 1971, Atomic Data and Nuclear Data Tables, 3, 371


Genda, H., & Abe, Y. 2003, Icarus, 164, 149


Hart, M. H. 1979, Icarus, 37, 351

Hinteregger, H. E., Fukui, K., & Gilson, B. R. 1981, Geophysical Research Letters, 8, 1147

Hu, Y., & Ding, F. 2011, Astronomy and Astrophysics, 526, A135


Kubis, H., et al. 2007, Astrobiology, 7, 185


Mizuno, H. 1980, Progress in Theoretical Physics, 64, 544


Penz, T., & Micela, G. 2008, Astronomy, 584, 579


Stevenson, D. J. 1982, Planetary and Space Science, 30, 755

—. 1999, Nature, 400, 32


Tilzer, M. 1987, New Zealand Journal of Marine and Freshwater Research, 21, 401


Wolf, E., & Toon, O. 2010, Science, 328, 1266


Yamanaka, M. 1995, Advances in Space Research, 15, 47

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Flux per unit surface area (W/m$^2$)

Surface pressure (bar)

- $280K$
- $300K$
- $320K$
- $340K$
- $360K$

$L = 40$ W/m$^2$

$L = 80$ W/m$^2$

**Fig. 1.**—Left panel: Determination of surface temperature from the top-of-atmosphere radiation budget. Solid curves show the OLR (infrared emission to space) as a function of surface pressure for the various surface temperatures indicated on the curves. Pairs of dashed lines give the absorbed solar radiation for stellar constant 40 Wm$^{-2}$ (short dashes) and 80 Wm$^{-2}$ (long dashes). The upper curve in each pair is for an M star spectrum while the lower is for a G star. Right panel: Surface pressure required to maintain 280K surface temperature, as a function of radius of a circular orbit. Results are given for an M star (0.013 times solar luminosity), and a G star (solar luminosity). All calculations were carried out for a pure H$_2$ atmosphere on a planet with surface gravity 17 ms$^{-2}$. Planetary albedos were computed assuming zero surface albedo.

**Fig. 2.**—Flux in the photosynthetically active band (400-700nm) reaching the surface at the substellar point as a function of distance from a G or M host star. The flux is calculated assuming an H$_2$ atmosphere with surface pressure sufficient to maintain 280 K surface temperature at each distance.

**Fig. 3.**—EUV-driven atmospheric escape (bars) at an age of 4.5 Gry as a function of planet mass and distance from a G star (left) or M star (right). The heavy solid line is where mass loss equals the estimated mass of proto-atmosphere acquired by a planet during its early phase of oligarchic growth (high rate of planetesimal accretion) and the heavy dashed line is the same for the case of the late phase of oligarchic growth (intermediate rate of planetesimal accretion). See text for details. Two microlensing-detected super-Earth-mass planets are plotted, with the boxes representing the uncertainties in their parameters.