Draft version March 1, 2023
Typeset using LaTeX twocolumn style in AASTeX62

Narrow loophole for H_2-dominated atmospheres on habitable rocky planets around M dwarfs

Renyu Hu,[1,2] Fabrice Gaillard,[3] and Edwin Kite[4]

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
[2]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA
[3]Institut des Sciences de la Terre d'Orléans, CNRS/Université d'Orléans/BRGM, 1a rue de la Férollerie, 45071 Orléans cedex 2, France
[4]Department of the Geophysical Sciences, University of Chicago, Chicago, IL 60637, USA

ABSTRACT

Habitable rocky planets around M dwarfs that have H_2-dominated atmospheres, if they exist, would permit characterizing habitable exoplanets with detailed spectroscopy using JWST, owing to their extended atmospheres and small stars. However, the H_2-dominated atmospheres that are consistent with habitable conditions cannot be too massive, and a moderate-size H_2-dominated atmosphere will lose mass to irradiation-driven atmospheric escape on rocky planets around M dwarfs. We evaluate volcanic outgassing and serpentinization as two potential ways to supply H_2 and form a steady-state H_2-dominated atmosphere. For rocky planets of $1-7\ M_\oplus$ and early, mid, and late M dwarfs, the expected volcanic outgassing rates from a reduced mantle fall short of the escape rates by $>\sim 1$ order of magnitude, and a generous upper limit of the serpentinization rate is still less than the escape rate by a factor of a few. Special mechanisms that may sustain the steady-state H_2-dominated atmosphere include direct interaction between liquid water and mantle, heat-pipe volcanism from a reduced mantle, and hydrodynamic escape slowed down by efficient upper-atmospheric cooling. It is thus unlikely to find moderate-size, H_2-dominated atmospheres on rocky planets of M dwarfs that would support habitable environments.

Keywords: Exoplanet atmospheres — Exoplanet surfaces — Extrasolar rocky planets — Super Earths — Exoplanet evolution — Transmission spectroscopy

1. INTRODUCTION

Rocky planets with H_2-dominated atmospheres would be ideal targets for atmospheric characterization via transmission spectroscopy, because of their large atmospheric scale height that causes large expected spectral features (e.g., Miller-Ricci et al. 2008; Seager & Deming 2010; Greene et al. 2016). A moderately irradiated rocky planet with a H_2-dominated atmosphere may have surface pressure and temperature consistent with liquid water (Pierrehumbert & Gaidos 2011; Wordsworth 2012; Ramirez & Kaltenegger 2017; Koll & Cronin 2019). Such potentially habitable worlds sustained by H_2-dominated atmospheres, if they exist around M dwarfs, would unlock the opportunity to study extrasolar habitability with spectroscopy (e.g., Seager et al. 2013), as TESS and ground-based surveys have found temperate rocky planets around M dwarfs (e.g., Sebastian et al. 2021; Kunimoto et al. 2022), and JWST has provided the sensitivity to analyze any H_2-dominated atmospheres on them with a wide spectral coverage (e.g., Batalha et al. 2018). Here we ask: Are such worlds likely?

To have surface liquid water, the H_2-dominated atmosphere cannot be much larger than ~ 10 bar, because the surface temperature is primarily a function of the size of the atmosphere (this is valid for the stellar irradiation of $200-1400$ W m^{-2} (Koll & Cronin 2019)). The exact size and irradiation limit depends on the cloud albedo effect (e.g., Popp et al. 2015). This moderate-size atmosphere is much smaller than the massive H_2-dominated atmospheres proposed to explain the sub-Neptune-sized low-density planet population, which are typically 1% planet mass or $> 10^4$ bar (e.g., Rogers et al. 2023). A 10-bar H_2 atmosphere would only add $<\sim 0.1\ R_\oplus$ to the planetary radius, which can be accommodated by

Corresponding author: Renyu Hu
renyu.hu@jpl.nasa.gov

typical uncertainties in planetary mass, radius, and Fe content (Luque & Pallé 2022).

Temperate planets around M dwarfs receive intense high-energy irradiation from host stars because of their close-in orbits, and this intense irradiation can drive hydrodynamic escape from a H_2-dominated atmosphere (e.g., Salz et al. 2016; Kubyshkina et al. 2018a,b). The high-energy irradiation will be measured by a bevy of new spacecraft (Ardila et al. 2022; France et al. 2023). We are thus motivated to determine the lifetime of a moderate-size H_2 atmosphere – permitting surface liquid water – on a large rocky planet orbiting an M dwarf against hydrodynamic escape, and evaluate the geologic processes that could resupply the H_2 atmosphere.

2. ATMOSPHERIC ESCAPE

The hydrodynamic escape rate, $f_{\rm es}$ (kg s^{-1}), can be approximated by the energy-limited escape rate formula,

$$f_{\rm es} = \frac{\eta_{\rm es}(F_{\rm X} + F_{\rm EUV})\pi R_{\rm p}^3 a^2}{KGM_{\rm p}}, \tag{1}$$

where $F_{\rm X}$ and $F_{\rm EUV}$ are the stellar fluxes in X-ray (5-100 Å) and extreme ultraviolet (EUV, 100-1240 Å), $a \geq 1$ is the ratio between the X-ray/EUV absorbing radius and the (optical) planetary radius, $K \leq 1$ is a factor that accounts for the Roche lobe effect (Erkaev et al. 2007), and $\eta_{\rm es}$ is the escape efficiency. Recent hydrodynamic escape models find the escape efficiency to be in a range of $0.1-0.25$ for solar-abundance atmospheres (Salz et al. 2016) and Equation (1) is a good approximation of the full hydrodynamic calculations in the Jeans escape parameter regime for temperate rocky planets (Jeans escape parameter $= 25-60$, Kubyshkina et al. 2018a,b). For a conservative estimate of the escape rate, we adopt $\eta_{\rm es} = 0.1$, $a = 1$, and $K = 1$.

As shown in Table 1, we pick GJ 832, GJ 436, and TRAPPIST-1 as the representative stars for early M, mid M, and late M dwarfs. Their emission spectra in X-ray, Lyman-α, FUV, and NUV bands have been measured, and their emission spectra and fluxes in the EUV band can be inferred from these measurements (Peacock et al. 2019a,b). We find that the lifetime of a 10-bar H_2 atmosphere on a rocky planet that receives Earth-like insolation from these stars would be uniformly < 0.1 Ga. Thus, a source of H_2 would be needed to maintain such an atmosphere.

3. VOLCANIC OUTGASSING

We first consider volcanic outgassing as the source of H_2 (e.g., Liggins et al. 2020). The volcanic outgassing rate, $f_{\rm og}$ (kg s^{-1}), can be modeled by the following equation,

$$f_{\rm og} = \eta_{\rm og} V x_{\rm H}, \tag{2}$$

where V is the rate of magma generation, $x_{\rm H}$ is the hydrogen content (wt %) of magma that degasses, and $\eta_{\rm og}$ is the outgassing efficiency. We do not expect the outgassing efficiency to be close to unity because, even though extrusive volcanism (magma that reaches and degases at the planetary surface) can probably degas effectively (but often not completely), intrusive volcanism (magma that does not reach the surface) probably degases poorly, especially for H_2 (to be detailed later in this section). For Earth, the extrusive:intrusive ratio is typically 3:1 to 10:1 (White et al. 2006), and so as a fiducial value, we assume $\eta_{\rm og} = 0.1$.

The rate of volcanism can be estimated for a rocky planet by modeling its thermal evolution history. We adopt the geodynamics model of Kite et al. (2009) for the rate of volcanism, which used a melting model from pMELTS (Ghiorso et al. 2002) for the plate tectonic mode and Katz et al. (2003) for the stagnant lid mode (Table 2). Focusing first on the planets around field M dwarfs, we take the 4-Gyr age values for the rate of volcanism. The values for the plate tectonic and stagnant lid modes are similar. Detailed models of mantle convection in the stagnant-lid regime predict that volcanism would cease much sooner than what Table 2 indicates (Noack et al. 2017; Dorn et al. 2018), but this model uncertainty does not impact the conclusion of this paper. For volcanic outgassing to sustain the atmosphere, it is required that $f_{\rm es} = f_{\rm og}$. With $f_{\rm es}$ and V, we derive the required $x_{\rm H}$ and list the values in Table 1.

Arc volcanoes on Earth, which are formed by flux melting caused by release of water from subduction of plates rich in hydrated materials, have magmas that contain $1-7$ wt % water (e.g., Rasmussen et al. 2022). The water content in the mid-ocean ridge basalt and the ocean island basalt is lower by $1-2$ orders of magnitude (Dixon et al. 2002). Complete outgassing of $1-7$ wt % water in the form of H_2 would provide an $x_{\rm H}$ of $0.1-0.8$ wt %. We consider this to be a very generous upper limit; comparing it with Table 1 shows that it is very unlikely for volcanic outgassing to sustain the H_2 atmosphere.

The hydrogen content of the magma for degassing depends on the oxygen fugacity of the magma and the pressure at which degassing takes place. We use the magma degassing and speciation model of Gaillard & Scaillet (2014) to calculate $x_{\rm H}$ for the typical volatile content of terrestrial magmas and a wide range of oxygen fugacities (Figure 1). The H_2 content is higher for a more reducing magma and when degassing at a lower pressure. In addition to counting the H_2 degassing, one may also include the potential for atmospheric photochemistry to post-process CO to form H_2, via $CO + H_2O \longrightarrow CO_2 +$

Star	Type	F (erg s^{-1} cm^{-2})		$f_{\rm es}$ (10^4 kg s^{-1})			Life of 10-bar atmos (Gyr)			Required $x_{\rm H}$ (wt %)		
		X-ray	EUV	1 $M_\oplus$	3 $M_\oplus$	7 $M_\oplus$	1 $M_\oplus$	3 $M_\oplus$	7 $M_\oplus$	1 $M_\oplus$	3 $M_\oplus$	7 $M_\oplus$
GJ 832	M1.5	2.17	149	3.1	2.3	2.2	0.05	0.07	0.09	9.2	1.7	0.35
GJ 436	M3.5	8.71	229	4.9	3.6	3.4	0.03	0.04	0.06	14	2.7	0.54
TRAPPIST-1	M8	171	1097*	26	19	18	0.006	0.008	0.01	77	14	2.9

Table 1. Escape rates and lifetimes of a 10-bar H_2 atmosphere, and the required hydrogen content in magma for degassing to sustain this atmosphere, on a hypothetical rocky planet of an M dwarf. The distance between the planet and the star results in a bolometric stellar flux the same as Earth's insolation (i.e., the 1-AU equivalent distance). The X-ray fluxes (5-100Å) are measured by XMM-Newton (Loyd et al. 2016; Ehrenreich et al. 2015; Wheatley et al. 2017) and the EUV fluxes (100-1240Å) are based on PHOENIX synthetic spectra guided by FUV and NUV observations (Peacock et al. 2019a,b). *Bourrier et al. (2017) reported a much lower EUV flux (126 erg s^{-1} cm^{-2} at TRAPPIST-1 e) based on Lyman-α measurements, but using this lower value does not change the conclusion of this paper.

Mode	Plate tectonics			Stagnant lid		
Age (Gyr)	2	4	6	2	4	6
1 $M_\oplus$, 1 $R_\oplus$	8	1.5	0.5	7	1.5	0
3 $M_\oplus$, 1.3 $R_\oplus$	-	2	0.7	-	2.5	0
7 $M_\oplus$, 1.7 $R_\oplus$	-	4	1	-	3.5	0.7

Table 2. Rate of volcanism (the mass of magma production divided by the mass of planet, in unit of current Earth's value 3.7516×10^{-19} s^{-1}), based on the parameterized model of Kite et al. (2009). Dashes correspond to the heat-pipe tectonic regime.

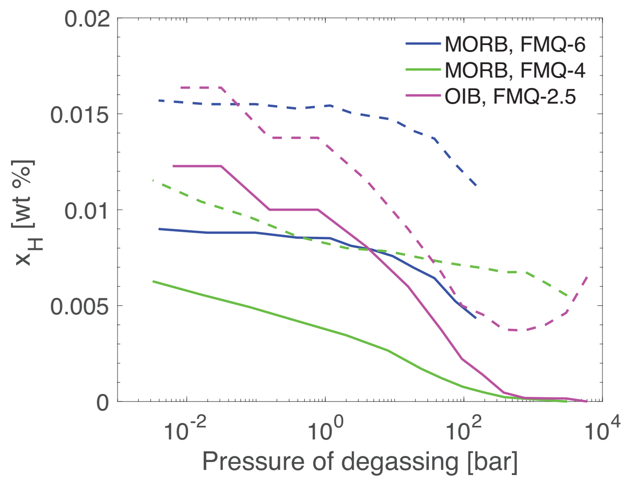

Figure 1. Degassing of H_2 from magma calculated by the magma degassing and speciation model of Gaillard & Scaillet (2014). We consider mid-ocean ridge basalt (MORB) with bulk H_2O content of 0.19 wt % and bulk CO_2 content of 0.16 wt %, degassing at the oxygen fugacities of FMQ-6 (corresponding to an undifferentiated planet) and FMQ-4 (corresponding to modern Mars), as well as ocean island basalt (OIB) with bulk H_2O content of 1 wt % and bulk CO_2 content of 0.3 wt %, degassing at the oxygen fugacities of FMQ-2.5. The solid lines count the degassing of H_2 and the dashed lines count the degassing of both H_2 and CO (with CO expressed in terms of its indirect effect on atmospheric H_2, see text).

H_2. The complete post-processing means that degassing 1 mole CO would be equivalent to degassing 1 mole H_2, and this situation is shown as dashed lines in Figure 1. However, $x_{\rm H}$ predicted by the geochemical model, even when including the CO conversion, is at least one order of magnitude lower than the minimum required $x_{\rm H}$ for a 7-$M_\oplus$ planet around an early M dwarf (Table 1). This again indicates that volcanic outgassing is unlikely to sustain an H_2 atmosphere.

4. SERPENTINIZATION

We turn to serpentinization as an alternative source of H_2. Serpentinization is water-rock reactions between warm water and mafic and ultramafic rocks (usually olivine-rich) in the fresh crust. This process probably occurs on all rocky planets with liquid water, and it may have produced H_2-rich water on early Earth (Sleep et al. 2004) and H_2 and CH_4 on early Mars and on modern Enceladus (Oze & Sharma 2005; Chassefière & Leblanc 2011; Batalha et al. 2015; Zandanel et al. 2021).

For an upper bound of the H_2 production rate from serpentinization, we assume that 1 mole H_2 is produced for every 3 moles Fe^{2+} oxidized, as the process can be written as $H_2O + 3\,FeO \longrightarrow H_2 + Fe_3O_4$. We also assume that the fresh crust is entirely composed of olivine, $(Mg_{0.9}Fe_{0.1})_2SiO_4$, and all Fe^{2+} is used by serpentinization to produce H_2. The olivine has a molar mass of 146.9 g, and it contains 0.2 moles Fe^{2+}, corresponding to 0.067 moles H_2, or a mass of 0.13 g. The corresponding $x_{\rm H}$ is thus $0.13/146.9 = 0.09$ wt. %. In reality, the fresh crust may not be entirely composed of olivine, and the rate of serpentinization is limited by the rate of dissolution of olivine in water (Oze & Sharma 2007), which is a function of temperature, pH, water/rock ratio, and the Fe/Mg composition of olivine (Wogelius & Walther 1992; Allen & Seyfried Jr 2003), as well as by the extent of fracturing of the crust (Vance et al. 2007). We thus expect the actual $x_{\rm H}$ provided by serpentinization to be much smaller than 0.09 wt. %. However, even this generous upper bound falls short of the required $x_{\rm H}$ by at least a factor of 4 (Table 1). It is thus also unlikely that serpentinization would sustain a moderate-size H_2 atmosphere on rocky planets around M dwarfs.

5. AGE AND DISTANCE DEPENDENCY

So far we have assumed 4 Gyr for the planet age, which broadly corresponds to the field M dwarfs. Now we consider the age dependency of the sources and sinks of H_2 and see if a steady-state H_2 atmosphere would be possible on younger planets. Richey-Yowell et al. (2019) recently presented the NUV, FUV, and X-ray fluxes of M dwarfs in their habitable zones as a function of age, and meanwhile, the EUV fluxes follow a similar age dependency as their FUV fluxes (Peacock et al. 2020). We adopt an age dependency of $t^{-0.9}$ for the X-ray fluxes and $t^{-1.3}$ for the EUV fluxes. Meanwhile, the rate of volcanism can be much higher for young planets, when the heat flux from the planetary interior is higher. We explore an age dependency that varies between t^{-1} (based on the model for Earth in Schubert et al. 2001) and t^{-2} (based on the model for large rocky planets of Kite et al. 2009). We consider an age as young as 1 Gyr. Before that, the planet could have a residual primordial H_2 atmosphere (Kite & Barnett 2020) and the stellar high-energy output may have different age dependencies (Richey-Yowell et al. 2019). As shown in Figure 2, it remains unlikely for volcanic outgassing or serpentinization to compensate for the intense atmospheric escape of H_2 experienced by rocky planets of M dwarfs from 1 to 5 Gyr.

How about a planet that is located further away from the star than the 1-AU equivalent distance? Moving the planets 2.6 times further away (or receiving 7 times less irradiation, or ~ 200 W m^{-2}) would still produce a potentially habitable climate (Koll & Cronin 2019), and this would reduce the escape rate by a factor of 7. In this case, the escape rate is comparable to the upper limit of serpentinization (Figure 2). However, the upper limit assumes complete oxidization of Fe^{2+} in the fresh crust and is thus unlikely. The utility of these distant habitable worlds for observations is probably limited, as they are less likely to transit and harder to find than the closer-in planets.

6. POTENTIAL ALTERNATIVE MECHANISMS

The estimates above show that it is unlikely to sustain moderate-size H_2-dominated atmospheres on rocky planets around M dwarfs through volcanic outgassing or serpentinization. Here we explore alternative mechanisms that could result in large source fluxes of H_2.

First, the rate of hydrogen generation during serpentinization is controlled by the Fe content of olivine (Klein et al. 2013). In Section 4, we have assumed a Fe:Mg ratio of 1:9, corresponding to the terrestrial value. On Mars, however, the Fe:Mg ratio of crustal olivine can be $\sim$1:1 (Koeppen & Hamilton 2008; Morrison et al. 2018). Such Fe-rich olivine could result in higher fluxes of H_2 from serpentinization than our estimates by a factor of ~ 5, making it more likely for serpentinization to meet the H_2 escape flux.

Second, on a planet with plate tectonics but amagmatic spreading, water-rock interaction near the ridge axis could produce H_2. Our discussion of serpentinization so far assumes that water interacts with the products of volcanism/partial melting. However, water could interact directly with the mantle if it is exposed by amagmatic spreading. This mechanism occurs on Earth today at Gakkel Ridge and Southwest Indian Ridge and has the potential to generate more H_2 because the Fe content of mantle rock is greater than that of the crustal basalt. This mechanism would decouple serpentinization from volcanism and allow serpentinization to continue even after volcanism has shut down. The upper limit of H_2 production from this mechanism is then given by assuming (unrealistically) a 100% fayalite (Fe_2SiO_4), which would give an equivalent $x_{\rm H}$ of 0.6 wt. %. Suppose fractures, and therefore hot-water alteration, penetrate as far down into the subsurface on this amagmatic planet as the base of the oceanic crust on our planet, which is probably unrealistic because fractures should self-seal at shallower depths (Vance et al. 2007). Then the present-day terrestrial production of 20 km^3/year of MORB, with full serpentinization, would correspond to 1×10^4 kg s^{-1} of H_2 output. This is on the same order of magnitude as the lower end of the escape rate (Table 1), and could be higher for younger or larger rocky planets.

Third, Earth's heat flux of ~ 0.1 W m^{-2} is $\sim 10\%$ in the form of advective cooling (magma moves upward and cools) and $\sim 90\%$ conductive cooling. This implies that the rates of volcanism could be $10\times$ higher without excessively cooling Earth's mantle. Indeed, it has been hypothesized that heat-pipe tectonics occurred early in Earth's history (e.g., Moore & Webb 2013). Small variations in exoplanet mantle composition or exoplanet mantle volatile content, among other factors, could make melting easier at a given mantle temperature (Spaargaren et al. 2020), perhaps enabling heat-pipe mode of planetary cooling even for planets that are as old as the Earth. If heat-pipe volcanism occurs then the amount of outgassing and serpentinization could be $\sim 10\times$ greater than for an Earth-scaled plate-tectonics model, because $\sim 10\times$ more eruptions would occur.

Fourth, N-, O-, and C-bearing molecules mixed in the H_2-dominated atmosphere may substantially reduce

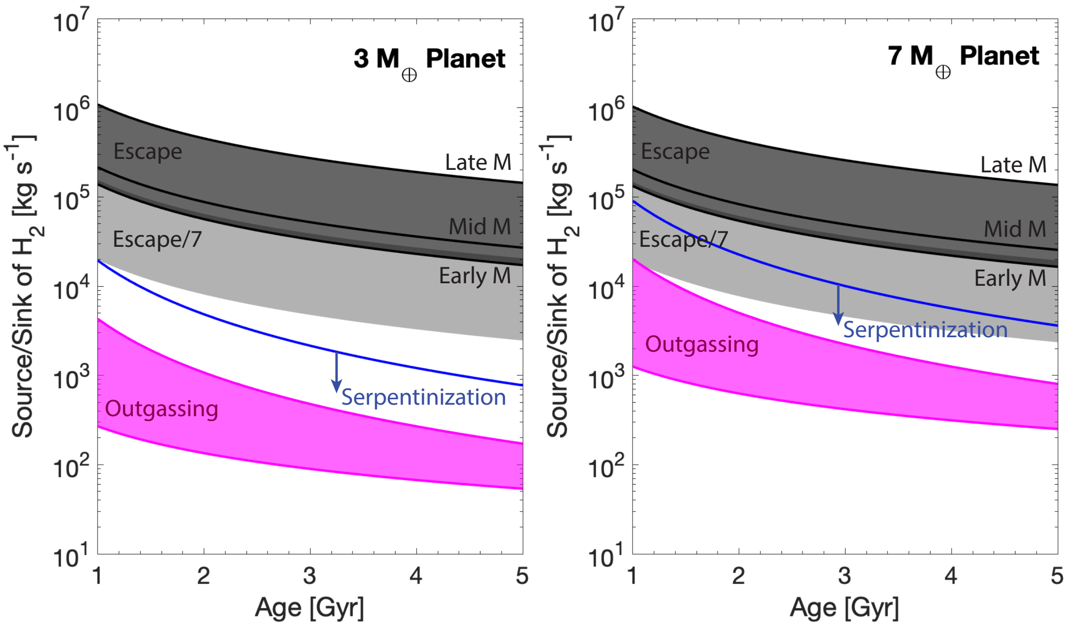

Figure 2. Comparison between sources and sinks of H_2 on rocky planets around M dwarfs. The grey areas show the range of escape rates depending on the type of the host star. The dark grey area is for a planet that locates at the 1-AU equivalent distance, while the light grey area is for a planet that locates 2.6 times farther away (i.e., receiving 7 times less irradiation). The outgassing rates encapsulate the plausible range from a highly reduced mantle (informed by Figure 1), with the lower bound corresponding to $x_{\rm H} = 0.005$ wt % and t^{-1} scaling, and the higher bound corresponding to $x_{\rm H} = 0.02$ wt % and t^{-2} scaling. The rate of serpentinization is a very generous upper limit (Section 4).

the escape rate. The escape rate and efficiency calculations have been based on solar-abundance atmospheres (Kubyshkina et al. 2018a,b). However, H_2-dominated atmospheres sustained by volcanism should also have H_2O, CO/CH_4, and N_2/NH_3 at the levels that exceed the solar abundance (Liggins et al. 2022). Recently, Nakayama et al. (2022) show that with an N_2-O_2 atmosphere, cooling from atomic line emissions (of N, N^+, O, O^+) and radiative recombination can prevent rapid hydrodynamic escapes for XUV irradiation fluxes that are up to 1000× the modern Earth value. It is thus conceivable that an H_2-dominated atmosphere richer in N, O, and C would be more stable. The challenge is that the N-, O-, and C-bearing molecules are separated from H_2 by diffusion (typically at ~ 1 Pa) and can be largely depleted in the upper atmosphere. It is thus unclear whether 10% non-H_2 species (which would still allow for a low molecular weight atmosphere for transmission spectroscopy) would slow down the hydrodynamic escape sufficiently to achieve long-term stability.

Lastly, there could be transient episodes of high volcanism and serpentinization that support H_2-dominated atmospheres. A leading hypothesis for why Early Mars sometimes had lakes is that a lot of H_2 was emitted transiently from the subsurface by volcanism or serpentinization (Wordsworth et al. 2021). The amount of H_2 needed to warm up Mars by H_2-CO_2 collision-induced absorption is now well understood (Turbet et al. 2020), and the H_2 flux needed is approximately 10^4 kg s^{-1}. A large rocky planet could have 10× the surface area of Mars and thus plausibly 10× the amount of serpentinization. This process-agnostic (but model-dependent) scaling hints at short-term source fluxes sufficient for H_2-dominated atmospheres on a 7-$M_\oplus$ planet (Figure 2).

7. SUMMARY

From the analyses presented above, we conclude that rocky planets around M dwarfs rarely have potentially habitable conditions accompanied by H_2-dominated atmospheres. This is because, forming a potentially habitable environment will require a moderate-size (~ 10 bar) atmosphere, but such an atmosphere is removed quickly by stellar X-ray and EUV irradiation, and could only exist on the planet as a steady-state atmosphere with replenishment. However, neither volcanic outgassing nor serpentinization provides the required H_2 source that would maintain such a steady-state atmosphere. Rocky planets around M dwarfs could have massive H_2 atmospheres, but to have a stable and moderate-size H_2 atmosphere consistent with habitability would require special circumstances such as direct interaction between liquid water and mantle (e.g., near a ridge axis undergoing amagmatic spreading), heat-pipe volcanism from a highly reduced mantle, or hydrodynamic escape quenched by efficient atomic line cooling. These special mechanisms to sustain the moderate-size H_2 atmosphere are generally more effective on large rocky planets (e.g., $\sim 7\text{-}M_\oplus$ planets exemplified by LHS 1140 b) than on Earth-sized planets. Generally, N_2-CO_2 or other high-mean-molecular-weight atmospheres should probably be considered as the default assumption when planning for future spectroscopic observations of rocky planets around M dwarfs.

ACKNOWLEDGMENTS

We thank Evgenya Shkolnik and Tyler Richey-Yowell for helpful discussion of stellar evolution. This work was supported in part by the NASA Exoplanets Research Program grant #80NM0018F0612. E.S.K. acknowledges support from a Scialog grant, Heising-Simons Foundation 2021-3119. Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

Allen, D. E., & Seyfried Jr, W. 2003, Geochimica et Cosmochimica Acta, 67, 1531

Ardila, D. R., Shkolnik, E., Scowen, P., et al. 2022, arXiv preprint arXiv:2211.05897

Batalha, N., Domagal-Goldman, S. D., Ramirez, R., & Kasting, J. F. 2015, Icarus, 258, 337

Batalha, N. E., Lewis, N. K., Line, M. R., Valenti, J., & Stevenson, K. 2018, The Astrophysical Journal Letters, 856, L34

Bourrier, V., Ehrenreich, D., Wheatley, P., et al. 2017, Astronomy & Astrophysics, 599, L3

Chassefière, E., & Leblanc, F. 2011, Earth and Planetary Science Letters, 310, 262

Dixon, J. E., Leist, L., Langmuir, C., & Schilling, J.-G. 2002, Nature, 420, 385

Dorn, C., Noack, L., & Rozel, A. 2018, Astronomy & Astrophysics, 614, A18

Ehrenreich, D., Bourrier, V., Wheatley, P. J., et al. 2015, Nature, 522, 459

Erkaev, N., Kulikov, Y. N., Lammer, H., et al. 2007, Astronomy & Astrophysics, 472, 329

France, K., Fleming, B., Egan, A., et al. 2023, The Astronomical Journal, 165, 63

Gaillard, F., & Scaillet, B. 2014, Earth and Planetary Science Letters, 403, 307

Ghiorso, M. S., Hirschmann, M. M., Reiners, P. W., & Kress III, V. C. 2002, Geochemistry, Geophysics, Geosystems, 3, 1

Greene, T. P., Line, M. R., Montero, C., et al. 2016, The Astrophysical Journal, 817, 17

Katz, R. F., Spiegelman, M., & Langmuir, C. H. 2003, Geochemistry, Geophysics, Geosystems, 4

Kite, E. S., & Barnett, M. N. 2020, Proceedings of the National Academy of Sciences, 117, 18264

Kite, E. S., Manga, M., & Gaidos, E. 2009, The Astrophysical Journal, 700, 1732

Klein, F., Bach, W., & McCollom, T. M. 2013, Lithos, 178, 55

Koeppen, W. C., & Hamilton, V. E. 2008, Journal of Geophysical Research: Planets, 113

Koll, D. D., & Cronin, T. W. 2019, The Astrophysical Journal, 881, 120

Kubyshkina, D., Fossati, L., Erkaev, N. V., et al. 2018a, Astronomy & Astrophysics, 619, A151

—. 2018b, The Astrophysical Journal Letters, 866, L18

Kunimoto, M., Winn, J., Ricker, G. R., & Vanderspek, R. K. 2022, The Astronomical Journal, 163, 290

Liggins, P., Jordan, S., Rimmer, P. B., & Shorttle, O. 2022, Journal of Geophysical Research: Planets, 127, e2021JE007123

Liggins, P., Shorttle, O., & Rimmer, P. B. 2020, Earth and Planetary Science Letters, 550, 116546

Loyd, R. P., France, K., Youngblood, A., et al. 2016, The Astrophysical Journal, 824, 102

Luque, R., & Pallé, E. 2022, Science, 377, 1211

Miller-Ricci, E., Seager, S., & Sasselov, D. 2008, The Astrophysical Journal, 690, 1056

Moore, W. B., & Webb, A. A. G. 2013, Nature, 501, 501

Morrison, S. M., Downs, R. T., Blake, D. F., et al. 2018, American Mineralogist: Journal of Earth and Planetary Materials, 103, 857

Nakayama, A., Ikoma, M., & Terada, N. 2022, The Astrophysical Journal, 937, 72

Noack, L., Rivoldini, A., & Van Hoolst, T. 2017, Physics of the Earth and Planetary Interiors, 269, 40

Oze, C., & Sharma, M. 2005, Geophysical research letters, 32

—. 2007, Icarus, 186, 557

Peacock, S., Barman, T., Shkolnik, E. L., Hauschildt, P. H., & Baron, E. 2019a, The Astrophysical Journal, 871, 235

Peacock, S., Barman, T., Shkolnik, E. L., et al. 2019b, The Astrophysical Journal, 886, 77

—. 2020, The Astrophysical Journal, 895, 5

Pierrehumbert, R., & Gaidos, E. 2011, The Astrophysical Journal Letters, 734, L13

Popp, M., Schmidt, H., & Marotzke, J. 2015, Journal of the Atmospheric Sciences, 72, 452

Ramirez, R. M., & Kaltenegger, L. 2017, The Astrophysical Journal Letters, 837, L4

Rasmussen, D. J., Plank, T. A., Roman, D. C., & Zimmer, M. M. 2022, Science, 375, 1169

Richey-Yowell, T., Shkolnik, E. L., Schneider, A. C., et al. 2019, The Astrophysical Journal, 872, 17

Rogers, J. G., Schlichting, H. E., & Owen, J. E. 2023, arXiv preprint arXiv:2301.04321

Salz, M., Schneider, P., Czesla, S., & Schmitt, J. 2016, Astronomy & Astrophysics, 585, L2

Schubert, G., Turcotte, D. L., & Olson, P. 2001, Mantle convection in the Earth and planets (Cambridge University Press)

Seager, S., Bains, W., & Hu, R. 2013, The Astrophysical Journal, 777, 95

Seager, S., & Deming, D. 2010, Annual Review of Astronomy and Astrophysics, 48, 631

Sebastian, D., Gillon, M., Ducrot, E., et al. 2021, Astronomy & Astrophysics, 645, A100

Sleep, N., Meibom, A., Fridriksson, T., Coleman, R., & Bird, D. 2004, Proceedings of the National Academy of Sciences, 101, 12818

Spaargaren, R. J., Ballmer, M. D., Bower, D. J., Dorn, C., & Tackley, P. J. 2020, Astronomy & Astrophysics, 643, A44

Turbet, M., Boulet, C., & Karman, T. 2020, Icarus, 346, 113762

Vance, S., Harnmeijer, J., Kimura, J., et al. 2007, Astrobiology, 7, 987

Wheatley, P. J., Louden, T., Bourrier, V., Ehrenreich, D., & Gillon, M. 2017, Monthly Notices of the Royal Astronomical Society: Letters, 465, L74

White, S. M., Crisp, J. A., & Spera, F. J. 2006, Geochemistry, Geophysics, Geosystems, 7

Wogelius, R. A., & Walther, J. V. 1992, Chemical Geology, 97, 101

Wordsworth, R. 2012, Icarus, 219, 267

Wordsworth, R., Knoll, A. H., Hurowitz, J., et al. 2021, Nature Geoscience, 14, 127

Zandanel, A., Truche, L., Hellmann, R., et al. 2021, Icarus, 364, 114461