The Interior and Atmosphere of the Habitable-zone Exoplanet K2-18b

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Abstract

Exoplanets orbiting M-dwarfs present a valuable opportunity for their detection and atmospheric characterization. This is evident from recent inferences of H$_2$O in such atmospheres, including that of the habitable-zone exoplanet K2-18b. With a bulk density between Earth and Neptune, K2-18b may be expected to possess a H/He envelope. However, the extent of such an envelope and the thermodynamic conditions of the interior remain unexplored. In the present work, we investigate the atmospheric and interior properties of K2-18b based on its bulk properties and its atmospheric transmission spectrum. We constrain the atmosphere to be H$_2$-rich with a H$_2$O volume mixing ratio of 0.02%–14.8%, consistent with previous studies, and find a depletion of CH$_4$ and NH$_3$, indicating chemical disequilibrium. We do not conclusively detect clouds/hazes in the observable atmosphere. We use the bulk parameters and retrieved atmospheric properties to constrain the internal structure and thermodynamic conditions in the planet. The constraints on the interior allow multiple scenarios between rocky worlds with massive H/He envelopes and water worlds with thin envelopes. We constrain the mass fraction of the H/He envelope to be $\lesssim$6%; spanning $\lesssim 10^{-3}$ for a predominantly water world to $\sim 6\%$ for a pure iron interior. The thermodynamic conditions at the surface of the H$_2$O layer range from the supercritical to liquid phases, with a range of solutions allowing for habitable conditions on K2-18b. Our results demonstrate that the potential for habitable conditions is not necessarily restricted to Earth-like rocky exoplanets.

Unified Astronomy Thesaurus concepts: Exoplanet atmospheres (487); Planetary interior (1248); Exoplanet atmospheric composition (2021); Exoplanet surface characteristics (496); Habitable planets (695); Habitable zone (696)

1. Introduction

Recent exoplanet detection surveys have revealed high occurrence rates of low-mass planets orbiting M-dwarfs (Dressing & Charbonneau 2015; Mulders et al. 2015). The low masses, sizes, and temperatures of M-dwarfs also mean that the planet–star contrast is favorable for planetary detection and characterization. This “small-star opportunity” has led to several detections of low-mass planets ($<10M_J$) in the habitable-zones of M-dwarf hosts such as Trappist-1 (Gillon et al. 2017), Proxima Centauri (Anglada-Escudé et al. 2016), K2-18 (Foreman-Mackey et al. 2015; Montet et al. 2015), and LHS 1140 (Dittmann et al. 2017).

The habitable-zone transiting exoplanet K2-18b is a particularly good example (Foreman-Mackey et al. 2015; Montet et al. 2015). The close proximity and small size of its host star make precise measurements of the planetary mass, radius, and atmospheric spectra viable (Benneke et al. 2017; Cloutier et al. 2019), as exemplified by the recent detection of H$_2$O in its atmosphere (Benneke et al. 2019; Tsiaras et al. 2019). The habitable-zone temperature of K2-18b provides further impetus for detailed characterization of its interior and atmosphere.

Given its mass ($M_p = 8.63 \pm 1.35 M_J$; Cloutier et al. 2019) and radius ($R_p = 2.610 \pm 0.087 R_J$; Benneke et al. 2019), K2-18b has a bulk density ($2.67^{+0.52}_{-0.47}$ g cm$^{-3}$; Benneke et al. 2019). This density, between that of Earth and Neptune, may be thought to preclude a purely rocky or icy interior and require a hydrogen-rich outer envelope. However, the extent of such an envelope and the conditions at the interface between the envelope and the underlying interior have not been explored. We note that the mass and radius of the planet have recently been revised (Benneke et al. 2019), which may have impacted inferences made using previous values (Cloutier et al. 2017; Tsiaras et al. 2019).

Previous studies of planets with similar masses and radii, such as GJ 1214b, suggested envelope mass fractions $\lesssim 7\%$ (Rogers & Seager 2010; Nettelmann et al. 2011; Valencia et al. 2013). GJ 1214b is expected to host supercritical H$_2$O below the envelope at pressures and temperatures too high to be conducive for life (Rogers & Seager 2010). However, while GJ 1214b has an equilibrium temperature ($T_{eq}$) of $\sim 500$ K, K2-18b may be more favorable given its lower $T_{eq}$ $\sim 250$–300 K.

In the present work, we conduct a systematic study to constrain both the atmospheric and interior composition of K2-18b based on extant data along with detailed atmospheric retrievals and internal structure models.

2. Atmospheric Properties

We retrieve the atmospheric properties of K2-18b using its broadband transmission spectrum reported by Benneke et al. (2019). The data include observations from the Hubble Space Telescope (HST) WFC3 G141 grism (1.1–1.7 $\mu$m), photometry in the Spitzer IRAC 3.6 and 4.5 $\mu$m bands, and optical photometry in the K2 band (0.4–1.0 $\mu$m). We perform the atmospheric retrieval using an adaptation of the AURA retrieval code (Pinhas et al. 2019; Welbanks & Madhusudhan 2019). Our model solves line-by-line radiative transfer in a plane-parallel atmosphere in transmission geometry. The model assumes hydrostatic equilibrium and considers prominent
opacity sources in the observed spectral bands as well as homogeneous/inhomogeneous cloud/haze coverage. Clouds are included through a gray cloud deck with cloud-top pressure \( P_c \) as a free parameter. Hazes are included as a modification to Rayleigh scattering through parameters for the scattering slope \( \gamma \) and a Rayleigh-enhancement factor \( \alpha \). The opacity sources include \( \text{H}_2\text{O} \) (Rothman et al. 2010), \( \text{CH}_4 \) (Yurchenko & Tennyson 2014), \( \text{NH}_3 \) (Yurchenko et al. 2011), \( \text{CO}_2 \) (Rothman et al. 2010), HCN (Barber et al. 2014), and collision-induced absorption due to \( \text{H}_2–\text{H}_2 \) and \( \text{H}_2–\text{He} \) (Richard et al. 2012).

The model comprises 16 free parameters: abundances of five molecules, six parameters for the pressure–temperature \((P–T)\) profile, four cloud/haze parameters, and one parameter for the reference pressure \( p_{\text{ref}} \) at \( R_p \) (e.g., Welbanks et al. 2019). The Bayesian parameter estimation is conducted using the Nested Sampling algorithm MultiNest (Feroz et al. 2009) through PyMultiNest (Buchner et al. 2014). We conduct retrievals for four model configurations: (1) a full model including inhomogeneous clouds and hazes, (2) a clear atmosphere, (3) an atmosphere with an opaque cloud deck but no hazes, and (4) an atmosphere with inhomogeneous clouds but no hazes. The atmospheric constraints are shown in Figure 1 and Table 1.

We confirm the high-confidence detection of \( \text{H}_2\text{O} \) in an \( \text{H}_2\)-rich atmosphere as reported by Benneke et al. (2019) and Tsiaras et al. (2019). Our abundance estimates are consistent to within 1\( \sigma \) between all four model configurations and with Benneke et al. (2019). The derived \( \text{H}_2\text{O} \) volume mixing ratio ranges between 0.02% and 14.80%, with median values of 0.7–1.6% between the 4 model cases, as shown in Table 1. The case with an opaque cloud deck (a clear atmosphere) retrieves slightly higher (lower) \( \text{H}_2\text{O} \) abundances as expected (Welbanks & Madhusudhan 2019). Our derived \( \text{H}_2\text{O} \) abundance range corresponds to an \( \text{O}/\text{H} \) ratio of 0.2–176.8 \( \times \) solar, assuming all the oxygen is in \( \text{H}_2\text{O} \) as expected in \( \text{H}_2\)-rich atmospheres at such low temperatures (Burrows & Sharp 1999). The median \( \text{H}_2\text{O} \) abundance is 9.3 \( \times \) solar for the full model, case 1. We cannot compare our results with Tsiaras et al. (2019) as their retrievals were based on only the HST WFC3 data and used older measurements of the planetary mass and radius, which could have biased their inferences.

We find a depletion of \( \text{CH}_4 \) and \( \text{NH}_3 \) in the atmosphere. For a \( \text{H}_2\)-rich atmosphere at \( \sim 300 \text{ K} \), \( \text{CH}_4 \) and \( \text{NH}_3 \) are expected to be dominant carriers of carbon and nitrogen, respectively, in chemical equilibrium (Burrows & Sharp 1999), as also seen for the gas and ice giants in the solar system (Atreya et al. 2016). Assuming solar elemental ratios (i.e., \( \text{C}/\text{O} = 0.55 \), \( \text{N}/\text{O} = 0.14 \)), the \( \text{CH}_4/\text{H}_2\text{O} \) \( (\text{NH}_3/\text{H}_2\text{O}) \) ratio is expected to be \( \sim 0.5 \) \( (\sim 0.1) \). However, we do not detect \( \text{CH}_4 \) or \( \text{NH}_3 \) despite their strong absorption in the HST WFC3 and/or Spitzer 3.6\( \mu \text{m} \) bands. As shown in Figure 1, the retrieved posteriors of the \( \text{CH}_4 \) and \( \text{NH}_3 \) abundances are largely sub-solar, with 99% upper limits of \( 3.47 \times 10^{-2} \) and \( 5.75 \times 10^{-5} \), respectively.
Four models are considered with different treatments of clouds and hazes. For each model, the volume mixing ratios shown along with the Bayesian evidence are as follows:

**Case 1: Full model, inhomogenous clouds and hazes**

- $\log(X_{\text{H}_2\text{O}}) = -2.11^{+1.16}_{-1.19}$
- $\log(X_{\text{CH}_4}) = -8.20^{+2.33}_{-2.34}$
- $\log(X_{\text{NH}_3}) = -8.64^{+1.35}_{-1.66}$
- $\ln(Z) = 179.15$
- Reference

**No H$_2$O**

- N/A

**Case 2: Clear atmosphere**

- $\log(X_{\text{H}_2\text{O}}) = -1.11^{+0.53}_{-0.52}$
- $\log(X_{\text{CH}_4}) = -7.27^{+2.91}_{-2.92}$
- $\log(X_{\text{NH}_3}) = -175.30$
- 3.25

**Case 3: Opaque cloud deck**

- $\log(X_{\text{H}_2\text{O}}) = -2.18^{+1.14}_{-1.12}$
- $\log(X_{\text{CH}_4}) = -8.27^{+2.24}_{-2.20}$
- $\log(X_{\text{NH}_3}) = -8.60^{+1.16}_{-1.15}$
- $\ln(Z) = 179.05$
- 1.20

**Case 4: Inhomogenous clouds**

- $\log(X_{\text{H}_2\text{O}}) = -2.10^{+1.16}_{-1.12}$
- $\log(X_{\text{CH}_4}) = -8.26^{+2.34}_{-2.20}$
- $\log(X_{\text{NH}_3}) = -8.61^{+1.18}_{-1.10}$
- $\ln(Z) = 179.41$
- N/A

Note. Four models are considered with different treatments of clouds and hazes. For each model, the volume mixing ratios ($\log(X_{\text{H}_2\text{O}})$, $\log(X_{\text{CH}_4})$, and $\log(X_{\text{NH}_3})$) are shown along with the Bayesian evidence ($\ln(Z)$) and DS. The DS is derived from the Bayesian evidence and a value below 2.0σ is considered weak (Trotta 2008). The preference of the reference model (case 1) over other models is quantified by the DS. For example, the DS for case 2 implies that case 1 is preferred over case 2 at 1.2σ. H$_2$O is detected at 3.25σ and clouds/hazes at only ~1σ.

These sub-solar values are in contrast to the largely super-solar H$_2$O, arguing against chemical equilibrium at solar elemental ratios.

We do not find strong evidence for clouds/hazes in the atmosphere. Our model preference for clouds/hazes, relative to the cloud-free case, is marginal (1.2σ) compared to Benneke et al. (2019; 2.6σ). Our retrieved cloud-top pressure ($P_\text{ct}$) for the full case is weakly constrained to 0.1 mbar to 2 bar, close to the observable photosphere. Finally, we retrieve $P_\text{ct}$ for the full case to be 12–174 mbar corresponding to $R_p$. The median value of 0.05 bar is used as the surface boundary condition, pressure $P_\text{s}$, for the internal structure models in Section 3.1.

### 3. Internal Structure and Composition

In this section we use the observed bulk properties of K2-18b, namely the planetary mass ($M_p$), radius ($R_p$), and its atmospheric properties, to constrain its internal structure and thermodynamic conditions.

#### 3.1. Internal Structure Model

We model the interior of the planet with a canonical four-layer structure. The model comprises a two-component Fe + rock core consisting of an inner Fe layer and an outer silicate layer, a layer of H$_2$O, and an outer H/He envelope. Such a model spans the possible internal structures and compositions of super-Earths and mini-Neptunes (e.g., Valencia et al. 2010, 2013; Rogers et al. 2011; Lopez & Fortney 2014), as well as terrestrial planets and ice giants in the solar system (Guillot & Gautier 2014). The mass fractions of the different components ($x_{\text{Fe}}$, $x_{\text{rock}}$, $x_{\text{H}_2\text{O}}$, $x_{\text{env}}$) are free parameters in the model and sum to unity. Our present model is adapted from a three-layer model for super-Earths from Madhusudhan et al. (2012) comprising of Fe, rock, and H$_2$O, with the H/He envelope added in the present work.

The model solves the standard internal structure equations of hydrostatic equilibrium and mass continuity assuming spherical symmetry. The equation of state (EOS) for each of the two inner layers is adopted from Seager et al. (2007), who use the Birch–Murnaghan EOS (Birch 1952) for Fe (Ahrens 2000) and MgSiO$_3$ perovskite (Karaki et al. 2000). For the H$_2$O layer we use the temperature-dependent H$_2$O EOS compiled by Thomas & Madhusudhan (2016) from French et al. (2009), Sugimura et al. (2010), Fei et al. (1993), Seager et al. (2007), and Wagner & Prüß (2002). For the gaseous envelope we use the latest H/He EOS from Chabrier et al. (2019) for a solar helium mass fraction ($Y = 0.275$).

The EOS in the H/He and H$_2$O layers can have a significant temperature dependence, which we consider in our model. Past studies (Rogers et al. 2011; Valencia et al. 2013) considered analytic $P$–$T$ profiles for irradiated atmospheres derived using double gray approximations (Hansen 2008; Guillot 2010) with the internal and external fluxes and opacities as free parameters. We calculate self-consistent dayside $P$–$T$ profiles for K2-18b in the H/He envelope using the GENESIS code (Gandhi & Madhusudhan 2017). GENESIS solves line-by-line radiative transfer under assumptions of hydrostatic, radiative-convective, and thermochemical equilibrium. We include opacity due to H$_2$O (Rothman et al. 2010), as detected in the transmission spectrum (Section 2), H$_2$ Rayleigh scattering, clouds and H$_2$–H–H$_2$–He collision-induced absorption. We use an H$_2$O abundance of $10 \times$ solar (see Section 2) and also use $10 \times$ solar abundances for the cloud species. We include KCl, ZnS, and Na$_2$S clouds (Morley et al. 2013), for which we obtain opacities from Pinhas & Madhusudhan (2017). We further include water ice clouds using opacities from Budaj et al. (2015).

The $P$–$T$ profile also depends on the planetary internal flux, which is characterized by the internal temperature $T_{\text{int}}$. We consider values of $T_{\text{int}}$ which span the range expected for a planet with the mass and radius of K2-18b and an age of 1–10 Gyr, with envelope compositions from solar to water-rich. We choose end-member cases of $T_{\text{int}} = 25$ and 50 K, consistent with previous studies on planets of similar mass and radius, e.g., GJ 1214b (e.g., Valencia et al. 2013). The GENESIS models are calculated between pressures of $10^{-5}$–$10^{3}$ bar, and assume full redistribution of the incident stellar irradiation. We explore a range of $P$–$T$ profiles and choose two representative cases, with different $T_{\text{int}}$, discussed further in Sections 3.2 and 3.3. Where required by the internal structure model, the bottom of the $P$–$T$ profile of the H/He envelope is continued to deeper pressures using the adiabatic gradient from Chabrier et al. (2019). We also employ an adiabatic temperature profile in the H$_2$O layer, following Thomas & Madhusudhan (2016).

#### 3.2. Constraints on Interior Composition

Figure 2 shows mass–radius ($M$–$R$) relations for models with different interior compositions. We explore the full range of plausible interior compositions in three components: $x_{\text{core}} = x_{\text{Fe}} + x_{\text{rock}}$, $x_{\text{H}_2\text{O}}$, and $x_{\text{env}}$, where $x_i = M_i/M_p$ is the mass fraction of each component $i$. For each atmospheric $P$–$T$ profile considered, we explore two different core compositions: (1) an Earth-like core made of 33% Fe, 67% rock by mass, and (2) a
mass fractions are shown in the legend. The solid magenta, teal, and orange lines represent the same composition as the solid magenta line, with but a mixed $H_2O$-$H/He$ envelope. Also shown are exoplanets whose masses and radii are known to span $\geq3\sigma$ with $T_{\text{eq}} < 1000$ K, from TEPCat (Southworth 2011).

3.3. Atmosphere–Ocean Boundary

Our constraints on the interior compositions of K2-18b result in a wide range of thermodynamic conditions at the $H_2O$-$H/He$ boundary (HHB). The pressure ($P_{\text{HHB}}$) and temperature ($T_{\text{HHB}}$) at the HHB for the model solutions are shown in Figure 4. Each point on the HHB loci denotes the transition from the $P–T$ profile in the $H/He$ envelope to the corresponding $H_2O$ adiabat. The $P_{\text{HHB}}$ and $T_{\text{HHB}}$ depend on the $H/He$ envelope mass fraction. For a given $P–T$ profile, larger envelopes result in higher $P_{\text{HHB}}$ and $T_{\text{HHB}}$. For example, solutions with $x_{\text{env}} \geq 1\%$ lead to $P_{\text{HHB}}$ and $T_{\text{HHB}}$ corresponding to the supercritical phase of $H_2O$. As shown in Figure 3, solutions with higher $x_{\text{env}}$ correspond to higher $x_{\text{core}}$ and lower $x_{H_2O}$.

Conversely, solutions with lower $x_{\text{core}}$ and, hence, lower $x_{\text{env}}$ and higher $x_{H_2O}$, lead to lower $P_{\text{HHB}}$ and $T_{\text{HHB}}$ with $H_2O$ in vapor or liquid phases at the HHB. For example, an $x_{\text{core}} \lesssim 30\%$ leads to a $P_{\text{HHB}}$ and $T_{\text{HHB}}$ corresponding to the liquid phase of $H_2O$, for the cooler $P–T$ profile (with $T_{\text{ini}} = 25$ K). For $x_{\text{core}} \lesssim 10\%$ or less, the $P_{\text{HHB}}$ and $T_{\text{HHB}}$ approach STP conditions for liquid $H_2O$. Below the HHB, $H_2O$ is found in increasingly dense phases spanning liquid, vapor, supercritical, and ice states depending on the location of the HHB and the extent of the $H_2O$ layer, as shown in Figure 4. In the case of a mixed $H_2O$-$H/He$ envelope, the HHB is undefined as it corresponds to an extreme case with no pure $H_2O$ layer.

4. Discussion

Our constraints on the interior and atmospheric properties of K2-18b provide insights into its physical conditions, origins, and potential habitability.

4.1. Possible Compositions and Origins

Here we discuss three representative classes that span the range of possible compositions, as indicated in Figures 2–4. The specific cases chosen here fit the $M_p$ and $R_p$ exactly, as shown in Figure 2. A wider range of solutions exist in each of these classes within the $1\sigma$ uncertainties.

Case 1: Rocky World. One possible scenario is a massive rocky interior overlaid by a $H/He$ envelope. For example, a pure Fe core of 94.7% by mass with an almost maximal $H/He$ envelope of 5% explains the data with minimal $x_{H_2O} = 0.3\%$, consistent with our retrieved $H_2O$ abundance in the atmosphere. The HHB in this case is at $\sim10^6$ bar, yielding supercritical $H_2O$ close to the ice $X$ phase. It is also possible in this case that the $H_2O$ and $H/He$ are mixed, meaning the HHB is not well defined. Such a scenario is consistent with either $H_2$ outgassing from the interior (Elkins-Tanton & Seager 2008; Rogers & Seager 2010) or accretion of a $H_2$-rich envelope during formation (Lee & Chiang 2016).

Case 2: Mini-Neptune. There are a range of plausible compositions consisting of a non-negligible $H/He$ envelope in addition to significant $H_2O$ and core mass fractions, akin to canonical models for Neptune and Uranus (Guillot & Gautier 2014). One such example is a 45% Earth-like core with $x_{\text{env}} = 0.03\%$ and $x_{H_2O} = 54.97\%$. In this case the HHB is at $P_{\text{HHB}} = 700$ bar and $T_{\text{HHB}} = 1500$ K, with $H_2O$ in the supercritical phase.

Case 3: Water World. A $\sim100\%$ water world with a minimal $H_2$-rich atmosphere ($x_{\text{env}} \sim 10^{-6}$) is permissible by the data.

Figure 2. Model $M–R$ relations for planets with different compositions. The mass fractions are shown in the legend. The solid magenta, teal, and orange lines represent the same composition as the solid magenta line, but with a mixed $H_2O$-$H/He$ envelope. Also shown are exoplanets whose masses and radii are known to span $\geq3\sigma$ with $T_{\text{eq}} < 1000$ K, from TEPCat (Southworth 2011).
However, such an extreme case is implausible from a planet formation perspective; some amount of rocky core is required to initiate further ice and gas accretion (Léger et al. 2004; Rogers et al. 2011; Lee & Chiang 2016). For example, a planet with $x_{\text{env}} = 10\%$, $x_{H_2O} = 89.994\%$ and a thin H/He envelope ($x_{\text{env}} = 0.006\%$) can explain the data. For this case, $P_{\text{HHB}} = 130$ bar and $T_{\text{HHB}} = 560$ K, corresponding to liquid H$_2$O. For the same core fraction, solutions with even smaller H/He envelopes are admissible within the $1\sigma$ uncertainties on $M_p$ and $R_p$, leading to $P_{\text{HHB}}$ and $T_{\text{HHB}}$ approaching habitable STP conditions.

4.2. Potential Habitability

A notional definition of habitability argues for a planetary surface with temperatures and pressures conducive to liquid H$_2$O (e.g., Kasting et al. 1993; Meadows & Barnes 2018). Living organisms are known to thrive in Earth’s extreme
hydrothermal vents

(Alternative pathways of liquid water: He-rich atmospheres orbiting M-dwarfs (e.g., Pierrehumbert & Gaidos 2011; Seager et al. 2013; Koll & Cronin 2019). Given our constraints above, we find that K2-18b has a realistic chance of being habitable. Furthermore, our constraints on CH₄ and NH₃ suggest chemical disequilibrium. Among other possibilities for chemical disequilibrium, e.g., photochemistry, the potential influence of biochemical processes may not be entirely ruled out. Future observations, e.g., with the James Webb Space Telescope, will have the potential to refine our findings. We argue that planets such as K2-18b can indeed have the potential to approach habitable conditions and searches for biosignatures should not necessarily be restricted to smaller rocky planets.

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References

Ahrens, T. J. 2000, Mineral Physics & Crystallography: A Handbook of Physical Constants (Washington, DC: American Geophysical Union).
Anglada-Escudé, G., Amado, P. J., Barnes, J. et al. 2016, Nature, 536, 437
Atreya, S. K., Crider, A., Guillot, T., et al. 2016, in Saturn in the 21st Century, ed. K. H. Baines et al. (Cambridge: Cambridge Univ. Press), 5
Barber, R. J., Strange, J. K., Hill, C., et al. 2014, MNRAS, 437, 1828
Benneke, B., Werner, M., Petigura, E., et al. 2017, ApJ, 834, 187
Benneke, B., Wong, I., Fialalet, C. et al. 2019, ApJL, 887, L14

Birch, F. 1952, JGR, 57, 227
Buchner, J., Georgakakis, A., Nandra, K., et al. 2014, A&A, 564, A125
Budaj, J., Kocifaj, M., Salmeron, R., & Hubeny, I. 2015, MNRAS, 454, 2
Burrows, A., & Sharp, C. M. 1999, ApJ, 512, 843
Chabrier, G., Mazevet, S., & Souffran, F. 2019, ApJ, 872, 51
Cloutier, R., Astudillo-Defru, N., Doyon, R., et al. 2017, A&A, 608, A35
Cloutier, R., Astudillo-Defru, N., Doyon, R., et al. 2019, A&A, 621, A49
Dittmann, J. A., Irwin, J. M., Charbonneau, D., et al. 2017, Natur, 544, 333
Dressing, C. D., & Charbonneau, D. 2015, ApJ, 807, 45
Elkins-Tanton, L. T., & Seager, S. 2008, ApJ, 685, 1237
Fei, Y., Mao, H., & Hemley, R. J. 1993, JChPh, 99, 5369
Feroz, F., Hobson, M. P., & Bridges, M. 2009, MNRAS, 398, 1601
Foreman-Mackey, D., Montet, B. T., Hogg, D. W., et al. 2015, ApJ, 806, 215
French, M., Mattsson, T. R., Nettelmann, N., & Redmer, R. 2009, PhRvB, 79, 054107
Gandhi, S., & Madhusudhan, N. 2017, MNRAS, 472, 2334
Gillon, M., Triaud, A. H. M. J., Demory, B.-O., et al. 2017, Natur, 542, 456
Guillot, T. 2010, A&A, 520, A27
Guillot, T., & Gautier, D. 2014, in Treatise on Geophysics, ed. T. Spohn & G. Schubert (2nd ed.; Amsterdam: Elsevier), 529
Hansen, B. M. S. 2008, ApJS, 179, 484
Karki, B. B., Wentzcovitch, R. M., de Gironcoli, S., & Baroni, S. 2000, PhRvB, 62, 14790
Kasting, J. F., Whitmire, D. P., & Reynolds, R. T. 1993, Icar, 101, 108
Koll, D. D. B., & Cronin, T. W. 2019, ApJ, 881, 120
Lee, E. J., & Chiang, E. 2016, ApJ, 817, 90
Léger, A., Selsis, F., Sotin, C., et al. 2004, Icar, 169, 499
Lopez, E. D., & Fortney, J. J. 2014, ApJ, 792, 1
Madhusudhan, N., Lee, K. K. M., & Mousis, O. 2012, ApJL, 759, L40
Meadows, V. S., & Barnes, R. K. 2018, in Handbook of Exoplanets, ed. H. J. Deeg & J. A. Belmonte (Berlin: Springer), 57
Merino, N., Aronson, H. S., Bojana, D. P., et al. 2019, Frontiers in Microbiology, 10, 780
Montet, B. T., Morton, T. D., Foreman-Mackey, D., et al. 2015, ApJ, 809, 25
Morley, C. V., Fortney, J. J., Kempton, E. M. R., et al. 2013, ApJ, 775, 33
Mulders, G. D., Pascucci, I., & Apai, D. 2015, ApJ, 814, 130
Nettelmann, N., Fortney, J. J., Kramm, U., & Redmer, R. 2011, ApJ, 733, 2
Pierrehumbert, R., & Gaidos, E. 2011, ApJL, 734, L13
Pinhas, A., & Madhusudhan, N. 2017, MNRAS, 471, 4355
Pinhas, A., Madhusudhan, N., Gandhi, S., & MacDonald, R. 2019, MNRAS, 482, 1485
Richard, C., Gordon, I. E., Rothman, L. S., et al. 2012, JQSRT, 113, 1276
Rogers, L. A., Bodenheimer, P., Lissauer, J. J., & Seager, S. 2011, ApJ, 738, 59
Rogers, L. A., & Seager, S. 2010, ApJ, 716, 1208
Rothman, L. S., Gordon, I. E., Barber, R. J., et al. 2010, JQSRT, 111, 2139
Seager, S., Bains, W., & Hu, R. 2013, ApJ, 777, 95
Seager, S., Kuchner, M., Hier-Majumder, C. A., & Militzer, B. 2007, ApJ, 669, 1279
Soubiran, F., & Militzer, B. 2015, ApJ, 806, 228
Southworth, J. 2011, MNRAS, 417, 2166
Sugimura, E., Komabayashi, T., Hirose, K., et al. 2010, PhRvB, 82, 134103
Thomas, S. W., & Madhusudhan, N. 2016, MNRAS, 458, 1330
Trotta, R. 2008, ConPh, 49, 71
Tsiaras, A., Waldmann, I. P., Tinetti, G., Tennyson, J., & Yurchenko, S. N. 2019, NatAs, 3, 1086
Valencia, D., Guillot, T., Parmentier, V., & Freedman, R. S. 2013, ApJ, 775, 10
Valencia, D., Ikoma, M., Guillot, T., & Nettelmann, N. 2010, A&A, 516, A20
Wagner, W., & Prü, A. 2002, JPCRD, 31, 387
Welbanks, L., & Madhusudhan, N. 2019, AJ, 157, 206
Welbanks, L., Madhusudhan, N., Allard, N. F., et al. 2019, ApJL, 887, L20
Yurchenko, S. N., Barber, R. J., & Tennyson, J. 2011, MNRAS, 413, 1828
Yurchenko, S. N., & Tennyson, J. 2014, MNRAS, 440, 1649