The Habitability of Proxima Centauri b I: Environmental Context

Rory Barnes[1,2,3], Russell Deitrick[1,2], Rodrigo Luger[1,2], Peter E. Driscoll[4,2], Thomas R. Quinn[1,2], David P. Fleming, Benjamin Guyer, Diego V. McDonald, Victoria S. Meadows, Giada Arney, David Crisp, Shawn D. Domagal-Goldman, Andrew Lincowski, Jacob Lustig-Yeager, Eddie Schwieterman

ABSTRACT

1. Introduction

The discovery of Proxima Centauri b, hereafter Proxima b, heralds a new era in the exploration of exoplanets. Although very little is currently known about it and its environment, the planet is likely terrestrial and receives an incident flux that places it in the "habitable zone" (HZ) (Kasting et al. 1993; Selsis et al. 2007; Kopparapu et al. 2013). Moreover, Proxima b is distinct from other discoveries in that it is the first potentially habitable planet that could be directly characterized by space telescopes such as WFIRST and concept missions such as LUVOIR, HDST, and HabEx. Such remote sensing is possible because the angular separation of the planet and star as viewed from Earth is 37 mas. Proxima b will likely be the first exoplanet to be spectroscopically probed for active biology.

The interpretation of these spectra require a firm understanding of the history of Proxima b and its host system. Proxima b exists in an environment that is significantly different from Earth and has likely experienced different phenomena that could preclude or promote the development of life. When viewed across interstellar distances, biology is best understood as a planetary process; life is a global phenomenon that alters geochemical and photochemical processes. Spectroscopic indicators of life, *i.e.* biosignatures, can only be identified if the abiotic processes on a planet are understood – no single feature in a spectrum is a "smoking gun" for life on all planets. A robust detection of extraterrestrial life requires that all plausible non-biological sources for all observed spectral features can be ruled out. This requirement is a tall order, especially in light of the expected diversity of terrestrial exoplanets

[1]Astronomy Department, University of Washington, Box 951580, Seattle, WA 98195

[2]NASA Astrobiology Institute – Virtual Planetary Laboratory Lead Team, USA

[3]E-mail: rory@astro.washington.edu

in the galaxy, but Proxima b may offer the best opportunity to begin the scientific process of searching for unambiguous signs of life.

In this study we leverage the known (but sparse) data on Proxima b and its host system to predict the range of evolutionary pathways that the planet may have experienced. As we show below, many histories are possible and depend on factors ranging from the cooling rate of b's core, to the orbital evolution of the stellar system through the Milky Way, and everywhere in between. The evolution of Proxima b, and by extension its potential habitability, depends on physical processes that have tended to be studied by scientists that work in different fields, such as geophysics and astrophysics. However, for the purpose of interpreting Proxima b, these divisions must be eradicated. Our examination of Proxima b will draw on simple, but realistic, models that have been developed in the fields of geophysics, planetary science, atmospheric science and astrophysics. From this synthesis, we identify numerous obstacles and opportunities for life to develop on Proxima b, as well as lay a foundation for the future interpretation of spectroscopic observations.

This paper is organized as follows. In § 2 we review the observational data on the system and the immediate implications for habitability. In § 3 we describe models to simulate the evolution of the system, with a focus on habitability. In this section we introduce a new software package called `VPLANET`, which couples physical models of planetary interiors, atmospheres, spins and orbits, stellar evolution, and galactic effects. In § 4 we present results of these models. An exhaustive analysis of all histories is too large to present here, so in this section we present highlights and end-member cases that bracket the plausible ranges. In § 5 we discuss the results and identify additional observations that could improve modeling efforts and connect our results to the companion paper (Meadows in prep.). Finally in § 6 we draw our conclusions.

2. Observational Constraints

In this section we review what is known about the triple star system Alpha Centauri (hereafter α Cen) of which Proxima Centauri may be a member. This star system has been studied carefully for centuries as it is the closest to Earth. We will first review the direct observational data, then we will make whatever inferences are possible from those data, and finally we qualitatively consider how these data constrain the possibility for life to exist on Proxima b, which will then guide the models described in the next section.

2.1. Properties of the Proxima Planetary System

Precious little data exist for Proxima b. The radial velocity data reveal a planet with a minimum mass m of 1.27 $M_\oplus$, an orbital period P of 11.186 days, and an orbital eccentricity e less than 0.35 and Anglada-Escudé (2016) report a mean longitude λ of 110°. These data are the extent of the direct observational data on the planet, but even the minimum mass relies on uncertain estimates of the mass of the host star, described below.

Proxima b may not be the only planet orbiting Proxima Centauri. The Doppler data suggest the presence of another planetary mass companion with an orbital period near 215 days, but it is not definitive yet (Anglada-Escudé 2016). If present, the planet has a projected mass of $\lesssim$ 10 $M_\oplus$, consistent with previous non-detections (Endl & Kürster 2008; Barnes et al. 2014; Lurie et al. 2014). The orbital eccentricity and it relative inclination to Proxima b's orbit are also unknown, but as described below, could take any value that permits dynamical stability. Additional, lower mass and/or more distant, planetary companions could also be present in the system.

2.2. Properties of the Host Star

As Proxima Centauri is the closest star to Earth, it has been studied extensively since its discovery 100 years ago (Innes 1915). It has a radius R_* of 0.14 $R_\odot$, a temperature T_{eff} of 3050 K, a luminosity L_* of 0.00155 $L_\odot$ (Boyajian et al. 2012), and a rotation period P_* of 83 days (Benedict et al. 1998). Wood et al. (2001) searched for evidence of stellar winds, but found none, indicating mass loss rates $\dot{M}_*$ less than 20% of our Sun's, *i.e.* $< 4 \times 10^{-15}$ $M_\odot$/yr. Proxima Centauri possesses a much larger magnetic field ($B = 600 \pm 150$ G) than our Sun (1 G) (Reiners & Basri 2008), but somewhat low compared to the majority of low mass stars.

Like our Sun, Proxima Centauri's luminosity varies slowly with time due to starspots (Benedict et al. 1993). HST observations of Proxima Centauri found variations up to 70 mmag in V (Benedict et al. 1998), which, corresponds to about a 17.5% change with a period of 83.5 days (*i.e.* the rotation period). Moreover, (Benedict et al. 1998) found evidence for two discrete modes of variability, one lower amplitude mode ($\Delta V \sim 30$ mmag) with a period of $\sim$ 42 days, and a larger amplitude mode ($\Delta V \sim 60$ mmag with a period of 83 days. These periods are a factor of 2 of each other, leading Benedict et al. (1998) to suggest that sometimes a large spot (or cluster of spots) is present on one hemisphere only, while at other times smaller spots exist on opposite hemispheres. Regardless, incident stellar radiation ("instellation") variations of 17% could impact atmospheric evolution and surface conditions of a planet (the sun's variation is of order 0.1% (Willson et al. 1981)).

Additionally the magnetic field strength may vary with time. Cincunegui et al. (2007) monitored the H and K CaII lines, which are indicators of chromospheric activity, as well as Hα for 7 years and found modest evidence for a 442 day cycle in stellar activity. Although it is unclear the strength of Proxima's magnetic field at the orbit of planet b, it could contribute to the stability of b's atmosphere and potentially affect any putative life on b.

Proxima Centauri is a known flare star (Shapley 1951)[1] and indeed several flares were reported during the Pale Red Dot campaign Anglada-Escudé (2016). Walker (1981) performed the first study of the frequency of flares as a function of energy, finding that high energy events ($\sim 10^{30}$ erg) occurred about once per day, while lower energy events ($\sim 10^{28}$ erg) occurred about once per hour. Numerous observational campaigns since then have continued to find flaring at about this frequency (Benedict et al. 1998; Anglada-Escudé 2016).

2.3. Properties of the Stellar System

Proxima Centauri is $\approx 15,000$ AU from two larger stars, Alpha Centauri A and B (hereafter α Cen A and B), but all three have the same motion through the galaxy. Finally, the proper motion and radial velocity of the center of mass of α Cen A and B permit the calculation of the system's velocity relative to the local standard of rest. Poveda et al. (1996) find the three velocities are (U, V, W) = (-25,-2,13) km/s for the center of mass. This velocity implies the system is currently approaching Earth, and is on a roughly circular orbit around the galaxy with an eccentricity of 0.07 Allen & Herrera (1998).

A recent, careful analysis of astrometric and HARPS RV data by Pourbaix & Boffin (2016) found the masses of the two stars to be 1.133 and 0.972 $M_\odot$, respectively, with an orbital eccentricity of 0.52 and a period of 79.91 years. The similarities between both A and B and the Sun, as well as their low apparent magnitudes, has allowed detailed studies of their spectral and photometric properties. These two stars (as well as Proxima) form a foundation in stellar astrophysics, and hence a great deal is known about A and B. However, as we describe below, many uncertainties still remain regarding these two stars.

The spectra of α Cen A and B can provide information about the stars temperature, gravitational acceleration in the photosphere, rotation rate, and composition. That these features can be measured turns out to be critical for our analysis of the evolution of Proxima

[1]Although Shapley is the sole author of his 1951 manuscript, the bulk of the work was performed by two female assistants, C.D. Boyd, and V.M. Nail.

b. Proxima Centauri is a low mass star and hence its composition is far more difficult to measure than for G and K dwarfs like α Cen A and B. Recently, Hinkel & Kane (2013) completed a reanalysis of published compositional studies, rejecting the studies of (Laird 1985) and (Neuforge-Verheecke & Magain 1997) because they were too different from the other 5 they considered, and found the means of metallicities [Fe/H] of the two stars to be +0.28 and +0.31 and with a large spread of 0.16 and 0.11, respectively. While it is frustrating that different groups have arrived at significantly different iron abundances, it is certain the stars are more metal-rich than the Sun.

(Hinkel & Kane 2013) go on to examine 21 other elements, including C, O, Mg, Al, Si, Ca, and Eu. These elements can be important for the bulk composition and/or are tracers of other species that are relevant to planetary processes. In nearly all cases, the relative abundance of these elements to Fe is statistically indistinguishable from the solar ratios. Exceptions are Na, Zn and Eu in α Cen A, and V, Zn, Ba and Nd in α Cen B. The discrepancies between the two stars is somewhat surprising given their likely birth from the same molecular cloud. On the other hand, the high eccentricity of their orbit could point toward a capture during the open cluster phase (cite). For all elements beside Eu, the elemental abundances relative to Fe are larger than in the Sun. In particular, it seems likely that the stars are significantly enriched in Zn.

α Cen A and B are large enough and bright enough for asteroseismic studies that can reveal physical properties and ages of stars to a few percent, for high enough quality data (cite). Indeed, these two stars are central to the field of asteroseismology, and have been studied in exquisite detail. However, significant uncertainties persist in our understanding of these stars, despite all the observational advantages.

A recent study undertook a comprehensive Bayesian analysis of α Cen A with priors on radius, composition, and mass derived from interferometric, spectroscopic and astrometric measurements, respectively (Bazot et al. 2016). Their adopted metallicity constraint comes from (Neuforge-Verheecke & Magain 1997) via (Thoul et al. 2003), which was rejected by the (Hinkel & Kane 2013) analysis. They also used an older mass measurement from (Pourbaix et al. 2002), which is slightly smaller than the updated mass from (Pourbaix & Boffin 2016). They then used an asteroseismic code to determine the physical characteristics of A. Although the mass of A is similar to the Sun at 1.1 $M_\odot$, the simulations of Bazot et al., found that α Cen A's core lies at the radiative/convective boundary and the transition between pp- and CNO-dominated energy production chains in the core. Previous results found the age of α Cen A to be 4.85 Gyr with a convective core (Thévenin et al. 2002), or 6.41 Gyr without a convective core (Thoul et al. 2003). The ambiguity is further increased by uncertainty in the efficiency of the $^{14}N(p,\gamma)^{15}O$ reaction rate in the CNO cycle, and by uncertainty regarding the possibility of convective overshooting of hydrogen into the core. They also consider the role of "microscopic diffusion" which is the settling heavy elements over long time intervals. All these uncertainties prevent a precise and accurate measurement of α Cen A's age. Combining the different model predictions and include 1σ uncertainties, the age of α Cen A is between 3.4 and 5.9 Gyr, with a mean of 4.78 Gyr.

α Cen B has also been studied via asteroseismology, but as with A, the results have not been consistent. Lundkvist et al. (2014) find significant discrepancies between their "Asteroseismology Made Easy" age (1.5 Gyr) with other values, but with uncertainties in excess of 4 Gyr. The asteroseismic oscillations on B are much smaller than on A, which make analyses more difficult (see, *e.g.* Carrier & Bourban 2003), leading to the large uncertainty. Combining studies of A and B, we must conclude that the ages of the two stars are uncertain to at least 25%. Given the difficulty in measuring B's asteroseismic pulsations, we will rely on A's asteroseismic data and assume the age of A and B to be $4.8^{+1.1}_{-1.4}$.

2.4. Inferences from the Observational Data

Because Proxima b was discovered indirectly, its properties and evolution depend critically on our knowledge of the host star's properties. Although many properties are known, the mass M_{Prox}, age, T, and composition are not. The spectra and luminosity suggest the mass of Proxima is $\sim$ 0.12 $M_\odot$ (Delfosse et al. 2000). If we adopt this value, then the semi-major axis of b's orbit is 0.0485 AU and the planet received 65% of the instellation as Earth receives from the Sun Anglada-Escudé (2016). Note that Sahu et al. (2014) suggested that Proxima's proper motion sent it close enough to two background stars for the general relativistic deflection of their light by Proxima to be detectable with HST and should allow the determination of M_{Prox} to better than 10%, but those results are not available yet.

Additional inferences rely on the assumption that Proxima formed with the α Cen binary. The similarities in the proper motion and parallax between Proxima and α Cen immediately led to speculation as to whether the stars are "physically connected or members of the same drift" (Voûte 1917), *i.e.* are they bound or members of a moving group? The intervening century has failed to resolve this central question. If Proxima is just a random star in the solar neighborhood, Matthews & Gilmore (1993) concluded that probability that Proxima would appear so close to α Cen is about 1 in a million, suggesting it is very likely the stars are somehow associated with each other. Using updated kinematic information, (Anosova et al. 1994) conclude that Proxima is not bound, but instead part of a moving group consisting of about a dozen stellar systems. Wertheimer & Laughlin (2006)'s reanalysis found that the observational data favor a configuration that is at the boundary between bound and unbound orbits. However, their best fit bound orbit is implausibly large as the semi-major axis is 1.31 pc, *i.e.* larger than the distance from Earth to Proxima. Matvienko & Orlov (2014) also failed to unequivocally resolve the issue, and conclude that RV precision of better than 20 m/s is required to determine if Proxima is bound, which should be available in the data from (Anglada-Escudé 2016). Perhaps the discovery data for Proxima b will also resolve this long-standing questions.

Regardless of whether Proxima is bound or not, the very low probability that the stars would be so close to each other strongly supports the hypothesis that the stars formed in the same star cluster. We will assume that they are associated and have approximately equal ages and similar compositions. An age near 5 Gyr for Proxima is also consistent with its rotation period and relatively modest activity levels and magnetic field (Reiners & Basri 2008).

The radial velocity data combined with aM_{Prox} only provide a minimum mass, but significantly larger planet masses are unlikely geometrically, and very large masses can be excluded because they would incite detectable astrometric signals (note that the minimum mass solution predicts an astrometric orbit of the star of ∼1 microsecond of arc). It is very likely the planet has a mass less than 10 $M_\oplus$, and probably $<$ 3 $M_\oplus$. We will assume the latter possibility is true, and hence the planet is likely rocky, based on statistical inferences of the population of *Kepler* planets Weiss & Marcy (2014); Rogers (2015). However, even at the minimum mass, we cannot exclude the possibility that Proxima b possesses a significant hydrogen envelope. Such a world is unlikely to be habitable (but see Pierrehumbert & Gaidos 2011) and hence we cannot at this time state unequivocally that Proxima b is not a "mini-Neptune", let alone if it is habitable.

If non-gaseous, the composition is still highly uncertain and depends on the unknown formation process. Several possibilities exist according to recent theoretical studies: 1) the planet formed *in situ* from local material; 2) the planet formed at a larger semi-major axis and migrated in while Proxima still possessed a protoplanetary disk; or 3) an instability in the system occurred that impulsively changed b's orbit. For case 1, the planet may be depleted in volatile material (Raymond et al. 2007; Lissauer 2007), but could still possess a significant water inventory (Mulders et al. 2015). For case 2, the planet would have likely formed beyond the snowline and hence could be very water-rich (Carter-Bond et al. 2012). For case 3, the planet could be either volatile-rich or poor depending on its initial formation location as well as the details of the instability, such as the frequency of impacts that occurred in its aftermath. We conclude that all options are possible given the data and for simplicity will assume the planet is Earth-like in composition. If we adopt the silicate planet scaling law of Sotin et al. (2007), the radius of a 1.3 $M_\oplus$ planet is 1.07 $R_\oplus$.

2.5. Implications for Proxima b's Evolution and Habitability

Given the above observations and their immediate implications, this planet may be able to support life. All life on Earth requires three basic ingredients: Water, energy, and the bioessential elements of C, H, O, N, S and P. Additionally these ingredients must be present in an environment that is stable in terms of temperature, pressure and pH for long periods of time. As we describe in this subsection, these properties are possible on Proxima b and hence the planet is potentially habitable, defined here to mean liquid water persisting on the surface for long timescales.

Proxima's luminosity and effective temperature combined with b's orbital semi-major axis place the planet in the habitable zone (HZ) of Proxima and nearly in the same relative position of Earth in the Sun's HZ. More specifically, the planet receives about 65% of Earth's instellation, which places b in the "optimistic" HZ, meaning that it would be very likely if the modern Earth would likely be habitable if it received that instellation. Even allowing for observational uncertainties, Anglada-Escudé (2016) find that the planet is in this optimistic HZ.

However, its habitability depends on many more factors than just the instellation. The planet must form with water and physical processes cannot subsequently remove it. Additionally, even if water is present, the evolution of Proxima depends on many other factors involving stellar effects, the planet's internal properties, and the gravitational influence of the other members of the stellar system.

The host star is about 10 times smaller and less massive than the Sun, the temperature is about half that of the Sun, and the luminosity is just 0.1% that of the Sun. These differences are significant and can have a profound effect on the evolution of Proxima b. Low mass stars can take billions of years to begin fusing hydrogen into helium in their cores, and the star's luminosity can change during that time. Specifically, the star contracts at constant temperature and so the star's luminosity drops with time. For the case of Proxima, this stage lasted $\sim$ 1 Gyr Baraffe et al. (2015) and hence Proxima b could have spend significant time interior to the HZ, *i.e.* in a runaway greenhouse state like Venus. This "pre-main sequence" phase could either strip away a primordial hydrogen atmosphere to reveal a "habitable evaporated core" (Luger et al. 2015), or, if b formed as a terrestrial planet, it could desiccate that planet and build up an oxygen-dominated atmosphere (Luger & Barnes 2015). Thus, the large early luminosity of the star could either be a help or hindrance for b's habitability.

Low mass stars also show significant activity, *i.e.* flares, coronal mass ejections, and bursts of high energy radiation (*e.g.* West et al. 2008). This activity can change the composition of the atmosphere through photochemistry, or even completely strip the atmosphere away. The tight orbit of Proxima b places it at risk of atmospheric stripping by these phenomena. A planetary magnetic field could increase the probability of atmospheric retention by deflecting charged particles, or it could decrease it by funneling high energy particles into the magnetic poles and providing enough energy to atmospheric particles to achieve escape velocity. Either way, the frequency of flaring and other high energy events, as well as the likelihood that Proxima b possesses a magnetic field, would be invaluable in assessing the longevity of Proxima b's atmosphere.

The close-in orbit also introduces the possibility that tidal effects can be significant on the planet. Tides can affect the planet in five ways. First, they could cause the rotation rate to evolve to a frequency that is equal to or similar to the orbital frequency, a process typically called tidal locking (Dole 1964; Kasting et al. 1993; Barnes 2016). Second, they can drive the planet's obliquity ψ to zero or π such that the planet has no seasons (Heller et al. 2011). Third, they can cause the orbital eccentricity to change, usually (but not always) driving the orbit toward a circular shape (Darwin 1880). Fourth, they can cause frictional heating in the interior called tidal heating (Peale et al. 1979; Jackson et al. 2008; Barnes et al. 2013). Finally, the can cause the semi-major axis to decay as orbital energy is transformed into frictional heat (Darwin 1880; Barnes et al. 2008). Except in extreme cases, these processes are unlikely to sterilize a planet, but they can profoundly affect the planet's evolution.

Although the abundances of elements relative to iron in α Cen A and B, and by extension Proxima, are similar to the Sun's, there is no guarantee that the abundance pattern is matched inside Proxima b. Planet formation is often a stochastic process and composition depends on the impact history of a given world. The planet could have formed near its current location, which would have been relatively hot early on and the planet could be relatively depleted in volatiles (Raymond et al. 2007; Mulders et al. 2015). These studies may even overestimate volatile abundances as they ignored the high luminosities that late M dwarfs have during planet formation. Alternatively the planet could have formed beyond the snowline and migrated in either while the gas disk was still present, or later during a large scale dynamical instability (see below). In those cases, the planet could be volatile-rich.

The depletion of Eu in α Cen A is also of note as it is often a tracer of radioactive material like ^{232}Th and ^{238}U (Young et al. 2014). These isotopes are primary drivers of the internal energy of Earth, and hence if they are depleted in Proxima b, it internal evolution could be markedly different than Earth's. However, since no depletion is observed in α Cen B, it is far from clear that such a depletion exists. One interesting radiogenic possibility is that the planet could form sufficiently quickly ($\sim$ 1 Myr) that ^{26}Al could still provide energy to the planet's interior. Hence any simulation of b's evolution should also consider its role.

The presence of additional planets can change the orbit and obliquity of planet b through gravitational perturbations. These interactions can change the orbital angular momentum of b and drive oscillations in e, the inclination i, longitude of periastron ϖ, and longitude of ascending node Ω. Changes in inclination can lead to changes in ψ as the planet's rotational axis is likely fixed in inertial space while the orbital plane precesses. These variations can significantly affect climate evolution and possibly even the planet's potential to support life (Armstrong et al. 2014).

If Proxima is bound to α Cen A and B, then perturbations by passing stars and torques by the galactic tide can cause drifts in Proxima's orbit about A and B (Kaib et al. 2013). During epochs of high eccentricity, Proxima may swoop so close to A and B that their gravity is able disrupt Proxima's planetary system. This could have occurred at any time in Proxima's past and can lead to a total rearrangement of the system. Thus, should additional planets exist in the Proxima planetary system, could be present on almost any orbit, with large eccentricities and large mutual inclinations with b's orbital plane.

The metallicity of Proxima Centauri is quite high for the solar neighborhood, which has a mean of -0.11 and standard deviation of 0.18 (Allende Prieto et al. 2004). Indeed, recent simulations of stellar metallicity distributions in the galaxy find that at the sun's galactic radius R_{gal} of $\sim$8 kpc, stars cannot form with [Fe/H]$> +0.15$ (Loebman et al. 2016). The discrepancy can be resolved by invoking radial migration (Sellwood & Binney 2002) in which stars on nearly circular orbits are able to ride corotation resonances with spiral arms inward and outward. Loebman et al. (2016) find that with migration, the metallicity distribution of stars in the Sloan Digital Sky Survey III's Apache Point Observatory Galactic Evolution Experiment (Hayden et al. 2015) is reproduced. Furthermore, Loebman et al. find that stars in the solar neighborhood with [Fe/H] $> +0.25$ must have formed at $R_{gal} < 4.5$ kpc. We conclude that this system has migrated outward at least 3.5 kpc, probably more. As the surface density scale length of the galaxy is $\sim$2.5 kpc, this implies that the density of stars at their formation radius was at least 5 times higher than the solar radius.

The observed and inferred constraints for the evolution of Proxima b are numerous, but the plausible range of evolutionary pathways is diverse. The proximity of two solar-type stars complicates the dynamics, but allows the extension of their properties to Proxima Centauri. In the next sections we apply quantitative models of the processes described in this section to full stellar system in order to explore the possible histories of Proxima b in detail.

3. Models

In this section we describe the models we use to consider the evolution and potential habitability of Proxima b. We generally use published models that are common to different disciplines of science. Although the models come from disparate sources, we have compiled them all into a new software program called VPLANET. This code is designed to simulate exoplanet evolution, with a focus on habitability. The problem of habitability is interdisciplinary, but we find it convenient to break the problem down into more manageable chunks, which we call "modules," that are applied when applicable. At this time, VPLANET consists of simple models that are all representable as an ordinary differential equation. Below we describe qualitatively the modules and direct the reader to the references for a quantitative description. We then briefly describe how VPLANET unifies these modules and integrates the system forward.

3.1. Stellar Evolution: STELLAR

3.2. Atmospheric Escape: ATMESC

3.3. Tidal Evolution: EQTIDE

To model the tidal evolution of the Proxima system, we will use a simple, but commonly-used model called the "constant-phase-lag" model (Goldreich 1966; Greenberg 2009; Heller et al. 2011). This model reduces the evolution to a single parameter Q which sets the timescale for the tidal evolution. While this model has known shortcoming (**?**Efroimsky & Makarov 2013), it provides a qualitatively accurate picture of tidal evolution, and is the model Kasting et al. (1993) used to calculate the "tidal lock radius". For this study, we use the model described in (Heller et al. 2011).

3.4. Orbital Evolution: `DISTORB`

3.5. Rotational Evolution from Orbits and the Stellar Torque: `DISTROT`

3.6. Radiogenic Heating: `RADHEAT`

3.7. Geophyiscal Evolution: `THERMINT`

3.8. Atmospheric Escape: `ATMESC`

3.9. Tidal Evolution: `EQTIDE`

To model the tidal evolution of the Proxima system, we will use a simple, but commonly-used model called the "constant-phase-lag" model (Goldreich 1966; Greenberg 2009; Heller et al. 2011). This model reduces the evolution to a single parameter Q which sets the timescale for the tidal evolution. While this model has known shortcoming (**?**Efroimsky & Makarov 2013), it provides a qualitatively accurate picture of tidal evolution, and is the model Kasting et al. (1993) used to calculate the "tidal lock radius". For this study, we use the model described in (Heller et al. 2011).

3.10. Galactic Effects: `GALHABIT`

3.11. The Coupled Model: `VPLANET`

The previous modules are combined into a single software program called `VPLANET`. This code is written in C and is designed to be modular so that for any given body, only specific modules are applied and specific parameters integrated forward. Parameters are integrated using a 4th order Runge-Kutta scheme with a timestep equal to η times the shortest timescale for all active parameters, *i.e.* $x/(dx/dt)$ where x is a parameter. We find converged results if $\eta < 0.01$. A more complete and quantitative description of `VPLANET` will be presented soon (Barnes et al., in prep.).

Each individual model is validated against observations in our Solar System or in stellar systems. When possible, conserved quantities are also tracked and required to maintain in acceptable limits. While a validation against a single system or uniform data set, not such observation exists for a full `VPLANET` simulation. Matching simulations to systems like Proxima Centauri is likely the only way to convincinly validate the code.

4. Results

4.1. Galactic Evolution

4.2. Orbital/Rotational/Tidal Evolution

We begin exploring the dynamical properties of the orbits and spins by considering the tidal evolution of planet b if it is in isolation. In this case, we need only apply `EQTIDE` to both Proxima and b and track a, e, P_{rot}, and ψ. We find that if planet b has $Q = 12$, then an initially Earth-like rotation state becomes tidally locked in $\sim 10^4$ years, so it seems likely that if b formed near its current location, then it formed in a tidally locked state and with negligible obliquity.

Unlike the rotational angular momentum, the orbit can evolve signficantly. In the top two panels of Fig. 1, we consider orbits that begin at $a = 0.05$ AU and with different eccentricities of 0.05 (dotted curves), 0.1 (solid curves) and 0.2 (dashed curves). In all cases a and e decrease and the amound of inward migration depends on the initial eccentricity, which takes 2–3 Gyr to damp to ~ 0.01.

The equilibrium tide model posits that the lost rotational and orbital energy is transformed in frictional heating inside the planet. The bottom pabel of Fig. 1 shows the average surface energy flux as a function of time. We address the geophysical implications of this tidal heating in § 4.4.2. Note that if planet b begins with a rotation period of 1 days and an obliquity of 23.5°, then the initial surface energy flux due to tidal heating is ~ 1000 W/m^2.

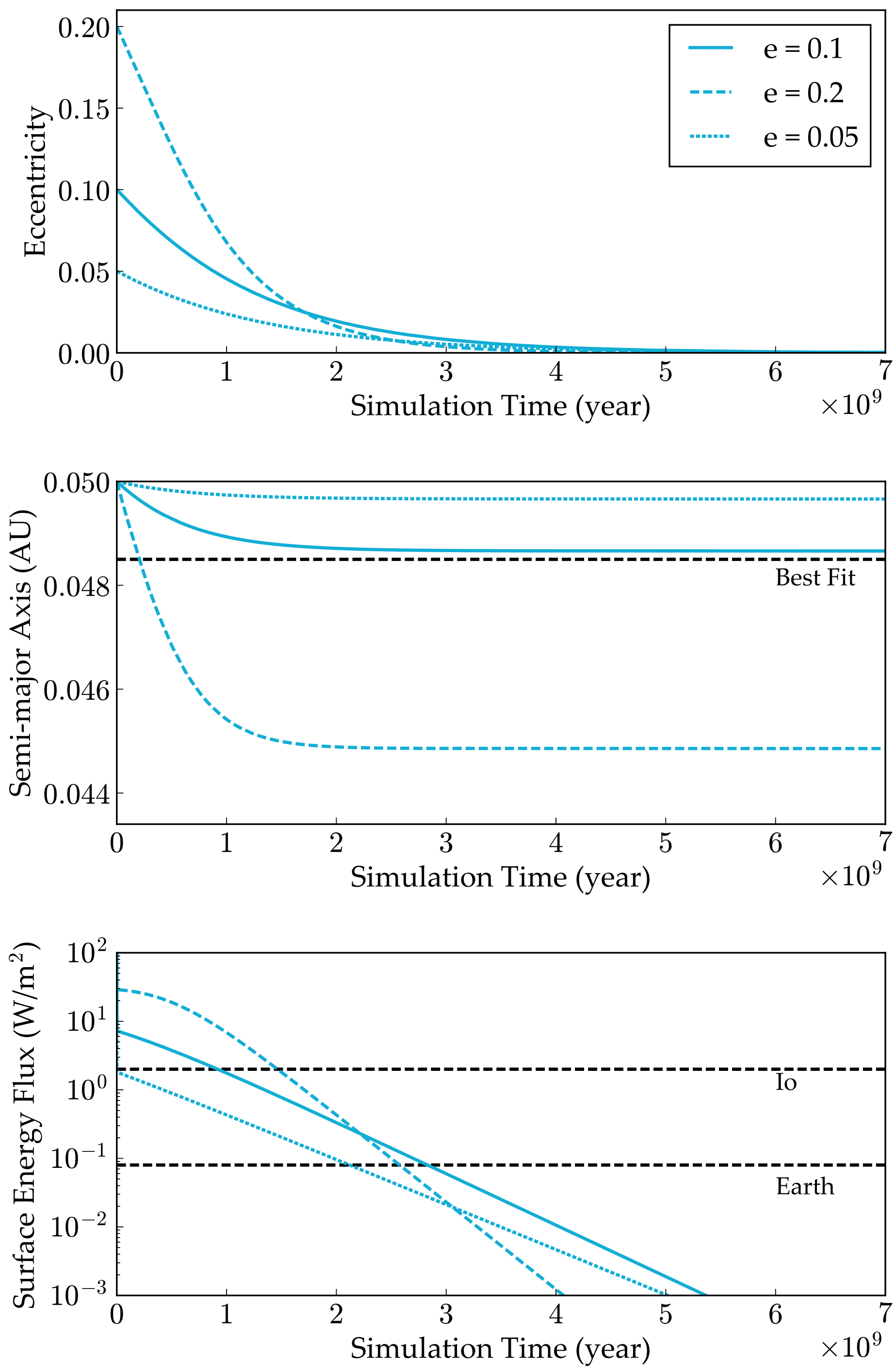

Fig. 1.— Evolution of planet b's eccentricity (top), semi-major axis (middle), and tidal heating surface flux (bottom) assuming that initially $a = 0.05$ AU and $e = 0.05$ (dotted), 0.1 (solid) or 0.2 (dashed). For reference the best fit semi-major axis and surface energy fluxes of Io and the modern Earth are shown by dashed black lines.

4.3. Stellar Evolution

4.4. Internal Evolution

4.4.1. Evolution without Tidal Heating

4.4.2. Evolution with Tidal Heating

4.4.3. Magnetic Fields

4.5. Atmospheric Evolution

5. Discussion

1) Proxima b is a habitable. We find that some scenarios allow for the planet to currently support surface water. In particular, the "habitable evaporated core" (Luger et al. 2015) is particularly promising as it can avoid both the high-luminosity pre-main sequence phase and any devastating tidal heating that may occur while the planet "surfs" the HZ migration, or during circularization after orbital destabilization. Such a world may be enriched in deuterium that remained during hydrogren escape, and it may also be geothermally active if it is young and enriched in potassium.

2) Proxima b is in a Venus-like state. Proxima spent signficant time in a runaway greenhouse prior to the arrival of the HZ, and hence it may have developed a dense CO_2 atmosphere as has occurred on Venus. In this case, the planet is uninhabitable as the surface temperature is too hot for liquid water, and the higher surface temperature results from greenhouse warming by CO_2

3) Proxima b has an oxygen-rich atmosphere. If Proxima b formed with a large water inventory, the pre-MS phase may have photolyzed water vapor and the hydrogen escaped. Although oxygen is highly reactive, thousands of bars of oxygen can be liberated through this mechanism (Luger & Barnes 2015) and hence all sinks for it may become saturated. In principle, thousands of bars of oxygen could remain. This planet is unlikely to be habitable, as the oxygen builds up early on, and large amounts of free oxygen are likely to stifle the pre-biotic chemistry necessary for life to originate.

5.1. Is Proxima b Habitable?

6. Conclusions

We have performed a comprehensive analysis of the evolution of the Proxima Centauri planetary system with a specific focus on planet b's habitability. We find that many disparate factors are important, including from the stellar system's orbit in the galaxy (§ 4.1), the orbital and rotational evolution of the planets (§ 4.2), the stellar evolution (§ 4.3), geophysical evolution (§ 4.4), and atmospheric evolution (§ 4.5). We find that many evolutionary pathways are admitted by the data and hence the planet may currently exist in many possible states.

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