THE EVOLUTION OF STELLAR ROTATION AND THE HYDROGEN ATMOSPHERES OF HABITABLE-ZONE TERRESTRIAL PLANETS

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ABSTRACT

Terrestrial planets formed within gaseous protoplanetary disks can accumulate significant hydrogen envelopes. The evolution of such an atmosphere due to XUV driven evaporation depends on the activity evolution of the host star, which itself depends sensitively on its rotational evolution, and therefore on its initial rotation rate. In this Letter, we derive an easily applicable method for calculating planetary atmosphere evaporation that combines models for a hydrostatic lower atmosphere and a hydrodynamic upper atmosphere. We show that the initial rotation rate of the central star is of critical importance for the evolution of planetary atmospheres and can determine if a planet keeps or loses its primordial hydrogen envelope. Our results highlight the need for a detailed treatment of stellar activity evolution when studying the evolution of planetary atmospheres.

Key words: planets and satellites: atmospheres – planets and satellites: terrestrial planets – planet–star interactions – stars: activity – stars: low-mass – stars: rotation

1. INTRODUCTION

Planetary atmospheres evolve under the influence of the winds and high energy radiation of their hosts stars. High-energy radiation drives chemistry (Tian et al. 2008; Koskinen et al. 2013; Shaikhislamov et al. 2014; Shematovich et al. 2014; Chadney et al. 2015) and heating, causing expansion and mass loss (Tian et al. 2005; Erkaev et al. 2013; Luger et al. 2015). In addition, atmospheres exposed to stellar winds often experience significant additional loss (Lammer et al. 2007; Lichtenegger et al. 2010; Lundin 2011; Kislyakova et al. 2013).

Atmospheric evolution is fundamentally linked to the evolution of stellar winds and XUV emission (where XUV is X-ray+EUV). A star’s XUV emission originates from magnetically heated chromospheric and coronal plasma (Güdel 2004; Jardine et al. 2006) and is determined primarily by the star’s rotation, with rapid rotators being more active than slow rotators, except at rapid rotation where the activity saturates (Wright et al. 2011). As a star ages, its activity declines due to spin-down (Güdel et al. 1997; Vidotto et al. 2014). Due to the fact that a star’s rotation evolves differently depending on its initial rotation rate, a star’s activity level is not uniquely determined by its mass and age (Johnstone et al. 2015a; Tu et al. 2015). Solar mass stars at ages of 1 Myr have a large distribution of rotation rates, ranging from a few to a few tens of times faster than the current solar rotation rate (Herbst et al. 2002; Bouvier et al. 2014, p. 433; Matt et al. 2015). At this age, due to their internal structures, all stars lie above the saturation threshold in rotation. Tu et al. (2015) found that the age at which a star falls out of saturation varies between $\sim$10 Myr and several hundred Myr depending on its initial rotation rate.

The simplest planetary atmospheres are those dominated by hydrogen collected from the circumstellar disk (Lammer et al. 2014; Stökl et al. 2015). For such an atmosphere to form, the planet must grow to a significant mass ($>0.1 M_\oplus$) before the disk dissipates. Disk lifetimes are typically a few Myr (Kraus et al. 2012), whereas standard planet formation theory suggests that terrestrial planet formation takes much longer (Lunine et al. 2011). However, the existence of low density terrestrial planets, such as those in the Kepler-11 system (Lissauer et al. 2011), suggest that at least some terrestrial planets are able to form in the gas disk. Furthermore, recent studies have indicated that a large fraction of observed terrestrial planets have low densities, suggesting that they have thick gaseous envelopes (Marcy et al. 2014; Rogers 2015).

The capture and subsequent escape of disk gas by terrestrial planets was studied by Lammer et al. (2014) who modeled the first 100 Myr of the planet’s life and assumed the star’s activity remains saturated for the entire time. The amount of disk gas captured is strongly dependent on the core mass, with low-mass cores capturing orders of magnitude less gas than high-mass cores. Lammer et al. (2014) showed that low-mass habitable-zone terrestrial planets will not keep hydrogen envelopes for evolutionary timescales, whereas many high-mass terrestrial planets will always keep such atmospheres. While the planet is embedded in the disk, thermal pressure from disk gas on the atmosphere provides additional support binding it to the core. Stökl et al. (2015) showed that when this thermal support is removed, the atmosphere can flow away at rates that also strongly depend on core mass.

In this Letter, we study the importance of the initial stellar rotation rate on the XUV driven evolution of hydrogen atmospheres. In Section 2, we describe our model for atmospheric evolution; in Section 3, we calculate models for a range of cases; in Section 4, we discuss our results.

2. ATMOSPHERIC EVOLUTION MODEL

Our atmospheric evolution calculations combine a hydrodynamic upper atmosphere model (Section 2.1), a hydrostatic lower atmosphere model (Section 2.2), and evolutionary tracks for stellar XUV luminosity (Section 2.3). In all models, we
assume the planet is in the habitable zone at 1 AU around a solar mass star and has an equilibrium temperature of 250 K. We therefore do not consider the evolutionary changes in the star’s bolometric luminosity, which will be studied in future work.

2.1. Atmospheric Mass Loss and the $F_{XUV}$ Dependence

To predict the atmospheric mass-loss rate, $\dot{M}_a$, we use hydrodynamic upper atmosphere simulations performed using the Versatile Advection Code (Tóth 1996). We run our simulations in 1D spherical geometry with 1000 unevenly spaced grid cells and include the planet’s gravity and XUV heat deposition. At the base of the simulation, we assume a constant density of $5 \times 10^{12}$ cm$^{-3}$ and a constant temperature of 250 K. The base density was chosen so that the entire XUV flux will be absorbed within the computational domain. We further assume that the upper atmosphere consists purely of neutral atomic hydrogen. The three input parameters are the planetary mass, $M_{\text{pl}}$, the stellar XUV energy flux, $F_{\text{XUV}}$, and the radius of the base of the simulation, $R_0$ (alternatively, we often use $z_0 = R_0 - R_{\text{core}}$).

We assume that mass loss happens evenly over the entire area of the planet, excluding the shadow cast by the planet itself (i.e., over $\sim 3\pi$ steradians). We average the total input flux over this area, which gives an input XUV flux at the top of the simulations of $F_{\text{XUV}}/3$. As in Murray-Clay et al. (2009) and Erkaev et al. (2013), we assume a single wavelength for all photons and use the absorption cross section from Erkaev et al. (2013) of $\sigma = 5 \times 10^{-18}$ cm$^2$. We integrate the input XUV flux downwards through the atmosphere by decreasing the radiation flux by a factor of $e^{-\tau}$ when traveling through each grid cell, where $\tau = n d s$, $d s$ is the grid cell thickness, and $n$ is the hydrogen atom number density. The heating of the gas within each grid cell is given by $q = g F_{\text{XUV}}$, where $F_{\text{XUV}}$ is in this case the XUV flux in the grid cell and $\epsilon = 0.15$ is the heating efficiency parameter (Shematovich et al. 2014; Erkaev et al. 2015; Ionov & Shematovich 2015).

To test the dependence of $\dot{M}_a$ on $F_{\text{XUV}}$, we run 14 models for Earth mass planets with $z_0 = 100$ km and $F_{\text{XUV}}$ ranging from 10 to 5000 erg s$^{-1}$ cm$^{-2}$. The current Earth receives an $F_{\text{XUV}}$ of $\sim$5 erg s$^{-1}$ cm$^{-2}$. For very similar simulations and $F_{\text{XUV}}$ of 10, 50, and 100 erg s$^{-1}$, Erkaev et al. (2013) found hydrogen atom loss rates of $5.0 \times 10^{30}$, $1.9 \times 10^{31}$, and $3.2 \times 10^{31}$ s$^{-1}$. We find similar values of $4.5 \times 10^{30}$, $3.0 \times 10^{31}$, and $6.1 \times 10^{31}$ s$^{-1}$.

The results of our 14 simulations are demonstrated in Figure 1. Clearly, $\dot{M}_a$ does not depend linearly on $F_{\text{XUV}}$ because as $F_{\text{XUV}}$ increases, the fraction of the input energy available to lift mass away from the planet decreases. In our models, $\dot{M}_a$ is only influenced by heating below the sonic point. As $F_{\text{XUV}}$ increases, the sonic point moves closer to the planet leading to a smaller fraction of the energy being deposited in the subsonic region. A similar effect can be seen in hydrodynamic stellar wind models (e.g., see Figures 8 and 9 of Johnstone et al. 2015b).

To derive a scaling law for $\dot{M}_a$, we run a grid of models with a range of $M_{\text{pl}}$, $F_{\text{XUV}}$, and $z_0$. In total, we run 230 simulations with $M_{\text{pl}}$ between 0.5 and 5.0 $M_\odot$, $F_{\text{XUV}}$ between 10 and 2000 erg s$^{-1}$ cm$^{-2}$, and $z_0$ between 100 km and 1$R_{\text{core}}$. Of these simulations, 46 did not give realistic results due to numerical difficulties. Motivated by experiments with different functions, we assume that $\dot{M}_a$ is given by

$$\dot{M}_a = a_m M_{\text{pl}}^{b_m} (\log F_{\text{XUV}})^c (M_{\text{pl}}, z_0),$$  

where

$$g(M_{\text{pl}}, z_0) = d M_{\text{pl}}^{c_0} z_0^f,$$

$m_a$ is the mass of a hydrogen atom and $z_0 = R_0 - R_{\text{core}}$ is the altitude of the base of the simulation. We find that $a = 1.858 \times 10^{31}$, $b = -1.526$, $c = 0.464$, $d = 4.093$, $e = 0.249$, and $f = -0.022$; in addition, $M_{\text{pl}}$, $z_0$, and $F_{\text{XUV}}$ must be in units of $M_\oplus$, $R_0$, and erg s$^{-1}$ cm$^{-2}$. The quality of this fit to our grid of simulations is shown in Figure 2. Although our scaling law is inelegant and gives little intuitive insight into the physics of evaporation, it likely gives good estimates of $\dot{M}_a$.

2.2. Lower Atmospheric Extent

The extent of a planet’s atmosphere is strongly influenced by the planet’s mass, the atmospheric mass, and the atmospheric composition (Mordasini et al. 2012; Howe et al. 2014; Lopez & Fortney 2014). Based on a few simplifying assumptions, we are able to estimate $z_0$ from the planetary and atmospheric masses. In general, in more massive atmospheres, $z_0$ is at higher altitudes, leading to higher $\dot{M}_a$. As an atmosphere evaporates, both $z_0$ and $\dot{M}_a$ decrease; when the atmosphere is gone, $z_0 = 0$ and Equation (1) predicts no mass loss.

The exact definition of $z_0$ is the altitude at which the hydrogen atom number density is $5 \times 10^{12}$ cm$^{-3}$, since that is what we take as the density at the base of our simulations. Calculating $z_0$ therefore requires the lower atmosphere density structure. For this, we use the initial model integrator of the TAPIR-Code (Stökl 2008; Stökl et al. 2015) to solve the hydrostatic structure equations (Equations (4)–(6) of Stökl et al. 2015) taking into account radiative and convective energy transport. We assume that the core density is equal to that of the Earth for all bodies, meaning that $R_{\text{core}} \propto M_{\text{pl}}^{1/3}$. To describe the gas in the lower atmosphere, we use the equation of state derived by Saumon et al. (1995) for a hydrogen and helium mixture, and the opacities for gas and dust from Freedman et al. (2008) and Semenov et al. (2003), respectively. The free parameters are the flux of energy from the planetary core, $L_{\text{pl}}$, and the dust depletion factor, $f$. As in Stökl et al. (2015), we take $L_{\text{pl}} = 10^2 (M_{\text{pl}}/M_\odot)$ erg s$^{-1}$ and $f = 0.01$. In reality, these two parameters depend on the specific planet formation scenario and on the age of the system; a more detailed treatment of these parameters will be the subject of further work.

The dependence of $R_0$ on planetary and atmospheric masses are shown in Figure 3. For masses above $0.5M_\oplus$, this dependence is approximately described by

$$\log \left( \frac{R_0}{R_{\text{core}}} \right) = (2.5)^{f_0} + 0.1 \left( \frac{M_{\text{pl}}}{M_\oplus} \right)^{-0.7}. $$

The dotted lines in Figure 3 show the quality of this fit. The mass-dependent upper limit for $f_0$, i.e., the value at which the lines in Figure 3 turn upwards, is given by

$$f_{0,\text{max}} \approx 0.3 \left( \frac{M_{\text{pl}}}{M_\oplus} \right)^{3.6}.$$


For a hydrogen atmosphere of a terrestrial planet, $\dot{M}$ can easily be estimated by combining Equation (1) with (3), though our scaling laws only apply to planets with equilibrium temperatures of $\sim 250$ K.

2.3. Stellar XUV Evolution

Tu et al. (2015) developed a rotational evolution model for solar mass stars at the 10th, 50th, and 90th percentiles of the rotational distributions based on the models of Gallet & Bouvier (2013) and Johnstone et al. (2015a). Tu et al. (2015) combined their rotation tracks with an empirical relation between rotation and $L_{\text{X}}$ ($5–100$ Å) derived by Wright et al. (2011), to predict evolutionary tracks for $L_{\text{X}}$ and $L_{\text{EUV}}$. For the pre-main-sequence phase, they used a time-dependent saturation threshold calculated using the stellar evolution models of Spada et al. (2013). Their XUV evolutionary tracks are shown in Figure 4. Although we use these tracks in this Letter, a set of simple power laws that approximately describe each track can also be found in Tu et al. (2015).

3. RESULTS: THE IMPORTANCE OF STELLAR ROTATIONAL EVOLUTION

By combining the XUV evolution tracks with Equations (1) and (3), we calculate the evolution of hydrogen atmospheres for planets with core masses between 0.5 and 10 $M_{\oplus}$, and the
different initial atmospheric masses. In Case A, the initial atmospheric mass \(10^{-5}M_{\oplus}\) is so small that everything is removed very quickly for all rotation tracks. In Case D, the atmosphere \(10^{-1}M_{\oplus}\) is so massive that thermal escape is negligible in all cases. In Case B, the entire atmosphere \(10^{-3}M_{\oplus}\) is removed in all cases, but the time required depends critically on the star’s initial rotation rate; for the slow and fast rotators, the atmosphere is removed in 50 Myr and 250 Myr, respectively. The most dramatic difference between the rotation tracks is in Case C, where the initial atmospheric mass \(10^{-2}M_{\oplus}\) is such that if the planet is orbiting the rapid rotator, the atmosphere is removed in 400 Myr, whereas if the planet is orbiting the slow rotator, 70\% of the atmosphere remains at 1 Gyr. Due to the low stellar activity, the subsequent evolution of the atmosphere is negligible and the hydrogen envelope will never be lost.

In Figure 5, we show how much atmosphere remains at ages of 100 Myr and 1 Gyr for all planetary masses. The boundary between the regimes where the planet has lost and retained its atmosphere is not only dependent on planetary mass and the age of the system, but also strongly dependent on the initial rotation rate of the host star. The cases shown in Figure 4 for Earth mass planets are similar for all planetary masses, with the only difference being that the boundaries between the regimes are shifted. The gray shaded areas show where our calculations are unrealistic because low-mass planets will not collect and hold onto such massive atmospheres (Lammer et al. 2014; Stökl et al. 2015).

4. DISCUSSION

In this Letter, we develop a method for estimating the evaporation of hydrogen atmospheres and give scaling laws that can easily be applied. We show that the initial rotation rate of the central star can be fundamentally important for the evolution of a planetary atmosphere. In all cases, we assume no intrinsic large scale planetary magnetic field, which could influence the flow and change \(M_{pl}\) if the gas is highly ionized (Khodachenko et al. 2015). We have also only considered thermal mass loss due to the heating of the upper atmosphere. For hydrogen atmospheres, thermal mass loss dominates (Kislyakova et al. 2013, 2014), and this is also likely to be the case for atmospheres made of heavier species if the XUV energy input is high enough (Tian et al. 2008, 2009). For example, Tian (2015) showed that thermal escape of \(O_2\) from initially \(H_2O\) dominated atmospheres can be significant in certain cases. In other cases, the mass loss might be dominated by non-thermal processes such as stellar wind charge exchange and pickup (Lichtenegger et al. 2010). The erosion of non-hydrogen dominated atmospheres therefore depends strongly on stellar winds; easily applicable models for the properties and evolution of stellar winds were given by Johnstone et al. (2015a, 2015b).

Our results provide further confirmation of the conclusions of Lammer et al. (2014) that higher-mass habitable-zone terrestrial planets could have difficulty losing hydrogen envelopes if they form in the circumstellar disk. Lower-mass terrestrial planets, on the other hand, will lose their hydrogen atmospheres much more effectively. For example, our results indicate that no \(\sim 0.5 M_{\oplus}\) planets will keep hydrogen atmospheres for more than 1 Gyr regardless of the activity evolutions of their host stars; this suggests that low-density habitable zone planets with such masses will only be found in young systems.

Although we have only considered hydrogen dominated protoatmospheres, the evolution of stellar rotation is also fundamentally important for the formation and evolution of secondary atmospheres and the development of habitability. For a planet to be habitable, it must first lose its
protoatmosphere, and then it must also develop and retain an appropriate secondary atmosphere. Consider a habitable-zone Earth mass planet formed early enough to pick up a substantial hydrogen envelope. The initial rotation rate of the host star not only determines if the planet will lose its protoatmosphere, but also how long this process will take. A rapid rotator might cause this to happen very quickly, whereas a slow rotator might allow the atmosphere to remain for hundreds of Myr, potentially slowing down the solidification of the planet’s surface and disrupting the formation of the secondary atmosphere.

Stellar magnetic activity evolves in non-trivial ways that depend sensitively on the star’s rotational evolution. Simple evolutionary decay laws that give one-to-one relations between age and XUV emission or winds are inappropriate at young ages. The aim of this Letter, however, is not simply to study the...
importance of the initial stellar rotation rate on atmospheric evaporation; our results clearly demonstrate that a strong understanding of stellar activity evolution is an essential ingredient in detailed studies of the evolution of planetary atmospheres.

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