PLANETS FORMED IN HABITABLE ZONES OF M DWARF STARS PROBABLY ARE DEFICIENT IN VOLATILES

JACK J. LISSAUER

Space Science and Astrobiology Division, 245-3, NASA Ames Research Center, Moffett Field, CA 94035

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ABSTRACT

Dynamical considerations, presented herein via analytic scalings and numerical experiments, imply that Earth-mass planets accreting in regions that become habitable zones of M dwarf stars form within several million years. Temperatures in these regions during planetary accretion are higher than those encountered by the material that formed the Earth. Collision velocities during and after the prime accretionary epoch are larger than for Earth. These factors suggest that planets orbiting low-mass main-sequence stars are likely to either be too distant (and thus too cold) for carbon/water based life on their surfaces or have abundances of the required volatiles that are substantially less than on Earth.

Subject headings: astrobiology — planetary systems: formation — planets and satellites: formation

1. INTRODUCTION

M (and early L) dwarfs are the lowest mass stars, and the smallest and least luminous members of the stellar main sequence. They are also by far the most numerous class of stars in our Galaxy, with \( \sim 75\% \) of the stars in the extended solar neighborhood being M dwarfs (Reid et al. 2002). Thus, if planets orbiting M stars can be habitable, the number of potentially inhabited worlds within our Galaxy could be much larger than if only planets orbiting solar type stars are capable of hosting life. The presence of liquid water on a planet for long periods of time is considered to be a requirement for the origin and evolution of life as we know it. It is shown herein that planets within M star habitable zones (HZs) formed rapidly while their star was quite luminous and are probably water-deficient. Thus, the dynamics of planetary accretion, together with the physics of stellar evolution, cast doubt on the suitability of planets orbiting M stars to host life.

Stars on the main sequence have relatively long periods of very slowly varying luminosity, potentially providing stable radiation fluxes for the origin and evolution of life. Giant planets, brown dwarfs, and post–main-sequence stars vary substantially in luminosity and thus are far less conducive energy sources for life on the surface of a planetary body (cf. Adams et al. [2005] for a possible exception involving a class of low-mass post–main-sequence stars in the very distant future).

The main-sequence luminosity of stars varies roughly as \( L_* \sim M_*^2 \), where \( M_* \) is the stellar mass. Thus, the locations of HZs (defined to be orbits in which liquid water can be present on the surface of an Earth-like planet) are much closer to low-mass main-sequence stars than they are to high-mass stars (Kasting et al. 1993). As stellar nuclear fuel varies in proportion to \( M_* \), stellar lifetime goes as \( M_*^{-1.3} \), so stars more than about twice as massive as the Sun are probably not sufficiently long-lived to provide the energy for the development of advanced life.

The lowest mass stars are very long-lived, but present a different set of challenges to life (Scalo et al. 2007). The most studied of these problems is that the proximity of HZs to very low mass stars implies that the rotation of a HZ Earth-like planet would be tidally altered to the synchronous state, with one hemisphere permanently illuminated and the other in the dark (Kasting et al. 1993). A thin atmosphere of such a planet would freeze out onto the planet’s night hemisphere, but a sufficiently massive atmosphere could transport enough heat to the dark side to prevent atmospheric collapse, thus allowing habitable regions on the planet’s lit hemisphere (Joshi et al. 1997). Perturbations from another planet could also maintain a HZ planet’s orbital eccentricity against tidal locking, especially if the HZ planet lacked a substantial permanent deformation (and thus could rotate just slightly faster than synchronously, in equilibrium with the tidal forcing experienced by an eccentric planet).

However, M dwarf stars present other challenges to planetary habitability. As shown below, a particularly severe problem is the difficulty that a 1 \( M_\odot \) (Earth mass) planet in the HZ of an M dwarf has in accumulating and retaining water and other volatiles. The Earth itself is volatile-poor. Oceans and other near-surface reservoirs of \( H_2O \) comprise less than 0.03% of our planet’s mass, with the mantle containing a comparable amount of water (K. Zahnle 2006, private communication). Thus, Earth’s total water abundance is very small compared to the cosmic rock : \( H_2O \) ratio of roughly unity. Earth accreted from planetesimals that condensed over a wide range of heliocentric distances (Wetherill 1994). The temperature distributions of protoplanetary disks are not tightly constrained. Thus, the best estimates of the volatile contents of planetesimals as a function of heliocentric condensation distance are provided by analysis of meteorites that are analogous to asteroids of known heliocentric distance and by matching Earth’s volatile inventory to planetary accumulation models (Morbidelli et al. 2000). Primitive meteorites that emanate from the inner asteroid belt (just beyond 2 AU) have water abundances <0.1%, whereas those from more distant regions of the asteroid belt can have more than 100 times this much water. Accretion simulations imply that a nontrivial amount of material from the region of the main asteroid belt reached Earth and that most of Earth’s water probably came from planetesimals that condensed beyond \( \sim 2.5 \) AU (Lunine et al. 2003; Raymond et al. 2004). Although current planetary accumulation models cannot be viewed as providing ab initio estimates of the accretion of water by terrestrial planets, models of this type are well suited for comparing the relative amounts of volatiles accreted by terrestrial planets around stars of differing masses.

Stars are substantially more luminous during their formation epoch than they are once they reach the main sequence. Low-mass stars are significantly more luminous than their main-sequence luminosities for longer than are solar mass stars (Stahler & Palla 2005), so ultimately habitable regions
around M stars are hotter at young stellar ages than are regions that are to be subjected to the same stellar flux around Sun-like stars. In addition, energy diffusion is slower in inner protoplanetary disks because of the greater optical thickness, so there is likely to be an even larger excess of temperature within young circumstellar disks near smaller mass protostars. The location of the snow line within protoplanetary disks orbiting small stars (Kennedy et al. 2006) is thus more distant in proportion to the eventual location of the HZ than is the case for solar mass stars.

The timescales of accretion of planets of a given mass in the HZs of M stars are shorter than those of comparable planets around more massive stars. This is because orbital periods are shorter, planetesimals are closer to one another, and they occupy a larger fraction of their Hill spheres. Moreover, orbital velocities are faster, implying higher impact speeds, so late accretion of volatile-rich bodies that condensed farther from the star may well remove more atmospheric gases and water than they provide. Thus, while lower mass pre-main-sequence stars remain more luminous than their main-sequence luminosities for a longer time, Earth-mass planets forming in HZs around these stars accrete more rapidly—of material that is likely less water-rich, and within a dynamical environment in which they are more likely to lose atmospheric volatiles via impact erosion. The dynamical characteristics of terrestrial planet accumulation around M stars are quantified in §2.

2. ACCRETION TIMESCALES AND IMPACT VELOCITIES

For stars of solar mass and smaller, main-sequence luminosity $L_\ast$ varies with stellar mass $M_\ast$ roughly as

$$L_\ast \approx \left( \frac{M_\ast}{M_\odot} \right)^4 L_\odot \approx M_\ast^4,$$

(1)

where the symbol $\propto$ signifies that the proportionality relationship is only approximate. Planetary temperature is proportional to $(L_\ast/r_c^2)^{1/4}$, where $r_c$ is the distance from the star.

The distance of the HZ from the star, $r_{HZ}$, thus varies as

$$r_{HZ} \propto L_\ast^{1/2} \approx M_\ast^{2/7}.$$

(2)

Terrestrial planet accretion proceeds until a stable configuration is reached (Lissauer 1995; Laskar 2000), and the separation of planets required for stability varies as $(M_j/M_\ast)^{3/7} r_c$ (Wisdom 1980). Thus, the surface mass density of the ensemble of solids within the protoplanetary disk, $\sigma$, required for local accretion of planets of a given mass (e.g., that of Earth) in the zone that becomes habitable varies as

$$\sigma \approx \frac{M_j^{2/7}}{r_{HZ}^{1/7}} \approx r_{HZ}^{13/7} \approx M_\ast^{26/7}.$$

(3)

When expressed in terms of surface density in the HZ, the value of $\sigma$ necessary for the formation of Earth-like planets is therefore a very steep function of stellar mass. But standard minimum-mass models of our protoplanetary disk\(^2\) (Weidenschilling 1977) give $\sigma(r) \propto r^{-3/2}$, which is only slightly less steep than the $r_{HZ}^{-13/7}$ dependence in equation (3). Note that masses of protoplanetary disks around low-mass stars are poorly constrained, but observations suggest that they typically are lower than those around 1 M\odot stars (Scholz et al. 2006; Muzerolle et al. 2006). If the surface density of the protoplanetary disk at the distance from the low-mass star where the HZ ultimately lies is not substantially larger than the surface density of the minimum-mass solar nebula at 1 AU, then planets that form at this location are small, unless they accreted large amounts of material that migrated inward from the outer disk or they themselves migrated inward substantially. Low-mass planets have shallower gravitational potential wells and thus are more susceptible to atmospheric loss than are more massive planets.

The growth rate of a terrestrial planet is proportional to the surface density of the disk and the orbital frequency; other factors related to gravitational enhancement in accretion cross section also play a role (Safronov 1969), but this enhancement is of order unity during the final high-velocity phase of planetary growth, which dominates accretion timescales (Lissauer 1987; Agnor et al. 1999). Growth times thus scale as

$$T_g \approx \left( \frac{r_c^2}{M_\ast^2} \right) \left( \frac{r_{HZ}^{3/2}}{M_\ast^4} \right) = \frac{r_{HZ}^{7/2}}{M_\ast^{11/4}} \approx M_\ast^{-2/7}.$$  

(4)

According to equation (4), Earth-mass planets that accrete within HZs of 0.5 M\odot stars should form in several million years; around 0.25 M\odot stars, the process should require $\lesssim 10^5$ yr. Migration inward requires the presence of a massive disk. Optically thick disks around young stars have a broad range of lifetimes, although most disappear 1–5 Myr after the stellar photosphere becomes visible (Fig. 5 of Briceño et al. 2007; Meyer et al. 2007). Thus, whether it has grown in situ or migrated inward from a greater distance, the planet should be in or very near its final orbit within the HZ no later than 10$^5$ yr after the star’s formation.

A slightly less steep scaling with stellar mass than that given by equation (4) is probably more appropriate to account for two physical effects: (1) the amount of gravitational focusing is reduced for accreting bodies that occupy a greater fraction of their Hill spheres (Greenzweig & Lissauer 1990), and (2) the formulae used to derive equation (4) assume crossing orbits, whereas the very late stages of terrestrial planet growth are dominated by the time required for chaotic perturbations to excite sufficient eccentricities for the continuation of orbital crossing.

The growth of terrestrial planets within the HZ of a 1 M\odot star [which has a main-sequence luminosity very close to (1/3)\(^4\) that of a 1 M\odot star (Hillenbrand & White 2004)] was modeled numerically to test the scaling derived above. The initial disk was analogous to that used for simulations of terrestrial planet growth around a 1 M\odot star, as well as within binary star systems (Quintana & Lissauer 2006 and references therein). As in these previous studies, the simulations began with 140 “planetesimals” of mass 0.00933 M\odot and 14 “plan-
etary embryos” of mass 0.0933 $M_\oplus$, and the density of each body was taken to be 3 g cm$^{-3}$. In order to leave the illumination of bodies that were at 1 AU in the initial disk unchanged according to equation (2) and maintain expected planetary sizes as per equation (3), the initial semimajor axes of these 154 bodies were scaled as

$$a = \frac{a_p^{(3/7)}}{9}$$

where $a_p$ are the values used in the previous simulations referenced above; both $a$ and $a_p$ are expressed in astronomical units. The other five initial orbital elements of each of the 154 accreting bodies were as in previous simulations. Bodies were removed from the integrations if they approached closer to the star than 0.01 AU, or if their distance from the star exceeded 10 AU. The integrations were performed using the hybrid symplectic integrator within the Mercury integration package (Chambers 1999). The time step was taken to be 1 hr. Deterministic chaos implies that integrations of this sort are valid only in a statistical sense, so multiple numerical experiments were run. A pair of simulations, differing only by moving the initial position of one of the smaller bodies along its orbit by 1 m, was performed without any giant planets, and four analogous runs were performed with giant planets similar to Jupiter and Saturn but with masses reduced by a factor of 3 and semimajor axes reduced by a factor of 9.

Results of the four numerical simulations of planetary growth in the HZ of a $\frac{1}{2} M_\odot$ star that has a pair of giant planets are displayed in Figure 1. The final systems have numbers of terrestrial planets that are similar to those formed in simulations of planetary growth around 1 $M_\odot$ stars on which the initial disk conditions were based. The final collision between two embryo-dominated bodies or loss of one such body occurred at 0.39, 0.38, 1.21, and 0.67 Myr in these 2 Myr simulations; in comparison, the last reduction in the number of embryos in the 31 simulations of terrestrial planet growth (each for a time span of 200 Myr) tabulated in Quintana & Lissauer (2006) occurred at times ranging from 18.7 to 134 Myr, with a median final loss time of 78 Myr. Growth rates around the $\frac{1}{2} M_\odot$ star thus are more than 100 times as rapid as those around the 1 $M_\odot$ star, which implies a somewhat less steep scaling than equation (4), consistent with the above discussion. The simulations lacking giant planets resulted in more final terrestrial planets extending to greater asterocentric distance, as in the case of a single star lacking in giant planet or stellar companions (Quintana et al. 2002). In these runs, the final collision between two embryo-dominated bodies or loss of one such body occurred at 0.11 and 0.18 Myr. Note that $\frac{1}{2} M_\odot$ stars are more than 10 times as luminous during their first $\sim 4$ Myr as they are when they reach the main sequence (D’Antona & Mazzitelli 1997).

Plants grow by accretionary impacts. Such impacts can remove previously accreted volatiles that reside in a planet’s atmosphere. Impact erosion is a favored mechanism for explaining the thinness of Mars’s atmosphere relative to that of Earth (Melosh & Vickery 1989). Orbital speeds, and thus impact velocities, are higher in HZs around low-mass stars than they are at Earth, and such high collisional velocities may lead to more erosive impacts. Earth is believed to have accumulated most of its water and other volatiles from solid bodies that condensed outward of the orbit of Mars and were accreted by Earth toward the end of or subsequent to the major phases of our planet’s growth (Morbidelli et al. 2000). Accretion from a similarly scaled distance around other stars would result in approach velocities, $v_a$, that vary in proportion to the orbital velocity, $v_o$.

$$v_a \propto \left( \frac{M_1}{r_{HZ}} \right)^{1/2} \propto M_\star^{-1/2}. \quad (6)$$

The larger ratio of the distance to the ice line to $r_{HZ}$ for M stars implies that fewer ice-rich planetesimals reach the HZ, and those that do have an even higher characteristic velocity than that given by equation (6). The specific energy of an impact varies as the square of impact velocity. According to Melosh & Vickery (1989), substantial impact erosion of atmospheres requires collision velocities faster than twice the planet’s escape speed. Parabolic comets with prograde orbits in the ecliptic plane impact Earth at $<2v_o$. However, all planetesimals with large semimajor axes impact a 1 $M_\odot$ planet orbiting at $\frac{1}{2}$ AU from a $\frac{1}{2} M_\odot$ star at $>2v_o$. Therefore, impacts in the HZs around small stars can significantly erode the atmospheres of $\approx 1 M_\oplus$ planets.

3. DISCUSSION

In summary, under nominal circumstances, planets in main-sequence habitable zones around M stars are likely to be fully formed and in their final orbits by the time the gaseous circumstellar disk has dissipated or several million years after planetesimal formation, whichever is later. If growth is in situ, dynamical and thermal factors imply that the planets are unlikely to have large volatile inventories, and planetary masses are likely to be small. The large collision speeds of impacting comets, as well as the high activity and luminosities of young M stars, may lead to substantial mass loss from planetary atmospheres, depleting any reservoirs of volatiles that planets within the HZs are able to accrete.

So are M dwarf stars totally unsuitable hosts for the development of advanced life? No, there are various ways out of the difficulties pointed out above. Theoretical estimates of planetary volatile inventories obtained from planet formation studies are not from first principles, but rather rely on normalization to the planets within our solar system; as accretion models suggest large stochastic variations in volatile delivery (O’Brien et al. 2006), it is possible that the terrestrial planets within our solar system are near the volatile-poor end of this distribution and thus the normalization used herein is incorrect. A water-rich planet formed farther from the star (Kennedy et al. 2006) could migrate inward to the HZ while the gaseous disk is still present; such a planet could initially have enough water that oceans could be retained even if it suffered significant losses during the star’s young active phase. A planet could be placed on an eccentric orbit that circularizes on the timescale it takes the star to reach the main sequence or somewhat longer, or be scattered inward by a fellow planet after the star reaches the main sequence and then be circularized by stellar tides. But such scenarios require precisely the right amount of initial water or just the right dynamics. Thus, while it is likely that some of the hundreds of billions of M dwarf stars in our Galaxy have planets with temperatures, masses, and compositions sim-
Fig. 1.—Temporal evolution of four protoplanetary disks incorporating the ultimately habitable zone around a $1 M_\odot$ star. Two giant planets, one-third the masses of Jupiter and Saturn, respectively, are also included. The planetary embryos and planetesimals are represented by circles whose sizes are proportional to the physical sizes of the bodies. The evolution of one disk is shown in black at 12 different times. The green and red filled circles and blue open circles show the results at late times of the other three runs, with one planetesimal initially moved by 1–3 m along its orbit. The horizontal locations of the circles show the orbital semimajor axes of the bodies in astronomical units, and vertical positions plot their eccentricities. The initially dynamically cold disk heats up during the first $5 \times 10^4$ yr, especially in the outer region, where the perturbations of the giant planets are the greatest. By $10^5$ yr into the simulation, 3–5 terrestrial planets have formed, with 0–2 planetesimals remaining. After $2 \times 10^5$ yr, each system contains 2–4 terrestrial planets. Note that the HZ is around 0.11 AU and that the largest planets formed have masses comparable to that of the Earth.

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