

# Observable Consequences of Planet Formation Models in Systems with Close-in Terrestrial Planets

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Submitted Sept 20

## ABSTRACT

To date, two planetary systems have been discovered with close-in, terrestrial-mass planets ( $\lesssim 5 - 10 M_{\oplus}$ ). Many more such discoveries are anticipated in the coming years with radial velocity and transit searches. Here we investigate the different mechanisms that could form “hot Earths” and their observable predictions. Models include: 1) *in situ* accretion; 2) formation at larger orbital distance followed by inward “type 1” migration; 3) formation from material being “shepherded” inward by a migrating gas giant planet; 4) formation from material being shepherded by moving secular resonances during dispersal of the protoplanetary disk; 5) tidal circularization of eccentric terrestrial planets with close-in perihelion distances; and 6) photo-evaporative mass loss of a close-in giant planet. Models 1-4 have been validated in previous work. We show that tidal circularization can form hot Earths, but only for relatively massive planets ( $\gtrsim 5 M_{\oplus}$ ) with very close-in perihelion distances ( $\lesssim 0.025$  AU), and even then the net inward movement in orbital distance is at most only 0.1-0.15 AU. For planets of less than  $\sim 70 M_{\oplus}$ , photo-evaporation can remove the planet’s envelope and leave behind the solid core on a Gyr timescale, but only for planets inside 0.025-0.05 AU. Using two quantities that are observable by current and upcoming missions, we show that these models each produce unique signatures, and can be observationally distinguished. These observables are the planetary system architecture (detectable with radial velocities, transits and transit-timing) and the bulk composition of transiting close-in terrestrial planets (measured by transits via the planet’s radius).

**Key words:** planetary systems: formation — planetary systems: protoplanetary discs — methods: *N*-body simulations — methods: numerical — astrobiology

## 1 INTRODUCTION

Both radial velocity (RV) and transit searches are biased toward finding large/massive planets at small orbital distances (e.g., Marcy & Butler 1998; Charbonneau *et al.* 2007). Given the increased sensitivity of new instruments, ever-smaller close-in planets are being detected. Currently, two systems are thought to contain close-in planets of less than 10 Earth masses ( $M_{\oplus}$ ): GJ 876 (Rivera *et al.* 2005) and GJ 581 (Udry *et al.* 2007). Transit missions *CoRoT* (Baglin 2003; Aigrain *et al.* 2007) and *Kepler* (Basri *et al.* 2005) expect to find perhaps a few hundred close-in planets with masses less than 5-10  $M_{\oplus}$ . In this paper we focus on these “hot Earth” planets, which we assume to have masses in the range  $0.1 < m_p < 10 M_{\oplus}$ , and semi-major axes  $a \lesssim 0.2$  AU.

We propose that it is possible to determine the formation history of a given hot Earth planetary system with two observable quantities: the architecture of the inner planetary system, and the bulk composition of the hot Earth(s). The planetary system architecture can be detected by a combination of RV and transit measurements, as well as additional analysis of transit signals (e.g., timing variations: TTV; Agol *et al.* 2005, Holman & Murray 2005). The composition of a transiting terrestrial planet can be determined by its physical size, i.e. the transit depth. Structure models indicate that very water-rich planets ( $\gtrsim 10\%$  water by mass) have detectably larger radii than dry, rocky planets or iron-dominated planets (Valencia *et al.* 2007a, 2007b; Fortney *et al.* 2007; Sotin *et al.* 2007; Seager *et al.* 2007), although a

massive H/He envelope can also inflate the observed planetary radius (Adams *et al.* 2007).

Several mechanisms for the formation of close-in terrestrial planets have been proposed (Zhou *et al.* 2005; Gaidos *et al.* 2007). In Section 2 we describe the observable quantities that can distinguish between models. In Section 3, we summarize four known models, and test two unproven models: a) tidal circularization of terrestrial planets on eccentric orbits, and b) photo-evaporation of hot Neptunes or hot Jupiters. We have tried to include all reasonable models, which include various combinations of accretionary growth, planet migration, and evaporative loss. Table 1 summarizes the observable differences between these models. In section 4, we apply these models to the two known hot Earth systems. Section 5 concludes the paper with a discussion of whether the mechanism for giant planet formation – core-accretion or gravitational instability – can affect the abundance of hot Earths, as claimed by Zhou *et al.* (2005).

## 2 OBSERVABLE QUANTITIES

The observables considered in this paper are the architecture of the inner planetary system and the bulk planetary composition. The planetary system architecture, i.e. the co-existence (or lack) of additional planets in hot Earth systems, can provide strong circumstantial evidence for or against certain formation models, as described below. In particular, certain characteristic planetary configurations are smoking guns (see Table 1). Determining the bulk composition of a planet requires transit measurements. Thus, our analysis applies only to systems with at least one transiting planet. In most cases, but not all, the transiting planet must be a hot Earth.

The architecture of hot Earth planetary systems may be determined in three primary ways: (i) via the detection of transits of multiple planets; (ii) via radial velocity (RV) monitoring of the host star; and (iii) by analysis of transit timing variations (TTV). Other techniques such as astrometry may be used in conjunction with these techniques, but note that astrometry is not optimal for detecting close-in planets (Black & Scargle 1982). Detection of multiple transiting planets in the same system requires extremely low mutual inclinations between planetary orbits, which are thought to be rare (e.g., Levison *et al.* 1998). The RV technique has discovered several planets with minimum masses less than Neptune, including the two known systems with hot Earths (Rivera *et al.* 2005; Udry *et al.* 2007). There exist several currently-operational instruments capable of RV followup for *CoRoT* and *Kepler* targets, such as Keck HIRES (Vogt *et al.* 1994), the Hobby-Eberly Telescope’s HRS spectrograph (Cochran *et al.* 2004), and the HARPS instrument at ESO (Mayor *et al.* 2003). In addition, the HARPS-North spectrograph is being built specifically to do RV followup of *Kepler* candidate transiting planets (Latham 2007). However, given that many of the target stars will be very faint, RV followup of a large number of stars may not be possible. For those that can be followed up, the  $\lesssim m s^{-1}$  sensitivity of current RV instruments should be able to detect close-in,  $\lesssim 5 - 10 M_{\oplus}$  planets and to probe the inner regions of *CoRoT* and *Kepler*-detected targets.

Transit timing variations (TTV) analysis measures the

deviation of a series of transits from a perfect chronometer, representing a deviation of the transiting planet’s orbit from a perfect Keplerian ellipse due to perturbations from one or more additional planets (Holman & Murray 2005; Agol *et al.* 2005). The TTV signal scales with the transiting planet’s orbital period, and increases for more massive and closer perturbing planets. For sufficiently accurate transit timing data, TTV analysis can either derive the mass and orbit of a perturbing planet or place constraints on the existence of nearby perturbers (Steffen & Agol 2005; Agol & Steffen 2007). TTV is especially sensitive to planets that lie in or close to mean motion resonances with the transiting planet, which is convenient given that several formation models predict near-resonant planetary configurations (see § 3 below).

The bulk composition of a planet determines its density and therefore its physical size: ice-planets are far larger than iron-planets. Recently, several studies have calculated mass-radius relations for planets with different compositions (Valencia *et al.* 2006, 2007a, 2007b; Fortney *et al.* 2007; Sotin *et al.* 2007; Seager *et al.* 2007). For a fixed mass, there exists a roughly 40% difference in radius between pure ice planets and pure rock planets, and a similar 40% difference between pure rock and pure iron planets; these ratios of sizes are independent of planet mass. In addition, there is a  $\sim 35\%$  difference in size between Earth-like planets (2/3 rock, 1/3 iron) and ocean planets (1/2 rock, 1/2 water; Fortney *et al.* 2007).<sup>1</sup>

Estimates of both the planetary mass and radius are needed to derive a bulk composition (Selsis *et al.* 2007). For transiting planets, errors in stellar masses and radii (Ford *et al.* 1999; Cody & Sasselov 2002; Fischer & Valenti 2005; Sozzetti *et al.* 2007) are likely to lead to errors in planetary radii on the order of 2-10% (see section 6 of Seager *et al.* 2007). With a determination of the planetary mass to within 5% and radius to within 10%, it may be possible to differentiate between mostly rocky (Earth-like) planets and icy planets with  $\geq 10\%$  water by mass (Valencia *et al.* 2007b). For transiting planets with very precise mass and radius measurements (better than 2%), more detailed compositions may be derived (Seager *et al.* 2007).

Atmospheric envelopes of H/He can inflate the observed radii of solid planets by tens of percent (Adams *et al.* 2007). For a given radius measurement, solutions for the planetary structure become degenerate with respect to water content and envelope mass: small radii are clear signatures of rocky planets, but larger radii are ambiguous. Theoretical models suggest that the ability of a planet to accrete a gaseous envelope depends on the planet’s mass, and is not sensitive to the orbital distance (e.g., Ikoma *et al.* 2001; Ida & Lin 2004).<sup>2</sup> Thus, additional information about the presence and thickness of the planet’s atmosphere is needed to determine whether the planet is water-rich or rocky. For example, more information could be gathered from a situation in

<sup>1</sup> Note that water contents of a few percent by mass, though  $\gtrsim 10$ -20 times larger than the Earth’s estimated water budget (Lécuyer *et al.* 1998), would have a negligible effect on the planetary radius compared with the observational uncertainties.

<sup>2</sup> In addition, as Adams *et al.* (2007) point out, significant envelopes of hydrogen may be formed as a result of outgassing from the planetary interior.

**Table 1.** Observable Predictions of Hot Earth Formation Models

Model	System Architecture	Planet Composition
<b>In Situ Accretion</b>	Several hot Earths, spaced by $\sim 20$ -60 mutual Hill radii	Relatively dry for Solar-type stars. Up to 0.1-1 percent water for low-mass stars
<b>Type 1 Migration</b>	Chain of many terrestrial planets, close to mutual mean motion resonances	Icy or Rocky, depending on formation zone. Most likely to be icy ( $\gtrsim 10$ % water by mass) .
<b>Giant Planet Migration Shepherding</b>	Co-existence of hot Earths and close-in giant planets near (but not in) strong mean motion resonances	Rocky with moderate water content: a few percent water by mass at time of formation.
<b>Secular Resonance Shepherding during Disk Dissipation</b>	Co-existence of hot Earths and at least two, interacting giant planets	Depends on the details of the giant planet's orbital history. Rocky if formed mainly <i>in situ</i>
<b>Tidal Circularization of Eccentric Planets</b>	Single hot Earth, with possible distant companion (giant planet or stellar binary) to explain high eccentricity	Depends on formation zone of planet – rocky unless migrated inward.
<b>Photo-evaporation of hot Neptunes</b>	Hot Earth inside 0.025-0.05 AU. Likely chain of several planets, as for type 1 migration. Correlation between hot Earth vs. hot Neptune frequency and stellar age.	Icy, assuming what remains is a giant planet core.

which an atmosphere has almost certainly photo-evaporated away (old stellar age plus very close-in planet). Another favorable case would be a situation for which some spectral information about the planet's atmosphere could potentially be obtained.

Observational limitations are such that certain planets will have no mass estimates, given the faintness of their host stars and the consequent difficulty of RV followup. For such cases, it is possible to place mass limits based on maximum and minimum radius estimates, i.e., by assuming the planet to be made of pure iron or pure water (or pure hydrogen for gaseous planets). In addition, the bulk planetary composition may not be determined in many cases because of observational limitations (Selsis *et al.* 2007) or degeneracy between model parameters (Adams *et al.* 2007). With no composition information it becomes more difficult to differentiate between formation models. Nonetheless, several cases can be distinguished if the inner planetary system architecture is known.

Thus, current and future programs have the sensitivity to determine the orbits, masses, radii and companions of a large number of hot Earths. Although it will not be feasible in all cases, information about other planets in hot Earth systems will be determined via RV, transits, and transit timing analysis. In this paper we focus on systems in which both the inner planetary architecture and the composition of a hot Earth (rocky vs.  $>10\%$  water) can be determined (i.e., the brightest *CoRoT* and *Kepler* targets; see Fig. 6 of Selsis *et al.* 2007). As explained below and summarized in Table 1, analysis of these data may be able to identify the formation mechanism of such planets.

### 3 MODELS FOR HOT EARTH FORMATION

Here we investigate six mechanisms for hot Earth formation, including proven and previously untested mechanisms. The six models are: (§3.1) *in situ* accretion; (§3.2) type 1 migration; (§3.3) shepherding during giant planet migration; (§3.4) shepherding via secular resonance sweeping; (§3.5) tidal circularization of eccentric planets; and (§3.6) photo-evaporation of close-in giant planets. For each model, we discuss the state of the inner planetary system, as well as the likely composition of the hot Earth(s). Table 1 summarizes the differences between models. The first four models listed have been demonstrated in previous work. We introduce two additional models for hot Earth formation, and test them quantitatively below.

#### 3.1 *In situ* formation

If protoplanetary disks contain a substantial mass in solids close to their stars, then perhaps hot Earths can form from local material. This depends critically on the condensation temperatures of grains (Pollack *et al.* 1994; Lodders 2003), disks' inner truncation radii (e.g., Eisner *et al.* 2005; Akeson *et al.* 2005), and the surface density profile of solids (Weidenschilling 1977; Hayashi 1981; Davis 2005; Raymond *et al.* 2005). If hot Earths form *in situ*, then their growth would be similar to that of Solar System's terrestrial planets (Wetherill 1990, 1996; Chambers & Wetherill 1998; Agnor *et al.* 1999; Morbidelli *et al.* 2000; Chambers 2001; Kenyon & Bromley 2006), but minus the dynamical effects of Jupiter and Saturn (although giant planets may co-exist with some hot Earths, e.g. Gliese 876; Rivera *et al.* 2005).

If there is sufficient mass to form one hot Earth *in situ*, then we expect a population of several hot Earths to

form, with masses determined by the local disk mass and spacings similar to those in the Solar System and in accretion simulations (roughly 20-80 mutual Hill radii:  $R_{H,m} = 0.5(a_1 + a_2)(M_1 + M_2/3M_\star)^{1/3}$ ;  $a_1$  and  $a_2$  are the orbital radii and  $M_1$  and  $M_2$  the masses of two adjacent planets). The surface density distribution of protoplanetary disks,  $\Sigma$ , is thought to scale with radial distance  $r$  as  $\Sigma \sim fr^{-\alpha}$ , where  $f$  is a scale factor to account for the large variability in observed disk masses (Andre & Montmerle 1994; Eisner & Carpenter 2003; Andrews & Williams 2005; Scholz *et al.* 2006), and the value of  $\alpha$  lies between 0.5 and 2 (Weidenschilling 1977; Hayashi 1981; Kuchner 2004; Davis 2005; Dullemond *et al.* 2007; Andrews & Williams 2007; Garaud & Lin 2007). Accretion models suggest that planets close to their stars are generally smaller than those farther out for  $\alpha < 2$  (Lissauer 1987; Kokubo & Ida 2002; Raymond *et al.* 2005, 2007; Kokubo *et al.* 2006).

For solar-type stars, hot Earths that form *in situ* are likely to be dry because of the low efficiency of water delivery from both comets (Levison *et al.* 2000) and asteroids (Raymond *et al.* 2004). Because of the very hot local temperatures, these planets would be mainly composed of refractory materials such as iron and rock (Pollack *et al.* 1994; Lodders 2003). However, for the case of low-mass stars, the snow line is located very close-in (as is the habitable zone – Kasting *et al.* 1993). Water delivery to hot Earths may therefore be more favorable around low-mass stars, although impact speeds are high and formation times fast compared with Earth’s formation zone (Lissauer 2007; Raymond *et al.* 2007), and the snow line moves significantly in the disk lifetime (Sasselov & Lecar 2000; Kennedy *et al.* 2006).

Figure 1 shows snapshots of *in situ* accretion of terrestrial material close to a 0.31  $M_\odot$  star from Raymond *et al.* (2007, in preparation), designed to examine the GJ 581 system. The simulation started from a disk of 57 planetary embryos (initially separated by 3-6 Hill radii, as in Raymond *et al.* 2006a) and 500 planetesimals in a very massive disk totaling 40  $M_\oplus$  between 0.03 and 0.5 AU. The disk’s surface density decreased with orbital distance  $r$  as  $r^{-1}$  (i.e.,  $\alpha = 1$ ), and was roughly 30 times more massive than the minimum-mass solar nebula model (Weidenschilling 1977; Hayashi 1981; Davis 2005).<sup>3</sup> The three planets that formed in this simulation have masses of 6.6  $M_\oplus$  (at 0.06 AU), 10.9  $M_\oplus$  (0.12 AU), and 10.6  $M_\oplus$  (0.30 AU). Each has a substantial water content, acquired via collisions with material originating beyond the “water line” at 0.29 AU, but note that the effects of water depletion during impacts (Genda & Abe 2005; Canup & Pierazzo 2006) and hydrodynamic escape (Matsui & Abe 1986; Kasting 1988) have not been accounted for.

Thus, if hot Earths form *in situ* then we expect systems of several hot Earths to form, with spacings comparable to the solar system terrestrial planets. These planets will contain mainly local, dry material, although for low-mass stars

they may contain up to perhaps 0.1-1% water by mass (but see Raymond *et al.* 2007, Lissauer 2007).

### 3.2 Inward Type 1 Migration

Earth- to >Neptune-mass planets excite density waves in the disk (Goldreich & Tremaine 1979). The back reaction of these waves on the planet causes inward orbital migration on a timescale of  $10^{4-6}$  years (Goldreich & Tremaine 1980; Ward 1986, 1997; D’Angelo *et al.* 2003; Masset *et al.* 2006a). However, type 1 migration may be stopped or even reversed in the very inner regions of the disk, because of net disk torque changes at disk edges (Masset *et al.* 2006b) or in the optically thick inner disk (Paardekooper & Mellema 2006). Thus, hot Earths could form far from their stars and migrate in to the location in the disk where the disk torques cancel out and migration is stopped. Presumably, if there is enough solid and gas mass to enable type 1 migration of one planet, then others should follow. Co-migrating planets may end up trapped in mean motion resonances (e.g., Lee & Peale 2002), and can form chains of many planets in paired resonances. These orbital chains of planets can survive for long times, as the outward-directed torques on the inner planets may be balanced by inward-directed torques on the outer planets (Terquem & Papaloizou 2007). Surviving planets do not remain on strictly resonant orbits, and collisions between planets can occur after the disk dissipates.

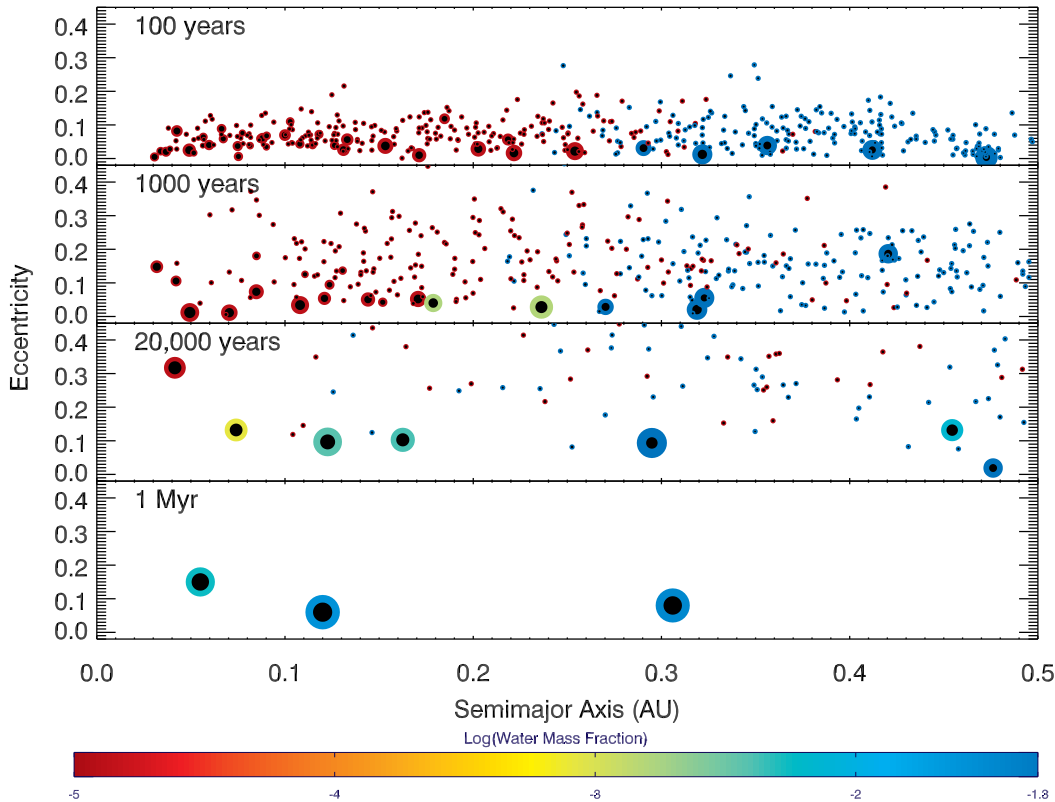
The amount of solid material in the disk is thought to increase by a factor of 2-4 or perhaps more beyond the snow line (Hayashi 1981, Stevenson & Lunine 1988; Lodders 2003). In addition, most disk surface density profiles contain far more mass in their outer regions. Thus, it seems reasonable to assume that, in this model, most hot Earths must form beyond the snow line and are therefore icy in composition rather than rocky. Indeed, transits of the hot Neptune GJ 436 b have been interpreted as an indication that it may be largely composed of water and may therefore have formed beyond the snow line and migrated inward (Gillon *et al.* 2007). Note, however, that inferring a detailed planetary composition from a radius measurement is ambiguous because different combinations of rock, ice and H/He envelopes can form planets with the same mass and radius (see Fig. 3 from Adams *et al.* 2007). In addition, formation and migration models suggest that in a system of several hot Earths it is possible for the innermost hot Earth to be rocky (Alibert *et al.* 2006).

The main consequence of the type 1 migration model is simply that hot Earths didn’t form locally but farther out in the disk, probably in the water-rich icy regions. Therefore, hot Earths should contain a large quantity of ice and have measurably larger radii. In addition, the migration process favors the formation of a chain of resonant or near-resonant planets (Terquem & Papaloizou 2007).

### 3.3 Shepherd by giant planet migration

Giant planets more massive than a critical value carve an annular gap in the protoplanetary disk and are thus locked to the disk’s viscous evolution (Lin & Papaloizou 1986; Takeuchi *et al.* 1996; Bryden *et al.* 1999; Rafikov 2002; Crida *et al.* 2006). These planet subsequently “type 2” migrate,

<sup>3</sup> Note that this disks as massive as the one in Fig. 1 (30 times the minimum-mass disk) are likely to be quite rare (e.g., Andrews & Williams 2005). Thus, *in situ* accretion of close-in planets of several Earth masses can probably occur only for a small fraction of protoplanetary disks (see § 4).



**Figure 1.** Snapshots of *in situ* accretion of a system of hot Earths. Each object’s size is proportional to its mass<sup>1/3</sup>, and the color corresponds to its water content, from 10<sup>−5</sup> water by mass (red) to 5% water by mass (darkest blue; see color bar). The dark circle in the center of each body refers to the relative size of its iron core (see Raymond *et al.* (2005) for details). In this case, the central star is 0.31  $M_{\odot}$ , the same as Gliese 581.

usually inward, on a  $\sim 10^5 - 10^6$  year timescale, depending on the disk’s viscosity (Lin & Papaloizou 1986, Lin *et al.* 1996; Ward 1997; D’Angelo *et al.* 2003). Such a planet migrates through a disk composed of both gas and solids in the form of km-sized planetesimals and Moon- to Mars-sized planetary embryos, which formed in series of dynamical steps from micron-sized dust grains (as in the *in situ* formation model; see § 3.1 or Chambers 2004, Papaloizou & Terquem 2006 for reviews). As the giant planet migrates inward, it shepherds material in front of strong mean motion resonances (MMRs). The evolution of a typical planetary embryo in the inner disk proceeds as follows. As the giant planet approaches the embryo, the embryo’s eccentricity is increased by an MMR (usually the 2:1 or 3:2, but higher-order resonances are stronger for more eccentric giant planets; Murray & Dermott 1999). Gas drag and dynamical friction with nearby planetesimals act to recircularize the embryo’s orbit and decrease its energy, thereby reducing its semimajor axis and moving it just interior to the MMR (Adachi *et al.* 1976; Tanaka & Ida 1999). As the giant planet continues its migration, the embryo is again excited by the approaching MMR and the cycle continues. Thus, embryos and planetesimals are shepherded inward by moving MMRs and accrete into planet-sized bodies during giant planet mi-

gration<sup>4</sup> (Fogg & Nelson 2005, 2007; Zhou *et al.* 2005; Raymond *et al.* 2006b; Mandell *et al.* 2007). However, during this process, many bodies’ eccentricities are damped too slowly to avoid a close encounter with the giant planet. Such bodies are usually scattered outward, and can form a subsequent generation of exterior terrestrial planets (Raymond *et al.* 2006b; Mandell *et al.* 2007).

Figure 2 shows snapshots in time of this shepherding process from a simulation by Mandell *et al.* (2007). It is clear that the 2:1 MMR is responsible for the bulk of the shepherding in this simulation. The two hot Earths formed are on low-eccentricity orbits immediately interior to strong resonances, as expected. However, in simulations including weaker gas drag, hot Earths can form on higher eccentricity orbits (Fogg & Nelson 2007, Mandell *et al.* 2007). The survival of high eccentricity hot Earths is uncertain, given that tides may act to alter the planets’ orbits and possibly lead them into unstable giant planet resonances or drive them into the star (see § 3.5 below).

<sup>4</sup> The formation timescale of shepherded hot Earths is on the order of the migration timescale (Mandell *et al.* 2007). Thus, hot Earths may form in  $\sim 10^5 - 10^6$  years, as opposed to the  $10^7 - 10^8$  year timescale for the Earth calculated from Hf/W isotopic measurements (Kleine *et al.* 2002; Jacobsen 2005). This very short formation timescale for hot Earths could have consequences for their geological evolution.

In the giant planet migration shepherding model, hot Earths are a mixture of material that originated interior to the giant planet's orbit. Both the core-accretion and gravitational collapse models predict that giant planets are likely to form at large orbital distances, beyond the snow line, which itself moves inward in time (Pollack *et al.* 1996; Boss 1997; Bodenheimer *et al.* 2000; Sasselov & Lecar 2000; Mayer *et al.* 2002). In the simulations of Raymond *et al.* (2006b) and Mandell *et al.* (2007), the hot Earths that formed contained 1-2% water by mass, as is the case for the two hot Earths in Fig. 2. The assumed starting water distribution in those cases was similar to that of current-day primitive asteroids (Abe *et al.* 2000; Fig. 2 from Raymond *et al.* 2004). Note that water depletion from impacts and hydrodynamic escape was neglected in these calculations.

The giant planet migration shepherding model predicts that hot Earths should lie close to a strong MMR, most likely the 2:1 MMR, interior to a giant planet (Fogg & Nelson 2005; Zhou *et al.* 2005; Raymond *et al.* 2006b; Mandell *et al.* 2007). In this model, hot Earths are formed from a mixture of material that originated interior to the giant planet's orbit. Giant planets are expected to form just outside the snow line, given the increase in solid material (Hayashi 1981; Stevenson & Lunine 1988; Ida & Lin 2004). Thus, hot Earths formed by shepherding are likely to contain up to a few percent water, but probably not more (Mandell *et al.* 2007). Note that planets with water contents of a few percent by mass cannot be distinguished from rocky planets by radius measurements given observational uncertainties (Valencia *et al.* 2007b; Fortney *et al.* 2007; Sotin *et al.* 2007; Seager *et al.* 2007).

### 3.4 Shepherding by Sweeping Secular Resonances during Disk Dispersal

Moving secular resonances (SRs) can shepherd material in a similar way to mean motion resonances (MMRs) if gas drag is present. An SR occurs when the apsidal precession frequency of two bodies' orbits are commensurate (e.g., Murray & Dermott 1999). In a disk with two or more giant planets, interactions between the planets cause each of their orbital alignments to precess. In addition, the gravitational potential of the massive gaseous disk affects the precession rates, and therefore the location of SRs with each planet in the disk (Ward 1981; Nagasawa *et al.* 2005). As the disk dissipates, SRs can move progressively ("sweep") across a given region, increasing the eccentricities of bodies. In the case of a smooth, inward-sweeping SR, shepherding of material can happen similar to MMR shepherding for migrating giant planets.

In the context of hot Earth formation, the SR shepherding model applies to cases with two or more giant planets that have stopped migrating. A smooth dissipation of the disk can induce SR sweeping. Much as in the migration shepherding mechanisms, a sweeping SR excites the eccentricities of nearby protoplanets. These eccentricities are subsequently damped by gas drag and the body's orbit is moved interior to the resonance. This process continues for the duration of the SR sweeping, unless a planet gets close enough to the star that its precession rate becomes dominated by general relativistic effects rather than dynamical ones (Zhou *et al.* 2005).

Thus, the secular resonance shepherding model involves a complex interaction between two giant planets, the massive gaseous disk, and relatively low-mass terrestrial material. It requires a monotonic, inward secular resonance sweeping which itself requires a smooth dispersal of the gaseous disk (Ward 1981), which is uncertain given that most stars form in large clusters and may lose disk mass in periodic photo-evaporation events (Lada & Lada 2003; Adams *et al.* 2004; Hester *et al.* 2004). In the SR shepherding model, a hot Earth system must also contain at least two more distant, interacting giant planets. The compositions of hot Earths in this scenario are a mixture of material from interior to the giant planets' starting orbits. Estimating the compositions of hot Earths in this model therefore requires a knowledge of the giant planet's formation locations, specifically how far past the snow line they formed.

### 3.5 Tidal Circularization of Eccentric Terrestrial Planets

The circular orbits of hot Jupiters have been attributed to energy and angular momentum dissipation via tides raised on the planet by the star (Rasio *et al.* 1996). In fact, it has been proposed that close-in giant planets may have been scattered onto high-eccentricity orbits and tidally circularized (Rasio & Ford 1996; Weidenschilling & Marzari 1996; Mardling & Lin 2004; Jackson *et al.* 2007). Could tidal circularization act as a mechanism to transport terrestrial planets inward? To address this possibility, we integrated the second-order, coupled semimajor axis  $a$  and eccentricity  $e$  tidal evolution equations (Goldreich & Soter 1966; Kaula 1964; Greenberg 1977):

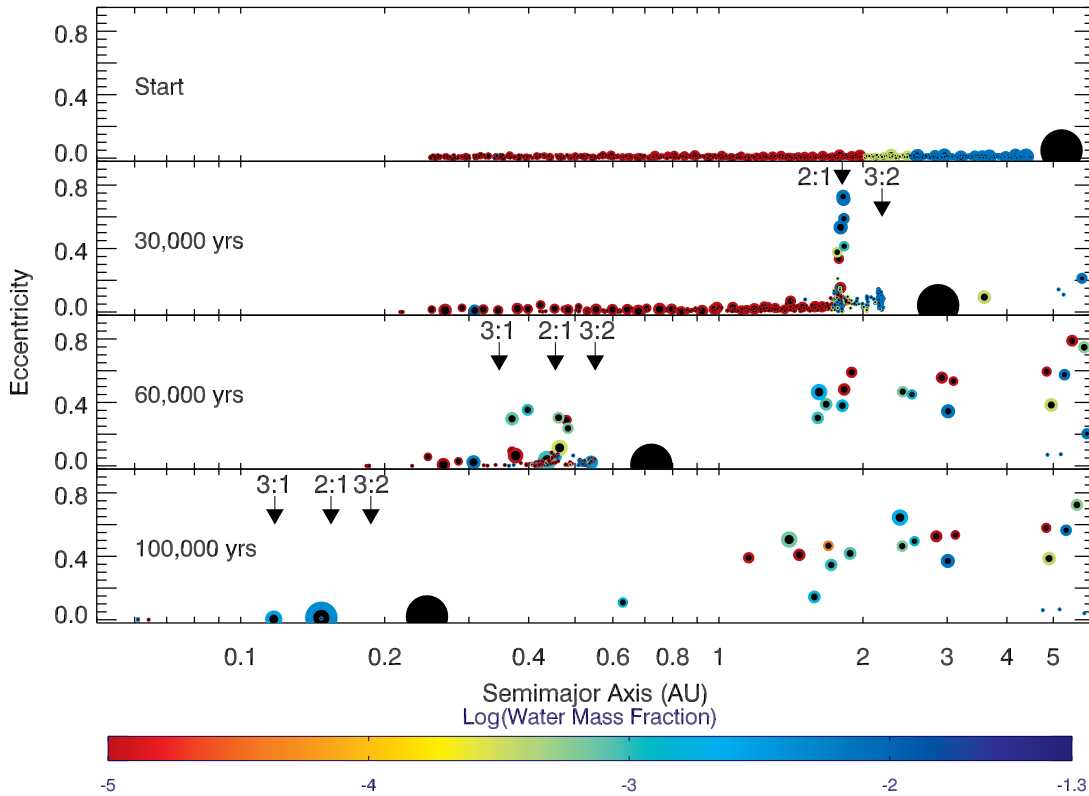
$$\frac{da}{dt} = - \left( 21 \frac{\sqrt{GM_*^3 R_p^5 k_p}}{m_p Q'_p} e^2 + \frac{9}{2} \frac{\sqrt{G/M_*} R_*^5 m_p k_*}{Q'_*} \right) a^{-11/2} \quad (1)$$

$$\frac{de}{dt} = - \left( \frac{21}{2} \frac{\sqrt{GM_*^3 R_p^5 k_p}}{m_p Q'_p} + \frac{171}{16} \frac{\sqrt{G/M_*} R_*^5 m_p k_*}{Q'_*} \right) a^{-13/2} e \quad (2)$$

where  $Q'_p$  and  $Q'_*$  are the tidal dissipation functions of the planet and star, respectively,  $k_p$  and  $k_*$  are the Love numbers of the planet and star,  $m_p$  and  $M_*$  are the masses of the planet and star,  $R_p$  and  $R_*$  are the radii of the planet and star, and  $G$  is the gravitational constant.

Note that solutions with higher order terms in  $e$  have been derived (e.g., Hut 1981; Eggleton *et al.* 1998). However, such models include, in effect, assumptions about how a body responds to the ever-changing tidal potential, effects that have not been observed. Therefore not enough is known about the actual response of real bodies to evaluate these higher-order effects. As we are only interested in the qualitative differences between planets whose orbits have evolved through tidal decay and those that did not, the second order solution should suffice.

We considered a stellar mass of 0.3, 1, and 3  $M_\odot$  with radii determined from Gorda & Svechnikov (1999), a planet mass of 1 and 5  $M_\oplus$  (assuming  $R_p \propto m_p^{0.27}$ , as suggested by Valencia *et al.* 2006), a perihelion distance from 0.025 to 0.1 AU, and eccentricities  $e$  from 0 to 0.9. For the planet, we assumed  $k_p = 0.3$  and  $Q'_p = 21.5$  (Dickey *et al.* 1994;



**Figure 2.** Snapshots in time of the migration of a Jupiter-mass giant planet through a disk of terrestrial bodies, including the effects of aerodynamic gas drag, from a simulation by Mandell *et al.* (2007). Specific strong resonances with the giant planet are indicated. Colors refer to bodies' water contents, as in Fig. 1. This version reproduced from Gaidos *et al.* (2007).

Mardling & Lin 2004); for the star,  $k_* = 1.5$  and  $Q'_* = 10^{5.5}$  (Ogilvie & Lin 2007; Jackson *et al.* 2007). Each orbit was integrated for 10 Gyr using a  $10^3$  year timestep, which convergence tests showed is three orders of magnitude smaller than necessary to produce reliable results.

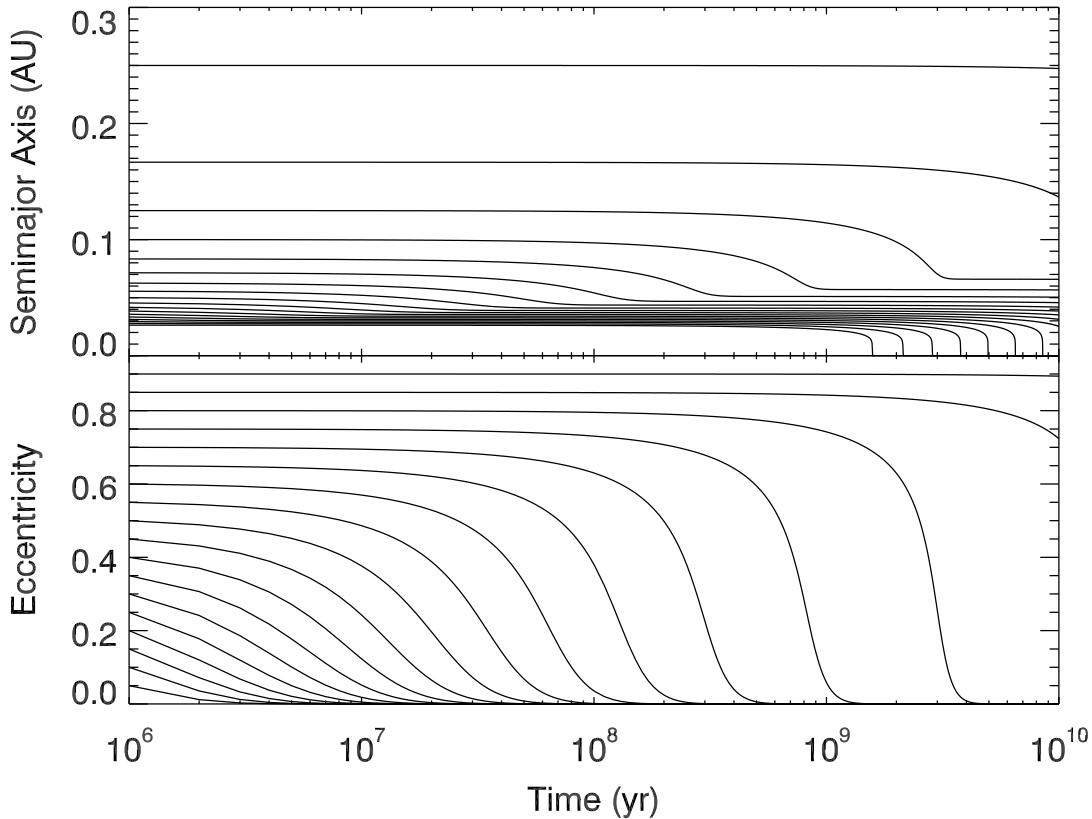
Figure 3 shows the evolution of a set of  $5 M_\oplus$  planets with the same initial perihelion distance of 0.025 AU, and starting eccentricities ranging from 0.05 ( $a = 0.026$  AU) to 0.9 ( $a = 0.25$  AU). As expected, evolution proceeds much faster for bodies at smaller orbital distances (in this case, those with lower eccentricities). For planets with starting eccentricities of 0.6 or less ( $a \leq 0.06$  AU), orbital circularization takes place within  $10^8$  years, including an inward drift in semimajor axis of up to 0.01-0.02 AU. Circularization takes longer for larger  $a$  values, but the amount of inward drift is also increased. For the  $e = 0.8$  planet, circularization requires several Gyr, but the planet moves inward from 0.125 to 0.065 AU. At still-larger orbital distances (and eccentricities), circularization takes longer than the age of the star. Note that orbital evolution continues slowly after the planet's orbit becomes circular, via tides raised on the star by the planet. Mardling & Lin (2004) showed that should  $a$  become very small ( $\lesssim 0.01$  AU), then the planet is doomed to fall into the star within a few Gyr. We confirm that assessment here. Therefore we expect no planets inside 0.01 AU for any formation scenario.

The degree to which tidal circularization can move a planet inward clearly depends on its starting orbit, size, and

ability to dissipate energy. Figure 3 shows the most tidal evolution of any of the cases we explored for a Solar-mass star; in most cases evolution was slower (except for the  $3 M_\odot$  cases, which were faster). Thus, it appears that inward movement of planets during tidal evolution is relatively small, at most a  $\sim 0.05$  AU change in semimajor axis. However, if the large eccentricity were due to a perturbative event, then the planet's starting aphelion might be representative of its pre-encounter semimajor axis. In that case, the effective inward movement due to tides is doubled (starting aphelion to final semimajor axis), although it would still be less than about 0.1-0.15 AU on a  $> \text{Gyr}$  timescale. The composition of the planet depends on its formation history, especially whether it formed locally or migrated inward.

What is the source of the large eccentricity needed to drive tidal circularization? Planet-planet scattering has been invoked to explain the large eccentricities of the known extra solar planets (Rasio & Ford 1996; Weidenschilling & Marzari 1996; Lin & Ida 1997; Ford *et al.* 2005; but see Barnes & Greenberg 2007). The strength of a scattering event depends on a combination of the escape speed of the perturber, the encounter velocity, and the escape speed from the system. For close-in planets, the system escape speed is large, and so only very massive bodies can excite large eccentricities. Indeed, accretion may be preferred over scattering in these situations (Goldreich *et al.* 2004).

One alternative mechanism for eccentricity growth is an instability in nearby giant planets could alter the orbit of a



**Figure 3.** Orbital semimajor axis  $a$  and eccentricity  $e$  vs. time for a series of  $5 M_{\oplus}$  planets orbiting Sun-like stars with starting perihelion distances of 0.025 AU. Each curve corresponds to a planet with a given starting eccentricity, from 0.05 ( $a = 0.026$  AU) to 0.9 ( $a = 0.25$  AU). If  $a$  drops below  $\sim 0.01$  AU, then the planet will fall into the star due to tidal evolution.

terrestrial planet (Veras & Armitage 2006). In that case, one or more exterior giant planets should exist in the system, on eccentric orbits. Another possible source of eccentricity could arise if the host star had a binary companion. If the orbital plane of the planet were significantly inclined with respect to that of the binary, then large eccentricities could be induced via the Kozai mechanism (Kozai 1962). In most of these models, some evidence for an external perturber should be evident.

Thus, tidal circularization can move a highly-eccentric terrestrial planet inward to some extent, although the planet must be relatively massive ( $\gtrsim 5 M_{\oplus}$ ) and have a very small starting perihelion distance ( $\lesssim 0.03$  AU). If the planet formed locally, then its composition is likely to be relatively dry ( $\lesssim 1\%$  water by mass). A source of high eccentricity may also be evident, such as a binary stellar companion or a distant eccentric giant planet.

### 3.6 Giant Planet Migration and Photo-evaporation

Baraffe *et al.* (2004, 2006) proposed that close-in, Neptune-mass planets might be the remains of larger planets that have been photo-evaporated away. Such planets would form farther from their parent stars and migrate inward (Ida *et al.* 2004, Alibert *et al.* 2005), losing a portion of their gaseous envelopes hydrodynamically via irradiative XUV heating (Lammer *et al.* 2003, Baraffe *et al.* 2004). Here we investigate

the possibility that photo-evaporation could lead to the removal of the entire envelope of a hot Jupiter or hot Neptune, leaving behind a solid planet, i.e., the core of the irradiated giant planet.

Recent estimates derive evaporation rates that are far smaller than those used by Lammer *et al.* (2003), and include the effects of two-dimensional layering (Tian *et al.* 2005) and improved atmospheric chemistry (Yelle 2004, 2006). Indeed, these new evaporation rates are closer to those of Watson *et al.* (1981). Perhaps most convincing that the Lammer *et al.* evaporation rates are too large is empirical evidence that the mass distribution of highly irradiated extra-solar planets (inside 0.07 AU) is identical to that of more distant planets (Hubbard *et al.* 2007a). A substantial change in the mass function is predicted for evaporation models (i.e., fewer massive planets and more less-massive ones).<sup>5</sup> Such an effect may exist at lower masses, but not in the currently-probed sample of planets. Hubbard *et al.* (2007b) show that at the

<sup>5</sup> Fortney *et al.* (2007) also showed that if hot Neptunes form via photo-evaporation of hot Jupiters, then their radii should be on the order of one Jupiter radius. However, if they are not remnants of hot Jupiters, then their radii should be  $0.3\text{--}0.4 R_J$ . The first transiting hot Neptune indeed has a radius of  $\sim 0.35 - 0.4 R_J$  (Gillon *et al.* 2007; Deming *et al.* 2007). Note, however, that Gliese 436 is an M dwarf ( $0.41 M_{\odot}$ ) and therefore has low EUV and FUV emission (except during flares), which are key for driving evaporative mass loss (Butler *et al.* 2004).



minimum orbital radius of known extra-solar planets (0.023 AU), the initial mass must be less than about a Saturn mass to evaporate completely, i.e., to its core. For more typical hot Jupiter orbits, at 0.05-0.1 AU, this critical mass is smaller still.<sup>6</sup> The models of Baraffe *et al.* (2004) and Hubbard *et al.* (2007b) do not account for the presence of a core, which is important once the planet mass is less than  $\sim 100 M_{\oplus}$ , such that a 5-10  $M_{\oplus}$  core constitutes a non-negligible fraction of the planet mass. Note that the Baraffe *et al.* (2006) models do incorporate this effect, as we do implicitly by using their internal structure models.

Mass loss due to hydrodynamic escape, limited only by energy deposition, depends critically on the stellar irradiance of the atmosphere, and can be approximated by the relation

$$\dot{M} = \frac{3\beta(F_*, a)^3}{G\rho} \frac{F_{XUV} + F_{\alpha}}{a^2} \quad (3)$$

where  $F_{XUV}$  and  $F_{\alpha}$  represent the high-energy radiation incident on the planet, and  $\rho$  and  $a$  are the planet density and orbital distance from the star respectively (Lammer *et al.* 2003; Baraffe *et al.* 2004). The parameter  $\beta$  is the ratio of the irradiated planetary radius to the planet's "original", non-irradiated radius for a specific stellar flux and orbital distance (Lammer *et al.* 2003, Baraffe *et al.* 2004, 2006, and Hubbard *et al.* 2007b all assume  $\beta = 3$  based on atmospheric models of Watson *et al.* 1981). For a constant orbital distance, the mass loss will therefore initially decrease in time as the planet cools and becomes more dense and the star's UV and x-ray flux decreases. Over time, as hot material escapes from the top of the planetary atmosphere new layers are irradiated and stellar flux is converted to expansion energy, gravitational contraction of the planet slows. If enough mass is evaporated, expansion surpasses contraction and the planet experiences run-away mass loss, leaving behind only the solid core.

To construct a simplified model of photo-evaporative mass loss, we need to constrain certain parameters. We assumed evaporation rates 100 times smaller than the energy-limited case from Lammer *et al.* (2003). The radius of an evaporating planet stays relatively constant regardless of mass, such that we extrapolated radii for planets of various masses and heavy-element abundances from Baraffe *et al.* (2006, with corrections for semimajor axis from Chabrier *et al.* 2004) to find a mass-radius relation for irradiated planets as a function of time. Planets less massive than  $\sim 50 M_{\oplus}$  are more likely than larger planets to contain significant concentrations of molecular species, simply because the ratio of core mass to envelope mass is decreased (e.g., Uranus and Neptune). Molecules such as  $H_2O$  and  $CH_4$  play an important part in the energetics of atmospheric expansion, and therefore affect the mass loss rate (Hubbard *et al.* 2007a). Although our approach does not directly incorporate changes in evaporation rate with chemistry, the mass-radius relations from Baraffe *et al.* (2006) are based on Alibert *et al.* (2005)s

values for heavy-element enrichment of the planets' atmospheres and therefore implicitly include a decreased evaporation rate for smaller planets with heavy-element-rich atmospheres since evaporation rates depend on the planet radius. Our simplified model demonstrates good agreement with the results from more detailed models by Hubbard *et al.* (2007b) and the reduced-evaporation models of Baraffe *et al.* (2006) for higher-mass planets.

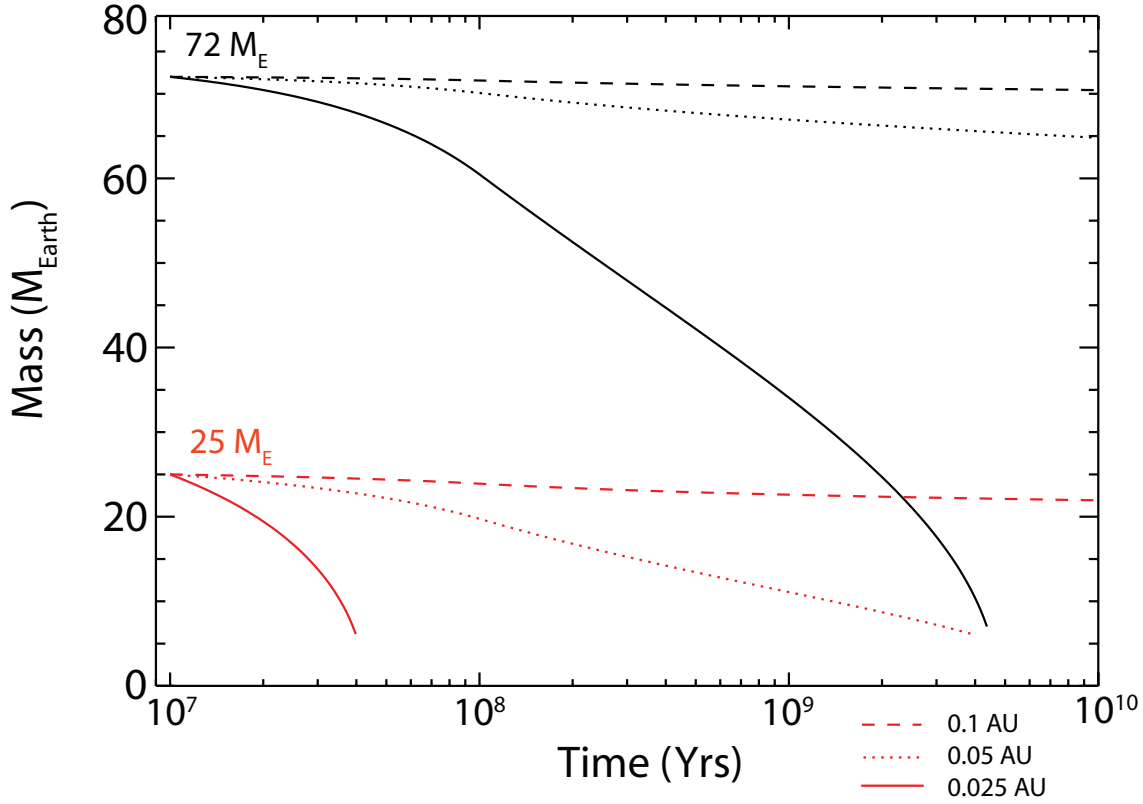
Figure 4 shows the masses of two highly-irradiated planets as a function of time, on circular orbits at 0.025, 0.05, and 0.1 AU. Even on its closest orbit, the more massive planet ( $72 M_{\oplus}$ ) took 5 Gyr to evaporate to its core. Given that the transition from type 1 to type 2 migration is thought to occur at roughly  $70 M_{\oplus}$  (Ward 1997; D'Angelo *et al.* 2003), this effectively rules out the formation of hot Earths by type 2 migration and subsequent photo-evaporation, simply because planets massive enough to type 2 migrate will not lose enough mass by photo-evaporation. In contrast, the less massive planet ( $25 M_{\oplus}$ ) evaporated to its core in less than 50 Myr at 0.025 AU, but required Gyr to lose mass past 0.05 AU. Additionally, beyond  $\sim 0.1$  AU the mass loss over 5 Gyrs is negligible; planets found beyond this orbital distance maintain their mass over the lifetime of the system.

After the primordial atmosphere has been lost, the core of the planet is exposed. If the core of the planet is composed primarily of low-temperature condensates (consistent with formation in the cold outer disk – Pollack *et al.* 1996; Boss 1997), the outer layers of the planetary core may continue to vaporize. To determine the original mass of a hot Earth formed from the core of a photo-evaporated massive planet, models of the evolution of intensely irradiated icy bodies must be developed; current models of volatile-dominated Earth-mass planets (Valencia *et al.* 2006, 2007a, 2007b; Fortney *et al.* 2007; Sotin *et al.* 2007; Seager *et al.* 2007) have not yet probed these processes.

Thus, photo-evaporation of close-in gaseous planets may remove their atmospheres and leave behind solid cores. This process is only effective for planets within about 0.05 AU that are below the type 2 migration threshold of  $\sim 70 M_{\oplus}$ . For those cases, "hot Neptunes" could become "hot Earths" on a  $10^8$ – $10^{10}$  year timescale. This process can occur in conjunction with the type 1 migration scenario discussed above in § 3.2. Indeed, the most likely source of hot Neptunes is the outer disk (Gillon *et al.* 2007). In some cases, a series of  $\gtrsim 10 M_{\oplus}$  planets may form in the cold outer disk and then type 1 migrate inward as described above, into a chain of hot Neptunes. Depending on their orbits, the innermost planet or two could be photo-evaporated over time into a very water-rich hot Earth. A diagnostic of photo-evaporation could therefore be a system with 1) a water-rich hot Earth inside 0.05 AU and 2) additional,  $\sim$  Neptune-mass planets exterior to the hot Earth in near-resonant orbits. However, it would still be difficult to definitely assess the degree of photo-evaporation in such a setting.

More definitive detections of the importance of photo-evaporation would require statistics of a large number of hot Earths and hot Neptunes orbiting stars with a range of ages. A correlation between the number of hot Earths vs. hot Neptunes and the stellar age would indicate that such planets were losing mass in time, presumably via photo-evaporation. Alternatively, exploring the mass functions of

<sup>6</sup> Tidal evolution models suggest that close-in planets may have originated at somewhat larger orbital distances and slowly evolved inward, concurrently decreasing their semimajor axes and eccentricities (Jackson *et al.* 2007). If close-in giant planets did indeed originate on somewhat more distant, eccentric orbits, then their time-averaged fluxes would likely be reduced.



**Figure 4.** The evolution of the masses of two highly-irradiated planets due to photo-evaporation. Our model is based on planetary structure models of irradiated planets from Baraffe *et al.* (2006) and Chabrier *et al.* (2004) and evaporation rates based on the model of energy-limited hydrodynamic escape from Lammer *et al.* (2003), but reduced by a factor of 100 in accordance with the results of Hubbard *et al.* (2007). The intermediate-mass planet ( $72 M_{\oplus}$ ) represents the boundary between planets that would undergo type I migration ( $M \lesssim 70 M_{\oplus}$ ) and planets that would undergo type II migration ( $M \gtrsim 70 M_{\oplus}$ ; D’Angelo *et al.* 2003). The planets are placed at three different orbital radii: 0.025 AU (solid), 0.05 AU (dotted), and 0.1 AU (dashed).

close-in planets down to lower masses could reveal time-dependent mass loss (as in Hubbard *et al.* 2007a).

## 4 ORIGIN OF THE KNOWN HOT EARTH SYSTEMS

### 4.1 Gliese 876

Gliese 876 is a  $0.32 M_{\odot}$  star (M4 dwarf) less than 5 parsecs from the Sun (Marcy *et al.* 1998). Its known planetary system contains a  $\sim 7.5 M_{\oplus}$  hot Earth at 0.02 AU, as well as two additional,  $\sim$ Jupiter-mass planets in a 2:1 resonance on more distant orbits (Marcy *et al.* 1998, 2001; Rivera *et al.* 2005). The separation between the hot Earth and the giant planets is significant: the ratio of orbital periods between the hot Earth and inner giant planet is 16.6. Both models and observations suggest that Jovian planets are rare around low-mass stars (Laughlin *et al.* 2004; Ida & Lin 2005; Endl *et al.* 2006; Butler *et al.* 2006; Gould *et al.* 2006). Thus, the existence of two such massive planets around GJ 876 may indicate that its protoplanetary disk was particularly massive (e.g., Wyatt *et al.* 2007; Lovis & Mayor 2007).

Could the GJ 876 hot Earth at 0.02 AU have formed *in situ*? If so, then there must have been at least  $7.5 M_{\oplus}$  in solids interior to  $\sim 0.05$  AU, assuming accretion was efficient.

In the minimum-mass solar nebula (MMSN) model, assuming the surface density  $\Sigma$  scales as  $r^{-3/2}$ , there is  $\sim 0.75 M_{\oplus}$  inside 0.05 AU, assuming the disk to extend all the way into the star (Weidenschilling 1977; Hayashi 1981; Raymond *et al.* 2007). For a more common disk profile of  $\Sigma \propto r^{-1}$  (e.g., Andrews & Williams 2007), and applying a MMSN prescription, there is only  $0.06 M_{\oplus}$  inside 0.05 AU. Thus, if  $7.5 M_{\oplus}$  of material existed in the inner 0.05 AU of GJ 876’s disk, then that disk must have been 10-100 times more massive than the solar nebula. This value is rather large, but it is not outside the realm of possibility, given the large spread in observed disk masses (Andrews & Williams 2005; Scholz *et al.* 2006). However, such a massive disk would be an anomaly, and the fraction of disks that could form such a close-in planet is small (Raymond *et al.* 2007). In addition, given the  $\sim$  linear relation between disk mass and stellar mass (e.g., Scholz *et al.* 2006), such a massive disk is an additional three times less likely. In addition, given the large dynamical separation between the hot Earth and the closest Jovian planet, there is no clear explanation for the lack of additional hot Earths. Thus, it is unlikely that GJ 876’s hot Earth formed *in situ*.

If the GJ 876 hot Earth formed at a distance and type 1 migrated inward, we would expect it to have companions of similar mass in near resonant orbits. No such compan-

ions have been discovered to date, although planets of a few  $M_{\oplus}$  would probably not be detectable (Rivera *et al.* 2005). However, given the existence of the two Jovian planets, perhaps there was a limited window of time for type 1 migration into the inner disk: once the giant planets formed, they would pose a barrier for smaller migrating bodies (Thommes 2005). A mass of  $7.5 M_{\oplus}$  is consistent with a single hot Earth migrating into the inner disk, then stalling where the type 1 torques disappear (Masset *et al.* 2006b; Paardekooper & Mellema 2006).

Zhou *et al.* (2005) explain the origin of the GJ 876 hot Earth with a combination of shepherding from giant planet migration and SR sweeping. In Zhou *et al.*'s model, the two Jovian planets formed on more distant orbits, and were trapped in resonance during migration (e.g., Lee & Peale 2002). This migration also induced the formation of planets inside strong resonances, by the migration shepherding mechanism described in § 3.3. The giants' migration stalled close to their current orbits, but subsequent dissipation of the disk induced SR sweeping, promoting further accretion and shepherding the hot Earth farther away from the giant planets. This two-step model does not require as large a disk mass as *in situ* accretion, because some mass from more distant regions is shepherded into the inner disk. In addition, it predicts a significant separation between the giant planets and the hot Earth, caused by the SR sweeping after migration. However, this model has some uncertainties. For example, the violent nature of star-forming environments may cause episodic pulses in the evaporation of the disk (Adams *et al.* 2004) and therefore in the location of SRs (Ward 1981). In such non-monotonic SR sweeping, it is unclear if material can still be shepherded.

In Zhou *et al.*'s model, it is likely that the hot Earth is relatively dry, assuming its composition is determined by the formation zone of the innermost giant planet, and that accretion followed roughly as in Mandell *et al.* (2007). In the type 1 model, the hot Earth could be rocky or icy, also depending on its formation zone. If GJ 876 d were to transit its host star, then its bulk composition (rocky vs. icy) could be determined (see § 2). If it were shown to be icy in nature, that would support the type 1 migration scenario. However, if it were rocky, it would lend support to Zhou *et al.*'s model.

## 4.2 Gliese 581

Gliese 581 is a  $0.31 M_{\odot}$  M3 dwarf at a distance of 6.3 pc from the Sun (Hawley *et al.* 1997). Its planetary system contains three hot Earths/Neptunes with orbits between 0.04 and 0.25 AU and minimum masses between 5 and  $15 M_{\oplus}$  (Bonfils *et al.* 2005; Udry *et al.* 2007). The innermost planet is the hot Neptune ( $M \sin i = 15.7 M_{\oplus}$ ). No Jovian planets have been detected in the system to date, ruling out the two shepherding mechanisms.

The most likely formation mechanism of the GJ 581 system is either *in situ* formation or type 1 migration (S. Raymond *et al.*, in preparation). The orbital periods of the planets do not form an obvious pattern – the period ratios between planets b/c and c/d are 2.38 and 6.34, respectively. The semimajor axes of planets b/c and c/d are separated by 20.5 and 47 mutual Hill radii, respectively, similar to values for the Solar System's terrestrial planets.

For the GJ 581 planets to have formed *in situ* would

require  $\sim 40 - 50 M_{\oplus}$  inside 0.5 AU. Indeed, the simulation from Fig. 1 is an attempt to reproduce the system via *in situ* accretion. By the same arguments as made above, this would require a disk that is, at least in its inner regions, 17-50 times more massive than a minimum-mass disk. Given that the spacing of planets b, c and d is comparable to those of Venus, Earth and Mars, *in situ* accretion remains a reasonable model for GJ 581. In this scenario, the innermost planet would have accreted first, and therefore may have been able to capture a small amount of nebular gas to account for its large mass (e.g., Pollack *et al.* 1996).

Formation at larger orbital distances followed by type 1 migration is the other viable mechanism for GJ 581. The planets' spacings are not next to obvious resonances, but b/c lie less than 10% from the 5:2 MMR and quite close to the 12:5. Planets c/d are more distant, but of course there exists the possibility of an additional, slightly lower-mass planet between planets c and d. If such a planet were discovered, it would support the type 1 migration scenario.

Tidal effects are important in the GJ 581 system, given the planets' proximity to the star. Given that tides damp both semimajor axes and eccentricities, it is likely that the GJ 581 planets b and c formed on more distant and more eccentric orbits (Barnes *et al.* 2007). Given the planets' already significant eccentricities ( $e \sim 0.2$  for each planet), it is not clear how the system could form with such high eccentricities. In addition, the fact that the innermost planet is the most massive of the three suggests that photo-evaporation has not occurred in this system. Indeed, given the star's low luminosity (1.3% of solar), the threshold distance for photoevaporation is likely to be at less than 0.01 AU.

Despite the uncertainties, the main difference between the two possible models is simply the composition of hot Earths. *In situ* formation predicts relatively dry planets, while type 1 migration predicts icy planets with  $> 10\%$  water by mass. Thus, if transits were measured for any of the GJ 581 planets and a composition were determined, then it would be possible to distinguish between these two models.

## 5 SUMMARY AND DISCUSSION

We anticipate that a large number of planetary systems containing close-in terrestrial planets, referred to here as "hot Earths", will be discovered in the coming years with radial velocity and transit measurements. In some cases, both an accurate determination of the architecture of the inner planetary system and of the bulk composition of a hot Earth (rocky vs. icy; but see Adams *et al.* 2007) will be possible (see § 2). The goal of this paper is to determine whether the formation history of such systems can be unraveled, given the relatively small amount of information available. In addition to four already-known mechanisms for hot Earth formation, we have shown that tidal circularization of highly eccentric planets can move terrestrial planets' orbits inward, but only by perhaps 0.1 AU, and only for very close-in perihelion distances ( $\lesssim 0.05$  AU). In addition, our simple model suggests that photo-evaporation can remove a giant planet's atmosphere and leave behind the core. However, this is only possible for very close-in orbits ( $< 0.025 - 0.05$  AU) and relatively low-mass planets ("hot Neptunes" with masses below  $70 M_{\oplus}$ ), as suggested by Hubbard *et al.* (2007a).

Table 1 summarizes the observable consequences of these six models for hot Earth formation. There exist several clear differences between the models that should be detectable in the near future. Given a planetary system with a transiting hot Earth, considerable RV measurements, and perhaps transit timing analysis, Table 1 provides a simple way to determine the formation history of hot Earth planetary system. Note that in some cases, more than one of these mechanisms can act in concert. For example, the case of GJ 876 may be explained in a two-step process, via shepherding during migration and then during secular resonance sweeping (see § 4.1; Zhou *et al.* 2005). In addition, tides affect the orbits of all hot Earths to some degree, regardless of their formation history. However, certain mechanisms cannot act together: planets massive enough to type 2 migrate cannot have their envelopes photo-evaporated and become hot Earths (see § 3.6).

The formation mechanisms of the two known hot Earth systems are not entirely clear (see § 4 above). However, transit measurements of the hot Earth of either of the known systems would make it far easier to discern between models. In particular, for the case of GJ 581, a transit measurement of planet c or d would distinguish between *in situ* formation (rocky) and type 1 migration (icy). Clearly, more work is needed to better characterize and quantify some of these models, and to examine the long-term survival of hot Earths in different systems. In addition, it is possible that additional mechanisms exist for hot Earth formation that have not yet been considered.

Zhou *et al.* (2005) claimed that hot Earths should be numerous if giant planets form via core-accretion (Mizuno 1980; Pollack *et al.* 1996; Lissauer & Stevenson 2007), but rare if they form via gravitational instability (Boss 1997; Mayer *et al.* 2002; Durisen *et al.* 2007). Given the large number of avenues for hot Earth formation, we disagree with Zhou *et al.* on this point. Indeed, three of the candidate mechanisms for hot Earth formation – *in situ* accretion, type 1 migration, and tidal circularization – do not require a giant planet at all and so are unaffected. Photo-evaporation of hot Neptunes may be affected because the two giant planet formation models predict different core masses: core-accretion predicts 5-20  $M_{\oplus}$  cores (e.g., Alibert *et al.* 2005) while the cores of giant planets formed via disk instability are likely to be smaller (Boss 1998, 2006). For the other two mechanisms – giant planet migration shepherding and secular resonance shepherding – is there a reason that the outcome should depend on the mode of giant planet formation? The main difference between the two models is the timing of giant planet formation: core-accretion predicts that giant planets form late in the lifetime of the gaseous disk, while gravitational instability forms planets very quickly. Giant planet migration starts immediately after, or even during, formation (Lufkin *et al.* 2004). Thus, if giant planets form via core-accretion, they migrate through a disk that has undergone at least 1 Myr of accretion, and contains both  $\sim$ Moon-sized planetary embryos and km-sized planetesimals (plus  $\sim$  99% gas; e.g., Kokubo & Ida 2000; Chambers 2004). If, however, giant planets form via gravitational instability, then they would migrate through a disk containing predominantly smaller bodies such as planetesimals. Fogg & Nelson (2005, 2007) showed that the prevalence of shepherding vs. scattering during migration is relatively insensitive to the accretion

history of the inner disk. In the secular resonance shepherding model, two giant planets must be on interacting orbits by the late stages of the dispersal of the gaseous disk; the planets' prior orbital histories are not relevant. Thus, we see no reason that the abundance or rarity of hot Earths should be affected by the mechanism for giant planet formation.

One other interesting difference between the core accretion and gravitational instability models is the expected location of giant planet formation. In core accretion, there are several reasons to expect giant planets to form just past the snow line: 1) the density of solid building blocks increases by a factor of 2-4 or more (Hayashi 1981; Stevenson & Lunine 1988; Lodders 2003), 2) accretion timescales are shorter than anywhere else beyond the snow line (Kokubo & Ida 2002; Ida & Lin 2004), and 3) the surface density jump at the snow line, if it is steep enough, can trap inward-migrating planetary cores and form a pileup (Masset *et al.* 2006b). If these arguments hold, then core-accretion predicts that material interior to the giant planet is therefore relatively dry. However, gravitational instability forms planets in the more distant reaches of protoplanetary disks, where the Toomre  $Q$  value is lowest (Boss 1997; Mayer *et al.* 2002). Thus, icy material is included interior to the giant planet. In the giant planet migration shepherding model, hot Earths are a mixture of material interior to the giant planet's starting orbit (Mandell *et al.* 2007); they would be rocky for the core accretion model, and icy for the instability model. Thus, transit measurements of hot Earth in systems formed by giant planet migration shepherding may provide a test to distinguish between the two dominant giant planet formation models.

As observational uncertainties of planetary orbits and masses become smaller, it will become possible to differentiate formation mechanisms based on these observations. We have laid out the qualitative differences between six different mechanisms that may form hot Earths (although some phenomena may operate simultaneously). Determining how hot Earths form is an important step toward understanding planet formation, identifying target stars for future surveys, and searching for habitable planets.

## 6 ACKNOWLEDGMENTS

We thank the reviewer, Jonathan Fortney, for constructive comments that improved the paper. This work was motivated in part by a special session on "hot Earths" at the 210th AAS meeting in Honolulu May-June 2007, organized by Eric Gaidos and Nader Haghighipour. We benefited from discussions with Bill Hubbard, Adam Burrows, Brian Jackson, Rick Greenberg, Dave Latham, Eric Agol, John Rayner, Jason Steffen, Eric Gaidos, and Ted von Hippel. S.N.R. and A.M.M. were supported by appointments to the NASA Postdoctoral Program at the University of Colorado Astrobiology Center and NASA Goddard Space Flight Center, respectively, administered by Oak Ridge Associated Universities through a contract with NASA. R.B. acknowledges supports from NASA's PG&G and TPFPS programs.

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