Exotic Earths: Forming Habitable Worlds with Giant Planet Migration

Sean N. Raymond, *et al.*

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Exotic Earths: Forming Habitable Worlds with Giant Planet Migration

Sean N. Raymond,[1]*†‡ Avi M. Mandell,[2,3]*†‡ Steinn Sigurdsson[2]‡

Close-in giant planets (e.g., "hot Jupiters") are thought to form far from their host stars and migrate inward, through the terrestrial planet zone, via torques with a massive gaseous disk. Here we simulate terrestrial planet growth during and after giant planet migration. Several-Earth-mass planets also form interior to the migrating jovian planet, analogous to recently discovered "hot Earths." Very-water-rich, Earth-mass planets form from surviving material outside the giant planet's orbit, often in the habitable zone and with low orbital eccentricities. More than a third of the known systems of giant planets may harbor Earth-like planets.

To date, giant planets have been detected around almost 200 main-sequence stars (*1*, *2*). An unexpected result is the abundance of planets very close to their host stars—about 40% of the known extrasolar planets are interior to Mercury's orbital distance of 0.4 astronomical units (AU; 1 AU is the Sun-Earth distance), although observational biases favor the detection of hot Jupiters (*3*). The occurrence of close-in giant planets is surprising because models predict that giant planets form much more easily in the cold, outer regions of protoplanetary disks (*4*, *5*). These planetary systems have been attributed to inward migration of a giant planet on 10^5-year time scales caused by an imbalance of torques generated by the gaseous protoplanetary disk (*6*–*9*). In the process, the giant planet moves through the terrestrial planet zone (located from a few tenths of an AU to about 2 to 3 AU). Radioactive dating of solar system material (*10*) and observations of dust dispersal in disks around young stars (*11*) indicate that rapid precipitation and coagulation of solid material in the inner regions of circumstellar disks are likely, leading to the question of the fate of these protoplanets during and after giant planet migration. Previous studies on the possibility of Earth-like planets coexisting with close-in giant planets are divided (*12*–*16*).

Here, we simulate the growth and dynamical evolution of protoplanetary material from small bodies to terrestrial planets during and after the migration of a giant planet through the terrestrial zone (see supporting online material for details). Simulations start from a circumstellar disk in the middle stages of planet formation, extending from 0.25 to 10 AU. The disk contains 17 Earth masses ($M_\oplus$) of rocky/icy material, evenly divided between 80 Moon- to Mars-sized "planetary embryos" (*17*) and 1200 "planetesimals" with properties modified so that each body behaves as a collection of less massive objects (*18*). The disk has a compositional gradient: The inner disk is iron-rich and water-poor whereas the outer disk is water-rich and iron-poor [as in (*19*) but with 50% water by mass beyond 5 AU]. A Jupiter-mass giant planet starts at 5 AU and is migrated in to 0.25 AU in 10^5 years (*8*). The orbits of all bodies in each simulation are integrated for 200 million years with the hybrid symplectic integrator Mercury (*20*), modified to include two additional effects: (i) "type 2" giant planet migration (*6*, *13*) and (ii) aerodynamic gas drag (*18*) from a gaseous disk that dissipates on a 10^7-year time scale (*21*).

At early times (Fig. 1) the giant planet migrates inward through the disk, causing nearby material to either be scattered outward onto high-eccentricity orbits (*13*) or shepherded inward by the giant planet's moving mean-motion resonances (*22*). The buildup of inner material induces rapid growth of a 4 $M_\oplus$ planet just inside the 2:1 mean motion resonance in 10^5 years [also shown by (*16*)]. Smaller bodies (planetesimals) feel a stronger drag force and are shepherded by higher-order resonances (in this case, the 8:1 resonance) and form a pileup of 0.2 $M_\oplus$ at 0.06 AU. At the end of the migration period, the remaining disk material is divided between bodies captured in low-eccentricity orbits in interior resonances with the Jupiter-mass planet and higher-eccentricity orbits beyond 0.5 AU. The protoplanetary disk is now dynamically hot (i.e., orbital eccentricities and inclinations are high), and accretion proceeds at a slower rate than would occur in a nonstirred, dynamically cold disk. However, the gas continues to damp eccentricities and inclinations, also causing the orbits of icy planetesimals from the outer disk to decay inward on million-year time scales, delivering a large amount of water to the growing terrestrial planets. After the gas dissipates (at 10^7 years), the disk is

Table 1. Properties of simulated planets. Results are from four simulations (see supporting online material for details).

	Hot Earths	Normal terrestrials	Hab. zone planets	Outer terrestrials	Solar system*
Mean number of planets	0.25†	2	0.5	11	4
Mean planet mass ($M_\oplus$)	4.2	1.1	2.0	0.6	0.49
Mean water mass fraction	2×10^{-2}	8×10^{-2}	8×10^{-2}	3.5×10^{-1}	4×10^{-4}
Mean iron mass fraction	0.25	0.28	0.27	0.14	0.32‡
Mean orbital eccentricity	0.01	0.23	0.10	0.23	0.08
Mean orbital inclination (°)	0.7	11	7	13	3.0

*Solar system physical properties are from (*37*) and orbital properties are from (*35*). †Every simulation with gas drag formed one to three hot Earths during giant planet migration. However, in many cases an artificial drag force caused continued inward migration of the giant planet. In these cases, the integrator usually introduced an error causing the eventual ejection of hot Earths when they entered ~0.05 AU. We therefore consider 0.5 a lower bound on the frequency of hot Earths in these systems. See also (*16*). ‡Solar system iron mass fractions are calculated without Mercury, because of its anomalously high iron content.

[1]Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80309–0392, USA. [2]Department of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802, USA. [3]NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.

*These authors contributed equally to this work.
†To whom correspondence should be addressed. E-mail: raymond@lasp.colorado.edu (S.N.R.), mandell@astro.psu.edu (A.M.M.)
‡Member of NASA Astrobiology Institute.

stirred by interactions between bodies, and clearing continues through scattering. After 200 million years the inner disk is composed of the collection of planetesimals at 0.06 AU, a 4 $M_\oplus$ planet at 0.12 AU, the hot Jupiter at 0.21 AU, and a 3 $M_\oplus$ planet at 0.91 AU. Previous results have shown that these planets are likely to be stable for billion-year time scales (*15*). Many bodies remain in the outer disk, and accretion and ejection are ongoing due to long orbital time scales and high inclinations.

Two of the four simulations from Fig. 2 contain a >0.3 $M_\oplus$ planet on a low-eccentricity orbit in the habitable zone, where the temperature is adequate for water to exist as liquid on a planet's surface (*23*). We adopt 0.3 $M_\oplus$ as a lower limit for habitability, including long-term climate stabilization via plate tectonics (*24*). The surviving planets can be broken down into three categories: (i) hot Earth analogs interior to the giant planet; (ii) "normal" terrestrial planets between the giant planet and 2.5 AU; and (iii) outer planets beyond 2.5 AU, whose accretion has not completed by the end of the simulation. Properties of simulated planets are segregated (Table 1): hot Earths have very low eccentricities and inclinations and high masses because

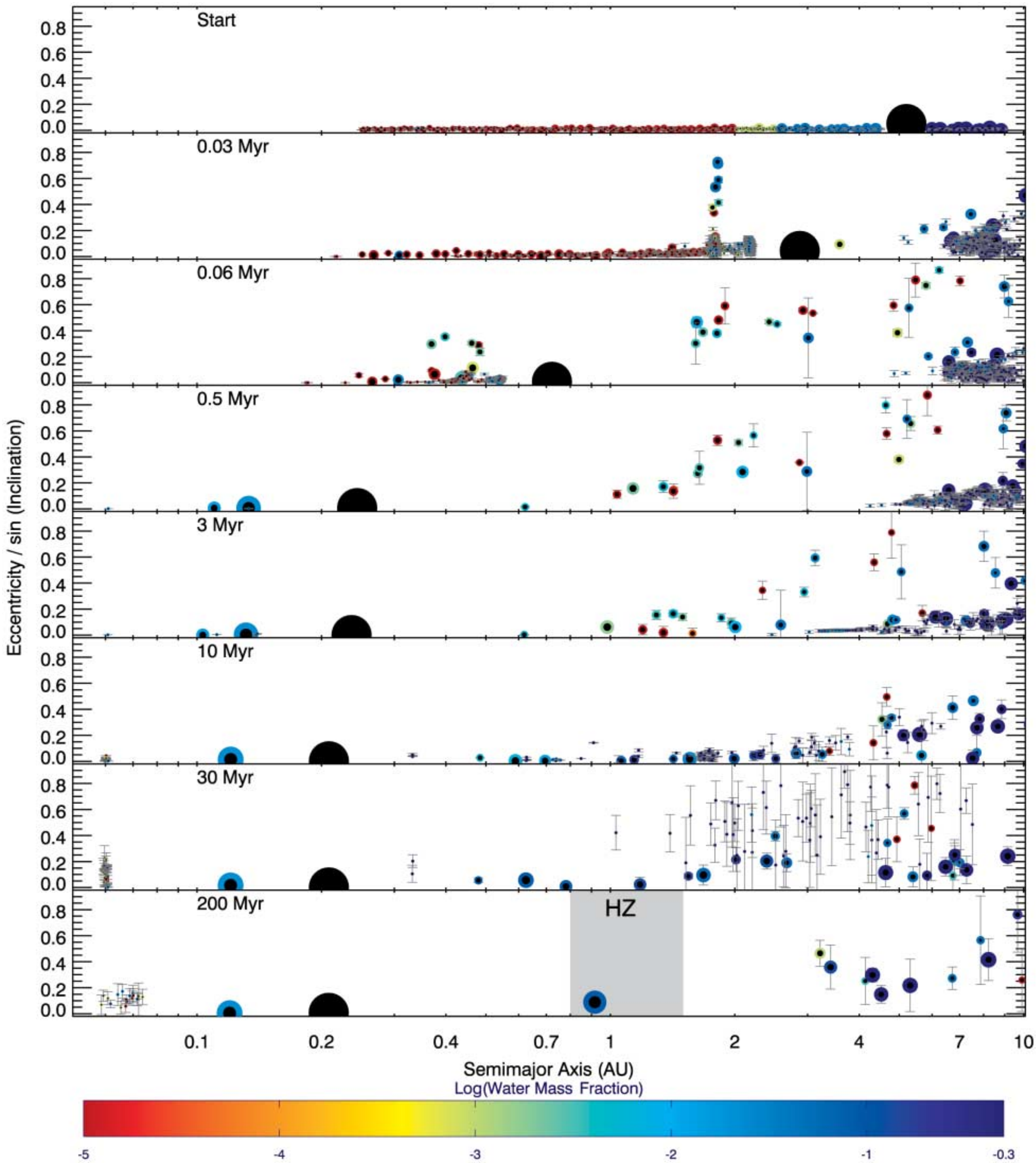

Fig. 1. Snapshots in time of the evolution of one simulation. Each panel plots the orbital eccentricity versus semimajor axis for each surviving body. The size of each body is proportional to its physical size (except for the giant planet, shown in black). The vertical "error bars" represent the sine of each body's inclination on the *y*-axis scale. The color of each dot corresponds to its water content (as per the color bar), and the dark inner dot represents the relative size of its iron core. For scale, the Earth's water content is roughly 10^{-3} (*28*).

they accrete on the migration time scale (10^5 years), so there is a large amount of damping during their formation. These planets are reminiscent of the recently discovered, close-in 7.5 $M_{\oplus}$ planet around GJ 876 (*25*), whose formation is also attributed to migrating resonances (*26*). Farther from the star, accretion time scales are longer and the final phases take place after the dissipation of the gas disk (at 10^7 years), causing the outer terrestrials to have large dynamical excitations and smaller masses, because accretion has not completed by 200 million years; collisions of outer bodies such as these may be responsible for dusty debris disks seen around intermediate-age stars (*27*). In the "normal" terrestrial zone, dynamical excitations and masses fall between the two extremes as planets form in a few times 10^7 years, similar to the Earth's formation time scale (*10*). In addition, the average planet mass in the terrestrial zone is comparable to the Earth's mass, and orbital eccentricities are moderate (Table 1).

Both the hot Earths and outer Earth-like planets have very high water contents [up to >100 times that of Earth (*28*)] and low iron contents compared with our own terrestrial planets (Table 1). There are two sources for these trends in composition: (i) strong radial mixing induced by the migrating giant planet, and (ii) an influx of icy planetesimals from beyond 5 AU from gas drag-driven orbital decay that is unimpeded by the scattering that Jupiter performs in our own system. The outer terrestrial planets acquire water from both of these processes, but the close-in giant planet prevents in-spiraling icy planetesimals from reaching the hot Earths. The accretion of outer, water-rich material dilutes the high iron content of inner disk material, so water-rich bodies naturally tend to be iron-poor in terms of mass fraction. The high water contents of planets that formed in the habitable zone suggest that their surfaces would be most likely covered by global oceans several kilometers deep. Additionally, their low iron contents may have consequences for the evolution of atmospheric composition (*29*).

The spacing of planets (Fig. 2) is highly variable; in some cases planets form relatively close to the inner giant planet. The ratio of orbital periods of the innermost >0.3 $M_{\oplus}$ terrestrial planet to the close-in giant ranges from 3.3 to 43, with a mean (median) of 12 (9). We can therefore define a rough limit on the orbital distance of an inner giant planet that allows terrestrial planets to form in the habitable zone. For a terrestrial planet inside the outer edge of the habitable zone at 1.5 AU, the giant planet's orbit must be inside ~0.5 AU (the most optimistic case puts the giant planet at 0.68 AU). We apply this inner giant planet limit to the known sample of extrasolar giant planets [including planets discovered by the radial velocity, transit, and microlensing techniques (*1*, *2*)] in combination with a previous study of outer giant planets (*30*). We find that 54 out of 158 (34%) giant planetary systems in our sample permit an Earth-like planet of at least 0.3 $M_{\oplus}$ to form in the habitable zone (Fig. 3). The fraction of known systems that could be life-bearing may therefore be considerably higher than previous estimates (*30*).

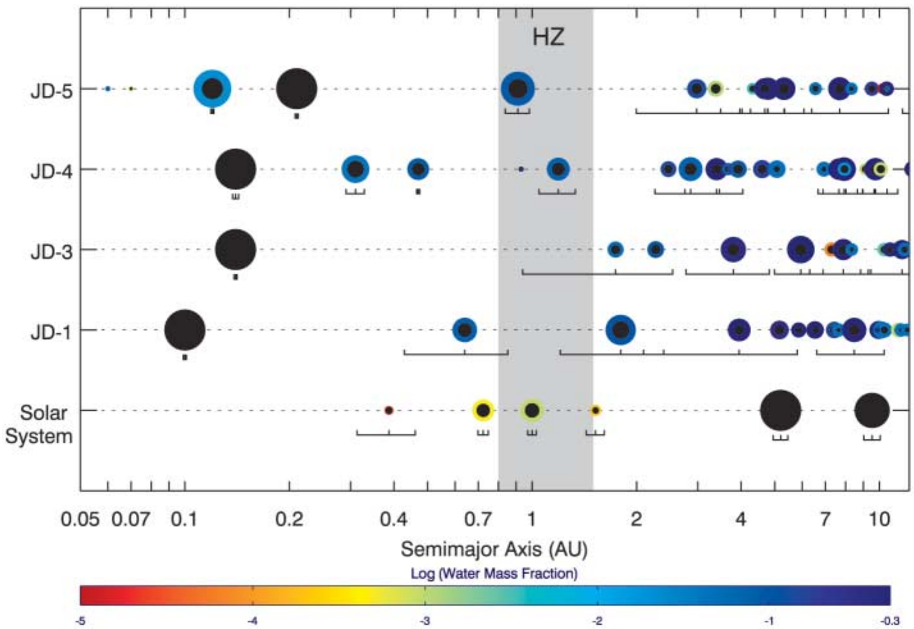

Fig. 2. Final configuration of our four simulations, with the solar system shown for scale. Each simulation is plotted on a horizontal line, and the size of each body represents its relative physical size (except for the giant planets, shown in black). The eccentricity of each body is shown beneath it, represented by its radial excursion over an orbit. As in Fig. 1, the color of each body corresponds to its water content, and the inner dark region to the relative size of its iron core. The simulation from Fig. 1 is JD-5. Orbital values are 1-million-year averages; solar system values are 3-million-year averages (*35*). See table S1 for details of simulation outcomes. Note that some giant planets underwent additional inward migration after the end of the forced migration, caused by an articial drag force. This caused many hot Earths to be numerically ejected, but had little effect outside the inner giant planet. See supporting online material for details.

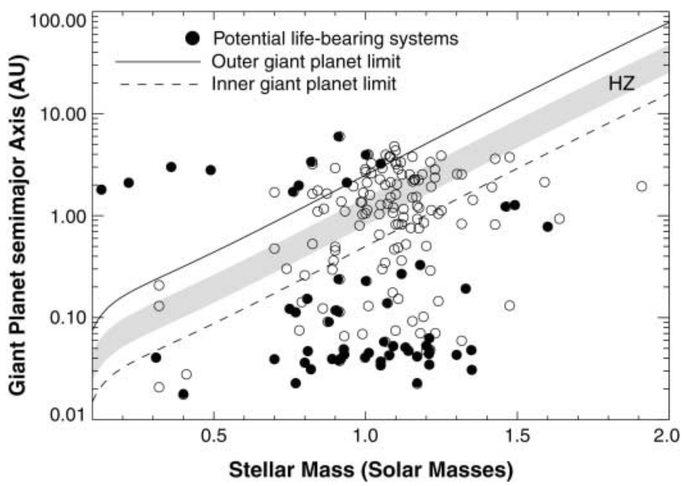

Fig. 3. Giant planet orbital parameter space that allows terrestrial planets to form in the habitable zone. The solid line indicates the limit for outer giant planets from (*30*). The dashed line is an approximate limit (0.5 AU with eccentricity less than 0.1—the maximum eccentricity achieved in most simulations—for a solar-mass star) inside which low-eccentricity giant planets allow for the formation of habitable planets, derived from our results and (*15*). We calculated the habitable zone (HZ, shaded area) by assuming the temperature to scale with the stellar flux (i.e., the square root of the stellar luminosity), using a stellar mass-luminosity relation fit to data of (*36*). Open circles represent known giant planets that are unlikely to allow habitable terrestrial planets in the habitable zone. Filled circles represent known planets with low enough orbital eccentricities to satisfy our criteria for habitable planet formation, deemed to be potentially life-bearing.

The occurrence of hot Jupiters appears to be a strong function of stellar metallicity (*31*). In addition, the solid component of protoplanetary disks is assumed to be proportional to metallicity. Therefore, systems such as the ones studied here may have very massive solid disks and could have systematically larger planet masses. If, for example, such disks are more likely to form $\sim 10\ M_\oplus$ "hot Neptunes" [e.g., 55 Cnc e (*32*)] than $\sim 4\ M_\oplus$ hot Earths, then our disk is too small by a factor of a few. Assuming that planet mass scales with disk mass, the typical mass of a habitable planet in such systems may be several Earth masses. In addition, our calculations were for a realistic but fixed giant planet mass and migration rate. Less (more) massive giant planets or faster (slower) migration rates increase (decrease) the survival rate of terrestrial material exterior to the close-in giant planet (*13*).

Upcoming space missions such as the National Aeronautics and Space Administration's Kepler and Terrestrial Planet Finder and the European Space Agency's COROT and Darwin will discover and eventually characterize Earth-like planets around other stars. We predict that a large fraction of systems with a close-in giant planet will be found to have a hot Earth or potentially habitable, water-rich planets on stable orbits in the habitable zone. Suitable targets may be found in the known giant planet systems.

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Supporting Online Material

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SOM Text
Table S1
References

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Observation of Electroluminescence and Photovoltaic Response in Ionic Junctions

Daniel A. Bernards,[1] Samuel Flores-Torres,[2] Héctor D. Abruña,[2] George G. Malliaras[1]*

Electronic devices primarily use electronic rather than ionic charge carriers. Using soft-contact lamination, we fabricated ionic junctions between two organic semiconductors with mobile anions and cations, respectively. Mobile ionic charge was successfully deployed to control the direction of electronic current flow in semiconductor devices. As a result, these devices showed electroluminescence under forward bias and a photovoltage upon illumination with visible light. Thus, ionic charge carriers can enhance the performance of existing electronic devices, as well as enable new functionalities.

Junctions between n-type and p-type semiconductors are the cornerstone of modern electronic materials technology because they enable a variety of solid-state devices such as transistors, light-emitting diodes, and photovoltaic cells (*1*). Diffusion of electronic charge across a pn junction sets up a built-in potential, which allows current to flow preferentially in one direction (rectification). Rectification is also observed in junctions of ionic conductors, where a built-in potential arises from diffusion of anions (N) and cations (P) across a membrane. Such ionic junctions play an important role in biology. In bilayer membranes, for example, voltage-gated ion channels control the direction of ion transport into and out of cells (*2*). Although such systems provide an inspiration for rectifying devices, their inherent complexity makes it difficult to study systematically. Electrolytic junctions formed by using positively and negatively charged polymer solutions offer a synthetic alternative. For example, by defining the interface with a permeable membrane, a junction was formed between a solution of a polymeric acid and a solution of a polymeric base, with mobile protons (H^+) and hydroxide ions (OH^-), respectively. Under an applied alternating current, this type of junction showed considerable rectification of ionic current (*3*).

The analogy between electronic (pn) and ionic (PN) junctions has not been exploited in solid-state devices. In addition to the fundamental merit of exploring the coupling between ionic and electronic carriers, such junctions may result in devices with improved performance and new functionalities. Progress toward this goal has been hampered by a lack of materials that combine semiconducting behavior with appreciable ionic conductivity. The

[1]Department of Materials Science and Engineering, Cornell University, Ithaca, NY 14853, USA. [2]Department of Chemistry and Chemical Biology, Cornell University, Ithaca, NY 14853, USA.

*To whom correspondence should be addressed. E-mail: ggm1@cornell.edu