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Producing a diversity of super Earths from a diversity of disk conditions

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Abstract

Multi-planet systems observed by Kepler that contain super Earths exhibit a diversity of orbit spacings and multiplicities. Here we investigate what planetary system outcomes arise from a range of protoplanetary disk solid surface densities and dissipative conditions shortly before disk dispersal, through simulating the giant impact phase of planet formation and subsequent dynamical evolution. We also compare the mass-radius and orbital distributions of these outcomes to the multi-transiting systems observed by the Kepler mission. For the same degree of dissipation from a gaseous disk and with no orbit migration, we find that larger solid surface densities lead to more tightly packed, flatter systems than at smaller solid surface densities. The orbit distributions arising from these solid surface densities in conjunction with moderate gas damping (corresponding to a protoplanetary disk depleted by a factor of 100 in mass before disk dispersal) agree with the distributions of observed systems. These disk conditions can also produce super Earth systems with successive pairs near and in mean motion resonances.

1. Introduction

Super Earth exoplanets, planets with radii between Earth and Neptune, are observed to span a large range of bulk densities [e.g., 8]. There is also an apparent enhancement of systems with only one transiting planet compared to what might be expected from the numbers of systems containing multiple transiting planets [e.g., 5, 7]. Meanwhile, some observed multi-planet systems with planets in or near mean motion resonances can result from fully formed planets undergoing long distance orbit migration, short distance orbit migration, or with little migration but some eccentricity dissipation [6]. In this context, we consider what kinds of formation conditions could produce these system-wide properties.

Here we investigate what planetary system properties arise from in situ formation within 1 AU of Solar mass stars under a diversity of disk conditions during the short-lived depleted gaseous disk phase and subsequent dynamical evolution post-disk dispersal.

2. Methods

We perform our planetary embryo growth simulations using the mercury6 hybrid symplectic integrator [2] that includes eccentricity damping as described and used by [3] for 1 Myr, followed by more than 27 Myr of subsequent evolution. These simulations start with planetary embryos spaced 3 mutual Hill radii apart and with individual masses set to be the isolation mass for the corresponding initial solid surface density. We performed several thousand simulations to build planetary system ensembles that arise from embryo mergers under dissipative conditions corresponding to gaseous disks undepleted as well as depleted by a factor *d* of 10, 100, 10^3, and 10^4 with respect to the minimum mass solar nebula (1700 g/cm^2 at 1 AU), along with solid surface densities ranging from 14-284 g/cm^2 at 1 AU. We also assess what portions of these systems would have been observable by *Kepler* using the *KeplerPORTS* pipeline [1] and the nebular accretion models of [4] to track gas fractions of planets as they grow through mergers.

3. Results and Conclusions

We find that higher disk solid surface densities tend to yield more compact, flat systems, but also can form higher mass, lower density planets than lower solid surface densities in the disk. As found in [2], we find that systems evolving in a d=100 disk produce planetary systems that are more closely spaced, with lower orbit eccentricities and inclinations on average than for the other dissipative conditions. We find successive chains of planets each with masses >=2 M_E at near integer ratios tend to form from disks with solid surface densities of about 70-150 g/cm^2 and a depletion factor of d=100.

Some of these chains are also actually in mean motion resonances with librating resonance angles. Most are in resonances at closer planet-planet separations than the 2:1 resonance. Planets with low orbit eccentricities (<~a few percent) that are spaced at adjacent period ratios of less than ~a few at late times tend to have accreted nearly all of their mass during the gas disk phase. Planetary systems arising from a range of solid surface densities and depleted gaseous disks with d=10 and 100 match the observed distribution of planet multiplicity, spacing in mutual Hill radii and period ratio for single and multiple transiting super Earth systems around Solar type stars. A spread of disk solid surface density can also roughly quantify the observed spread of planet mass and radius. This result indicates that a continuum of disk conditions can produce the observed diversity of super Earth systems as observed by Kepler.

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