Formation of Giant Planets Through Core-Accretion

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In the quest to find habitable terrestrial planets, it is essential to first assess the frequency of earth-size rocky planets around nearby stars. In the foreseeable future, radial velocity surveys will continue their successful discovery and characterization of Jupiter-mass planets with periods less than a few years around mature solar type stars. An important task is to establish a reasonably reliable approach to extrapolate the dynamical characteristics of terrestrial planets from the observational properties of giant planets.

In this context, the central issues concerning the origin of planets and evolution of planetary systems are: 1) whether known planets are formed through core accretion or gravitational instability; and 2) whether planetary systems' asymptotic dynamical properties are determined by their formation or evolutionary processes. If massive planets are formed through gas accretion onto pre-existing cores, their current 10% observed frequency would imply the existence of earth-size planets around nearly all nearby stars. If, however, they were formed through gravitational instability, their statistical properties would provide very little information on the potential existence of terrestrial planets.

We discuss the physical processes and implication of the core accretion scenario. We show that there is a tendency for grains to accumulate near the snow line and to efficiently grow into planetesimals which coagulate into protoplanetary embryos through cohesive collisions. Based on recent theory of planetesimals dynamics and gas accretion, we show gas giants can prolifically emerge near the snow line well before the depletion of the disk gas. In addition, their interaction with the disk and with each other leads to both orbital migration and eccentricity evolution among gas giants and residual cores. Based on this scenario, we construct the mass period distribution for gas giant planets. We also discuss the impact of gas giant formation on the formation of terrestrial planets.

We outline several observable planetary properties which can be used to identify the dominant modes of planet formation:

- The most distinguishing characteristics of the core accretion process are the super solar metallicity in the envelope and the presence of a core in the deep interior of gas giants. These properties can be inferred from the spectroscopic observation of the planets' atmospheres and the theoretical models of the observed radius, luminosity, and temperature of the planets as function of their age, and correlation between their frequency and the metallicity of their host stars.

- During core accretion, an upper mass limit of gas giants is set by their tidally induced gap formation criteria which can be inferred from a break in their observed mass function. The mass function of the emerging fragments resulting from the gravitational instability of protostellar disks is expected to be continuous up to the stellar mass ranges. This test can be made by the mass determination of planets.

- In the core formation scenario, the growth of cores prior to disk depletion is limited to a few M_{Earth} by their dynamical isolation interior to the snow line and the sparsity of nearby planetesimals beyond 10 AU. Solar system architecture, in which gas giants are flanked by internal terrestrial planets and external Neptune-mass ice giants, is common. Such a configuration is not expected in the gravitational instability scenario.

- As a consequence of the core accretion process, multiple gas giants are formed on nearly circular orbits. Systems with massive gas giants may undergo post-formation dynamical instabilities which would lead to large eccentricities. But widely separated planets with mass comparable to or less than that of Jupiter are expected to retain their primordial low eccentricity. Gravitational instabilities always induce planets to attain large orbital eccentricities.

- Along the path of their orbital evolution, gas giants can capture residual planetesimals and embryos which failed to form protoplanetary cores. In the core accretion scenario, hot Earths are expected to be associated with hot Jupiters whereas no such correlation is expected in the gravitational instability picture.

These tests can be made using a variety of observational techniques within the next few years.