Session V

Extrasolar Planets: The Chemical Abundance Connection

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Planet formation modeller Alan Boss.

Jorge Meléndez during his talk.

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Chemical Abundances in the Universe: Connecting First Stars to Planets
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Metallicity and Planet Formation: Models

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Abstract. Planets typically are considerably more metal-rich than even the most metal-rich stars, one indication that planet formation must differ greatly from star formation. There is general agreement that terrestrial planets form by the collisional accumulation of solids composed of heavy elements in the inner regions of protoplanetary disks. Two competing mechanisms exist for the formation of giant planets, core accretion and disk instability, though hybrid combinations are possible as well. In core accretion, a higher metallicity in the protoplanetary disk leads directly to larger core masses and hence to more gas giant planets. Given the strong correlation of gas giant planets detected by Doppler spectroscopy with stellar metallicity, this has often been taken as proof that core accretion is the mechanism that forms giant planets. Recent work, however, implies that the formation of gas giants by disk instability can be enhanced by higher metallicities, though not as dramatically as for core accretion. In both scenarios, the ongoing accretion of planetesimals by gas giant protoplanets leads to strong enrichments of heavy elements in their gaseous envelopes. Both scenarios also imply that gas giant planets should have significant solid cores, raising questions for gas giant interior models without cores. Exoplanets with large inferred core masses seem likely to have formed by core accretion, while gas giants at distances beyond 20 AU seem more likely to have formed by disk instability. Given the wide variety of exoplanets found to date, it appears that both mechanisms are needed to explain the formation of the known population of giant planets.

Keywords. accretion, accretion disks; hydrodynamics; instabilities; planets and satellites: formation; (stars:) planetary systems: formation

1. Introduction

The discovery to date of over 350 extrasolar planets has revolutionized not only the field of exoplanet hunting, but also theoretical efforts to explain the mechanisms of planet formation and orbital evolution. Exoplanet detections have revealed an incredible variety of planet characteristics, including a wide range of masses, semi-major axes, and orbital eccentricities (e.g., Butler *et al.* 2006). One of the first correlations to emerge from a handful of exoplanets was the high metallicities of their host stars (Gonzalez 1997). Figure 1 shows that the evidence for this metallicity correlation has only continued to increase (e.g., Fischer & Valenti 2005; see chapter by Valenti in this volume). Given the fact that planets are generally more metal-rich than the most metal-rich star, explaining this correlation promises to place strong constraints upon planet formation and evolution processes. The goal of this chapter is thus to briefly summarize current theoretical work on planet formation models, with an emphasis on the theoretical implications for forming planets around host stars with varied metallicities, which are presumed to be identical to the metallicities of the protoplanetary disks in which their planets form.

2. Core Accretion

All planet formation theorists agree that terrestrial planets form by the collisional accumulation of solids composed of heavy elements in the inner regions of protoplanetary disks (e.g., Wetherill 1996). This process begins with the sedimentation of dust grains to the disk midplane and their growth by coagulation, continuing through increasingly energetic collisions between progressively larger bodies: m-sized boulders, km-sized planetesimals, 1000-km-sized planetary embryos, and ending with 10,000-km-sized terrestrial planets.

Given this agreement, it is only natural that the generally accepted mechanism for giant planet formation is core accretion, where roughly 10-Earth-mass, solid cores form by collisional accumulation in the outer disk, growing larger than in the inner disk because of the greater amount of solids available in the outer disk. Disk gas is accreted slowly at first by the cores, but rapidly once the gaseous atmospheres become dynamically unstable and collapse, leading to gas giant planet formation on a time scale of $\sim$1 Myr. In the core accretion mechanism, ice giant planets are rock/ice cores that failed to accrete much disk gas, presumably because most of the disk gas had been depleted by the time that the cores grew large enough to accrete significant gas.

Wetherill (1996) showed that the masses of the terrestrial planets depend directly on the total mass of the solids available for planet formation in the inner disk. I.e., when the surface densities of solids is tripled, the maximum planet masses rise by about a factor of three. One would expect the same dependence of core mass in the outer disk on surface density of solids as in the inner disk, so that metal-rich disks should be increasingly able to form core masses large enough to undergo dynamical gas accretion and complete their evolution into gas giant planets.

The correlation of Doppler-detected planets with stellar metallicity (e.g., Fischer & Valenti 2005) is cited as proof that core accretion is the *only* formation mechanism. Ida & Lin (2004) have shown that core accretion is able to produce a metallicity correlation consistent with the observations (Figure 2), once the model parameters are suitably chosen (see the range of theoretical outcomes evident in Figure 2).

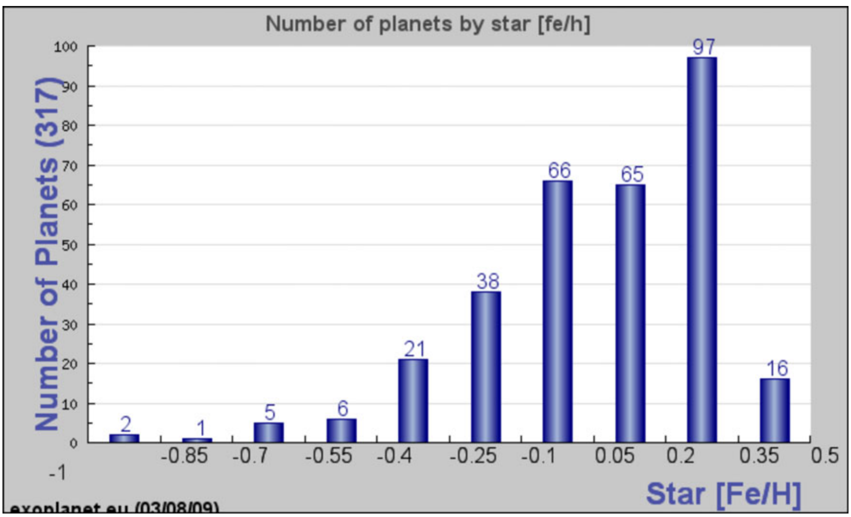

Figure 1. Metallicity of planet host stars, from the Encyclopedia of Extrasolar Planets web site: http://exoplanet.eu/.

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The evidence for large solid cores in a number of Doppler exoplanets that have been observed to transit, yielding determinations of their mean densities, is consistent with their formation by core accretion. In particular, the most Saturn-like exoplanet to date, HD 149026b, with a core mass of $\sim$70 $M_\oplus$ and a gaseous envelope of $\sim$40 $M_\oplus$ (Sato *et al.* 2005), is a strong candidate for formation by core accretion (Dodson-Robinson & Bodenheimer 2009), assuming that the rapidly growing core can open a gap in the surrounding gaseous disk and stop accreting any further disk gas once it has reached the desired total planet mass (Figure 3).

3. Disk Instability

The competing scenario for giant planet formation is disk instability, where a gravitationally unstable disk forms spiral arms and self-gravitating clumps of gas and dust on time scales of $\sim$0.001 Myr (Boss 1997, 1998; Mayer *et al.* 2002). Dust grains sediment to the center of the clumps and form solid cores on time scales of $\sim$0.1 Myr, resulting in gas giant protoplanets. Ice giant planets could be formed by UV photoevaporation of the outermost gas giant protoplanets (Boss, Wetherill, & Haghighipour 2002; Boss 2003), or by collisional accumulation, which must also be invoked to form terrestrial planets in this necessarily hybrid scenario.

Disk instability requires a protoplanetary disk that is massive enough to be at least marginally gravitationally unstable. For a solar-mass star, this typically requires a disk with a mass of $\sim$0.1 $M_\odot$. Estimated disk masses for T Tauri stars with ages of a few Myr range from 0.01 to 0.1 $M_\odot$ (Kitamura *et al.* 2002), suggesting that at least some protoplanetary disks are massive enough to form gas giant planets by disk instability. Current estimates are that roughly 10% of nearby solar-type stars harbor gas giant planets with masses greater than that of Saturn inside 3 AU (Cumming *et al.* 2008). Provided then that at least 10% of protoplanetary disks are massive enough to undergo disk instability, this mechanism could be a major contributer to the giant planet population.

Disk instability appears to be a strong candidate for forming planets in metal-poor systems, such as the M4 pulsar planet, where the metallicity [Fe/H] = -1.5 (Sigurdsson

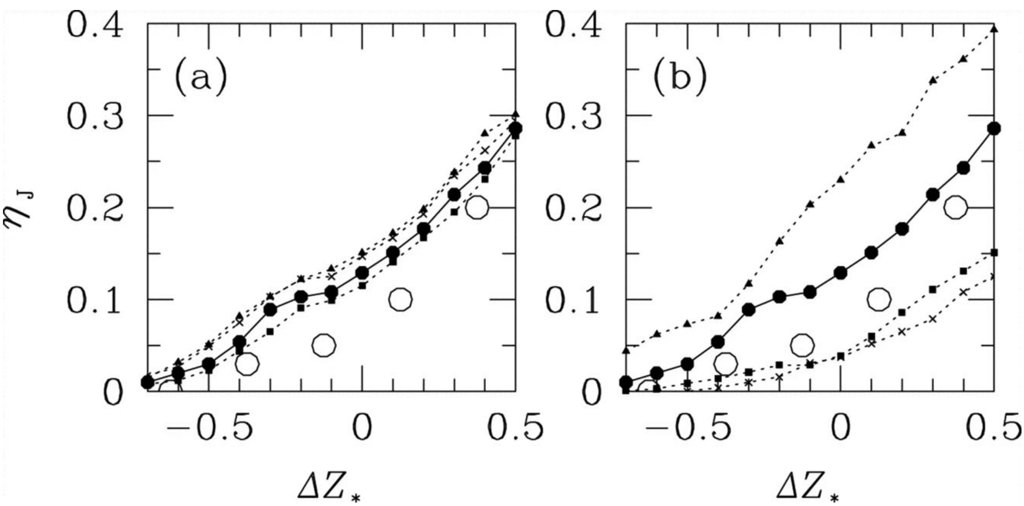

Figure 2. Predicted fraction (Ida & Lin 2004) of stars with gas giants formed by core accretion (filled symbols) that are detectable by Doppler surveys (open circles), as a function of stellar metallicity.

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et al. 2003), the giant planets orbiting HD 155358 and HD 47536, both of which have [Fe/H] = -0.68 (Cochran *et al.* 2007), and the giant planet around HD 171028, with [Fe/H] = -0.49 (Santos *et al.* 2007).

Boss (2002) found that disk instability proceeded in much the same way in models where the dust grain opacities were varied by factors of 10 or 0.1 (Figure 4). Cai *et al.* (2006) found that lowering the disk opacity by factors of 2 or 4 led to enhanced instability. However, models by Mayer *et al.* (2007) found that lowering the opacity by a factor of 50 led to "almost no difference in the outcome, confirming the results of Boss (2002)." The Mayer *et al.* (2007) models also suggested that disks with enhanced metallicity would have higher mean molecular weights, leading to reduced gas pressure, which would aid in gas giant planet formation and lead to a metallicity correlation for disk instability (cf. Matsuo *et al.* 2007). Clearly this possibility is deserving of further investigation.

Helled *et al.* (2006) considered the question of the capture of planetesimals by a clump formed by disk instability. They modeled the spherically symmetric contraction of a Jupiter-mass clump for $\sim 3 \times 10^5$ yr, using a modified stellar evolution code, finding that the protoplanet's envelope would capture a large fraction of the planetesimals in its feeding zone, leading to a heavy element enrichment over solar abundances (Figure 5). Helled *et al.* (2008) considered the coagulation and sedimentation of dust grains in the same Jupiter-mass, contracting clump, finding that a small heavy element core would form, in basic agreement with the simplified analysis by Boss (1998). More recently, Helled & Schubert (2009) showed that the heavy element enrichment of a giant gaseous protoplanet depends strongly on the planet's initial orbital distance and the assumed surface density of solids. It is clear from this work that giant planets formed by disk instability are likely to have highly non-solar compositions, just as is the case for planets formed by core accretion.

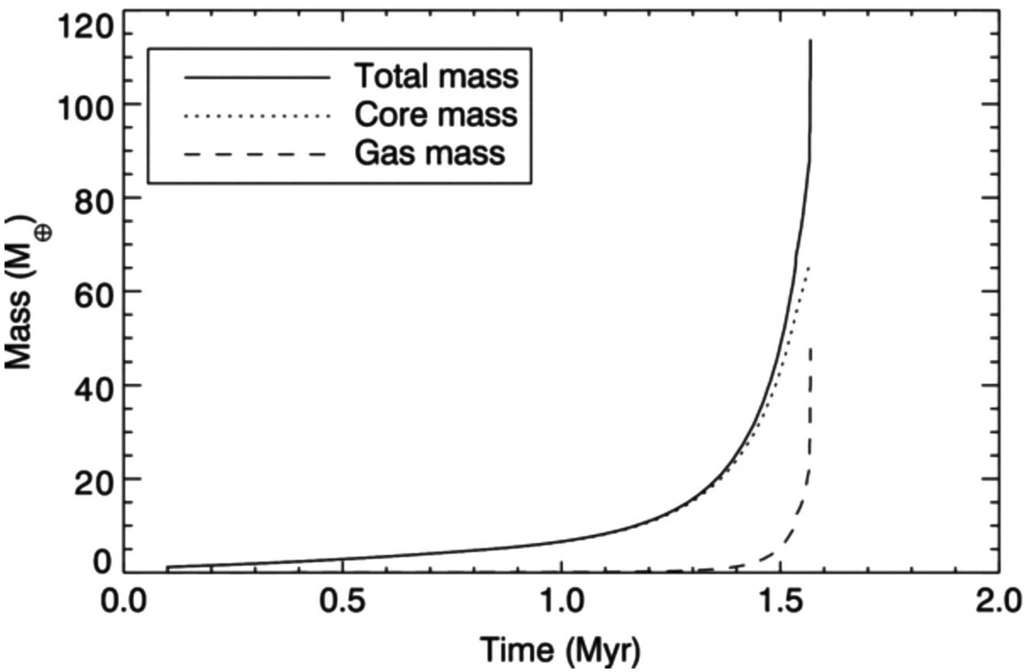

Figure 3. Mass accreted by a Saturn-like planet intended to represent HD 149026b in the core accretion scenario (Dodson-Robinson & Bodenheimer 2009). Shortly after 1.5 Myr, the total mass is ~120 Earth-masses, and the solid core mass is ~70 Earth-masses.

4. Interior Models

Models of the interiors of Jupiter and Saturn by Guillot, Gautier, & Hubbard (1997) and Guillot (1999) require considerably smaller core masses than were previously thought to be the case, or even no core at all. Based on recent shock wave experiments, the best-fitting models of the Jovian interior restrict its core mass to be either $\sim 1 M_\oplus$ or to lie in the range 0 to $4 M_\oplus$ (Saumon & Guillot 2004), depending on the equation of state (EOS) that is assumed. In these interior models, Jupiter's present core mass does not appear to be large enough to trigger hydrodynamic accretion of disk gas, at least not before the disk gas disappears. The suggestion has thus been made (Saumon & Guillot 2004) that Jupiter's core (but not Saturn's, for uncertain reasons) largely dissolved into the overlying envelope after the planet formed, in which case the present Jupiter core mass may not constrain the primordial core mass.

More recent work on the H-He EOS leads to a core mass of 14-18 $M_\oplus$ for Jupiter (Militzer *et al.* 2008), while a different group finds a Jupiter core mass between 1 and 6 $M_\oplus$ (Nettelmann *et al.* 2008). Given that both core accretion and disk instability predict the formation of sizable cores in gas giant planets, core erosion might need to be invoked to explain the absence of a Jovian core for either formation mechanism.

There does seems to be agreement, however, between the different EOS calculations that Saturn has a core mass of about 15 $M_\oplus$. Helled & Schubert (2008) found that a Saturn-mass protoplanet formed by disk instability would contract slower than a Jupiter-mass protoplanet, leading to the capture of more planetesimals and hence a larger core mass. In the core accretion scenario, Saturn's formation is explained by shutting off gas accretion at the right moment, as in the case for HD 149026's planet (Dodson-Robinson & Bodenheimer 2009).

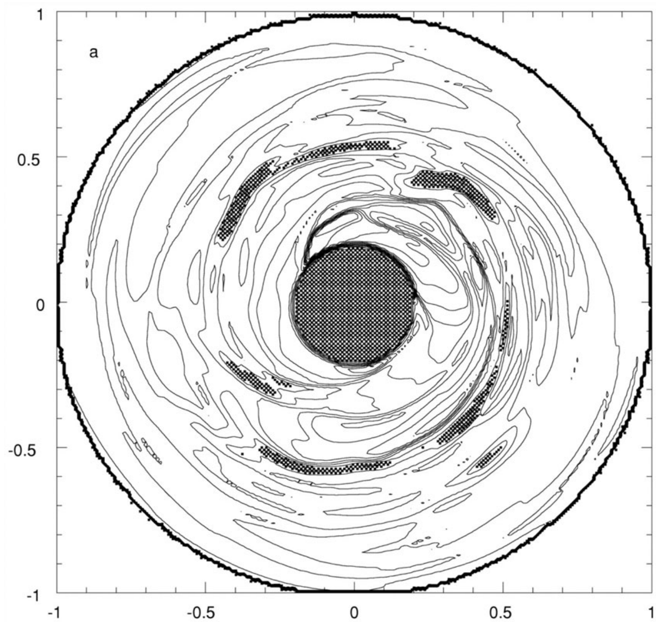

Figure 4. Density contours in the equatorial plane in the high opacity 3D disk instability model of Boss (2002), showing multiple clump formation in a disk with a radius of 20 AU. The inner 4 AU in radius is excluded from the calculation for time step reasons. A solar-mass protostar lies at the center of the disk. Cross-hatched regions denote midplane densities above 10^{-10} g cm^{-3}.

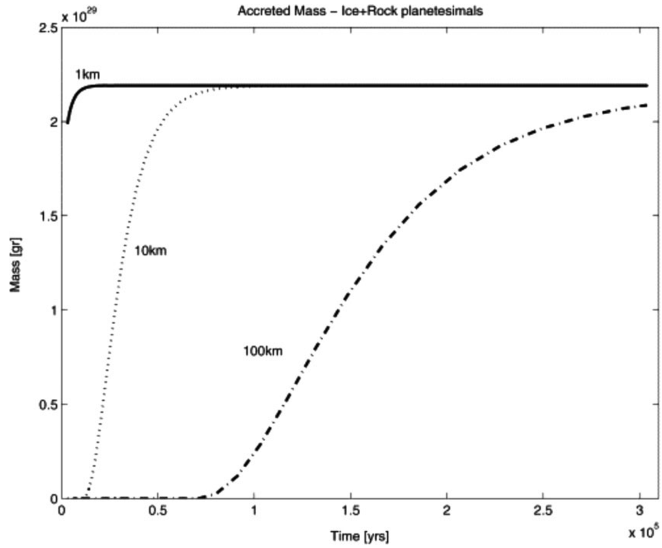

Figure 5. Mass accreted by a gaseous protoplanet formed by disk instability as a function of time (Helled *et al.* 2006). The protoplanet accretes all of the ice and rock planetesimals (36 Earth-masses) in its feeding zone on a time scale of order 1 Myr, which depends on the assumed planetesimal size.

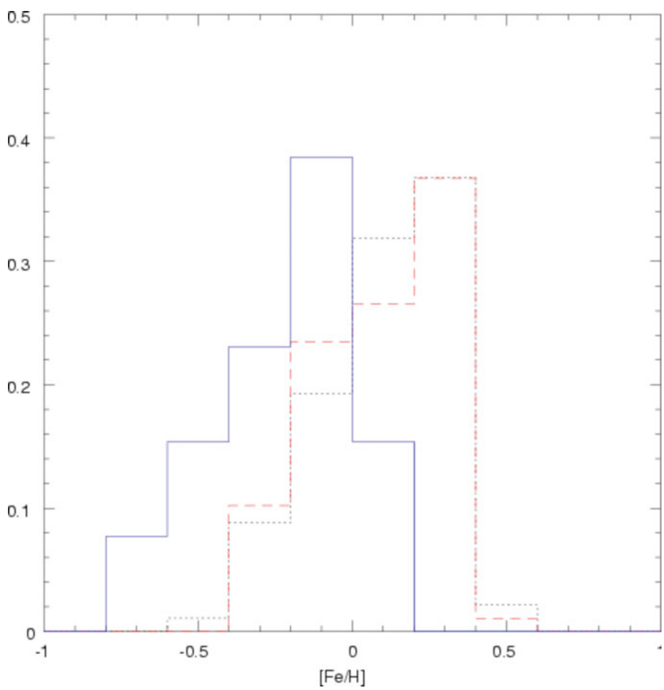

Figure 6. Metallicity distributions (Pasquini *et al.* 2007) of giant stars hosting detected planets (solid blue or dotted lines) compared to dwarf stars with detected planets (dashed red or dash-dotted lines) and dwarf stars with planets with orbital periods greater than 180 days (grey dotted or dash-dash-dotted lines). The giant star planet hosts do not show the strong metallicity enhancement found for the dwarf star planet hosts (e.g., Fischer & Valenti 2005).

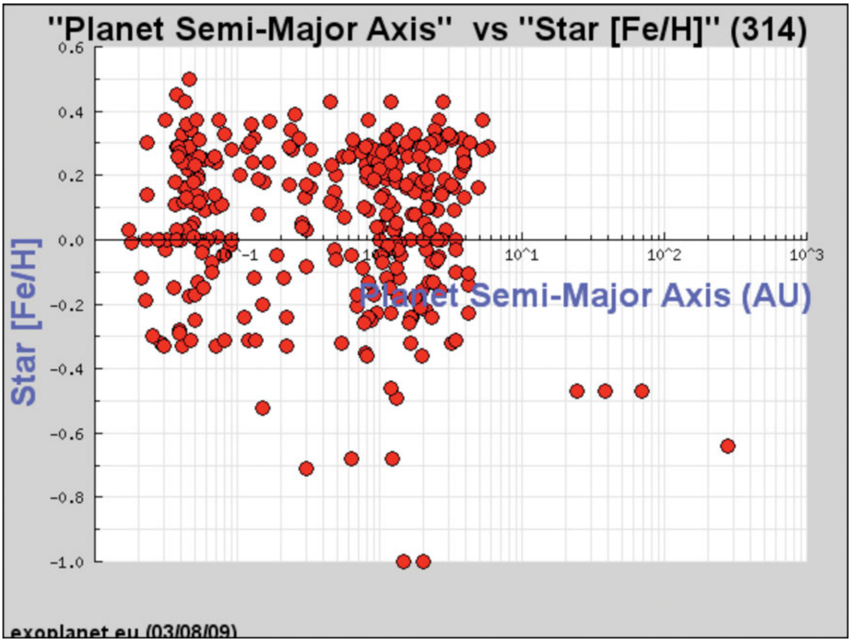

Figure 7. Metallicity of planet host stars versus semi-major axes of the planet's orbits, from the Encyclopedia of Extrasolar Planets web site: http://exoplanet.eu/.

5. Metallicity Correlations

Support for the original suggestion by Gonzalez (1997) that a metallicity correlation exists and might be explainable by self-pollution (i.e., stellar ingestion of inwardly migrating planets) has waxed and waned in the last decade, but seems to be resurging. Pasquini *et al.* (2007) showed that giant stars with gas giant planets have the same metallicities as giant stars without known planets (Figure 6), suggesting that the metallicity correlation seen in dwarf stars is a self-pollution effect that is erased by much more extensive convective mixing in the giant star phase. Recently, Gonzalez (2008) has shown that Li abundances in stars with planets correlate with the stellar surface temperature, and concludes that this finding also supports the self-pollution hypothesis. There should also be a correlation between the extent of inward orbital migration and metallicity, as disks with higher dust grain opacities should have hotter midplanes, leading to higher sound speeds and disk scale heights, and hence enhanced rates of migration through gravitational interactions with a disk that evolves in the manner of a viscous accretion disk. Clearly much more remains to be learned about the metallicity correlation and its implications for planet formation, orbital migration, and pollution of the outer layers of host stars.

6. Conclusions

The recent claims for the discovery by direct imaging of massive gas giant planets orbiting at distances from their host stars beyond 20 AU (Figure 7) have been taken by many as evidence that at least some gas giant planets form by disk instability, as disk instability is able to operate at such distances (e.g., Boss 2003, but see Boss 2006), whereas core accretion is unable to do so (e.g., Ida & Lin 2004) due to the low surface density of solids at such distances. The low metallicities of the gas giants on wide orbits

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discovered to date also argues in favor of formation by disk instability (Figure 7). We thus appear to be in a situation where both core accretion and disk instability are required to explain the full range of exoplanets discovered to date. In that case, the main theoretical challenge is to try to determine which, if either, mechanism dominates. The question of host star metallicities is certain to continue to play a leading role in the ongoing debate over the formation mechanisms of giant planets.

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