Wide Separation Planets and Their Implications for Planet Formation Theory

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ABSTRACT

We discuss significance of direct imaging observations of extrasolar planets from theoretical points of view. Statistical properties of frequency and correlations of mass, semimajor axis and eccentricity for wide separation ($\gtrsim$ 30 AU) gas giants will determine which is the dominant process for formation of gas giant planets, standard core accretion model or disk instability model. We also point out that direct imaging and spectroscopic observation for "habitable" rocky planets is not completely impossible by *SPICA* SCI, so that it is worth challenging.

1. INTRODUCTION

Since the first discovery of extrasolar planets in 1995, the pace of observational discovery (with radial velocity, transit, microlensing, and direct imaging surveys) has been accelerated. As of 2013, over 1000 extrasolar planets have been confirmed, mostly found by means of precise radial velocity surveys (see e.g., exoplanet.eu). Additionally, there are more than 2700 transiting candidate planets found by the *Kepler* space telescope[1]. All these detections have revealed that planets are quite common objects and that planetary systems are much more diverse than expected from our own Solar System. The increasing numbers of discovered extrasolar planets provide rich data sets on the statistical properties of extrasolar planets and planetary systems.

To discuss the statistical properties and subtract intrinsic physics of planet formation, "planet population synthesis" is a powerful tool (e.g., Ida & Lin 2004a,b, 2005, 2008a,b, 2010; Ida et al. 2013; Mordasini et al. 2009a,b; Alibert et al. 2011, 2013). Planet formation is composed of multi-step processes such as formation and evolution of a circumstellar disk, dust coagulation to form planetesimals in the disk, planetesimal accretion to form planetary embryos and cores, disk gas accretion onto the cores, orbital migration of planets/cores due to gravitational interactions with the disk, and gravitational scattering between planets. Planet population synthesis is a theoretical model integrating tractable models for the individual processes of planet formation that are based on detailed N-body simulations, fluid dynamical simulations and so on.

Radial velocity and *Kepler* surveys show that Earths/super-Earths are ubiquitous in extrasolar planetary systems and most of them are members of multiple planets. To calibrate the planet formation theory, it is important to compare theoretical predictions for statistical distributions of overall configurations of planetary systems with observations, rather than individual planets only. While radial velocity and transit observations are biased to close-in planets, direct imaging observations detect wide separation planets.

One possible survey for planetary "systems" is a survey of close-in planets ($\lesssim$ 0.5 AU) by *TESS* (the Transiting Exoplanet Survey Satellite) with follow-up by ground-based radial velocity observations for planets with moderate semimajor axes ($\sim$ 0.5–5 AU) and that by direct imaging of wide separation gas giants ($\gtrsim$ 10 AU). *TESS* will be launched in 2017. It is designed to search for extrasolar planets using the transit method like *Kepler*. While radial velocity follow-up is difficult for *Kepler* candidates due to faintness of *Kepler* target stars, *TESS* is all-sky survey and target stars for *TESS* are relatively bright, which makes the follow-up easier. *SPICA* SCI is one of the most important tools for the direct imaging follow-up.

On the other hand, direct imaging surveys for wide separation gas giants will discriminate between core accretion theory and disk instability theory for formation of gas giants, which we will discuss in section 2. A challenging observation that might be possible for *SPICA* SCI is direct imaging of "habitable" rocky planets, which will be commented on in section 3.

2. CORE ACCRETION VS. DISK INSTABILITY

Core accretion model is a standard model for formation of gas giants (e.g., Mizuno 1980; Bodenheimer & Pollack 1986; Pollack et al. 1996; Ikoma et al. 2000), based on planetesimal hypothesis (Safronov 1969; Hayashi et al. 1985). In this model, 1) rocky/icy cores accrete from planetesimals, 2) atmosphere of the core starts quasi-static contraction when the core mass exceeds a critical core mass ($\sim 5 - 10 M_\oplus$ where $M_\oplus$ is Earth mass), and 3) the gas accretion onto the core is accelerated until the planet opens up a gap in the disk or the disk gets depleted.

In disk instability model, gas giants are directly formed by self-gravitational instability of the disk (e.g., Cameron 1978; Boss 1997; Boley 2006). Difficulty of formation of rocky and icy planets was pointed out in this model, while core

[1] see e.g., http://www.kepler.nasa.gov/

accretion model reasonably accounts for formation of rocky/icy planets and gas giants in the same planetary system. As a result, core accretion model has been regarded as a "standard" model. However, recently, a tidal downsizing model for the gas clumps formed by the disk instability (e.g., Nayakshin 2010a,b, 2011) was proposed. This model suggests that rocky/icy planets can be formed by tidal stripping of outer gas envelope of inwardly migrating gas clumps, if dust settling into the central part of the clumps occurs quickly.

Because core growth rapidly becomes slower as orbital radius increases, formation of gas giants are limited within ~ 30 AU (Ida & Lin 2004a) in core accretion model. The discoveries of wide separation ($\gtrsim 30$ AU) gas giants by direct imaging such as HR 8799 b, c, d and d, GJ 504 b and HD 95086 b raised the possibility of gas giant formation through disk instability model. Scattering between gas giants can send some fraction of gas giant to large orbital radius (e.g., Marzari & Weidenschilling 2002; Nagasawa et al. 2008; Chatterjee et al. 2008). In that case, the orbit of the outwardly scattered planet must be highly eccentric, because the periastron must be preserved in planet forming region at $\lesssim 30$ AU. For example, planets scattered to attain a semimajor axis $\gtrsim 100$ AU necessarily have orbits with eccentricity $e \gtrsim 0.7$. However, observations suggest that the orbits of the discovered wide separation gas giants are nearly circular.

Ida et al. (2013) showed that their population synthesis model generated a population of relatively massive gas giants in nearly circular orbits with large semimajor axis ($a \gtrsim 30$ AU) as shown in Figure 1. In their fiducial model, the fraction of host stars that have these planets is several %. They found that the rapid gas accretion of giants destabilize the orbits of nearby residual planetary embryos (cores) and some cores are scattered to large distance. Because the scattered cores are usually well below the local disk mass, even the relatively low surface density gas damps the core's eccentricity. A reduction in the planetesimal accretion rate at these distance also lowers the critical core mass. As a result, the core starts gas accretion.

During the course of mass accretion, the planets acquire angular momentum of the disk gas. The scattered core initially has high eccentricity. Since the core spends most of time near the apoastron for a highly eccentric orbit, the gas the core accretes has higher specific angular momentum than that of the core. Accordingly, as the core evolves into gas giants, its orbit is circularized with a radius close to its apoastron radius.

The wide separation gas giants in nearly circular orbits formed by this process should have a clear correlation between their mass M_p and semimajor axis a. The maximum mass of gas giants that is limited by gap opening along their orbits in their natal disks is proportional to their natal disks' aspect ratio which is generally an increasing function of a (e.g., Hayashi 1981; Lin & Papaloizou 1985; Ida & Lin 2004a). Whether this trend exists or not is an important target for direct imaging observations.

In this process, multiple cores can be scattered outward to initiate gas accretion. Ida et al. (2013) showed that in their fiducial models, the fraction of systems with two, three, and four giants with low-eccentricity orbits is 0.4%, 0.07%, and 0.04%, respectively.

If a finite disk size is considered, the outwardly scattered cores would not accrete gas beyond the truncation radius. Then, the final semimajor axes of the formed giants would be comparable to the disk size. The observed semimajor axis distribution of gas giant planets could be used to place constraints on the structure and evolution of their natal disks.

Planet population synthesis for disk instability model has been addressed by only one paper (Forgan & Rice 2013). Because the population synthesis for disk instability model has just begun, it has not produced predictions for quantitative probability of wide separation gas giants and correlations in their distributions that can be compared with observations. It is very important to develop the population synthesis for disk instability model in order for direct imaging observation to discriminate between core accretion and disk instability models.

3. DIRECT IMAGING OF HABITABLE PLANETS

While direct imaging surveys of wide separation gas giants are important, it might be possible for *SPICA* SCI to directly image "habitable" rocky planets. It is a challenging observation, but its impact is very big.

Matsuo et al. (2011) showed that SCI can detect planets with a few $R_\oplus$ at $\gtrsim 10$ AU, where $R_\oplus$ is Earth physical radius. Such planets can be rocky super-Earths. The location of the ice line beyond which icy grains condense is $\sim 3(L_*/L_\odot)^{1/2}$ AU (Hayashi 1981), where L_* and $L_\odot$ are stellar and solar luminosities. Around A dwarfs, the ice line can be beyond 10 AU. Around solar-type stars, while the ice line is well inside 10 AU, super-Earths could be scattered outward from the regions inside the ice line.

However, conventional determination of "habitable" zone is located well inside of the ice line. "Habitable" zone is defined by a range of semimajor axis at which liquid water (ocean) can be maintained on planets with thick atmosphere. Kasting et al. (1993) considered stellar irradiation and CO_2 green house effect to determine habitable zone. They determined the outer boundary of habitable zone by condensation of CO_2 (disappearance of green house effect). In that case, the outer boundary is at most $\sim 1.5(L_*/L_\odot)^{1/2}$ AU. Even around A dwarfs with $L_* \sim 10L_\odot$, the outer boundary is ~ 5 AU. Then, super-Earths at $\gtrsim 10$ AU are not likely to be habitable in this framework.

However, if we consider super-Earths or Neptunes, habitable zone could be much broader. It is suggested that some of transiting super-Earths and Neptunes discovered by *Kepler* may have thick H/He atmosphere that may have been acquired from their natal protoplanetary disks. H_2 atmosphere has collision-induced opacity that is important for high density (e.g., Pierrehumbert & Gaidos 2011). Note that the H_2 gas does not condense except for extremely low temperature. Under

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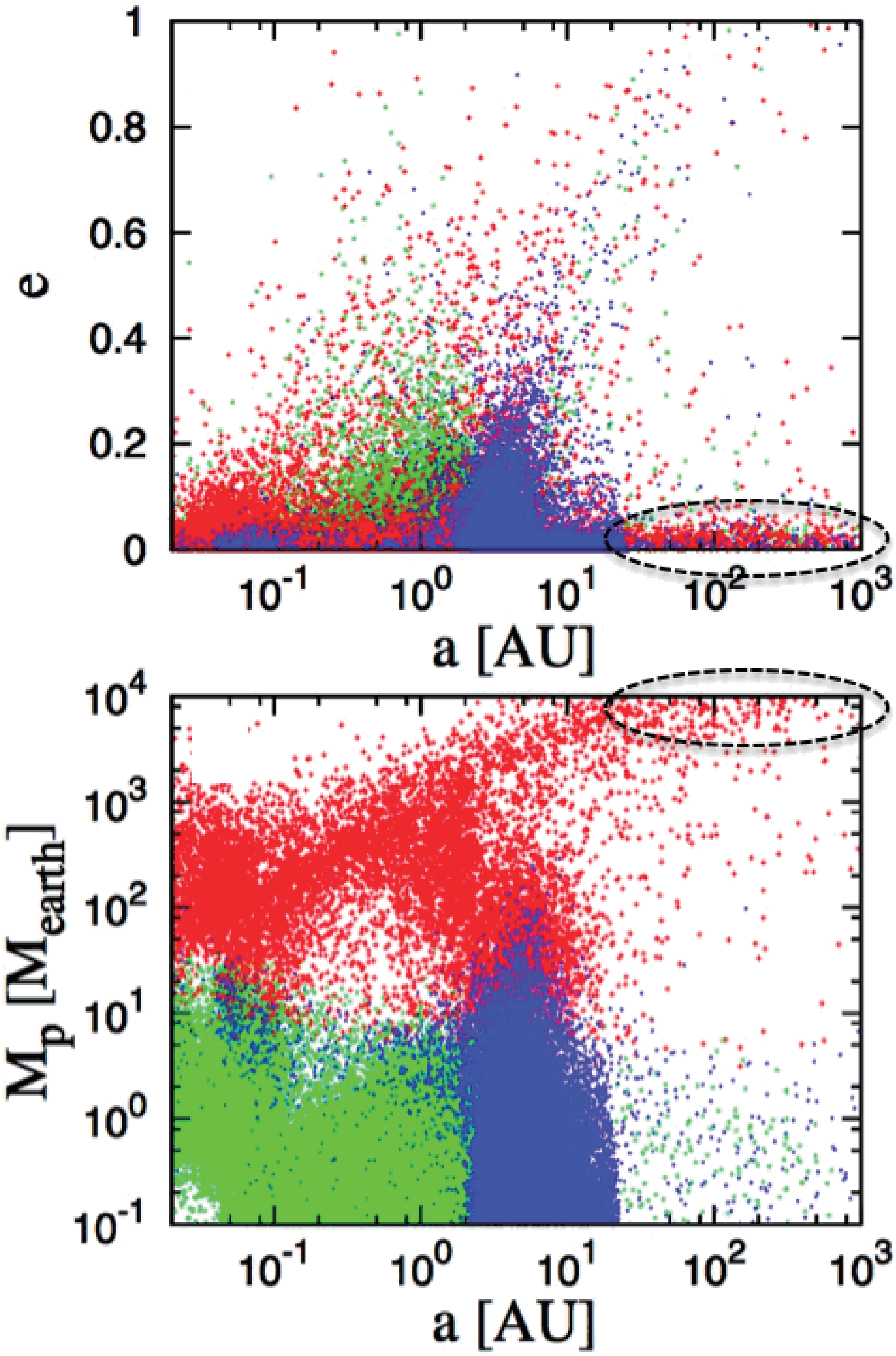

Figure 1. Distributions of planets of 10000 systems produced by a fiducial model of population synthesis calculations in Ida et al. (2013). *Top:* Orbital eccentricity e vs. semimajor axis a in AU, *Bottom:* Planet mass M_p in Earth mass vs. a. The planets surrounded by dashed circles are gas giant planets with $a \gtrsim 30$ AU and e. (modified from the result in citetIL13)

the dense H/He atmosphere, long-lived radioactive decay may provide enough heating for maintaining liquid water even without stellar irradiation (Stevenson 1999). Thus, planets with a few $R_\oplus$ at $\gtrsim 10$ AU could be habitable planets.

A problem is how to identify habitability of such planets. If spectroscopic observation is available, detection of H_2O vapor or measurement of atmospheric mass and pressure to evaluate surface temperature may give information of existence of liquid water. Biomarker is also a problem. So far, detection of O_3 line at 10μm has been proposed to identify existence of photosynthesis life, because the detection implies abundant O_2 atmosphere. However, in the dense H/He atmosphere, O_2 is quickly depleted by reacting with H_2 to form H_2O. So, photosynthesis life may not emerge on such planets. Detection of habitable planets is really challenging, but it is not completely impossible. Because just a single detection gives a big impact, it may be worth trying.

4. SUMMARY

We have discussed how direct imaging observations of extrasolar planets constrain planet formation theory. We pointed out that frequency and correlations of wide separation ($\gtrsim$ 30 AU) gas giants are important. Planet population synthesis simulations predict that in core accretion model, wide separation gas giants should show a clear correlation that planet mass increases with semimajor axis and the frequency of solar type stars harboring such planets may be several %. Although similar simulations for disk instability model have not been established yet, statistical distributions of wide separation gas giants that will be revealed by direct imaging surveys can discriminate between standard core accretion model and disk instability model for dominant formation mechanism of gas giants.

We also pointed out theoretical arguments that super-Earths with thick H/He atmosphere can have ocean even at $\gtrsim$ 10 AU. Direct imaging of such planets is not impossible for *SPICA* SCI. Although it is highly challenging, its impact is huge. More detailed considerations may be needed for this observation.

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