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The formation of Uranus and Neptune in solid-rich feeding zones: Connecting chemistry and dynamics

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ABSTRACT

The core accretion theory of planet formation has at least two fundamental problems explaining the origins of Uranus and Neptune: (1) dynamical times in the trans-saturnian solar nebula are so long that core growth can take >15 Myr and (2) the onset of runaway gas accretion that begins when cores reach $\sim 10 M_\oplus$ necessitates a sudden gas accretion cutoff just as Uranus and Neptune's cores reach critical mass. Both problems may be resolved by allowing the ice giants to migrate outward after their formation in solid-rich feeding zones with planetesimal surface densities well above the minimum-mass solar nebula. We present new simulations of the formation of Uranus and Neptune in the solid-rich disk of Dodson-Robinson et al. (Dodson-Robinson, S.E., Willacy, K., Bodenheimer, P., Turner, N.J., Beichman, C.A. [2009]. Icarus 200, 672–693) using the initial semimajor axis distribution of the Nice model (Gomes, R., Levison, H.F., Tsiganis, K., Morbidelli, A. [2005]. Nature 435, 466–469; Morbidelli, A., Levison, H.F., Tsiganis, K., Gomes, R. [2005]. Nature 435, 462–465; Tsiganis, K., Gomes, R., Morbidelli, A., Levison, H.F. [2005]. Nature 435, 459–461), with one ice giant forming at 12 AU and the other at 15 AU. The innermost ice giant reaches its present mass after 3.8–4.0 Myr and the outermost after 5.3–6 Myr, a considerable time decrease from previous one-dimensional simulations (e.g. Pollack, J.B., Hubickyj, O., Bodenheimer, P., Lissauer, J.J., Podolak, M., Greenzweig, Y. [1996]. Icarus 124, 62–85). The core masses stay subcritical, eliminating the need for a sudden gas accretion cutoff.

Our calculated carbon mass fractions of 22% are in excellent agreement with the ice giant interior models of Podolak et al. (Podolak, M., Weizman, A., Marley, M. [1995]. Planet. Space Sci. 43, 1517–1522) and Marley et al. (Marley, M.S., Gómez, P., Podolak, M. [1995]. J. Geophys. Res. 100, 23349–23354). Based on the requirement that the ice giant-forming planetesimals contain >10% mass fractions of methane ice, we can reject any Solar System formation model that initially places Uranus and Neptune inside of Saturn's orbit. We also demonstrate that a large population of planetesimals must be present in both ice giant feeding zones throughout the lifetime of the gaseous nebula. This research marks a substantial step forward in connecting both the dynamical and chemical aspects of planet formation. Although we cannot say that the solid-rich solar nebula model of Dodson-Robinson et al. (Dodson-Robinson, S.E., Willacy, K., Bodenheimer, P., Turner, N.J., Beichman, C.A. [2009]. Icarus 200, 672–693) gives *exactly* the appropriate initial conditions for planet formation, rigorous chemical and dynamical tests have at least revealed it to be a *viable* model of the early Solar System.

1. Introduction: statement of the problem and previous work on ice giant formation

The canonical core accretion theory of planet formation, in which planetesimals collide to form solid cores which then destabilize the surrounding gas to accrete an atmosphere (Safronov, 1969; Pollack et al., 1996), has at least two fundamental problems explaining the origins of Uranus and Neptune. First, dynamical times in the trans-saturnian solar nebula are so long and solid surface densities Σ are so low (<1 g cm^{-2}) according to the assumed $\Sigma \propto R^{-2}$ mass distribution (Pollack et al., 1996) that planet growth takes >15 Myr, far longer than both observed and theoretical protostellar disk lifetimes (Haisch et al., 2001; Alexander et al., 2006). Second, runaway gas accretion begins when solid cores reach 10–15$M_\oplus$, requiring a sudden and complete gas accretion cutoff just as Uranus and Neptune reach their current masses. Pollack et al. (1996) pointed out these problems in their seminal paper on the viability of the core accretion theory. More recently, Benvenuto et al. (2009) showed that Uranus and Neptune could grow within a few million years in a population of planetesimals with a distribution of radii between 30 and 100 km. However, planetesi-

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mals as small as 30 km are not consistent with the prevailing theory of planetesimal formation, based on the streaming instability, which produces planetesimals around 100 km and in some cases up to the radius of Ceres (457 km; Johansen et al., 2007).

Uranus and Neptune's total masses, 14.5 and $17.2M_\oplus$ respectively, place them squarely in the predicted critical mass range for nucleating an instability in the surrounding gas and accreting Jupiter's mass or more in under 1000 years (Mizuno, 1980; Papaloizou and Nelson, 2005). *The first challenge for theorists is to find a combination of the parameters that control core accretion—feeding zone location, ice inventory and planetesimal surface density—that leads to solid planet cores of* $>14M_\oplus$ *that form within observed protostellar disk lifetimes and are subcritical with respect to the surrounding gas density*. An ice giant formation theory should also account for the planets' bulk composition, particularly their 20–50× solar tropospheric C/H ratios (Encrenaz, 2005). Treating feeding zone location as a free parameter creates the further challenge of moving Uranus and Neptune into their current orbits.

Two previous theories attempted to explain both the timely formation and subsequent orbital evolution of the ice giants. Thommes et al. (1999, 2002) proposed that Uranus and Neptune are failed gas giants that formed between Jupiter and Saturn. Jupiter scattered the ice giants into orbits with semimajor axes $a > 15$ AU once it reached runaway gas accretion, while interactions with planetesimals further forced the ice giants slowly outward. The "collisional damping scenario" was put forth by Goldreich et al. (2004a,b). According to Goldreich et al., Uranus and Neptune formed *in situ* from a dynamically cold planetesimal disk that also produced three other proto-ice giants. The protoplanets formed quickly despite long dynamical times because the planetesimal disk scale height fit within the Hill sphere (the protoplanet's zone of gravitational dominance), leading to high solid accretion rates. Dynamical friction could no longer damp the eccentricities of the ∼5 trans-saturnian oligarchs once they attained a surface density comparable to the surrounding planetesimal disk. The oligarchs suffered close encounters and the resulting instability ejected all proto-ice giants but Uranus and Neptune.

The assumptions underlying the order-of-magnitude analysis in Goldreich et al. (2004a,b) have ultimately proven unreliable. Levison and Morbidelli (2007) demonstrated that the collisional damping scenario cannot reproduce the current Solar System: rather than ejecting three of five ice giants, the trans-saturnian protoplanets simply spread out and all planets were retained. Furthermore, the collisional damping scenario requires that oligarchs grow while planetesimals fragment to sizes ≪1 km. Since low-velocity particles ($v < 10$ cm s^{-1}) in the COLLIDE-2 microgravity experiment burrowed into the target material without producing ejecta (Colwell, 2003), there is no reason planetesimals should fragment in the dynamically cold planetesimal disk required to produce Uranus and Neptune *in situ*.

The Thommes et al. (1999, 2002) "failed gas giant" model has substantial success reproducing the current Solar System and does not require finely tuned planetesimal behavior. Studies of planet formation in the 5–10 AU region demonstrate the efficiency of growing ice giant-sized cores between Jupiter and Saturn (Hubickyj et al., 2005; Dodson-Robinson et al., 2008). However, the compositions of Uranus and Neptune strongly indicate an origin in the trans-saturnian solar nebula. Tropospheric abundances of methane show carbon enrichments of 20–50 times solar (Encrenaz, 2005), and interior models find methane mass fractions of ∼20% (Marley et al., 1995; Podolak et al., 1995). The combined dynamical and chemical model of the solar nebula calculated by Dodson-Robinson et al. (2009) shows that the methane condensation front is beyond Saturn's orbit during the first 5×10^5 years of solar nebula evolution. Without methane ice present during the planetesimal-building epoch—which lasts only 5×10^4 years according to Johansen et al. (2007)—neither planet could obtain its methane-rich composition.

The Nice model of planetary dynamics (Tsiganis et al., 2005; Gomes et al., 2005; Morbidelli et al., 2005) uses initial conditions that place Uranus and Neptune initially in the methane ice-rich regions beyond 10 AU. In the Nice model, Neptune and Uranus assume initial semimajor axes of ∼12 and ∼15–17 AU. When planetesimal perturbations pull Jupiter and Saturn across their 1:2 mean motion resonance (MMR), their eccentricities suddenly increase, forcing close encounters between all possible pairs of giant planets except Jupiter and Saturn. In about half of the simulations, Neptune is scattered across Uranus' orbit, leapfrogging to ∼23 AU within a few 10^5 years. Slow outward migration due to interaction with a planetesimal disk pulls Uranus and Neptune into their current orbits over the course of ∼40 Myr.

Although the Nice model explains the current orbits of the giant planets, it is incomplete without an assessment of the planets' ability to form in their predicted initial orbits. With high solid surface-density, methane-rich planetesimals, the protostellar disk model of Dodson-Robinson et al. (2009) contains promising initial conditions for ice giant formation between 12 and 15 AU. None of the three dynamical theories discussed—the Nice model, the failed gas giant theory and the collisional damping scenario—treats the growth of the ice giants' envelopes, a gap in the literature that this work is partly intended to fill. Verifying that $\sim 10–15M_\oplus$ solid cores can form is an important step—one which N-body simulations show is extremely difficult even in the inner nebula (McNeil et al., 2005; Chambers, 2008)—but one also has to verify that the ice giant atmospheres stay under 10% of the total planet mass and do not experience runaway growth.

In this paper, we demonstrate that Uranus and Neptune can form by core accretion, in the feeding zone approximation, in the trans-saturnian solar nebula using the Nice model initial semimajor axis distribution. In Section 2 we describe the numerical methods used in our experiments. In Section 3 we discuss the results of our core accretion simulations, focusing on formation timescale, accretion efficiency and solid/gas ratio. In Section 4 we discuss the strengths and weaknesses of our model as a realistic descriptor of Uranus and Neptune's formation. We present our conclusions in Section 5.

2. Core accretion model

The contraction and buildup of protoplanetary cores and their gaseous envelopes embedded in our model evolving disk are computed with a Henyey-type code (Henyey et al., 1964), which solves the standard equations of stellar structure for the envelope. A detailed description of the core accretion–gas capture code is available in Pollack et al. (1996), Bodenheimer et al. (2000) and Hubickyj et al. (2005). Here we explain the initial conditions used for our experiments and give an overview of our numerical method, describing its strengths and weaknesses.

We use a core accretion rate of the form

$$\frac{dM_{\rm core}}{dt} = C_1 \pi \Sigma_{\rm solid} R_c R_h \Omega, \quad (1)$$

(Papaloizou and Terquem, 1999), where $\Sigma_{\rm solid}$ is the surface density of solid material in the disk, Ω is the orbital frequency at the position of the planet, R_c is the effective capture radius of the protoplanet for solid particles, $R_h = a[M_{\rm planet}/(3M_*)]^{1/3}$ is the tidal radius of the protoplanet (where a is the semimajor axis of the protoplanet's orbit), and C_1 is a constant near unity.

Our numerical experiments are based on the feeding zone approximation, in which the growing embryo accretes planetesimals from an annulus extending $\sim 4R_h$ on either side of its semima-