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A new view on planet formation

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Abstract. The standard picture of planet formation posits that giant gas planets are over-grown rocky planets massive enough to attract enormous gas atmospheres. It has been shown recently that the opposite point of view is physically plausible: the rocky terrestrial planets are former giant planet embryos dried of their gas "to the bone" by the influences of the parent star. Here we provide a brief overview of this "Tidal Downsizing" hypothesis in the context of the Solar System structure.

Keywords. planetary systems, planets and satellites: formation

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1. Introduction

In the popular "core accretion" scenario (CA model hereafter; e.g., Safronov 1969; Wetherill 1990; Pollack *et al.* 1996), the terrestrial planet cores form first from much smaller solid constituents. A massive gas atmosphere builds up around the rocky core if it reaches a critical mass of about $10\,\mathrm{M}_\oplus$ (e.g., Mizuno 1980). The CA model's main theoretical difficulty is in the very beginning of the growth: it is not clear how metre-sized rocks would stick together while colliding at high speeds, subject to high radial drifts into the parent star (Weidenschilling 1977, 1980), although gas-dust dynamical instabilities are suggested to help (e.g., Youdin & Goodman 2005; Johansen *et al.* 2007). Nevertheless, believed to be the only viable model for terrestrial planet formation, the model has enjoyed an almost universal support (e.g., Ida & Lin 2008).

This strongest asset of the theory – a "monopoly" on making terrestrial planets – is actually void. Recently, it has been proposed by (Boley *et al.* 2010; Nayakshin 2010a, 2011b, 2010b) that a modified version of the gravitational disc instability model for giant planet formation(Kuiper 1951; Boss 1998) may account for terrestrial planets as well, if gas clump migration (Goldreich & Tremaine 1980) and clump disruption due to tidal forces (McCrea & Williams 1965) are taken into account. This new scheme addresses (Nayakshin 2010b) all of the well known objections (Wetherill 1990; Rafikov 2005) to forming Jupiter in the Solar System via disc fragmentation.

The TD hypothesis is a new combination of earlier ideas and contains four important stages (Figure 1):

(1) Formation of gas clumps (which we also call giant planet embryos; GEs). As the protoplanetary disc cannot fragment inside $R \sim 50$ AU (Rafikov 2005; Boley *et al.* 2006), GEs are formed at somewhat larger radii. The mass of the clumps is estimated at $M_{\rm GE} \sim 10 M_J$ (10 Jupiter masses) (Boley *et al.* 2010; Nayakshin 2010a); they are intially fluffy and cool ($T \sim 100$ K), but contract with time and become much hotter (Nayakshin 2010a).

(2) Inward radial migration of the clumps due to gravitational interactions with the surrounding gas disc (Goldreich & Tremaine 1980; Vorobyov & Basu 2010; Boley *et al.* 2010; Cha & Nayakshin 2011).

(3) Grain growth and sedimentation inside the clumps (McCrea & Williams 1965; Boss 1998; Boss *et al.* 2002). If the clump temperature remains below $1400-2000$K, massive terrestrial planet cores may form (Nayakshin 2011b), with masses up to the total high Z element content of the clump (e.g., ~ 60 Earth masses for a Solar metalicity clump of $10M_J$).

(4) A disruption of GEs in the inner few AU due to tidal forces (McCrea 1960; McCrea & Williams 1965; Boley *et al.* 2010; Nayakshin 2010b) or due to irradiation from the star (Nayakshin 2010b) can result in (a) a smallish solid core and a complete gas envelope removal – a terrestrial planet; (b) a massive solid core, with most of the gas removed – a Uranus-like planet; (c) a partial envelope removal leaves a gas giant planet like Jupiter or Saturn. For (b), an internal energy release due to a massive core formation removes the envelope (Handbury & Williams 1975; Nayakshin 2011b).

It is interesting to note that it is the proper placement of step (1) into the outer reaches of the System and then the introduction of the radial migration (step 2) that makes this model physically viable. The theory based on elements (3,4) from an earlier 1960-ies scenario for terrestrial planet formation by McCrea (1960); McCrea & Williams (1965) were rejected by Donnison & Williams (1975) because step (1) is not possible in the inner Solar System. Similarly, the giant disc instability (Kuiper 1951; Boss 1998) cannot operate at $R \sim 5$ AU to make Jupiter (Rafikov 2005). It is therefore the proper placement of step (1) into the outer reaches of the System and then the introduction of the radial migration (step 2) that makes this model physically viable. The new hypothesis resolves (Nayakshin 2011a) an old mystery of the Solar System: the mainly coherent and prograde rotation of planets, which is unexpected if planets are built by randomly oriented impacts.

2. Solar System structure

The gross structure of the Solar System planets is naturally accounted for by the TD model. The innermost terrestrial planets are located within the tidal disruption radius of $r_t \sim 2-3$ AU (Nayakshin 2010b), so these are indeed expected to have no massive atmospheres. The asteroid belt in this scheme are the solids that grew inside the giant planet embryos but not made into the central core, and which were then left around the r_t. The gas giant planets are somewhat outside the tidal disruption radius, and thus have been only partially affected by tidal disruption/Solar irradiation.

The outer icy giant planets are too far from the Sun to have been affected strongly by it, so they are interesting cases of *self-disruption* in the TD model. In particular, 35 years ago, (Handbury & Williams 1975) suggested that the massive core formation in Uranus and Neptune evaporated most of their hydrogen envelopes. To appreciate the argument, compare the binding energy of the solid core with that of the GE. We expect the core of high-Z elements to have a density $\rho_c \sim$ a few g cm^{-3}. The radial size of the solid core, $R_{\rm core} \sim (3M_{\rm core}/4\pi\rho_c)^{1/3}$. The binding energy of the solid core is

$$E_{\rm bind,c} \sim \frac{3}{5}\frac{GM_{\rm core}^2}{R_{\rm core}} \approx 10^{41}\ {\rm erg}\ \left(\frac{M_{\rm c}}{10\,{\rm M}_\oplus}\right)^{5/3}. \quad (2.1)$$

The clump radius $R_{\rm GE} \approx 0.8$ AU at the age of $t = 10^4$ years, independently of its mass(Nayakshin 2010b), $M_{\rm GE}$. Thus, the GE binding energy at that age is

$$E_{\rm bind,GE} \sim \frac{3}{10}\frac{GM_{\rm GE}^2}{R_{\rm GE}} \approx 10^{41}\ {\rm erg}\ \left(\frac{M_{\rm GE}}{3M_J}\right)^2. \quad (2.2)$$

The two are comparable for $M_{\rm core} \sim 10\,{\rm M}_\oplus$. Radiation hydrodynamics simulations confirm such internal disruption events: the run labelled M0α3 in Nayakshin (2011b) made a $\sim 20\,{\rm M}_\oplus$ solid core that unbound all but $0.03\,{\rm M}_\oplus$ of the gaseous material of the original $10 M_J$ gas clump.

Future work on the TD hypothesis should address the outer Solar System structure (Kuiper belt; comet compositions, etc.). Detailed predictions for exo-planet observations are difficult as the model dependencies are non-linear (Nayakshin 2011b), but some predictions distinctively different from the CA scenario may be possible as planets loose rather than gain mass as they migrate inwards.

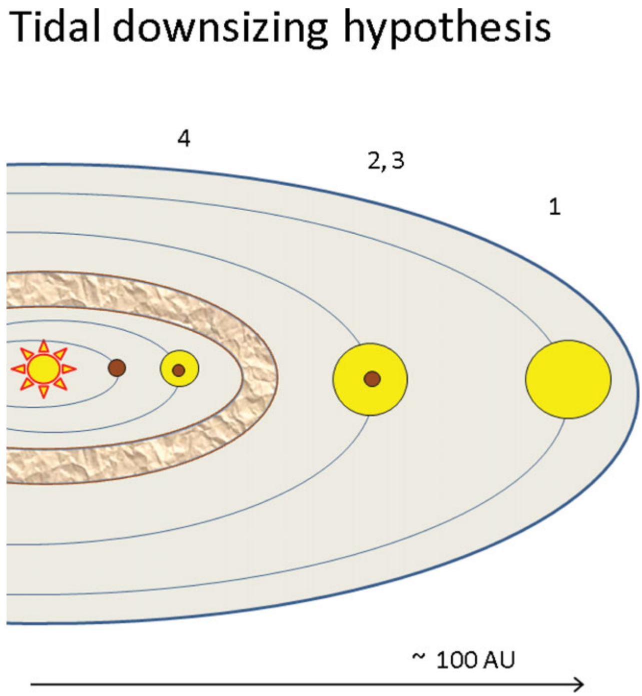

Figure 1. A cartoon of the Tidal Downsizing hypothesis. A protostar (the central Sun symbol) is surrounded by a massive $R \gtrsim 100$ gas disc (the larger grey oval). The four planet formation stages are schematically marked by numbers: (1) The formation of massive gas clumps (embryos) in the outer disc; (2) migration of the clumps closer in to the star, occurring simultaneously with (3) dust grains growth and (possibly) sedimentation into a massive solid core in the centre. The core is shown as a small brown sphere inside the larger gas embryo; (4) disruption of the embryo by tidal forces, irradiation or internal heat liberation. The brown pattern-filled donut-shaped area shows the solid debris ring left from an embryo disruption. The most inward orbit in the diagram shows a terrestrial-like planet, e.g., a solitary solid core whose gas envelope was completely removed. The planet on the next smallest orbit is a giant-like planet with a solid core that retained some of its gas envelope.

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