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The tidal downsizing hypothesis for planet formation and the composition of Solar system comets

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ABSTRACT

Comets are believed to be born in the outer Solar system where the temperature is assumed to have never exceeded $T \sim 100$ K. Surprisingly, observations and samples of cometary dust particles returned to Earth showed that they are in fact made of a mix of ices, as expected, but also of materials forged at high temperatures ($T \sim 1500$ K). We propose a radically new view regarding the origin of the high-temperature processed materials in comets, based on the recent 'tidal downsizing' hypothesis for planet formation. In the latter, the outer protoplanetary disc is gravitationally unstable and forms massive giant planet embryos (GEs). These hot ($T \sim$ 100–2000 K) and dense regions, immersed in the background cold and low-density disc, are eventually disrupted. We propose that both planets and the high-temperature materials in comets are synthesized inside the GEs. Disruption of GEs separates planets and small solids as the latter are 'frozen-in' into gas and are peeled off together with it. These small solids are then mixed with the ambient cold disc containing ices before being incorporated into comets. Several predictions of this picture may be testable with future observations of the exoplanets.

Key words: astrochemistry – comets: general.

1 INTRODUCTION

Comets are icy bodies $\gtrsim$km across that leave spectacular tails of material (dust) when ices are vaporized. Comets are believed to contain some of the most pristine materials from the dawn of the Solar system, and may offer vital clues about its formation process. The composition of comets is confusingly diverse. Some of the materials found in cometary nuclei have never (Kawakita et al. 2004) experienced temperatures above ∼30–150 K, confirming their formation very far out, probably around the present day orbits of Uranus and Neptune. However, the mass fraction of crystalline silicates in the comae of the short-period comet 81P/Wild 2, and in the ejecta of comet 9P/Tempel 1 is tantalisingly high (Zolensky et al. 2006), perhaps as high as (Westphal et al. 2009) $\psi \sim 0.5$–0.65. This is surprising as some crystalline silicates such as olivine require temperatures in excess of 1000 K to make (Wooden et al. 2007), although not all crystalline silicates form at high temperature.

In the 'core accretion' (CA) paradigm of planet formation (Safronov 1972; Pollack et al. 1996; Ida & Lin 2008), the outer disc is a rather uninteresting and cold place where planet formation is not very likely as the solid core formation time-scales are long (Safronov 1972; Rafikov 2011). The temperature outside $R \sim 10$ au is generally expected to remain below 100 K. Therefore, in the context of the CA model, the presence of materials made at $T \gtrsim 1000$ K in comets strongly suggests (Wooden, Harker & Brearley 2005) a radial transport of high-temperature grains from the inner $R \lesssim 1$ au regions into the outer $R \gtrsim 10$–30 au regions. Detailed models of the process (Gail 2001; Hughes & Armitage 2010) show numerous constraints necessary to satisfy in order to yield a significant enough outward transfer of solids.

Here we show that a set of recent ideas (Boley et al. 2010; Nayakshin 2010a,b, 2011b), proposed as an alternative to the CA model for planet formation, as a by-product may naturally explain the otherwise puzzling composition of comets. The defining difference of the model from the CA scenario, as far as comet formation is concerned, is the non-unique radius–temperature relation in the disc.

In the 'tidal downsizing' (TD) model, in a stark contrast to the CA picture, the outer disc is the most important region for planet formation, as it is the birthplace of the giant planet embryos (GEs). These massive [$\sim 10 M_{\rm J}$ (∼10 Jupiter masses)] planet-forming gas clumps are very hot and dense not due to being close to the parent star or viscous disc heating, but simply due to contraction of the clumps. The clumps are in fact undermassive isolated 'first cores' – embryos of stars (Larson 1969) – that are not destined to develop into a low-mass star due to the imposing presence of the parent star (Nayakshin 2010b) that anchors the protostellar disc. It

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should thus not be surprising that these clumps manage to become as hot as ∼1000 K all on their own, at arbitrary distances from the parent star.

The first cores (gas clumps) are excellent sites for grain growth (Nayakshin 2010b, 2011b) and thermal processing of solid materials. Inside of these hot gaseous 'ovens', chemical compounds can be baked into materials not normally expected to form at tens to hundreds of au. Furthermore, a vital part of the TD model is the eventual disruption of gas embryos which release the planets back into the 'ambient' disc. This disruption process, as we argue below, also releases the smaller thermally reprocessed solids back into the disc. The thermally reprocessed materials can then be rapidly mixed with the cold materials. As this is an *in situ* model, no outward transport of solids is required.

2 THE TIDAL DOWNSIZING HYPOTHESIS

The TD hypothesis is a new combination of earlier well-known ideas and contains four important stages (as illustrated in fig. 1 of Nayakshin 2010c).

(1) Formation of gas clumps (which we also call 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 $M_{\rm GE} \sim 10 M_{\rm J}$ (Boley et al. 2010; Nayakshin 2010b); they are initially fluffy and cool ($T \sim 100$ K), but contract with time and become much hotter (Nayakshin 2010b).

(2) Inward radial migration of the clumps due to gravitational interactions with the surrounding gas disc (Goldreich & Tremaine 1980; Lin, Bodenheimer & Richardson 1996; Boley et al. 2010; Vorobyov & Basu 2010; Cha & Nayakshin 2011).

(3) Grain growth and sedimentation inside the clumps (McCrea 1960; McCrea & Williams 1965; Boss 1998; Boss, Wetherill & Haghighipour 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. $\sim 60\,{\rm M}_\oplus$ for a solar metallicity clump of total mass $10 M_{\rm J}$).

(4) A disruption of GEs in the inner few au due to tidal forces (McCrea & Williams 1965; Boley et al. 2010; Nayakshin 2010a) or due to irradiation from the star (Nayakshin 2010a) 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).

In contrast to the CA model, the TD scheme cannot work without a massive outer $R \gtrsim$ tens to a hundred au region of the disc. The elements (3) and (4) from an earlier 1960s scenario for terrestrial planet formation (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 Solar system and then the introduction of the radial migration (step 2) that makes this model physically viable.

Nayakshin (2011a) suggested that, as a bonus, the new hypothesis resolves an old mystery of the Solar system: the mainly coherent and prograde rotation of planets, which is unexpected in the CA framework since the planets are built by randomly oriented impacts. Note, however, that Johansen & Lacerda (2010) show that accretion of pebble-sized grains on to a planetary core could provide another explanation for the observed planetary spins.

It is also not impossible (Nayakshin 2010a) that both the TD and the CA processes operate to sculpture the planetary systems we observe: the first in the early, gas rich but short ($t \lesssim 10^5$ yr) embedded period (Vorobyov & Basu 2010), and the second in the later, much more quiescent phase $t \lesssim$ a few Myr. In such a hybrid model the CA would kick-start with the benefit of the massive terrestrial cores pre-assembled in the early TD phase.

3 RETAINING SMALL SOLIDS

Although our arguments can be made completely analytical, simulations of Cha & Nayakshin (2011) illustrate our model here. In the simulations, evolution of a massive $0.4\,{\rm M}_\odot$ gas disc around a $0.6\,{\rm M}_\odot$ protostar was followed for about 6000 yr. The massive disc becomes gravitationally unstable, develops spiral arms, which then fragment into clumps. The black solid curve in Fig. 1(a) shows the annuli-averaged and density-weighted gas temperature from the simulation, defined as $\langle \rho T\rangle/\langle\rho\rangle$, whereas the solid curve in Fig. 1(b) shows the corresponding density profile, $\langle\rho\rangle$, as a function of radius R. The temperature and the density spikes correspond to the GEs in the simulation. To emphasize that even higher temperatures are present in the centres of the gas clumps, the red dashed curve in Fig. 1(a) shows the same as the black curve except for regions where

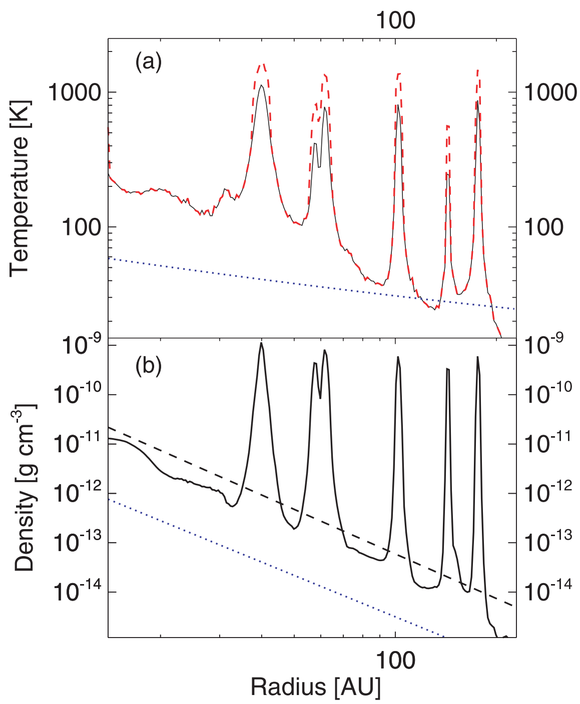

Figure 1. Solid curves: gas density (b) and temperature (a) averaged on annuli for numerical simulation of a gas disc presented in Cha & Nayakshin (2011). The red curve shows the maximum temperature found inside the clumps. The blue dotted curves show the corresponding temperature and density profiles in the standard picture of planet formation (Chiang & Goldreich 1997). The need for radial transfer of solids by factors of 10 or more is obvious (Gail 2001; Wooden et al. 2007) in that theory. In contrast, in the TD hypothesis, the outer disc has both hot and cold regions. Mixing of solids produced in these two components may yield a better explanation for the observed composition of comets.

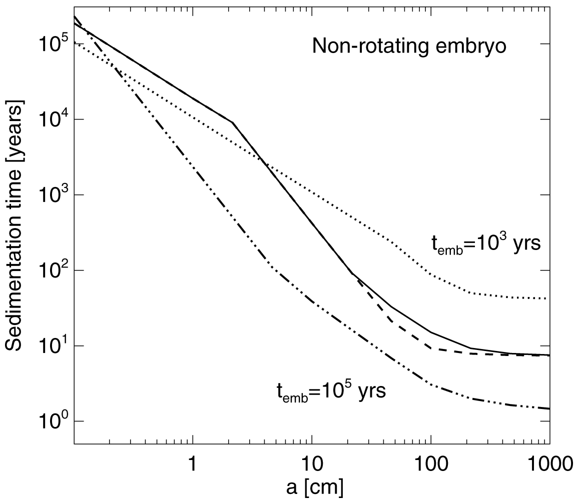

Figure 2. Sedimentation time-scales for grains versus their size, a. All the curves are calculated assuming the $M_{GE} = 10M_J$ gas embryo according to the model of Nayakshin (2010a), but at three different embryo ages: $t = 10^3, 10^4$ and 10^5 yr for the dotted, the solid and the triple-dot-dashed curves, respectively. For these curves, the grains are located at half the gas clump radius, whereas the dashed curve shows same as the solid curve but the grains are located at 0.02 the clump radius. The results are thus largely independent of the grain location inside the embryo. Grains smaller than a few mm to a few cm may remain suspended inside the embryo for a long time due to the gas drag forces. If the embryo is disrupted, these grains are released into the surrounding cold disc.

density exceeds $\rho > 10^{-10}\,\mathrm{g\,cm^{-3}}$, where the red curve shows the maximum temperature of the gas inside those regions.

The black dashed curve in Fig. 1(b) shows the tidal density of the disc, $\rho_t = M_*/(2\pi R^3)$. Density of a disc marginally stable to the gravitational instability would follow the dashed curve. The 'ambient' disc, i.e. the disc between the gas clumps, has a density lower than ρ_t and is also very cold, as expected. This confirms the two-phase division of the outer disc suggested above.

A GE disruption should release gas and small solids with it back into the cold disc. Fig. 2 shows the dust sedimentation time-scale as a function of dust particle radius, a, for GEs at three different ages from birth, 10^3, 10^4 and 10^5 yr (dotted, solid and dash-triple-dotted, respectively; Nayakshin 2010a). The grains are assumed to be located at r_d, set to equal exactly the half-radius of the embryo, R_{GE}, from the embryo centre, but the results are almost independent of r_d. For example, the dashed curve is same as the solid one but calculated for $r_d = 0.02R_{GE}$. As the embryos are disrupted in $\sim 10^4$ to 10^5 yr (Nayakshin 2010a), small $a \ll 1$ cm grains should be abundant in the gas envelope at the moment of disruption. Rapid radiative cooling and mixing with the cold background naturally deposits the high-temperature processed materials into the cold disc.

4 HOW ARE THE GAS CLUMPS DISRUPTED AT LARGE RADII?

In the 'bare-bone' version of the TD model, step (4) disrupts the envelope by tidal forces (Boley et al. 2010; Nayakshin 2010a) or due to stellar irradiation (Nayakshin 2010a). Both of these effects are weak in the outer disc, e.g. beyond ∼10 au. What could disrupt the GE there, and is there any evidence for such disruption(s) in the Solar system?

As early as 35 years ago, Handbury & Williams (1975) suggested that the massive core formation in Uranus and Neptune evaporated most of their hydrogen envelopes. The idea here is that the energy due to core formation is trapped inside the optically thick embryo, making it expand to sizes much larger than is expected in the simple analytical model of the gas clumps that do not take into account the energy release by core formation (Nayakshin 2010a). A more extended gas envelope is then much easier to disrupt, even at tens of au.

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 $\mathrm{g\,cm^{-3}}$. The radial size of the solid core, $R_{core} \sim (3M_{core}/4\pi\rho_c)^{1/3}$. The binding energy of the solid core is

$$E_{bind,c} \sim \frac{3}{5}\frac{GM_{core}^2}{R_{core}} \approx 10^{41}\,\mathrm{erg}\,\left(\frac{M_c}{10\,\mathrm{M}_\oplus}\right)^{5/3}. \quad (1)$$

Let us now look at the gas clump itself. The clump radius $R_{GE} \approx 0.8$ au at the age of $t = 10^4$ yr, independently of its mass (Nayakshin 2010a), M_{GE}. Thus, the GE binding energy at that age is

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

The two are comparable for $M_{core} \sim 10\,\mathrm{M}_\oplus$. Radiation hydrodynamics simulations confirm such internal disruption events: the run labelled $M0\alpha3$ in Nayakshin (2011b) made a $\sim 20\,\mathrm{M}_\oplus$ solid core that unbound all but 0.03 $\mathrm{M}_\oplus$ of the gaseous material of the original $10M_J$ gas clump.

If our model is right, then the outer ∼tens of au Solar system must have produced at least one 'naked' or almost so core as massive as $10\,\mathrm{M}_\oplus$. There are actually two – Uranus and Neptune with core masses of ∼13 and 15 $\mathrm{M}_\oplus$, respectively.

The self-disruption of GEs at tens or hundreds of au is potentially observationally testable in exoplanetary systems. The CA model (Pollack et al. 1996) is unlikely to produce $\gtrsim 10\,\mathrm{M}_\oplus$ solid cores that far out; the conventional disc instability model (Boss 1998; Boley et al. 2006) would result in massive gas-dominated giant planets. Thus super-Earth to Saturn mass planets on orbits of moderate eccentricity, if found at semimajor distances of $\gtrsim$tens of au, may be signposts of the gas clump self-destruction events.

Another implication of our picture is that the composition of comets and Neptune/Uranus may be related to some degree. The crystalline materials found in comets are materials that did not contribute to the building of the gas giant planets. Estimates above show that forming solid cores is absolutely essential to the release of the high-temperature processed materials back into the cold disc. For the release to occur, the cores must be as massive as these outer planets, and so may have used up a significant fraction of the solids originally present in the GEs. Therefore, materials in comets that came from the same GE may be deficient in materials/elements abundant in Uranus and Neptune.

5 IMPLICATIONS FOR THE ORIGIN OF OTHER HIGH-TEMPERATURE MINERALS IN THE SOLAR SYSTEM

Other types of materials requiring high-temperature processes are chondrules and calcium-aluminium-rich inclusions (CAIs). Chondrules are igneous-textured, mm-size particles, composed mainly of olivine and low-Ca pyroxene set in a feldspathic or glassy matrix (e.g. Scott & Krot 2005). They are a major constituent of most chondrite groups (e.g. ∼80 per cent of ordinary chondrites). The origin of chondrules is controversial, but in general they are believed to have formed as rapidly cooling molten silicate droplets.

The maximum temperatures are taken to be approximately around the liquidus temperatures of 1200–1500 K. The cooling rates remain uncertain for the range of different textural types but it is thought that if chondrules had been molten for more than a few minutes they would not have preserved the sort of volatile abundances that they often contain (Yu & Hewins 1998).

CAIs are the light-coloured inclusions commonly found in carbonaceous chondrites. CAIs are more refractory rich than chondrules. Their shapes are less regular, while common chondrules are more uniformly spherical. Radiometric dating using the ^{26}Al–^{26}Mg chronometer suggests that chondrules started to form ≈2 Ma after CAIs (McKeegan & Davis 2005). A Pb–Pb absolute age for CAI formation is 4567 Ma (Amelin et al. 2002).

Thus CAIs are considered to predate chondrules. Numerous chondrule and CAI formation models include nebular shocks (Cassen 1996), lightning (Desch & Cuzzi 2000), jets from near the proto-Sun (Shu et al. 2001) and impacts (Bridges et al. 1998). No one model is universally accepted but the impact models have the advantage of producing abundant chondrules (e.g. Scott & Krot 2005). Hevey & Sanders (2006) used the likely abundance of ^{26}Al shortly after CAI formation in the early Solar system to show that nebular dust which rapidly accreted into ∼60 km, or larger, planetesimals would start melting. Disruption of these planetesimals by impact would cause the sprays of melt droplets now seen preserved in chondrites.

The GEs are present only in the early 'embedded' stage of star formation (Vorobyov & Basu 2006, 2010; Nayakshin 2010a), which is likely to last $t \lesssim 10^5$ yr. If this is true, and if the inferred age difference between the CAIs and chondrules is real, then GEs are likely to be dispersed or become very massive giant planets by the time of chondrule formation.

If we assume that formation of CAIs is coeval with the early GE-rich epoch of star and planet formation, then one may question whether GEs have anything to do with CAIs. We believe such a view is attractive because the temperatures near the solid core inside the gas embryos may (Nayakshin 2010b) reach 1500–2000 K, e.g. high enough formation of CAIs. Vigorous convection near the solid core (Helled & Schubert 2008; Nayakshin 2011b) probably drives strong shocks, which might be one way of producing CAIs. One-dimensional simulations of Nayakshin (2011b) also show melting/re-forming cycles for grains in some cases, e.g. see the right-hand panel of his fig. 8, the simulation M2α4. Physically, the cycles result from a negative feedback loop. The accretion luminosity of the solid core increases as grains increase in size. However, this causes the inner GE regions to heat up, melting the grains. As grains become smaller, the rate of their accretion on to the solid core drops, and hence the luminosity of the core drops as well. The inner region cools down and the grains start growing again, repeating the cycle. Thus, in the TD model, this might explain the presence of CAIs with original sizes up to $\lesssim$cm being found in comets. There is evidence for this from the comet Wild2 analyses and from interplanetary dust particles (IDPs).

6 CONCLUSIONS

We have argued for an entirely different origin of the puzzling comet compositions. Instead of assuming that hot $T \sim 1500$ K regions needed for thermal processing of hot minerals are located in the inner ($R \sim 1$ au) Solar system, we identify them with the massive and appropriately hot gas clumps inside of which planets are born in the TD hypothesis for planet formation. In the latter, the clumps are born at radii of many tens to hundreds of au, and migrate inwards due to disc torques. The clumps are hot due to their self-gravity, and due to contraction caused by radiative cooling. We showed that small ≪cm sized solids are suspended inside the gas clumps and ought to be released back into surrounding cold disc if the clump is disrupted. Disruption of the clumps in the outer Solar system requires a rapid formation of massive $M > 10\,\mathrm{M}_\oplus$ cores inside the gas clumps, which puffs up the gaseous envelope to the point of its removal. We tentatively identify Uranus and Neptune as two such cores that could have disrupted their gas embryos and contributed to building the comets in the Solar system. Our ideas are similar to that of Vorobyov (2011), whose work we became aware of after the submission of our paper. In addition, somewhat similar ideas – that planets are responsible for the puzzling compositions of comets – were formulated by E. Drobyshevski in a number of papers (cf. Drobyshevski 2008) on the basis of his 'binary cosmogony' origin for planetary systems (e.g. Drobyshevski 1975).

There may be chemical signatures of a casual link between compositions of comets and the cores of the icy giants confirming (or rejecting) our model, perhaps testable with future results from the *Rosetta* mission. We also note that TD hypothesis predicts massive solid cores (tens of Earth masses, e.g. planets like Uranus and Neptune and possibly more massive) and Saturn-mass planets on semicircular orbits at tens to hundreds of au from the parent stars. Such planets are unlikely to be born in either the CA picture, where the core formation time is too long at $R \sim 100$ au, or in the disc instability model (e.g. Boss 1998) where the mass of the fragment is much more likely to exceed that of Jupiter (e.g. Boley et al. 2010). This model-differentiating prediction may be testable with future observations of exoplanetary systems.

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