The Tidal Downsizing hypothesis for planet formation and the composition of Solar System comets.

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1 INTRODUCTION

Comets are icy bodies ≥ km across that leave spectacular tails of material (dust) when ices are vaporised. Comets contain some of the most pristine materials from the dawn of the Solar System, and offer vital clues about its formation process. The composition of comets is confusingly diverse. Some of the materials found in cometary nuclei, e.g., amorphous water and ammonia ices, have never 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/Temple 1 is tantalisingly high (Zolensky et al. 2006), perhaps as high as (Westphal et al. 2009) ψ ∼ 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 1969; Rafikov 2010). The temperature outside R ∼ 10 AU is generally expected to remain below 100 K. Therefore, in the context of CA model, the presence of materials made at T ≥ 1000 K in comets strongly suggests (Wooden et al. 2003) a radial transport of high-T grains from the inner R ≤ 1 AU regions into the outer R ≥ 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 2010b), 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 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. These massive (∼ 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 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) and thermal processing of solid materials. Inside of these hot gaseous “ovens”, chemical com-

ABSTRACT

Comets are believed to be born in the outer Solar System where the temperature is assumed to have never exceeded T ∼ 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 ∼ 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” (TD) hypothesis for planet formation. In the latter, the outer proto-planetary disc is gravitationally unstable and forms massive giant planet embryos (GEs). These hot (T ∼ hundreds to 2,000 K) and dense regions, immersed in the background cold and low density disc, are eventually disrupted. We propose that both planets and the high-T materials in comets are synthesised 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 Solar System and exoplanets.
pounds 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 Figure 1 of Nayakshin [2010a]):

1. Formation of gas clumps (which we also call giant planet embryos; GEs). As the protoplanetary disc cannot fragment inside \( R \sim 50 \text{ AU} \) (Rafikov 2005; Boley et al. 2006), GEs are formed at somewhat larger radii. The mass of the clumps is estimated at \( M_{\text{GE}} \sim 10M_J \) (10 Jupiter masses) (Boley et al. 2014; Nayakshin 2010b); they are initially fluffy and cool (\( T \sim 100 \text{ K} \)), but contract with time and become much hotter (Nayakshin 2010c).

2. Inward radial migration of the clumps due to gravitational interactions with the surrounding gas disc (Goldreich & Tremaine 1980; Lin et al. 1996; Vorobyov & Basu 2010; Boley et al. 2010; Cha & Nayakshin 2010a). This develops spiral arms, which then fragment into clumps.

3. Grain growth and sedimentation inside the clumps (McCrea 1969; McCrea & Williams 1965; Boss 1993; Boss et al. 2002). If the clump temperature remains below \( 1400 - 2000 \text{ K} \), massive terrestrial planet cores may form (Nayakshin 2010c), with masses up to the total high Z element content of the clump (e.g., \( \sim 60 \text{ M}_\oplus \) for a Solar metallicity clump of total mass \( 10M_J \)).

4. A disruption of GEs in the inner few AU due to tidal forces (McCrea & Williams 1965; Boley et al. 2010; Nayakshin 2010b) or due to irradiation from the star (Nayakshin 2010b). This 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 1973; Nayakshin 2010b).

In contrast to the CA model, the TD scheme cannot work without a massive outer \( R \gtrsim \text{tens to a hundred AU} \) region of the disc. The elements (3.4) from an earlier 1960s scenario for terrestrial planet formation (McCrea 1969; McCrea & Williams 1965) were rejected by Donnison & Williams (1973) because step (1) is not possible in the inner Solar System. Similarly, the giant disc instability (Kuiper 1951; Boss 1998) cannot operate at \( R \sim 5 \text{ AU} \) to make Jupiter (Rafikov 2002). 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 (2011) 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) shows that accretion of pebble-sized grains onto a planetary core could provide another explanation for the observed planetary spins.

It is also not impossible (Nayakshin 2010b) that both the TD and the CA processes operate to sculpt the planetary systems we observe: the first in the early, gas-rich but short \( (t \lesssim 10^5 \text{ yrs}) \) embedded period (Vorobyov & Basu 2011), and the second in the latter, much more quiescent phase \( t \gtrsim \text{a few Myrs} \). 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 (2010) illustrate our model here. In the simulations, evolution of a massive 0.4 \( M_\odot \) gas disc around a 0.6 \( M_\odot \) proto-star was followed for about 6000 years. The massive disc becomes gravitationally unstable, develops spiral arms, which then fragment into clumps. The black solid curve in Figure 3b shows the annuli-averaged density profile, \( < \rho > \), whereas the solid curve in Figure 3b shows the corresponding density profile, \( < \rho > \). The temperature and the density spikes correspond to the GEs in the simulation. To emphasise that even higher temperatures are present in the centres of the gas clumps, the red dashed curve in Figure 3b shows the same as the black curve except for regions where density exceeds \( \rho > 10^{-10} \text{ g cm}^{-3} \), where the red curve shows the maximum temperature of the gas inside those regions.

The black dashed curve in Figure 3b shows the tidal density of the disc, \( \rho_t = M_\star/(2\pi R^3) \). 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 \( \rho_t \) and is 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. Figure 2 shows the dust sedimentation time scale as a function of dust particle radius, \( a \), for GEs at three different ages from birth, \( 10^5 \), \( 10^4 \) and \( 10^3 \) years (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, \( R_{\text{GE}} \), 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 \( r_d = 0.92 R_{\text{GE}} \). As the embryos are disrupted in \( \sim 10^4 \) to \( 10^3 \) years (Nayakshin 2010b), small \( a \ll 1 \text{ cm} \) 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-T processed materials into the cold disc.
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show the corresponding temperature and density profiles in the
b averaged on annuli for numerical simulation of a gas disc presented
in Cha & Nayakshin (2010). 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 ten or more is
obvious (Gail 2001; Wooden et al. 2007) in that theory. In con-
trast, 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.

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. 2011;
Nayakshin 2010b) or due to stellar irradiation (Nayakshin
2010b). 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 (1973)
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 2010b). A more ex-
tended gas envelope is then much easier to disrupt, even at
tens of AU.

\[ E_{\text{bind,GE}} \approx \frac{3}{10} GM_{\text{GE}}^2 \rho a \approx 10^{41} \text{erg} \left( \frac{M}{10 M_\oplus} \right)^{5/3} \]  

(1)

The two are comparable for \( M_{\text{core}} \sim 10 M_\oplus \). Radiation hy-
drodynamics simulations confirm such internal disruption
events; the run labelled M033 in Nayakshin (2010a) made
a ~ 20 \( M_\oplus \) solid core that unbound all but 0.03 \( M_\oplus \) of
the gaseous material of the original 10 \( M_\oplus \) gas clump.
If our model is right, then the outer ~ 10s of AU Solar
System must have produced at least one “naked” or almost
so core as massive as 10 \( M_\oplus \). There are actually two – Uranus
and Neptune with core masses of ~ 13 and 15 \( M_\oplus \), respec-
tively.

Another implication of our picture is that the composi-
tion of comets and Neptune/Uranus may be related to some
degree. The crystalline materials found in comets are ma-
terials that did not contribute to the building of the gas giant
planets. Estimates above show that forming solid cores is
essentially essential to the release of the high-T 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 origi-
nally present in the GEs. Therefore materials in comets
that came from the same GE may be deficient in materi-
als/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 pro-
cesses are chondrules and Calcium Aluminium-rich Inclu-
sions (CAIs). Chondrules are igneous-textured, mm-size par-
ticles, 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% 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 $\approx 2$ Ma after CAIs (McKeegan & Davis 2005). A Pb-Pb absolute age for CAI formation is 4,567 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 explaining 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 $\sim 60$ 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 2014, Nayakshin 2010b), which is likely to last $t < 10^5$ yrs. 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 co-eval 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 2010a) reach 1500-2000 K, e.g., high enough formation of CAIs. Vigorous convection near the solid core (Helld & Schubert 2004, Nayakshin 2010c) probably drive strong shocks, which might be one way of producing CAIs. One-dimensional simulations of (Nayakshin 2010c) also show melting/re-forming cycles for grains in some cases, e.g., see the right panel of his Fig. 8, the simulation M2v4. 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 onto 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 $\lesssim 10^{-1}$ cm being found in comets. There is evidence for this from the Comet Wild2 analyses and from IDPs (interplanetary dust particles).

![Figure 2. Sedimentation time scales for grains versus their size.](image)

**Figure 2.** Sedimentation time scales for grains versus their size, $a$. All the curves are calculated assuming the $M_{\text{Ge}} = 10 M_J$ gas embryo according to the model of Nayakshin (2010c), but at three different embryo ages: $t = 10^3, 10^4$ and $10^5$ years, 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.

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 Tidal Downsizing 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 $\ll cm$ 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 $M > 10 M_\oplus$ 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.

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 Tidal Downsizing hypothesis predicts massive solid cores (tens of Earth masses, e.g., planets like Uranus and Nep-
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...tune and possibly more massive) and Saturn-mass planets on semi-circular orbits at tens to hundreds of AU from the parent stars. Such planets are unlikely to be born in either the Core Accretion picture, where the core formation time is too long at $R \sim 100\text{AU}$, or in the disc instability model of (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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