The formation of comet nuclei

Dr. Björn J. R. Davidsson

Jet Propulsion Laboratory
California Institute of Technology
Pasadena (CA), USA

Jet Propulsion Laboratory
California Institute of Technology

A&A 592, A63 (2016)
DOI: 10.1051/0004-6361/201526968
© ESO 2016

Astronomy & Astrophysics

The primordial nucleus of comet 67P/Churyumov-Gerasimenko

B. J. R. Davidsson[1,2], H. Sierks[3], C. Güttler[3], F. Marzari[4], M. Pajola[5], H. Rickman[1,6], M. F. A'Hearn[7,8], A.-T. Auger[9], M. R. El-Maarry[10], S. Fornasier[11], P. J. Gutiérrez[12], H. U. Keller[13], M. Massironi[5,14], C. Snodgrass[15], J.-B. Vincent[3], C. Barbieri[16], P. L. Lamy[17], R. Rodrigo[18,19], D. Koschny[20], M. A. Barucci[11], J.-L. Bertaux[21], I. Bertini[5], G. Cremonese[22], V. Da Deppo[23], S. Debei[24], M. De Cecco[25], C. Feller[11,26], M. Fulle[27], O. Groussin[9], S. F. Hviid[28], S. Höfner[3], W.-H. Ip[29], L. Jorda[17], J. Knollenberg[28], G. Kovacs[3], J.-R. Kramm[3], E. Kührt[28], M. Küppers[30], F. La Forgia[16], L. M. Lara[12], M. Lazzarin[16], J. J. Lopez Moreno[12], R. Moissl-Fraund[30], S. Mottola[28], G. Naletto[31], N. Oklay[3], N. Thomas[10], and C. Tubiana[3]

(Affiliations can be found after the references)

Received 15 July 2015 / Accepted 15 March 2016

Outline

- Formation of TNOs (D>50km bodies)
  - Rapid formation due to streaming instabilities
  - Thermal processing by ^{26}Al (compaction, differentiation, aqueous alteration)
  - Collisional processing (compaction, formation of low-dens/ice-rich bodies)
- Are TNOs suitable parents of comets (collisional rubble piles)? *No!*
- Formation of comet nuclei
  - Slow formation due to hierarchical agglomeration (from pebbles remaining after TNO formation)
  - Explains bi-lobed nuclei, existence of extensive layering, low density, high porosity, weak strength, high abundance of super-volatiles, lack of aqueous alteration, presence of ~3Myr old material from inner Solar System, allows for amorphous water ice.
  - Predicts a low mass, dynamically cold primordial disk. May solve a LHB problem.
  - Predicts rather few comets in Scattered Disk ($6.3 \cdot 10^7$ vs. $6 \cdot 10^8$). May explain Bernstein (2004) HST observations. May require higher fraction loss rate from Scattered Disk and/or tidal splitting during the Centaur phase to explain JFC population. May require that comets from the giant planet region filled the Oort cloud (in addition to the primordial disk).

Initial conditions

CAI forming during *protostar class 0* stage: $t=t_0=0$ (^{26}Al abundance “canonical”)
Solar Nebula (a thin ~0.05 solar-mass gas/dust disk) formation: $t\sim 3\cdot 10^5$ yr (astrophys. obs.)

A 15 Earth-mass disk of solids at 15-30 AU (lowest possible consistent with the *Nice model)*

Dust growth from ~1μm to ~1cm in $\sim 10^5$ yr

Cm-sized pebbles rich in ^{26}Al:

- Short-lived radioactive nuclei inserted at all heliocentric distances, or spread there by efficient radial mixing (Stardust)

- Formed at t~0.4 Myr after CAI (^{26}Al half-life 0.7 Myr).

Streaming instabilities

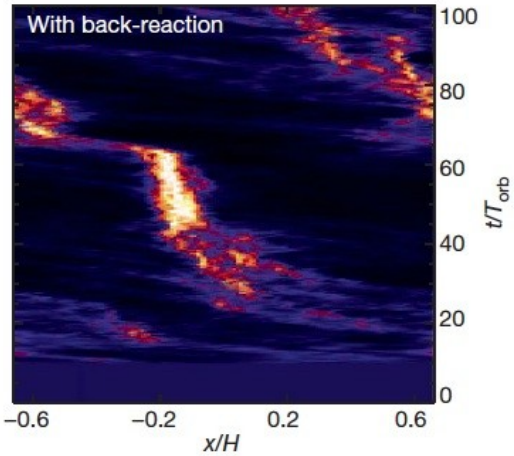
Swarms form in 10^3 yr, collapse in 10^2 yr

100 km-class objects form rapidly; ^{26}Al-rich

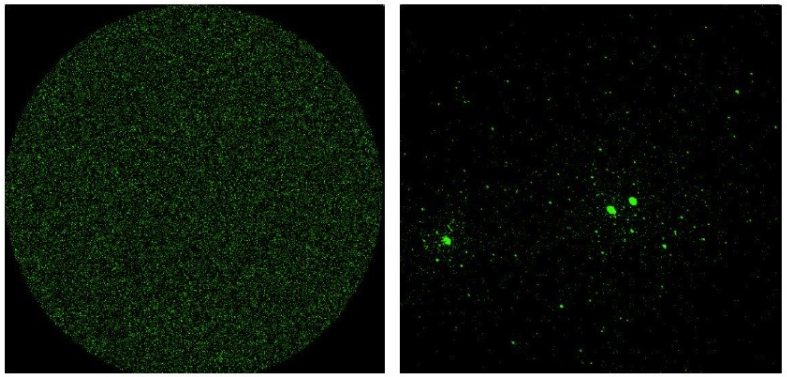
Accretion v=10-30 m s^{-1}:
D=65km has porosity ψ=72% throughout
D=250km has ψ=31% (center) – 45% (surface)
Low density (ρ=500-1000 kg m^{-3})

Our model has 13 Earth-masses of TNOs
with size-distribution of current *cold classical* EKB:
$8.5 \cdot 10^7$ at D>50km
$3.0 \cdot 10^7$ at D>80km

$(3\text{-}4) \cdot 10^7$ at D>80km needed to explain
Trojan swarms (Nesvorny *et al.* 2013)



Credit: Johansen *et al.* (2007). *Nature* **448**,1022



Credit: Nesvorny *et al.* (2010). *Astron. J.* **140**, 785

Thermal processing I

67P has dust/ice mass ratio 4±2 (Rotundi *et al.* 2015) or ice mass fraction f_{ice}~14-33%

Bodies with f_{ice}=25% and D=4-50km *disrupt* by steam pressure (Merk & Prialnik 2006) :

- Small bodies formed by streaming instabilities will not survive

Ice melting leads to chemical modification and compaction:

- Loss of supervolatiles
- Crystallization of amorphous ice (if any)
- Loss of porosity, increased bulk density
- Strength increases significantly during re-freezing

Ice melting may lead to differentiation:

- Rock/metal core
- Ice/organics mantle
- Thin crust still porous, rich in supervolatiles (re-setting of T_{spin}?)

Thermal processing II

Absence of liquid water (unequilibrated enstatite/ordinary chondrites, Wild 2):

- Pyroxene like enstatite ($MgSiO_3$)
- Olivine like forsterite (Mg_2SiO_4)
- Feldspar like albite ($NaAlSi_3O_8$); the most common sodium host

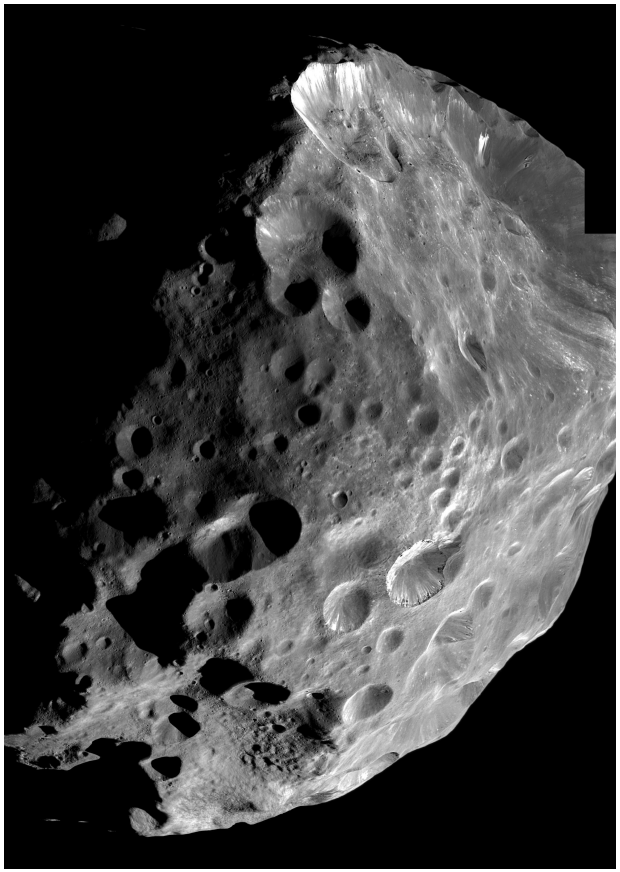
Presence of liquid water – *metasomatism* (CO3,CV3 carbonaceous chondrites):

- Albite replaced by feldspathoids like nepheline ($Na_3KAl_4Si_4O_{16}$) and sodalite ($Na_8[Al_6Si_6O_{24}]Cl_2$) being the most common sodium hosts

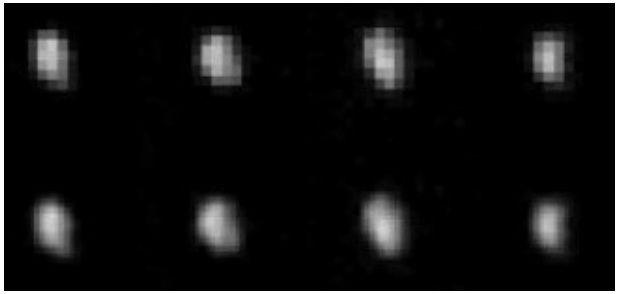
Presence of liquid water – *aqueous alteration* (CI, CM, CR, type 1-2 carbonaceous chondrites):

- Olivine, pyroxene extremely rare
- Phyllosilicates like saponite ($Ca_{0.25}[Mg,Fe]_3[\{Si,Al\}_4O_{10}][OH]_2 \cdot n[H_2O]$), and serpentine ($[Mg, Fe]_3Si_2O_5[OH]_4$), the former often the dominating sodium host

Small, dense primordial disk objects



Credit: JPL/Space Science Institute



Credit: Porco *et al.* (2003, *Science* **299**, 1541)

<u>Phoebe</u>

Captured onto retrograde orbit around Saturn

At D=217.7±1.5km, all known formation scenarios suggest ψ=45-60%, ρ=500-1000 kgm^{-3} and significant irregularity expected

But ρ=1634 ± 46 kg m^{-3} and a/b=0.93 oblate ellipsoid

<u>Himalia</u>

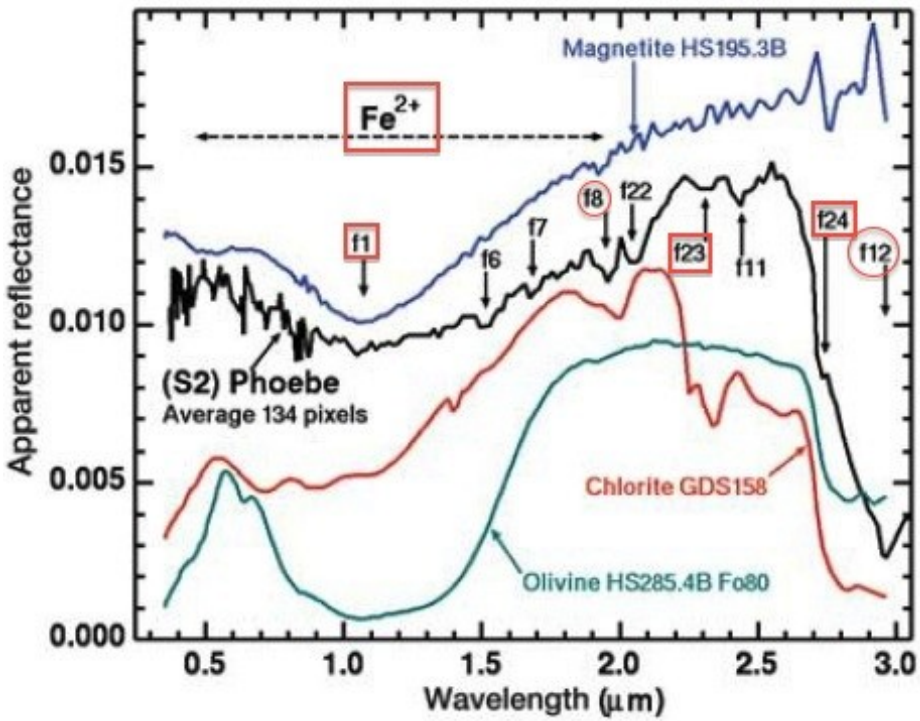
Captured onto eccentric, inclined orbit around Jupiter
Dimensions: 120±20km by 150±120km
Density: ρ>1400 kgm^{-3},nominally ρ=2400 kgm^{-3}
Porco *et al.* (2003, *Science* **299**, 1541); Emelyanov (2005, *A&A* **438**, L33)

<u>Cold classical EKB</u>

(66625) Borasisi: D_{prim}=126 km, ρ=2100 kgm^{-3}
2001 QW_{322}: D_{prim}=108 km, ρ=1270 kgm^{-3}

Aqueous alteration

Credit: Clark *et al.* (2005, *Nature* **435**, 66)



Phoebe, Cassini:
Phyllosilicates (squares)
Metal-OH absorption: 2.16μm, 2.3μm
OH stretch fundamental: 2.72μm

Water bound in phyllosilicates (circles)
1.5μm, 1.95μm, 2.95μm
Clark *et al.* (2005, *Nature* **435**, 66)

Phyllosilicates: 0.7μm

Seen in 11 of 16 Jovian irregular satellites, including Himalia, and D= 6-8km Callirrhoe, Megaclite, Themisto.

Uranus irregular satellite Caliban
Vilas *et al.* (2006, *Icarus* **180**, 453)

Centaur (10199) Chariklo
Lederer *et al.* (2004, *Earth Moon Planets* **92**, 193)

Plutinos: 2003 AZ_{84}
Fornasier *et al.* (2004, *A&A* **421**, 353)
2000 GN_{171} and 2000 EB_{173}
Lazzarin *et al.* (2003, *Astron. J.* **125**, 1554)

Al/Mg-rich OH-bearing minerals: 1.4μm, 2.28μm

Centaur 1999 DE_9
Jewitt & Luu (2001, *Astron. J.* **122**, 2099)
Plutino 2000 EB_{173}
de Bergh *et al.* (2004, *A&A* **416**, 791)

Evolution during 400 Myr

Goal: “make” Pluto, Eris, Triton (D=2300-2700km)

Cannot *start* at these sizes! Runaway growth during 400 Myr will create much larger bodies.

Postulate that streaming instabilities form D≤400km bodies

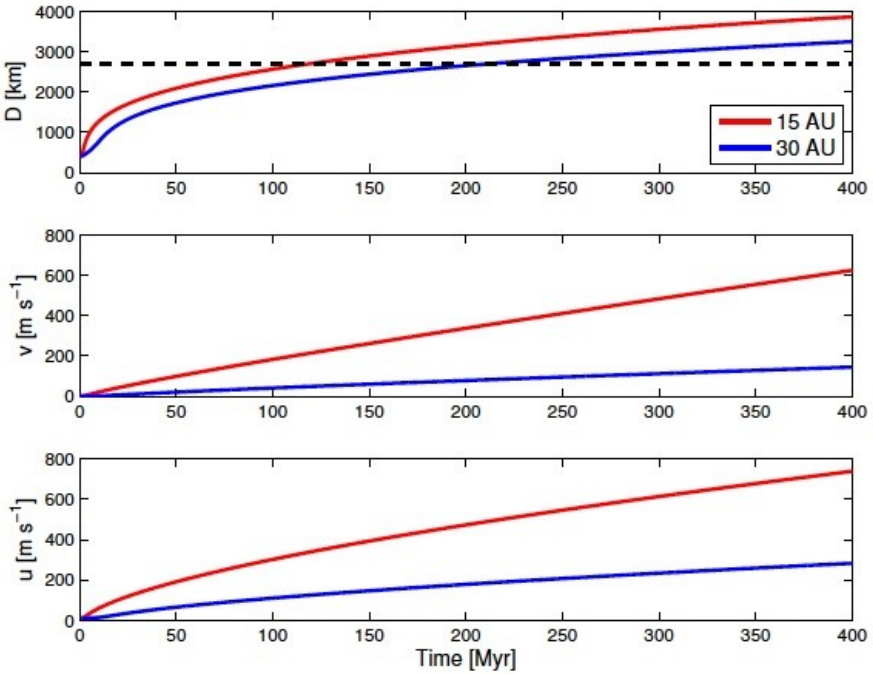
- Inspired by cold classical disk
- Little/no post-formation accretion (would kill ultrawide binaries)

Two-group approximation:

- Largest body grow to size of Triton in 400 Myr in a 15 Earth-mass disk
- Based on size-distribution we expect 350 large (runaway) bodies.

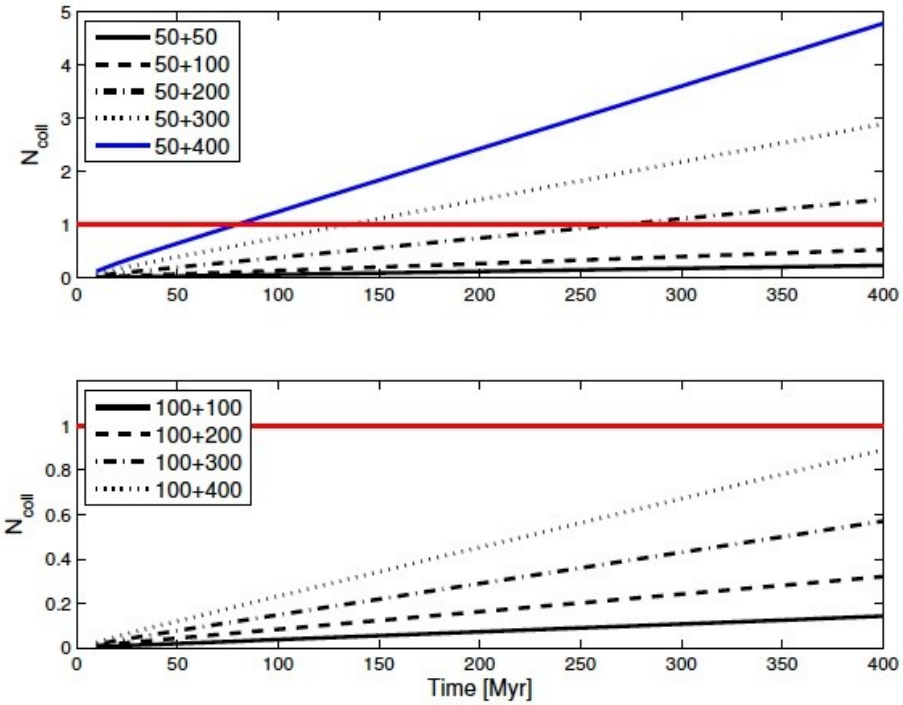
Viscous stirring (among large TNOs)

- Less than 600 m/s at 15 AU
- Less than 150 m/s at 30 AU



Credit: Davidsson *et al.* (2016, *A&A* **592**, A63)

Debris production during TNO collisions



Similar-sized bodies collide infrequently

Small bodies collide often with big targets BUT do not produce much escaping debris at <150-600 m s^{-1}.

Thermally processed material do not spread efficiently within the primordial disk!

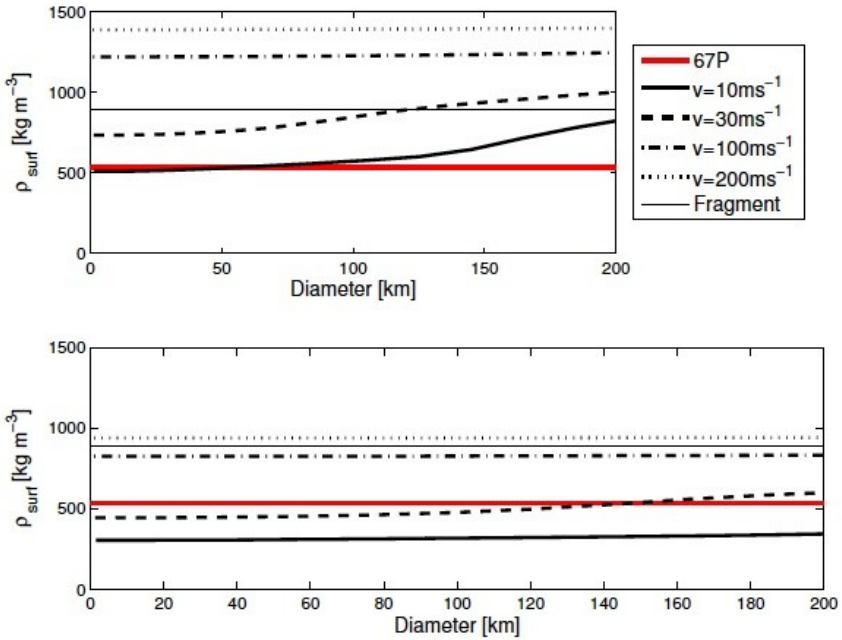
Credit: Davidsson *et al.* (2016, *A&A* **592**, A63)

TNO collisions

Projectile D [km]	Target D [km]	V_{rel} = 30 m s^{-1}	100 m s^{-1}	200 m s^{-1}	500 m s^{-1}	700 m s^{-1}
50	50	0.13	2.02	9.65	75.86	161.7
100	100	0.05	0.80	3.82	30.00	63.97
200	200	0.02	0.32	1.51	11.86	25.29
50	100	0.01	0.15	0.70	5.52	11.78
50	200	–	0.01	0.03	0.24	0.50
100	200	–	0.06	0.28	2.18	4.66
100	300	–	0.01	0.04	0.35	0.75

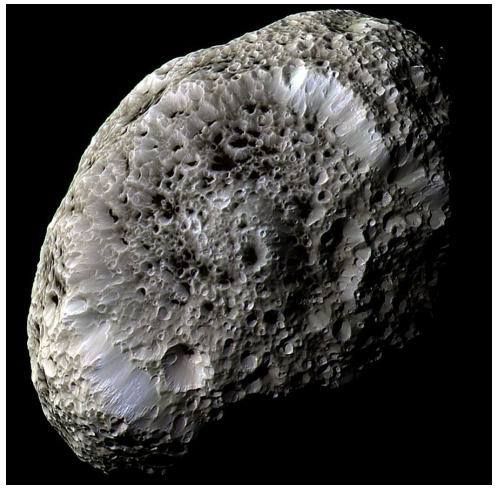
Collisional compaction

Credit: Davidsson *et al.* (2016, *A&A* **592**, A63)



Credit: NASA/JPL/JHUAPL

Asteroid (253) Mathilde
Housen *et al.* (1999, *Nature* **402**, 155)



Credit: NASA/JPL/Space Science Institute

Saturnian satellite Hyperion
Housen *et al.* (2012, Icarus **219**, 297)

Collisions above 10-30 m s^{-1} compress granular ice/dust above density of 67P

TNOs sweep up each other (and comets) with velocities up to ~700 ms^{-1}

Even cold, porous, thermally unprocessed crusts becomes compacted!

Transfer to the EKB and SD

About 0.19% is transferred to the EKB (and ~12% lost in last 4 Gyr):

- $5.6 \cdot 10^7$ at D>50km => $9.3 \cdot 10^4$, very close to Deep Ecliptic Survey $(8.07 \pm 2.45) \cdot 10^4$ (Adams *et al.* 2014)
- Of the 350 largest => 0.7 bodies, i.e., *Pluto*

The current SD population is 0.95% of the primordial disk:

- $5.6 \cdot 10^7$ at D>50km => $5.3 \cdot 10^5$, very close to Deep Ecliptic Survey $1.7 \cdot 10^5$ (Adams *et al.* 2014)
- Of the 350 largest => 3 bodies, i.e., *Eris* (plus a couple undiscovered?)

Current EKB dynamically hot: 1650-2700 m s^{-1} (Dell'Oro *et al.* 2013, *A&A*, **558**, A95)

- Pluto/Charon system formed in gigantic collision
- Collisions between differentiated bodies can result in f_{ice}~100% bodies!
- Consider 2002 UX_{25} with D=650km and ρ=800 kg m^{-3}

Do not confuse low TNO densities with low comet densities!
TNOs may be rather compact but extremely ice-rich,
comets are very porous and dust-rich

Comets: collisional rubble piles?

In a massive and dynamically hot primordial disk collisions among small TNOs is envisioned to launch a *collisional cascade* resulting in a large number of comets that are *collisional rubble piles.*

Is this a viable scenario?

No!

Density, porosity, and strength

<u>Collisional rubble-piles</u>

Parent compacted to 1200-1800 kg m^{-3}

Small (D~0.5km) collisional-rubble piles like Itokawa only have 40% macroporosity
Abe *et al.* (2006 *Science* **312**, 1344)

Such blocks with 40% macroporosity yields ρ_{bulk}=700-1100 kg m^{-3}
Abe *et al.* (2006 *Science* **312**, 1344)

Weak on large scales, but strong on size-scale of blocks. Terrestrial snow with ρ_{bulk}=600 kg m^{-3} has 1 MPa tensile strength.
Hagenmuller *et al.* (2014, *Geophys. Res. Lett.* **41**, 86)

<u>Cometary nuclei</u>

Comet 67P inferred to have $\psi \approx 70\%$,
Sierks *et al.* (2015, *Science* **347**, aaa1044)

Measured bulk density of 67P is ρ_{bulk}=535 ± 35 kg m^{-3}
Preusker *et al.* (2015, *A&A*)

Comet material in meteor showers have tensile strengh <35 kPa
Trigo-Rodriguez et al. (2006, *MNRAS* **372**, 655)

67P strength <1.5 kPa
Groussin *et al.* (2015, *A&A*)

Aqueous alteration and metasomatism

<u>Collisional rubble-piles</u>

Phyllosilicates expected in parents (analogues: Phoebe, Himalia)

Collision fragments would inherit phyllosilicates (analogues: Callirrhoe, Megaclite, Themisto).

<u>Cometary nuclei</u>

No phyllosilicates found in *Stardust* samples
Stodolna *et al.* (2010, *LPSC* **41**, 1657); Berger *et al.* (2011, *Geochin. Cosmochim. Acta* **75**, 3501); Brownlee *et al.* (2012, *Meteo. Planet. Sci.* **47**, 453); Stodolna *et al.* (2012, *Geochim. Cosmochim. Acta* **87**, 35); Joswiak *et al.* (2012, *Meteo. Planet. Sci.* **47**, 471).

Stardust samples contain ~2% cristobalite, that is common protostellar disk but is missing in carbonaceous chondrites (destroyed by water)
Roskosz *et al.* (2015, *Astrophys. J. Lett.* **801**, L7)

Stardust samples do contain magnetite, carbonate, cubanite. *In situ* aqueous alteration unlikely.

No detectable 0.7μm absorption in 67P, and only water ice 3.0μm absorption
Fornasier *et al.* (2015, *A&A*)
Capaccioni *et al.* (2015, *Science* **347**, aaa0628)

How did comets form?

Back to the early Solar Nebula

Pebbles are consumed by TNO formation through streaming instabilities.
Can this process continue until the last pebble is gone?

No! When density of pebbles in swarms no longer can be elevated
above the Roche density, such growth stops.

We estimate that ~87% of the pebbles are consumed, while
~13% are left behind (2 Earth masses)

The remaining crumbles from the TNO bakery merge slowly in low-velocity collisions.

This is classical *hierarchical agglomeration growth.*

Weidenschilling (1997)

Original model at 30 AU scaled to our (somewhat lower) number densities

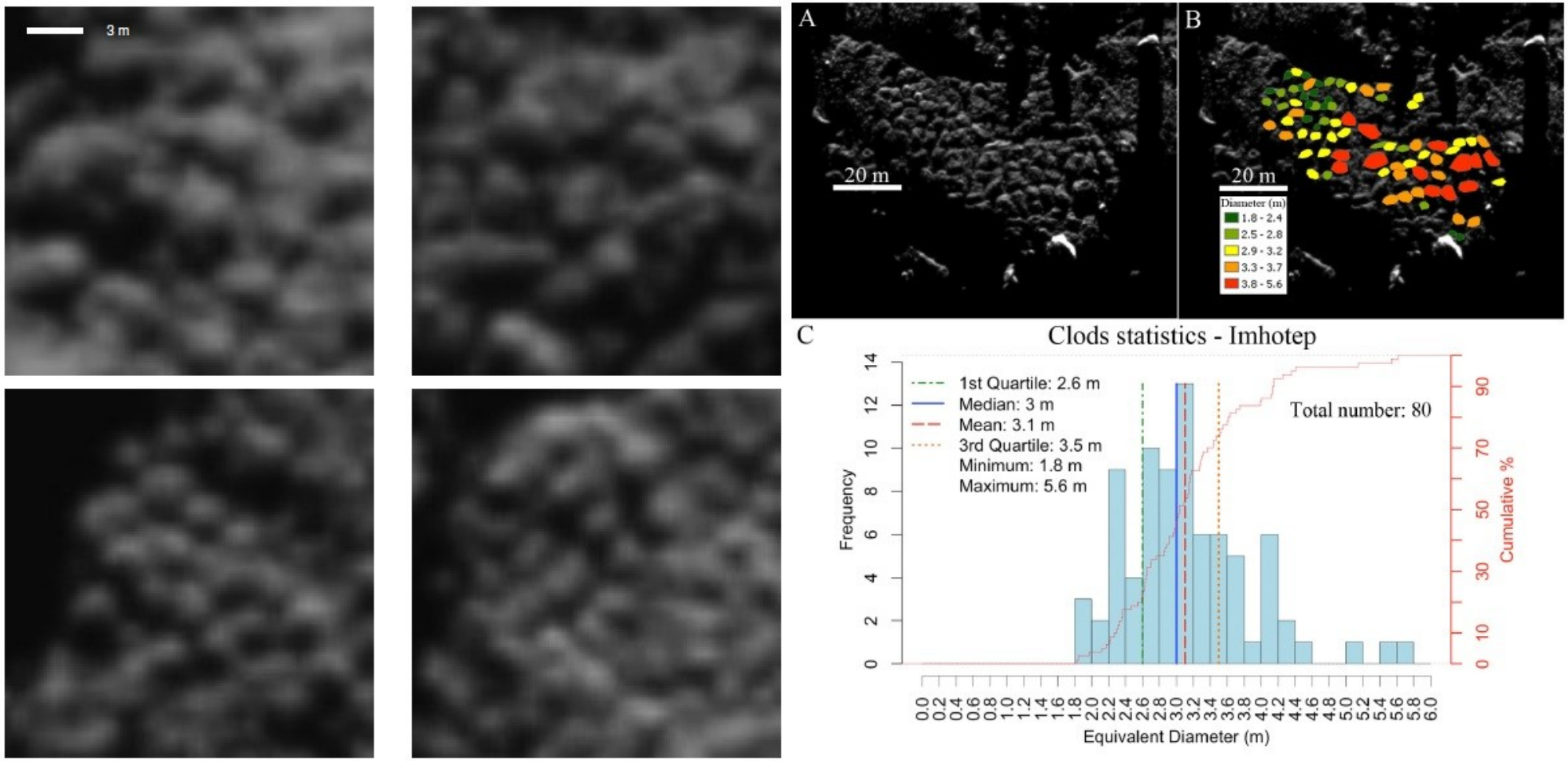
TIME (15/30 AU)	TARGET	PROJECTILE	RELATIVE VELOCITY
~0.1 Myr	0.1m	30-50μm	10 m s^{-1}
0.28 / 0.56 Myr	1 m	0.1m	30 m s^{-1}
	7m	2-3m	2 m s^{-1}
0.41 / 0.83 Myr	70m	20m	0.8 m s^{-1}
1.18 / 2.43 Myr	500m	200m	0.2 m s^{-1}
1.74 / 3.57 Myr	6 km	1km	2 m s^{-1}

Note that *peak impact velocity* takes place when *meter-sized objects grow.*
Porosity ~60% and density 730 kg m^{-3} expected
They will have *higher tensile strength* than unit on any other size scale.

Are these our goosebumps?

Goosebumps and clods

Credit: Davidsson *et al.* (2016, *A&A* **592**, A63)



The sizes (2.5m on average) and narrow range (±1m) are consistent with hierarchical growth models.

Other formation mechanisms (fracturing + sublimation?) cannot be excluded.

Solar Nebula dissipates at t~3Myr

PROPERTIES AT THIS STAGE:

1) Peak density and strength for units with size ~1m (goosebumps?)

2) Growth is so slow (bodies small!) that heating from ^{26}Al can be dissipated
   - No problem to preserve super-volatiles (CO, NH_3, N_2, CO_2)
   - No problem to preserve amorphous water ice (if there to begin with)
   - No liquid water, thus no aqueous alteration
   - No re-setting of spin temperatures (ortho-para-ratios)

3) Plenty of time to accumulate "old" material from the inner Solar System
   - Stardust samples contain CAI and chondrules that had their ^{26}Al-^{26}Mg systematics reset 1.7-3 Myr after CAI, *before* baked into Wild 2

4) <u>Single-lobed bodies</u> that are very porous
   - Bodies only grow by colliding with much smaller bodies (gas drag heavily suppresses collisions between similar-sized bodies)
   - Predicted bulk density 210-440 kg m^{-3}. Large voids (Imhotep sinkhole?)

5) Size distribution: q=3.5 (diff), equivalently α_c=2.5 (cumu), D<6km

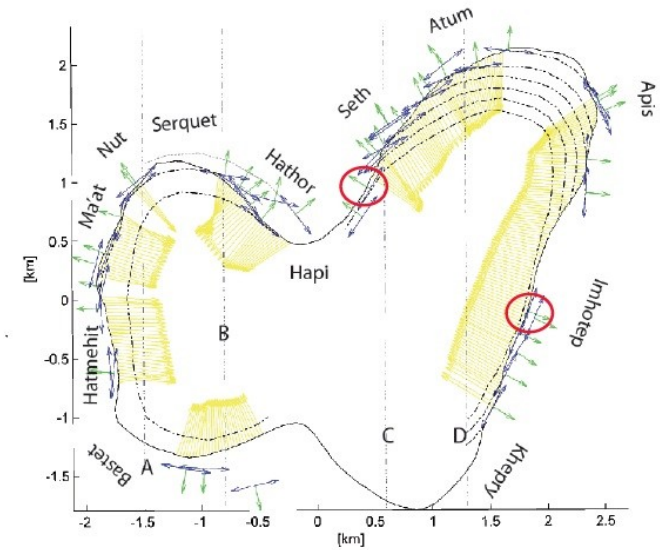
Creation of layering

When gas is gone, *viscous stirring* from TNOs increase collision velocities to 40 m s^{-1} on average during the first ~25 Myr

Most planetesimals will get flattened upon impact
- Break-up into a thin extended “talps” of goosebumps?
- Disintegration of goosebumps into pebbles?
- *This is a possible mechanism to form layers*
- CONSERT: <u>outer</u> part of head homogeneous (>few m)

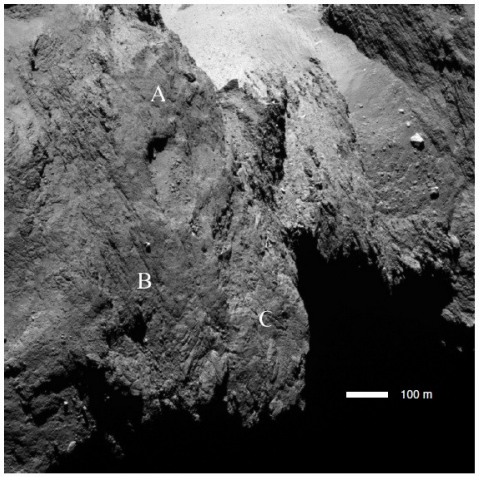
Prediction of density decreasing towards interior:
- Interior has 210-440 kg m^{-3}
- Layers predicted to have 670-990 kg m^{-3}
- Layer thickness 70-350m needed to yield 535 kg m^{-3}
- Outer/inner density ratio 2.2-3.2
- Can be confirmed from moments of inertia?

Impacts at unusually low speed:
- Local preservation of cometesimal shapes (PRFs?)
- Local survival of goosebumps (Seth sinkhole)?
- Local creation of macroscopic voids, seen as pits?



Credit: Massironi *et al.* (2015, *Nature* ***526****, 402*)

Lobes are *individually layered*



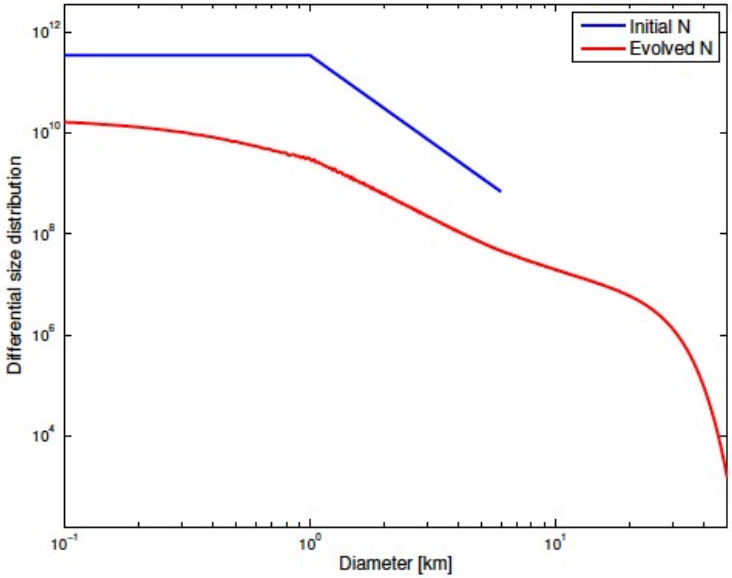
Credit: Davidsson *et al.* (2016, *A&A* **592**, A63)

Positive Relief Features (PRFs)

The bi-lobed shape

Viscous stirring removes size-dependence of relative velocities: equal-sized bodies can (also) merge!

- The number of “heads” drop a factor ~58 in 25 Myr
- In the beginning: only takes 3.2Myr for a head to meet a body. After 25Myr, it takes 184 Myr.
- 67P became bi-lobed at a point when merger with a third body was unlikely?
- Is Hatmehit a contact surface to a third lost lobe? Imhotep?



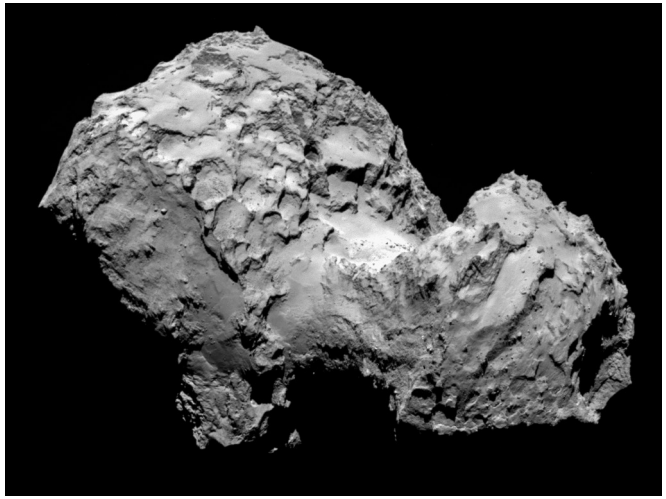
Credit: Davidsson *et al.* (2016, *A&A* **592**, A63)

Another effect of mergers:

- We build a new population of 6-50km bodies. *Is this how Hale-Bopp and other large nuclei formed?*
- Large comets form too late to be affected by ^{26}Al
- Supervolatiles, amorphous ice... everything possible.

Size distribution for D=0.5-10km nuclei is now q=2.39 (diff), equivalently α_c=1.39 (cumu)

Most (~8/10) observational studies obtain α_c=1.5-1.9 for JFCs or their impact craters on jovian satellites



Credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA

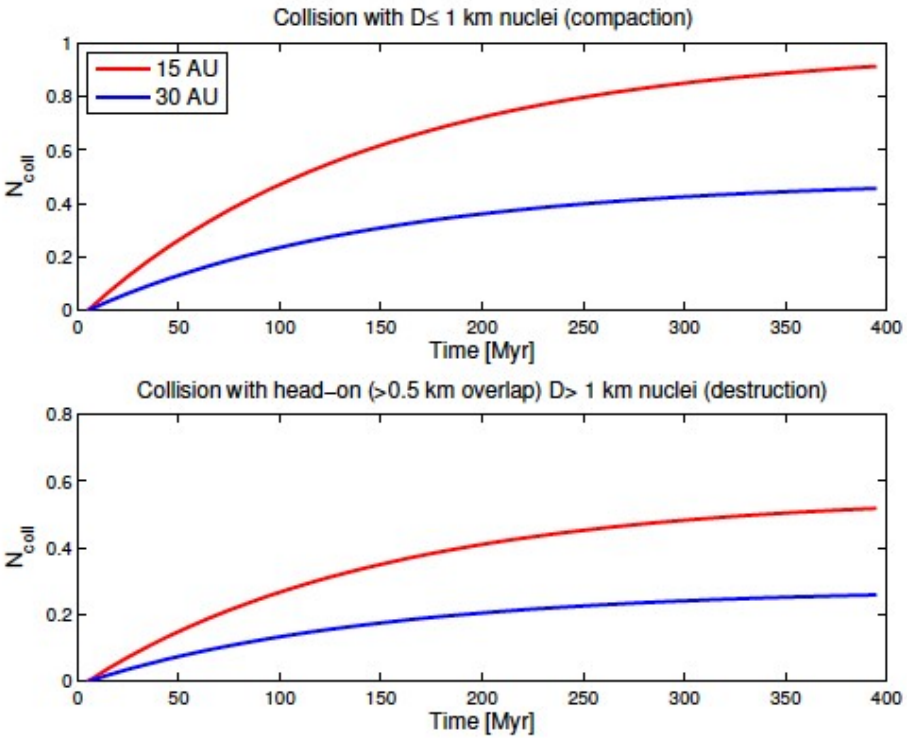
Evolution during remainder of the 400 Myr

Comets swept up by TNOs:
- Number of D=0.1-10km nuclei decreases by a factor ~17

67P-class nuclei avoiding to collide with D<1km object (will lead to local compaction):
- 40% at 15 AU, 63% at 30 AU

67P-class nuclei avoiding to collide with D>1km object (or only experiencing grazing collision):
- 59% at 15 AU, 77% at 30 AU

Intrinsic collision probabilities have been calculated that are more accurate
- Simple method seem to exaggerate the risk of collision a factor 2-7
- *The majority of 67P-class nuclei will not collide with another nuclei during the rest of the 400 Myr.*



Credit: Davidsson *et al.* (2016, *A&A* **592**, A63)

Solving a problem with the LHB?

We have a total of $2.7 \cdot 10^9$ nuclei with D=2-20km. That is 70 times less than some previous estimates (e.g., Brasser & Morbidelli 2013).

Lunar crater size distribution suggests a very small contribution from comets during the LHB (Strom et al. 2005).

Bottke et al. (2012) calculated that there had to be less than $3 \cdot 10^9$ -$2 \cdot 10^{10}$ nuclei in the primordial disk to produce the correct lunar crater size distribution.

Our number is just below....

HST deep survey

If applying the 0.95% transfer rate to the SD, we get $6.3 \cdot 10^7$ nuclei with D=1-10km ($2.6 \cdot 10^7$ nuclei with D=2-20km). Lower than previous estimates e.g. $6 \cdot 10^8$ (Duncan & Levison 1997).

Bernstein et al. (2004): HST deep survey to m~29 (D>15km) in a 0.02 deg^2 region

Three objects discovered, the faintest having D=25km.

Volk & Malhotra (2008) used this to obtain a best estimate of the number of D=1-10km nuclei: $3 \cdot 10^5$ nuclei in the 30-50 AU region, ±3º (15% of the total).
The upper limit (95% confidence limit) was $2 \cdot 10^8$.

Our number is $9.5 \cdot 10^6$, that of Duncan & Levison (1997) is $9 \cdot 10^7$.

Jupiter Family Comets

To calculate number of JFCs with H_T<9 and q<2.5 AU:

- Yearly loss of objects from the SD (between $R_{esc}=1\cdot10^{-11}$ yr^{-1} to $9.3\cdot10^{-11}$ yr^{-1})
- Fraction of those that enter the JF (30%)
- Dynamical life-time of JFCs ($3.3\cdot10^5$ yr)
- Fraction of their time spent at q<2.5 AU (7%)
- Compare with active+dormant comets at q<2.5 AU (280-750)

With our D=1.4-20km (H_T<9 not well-defined) nuclei ($4.2\cdot10^7$)
we get 29-270 JFCs (a bit too few).

Duncan & Levison (1997) “postulated” $6\cdot10^8$ objects to get 500 comets, (implies ~$2\cdot10^{11}$ objects in the primordial disk). We have tried to derive a number from “first principles”

Solutions (?):

- Is R_{esc} higher than thought? Depends on how SD population is debiased...
- Tidal splitting during the time spent as Centaur? Many close encounters...

Summary

All observable properties of comet nuclei are consistent with them being primordial rubble-piles

We propose a concurrent comet and TNO formation scenario that explain several observable properties of comets.

The lack of extensive collisional comet evolution implies a low-mass primordial disk that was dynamically cold

Rosetta observations teach us about the Solar Nebula, and perhaps the interstellar medium, not about parent body processing and collisional physics