A concurrent comet and TNO formation scenario

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Thank you Hans!!

- Hans inspired me to study comets at age 12 through his popular writing
- Hans taught astronomy classes during my undergraduate training
- Hans was my Master's thesis supervisor in 1998
- Hans was my Ph.D. supervisor in 1999-2003
- Hans has been my colleague and mentor for almost 20 years

Outline

- A novel comet formation scenario
  - I will argue that comets are primordial rubble piles and not collisional rubble piles

- 67P properties consistent with scenario
  - Nucleus spectrophotometry
  - Nucleus morphology
  - Nucleus mass (distr.), density, porosity, dust/ice mass ratio

The primordial nucleus of comet 67P/Churyumov–Gerasimenko

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Solar Nebula (first ~ 3 Myr)

We envision a low-mass disk (15 Earth masses of cm-sized pebbles at 15-30 AU)

Pebbles are consumed by D=50-400km TNO formation through <u>streaming instabilities.</u> These bodies become substantially thermally processed by ^{26}Al.

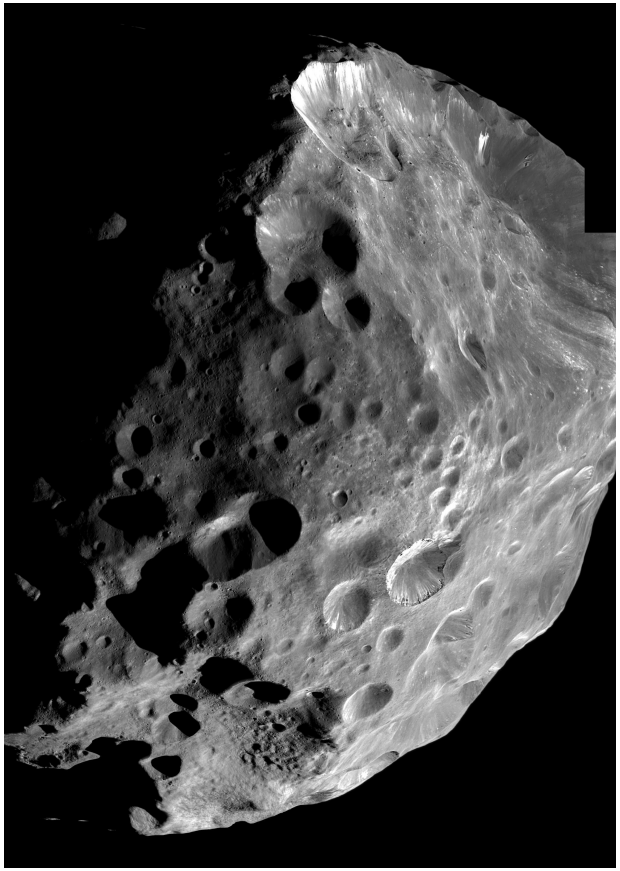
When ~2 Earth masses of pebbles remain, the Roche density no longer can be reached. TNO formation stops.

Remaining pebbles merge to cometesimals through very slow <u>hierarchical agglomeration</u>.

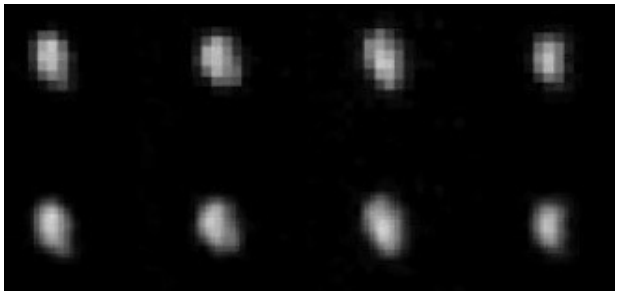
Streaming instabilities: Youdin & Goodman 2005, Astrophys. J., 620, 459
Johansen et al. 2007, Nature, 448, 1022

Hierarchical agglomeration: Weidenschilling 1997, Icarus, 127, 290
Windmark et al. 2012, Astron. Astrophys., 540, A73

Phoebe & Himalia: examples of TNOs with ^{26}Al?



Credit: NASA



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

<u>Phoebe</u>

Captured onto retrograde orbit

D=217.7±1.5km: high porosity ψ=45-60%, low density ρ=500-1000 kgm^{-3}, and significant irregularity expected

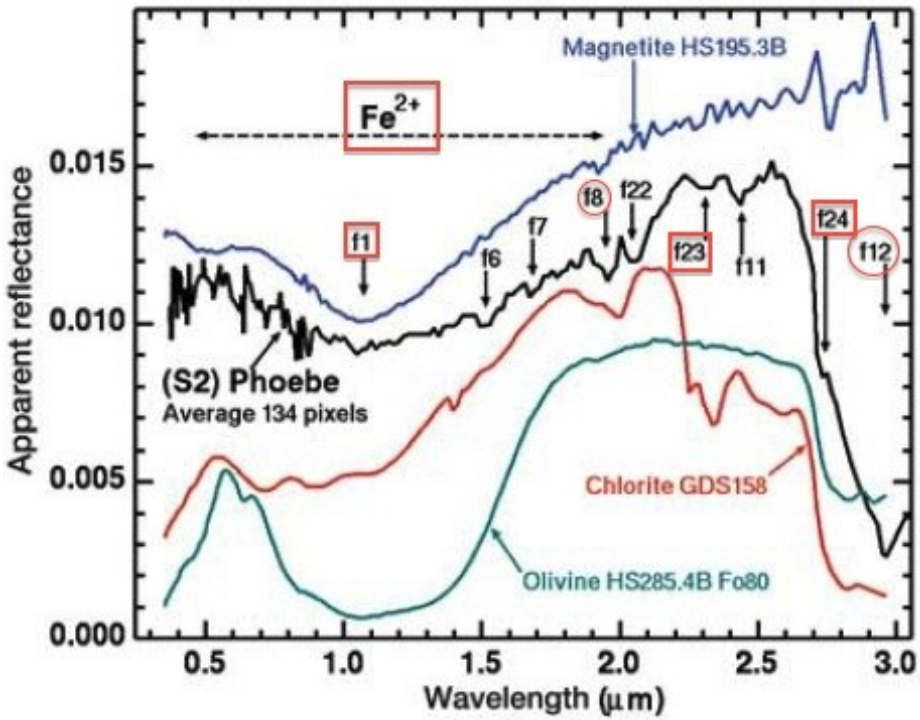
But ρ=1634 ± 46 kgm^{-3} (if chondritic ψ=10%) and shape oblate ellipsoid (a/b=0.93)

^{26}Al readily explains high density and shape
Castillo-Rogez *et al.* (2012, *Icarus* **219**, 86)

<u>Himalia</u>

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)

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)

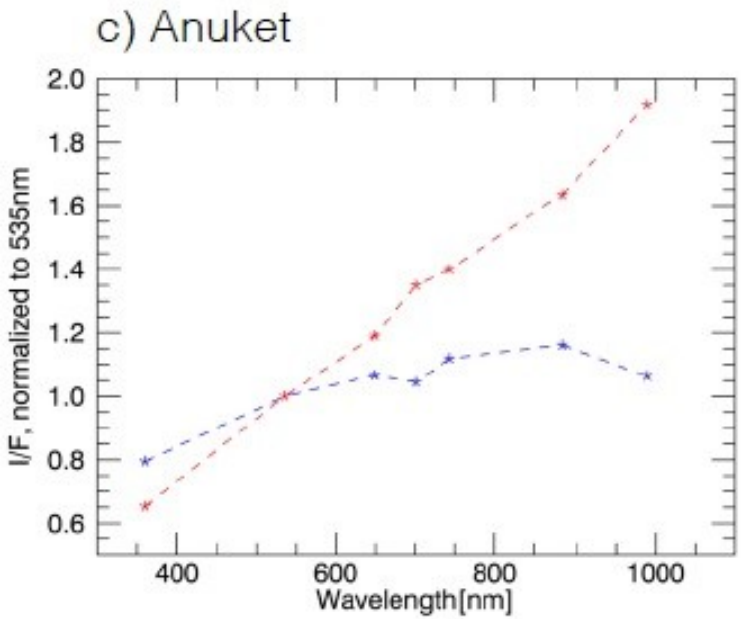
Centaur (10199) Chariklo
Lederer *et al.* (2004, *Earth Moon Planets* **92**, 193)

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)

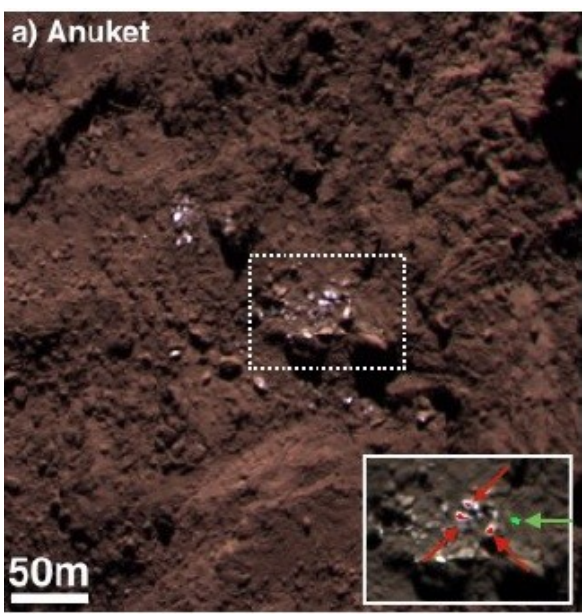
Al/Mg-rich OH-bearing minerals: 1.4μm, 2.28μm

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

No aqueous alteration on 67P or 81P: comets probably *not* collisional rubble piles



Credit: Pommerol et al. 2015 A&A 583, A25



OSIRIS (Fornasier *et al.* 2015 *A&A* **583**, A30; Pommerol *et al.* 2015 *A&A* **583**, A25; Oklay *et al.* 2016 *A&A* in press) and VIRTIS (Capaccioni *et al.* 2015, *Science* **347**, aaa0628; De Sanctis *et al.* 2015, *Nature* **525**, 500):

0.29 μm: possibly SO_2 ice

2.9-3.6 μm: organics

~3μm: water ice

No spectral resemblance with aqueously altered carbonaceous chondrites!

No global 0.7 μm phyllosilicate absorption!

No phyllosilicates found in *Stardust* samples from comet 81P/Wild 2!

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).

^{26}Al in comet-sized bodies

67P has dust/ice mass ratio 4±2, i.e., ~20% (+13%/-6%) ice by mass
Rotundi *et al.* 2015, *Science* **347**, aaa3905

Formation at t_0 (canonical CAI) with 25% ice: D≳4km nuclei reach T=320K, may disrupt
Merk & Prialnik (2006, *Icarus* **183**, 283)

To avoid loss of supervolatiles (amorphous water ice crystallization last line of defense!) in D=4km body:

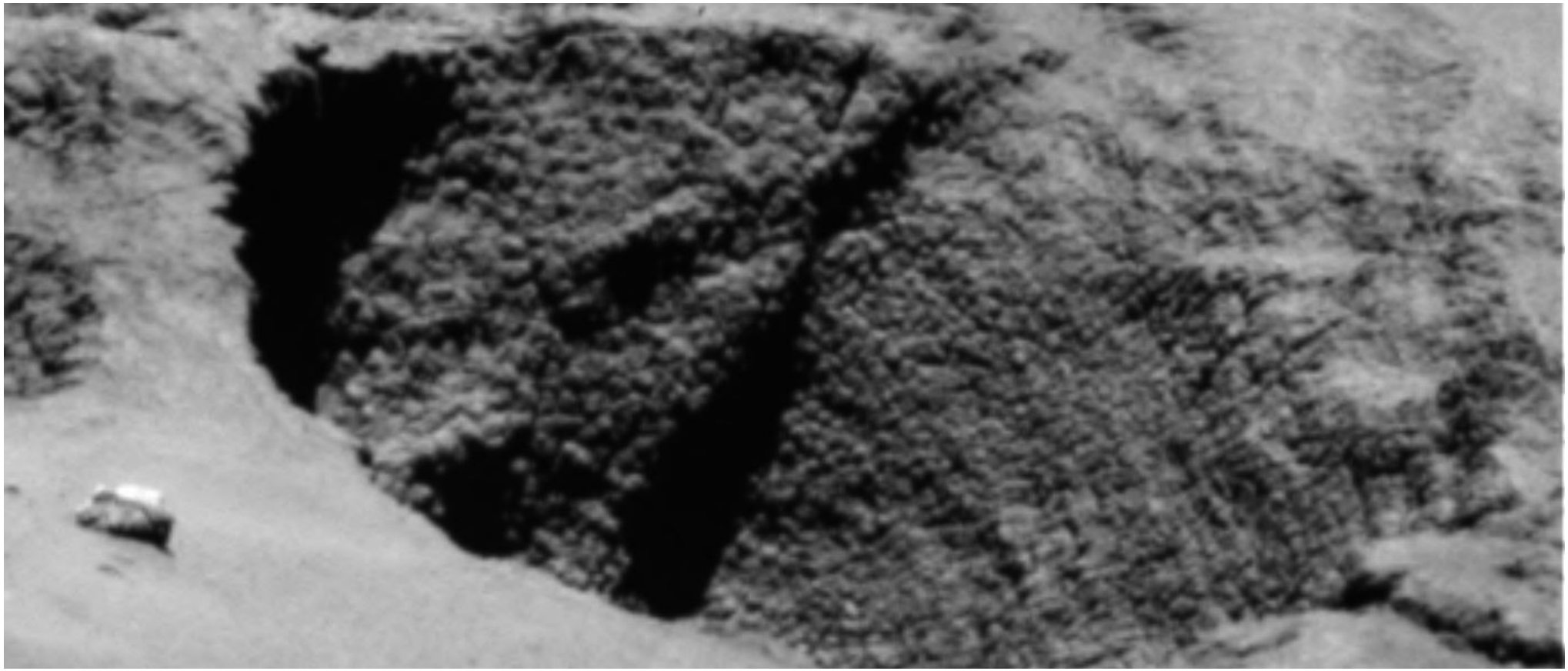
Γ=500 MKS: formation not earlier than t_0 +1.5 Myr
Prialnik *et al.* (1987, *Astrophys. J.* **319**, 993)

Γ=3 MKS: formation not earlier than t_0 +4.7 Myr
Haruyama *et al.* (1993, *Geophys. Res. Lett.* **98**, 15079)

Formation of ~1 km cometesimals must be delayed to end of Solar Nebula lifetime (circa t_0 +3 Myr).

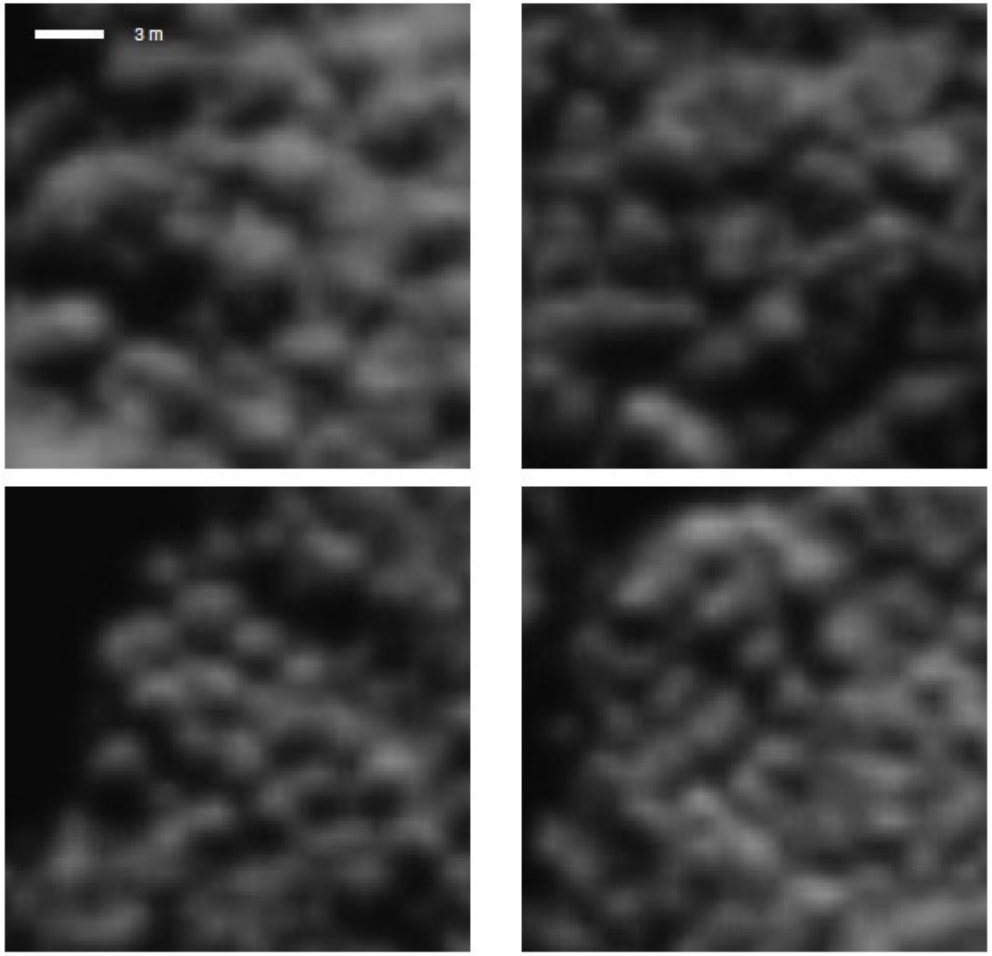
Our scenario has D=0.1-1 km objects formed by 3 Myr.

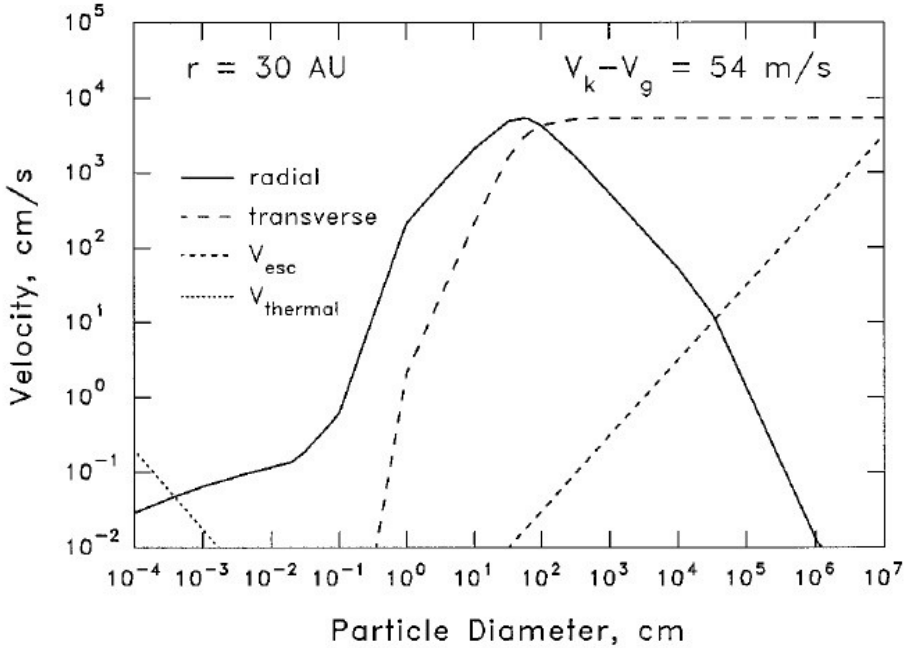
Goosebumps in the Seth pit



Credit: Sierks et al. 2015, Science 347, aaa1044

Goosebumps



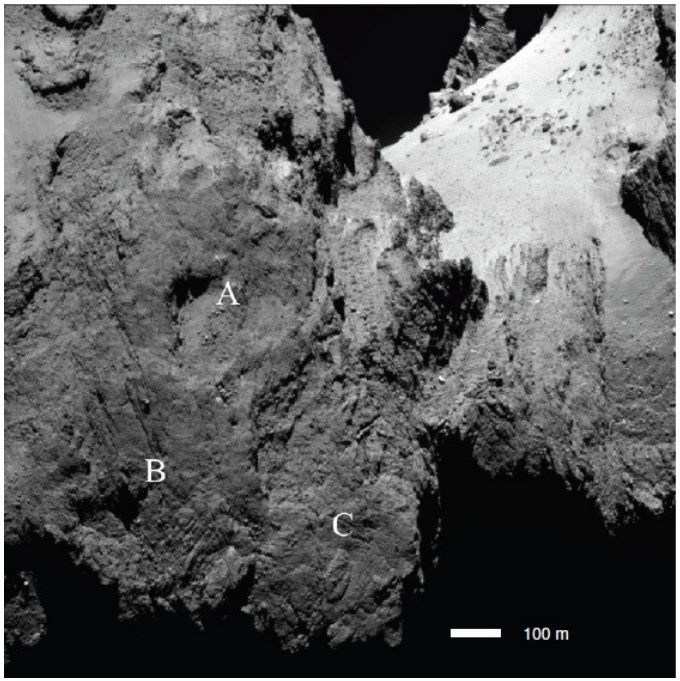


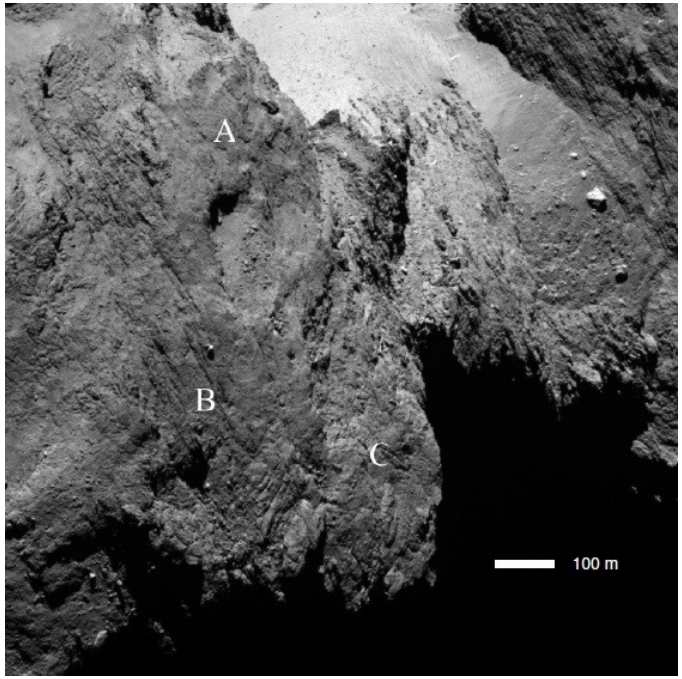
Credit: Weidenschilling 1997, Icarus, 127, 290

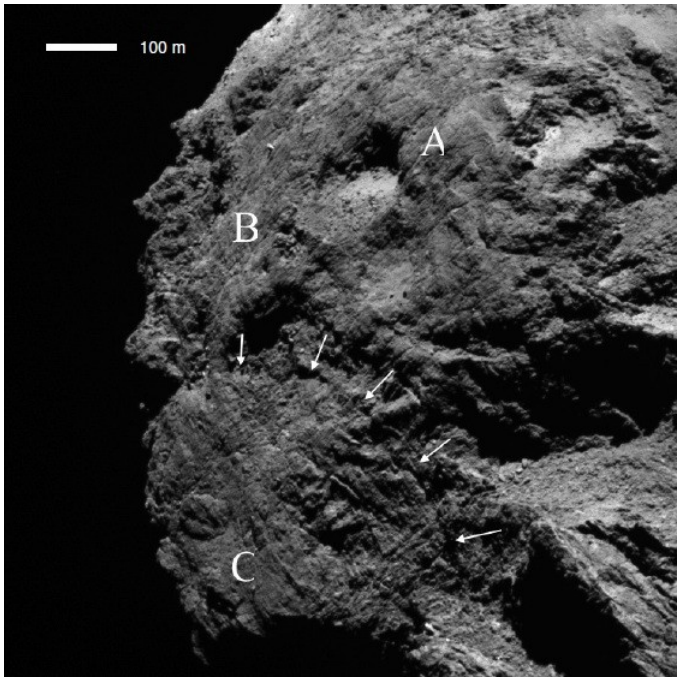
Hierarchical growth in Solar Nebula: relative velocity (thus compaction, strength, resilience) peaks during growth of m-sized objects (we estimate ρ=750 kgm^{-3})

Goosebumps (D=2.5m ±1m) are consistent with such growth.

Bastet: Positive Relief Features (PRFs)







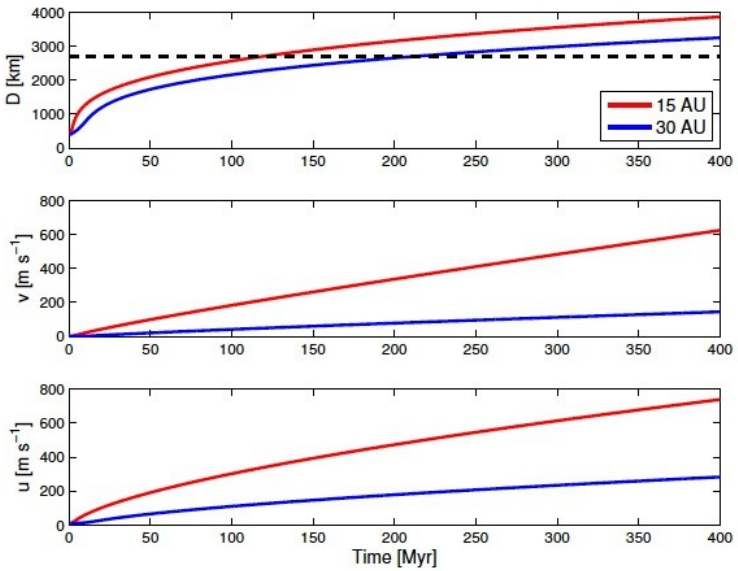
Goosebumps merge at < 1 m/s to highly porous cometesimals

Cometesimals may maintain shape if accretion velocities are low (a few m/s)

Weidenschilling (1997, Icarus, 127, 290):
D=2km bodies (67 head lobe?) primarily grow by accreting D=300-700m bodies

PRFs: spherical caps, each 320-450 m across. Intact cometesimals?

Primordial disk (first ~25 Myr)



TNOs will sit in the primordial disk for ~400 Myr. Growth unavoidable!

Morbidelli et al. 2012, Earth Planet. Sci.Lett., 355, 144
Marchi et al. 2013, Nature Geosci., 6, 303

They *started* small (50-400km) and reach Triton/Pluto size (2300-2700km) toward *end* of primordial disk lifetime.

This minimizes their viscous stirring of cometesimals

In the first ~25 Myr:

1) Relative velocities among cometesimals gradually increase to ~40 m/s

We predict cometesimals acquire outer compact layers

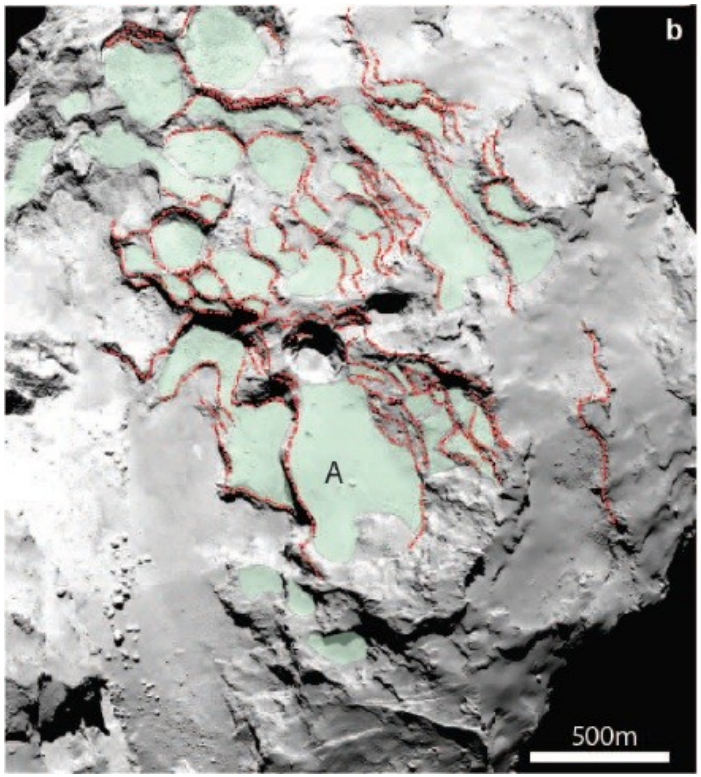
2) Gas drag effects gone; similarly-sized cometesimals collide

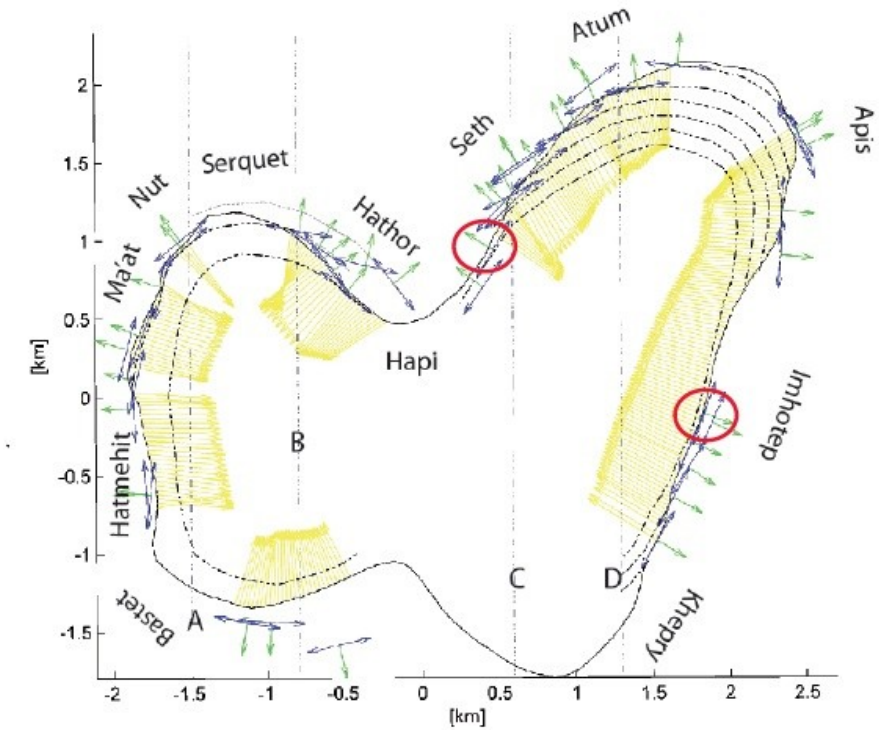
We predict formation of bi- and multi-lobed comet nuclei

3) Large comets like Hale-Bopp need late formation to avoid thermal processing

We predict formation of 50km+ size comets by ~25 Myr

Layering





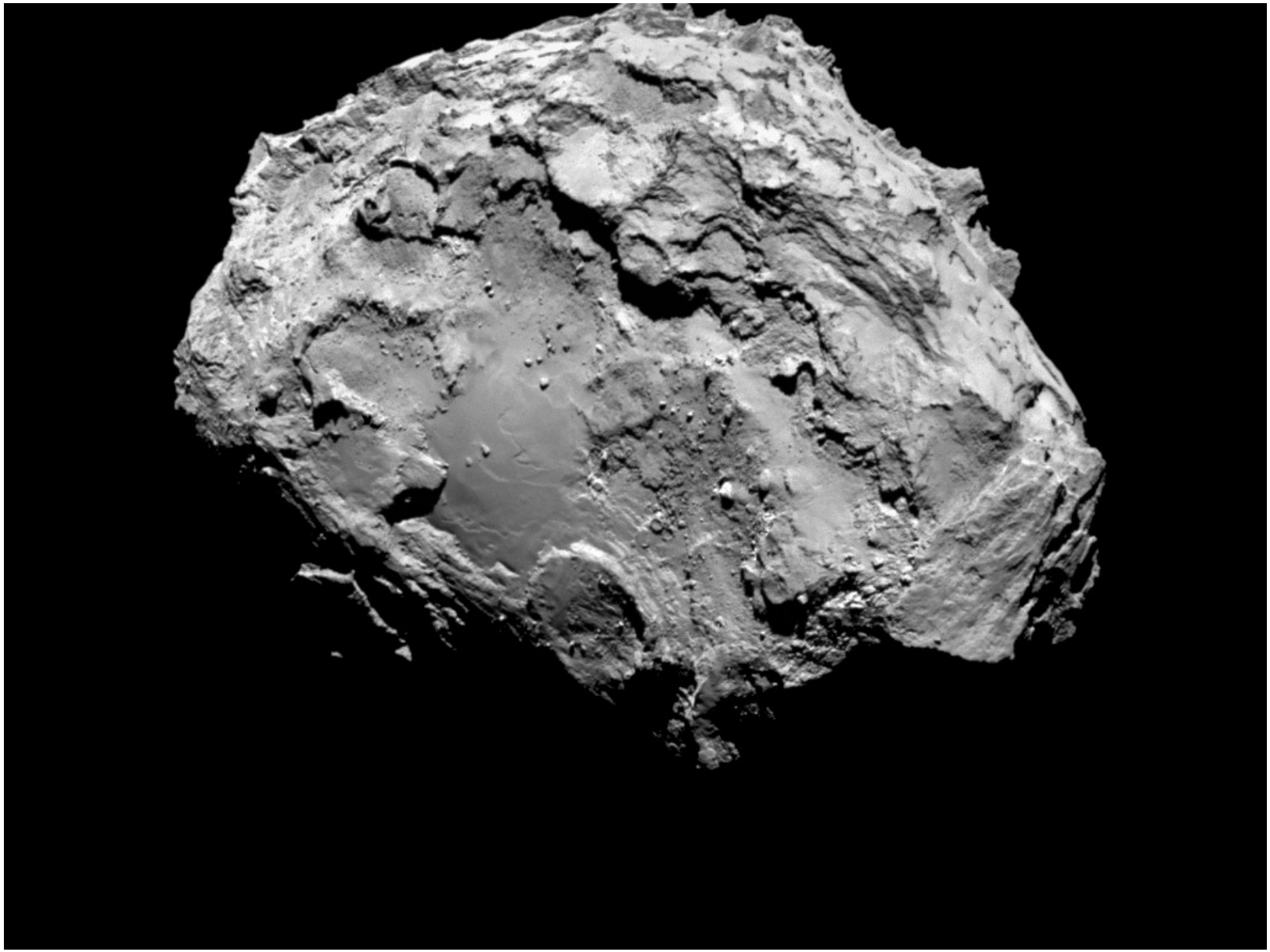
Credit: Massironi *et al.* (2015, *Nature* **526**, 402)

Numerous terraces: onion-shell stratification (650 m thick)

Lobes are *individually* layered: merger of two bodies

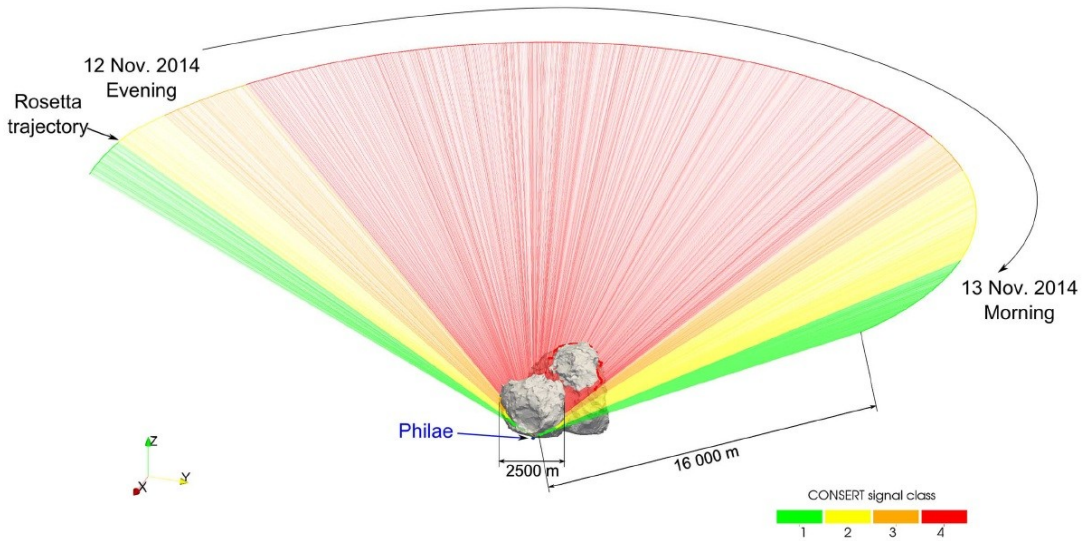
Accretion smear most cometesimals, goosebumps may remain intact.
Similar to “talps” (Belton *et al.* 2007 *Icarus* **187**, 332)

Accumulation basins: accretion scars?



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

Evidence of core/shell structure?



Credit: Kofman et al. 2015 Science 349, aab0639

CONSERT:
Kofman *et al.* (2015 *Science* **349**, aab0639)
Ciarletti *et al.* (2015 *Astron .Astrophys.* **583**, A40)

Homogeneous on ~10m size scales

But: “Two or three well-defined propagation paths could indeed be potentially due to the presence of a large structure inside the nucleus”

Consistent with dominance of goosebump-sized structures in strata + some intact PRFs and larger voids?

Dielectric constant drops ~24% over top 150m:

Porosity increases 15% with depth?
Dust/ice mass ratio from 4 to 0.1?

We predict a 9-11% porosity decrease in top 150m

The mass and bulk density of 67P

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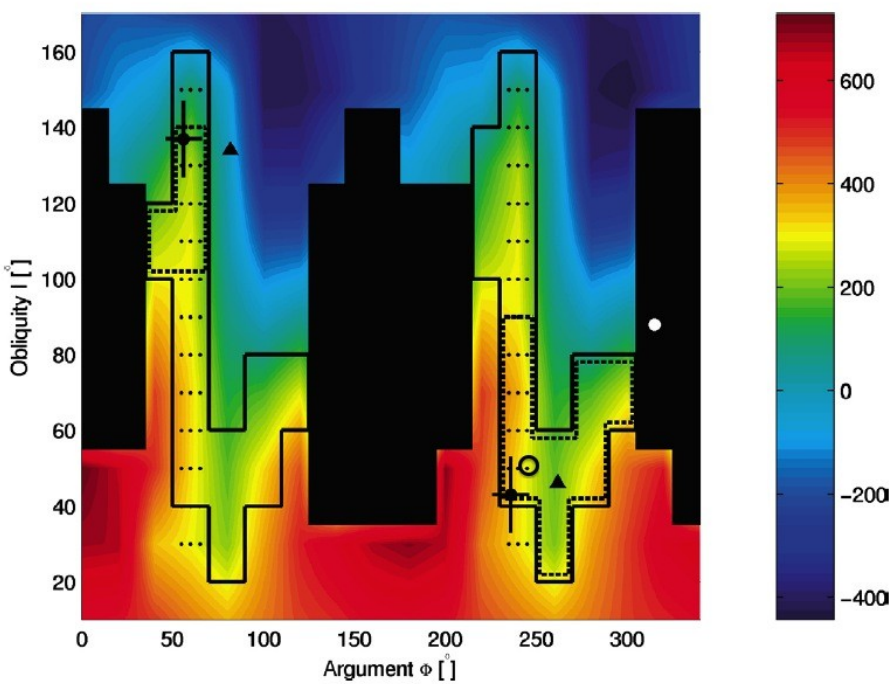
Nucleus properties of Comet 67P/Churyumov–Gerasimenko estimated from non-gravitational force modeling

Björn J.R. Davidsson [a,*], Pedro J. Gutiérrez [b]



For the spin axis orientation "CM" about 7° from correct one.

M=$1.1 \cdot 10^{13}$ kg
(range 0.9-$1.4 \cdot 10^{13}$ kg)

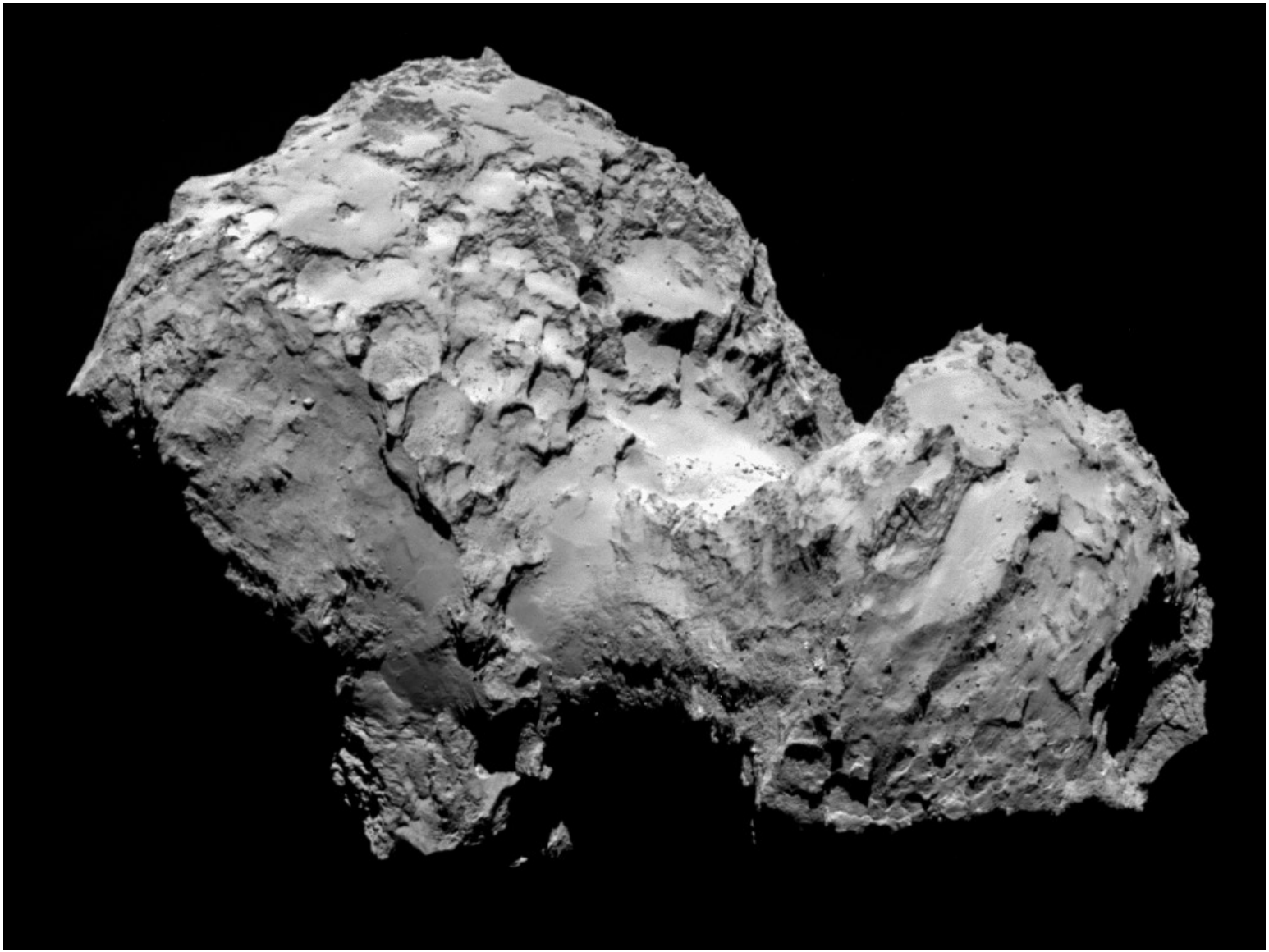
Corresponding density for *assumed* volume:
ρ=330 kg m^{-3}
(range 270-420 kg m^{-3})

In situ measurements by Rosetta/RSI (Pätzold *et al.* 2016, *Nature* **530**, 63)

M=$9.982 \cdot 10^{12}$ kg
ρ= 535 kg m^{-3} (correct volume)

We predict ~440 kg m^{-3} near core, up to ~1000 kg m^{-3} near surface.

Bi-lobed nucleus



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

Early primordial disk: it takes ~2.2 Myr for a “body” to sweep up a “head”

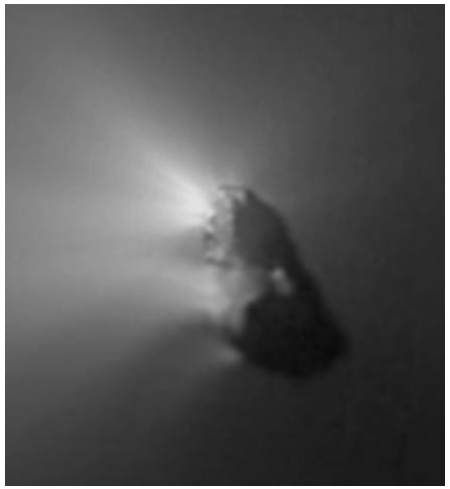
At t=25 Myr the same process takes ~110 Myr

Hard shell conserves lobe shape during merger?

Mixture of single- and bi-lobed 1-10km nuclei expected

Large comets may be multi-lobed

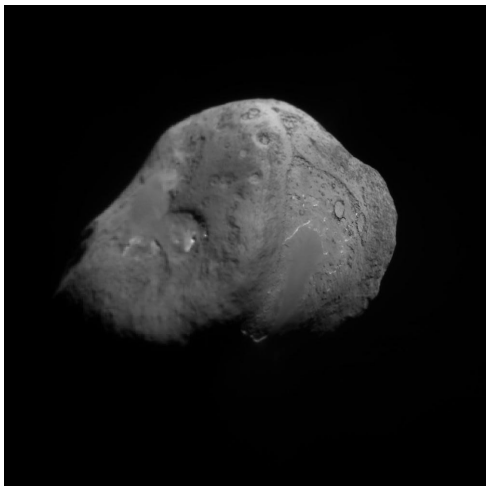
Comet nuclei imaged by spacecraft



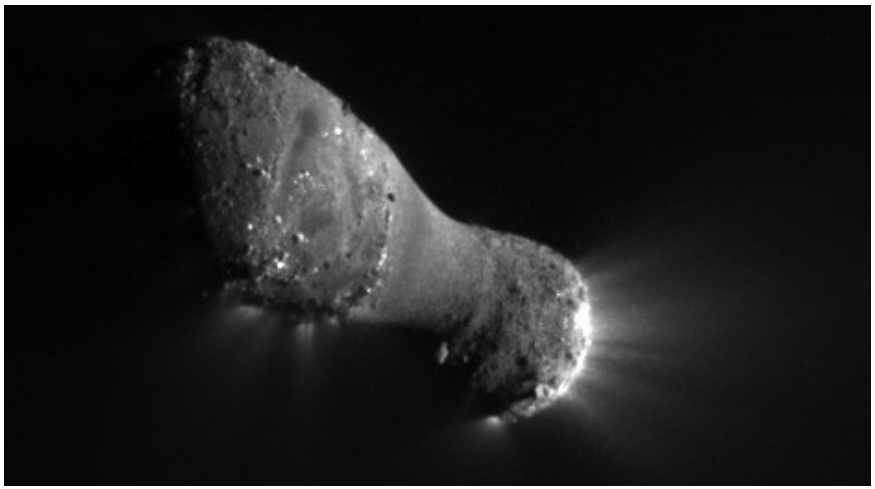
1P/Halley from 600km
Giotto, 1986

19P/Borrelly from 2200km
Deep Space 1, 2001

81P/Wild 2 from 240km
Stardust, 2004



9P/Tempel 1 from 500/180km
Deep Impact/Stardust-Next, 2005/2011



103P/Hartley 2 from 700km
EPOXI, 2010

Credit:
ESA
NASA
JPL/Caltech
UMD

Primordial disk (~ next 375 Myr)

The TNOs are too few and dynamically cold to initiate a collisional cascade. Their collisions are *constructive* and not destructive.

Some TNOs (we estimate ~350) experience runaway growth and reach the sizes of Triton (D=2600km), Pluto and Eris (D=2300km) by t=400 Myr.

A low-mass dynamically cold primordial disk is necessary to avoid a collisional cascade and to ensure survival of primordial comet nuclei.

At least 40-60% of the comet nuclei avoid a small compaction impact.

At least 60-80% of the comet nuclei avoid destructive impacts.

Uranus and Neptune enters the primordial disk and relocates comets to the Edgeworth-Kuiper Belt, the Scattered Disk, and the Oort cloud.

Rather few comets in the Scattered Disk?

We have a total of $2.7 \cdot 10^9$ nuclei with D=2-20km in the primordial disk.
That is 100 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....

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, i<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 fractional loss in 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 ($4.19\cdot10^7$)
we get 29-270 JFCs (marginally overlapping if R_{esc} high).

Solutions (?):

- Is R_{esc} higher than thought?
- Tidal splittings *(lobe separations)* during the time spent as Centaur?

Summary

- Rosetta has made a detailed characterization of comet 67P/Churyumov-Gerasimenko
- The comet has an unusual set of properties that require very special formation conditions
- The observed properties are consistent with a primordial rubble pile origin. The extremely high porosity and the lack of aqueous alteration is inconsistent with a collisional rubble pile origin since parent bodies appear being thermally processed
- We propose that most D>50km TNOs and comets originate from the same cm-sized pebble population but grew according to different mechanisms and on different time scales
- We propose that comet growth started in the Solar Nebula and finished in the primordial disk

Back-up slides

Are comets collisional rubble piles?

Oort cloud: Stern (1988, *Icarus* **73**, 499)
Edgeworth-Kuiper belt: Farinella & Davis (1996, *Science* **273**, 938)
Giant planet region: Stern & Weissman (2001, *Nature* **409**, 589)

Primodial disk:

Comets as collisional fragments of a primordial planetesimal disk

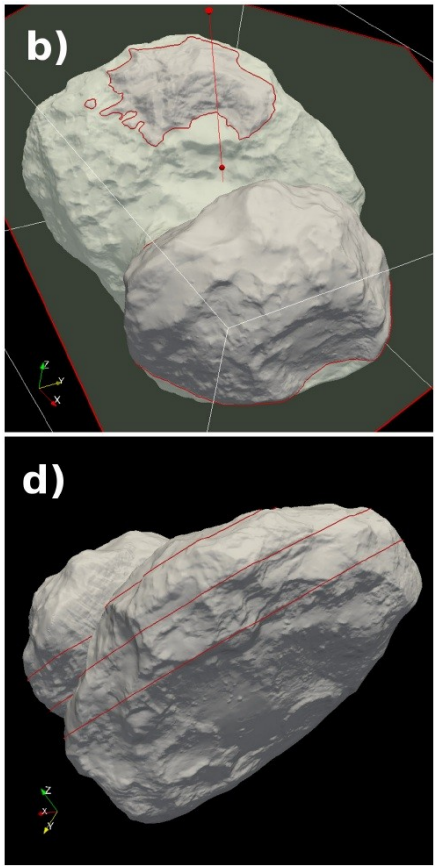
A. Morbidelli[1] and H. Rickman[2,3]

(2015) *A&A* **583**, A43

Comet 67P/Churyumov-Gerasimenko: Constraints on its origin from OSIRIS observations

H. Rickman[1,2], S. Marchi[3], M. F. A'Hearn[4] C. Barbieri[5], M. R. El-Maarry[6], C. Güttler[7], W.-H. Ip[8], H. U. Keller[9], P. Lamy[10], F. Marzari[5], M. Massironi[11,12], G. Naletto[12,13,14], M. Pajola[12], H. Sierks[7], D. Koschny[15], R. Rodrigo[16,17], M. A. Barucci[18], J.-L. Bertaux[19], I. Bertini[12], G. Cremonese[20], V. Da Deppo[14], S. Debei[21], M. De Cecco[22], S. Fornasier[18], M. Fulle[23], O. Groussin[10], P. J. Gutiérrez[24], S. F. Hviid[25], L. Jorda[10], J. Knollenberg[25], J.-R. Kramm[7], E. Kührt[25], M. Küppers[26], L. M. Lara[24], M. Lazzarin[5], J. J. Lopez Moreno[24], H. Michalik[27], L. Sabau[28], N. Thomas[6], J.-B. Vincent[7], and K.-P. Wenzel[15]

(2015) *A&A* **583**, A44



Massive (35 Earth masses) and dynamically warm (v_{rel}~600 ms^{-1}) primordial disk: 67P must be a collisional fragment of a larger body, or a bound bunch of such fragments

Credit: Rickman et al. 2015 A&A 583, A44

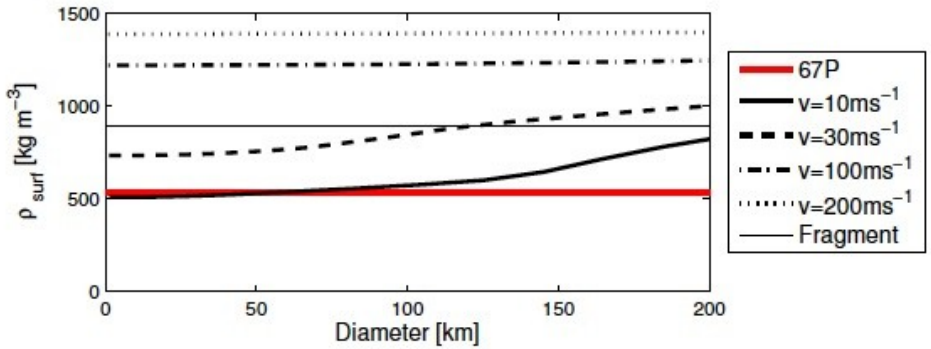
Problems

- Parent bodies are compacted by gravity (when heated by ^{26}Al) and by collisions. How come comets are so fluffy?
- Parent bodies are aqueously altered. How come comets lack phyllosilicates?
- *How to form comets out of something looking like Phoebe? A collisional origin of comets must be questioned.*

- A comet like Hale-Bopp (D=70km) cannot reach its final size until >5 Myr after CAI (immediate formation) or until >20 Myr after CAI (gradual growth) in order to keep supervolatiles. *Did comets form after Solar Nebula dispersal at ~ 3 Myr after CAI?*

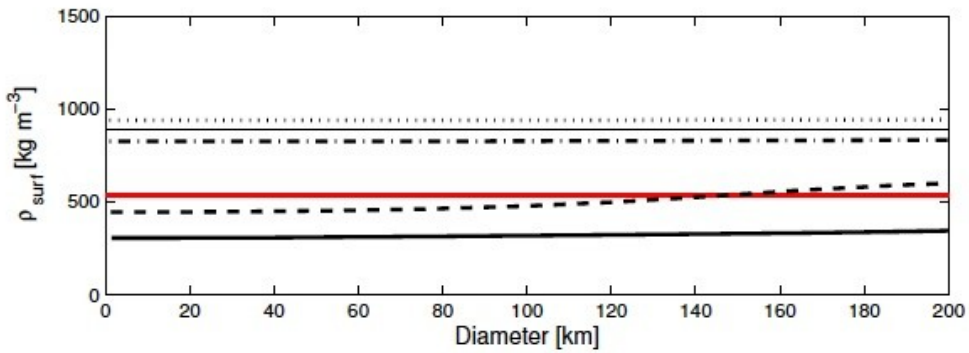
Collisional compaction

32wt% ice



Accretion velocity of 10-30 m/s optimal to form 67P (pebbles need >80% porosity)

65wt% ice



Collisional rubble pile Itokawa only has 40% macroporosity (Abe *et al.* 2006, *Science* **312**, 1344)

Laboratory pressure-porosity relation: silica + ice μm grain mixture, weighted by vol. fractions
Güttler *et al.* (2009, *Astron. J.* **701**, 130), Lorek *et al.* (2016 A&A *in press*).

Hydrostatic equilibrium under self-gravity and collisional impact pressure

Diagram shows density in outer 20% by radius (i.e., 50% by mass)

Surface region of large bodies easily compact to densities in excess of 1000 kg m^{-3}