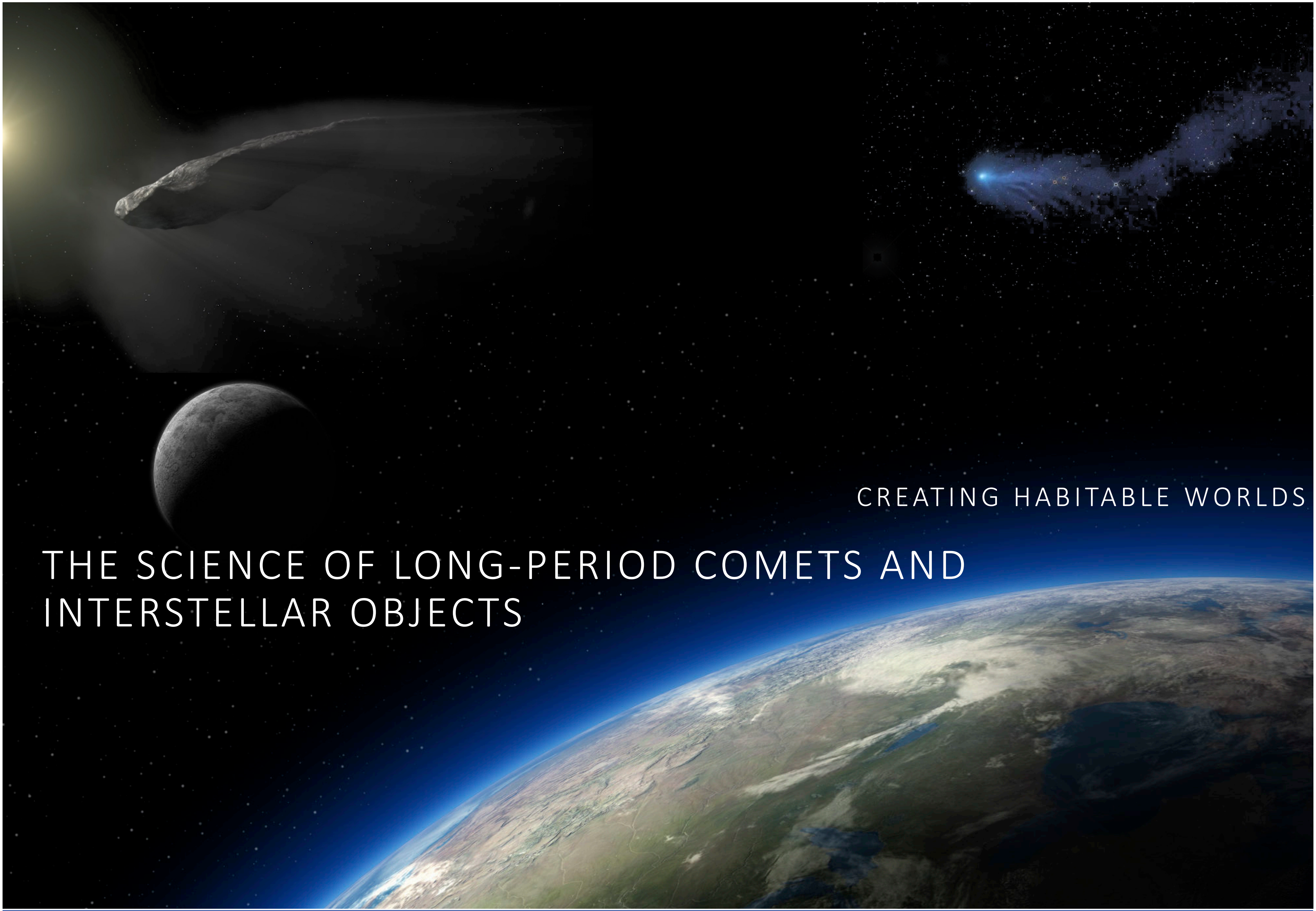
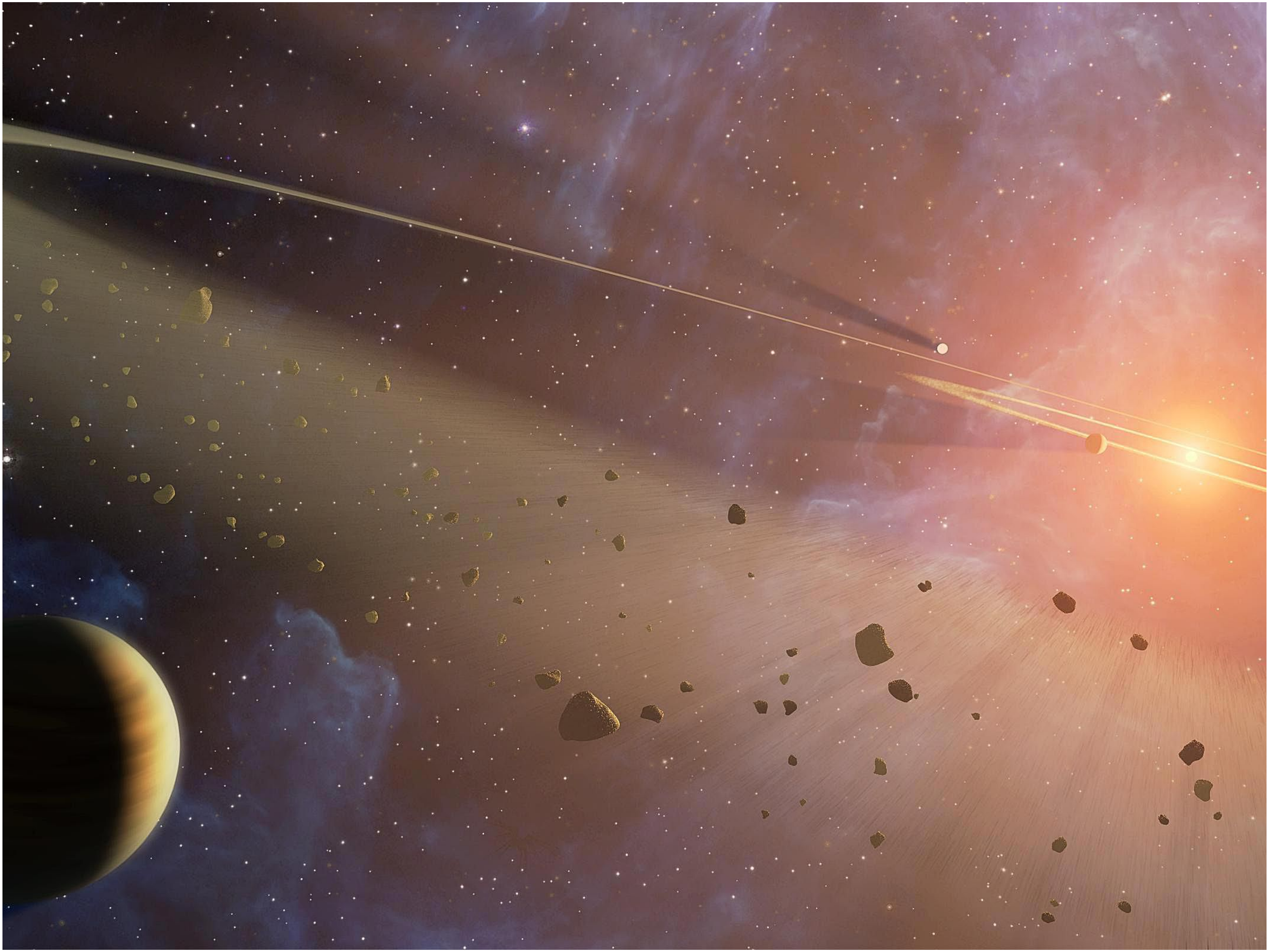
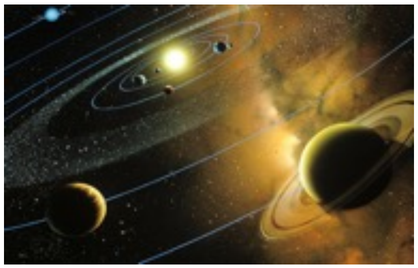


CREATING HABITABLE WORLDS

THE SCIENCE OF LONG-PERIOD COMETS AND INTERSTELLAR OBJECTS



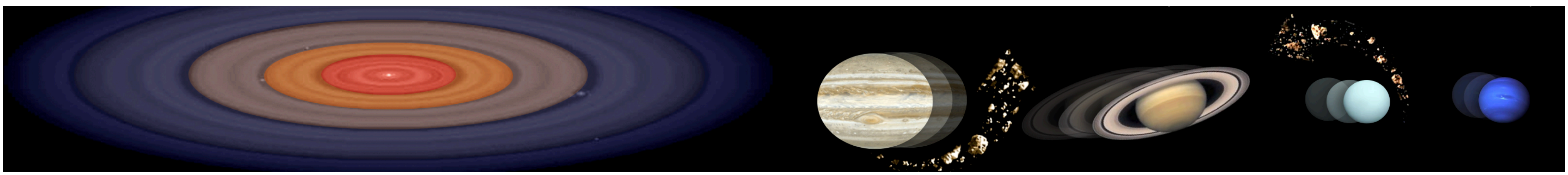
SMD Vision & Voyages (2013-2022) & the Astrobiology Roadmap



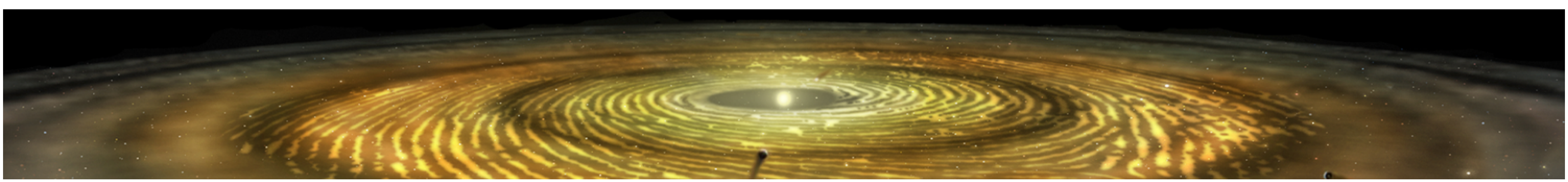
How do Habitable Worlds Form?

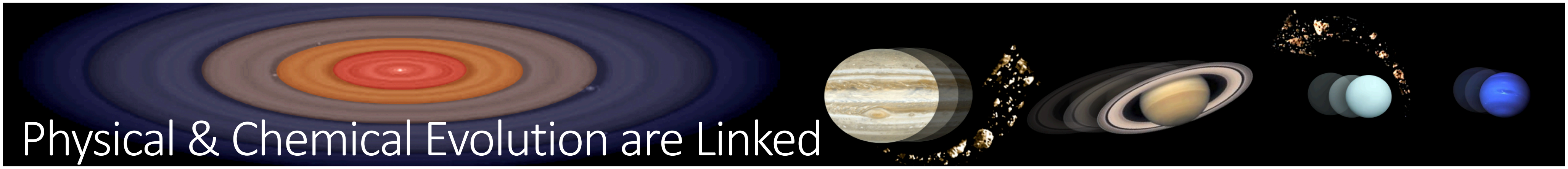
With thousands of exoplanetary systems known, ours, so far is unique in its architecture with a habitable planet in the habitable zone. Water is the most abundant condensable molecule so solar composition gas should condense water-rich planets, yet the inner solar system is dry.

- Planetesimals gain chemical fingerprints from the disk
- Planetesimals were then scattered by the giant planets

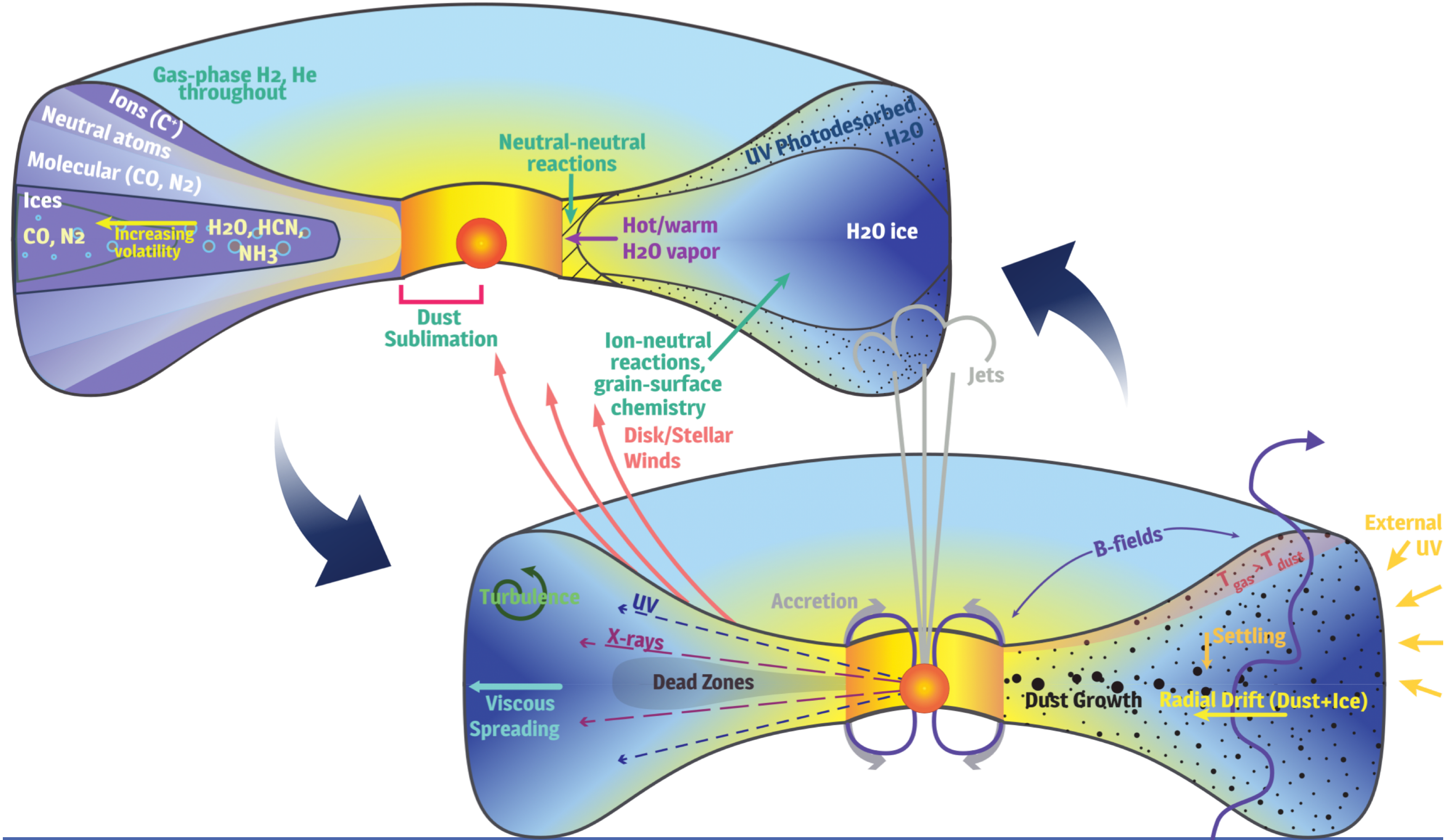


- Did planetesimals drive inward from beyond the snow line to form terrestrial planets?
- Meteorites (cosmochemistry) gives us clues to what happened
- Volatiles in small primitive bodies are the best connection to protoplanetary disks and how habitable worlds are built.

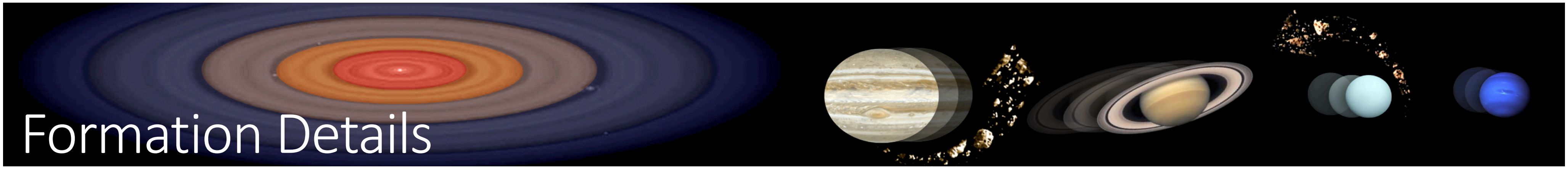




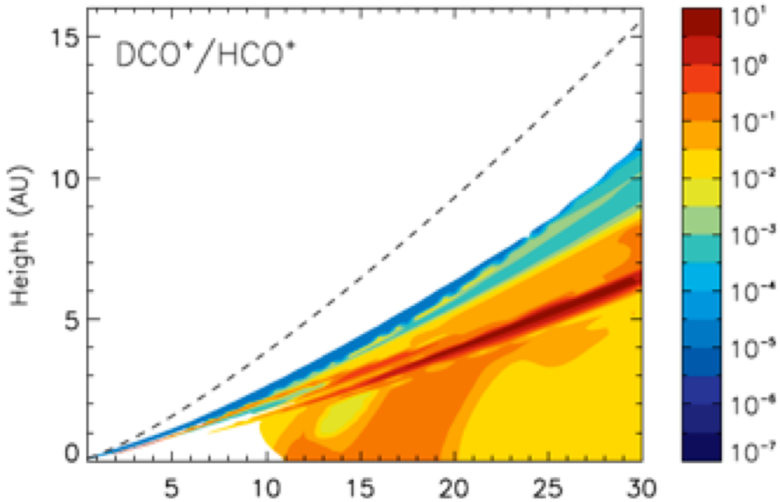
Physical & Chemical Evolution are Linked



Figures from I. Cleeves



Formation Details

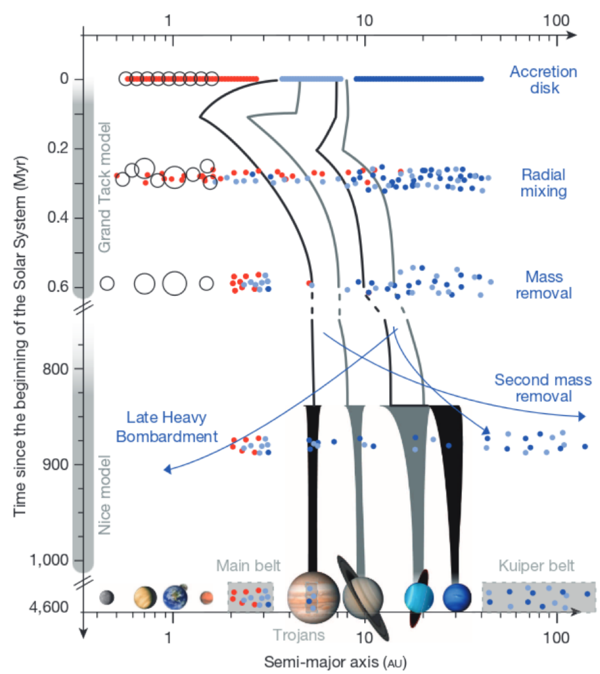


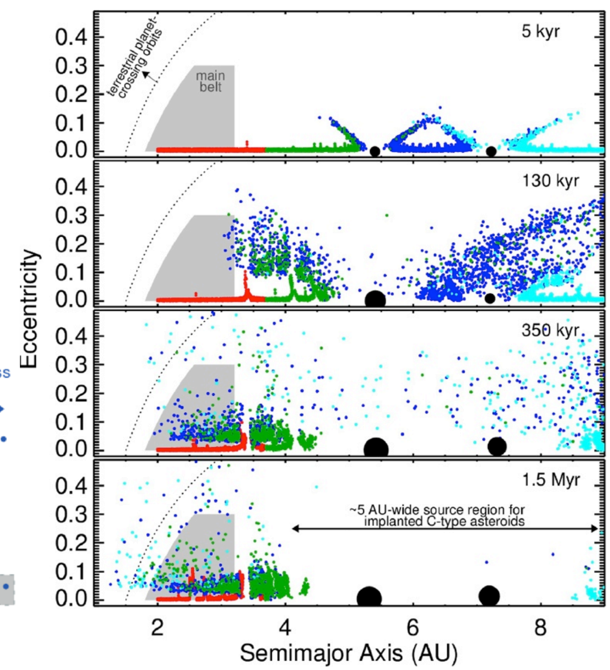
Solar System Dynamics

- Planetesimal growth over 20 orders of magnitude in size in a few Myr
- Streaming instabilities can concentrate pebbles
- In-situ formation vs giant planet migration
- Very different planetesimal scattering

Disk Chemistry Models

- Ionization at surface
- Thermal structure, snow lines
- Turbulence & accretion
- Chemical reactions
- Ion-molecule reactions / isotope effects
- Interaction with the dust





Willacy et al. (2009), ApJ 703, 479.

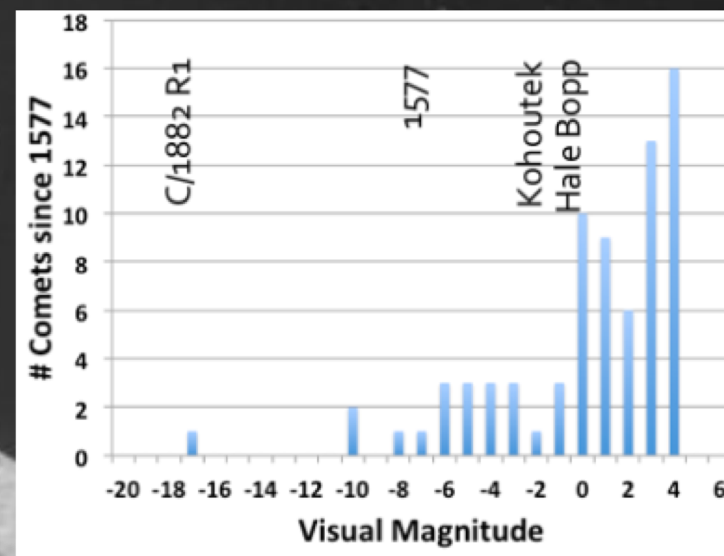
DeMeo & Carry (2014), Nature 505, 629.

Raymond & Izidoro (2017), Icarus 297, 134.

Comet science pre- & post-Rosetta

LPCs – A long historical interest

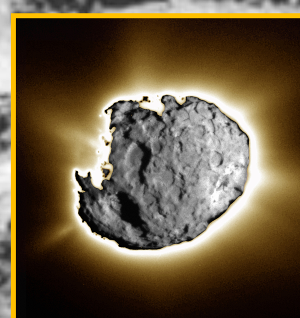
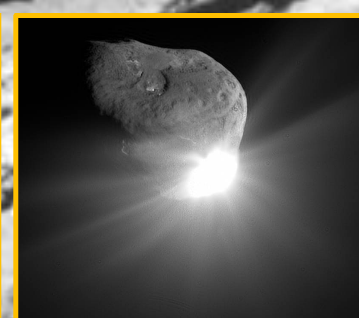
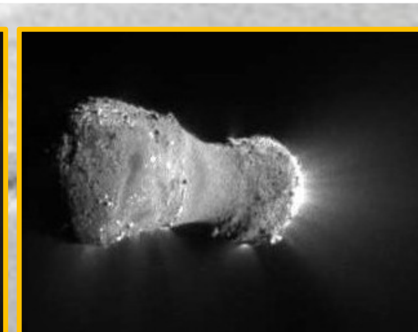
- Long period comets account for all of the "great comets" observed historically
  - LPCs are more active at larger distances
  - Evolution or formation difference?









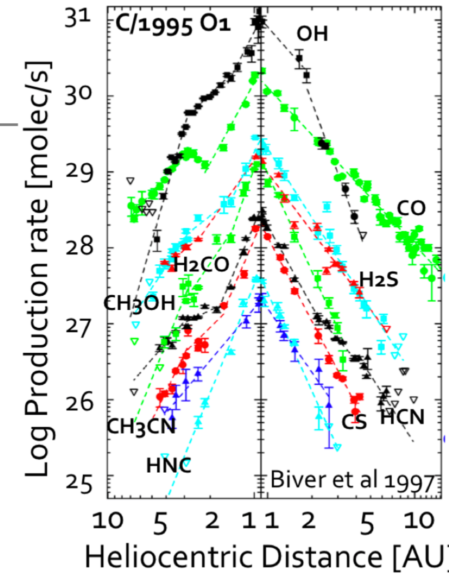




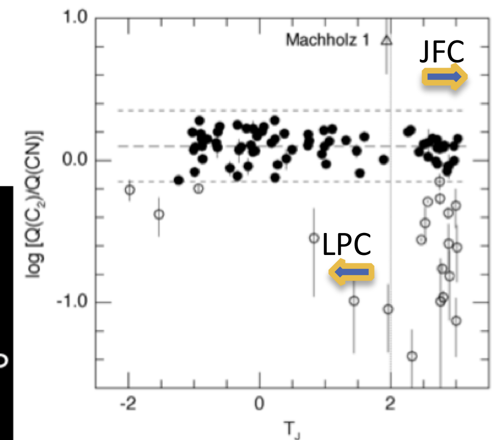
"Recent" Great Comets

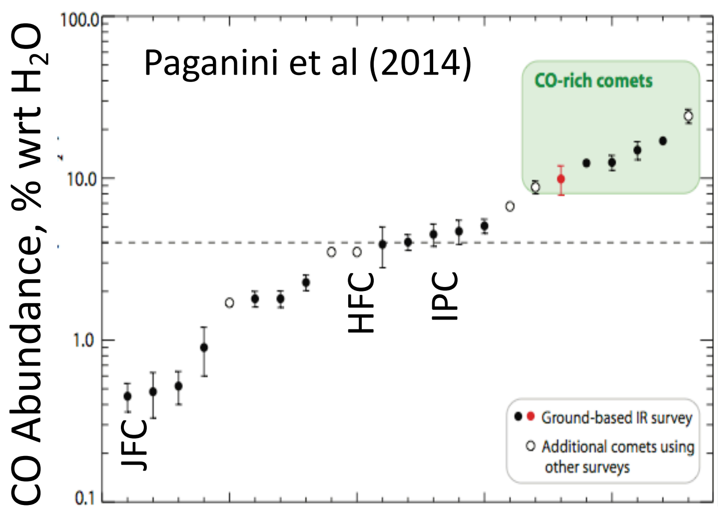
Pre-Mission Knowledge: Earth-based

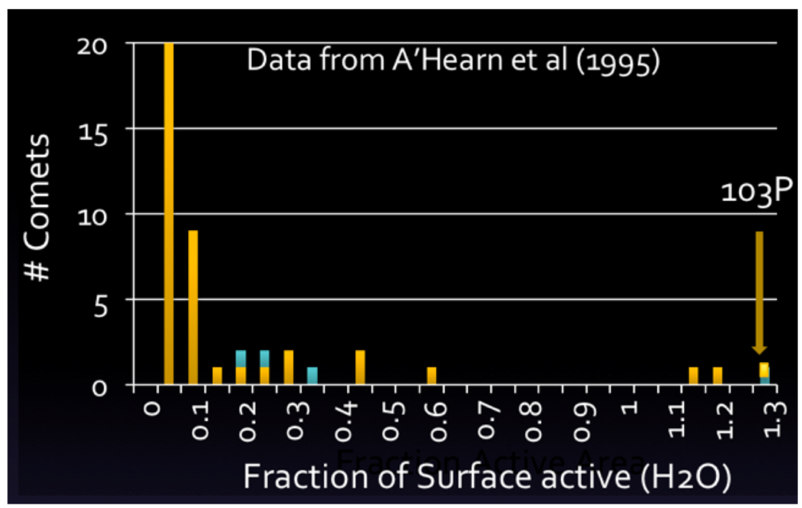
Volatiles and activity

- Activity controlled by H_2O & CO, other species trapped in amorphous ice
- Evidence of different chemical reservoirs → not correlated with dynamics (optical and IR data)
- Suggestion that some comets have more volatile ices: CO, CO_2
- Isotopes H, C, N, O for a few to a couple dozen comets only









Pre-Mission Knowledge: Earth-based

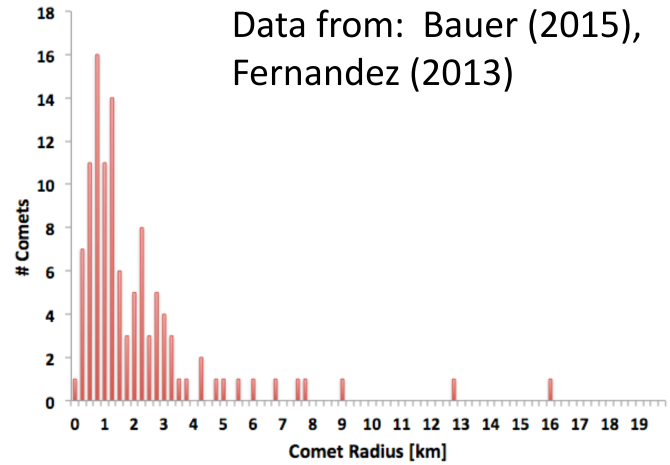
Isotopic ratio	Species	Value	Comet	Reference
D/H	H_2O	$(3.06 \pm 0.34)\ 10^{-4}$	1P/Halley	Eberhardt et al. (1995)
		$(3.08+0.38/-0.53)\ 10^{-4}$	1P/Halley	Balsiger, Altwegg & Geiss (1995)
		$(2.9 \pm 1.0)\ 10^{-4}$	C/1996 B2 (Hyakutake)	Bockelée-Morvan et al. (1998)
		$(3.3 \pm 0.8)\ 10^{-4}$	C/1995 O1(Hale-Bopp)	Meier et al. (1998b)
		$(2.5 \pm 0.7)\ 10^{-4}$	C/2002 T7 (LINEAR)	Hutsemékers et al. (2008)
		$(4.6 \pm 1.4)\ 10^{-4}$	C/2001 Q4 (NEAT)	Weaver et al. (2008)
		$(4.0 \pm 1.4)\ 10^{-4}$	8P/Tuttle	Villanueva et al. (2009)
	HCN	$(2.3 \pm 0.4)\ 10^{-3}$	C/1995 O1(Hale-Bopp)	Meier et al. (1998a)
$^{14}N/^{15}N$	CN	147.8 ± 5.7	18 comets	Manfroid et al. (2009)
	HCN	205 ± 70	C/1995 O1(Hale-Bopp)	Bockelée-Morvan et al. (2008)
	HCN	139 ± 26	17P/Holmes	Bockelée-Morvan et al. (2008)
$^{12}C/^{13}C$	C_2	93 ± 10	4 OC comets	Wyckoff et al. (2000)
	CN	91.0 ± 3.6	18 comets	Manfroid et al. 2009
	HCN	111 ± 12	C/1995 O1(Hale-Bopp)	Jewitt et al. (1997)
	HCN	114 ± 26	17P/Holmes	Bockelée-Morvan et al. (2008)
$^{16}O/^{18}O$	H_2O	518 ± 45	1P/Halley	Balsiger, Altwegg & Geiss (1995)
		470 ± 40	1P/Halley	Eberhardt et al. (1995)
		520 ± 25	4 OC comets	Biver et al. (2007)
	OH	425 ± 55	C/2002 T7 (LINEAR)	Hutsemékers et al. (2008)
$^{32}S/^{34}S$	S^+	23 ± 6	1P/Halley	Altwegg (1996)
	CS	27 ± 3	C/1995 O1(Hale-Bopp)	Jewitt et al. (1997)
	H_2S	17 ± 4	C/1995 O1(Hale-Bopp)	Crovisier et al. (2004a)

Mumma & Charnley (2011), ARAA 49, 471. C, O, S are terrestrial, N is depleted 2x, H enriched

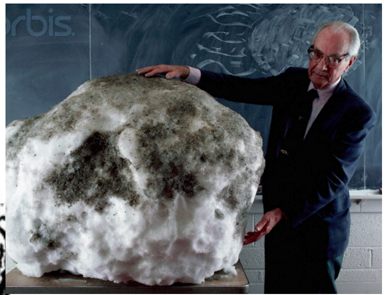
Pre-Mission Knowledge: Earth-based

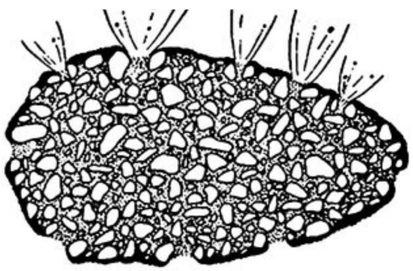
Nucleus and Dust

- Short period comet nucleus sizes consistent with collisional population; small ones (sub-km) missing
  - Upper limits for 5 dynamical new comets from HST
  - Measurements (WISE) for 8 LPCs
- Very low albedos 2-6%, little variation
- Dust: amorphous olivine, pyroxene, crystalline olivine
- Low density (< 1000 kg/m^3)
  - Non gravitational motion, Giotto, SL9, Rotation, Chiron exopause: 100-200 kg/m^3



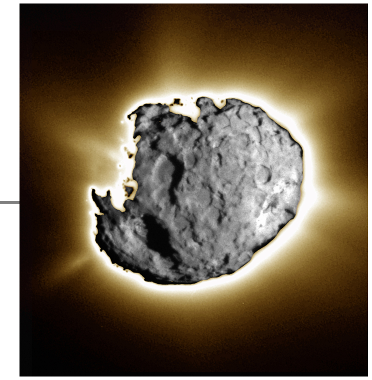
Data from: Bauer (2015), Fernandez (2013)





Biver et al, (1997); A'Hearn et al (1995); Mumma & Charnley (2011),

Missions Pre-Rosetta

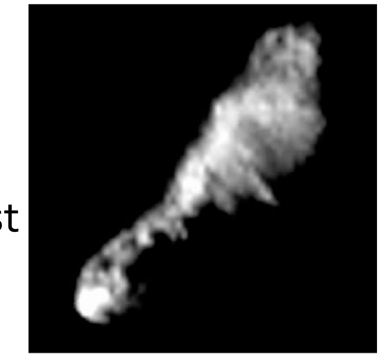


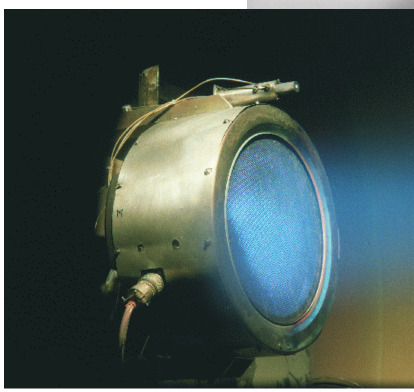
ICE: Giacobini Zinner

- L: Aug 12, 1978; E: Sep 11, 1985
- Fly through plasma tail

Giotto (+ Russia, Japan): Comet Halley

- L: July 2, 1985; E: Mar 14, 1986
- Science: Proved solid nucleus; organic dust (CHON); volatiles: 80% H_2O, 10% CO_2



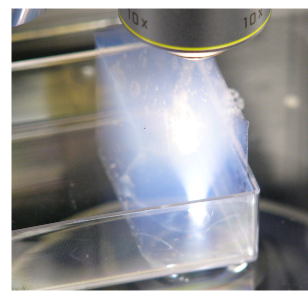


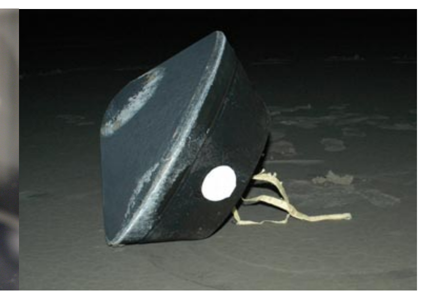
Deep Space 1: 19P/Borrelly

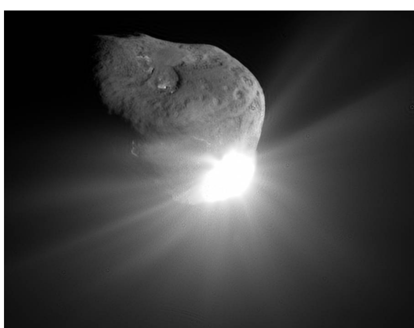
- L: Oct. 4, 1998; E: Sep. 22, 2001 (Test space technologies)
- Science: 1st hint of smooth plateaus; No direct evidence of H_2O ice

Stardust - 1st sample return

- L: Feb. 7, 1999, E: Jan. 2, 2004, R: Jan. 15, 2006
- Science: Comets dust → migration in early solar system







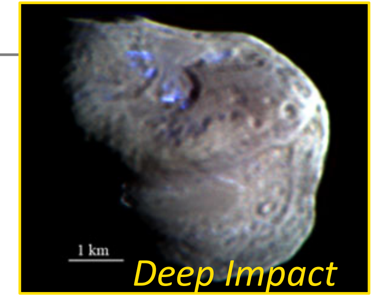
Deep Impact (EPOXI, NExT)

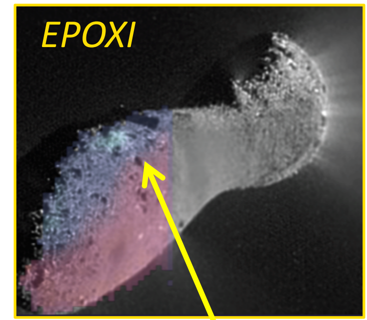
- L: Jan. 12, 2005, E: Jul. 4, 2005 (1st Active experiment)
- Science: Comets are good insulators; Little surface ice; New ideas about formation; cryovolcanos

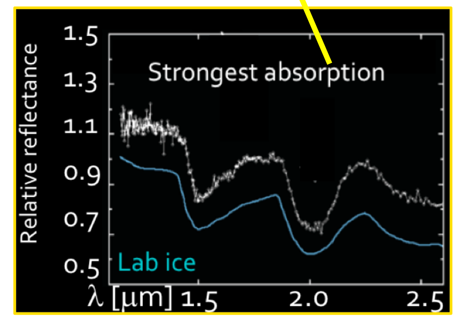
Rosetta Results - Volatiles

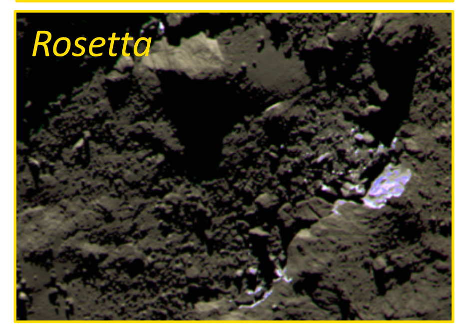
- Little surface ice exposure
- Prebiotic materials detected
- Noble gases –
  - Ar/Kr and Kr/Xe lower than solar (formed very cold)
  - Measurements not precise enough to distinguish between SS reservoirs
  - Xe required an exotic pre-solar component
- Nitrogen (N_2) / CO – 25±9 x depletion from protosolar
- D/H – enriched; *this comet* didn't deliver Earth's water
- Abundant super volatiles, don't see solar nebula chemistry – Comet has remained cold → interstellar signature?

Clear primordial signature preserved. High precision isotope measurements will be the key to understanding what this means with respect to formation



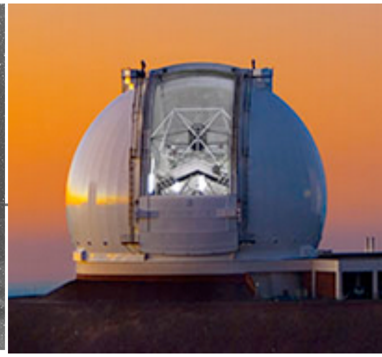




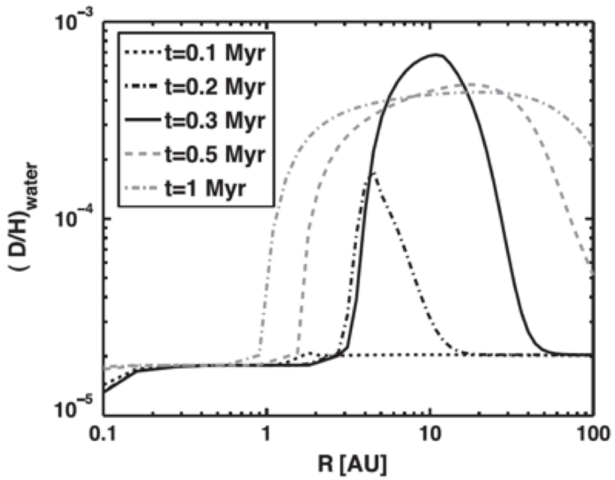


Sunshine et al 2006, 2012

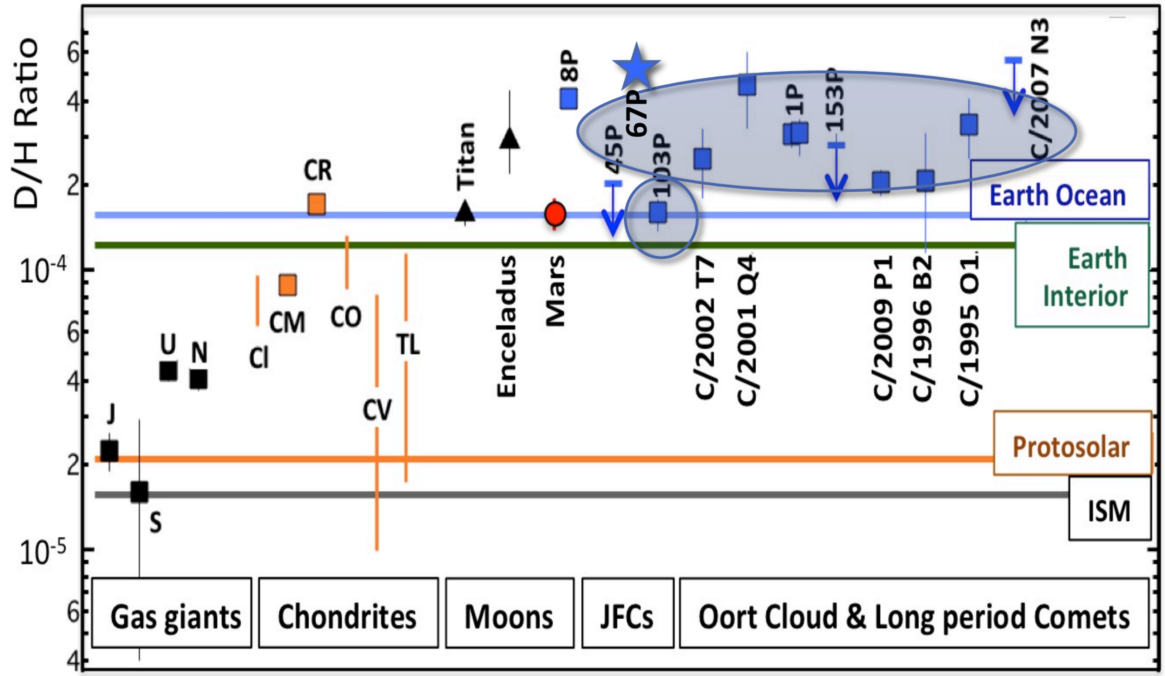
Auger et al 2015, 9/5/2014, 81 cm/pix – Altitude 43 km



The Disk connection: D/H

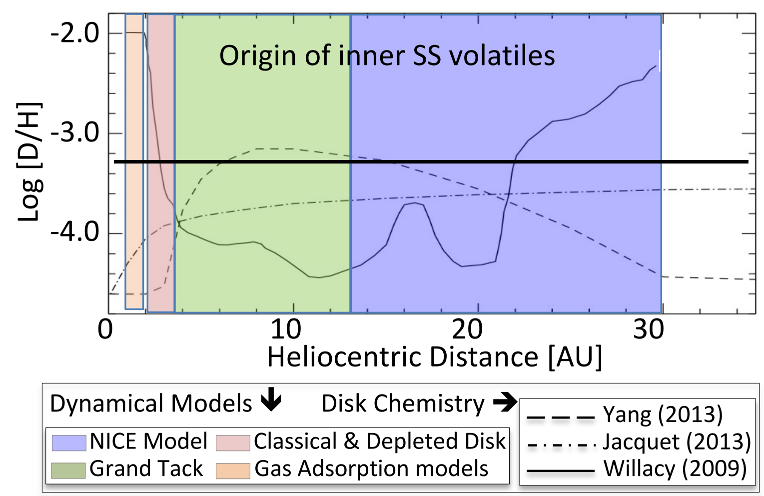


Yang et al. (2013)



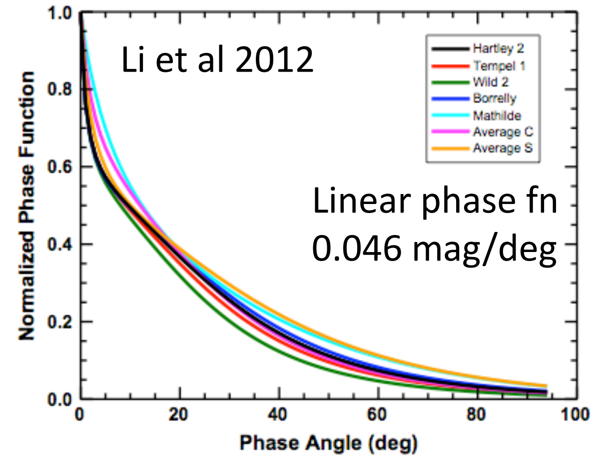
- Initial Observations – Matched disk chemistry models
- Herschel measurement of 103P – Revise disk chemistry models
- Rosetta – "we have to re-think where oceans came from"

Comets formed over a wide range of distances; disk dynamics has scrambled the signature – one isotope isn't enough to understand origins

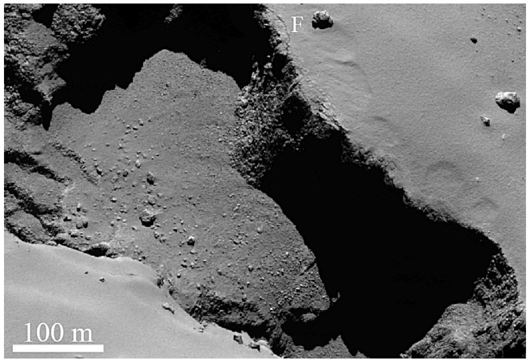


Rosetta (& other Mission) Results - Nucleus

- **Dust**
  - 1P – CHON, 81P – nebular mixing, 9P – nebular processing, hydration
  - 67P – organics, compounds needed to make sugars
- **Albedo**
  - Very low (0.02-0.06) – organic rich
  - Small variations (icy regions brighter, bluer)
- **Nucleus Density (kg/m^3) – Low**
  - 67P: 532±7, 9P: 450; 19P: 180-300; 81P: 600-800
- **Porosity & Strength**
  - Strength SL9: 3-270 Pa Rosetta: Overhangs: 3-30 Pa; Hard substrate: kPa-MPa
  - Porosity 9P: 88% 67P: 75-85%;



Dark, organic rich surfaces
Low densities suggest highly porous → primitive
Sizes consistent with collisional fragments



Where Do We Stand after Rosetta?

Rosetta is the most ambitious and productive comet mission to date

- "The findings at 67P are similar to what we see on 81P and 9P, but at higher resolution"
- "Comets have heritage from their formation, but it is a really mixed reservoir"

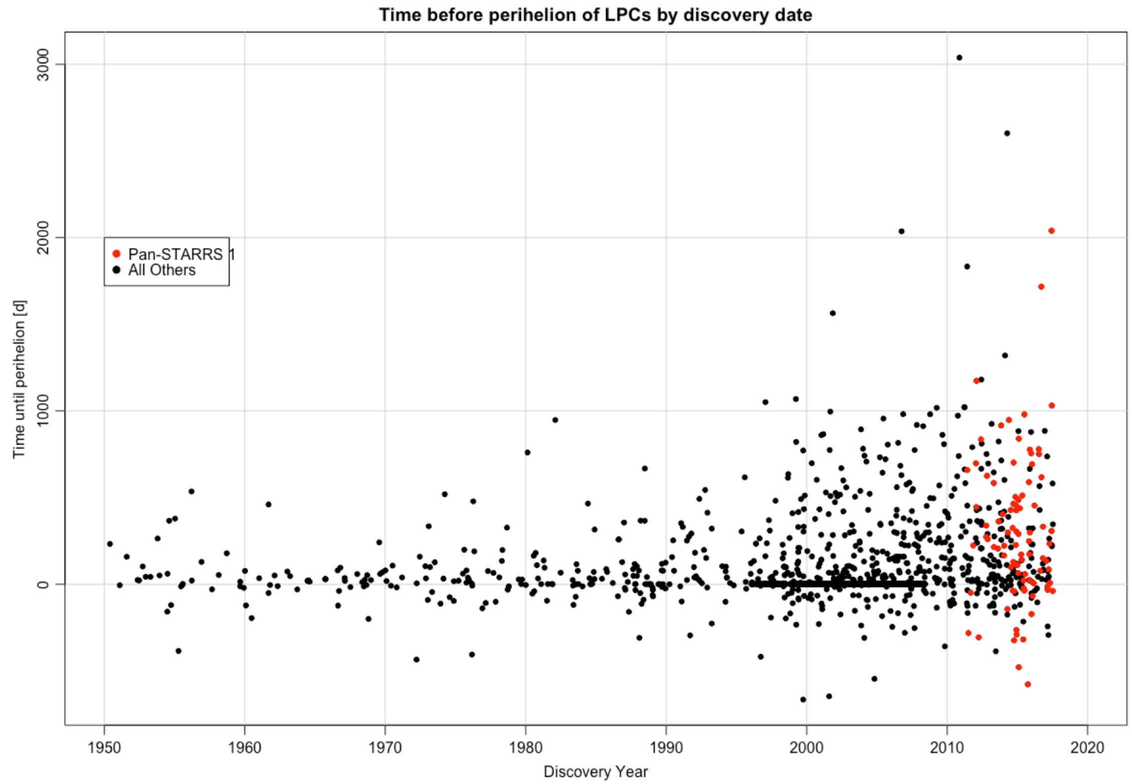
Findings

- Interior structure relatively uniform
- Rich array of pre-biotic chemical species
- Comets may represent primordial planetesimals (density, porosity, low T ices)
- Comets form from a wide range of distances
- New insight into how comets work

Questions

- What is primordial and what is the effect of insolation? (How do comets work?)
- How and where do comets form?
- What role do comets play in bringing volatiles to the inner solar system – i.e. Earth?

LPC vs SPC

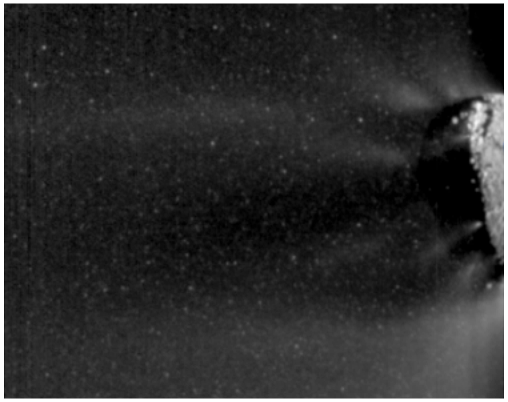


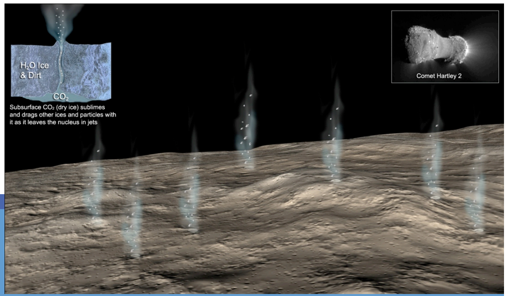
Discovery stats on LPCs

- Big surveys – routinely 3 yrs pre-perihelion, sometimes >6 yrs
- LSST brings this ~ 10 yrs

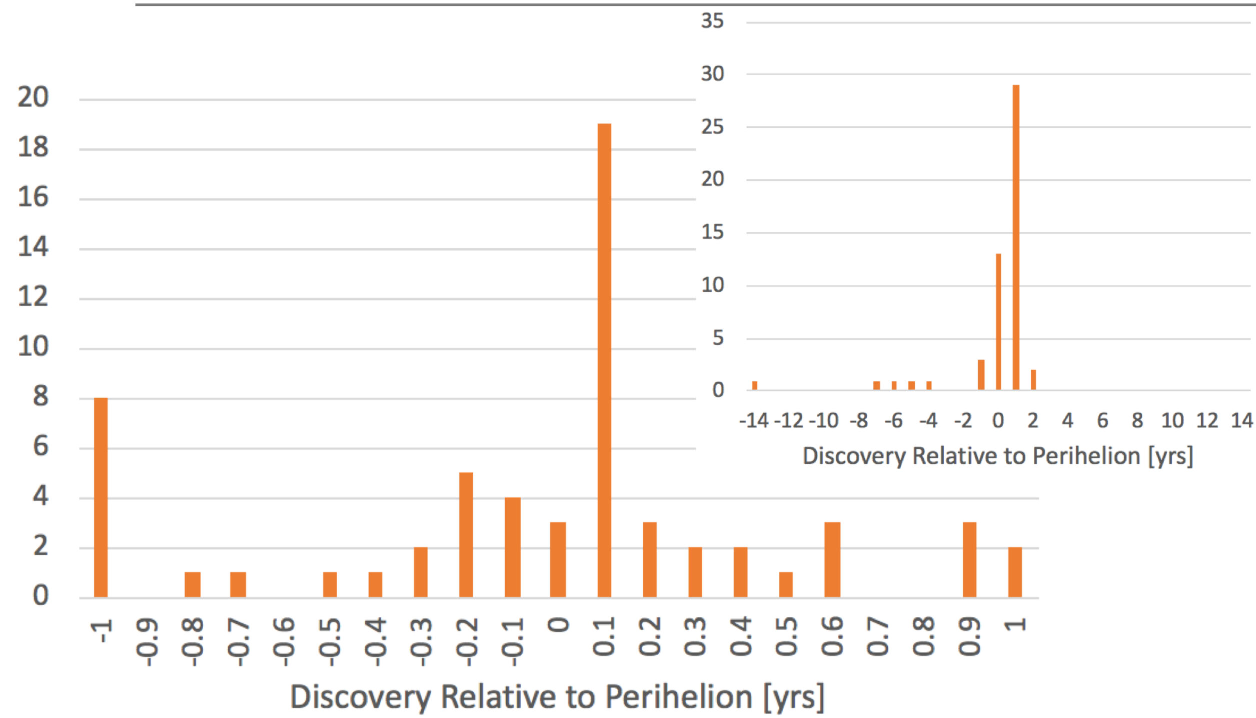
Differences between LPC and SPCs

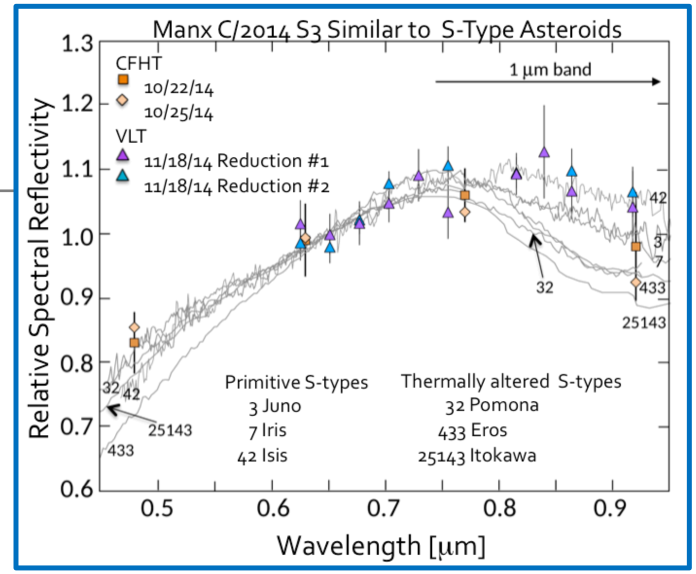
- Only the LPCs are CO rich, both classes have CO_2
- Sublimation from CO or CO_2 from sub surface → large debris
- We are likely sampling a different part our Solar System's primordial disk

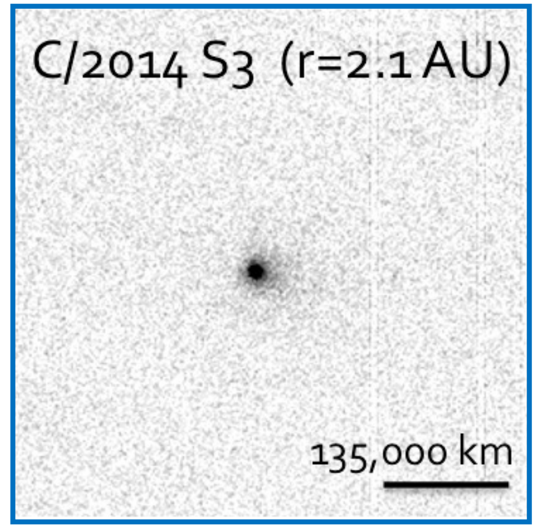




New Types of LPOs – The Manxes





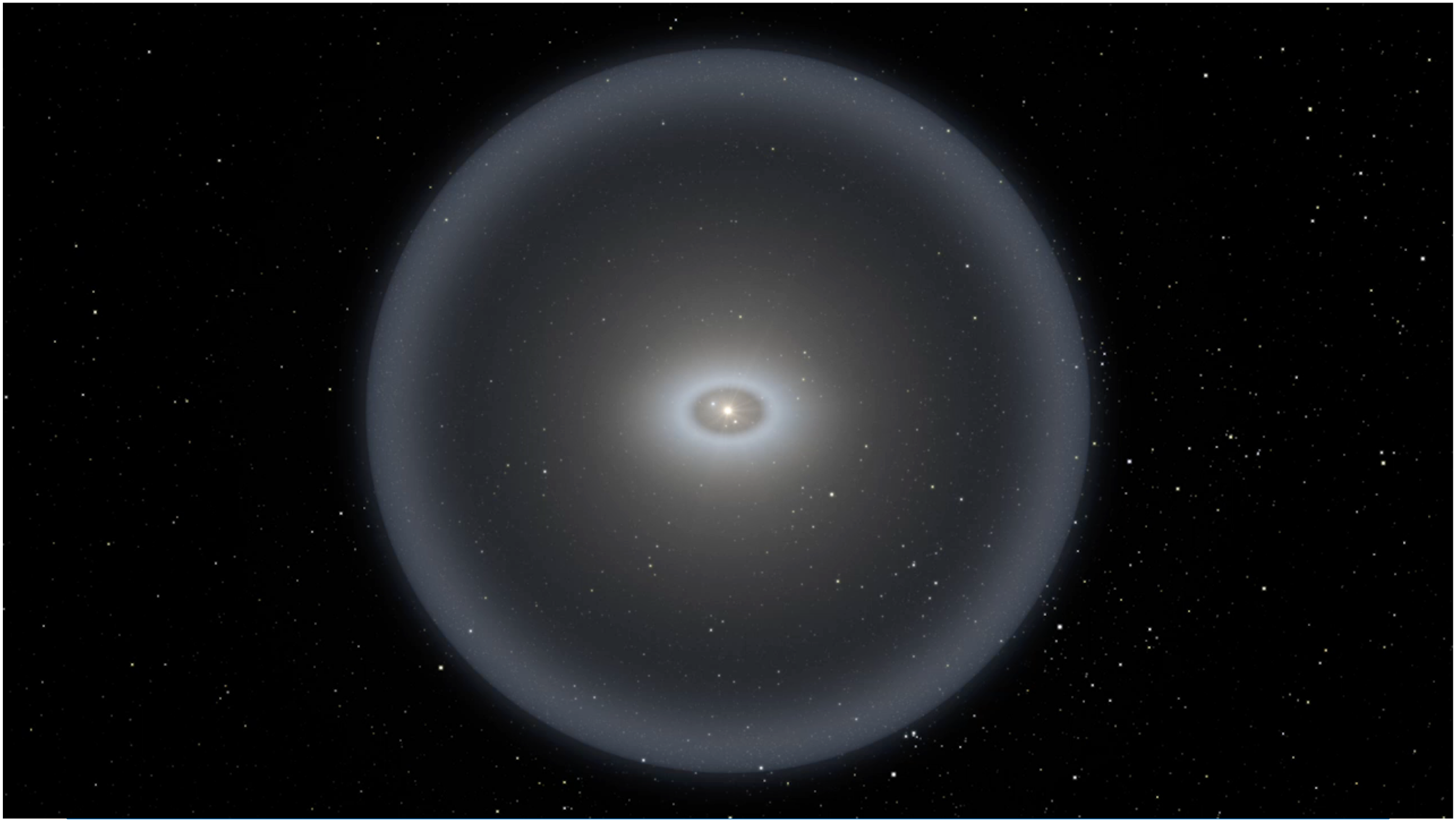


PANSTARRS1 Survey discovers ~inactive LPC

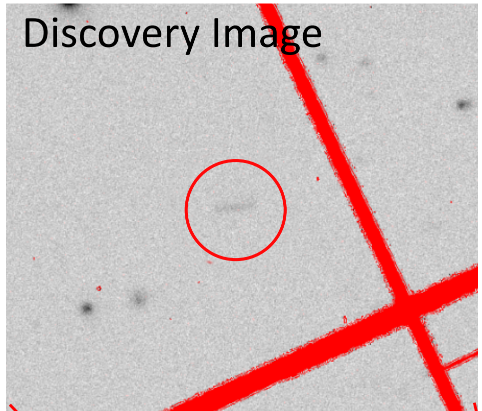
- Faint tail, consistent with H_2O sublimation
- Spectrum consistent with S-type asteroids
- May have formed near snowline, ejected to Oort cloud early in SS history

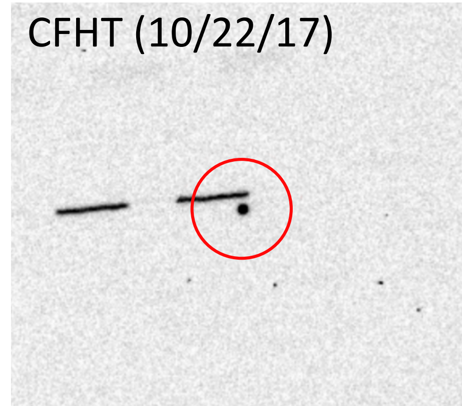
We may be seeing fresh “preserved” Earth building material

New Types of LPOs – The Manxes



The First ISO: The Discovery Timeline 2017





10/19 – Discovered by PS1 → P10Ee5V

10/18 – Pre-discovery images found in PS1 data

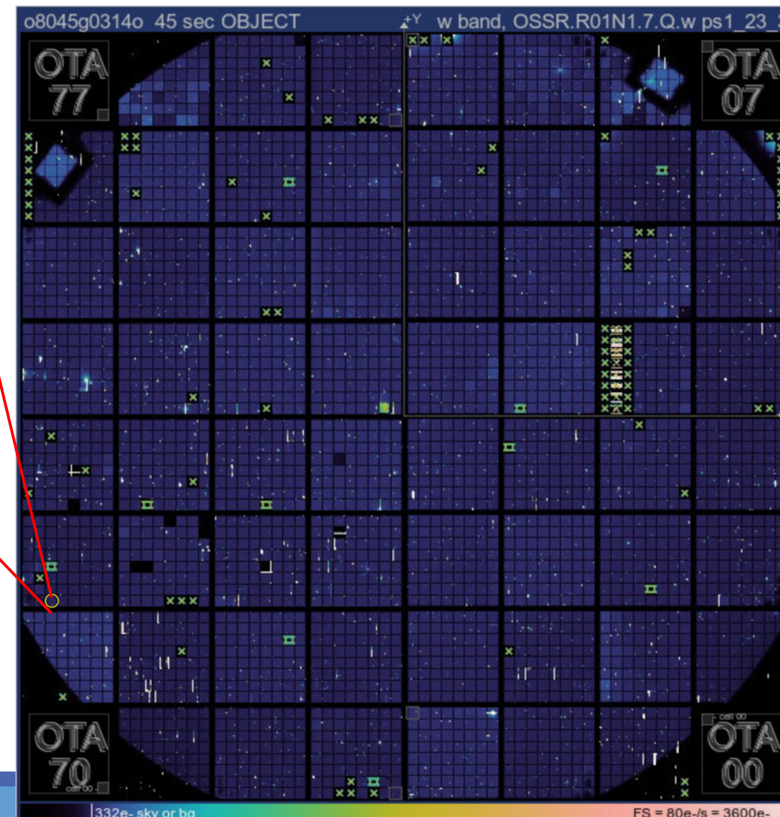
- Follow up ESA ground station – data rejected, large e
- Classified as an Earth-orbit crossing asteroid

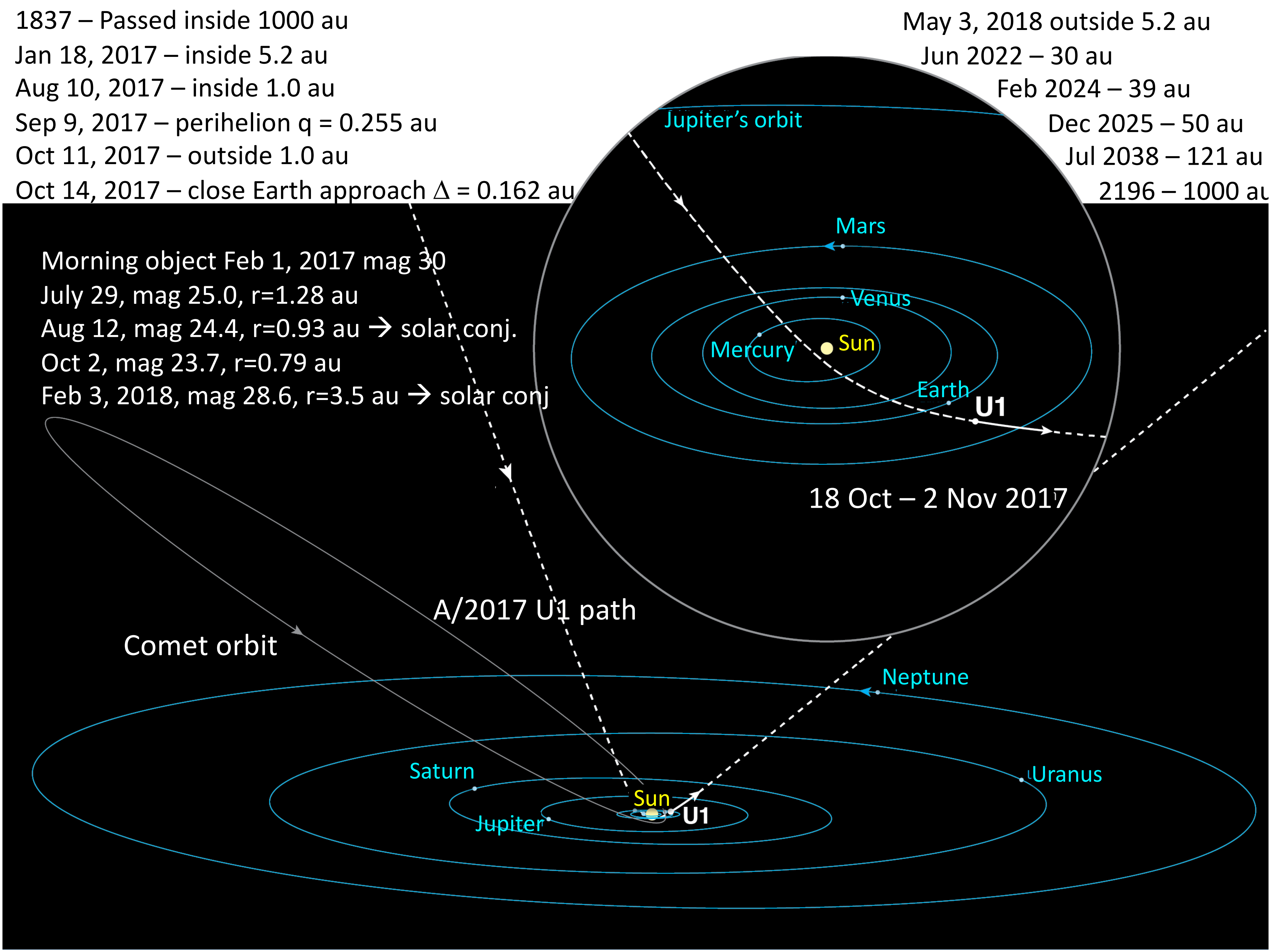
10/20 – Catalina Sky Survey data → short-period comet

10/22 – CFHT observations: orbit is hyperbolic: e = 1.188

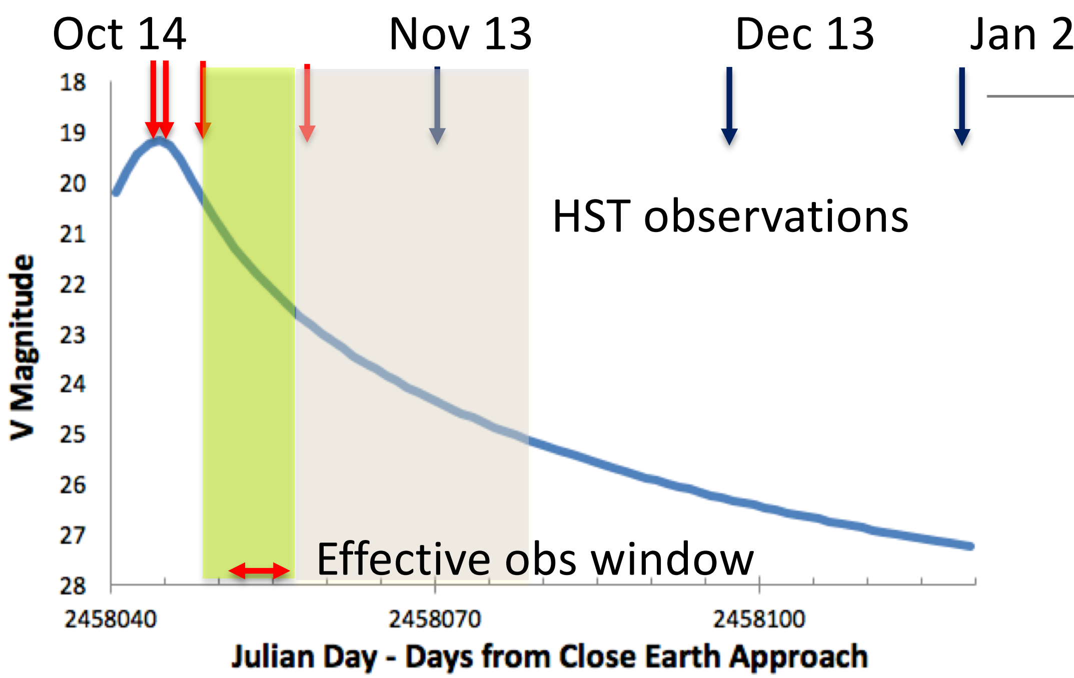
10/24 – MPEC 2017-U181 posted a name: C/2017 U1

10/26 – MPEC 2017-U183 – named A/2017 U1




1837 – Passed inside 1000 au
Jan 18, 2017 – inside 5.2 au
Aug 10, 2017 – inside 1.0 au
Sep 9, 2017 – perihelion q = 0.255 au
Oct 11, 2017 – outside 1.0 au
Oct 14, 2017 – close Earth approach Δ = 0.162 au
May 3, 2018 outside 5.2 au
Jun 2022 – 30 au
Feb 2024 – 39 au
Dec 2025 – 50 au
Jul 2038 – 121 au
2196 – 1000 au
Morning object Feb 1, 2017 mag 30
July 29, mag 25.0, r=1.28 au
Aug 12, mag 24.4, r=0.93 au → solar conj.
Oct 2, mag 23.7, r=0.79 au
Feb 3, 2018, mag 28.6, r=3.5 au → solar conj
Jupiter's orbit
Mars
Venus
Mercury
Sun
Earth
U1
18 Oct – 2 Nov 2017
A/2017 U1 path
Comet orbit
Neptune
Saturn
Uranus
Sun
Jupiter
U1

The Timeline



Observations

- ~65 hrs on 4-10 m telescopes (1 wk)
- ~30 hrs on Spitzer, 9 HST orbits

Results

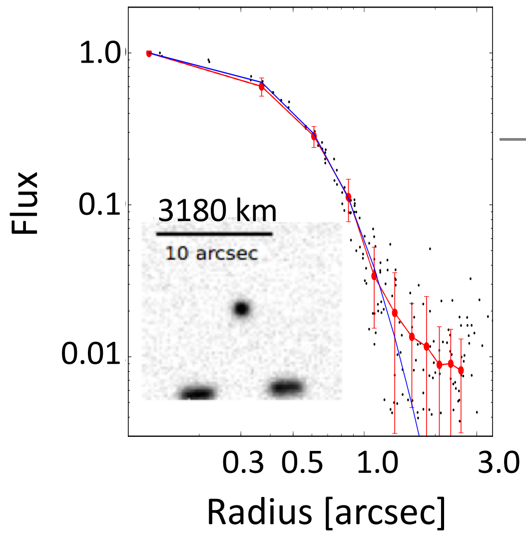
- 53 papers arXiv, 37 published

Sun	Mon	Tue	Wed	Thu	Fri	Sat
← Sep 9 Perihelion						14- Close Earth, CSS Pre-covery
15	16	17	18-PS1 Pre-covery	19-PS1 Discovery	20-Astrometry	21-Astrometry
22- Hyperbolic orbit confirmed	23-DD prop VLT, GS; VLT Approve	24- GS prop Approved; MPEC orbit announce	25-VLT Obs, HST prop submit, UKIRT DD award; ✯	26- VLT, GS obs; HST Approve; PR ✯	27- GS,CFHT, UKIRT, Keck obs	28- UKIRT obs ✯
29 – Hawaiian name	30- ✯	31- Nature paper submit	1	2	3	4
5	6-Ref. Rpt. IAU Name OK	7	8-Resubmit paper	9	10-Paper in production	11

Our Nature paper was accepted Nov. 13 published online on Nov. 20


Classical Electrodynamics
COSMOS

Results from the international campaign

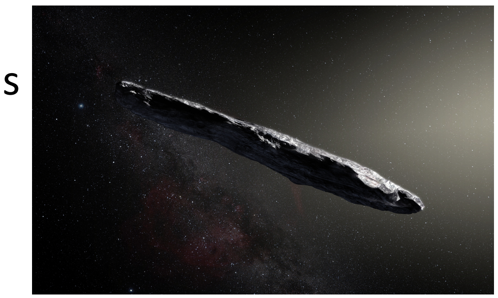


Brightness is related to size (and how reflective)

- Average radius 102 ± 4 m (assuming albedo 0.04)

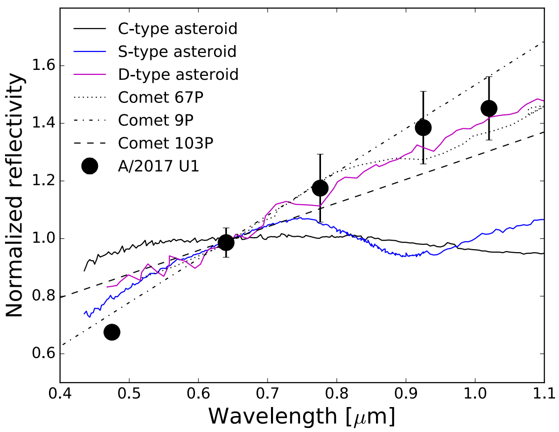
Dust & Activity Limits

- < 1 kg µm-sized dust w/in 750 km from nucleus



Surface composition

- Red (23±3% / 100 nm) – "comet-like"



Excited Rotation

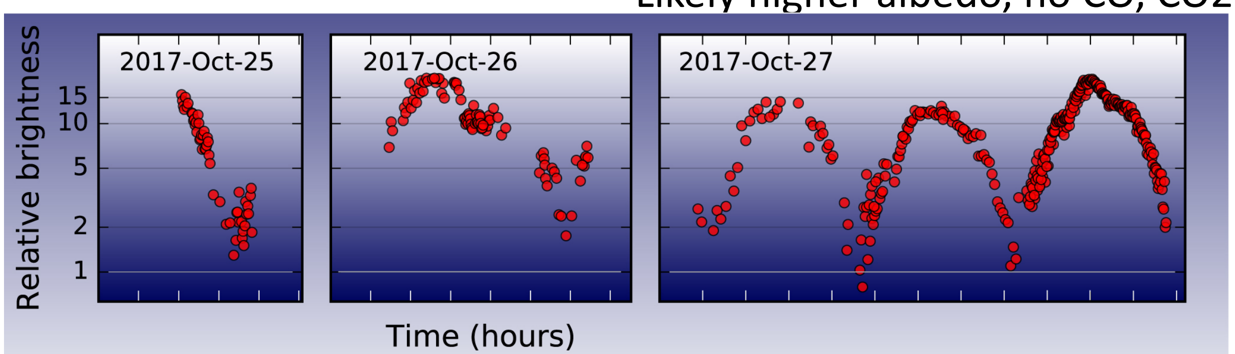
- 8.67±0.34 h – precesses around L vector
- Long-lived – damping time 10^9-10^{10} yr

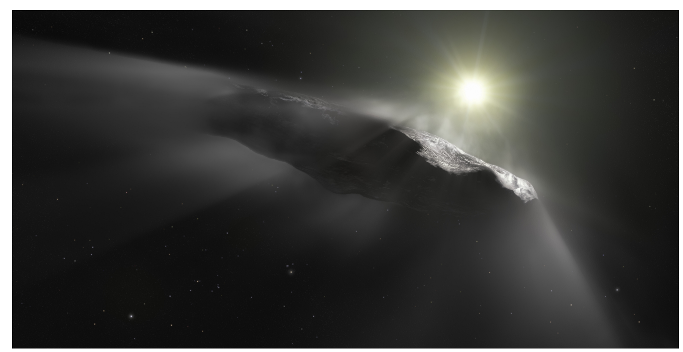
Astrometric orbit fit

- Requires an acceleration away from sun r^{-2}

Spitzer non-detection

- Likely higher albedo, no CO, CO2

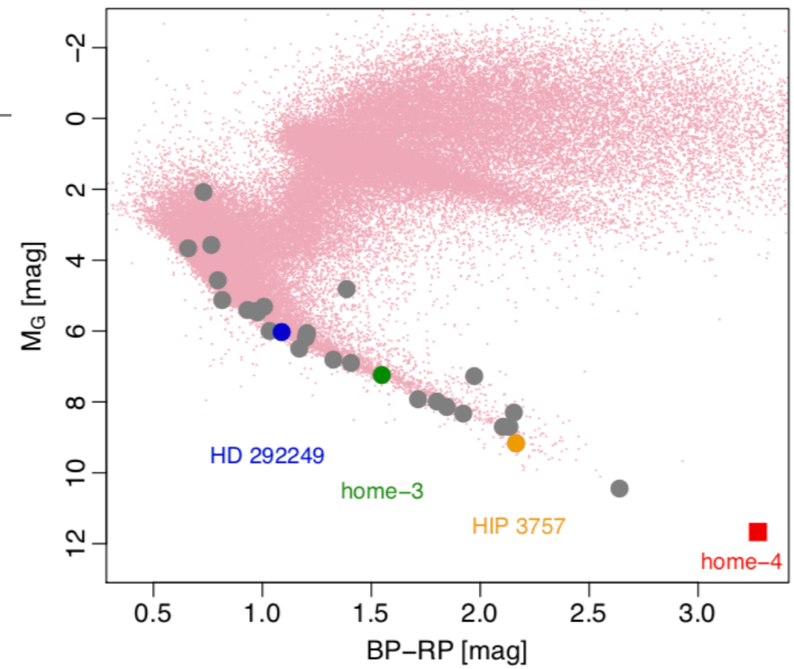




Meech et al. (2017), *Nature* 552, 378; Belton et al (2018) ApJL 856, issue 2, L21.
Fraser et al. *Nature Astron*, 2/9/18; Drahus et al. *Nature Astron, May 2018*

Which Way Home and Gaia DR2

Star	Type	Enc Dist	Enc vel	When
HIP 3757	M2.5 dwarf	0.6 pc	24.7 km/s	1.0 Myr
HD 292249	G5 dwarf	1.6 pc	10.7 km/s	3.8 Myr
Home 3		1.0 pc	14.3 km/s	6.3 Myr
Home 4		0.9 pc	18.0 km/s	1.2 Myr

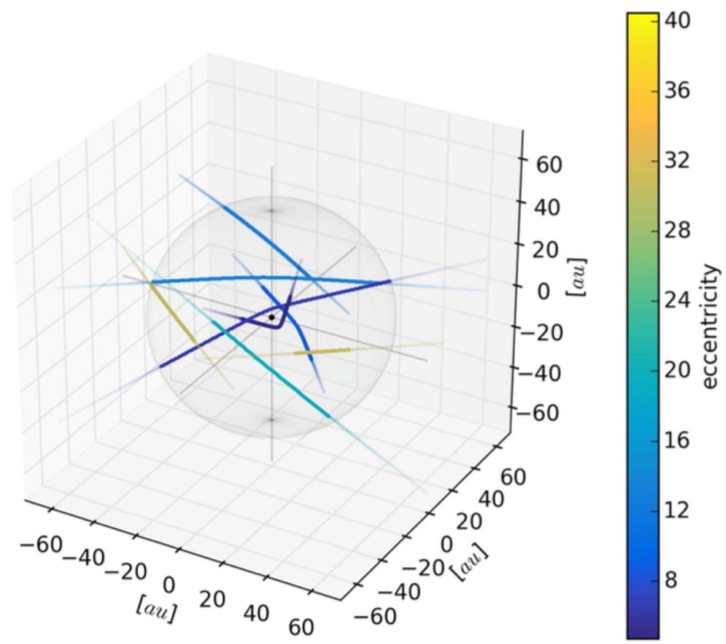


Which way home?

- Non-grav asymptote to trace back the path
- Giant planet – difficult because of high ejection velocities
- Binary system more likely to match velocities
- None of the 4 systems have known exoplanets or are known binaries

The ISO Population

- Generated random (direction, v) ISO population
- Simulated the detection of synthetic ISOs using PS1, Mt. Lemmon, and Catalina sky surveys



Science From Long Period Objects

Long Period Comets

1. Bulk physical properties
2. Chemistry different?
3. Isotopic composition
4. Dust composition
5. Noble gases

Items 1, 5 require in-situ

Going after some of the ices seen in Rosetta N_2, O_2 requires in-situ

Manxes

1. Surface composition
2. Gas composition
3. Isotopes

Item 1 from the ground (want statistics)

Items 2,3 requires in situ

ISOs

1. Basic physical properties
2. Surface composition
3. Gas composition
4. Isotopes
5. Are these the same as our SS planetesimals?
6. Detailed view of the surface – affects of travel through ISM

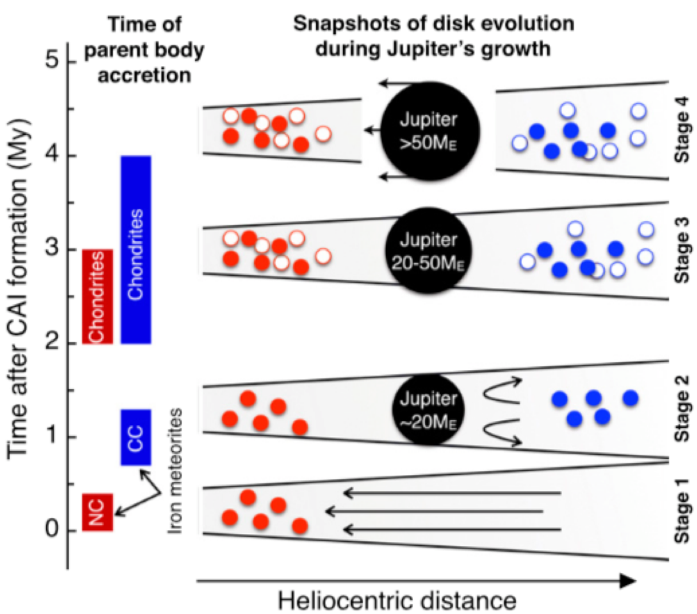
Items 1-3 – From Earth

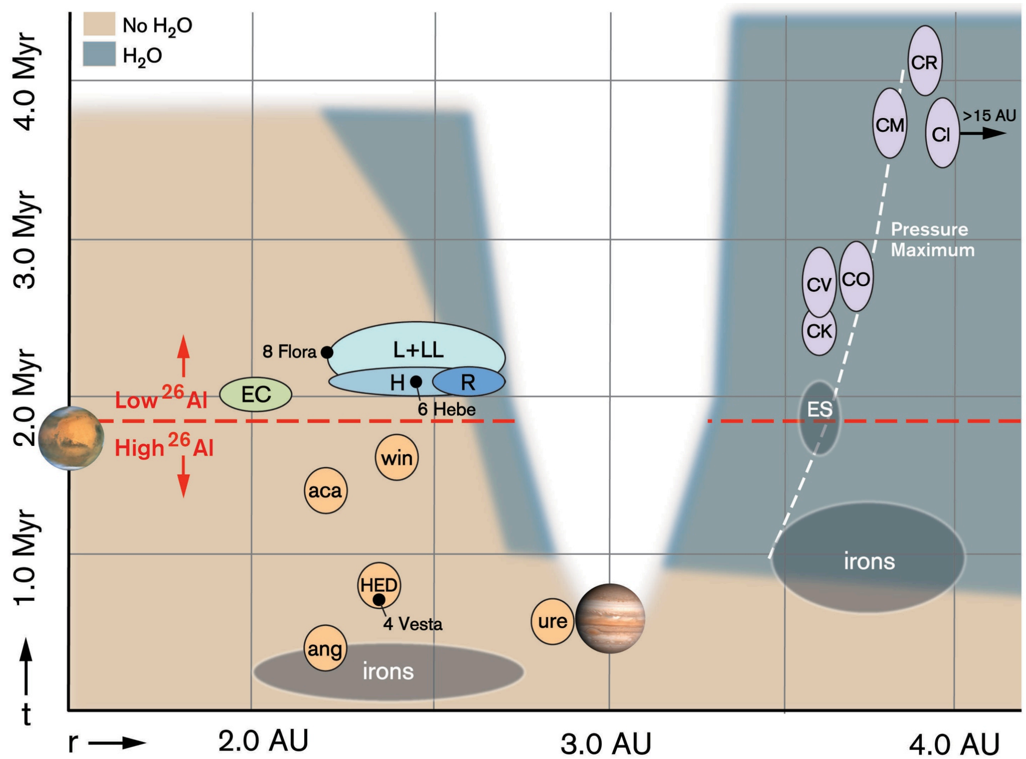
Items 4 -6 – in-situ

Input from Cosmochemistry

Rapid growth of Jupiter's Core

- Distinct W and Mo isotopic composition between carbonaceous chondrites and ordinary chondrites → spatially separated
- Jupiter core after 1 Myr opens disk gap
- Groups remained separated for 3-4 Myr





Gap in disk controls what arrives in inner solar system

- Stops inward drift of particles from the outer disk
- As Jupiter grows it can scatter planetesimals as it grows and / or migrates in the disk