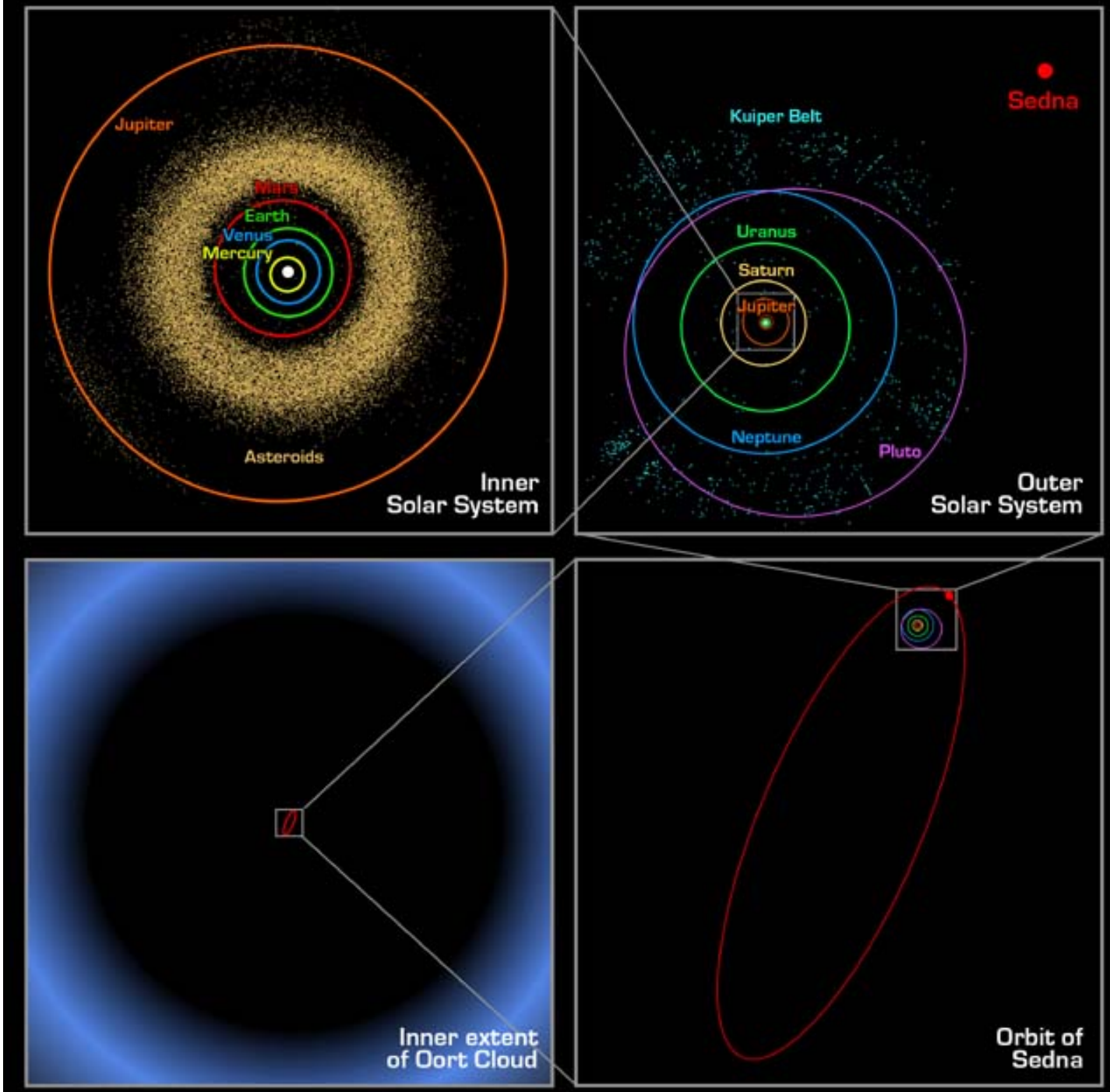
Chap 12: Asteroids, and Comets of the Inner Solar System, and of the Oort Cloud

- The Oort Cloud
- Origin of the Kuiper Belt
- Short period *vs* Long Period comets; origin in Kuiper Belt *vs* Oort Cloud
- The Asteroids. Big *vs.* Little and their Origin
- I have a new, separate PowerPoint on the Kuiper Belt, now that we have much new data

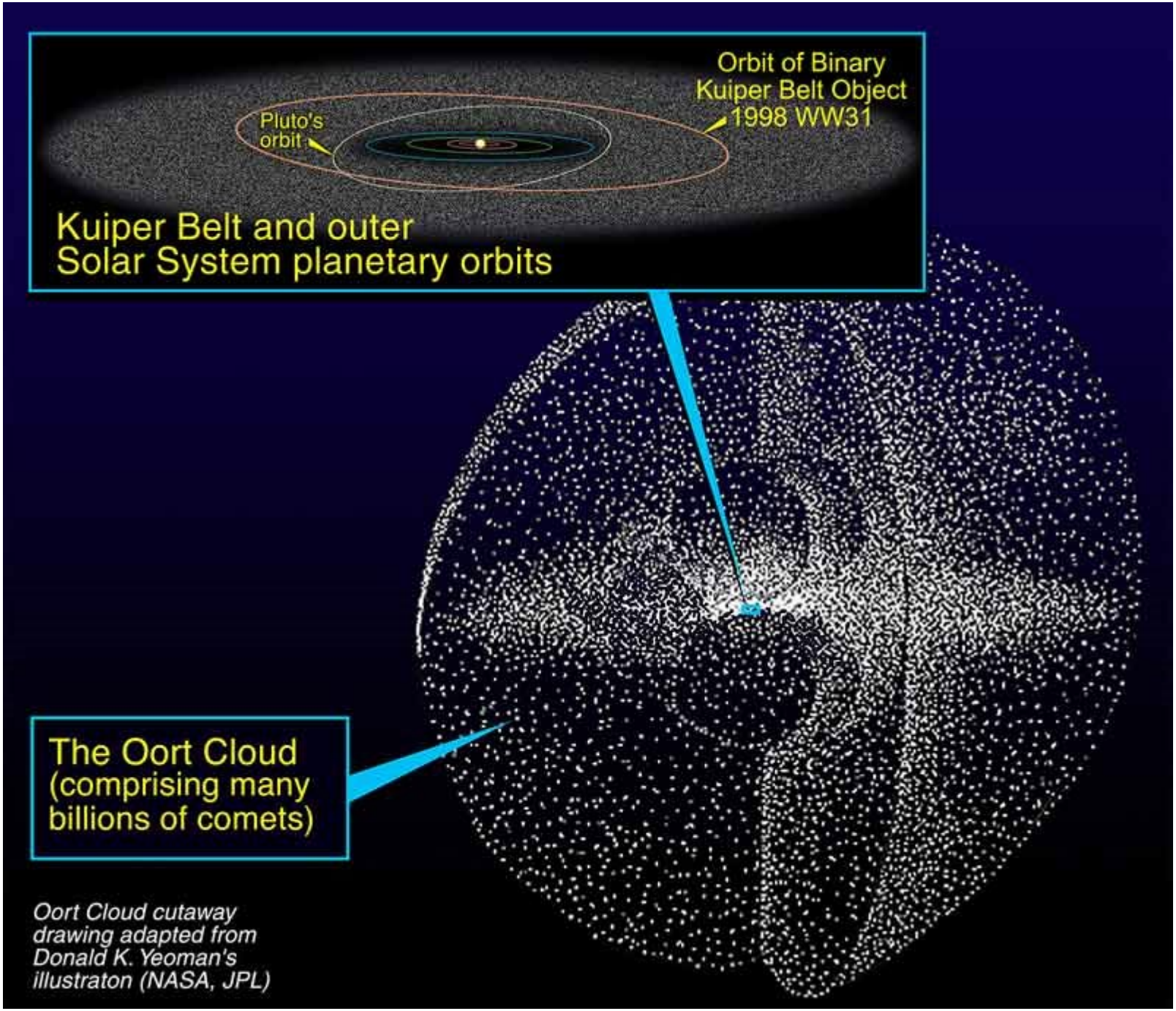

Jupiter
Mars
Earth
Venus
Mercury
Asteroids
Inner
Solar System
Kuiper Belt
Sedna
Uranus
Saturn
Jupiter
Neptune
Pluto
Outer
Solar System
Inner extent
of Oort Cloud
Orbit of
Sedna

Beyond Neptune – cold and dark

- No planets beyond Neptune, instead, the **Kuiper Belt** and Oort Cloud of large comets… (except "Planet 9"! See later)
- "Rocks" of light elements (hydrogen, oxygen, nitrogen, carbon, chlorine…) are called "ice" and melt at very low temperatures.
- Globs of this stuff, mixed with plenty of dust and dirt, are called "Comets"!

The Oort Cloud

- **A roughly spherical distribution of comets surrounding the outer solar system all the way out to about ½ light year away.**
- Inferred by **Jan Oort** in the mid 20th Century, because there were so many comets on orbits with periods of thousands of years.
- Kepler's Laws imply outer end of orbit (call aphelion) as far as half a light year away
- This is about the tidal limit beyond which passing stars during past 5 billion years would gravitationally pull off material, so this makes sense
- We cannot directly image anything in the Oort Cloud. Way too far away and too dim to ever hope to see. Instead, we see the individual comets when they swing by the sun
- Little angular momentum in this material, so not flattened like a disk as we see closer in to the sun. So, called the Oort "Cloud", not the Oort "Belt".



Oort Cloud cutaway drawing adapted from Donald K. Yeoman's illustraton (NASA, JPL)

Collisions between Kuiper Belt Objects Thought to be the Main Source of Short-Period Comets

- Simulations show that at the relative velocities KBO's experience, that the pieces from collisions would result in many losing angular momentum and falling in on the highly elliptical orbits, like short-period comets have.
- Short period comets – a few miles across, not hundred(s) of miles across like KBO's.
- Highly elliptical orbits falling deep in towards the sun, where sunlight makes them easy to see (and fun to watch!)

Halley's Comet in 1986 Passage Inside Earth's Orbit

C/Wild closeup. Short and long exposures combined

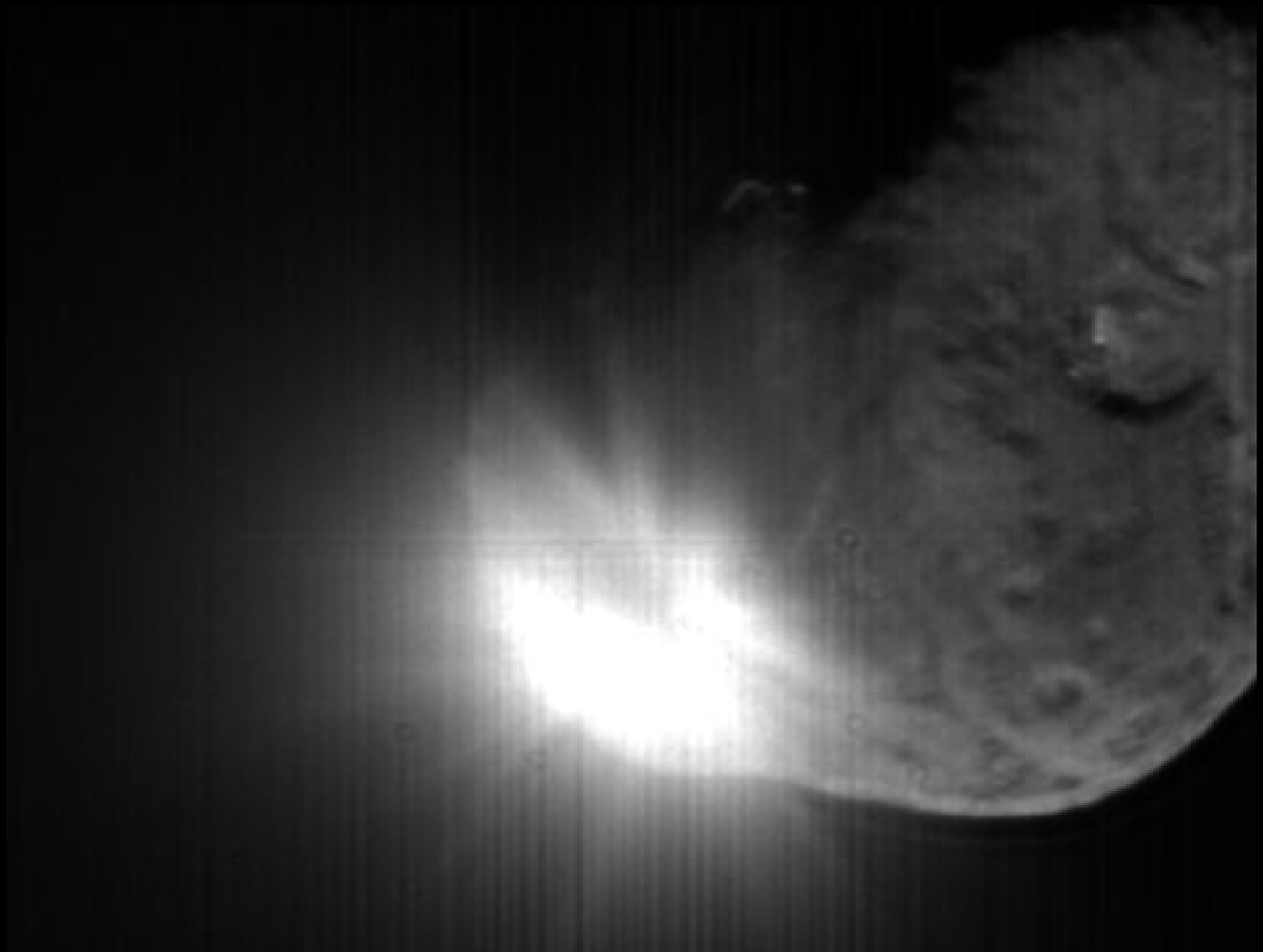
C/Borrelly closeup

Comet Hartley 2: Bizarre "Chess Piece" Comet

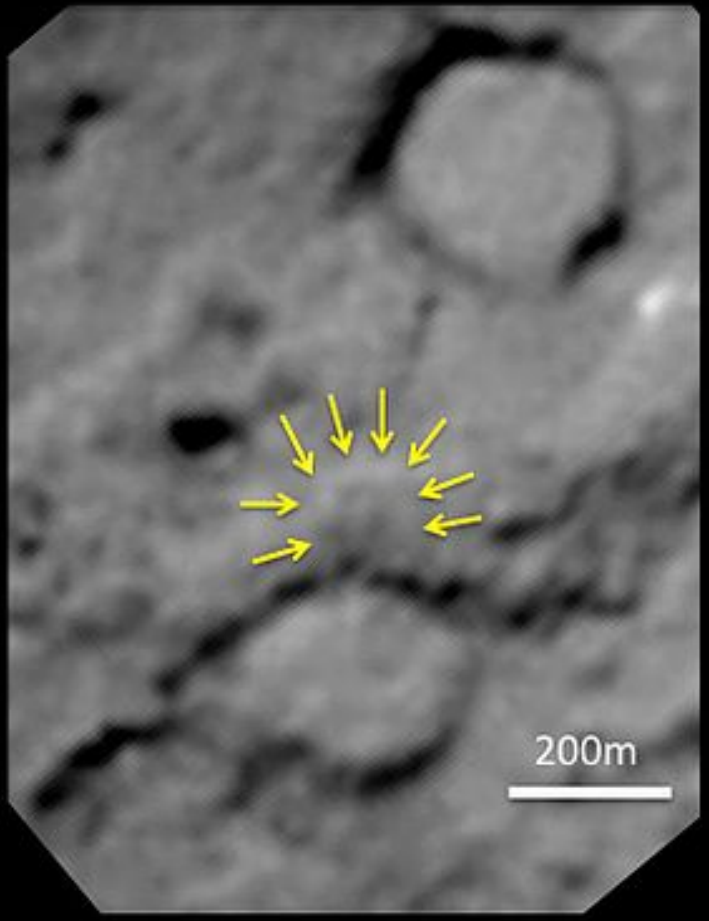
Vaporizing water from C/Hartley 2

Comet Temple I: From “Deep Impact” Mission

Mission: “Deep Impact” – colliding a 200 lb mass of pure copper with Comet Temple I



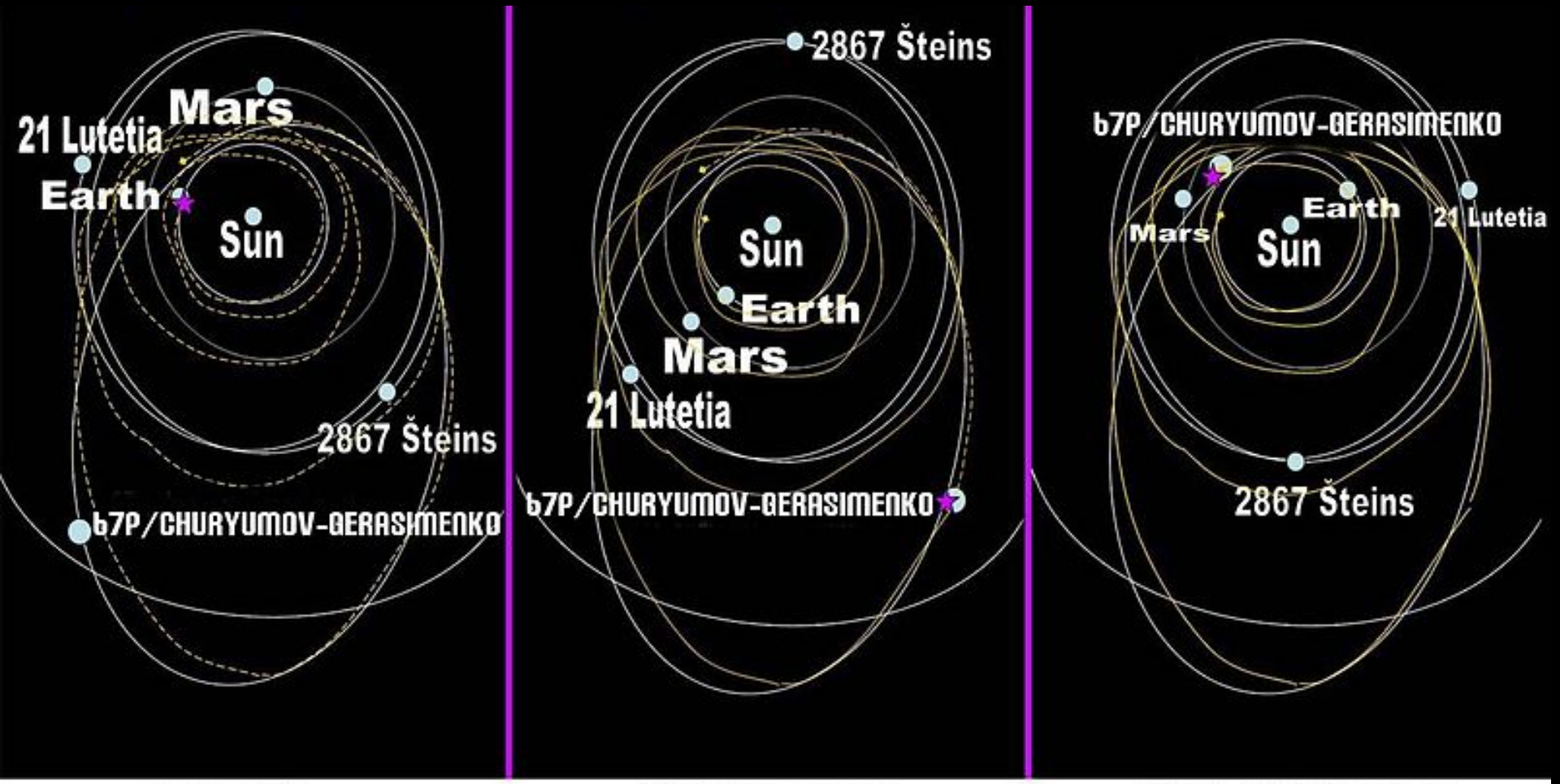
Copper Impactor made this shallow new crater



What did we Learn about C/Temple I?

- The material excavated by the impact material contained **more dust** and **less ice** than had been expected.
- Ruled out: Comet models which assumed comets were loose aggregates. Material was "welded"
- The material was finer than expected; scientists compared it to talcum powder rather than sand. Other materials found included clays, carbonates, and sodium, and crystalline silicates which were found by studying the spectroscopy of the impact.
- Clays and carbonates usually require liquid water to form and sodium is rare in space.
- **Comet Temple I is about 75% empty space, similar to a fresh snow bank, but stiff**.

Rosetta's 15 Year Mission – Flyby of asteroid Steins, then asteroid Lutetia, then the main mission: Orbit 67P/Churyumov–Gerasimenko and deploy lander in 2014



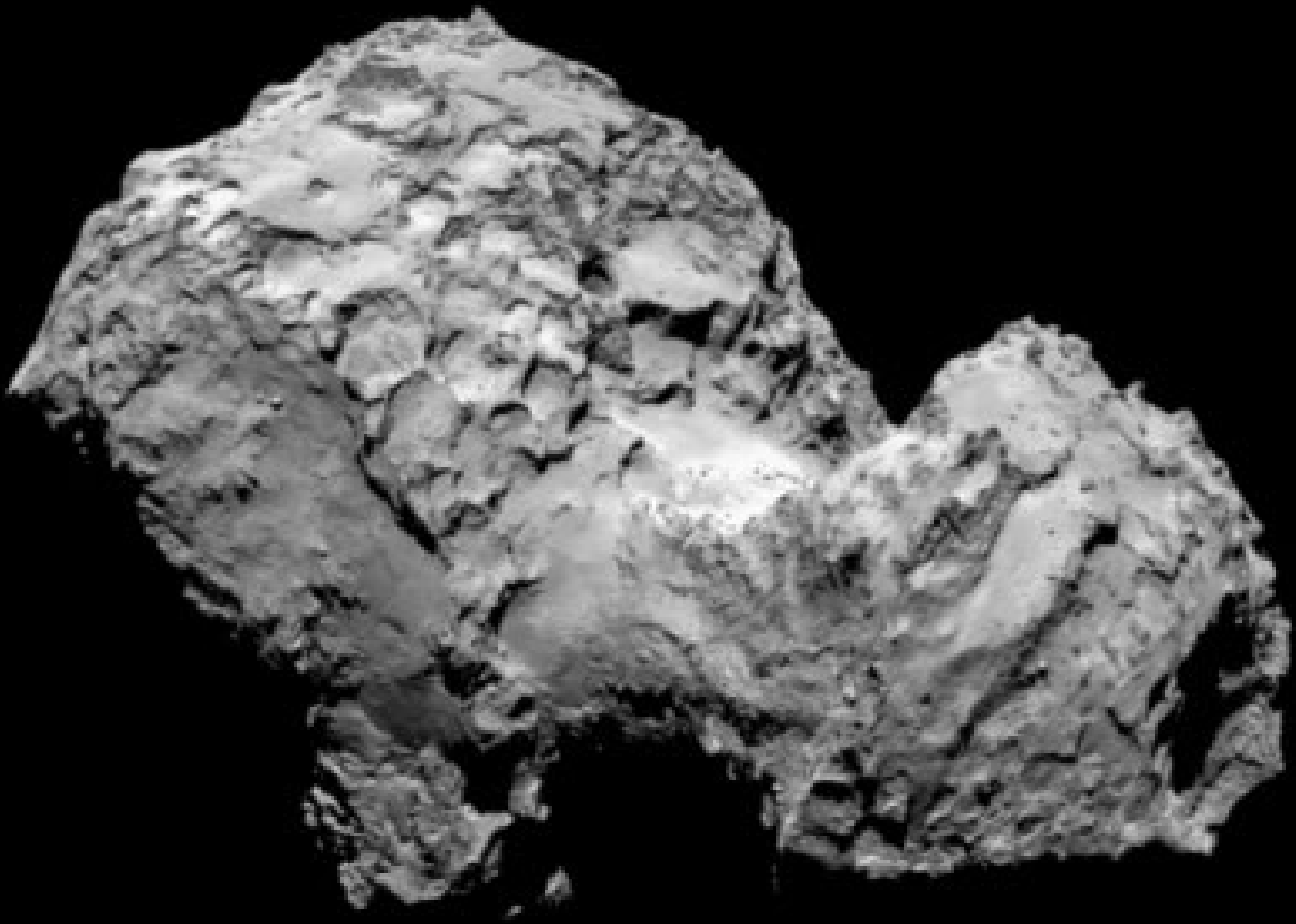
Launch
March 2004

Rendezvous
May 2014

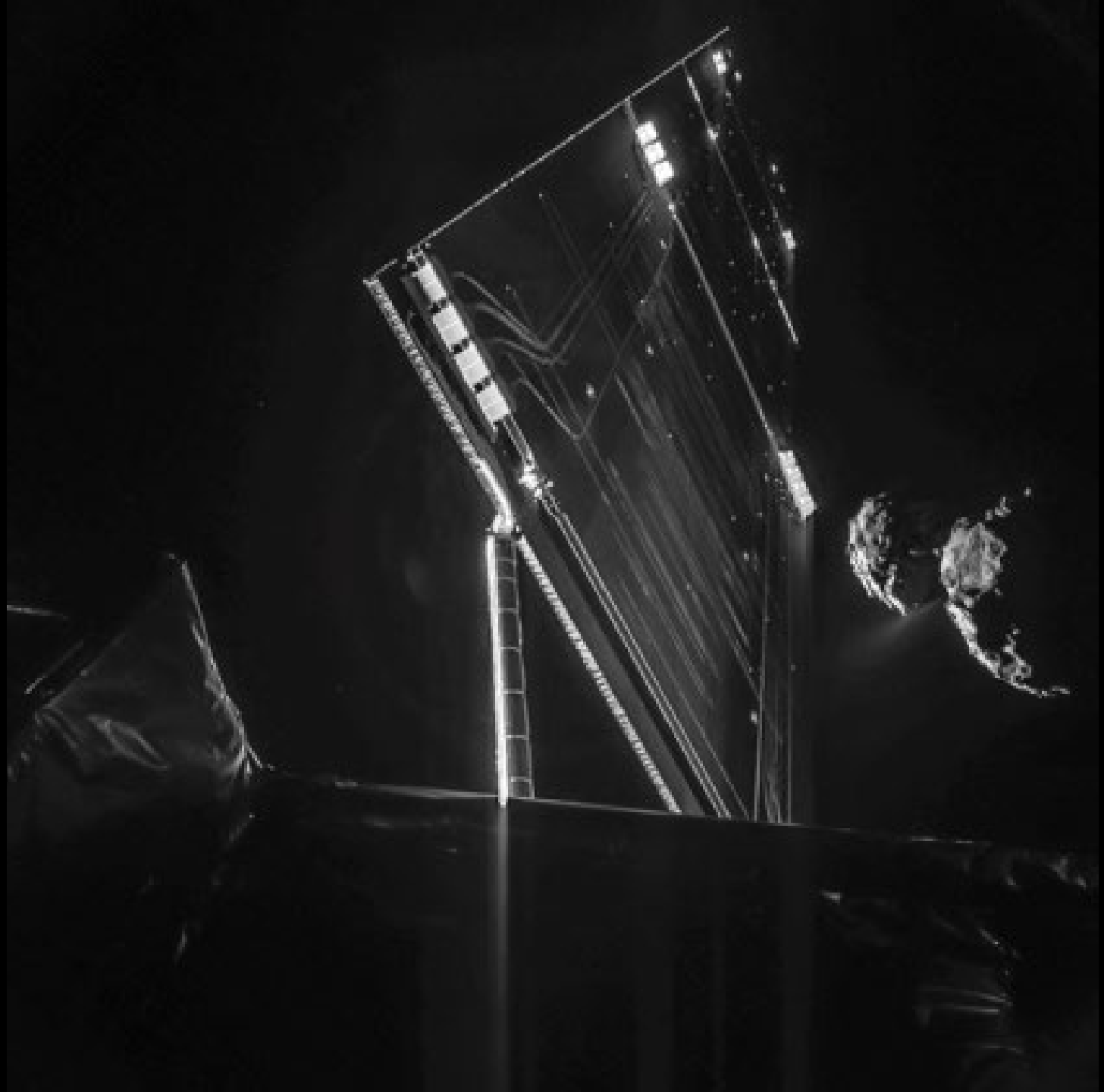
End of Mission
December 2015

2014: Rosetta Arrives at Comet 67P Comet Churyumov-Gerasimenko, looking down the axis

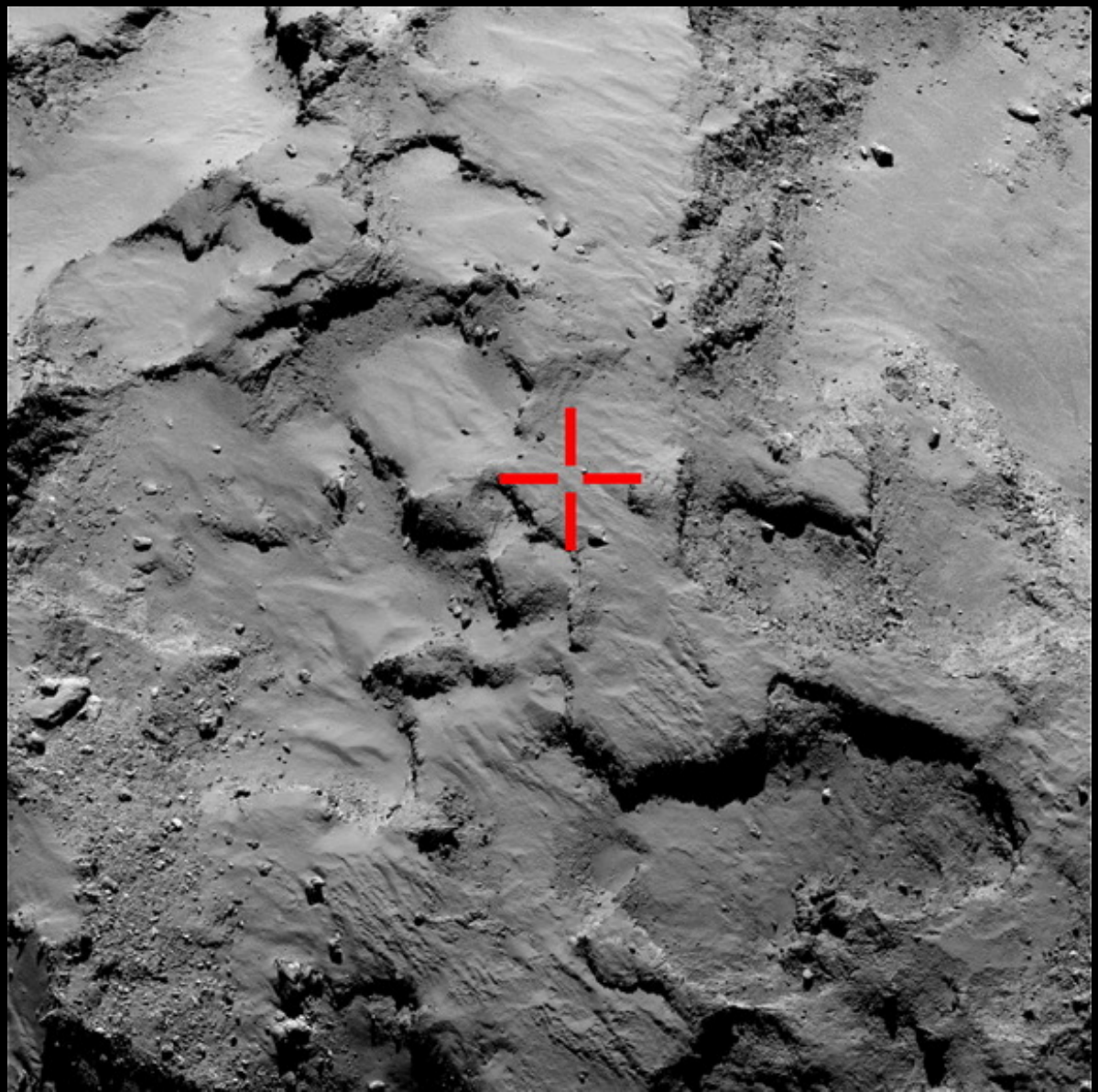
Comet 67P – Neck: Between Merging Comets? Or Excess Evaporation at the Neck?



Comet 67P CG: Like a Sci-Fi Scene



Rosetta's Philae Lander went "Crunch" When it Landed



What Are We Learning from Rosetta's Philae?

- Philae's drill broke, trying to drill into the surface!
- Turns out, surface ice starts out amorphous in structure, but turns crystalline when melting, expunging organics and dirt, which collect and freeze solid on the surface.
- Surface has the color of charcoal! And very hard
- Best analogy – **deep fried ice cream!**

Comets Are Like Deep Fried Ice Cream (Vanilla, we think, not pistachio)

Comets – A Tale of Two Tails

- Comets swing by the sun on big arcing orbits.
- The gas is blown back rapidly, since gas atoms are very light. Gas tail is very straight and moves very fast – gas atoms left comet very recently.
- Dust tail is yellowish and often curved, as the dust grains move very slowly, showing the history of the comets path over a longer history.

C/Hyakutake in 1996, fisheye all-sky

Ion tail: Bluish, from Emission lines

Dust tail: scatters and reflects sunlight: yellowish and broad.

Coma (head): Emission of molecular carbon (C2) = green

C/Bradfield & C/LINEAR T7, at Joshua Tree Nat. Park

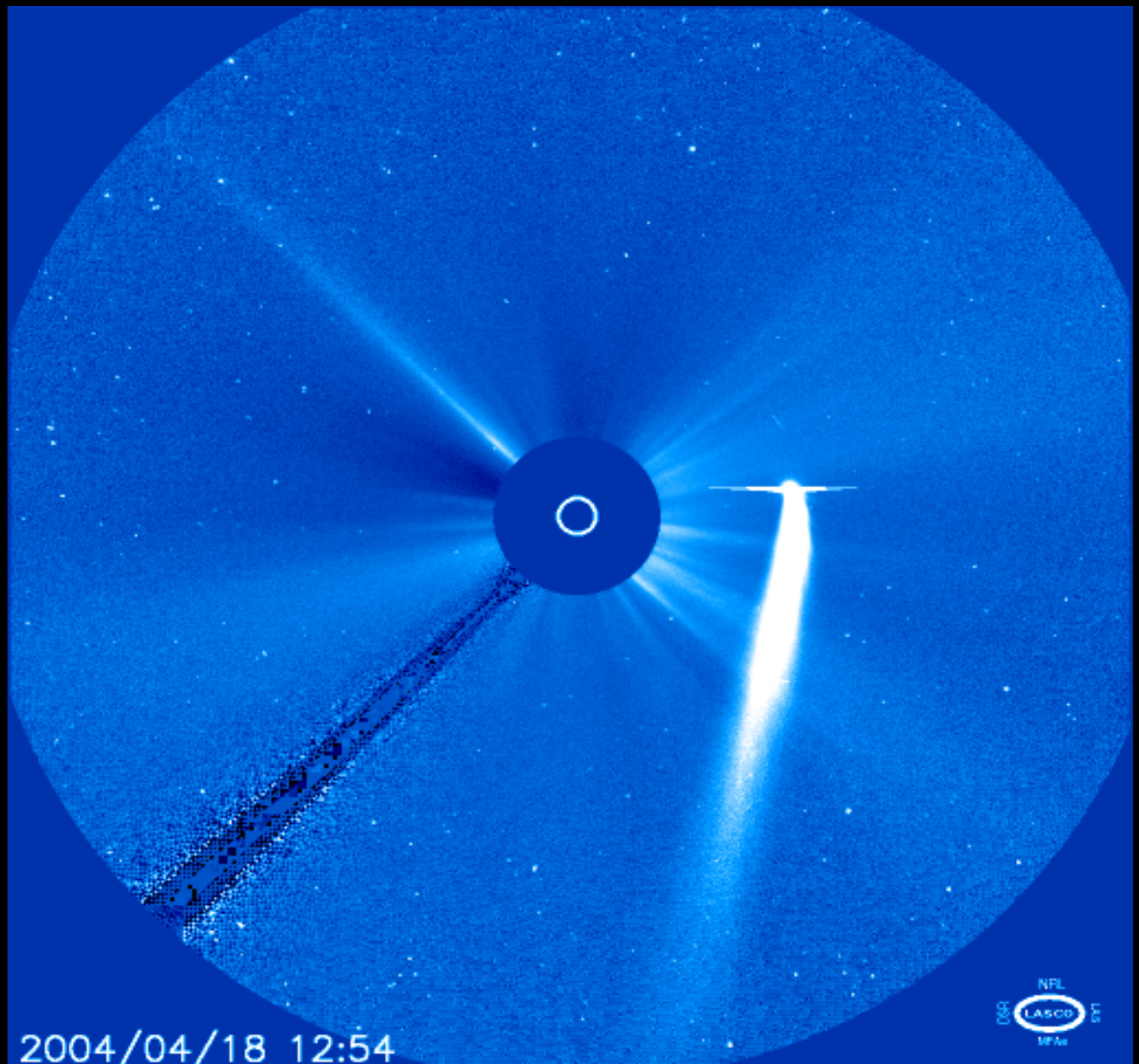
C/Ikeya-Zhang and Andromeda Galaxy in 2001

C/Holmes after Outburst ‘07

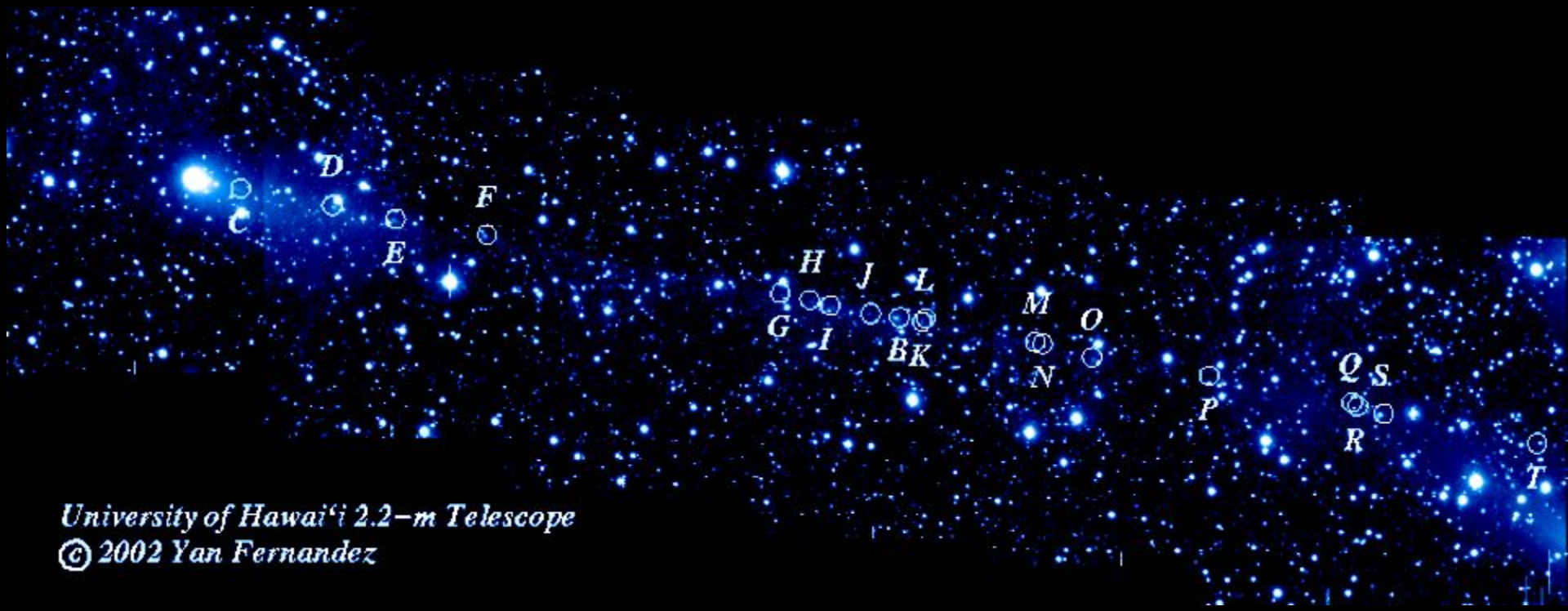
Comets Don't Live Forever…

- Short period comets will melt and lose surface on each passage around the sun
- Gerard Kuiper realized this happens quickly enough there must be a continual re-plenishment of fresh short-period comets, and hypothesized the existence of a belt of perhaps a million giant icy objects a few hundred km across, beyond Neptune.
- **He was right. The Kuiper Belt** was later discovered after his death, with the new generation of Big 10 meter class telescopes and CCD imaging
- Halley's Comet loses ~ 3 feet depth of surface on each orbit
- We've seen several comets disintegrate and melt away…

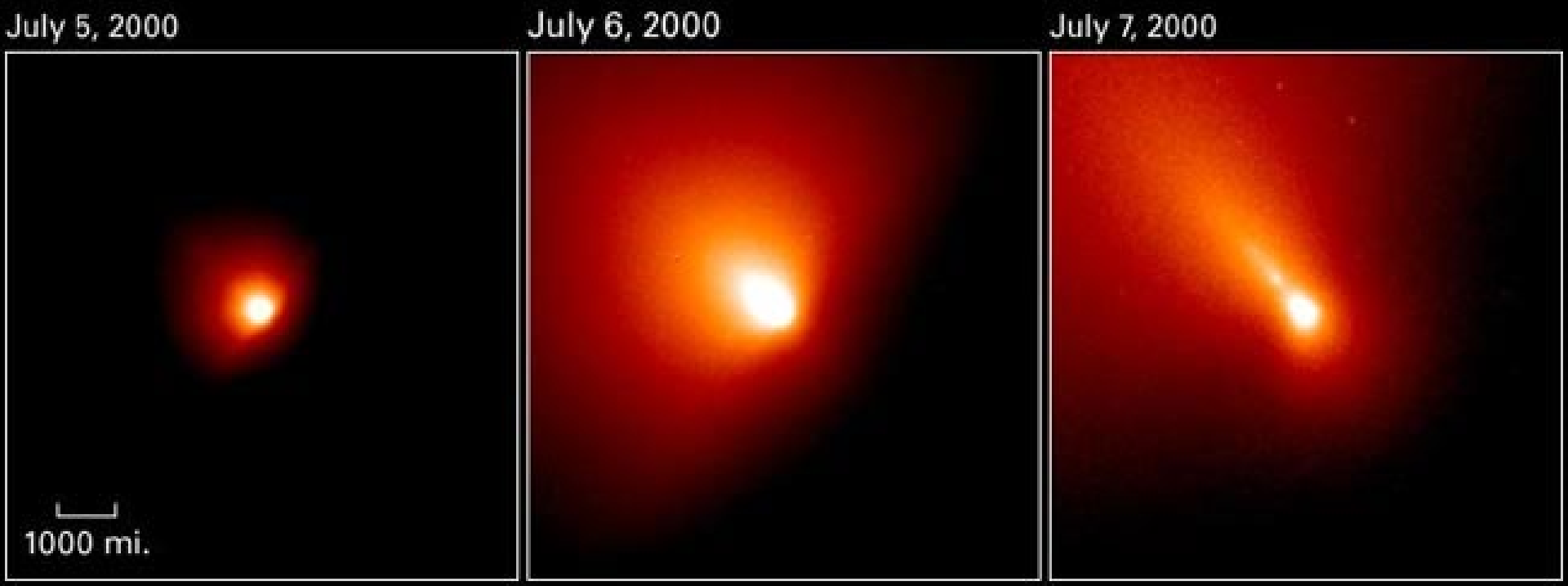
C/NEAR Photo'd by SOHO Satellite

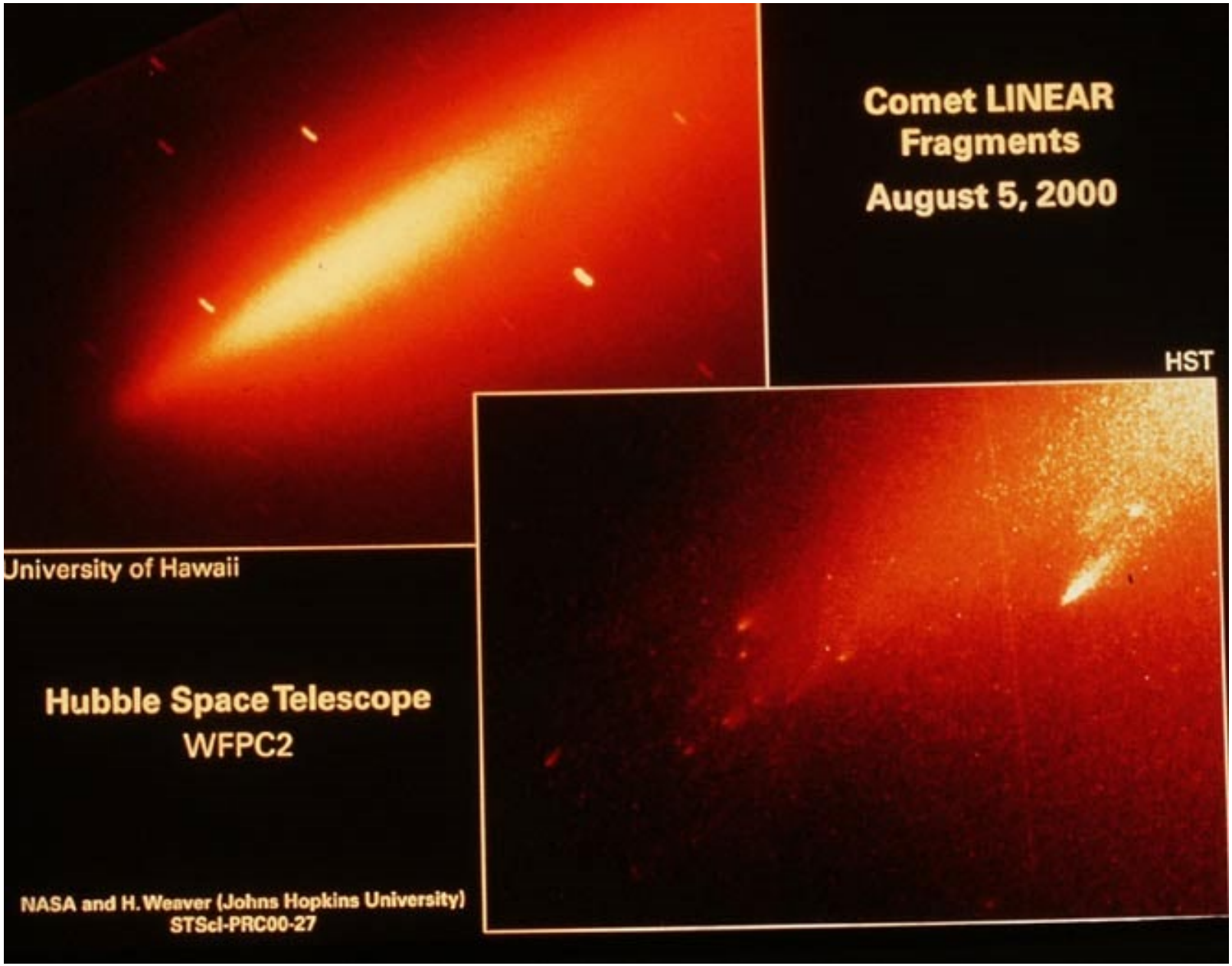


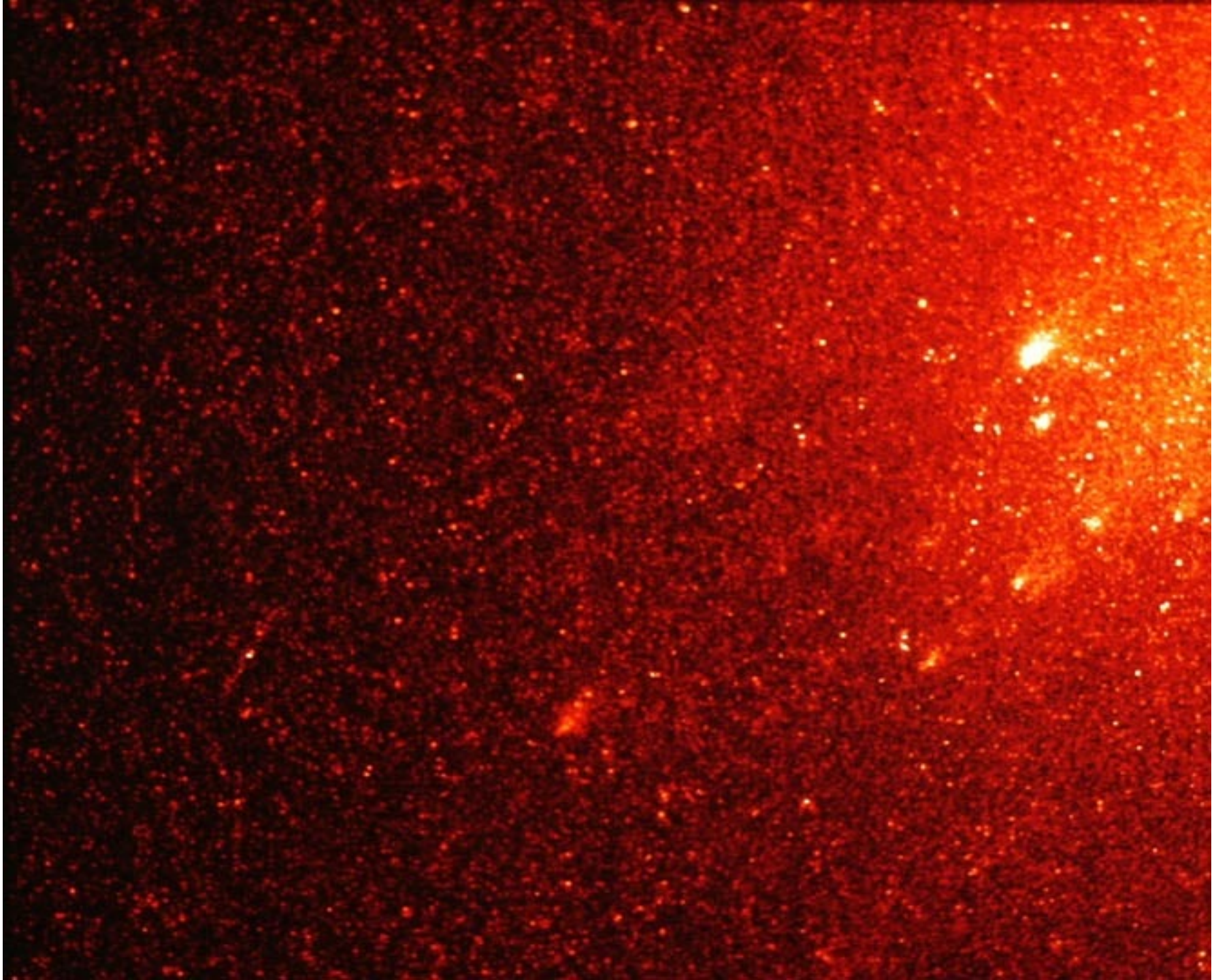
Comet 57P: Breaking Up



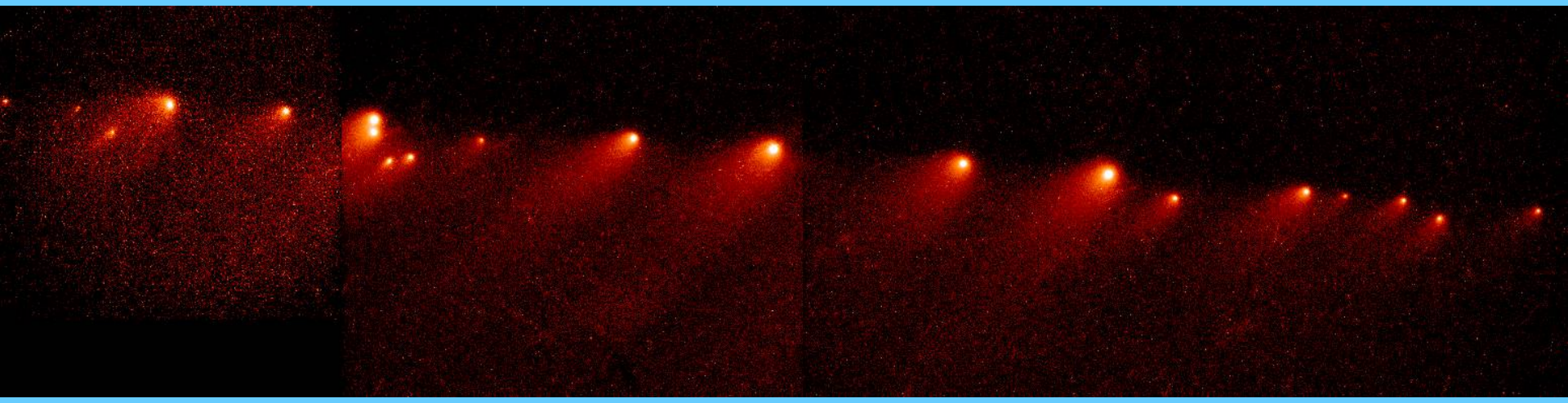
Comet LINEAR S4 breaking up




Comet LINEAR
Fragments
August 5, 2000
HST
University of Hawaii
Hubble Space Telescope
WFPC2
NASA and H. Weaver (Johns Hopkins University)
STScI-PRC00-27



SL9 - string of comets tidally disrupted by Jupiter, before impacting Jupiter



Video Sequences: Comets Vaporizing as they come too close to the Sun

- C/ISON – SOHO and CoRot Video (1:37)

Dust, pebbles, are set free during this melting process

- These remain in the orbit of the comet, but drift either ahead or behind the main comet as time goes on, and also spreading laterally up to several million miles away from the comet's orbit path
- If this torus of material crosses the Earth's orbit, we see a ***meteor shower*** for a few hours or a few days
- Comets do not seem to have solid inclusions larger than pebbles or perhaps small rocks – no giant boulders capable of surviving atmospheric impact

Left: More like the Perseids. **Right:** More like the Leonids

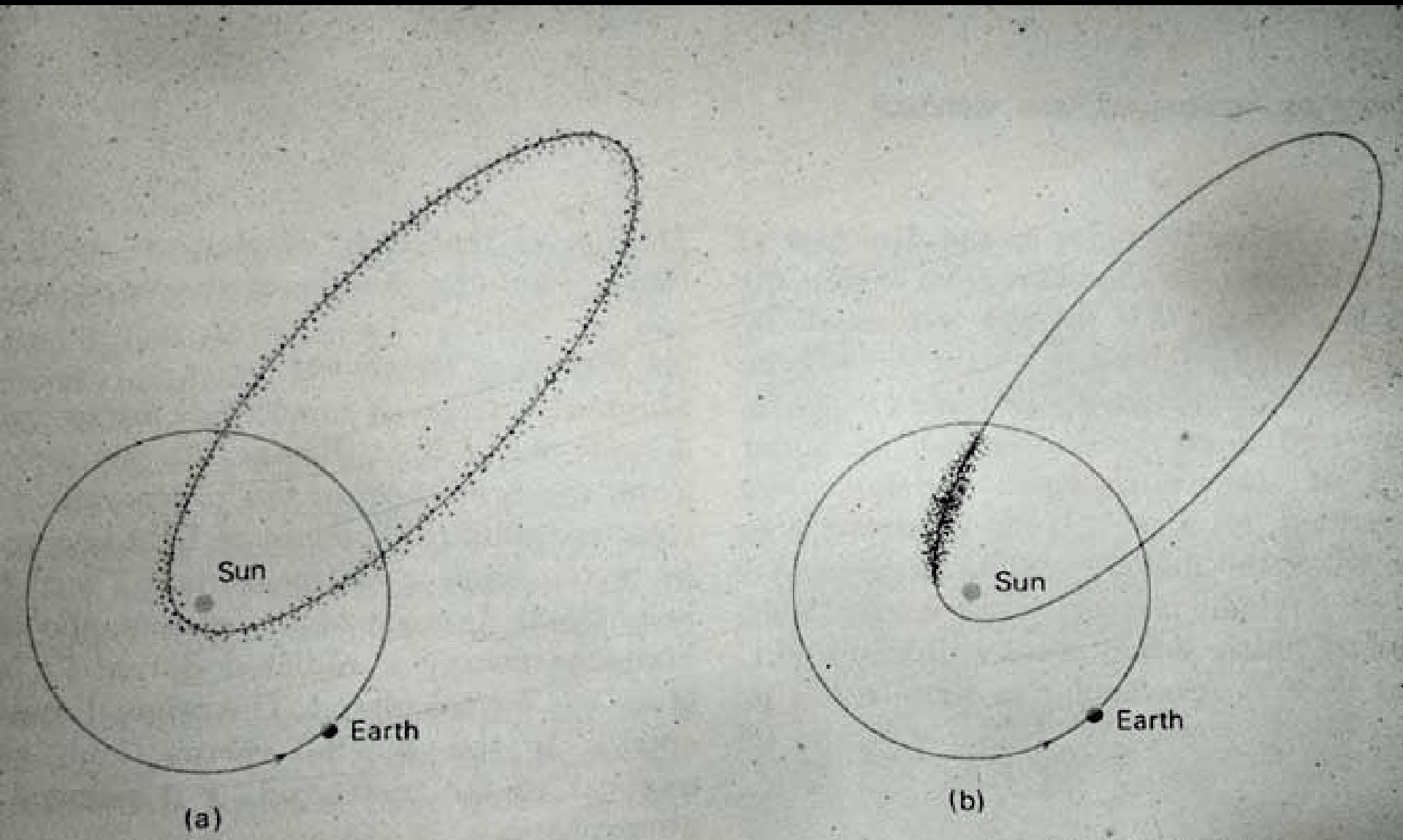


FIG. 17-6 Meteoroids in a swarm may be strewn more or less uniformly along their orbit (a), or bunched up (b).

Some of the Stronger Annual Meteor Showers

- Jan 4 – 100/hr **Quadrantids**
- Apr 22 – 20/hr **Lyrids**
- May 6 – 55/hr **Eta Aquarids** (from Halley's Comet)
- June 16 – 3/hr **June Lyrids** (Dr Rick co-discovered!)
- July 30 – 20/hr **Delta Aquariids**
- Aug 12 – 100/hr **Perseids**
- Oct 21 – 20/hr **Orionids** (from Halley's Comet)
- Nov 17 – 15/hr or storm **Leonids**
- Dec 13 – 100/hr **Geminids**

Comet Temple-Tuttle; parent of the Leonids

Leonids ’99 at Ayers Rock. Note anti-radiant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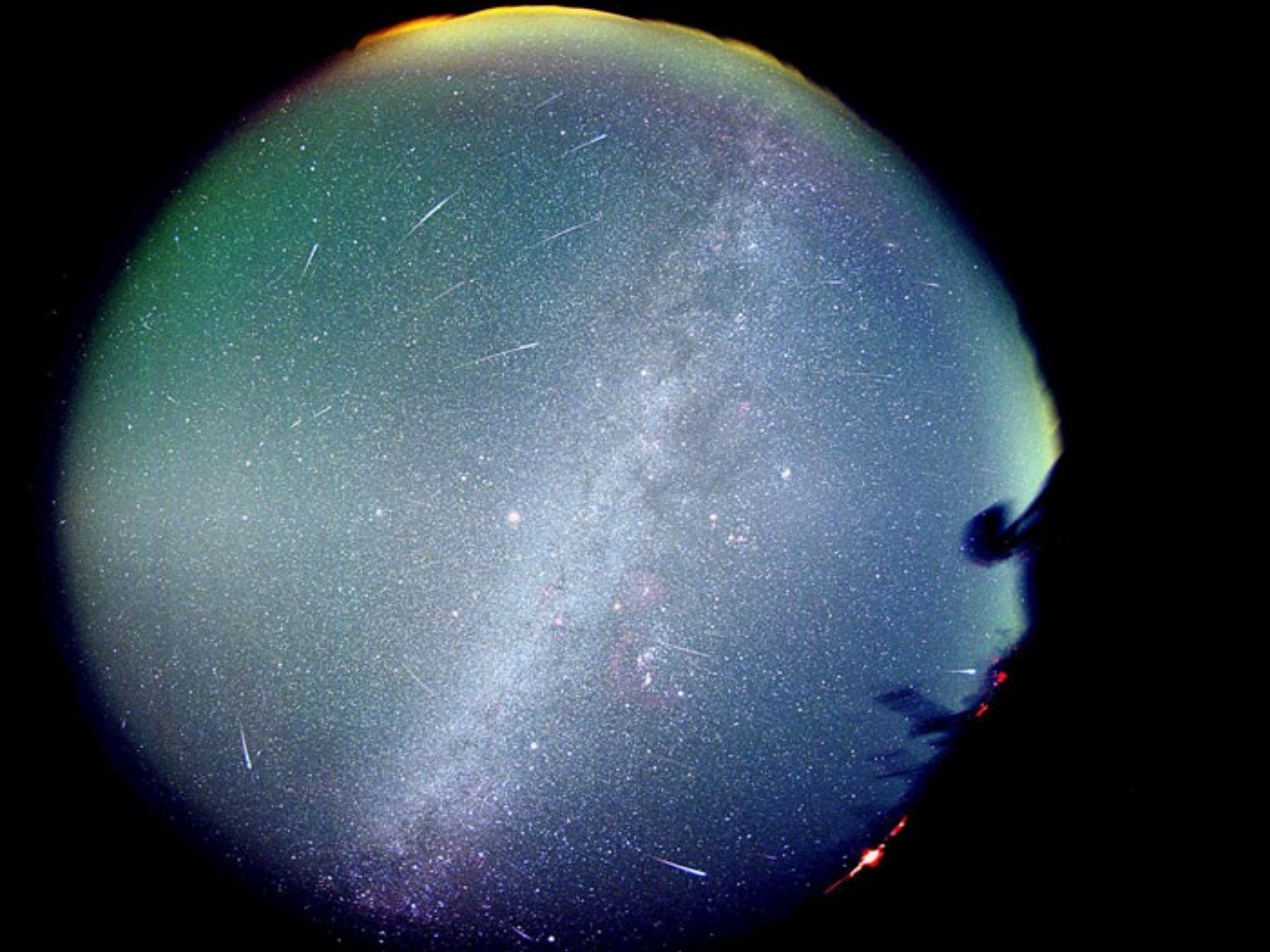
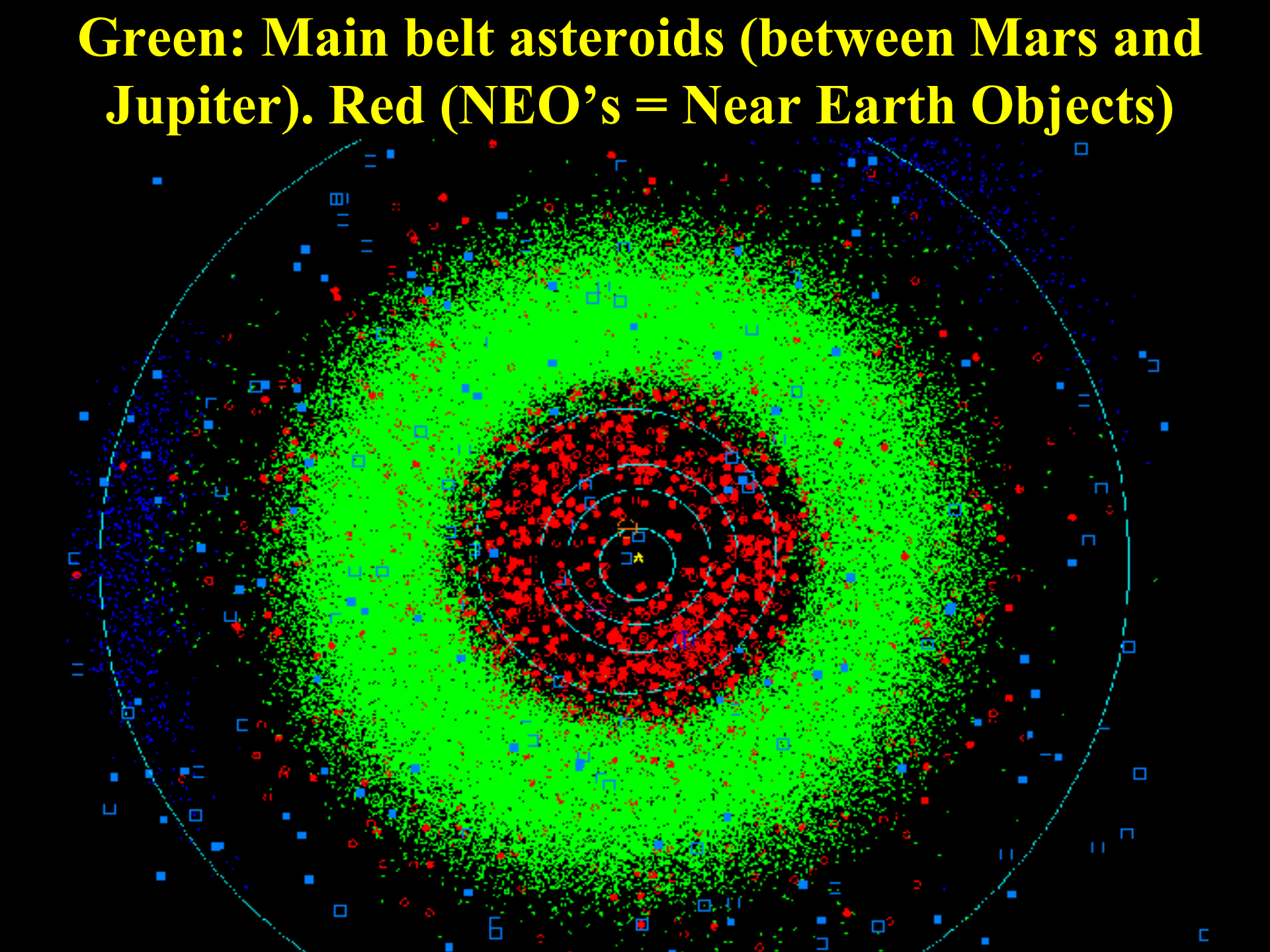


Leonids 2002: The Grand Finale

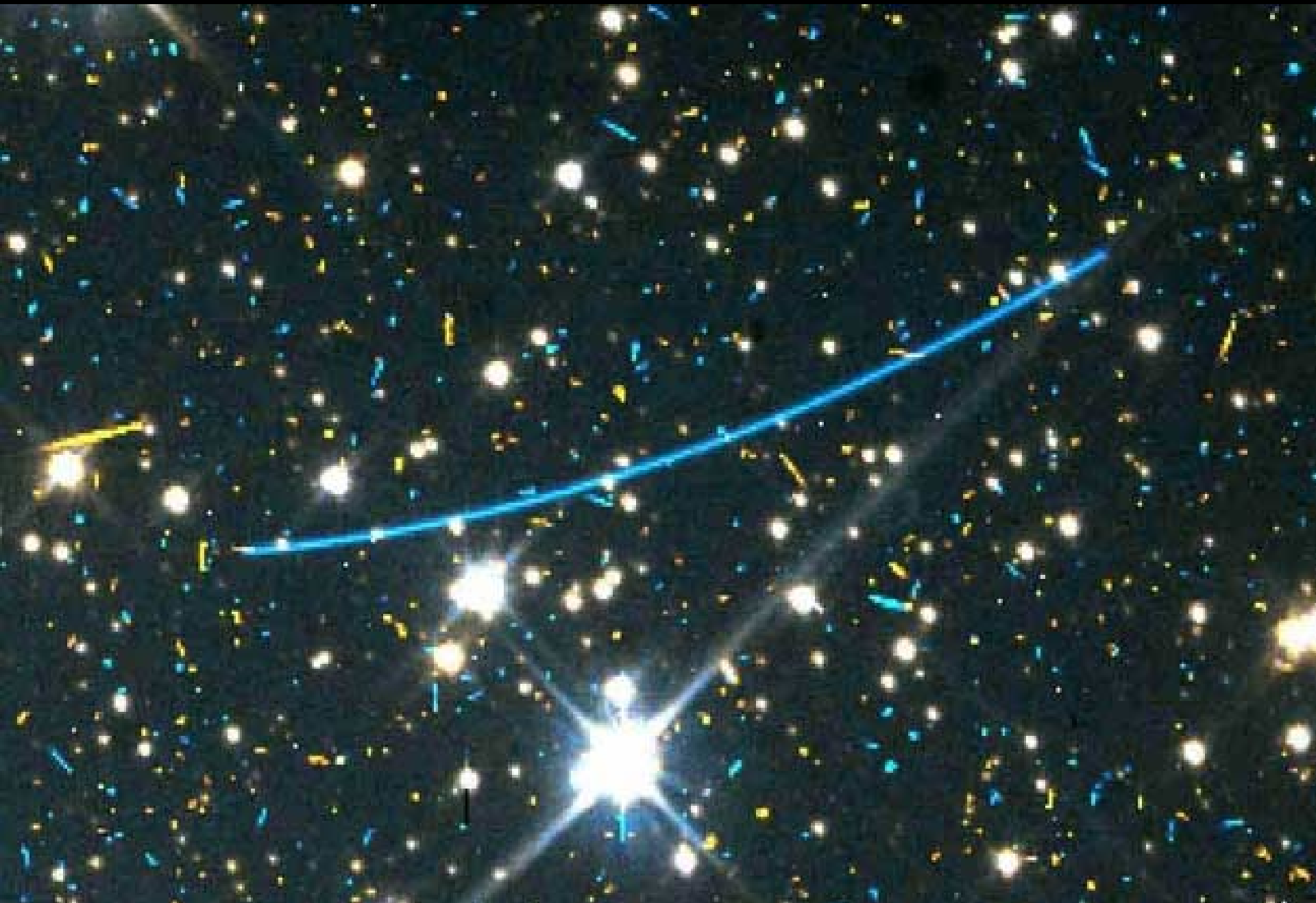
Asteroids – Remnants of Proto-planets whose Orbits were Roughed up by Jupiter's Gravity

- Giant gap from Mars to Jupiter, plenty big enough to house another planet or two. But instead…
- Hundreds of Thousands of bits and pieces of rock
- Resonances and orbit crossings led to collisions, and maybe never came together in the first place (tidal stretching)
- Total mass is less than that of Mars, but was probably much higher initially.
- Orbits of many no doubt collided with Jupiter or the sun
- History of the Discovery of Asteroids 1980-2010 very cool video!

Green: Main belt asteroids (between Mars and Jupiter). Red (NEO's = Near Earth Objects)



Hubble Picture: LOTS out there. Short trails are asteroids



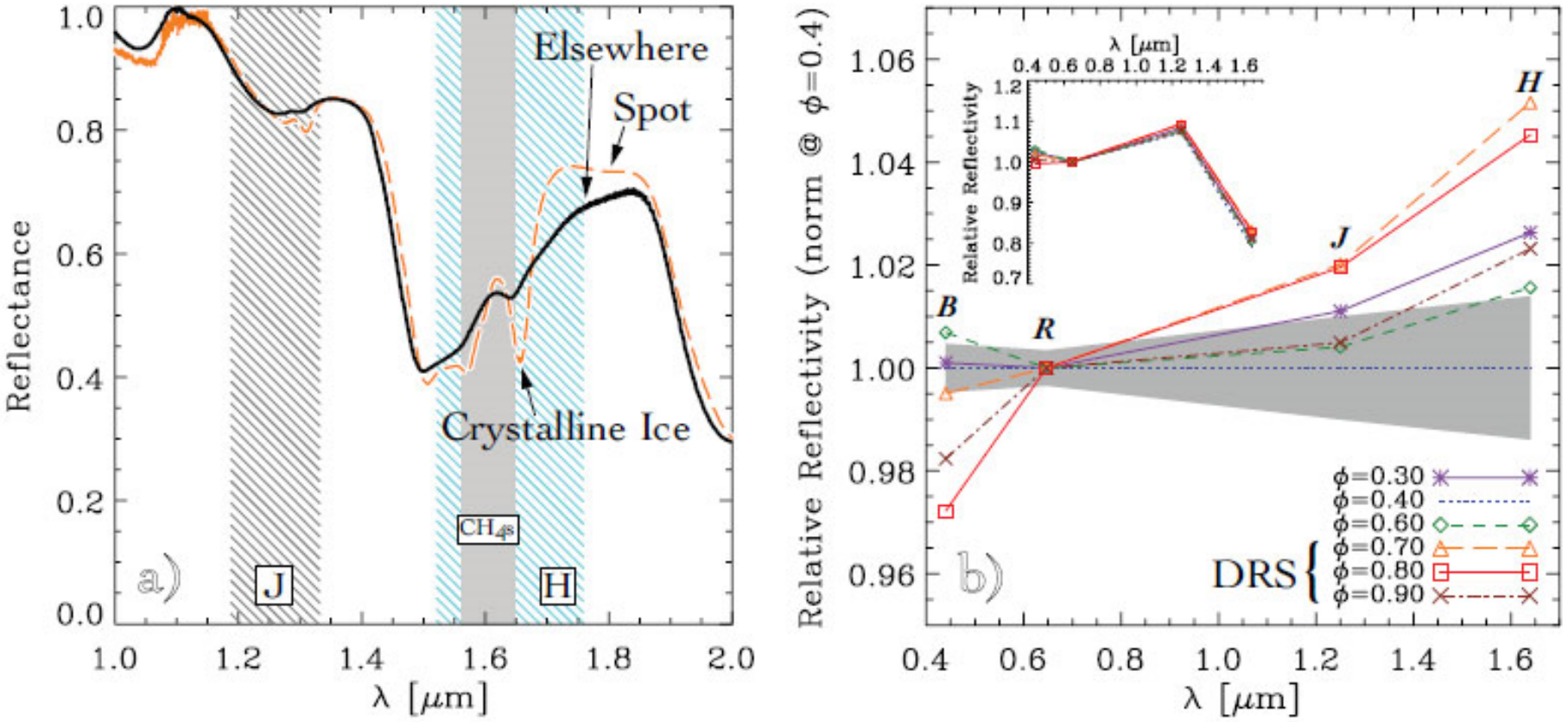
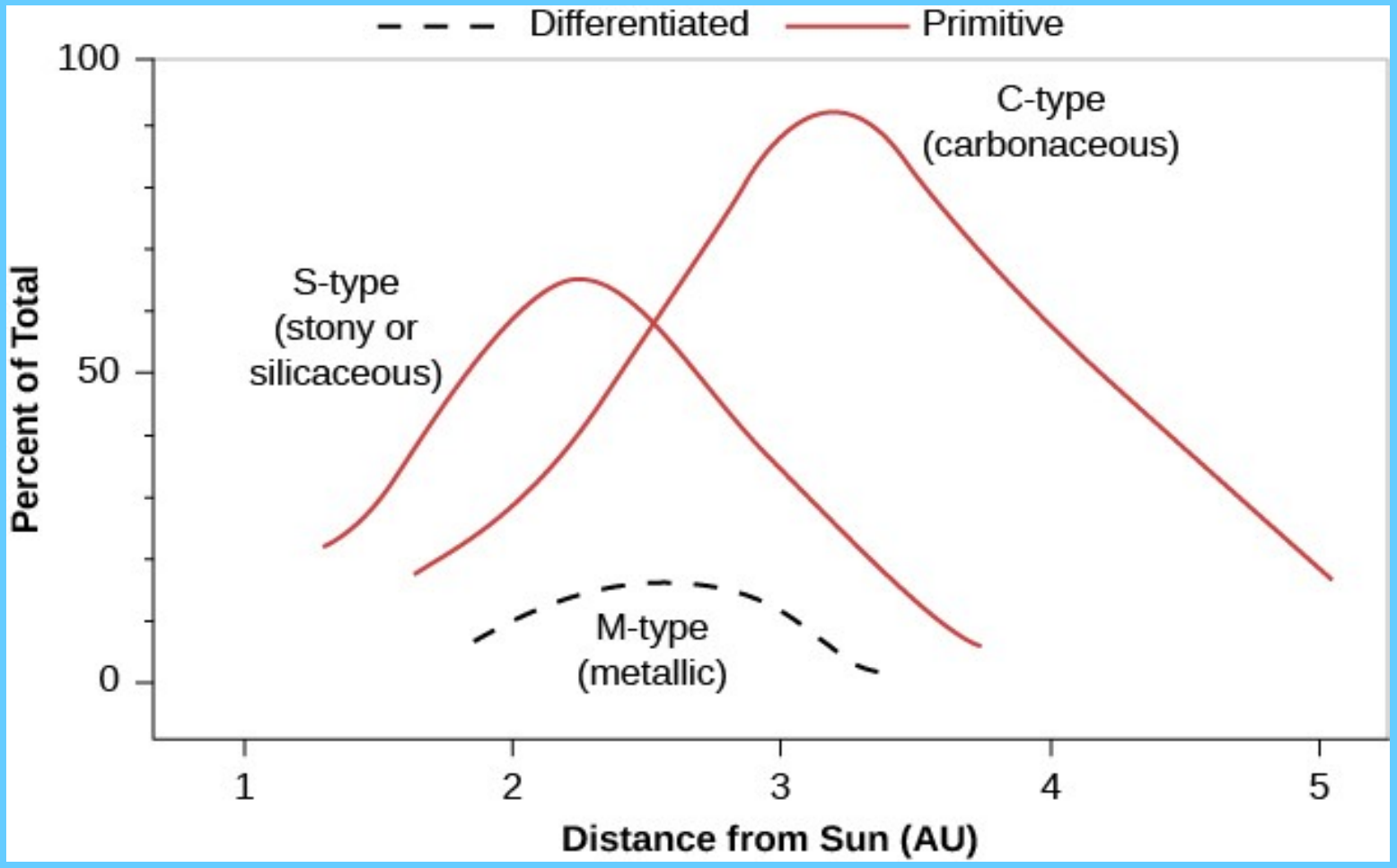


Fig. 2.— a) Near-infrared synthetic spectra of H_2O-ice. The orange dashed line shows a spectrum of crystalline ice (indicated by the 1.65 μm feature) while the solid black line corresponds to ice with a lower degree of crystallinity. b) Time-resolved 4-band spectrum of Haumea [adapted from Lacerda (2009)]. Each line is a spectrum at a given rotational phase. At rotational phases when the DRS faces the observer ($0.7 \lesssim \phi \lesssim 1.0$) the B band is depressed and the H band is enhanced. Spectra at each rotational phase are plotted relative to R band and all rotational phases have been normalised by $\phi = 0.4$. Inset shows spectra before normalisation at $\phi = 0.4$.

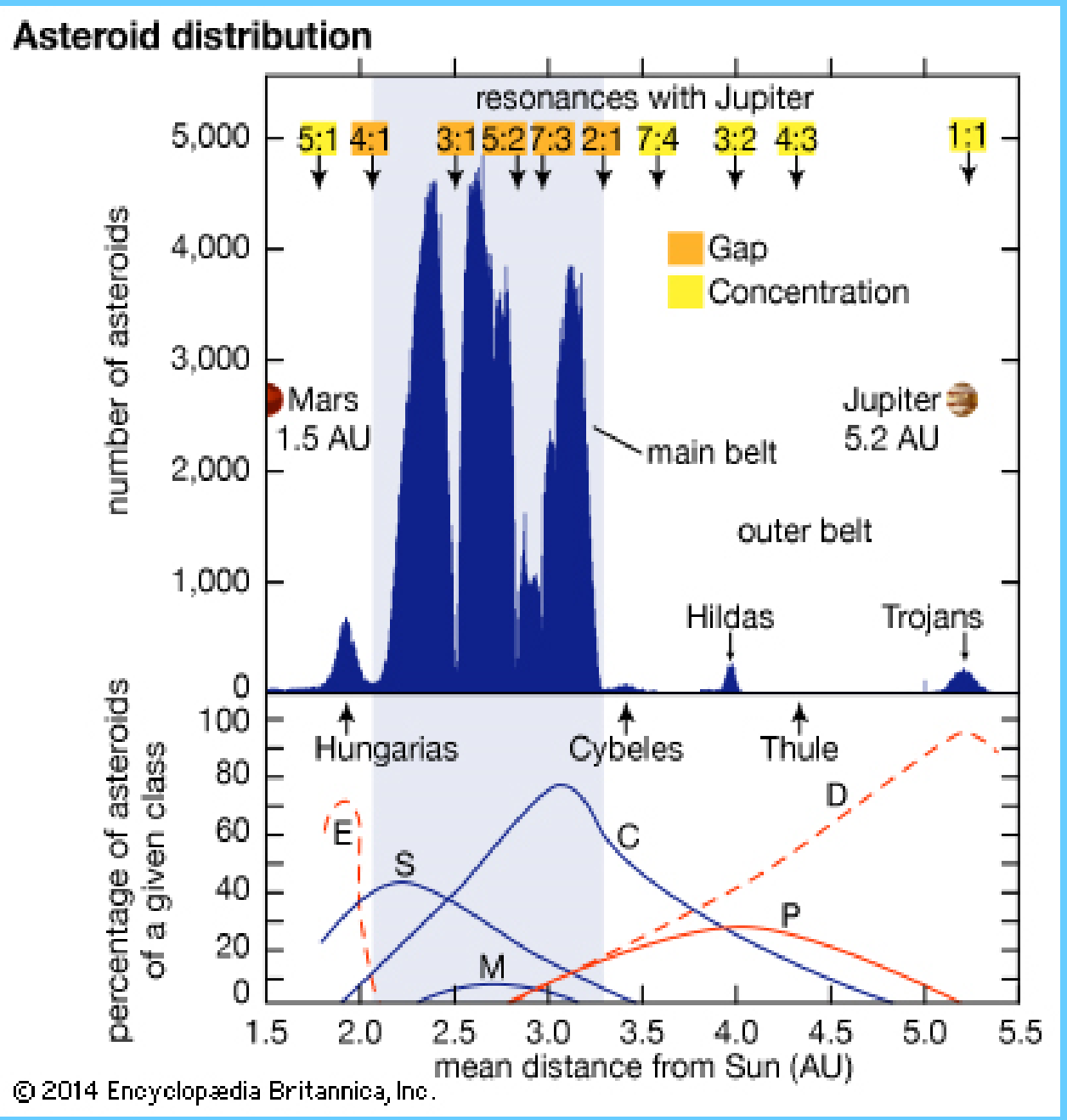
The Asteroid Compositions Roughly Depend on Distance From Sun



Inner asteroids are rocky, middle asteroids metallic, and outer asteroids carbonaceous

Why?

- Carbon bonds with other elements in such as way as to make ices; e.g. CO, CO2, CH4, and these all will melt or vaporize a low temperatures.
- For water ice to be stable in a vacuum, it must be colder than 170K, which happens in the outer asteroid belt at 2.7 AU.
- Inside this, the carbon compounds would tend to evaporate, leaving rock and metals
- The metallic asteroids are clearly from the inner cores of collision remnants of larger and therefore differentiated (layered) asteroids or early planets

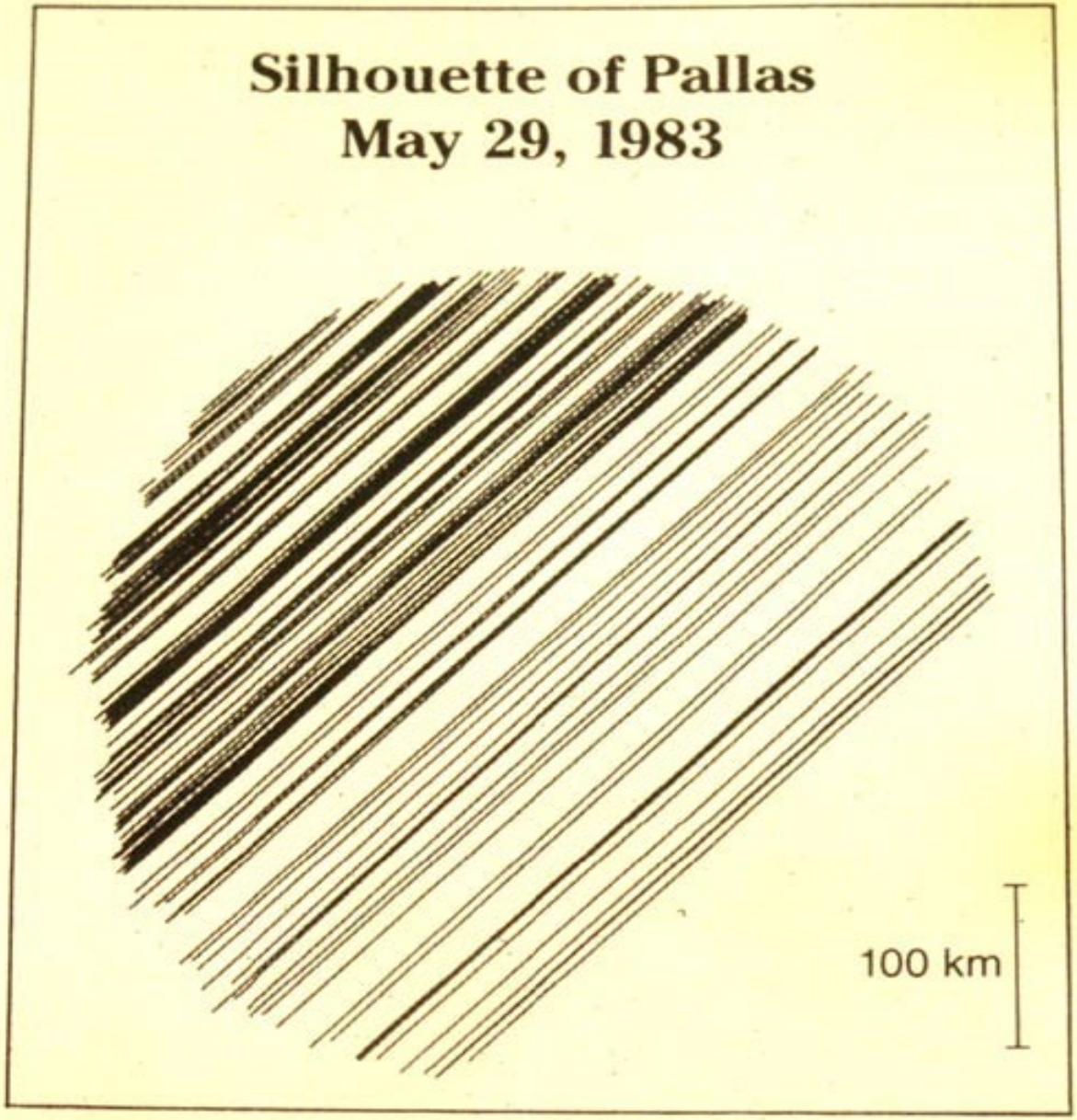


Orbit sizes show ring structure just like Saturn's rings, for the same reason: Orbital resonances, here with Jupiter

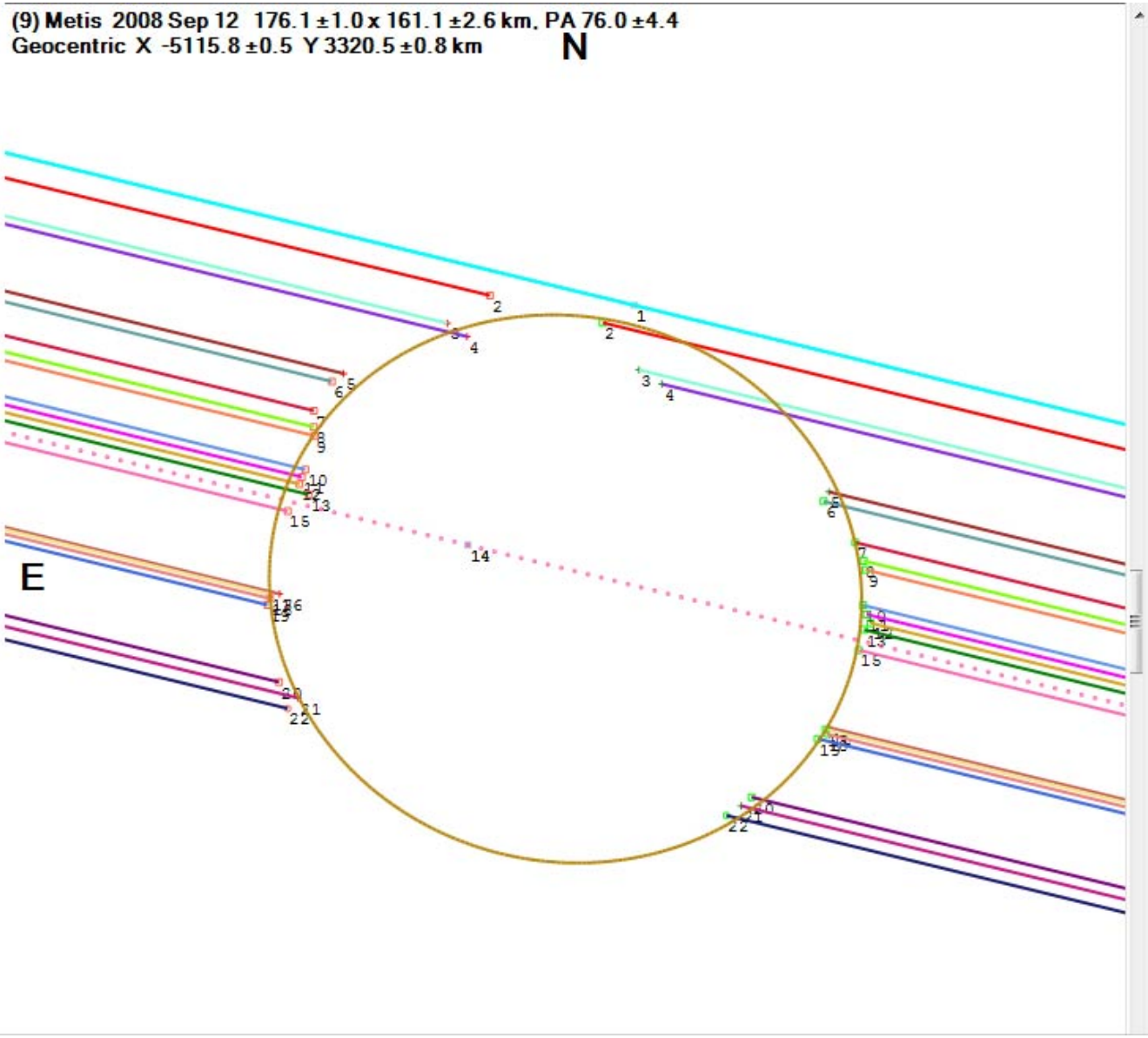
Amateur Astronomers are Helping to Advance our Understanding of Asteroids

- Asteroid occultations of stars allow us to measure the size, shape, and precise orbits of asteroids.
- IOTA provides software, website info etc and data collection and analysis of this data
- Here's a YouTube video of an asteroid occultation…
- Palma occultation, by R Nugent (0:25)

- Binary asteroid Antiope: Video of visualization of shadows crossing California and occultation observers - YouTube



Scores of observers timed the occultation of a star by Pallas nine years ago, yielding this high-resolution profile of most of the



Find best fit

Center X	-1.1	☑ 0.0	
Center Y	-9.9	☑ 0.0	
Major axis (km)	176.1	☑ 0.0	a/b=1.09
Minor axis (km)	161.1	☑ 0.0	dM=-0.10
Orientation	76.0	☑ 0.0	

Double star

Sepn (masec)	0.0	☐ 0.0
PA of 2nd	0.0	☐ 0.0

◉ Both ○ Primary ○ Secondary

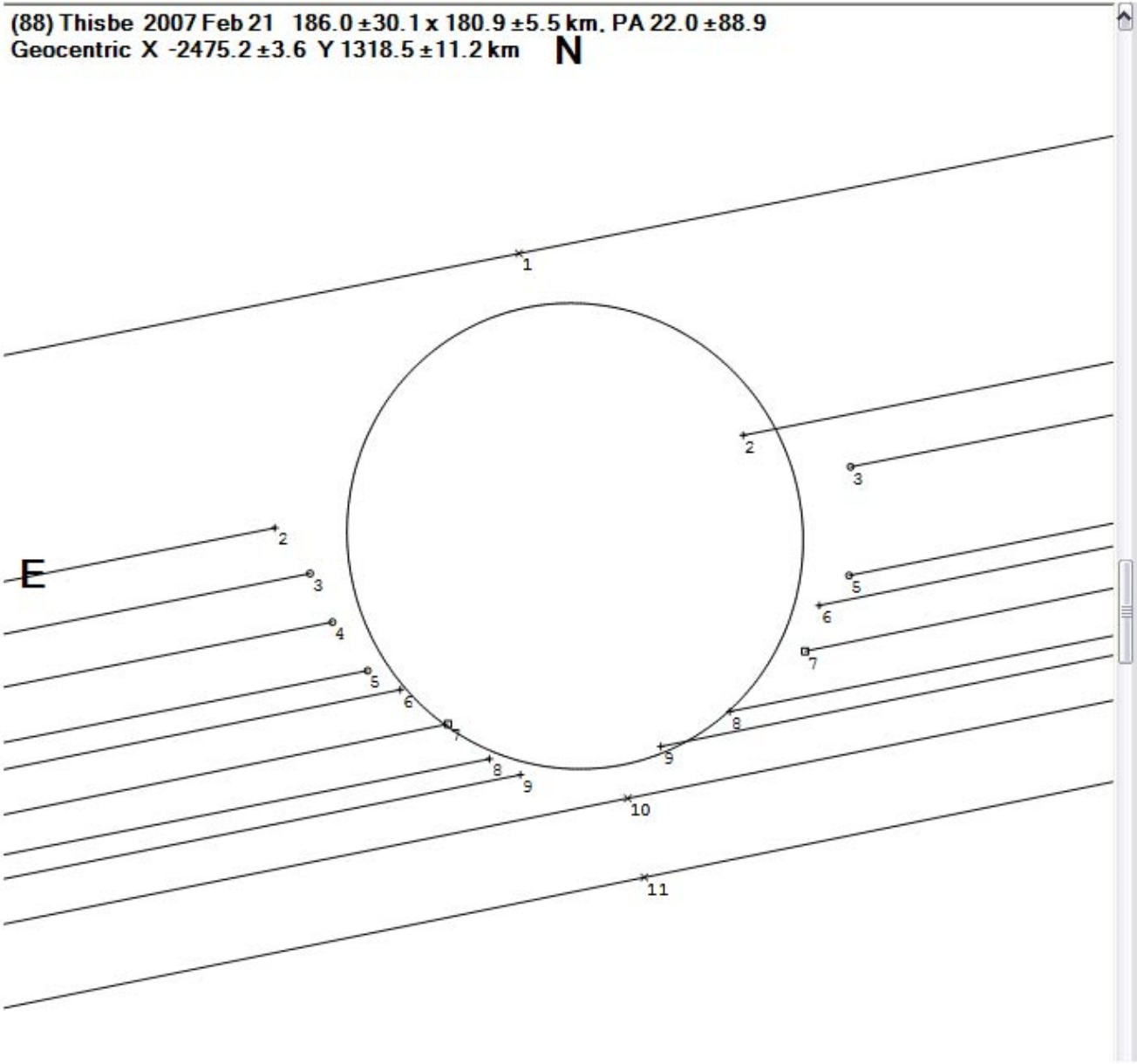
☐ Circular ☐ Include Miss events

Plot scale

Quality Not fitted

RMS fit -0.5 ±4.2 km

1 (M)	S Degenhardt,Taft, C	
2	R Nolthenius,Carrizo	
3	J Clark,Ridgecrest,	
4	D Blanchette,Las Veg	
5	R Lambert,North Las	
6	P Maley,Las Vegas NV	
7	G Lucas/E Wilson,Kra	
8	W Morgan,Kramer Junc	
9	W Morgan,Kramer Junc	
10	D Breit,Kramer Junct	
11	D Dunham,Kramer Junc	
12	R Nugent,Edwards AFB	
13	D Dunham,Kramer Junc	
14 (P)	Predicted Centerline	
15	D Dunham,Kramer Junc	
16	L Benner,Sierra Madr	
17	K Coughlin,Victorvil	
18	M Hicks,Wrightwood,	
19	G Lyzenga,Mt. Wilson	
20	R Jones,Sky Forest,	
21	M Vincent,Big Bear C	
22	M Vincent,Big Bear C	



Find best fit

Center X	4.9	0.0
Center Y	11.7	0.1
Major axis (km)	186.0	-5.3
Minor axis (km)	180.9	26.2
Orientation	22.0	-0

Double star

Sepn (masec)	0.0	0.0
PA of 2nd	0.0	0.0

Both Primary Secondary

Circular Include Miss events

Plot scale Quality Not fitted

RMS fit 8.1 ±10.3 km

```
 1(M) C Stephan, Sebring, FL
 2    B Konior, Cape Coral, FL
 3    D Dunham 1, levee near US 27, FL
 4    T Campbell, Bonita Springs, FL
 5    D Dunham 2, Weston, FL
 6    P Gabriel, McAllen, TX
 7    K Coughlin, Baja California Sur, MX
 8    D Parker, Coral Gables, FL
 9    R Chavez, M Escobedo Int Aprt, MX
10(M) P Sada, Univ. de Monterrey Obs, MX
11(M) R Fleishman, Santa Rita, BCS Mexico
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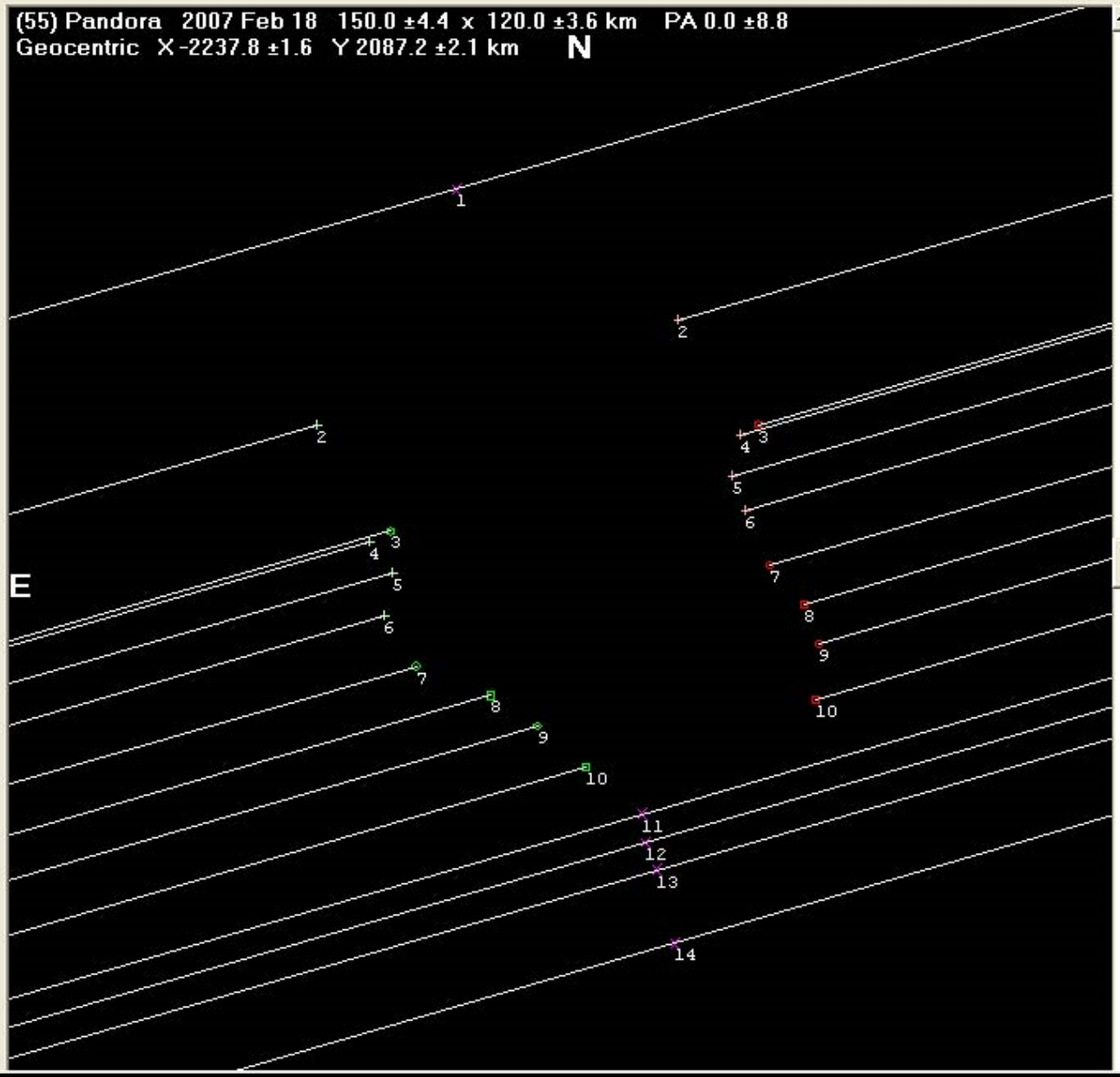
Another very Oblong Asteroid



Center X	0.0	3.1
Center Y	0.0	8.4
Major Axis (km)	150.0	-49.5
Minor Axis (km)	120.0	-53.8
Orientation	0.0	45.6
Sepn (masec)		0.0
PA of 2nd star		0.0

Include Miss events

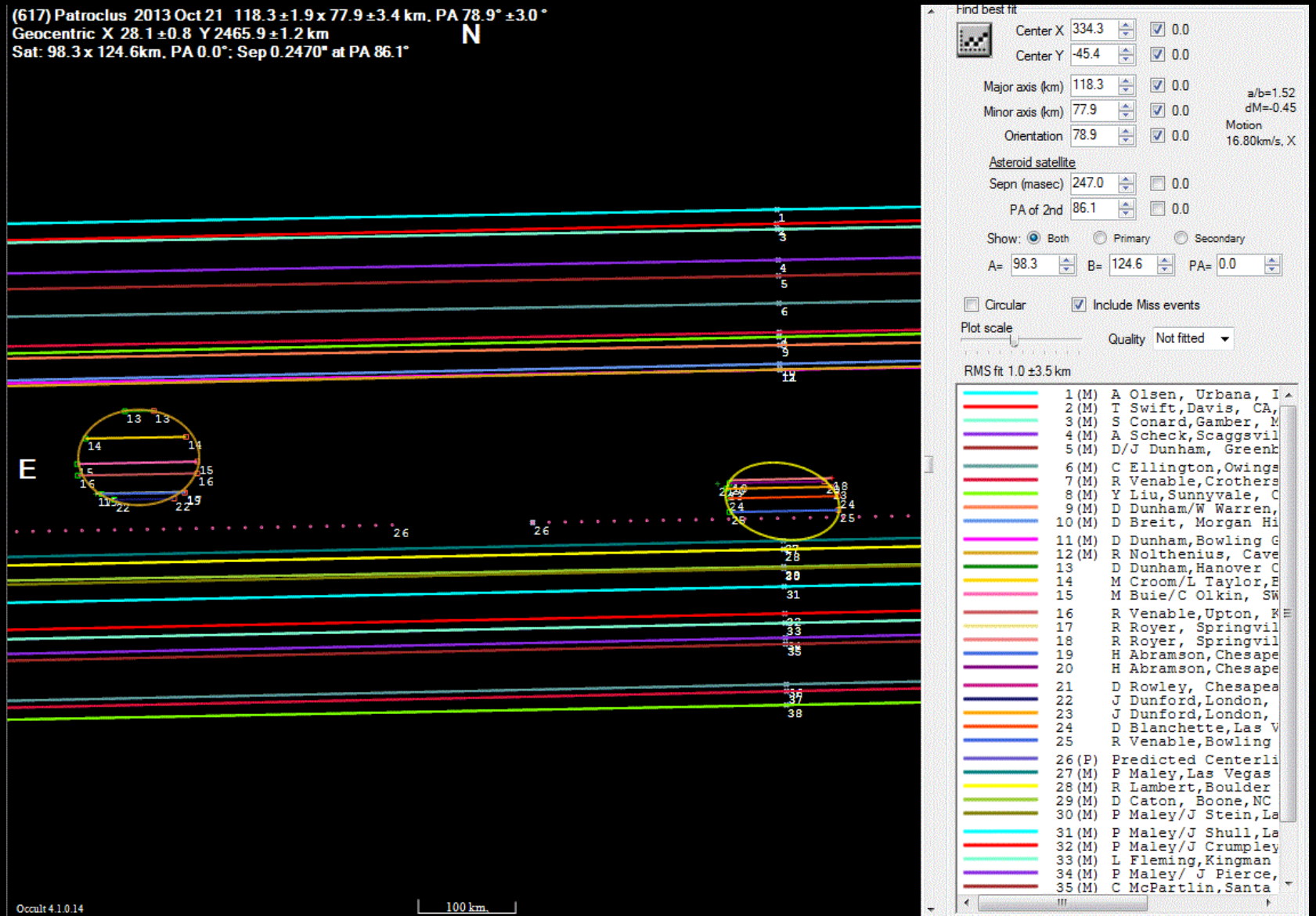
Circular Quality Not fitted

Plot Scale

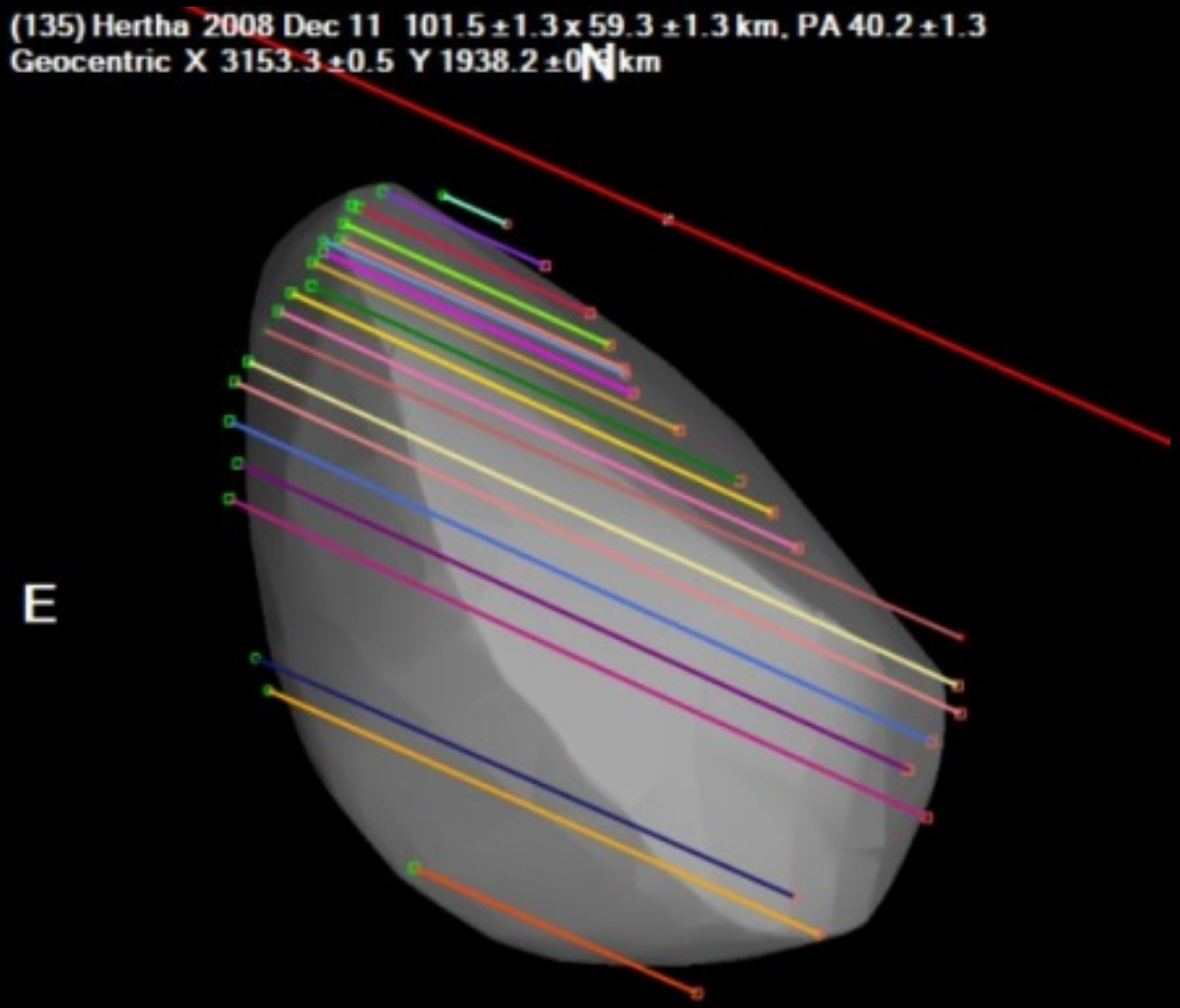
rms Fit: -28.8 ±9.2km

1(M)	Steve Welch/Bill Wallace, Belen, NM
2	Kevin McKeown, San Acacia, NM
3	Daniel Klinglesmith, Socorro, NM
4	Mark B. Vincent, Sorocco, NM
5	Ben Hudgens, Albany, TX
6	Richard Nolthenius, Pismo Beach, CA
7	Paul Maley, Ennis, TX
8	Gregory Lyzenga, Rosamond, CA
9	Rick Wasson, Adelanto, CA
10	Robert Jones, Adelanto, CA
11(M)	David Meyer, Apple Valley, CA
12(M)	Wayne Thomas, Black Canyon City, AZ
13(M)	Randy Peterson, Payson, AZ
14(M)	Karen Young, Wrightwood, CA

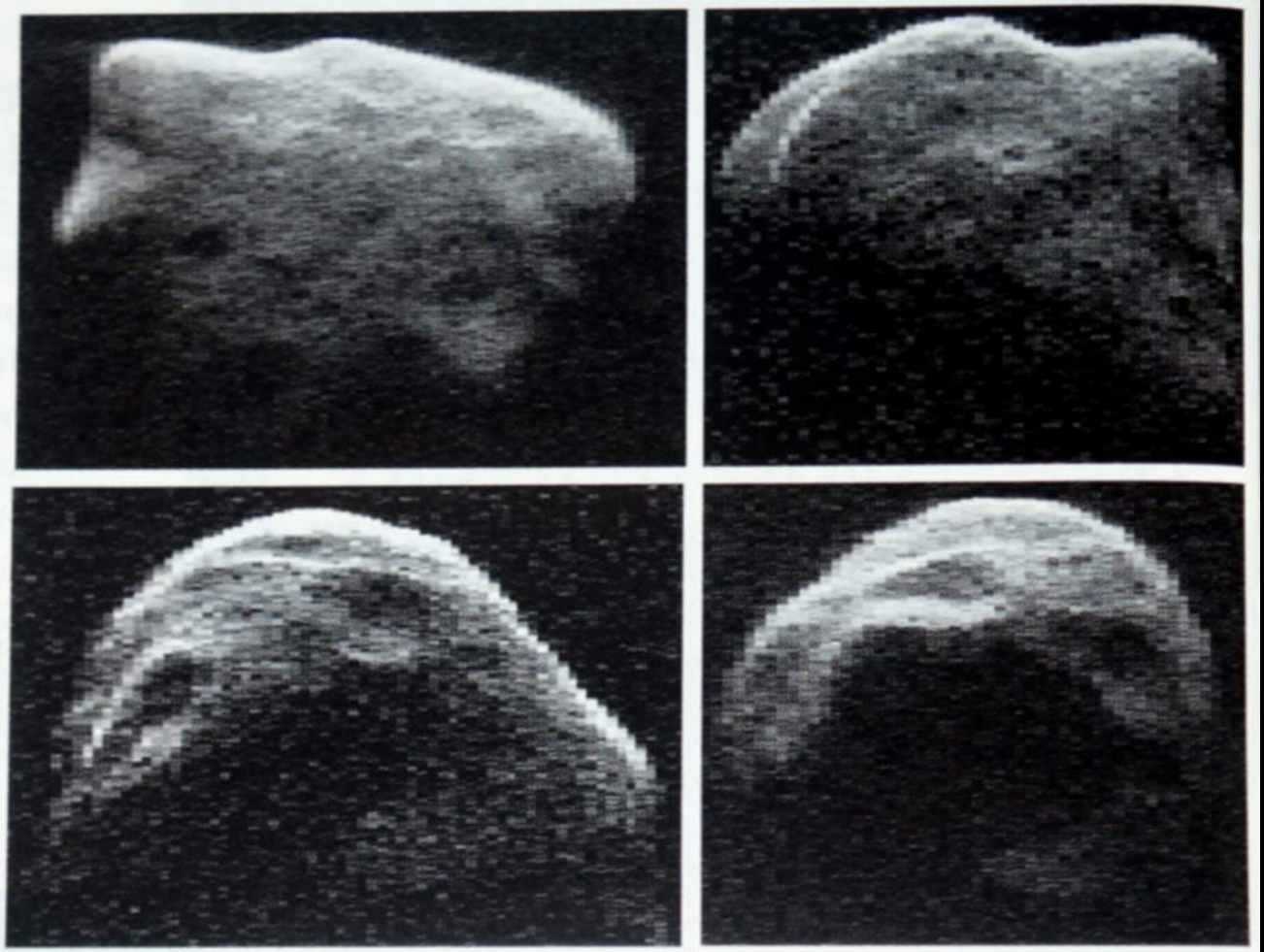
A Binary Asteroid Mapped by the Occultation Method



Combining with Photometry can Given and Even Better Model of the 3D Shape



Radar Echos Can Also Give Shape if Asteroid Makes Close Approach to Earth, Like this 3.5km NEO



S. OSTRO, L. BENNER / JPL / NAIC

With a diameter of about 3.5 kilometers, 1999 JM_8 became the largest near-Earth asteroid to be imaged by radar when it tumbled past our planet three years ago. It missed us by a wide 8.5 million kilometers, 22 times the distance of the Moon.

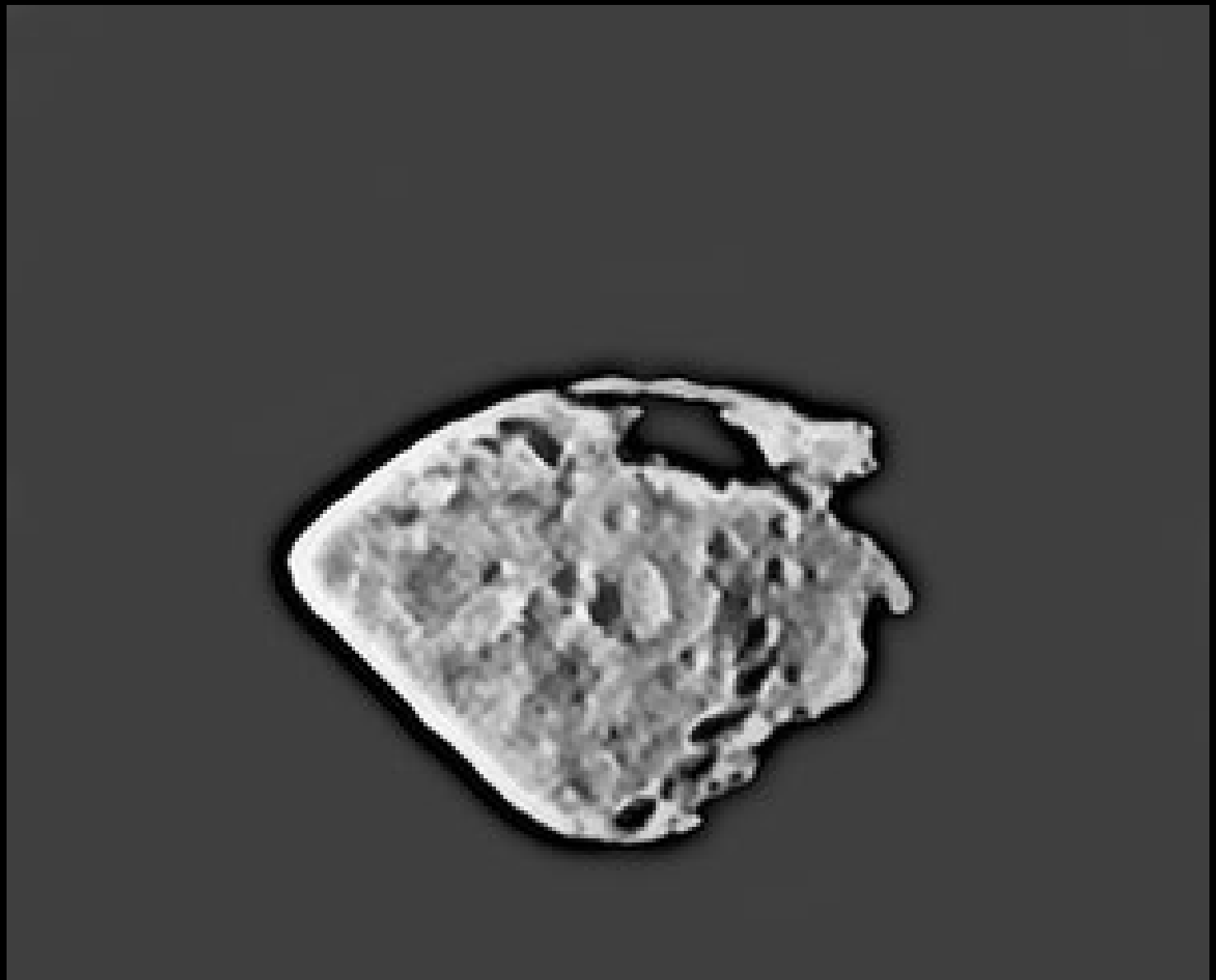
Radar Imaging of 2015HM10, a Boeing 777 sized NEO sliding by Earth in summer 2015

Radar Imaging of Asteroid 2011 UW158

- https://www.youtube.com/watch?t=18&v=l4uO69DEcMI (57 seconds)

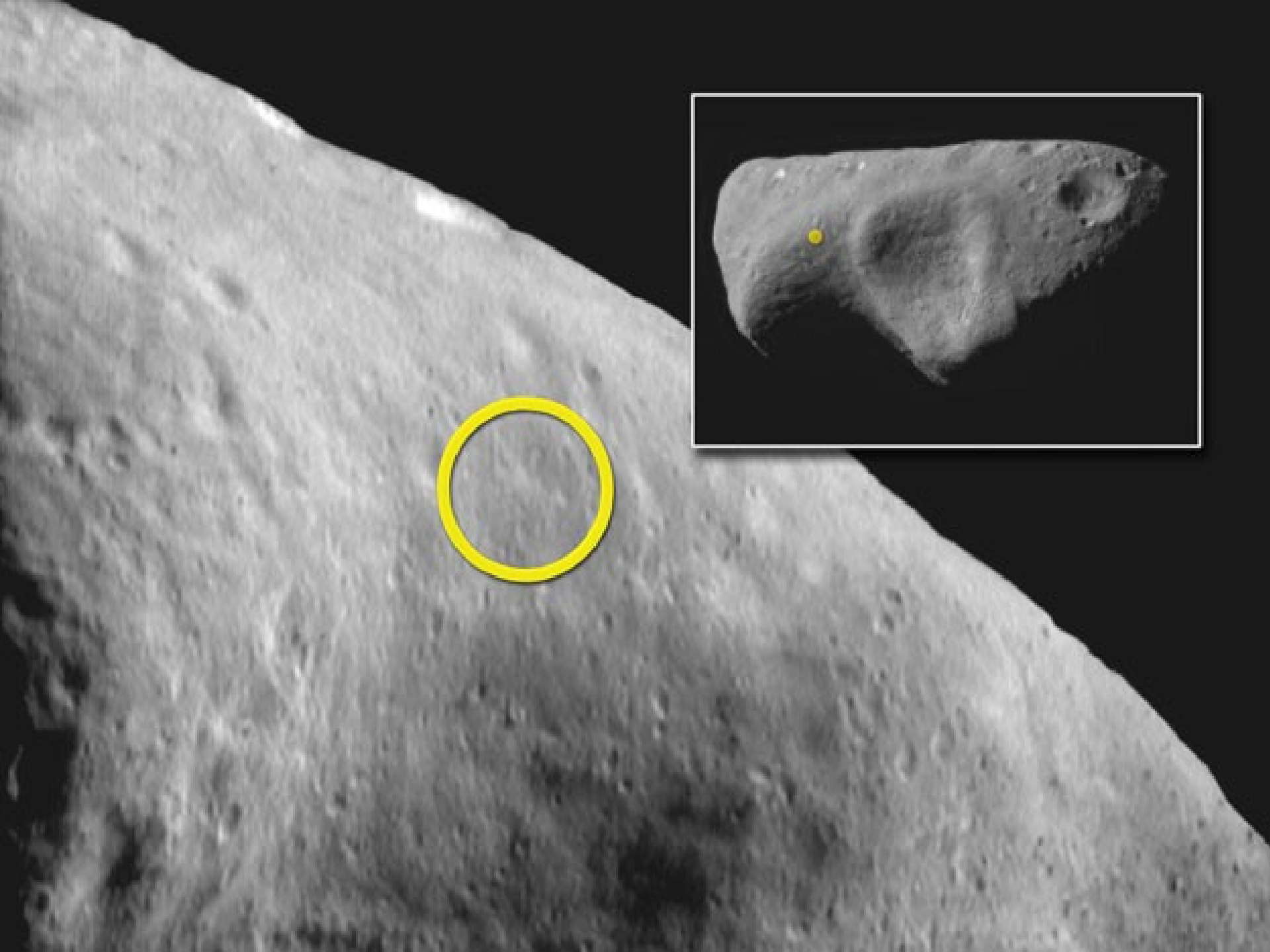
The Asteroid AnneFrank

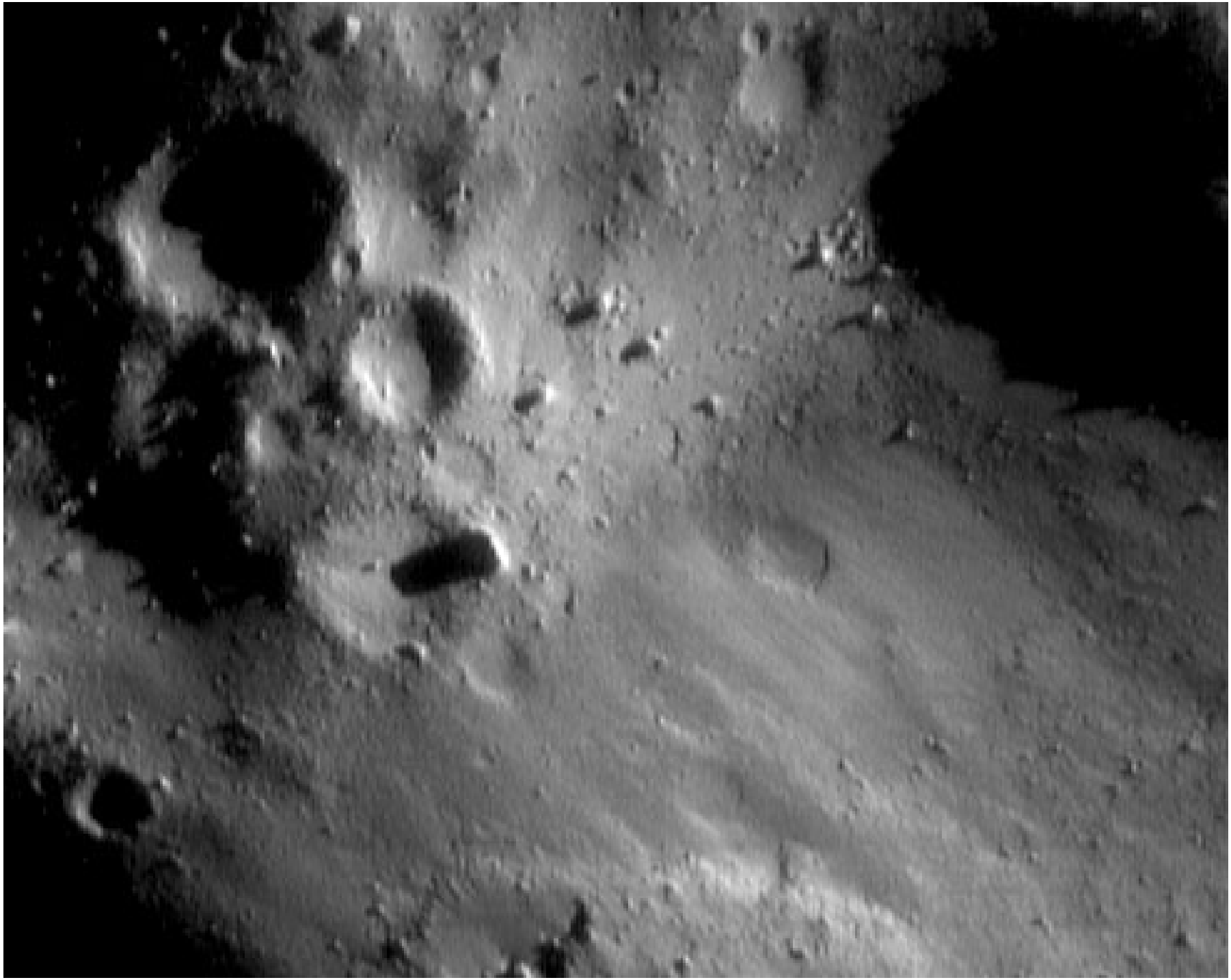
Rosetta Mission: Flyby of Asteroid Steins

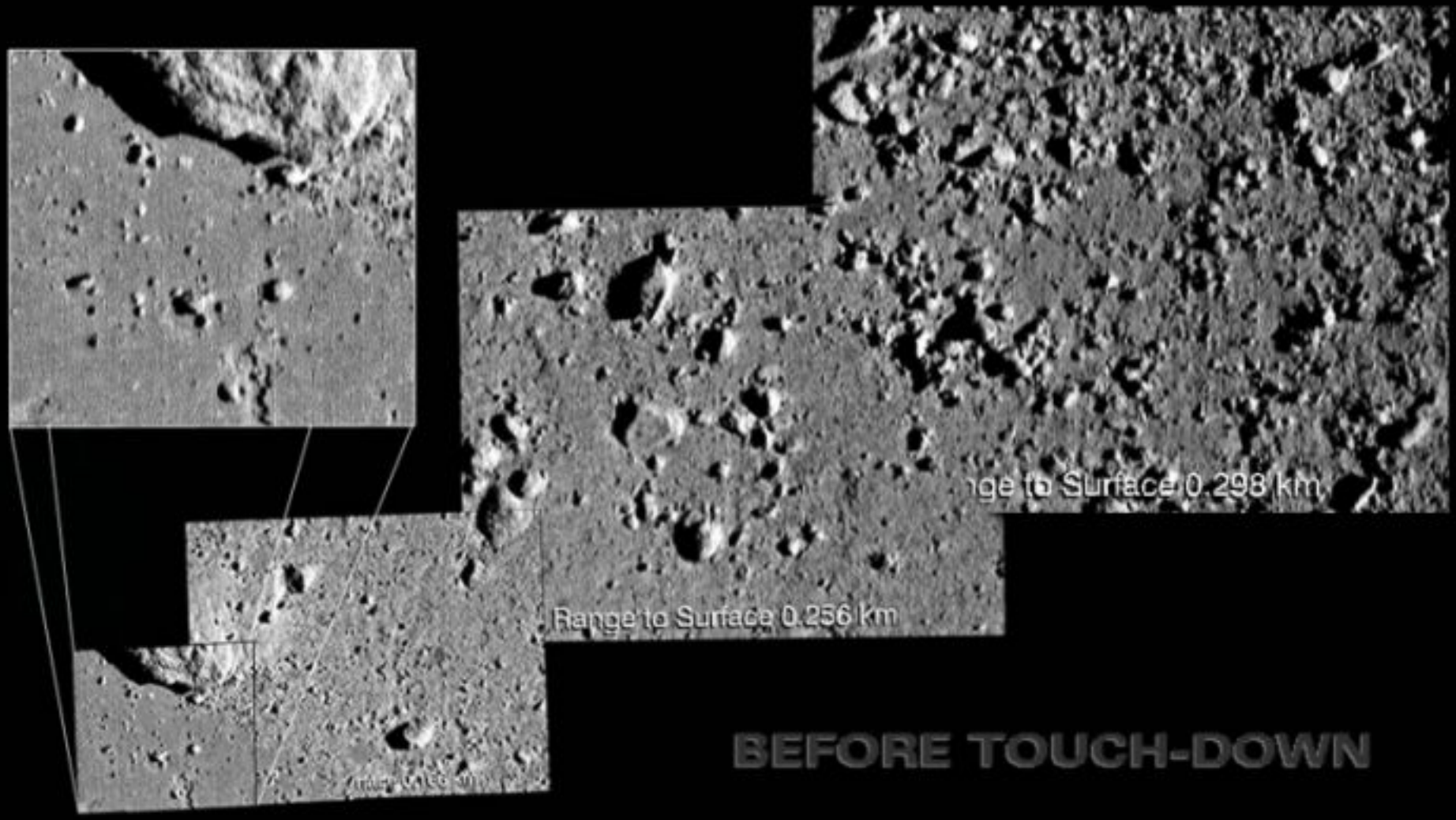


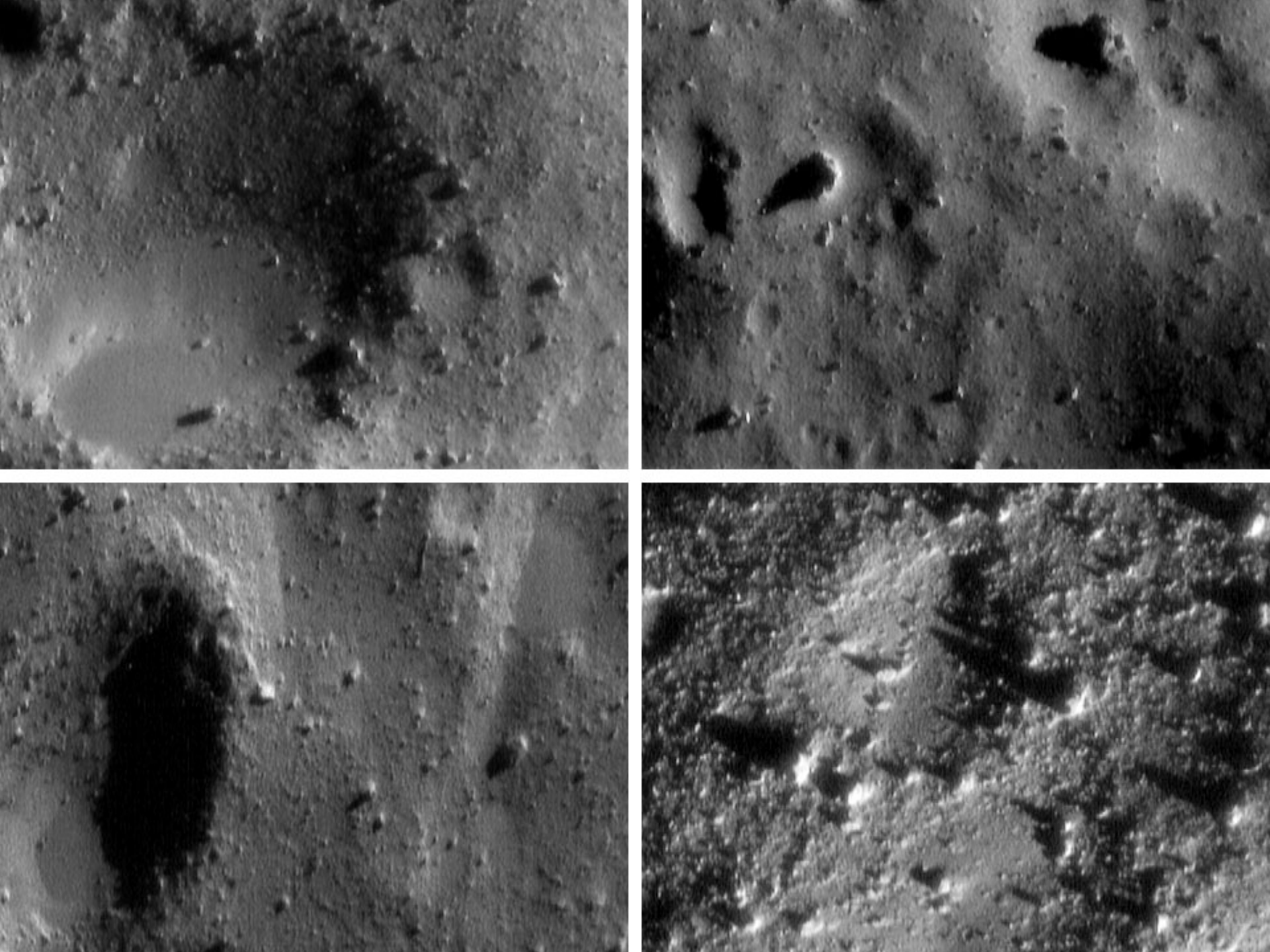
Rosetta flyby: Asteroid Lutetia

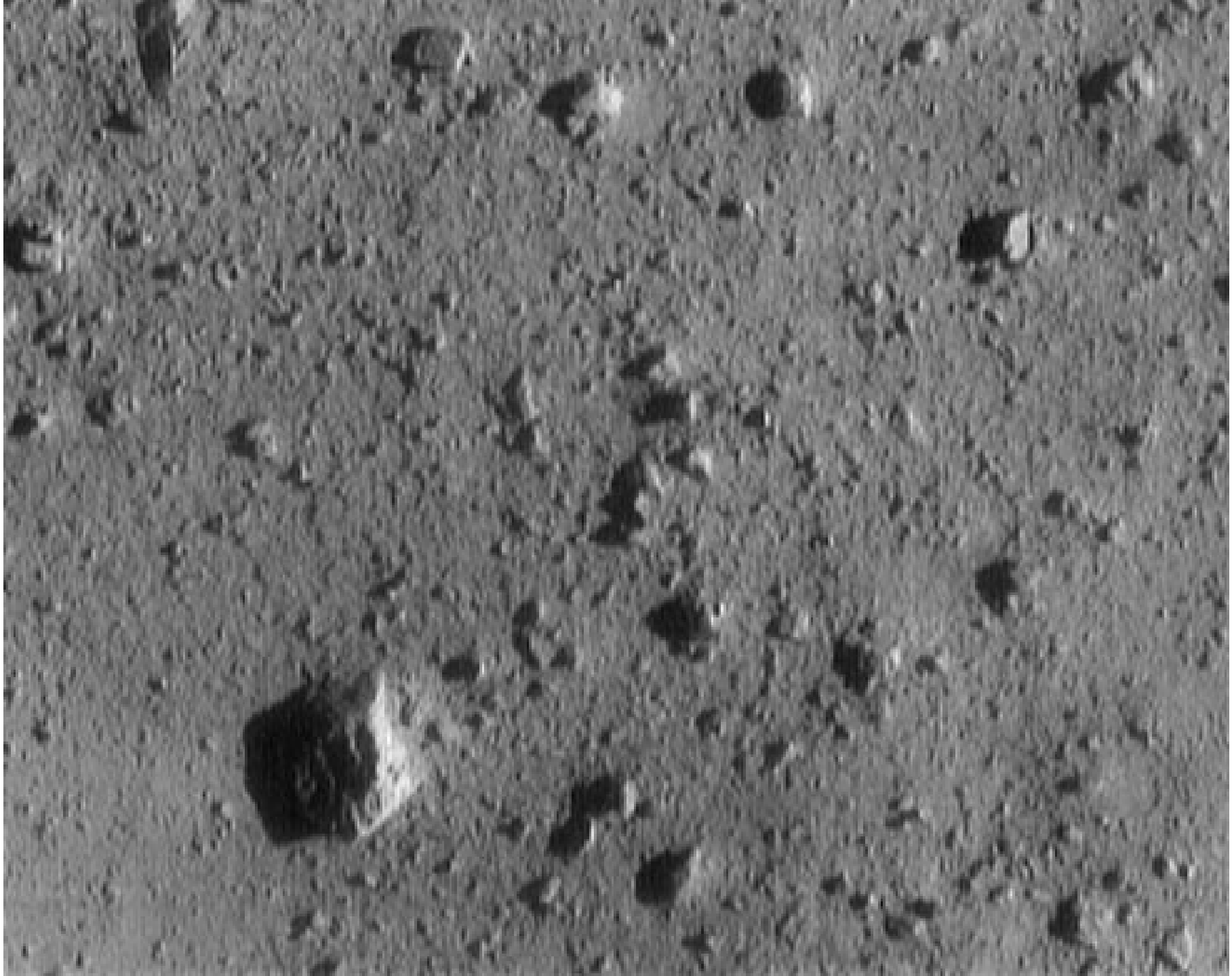
Eros – Largest Near Earth Object (NEO). We Sent a Space Mission Here. The Only Asteroid Landed On

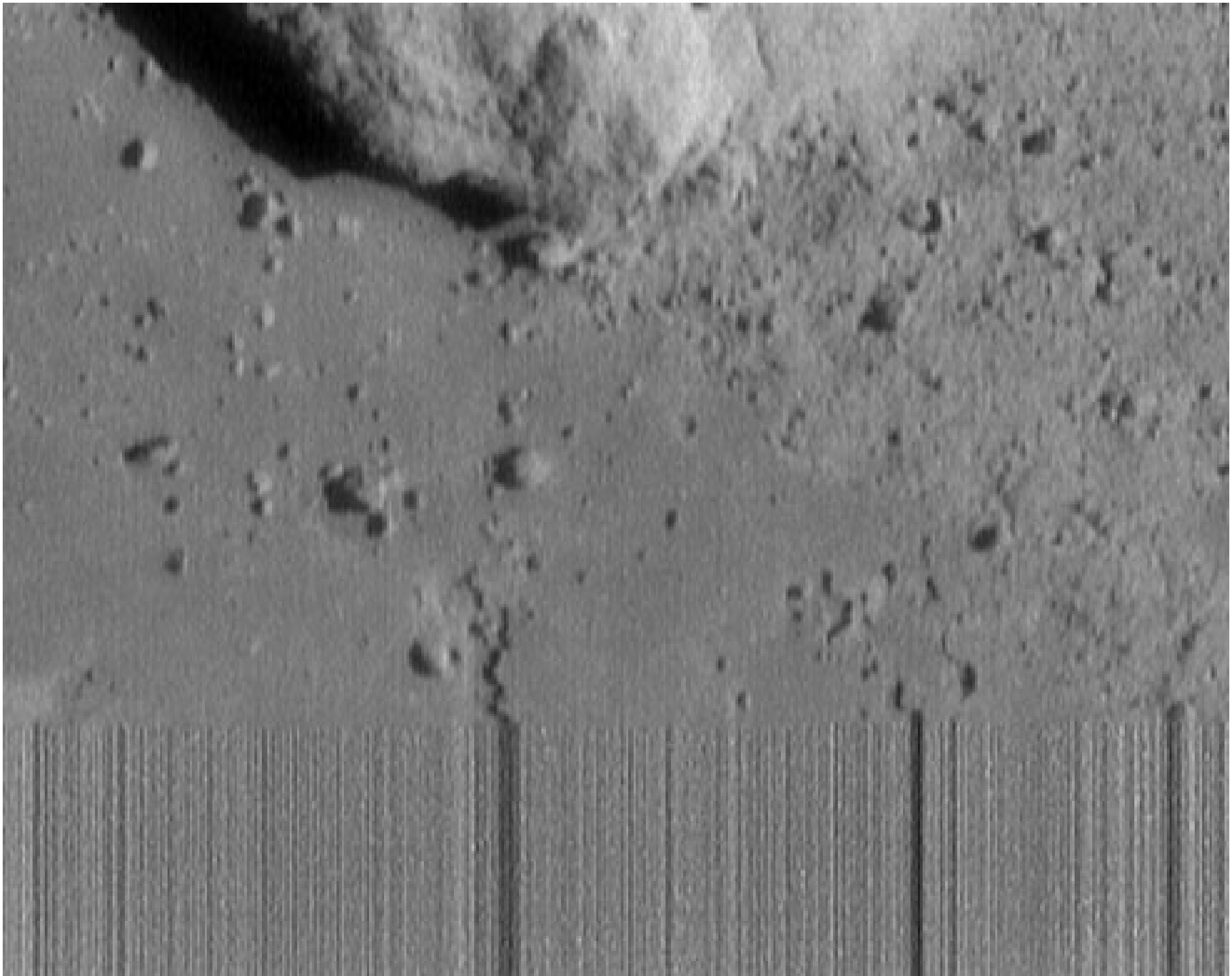





nge to Surface 0.298 km
Range to Surface 0.256 km
BEFORE TOUCH-DOWN







Eros – Not so Romantic…

- Not a "rubble pile", but instead a consolidated object, held together not by gravity but like a solid rock.
- Covered by a million boulders scattered by a large impact 1 billion years ago
- All small craters within 9 km of the impactor site were seismic shaken and erased
- **Expected to become an Earth-crossing asteroid by orbital migration, in just ~2 million years. 50/50 odds it will eventually hit the Earth, causing more mayhem…**
- **A Disaster of Biblical Proportions, like the K-Pg boundary impact which killed the dinosaurs.**

Gaspra – Shape says a giant “boulder”, like Eros, not gravity-held loose stuff

Ida and its moon - Dactyl

The Hayabusa I Mission

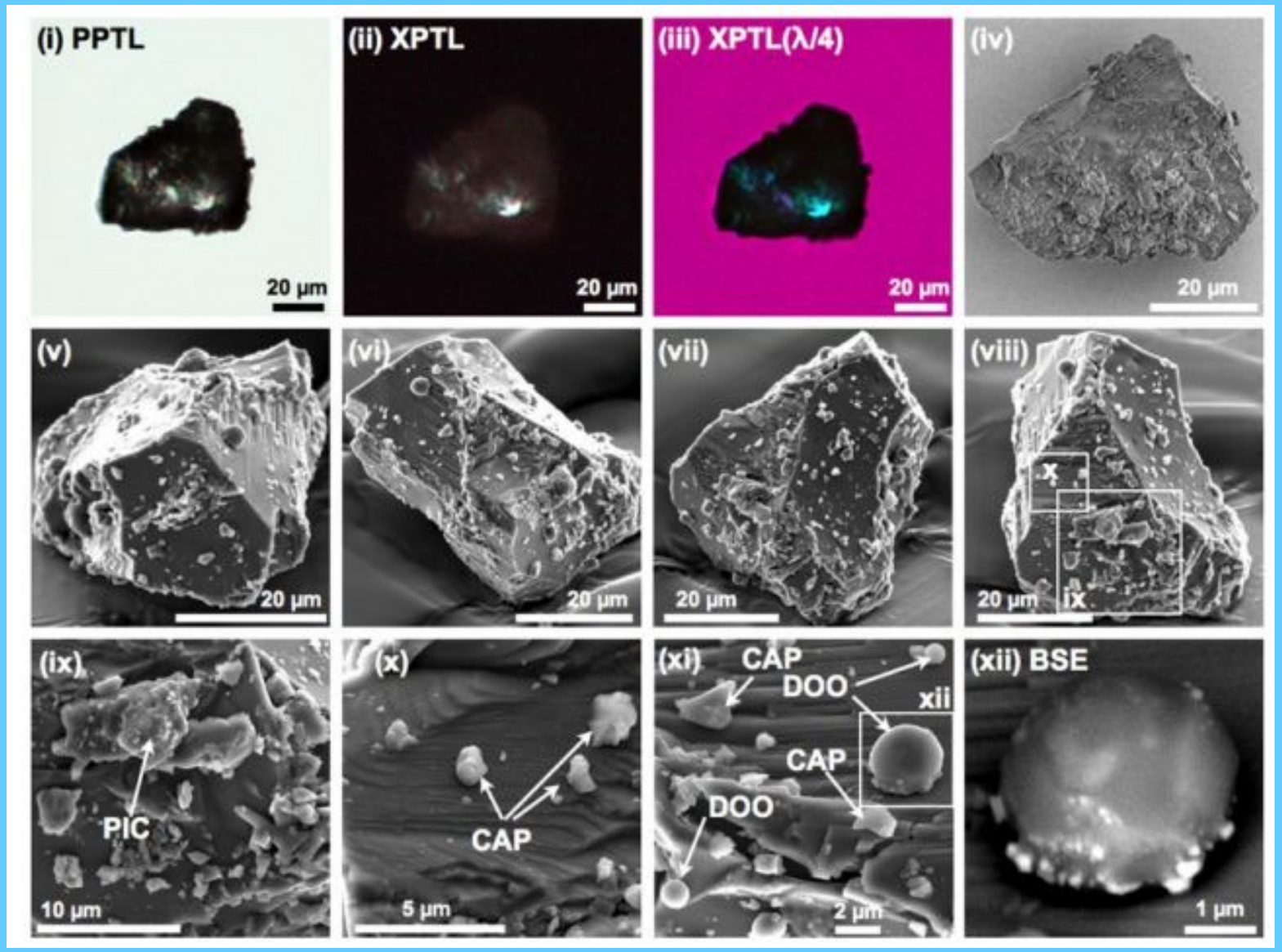
- This mission, launched in 2003, a project of the Japanese Aerospace Agency (JAXA) and NASA JPL, went to the asteroid Itokawa.
- As the first mission to return material from an asteroid, it was trial by fire, with many harrowing brushes with failure.
- *"Problems with frozen pipes, leaking fuel, and communications glitches caused even more consternation as the spacecraft attempted to depart the asteroid," Gizmodo added. "By the time the return capsule was headed back to Earth, only two of four ion engines and seven of 11 batteries were working; another ion engine automatically shut down partway through the journey home. By re-entry, the reaction control system was no longer functional."*

I’m doing last minute calculations for the incoming re-entry coordinates, in the Australian Outback

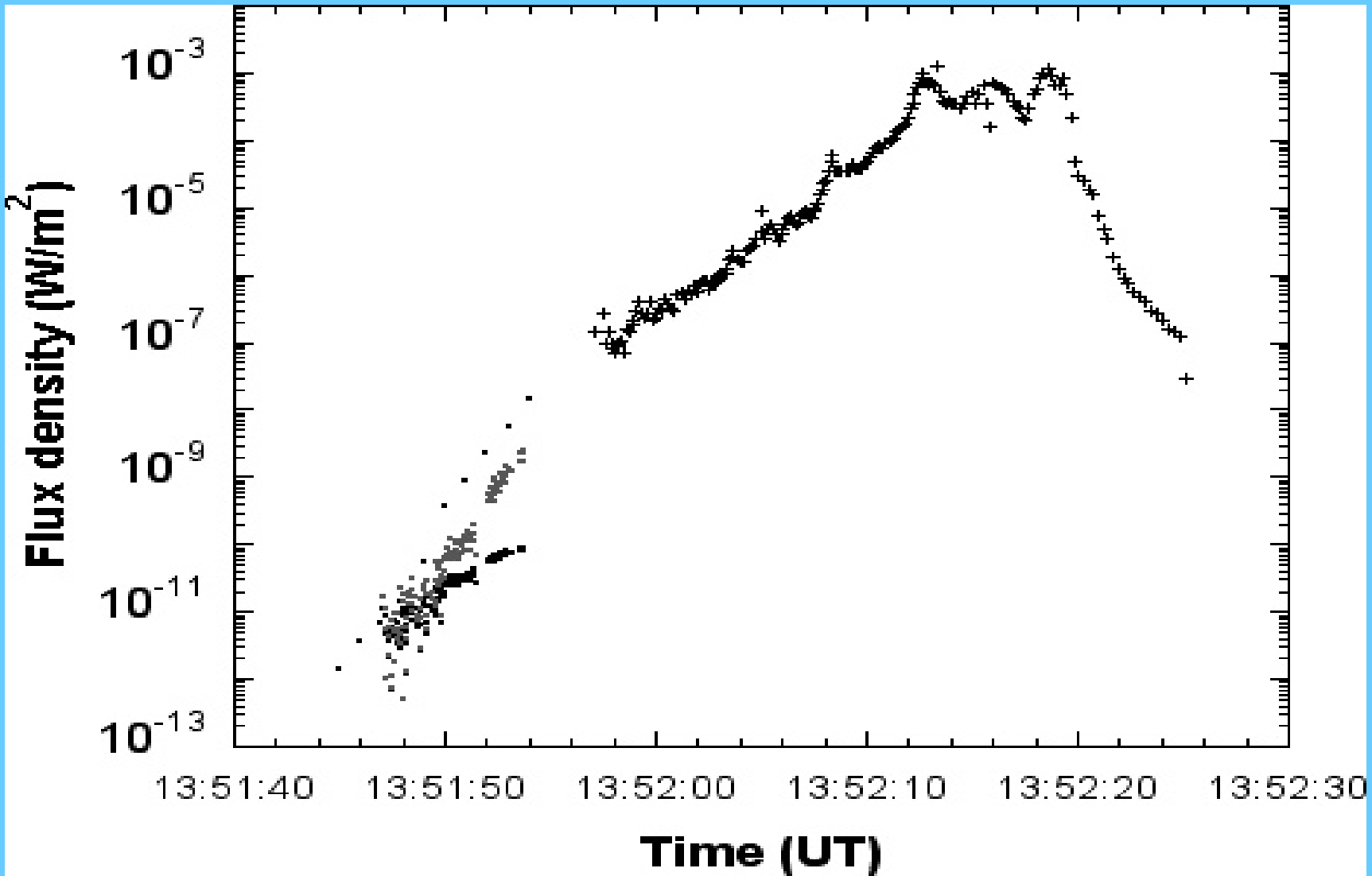
Nevertheless – The mission was a success! Over a thousand asteroid mineral grains were recovered

- I was the astronomer on the forward ground team at recovery, deep in the Australian outback, for re-entry June 13, 2010. Look at the fun astronomers have!
- Our paper, presented at the JAXA/NASA conference on the science, in Australia, is here

Electron micrographs of mineral grains from Itokawa, gathered from Hayabusa I



The new heat shield design was successfully characterized by my photometry of the early re-entry fireball



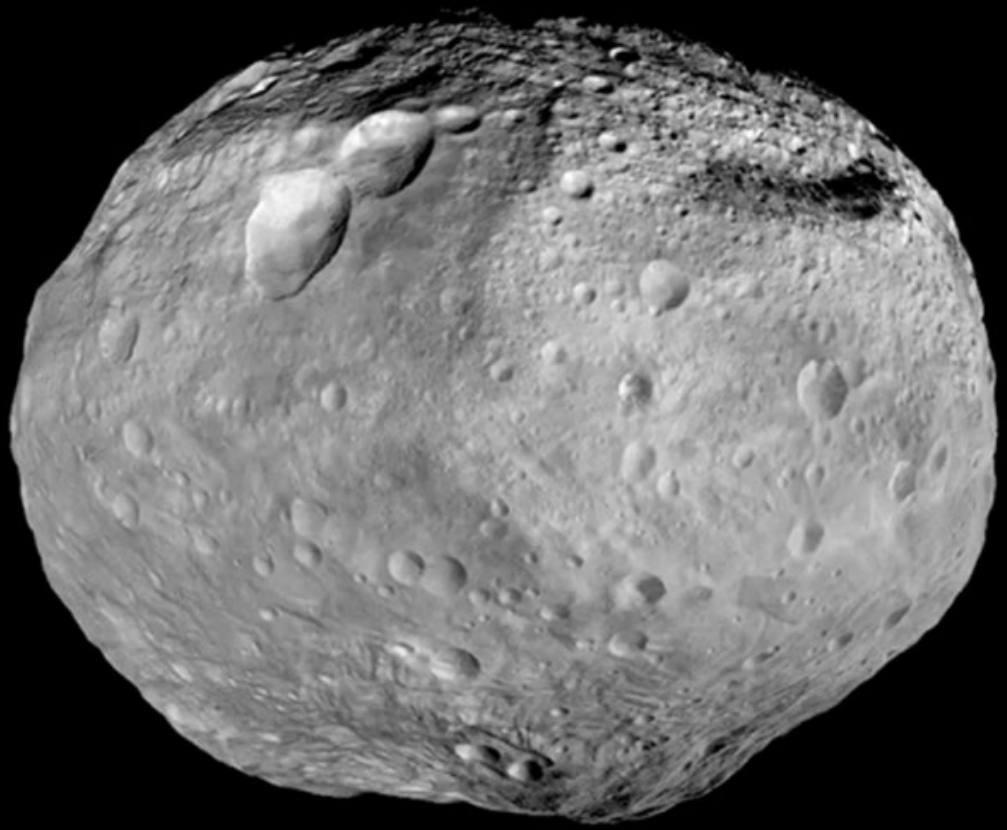
Hayabusa II

- JAXA fine-tuned the space craft and procedures from what was learned from Hayabusa I, and in Feb 2019 arrived at the asteroid Ryugu.
- Here's a really great YouTube video (1:55) of the sample gathering on the asteroid.
- What's frustrating, is that it took crowd-funding from citizens to get the video camera on the mission. Meanwhile we spend hundreds of billions just in tax breaks and subsidies to Big Oil, to do what they do.

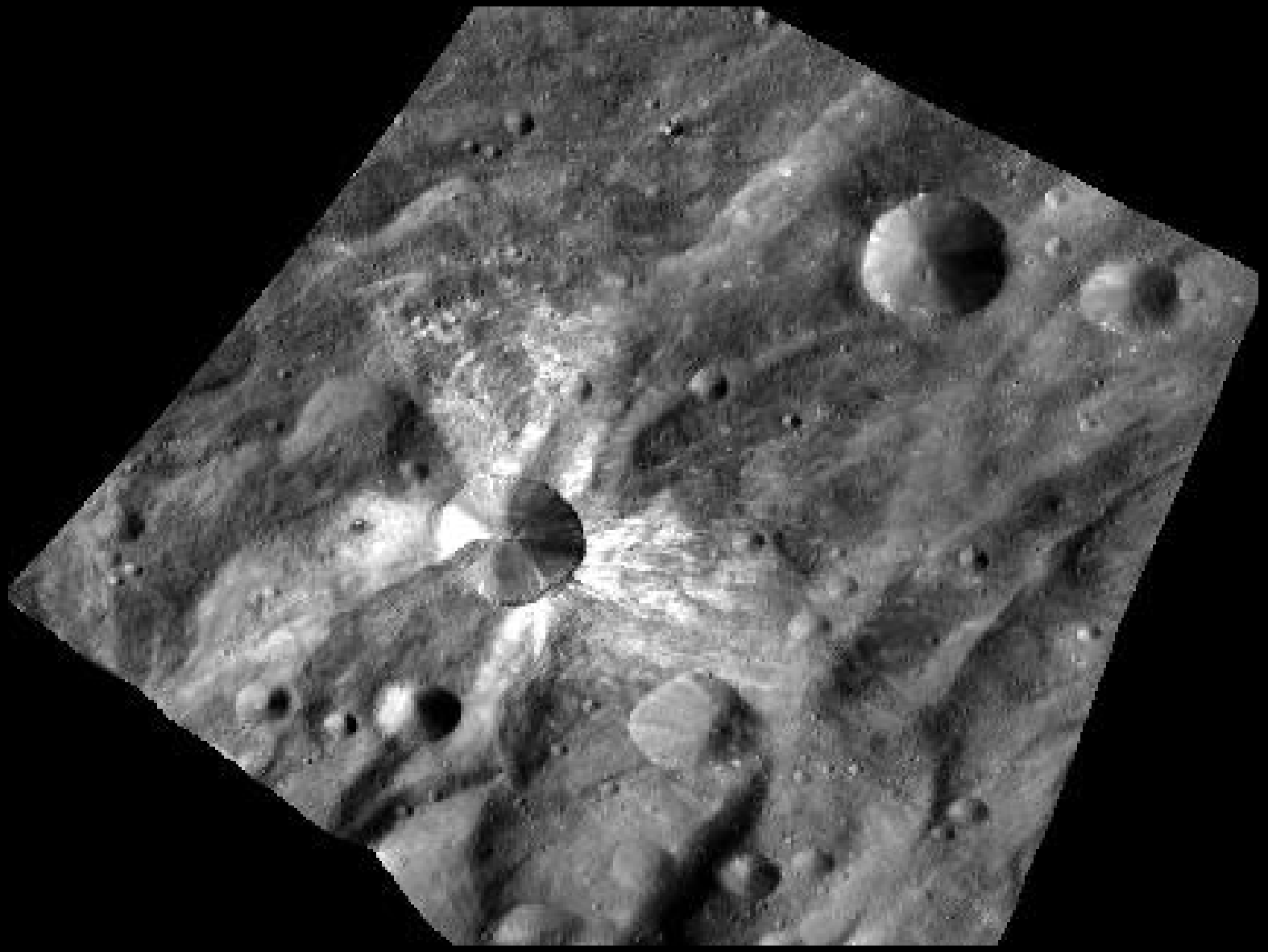
The “Dawn” Mission to Vesta

- In 2011, the NASA’s “Dawn” mission arrived at Vesta and took up orbit, to map and study the brightest of all asteroids – Vesta
- A cool little video of Dawn at Vesta (2:00)

Composite Image of Vesta – Brightest and One of the Largest Asteroids



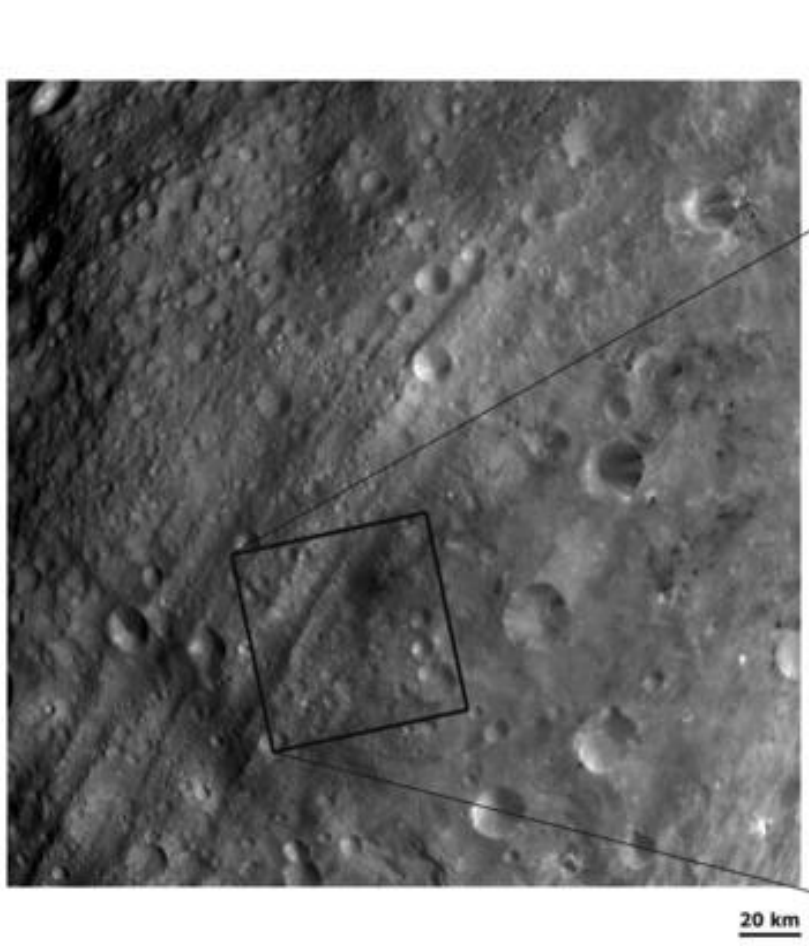
Freshly Excavated Material from this new Crater on Vesta: Very Reflective

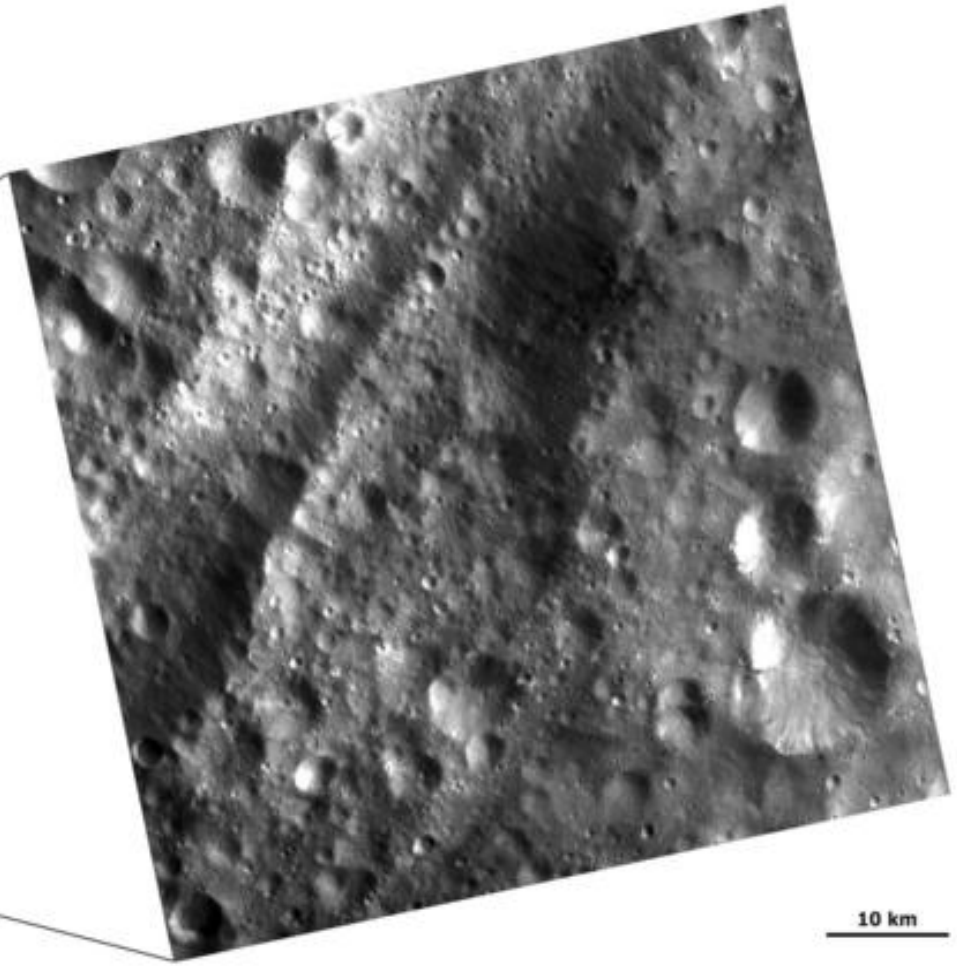


What Did Dawn Teach Us About Vesta?

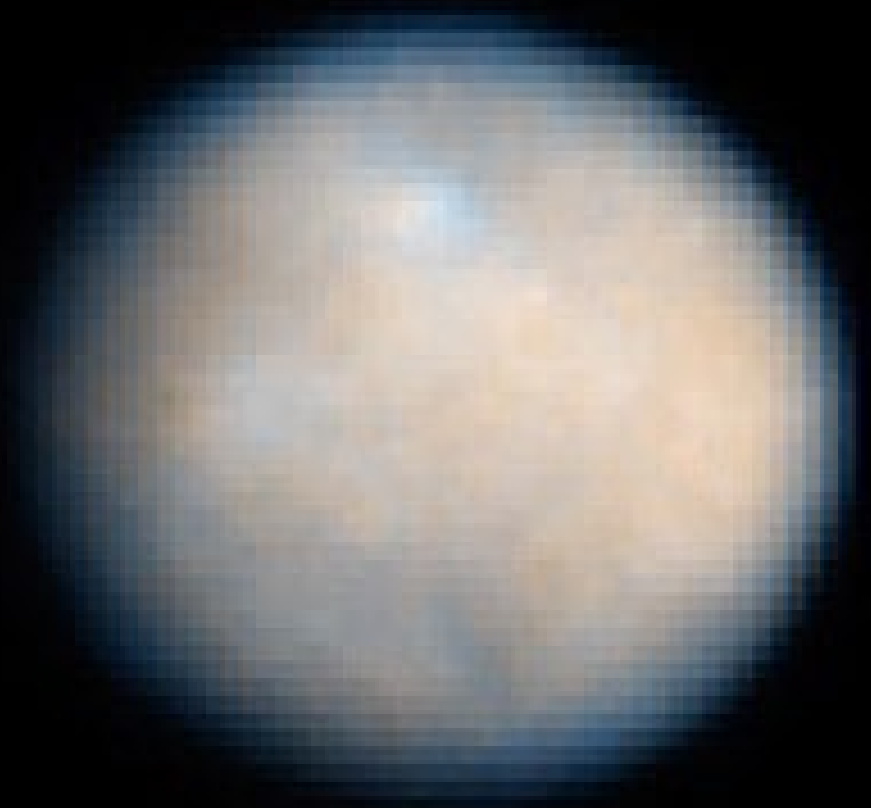
- Impact on South Pole splattered material which eventually reaches Earth: Howardite meteorites
- Large impacts fractured interior, created grooved cracks, delivered carbonaceous material which would normally only be found much farther out in the Asteroid Belt
- It's differentiated, like other large round asteroids; heavies in core, lighter crust

Grooved Cracks, High Density of Small Craters on Vesta. It's Been Hit a Lot

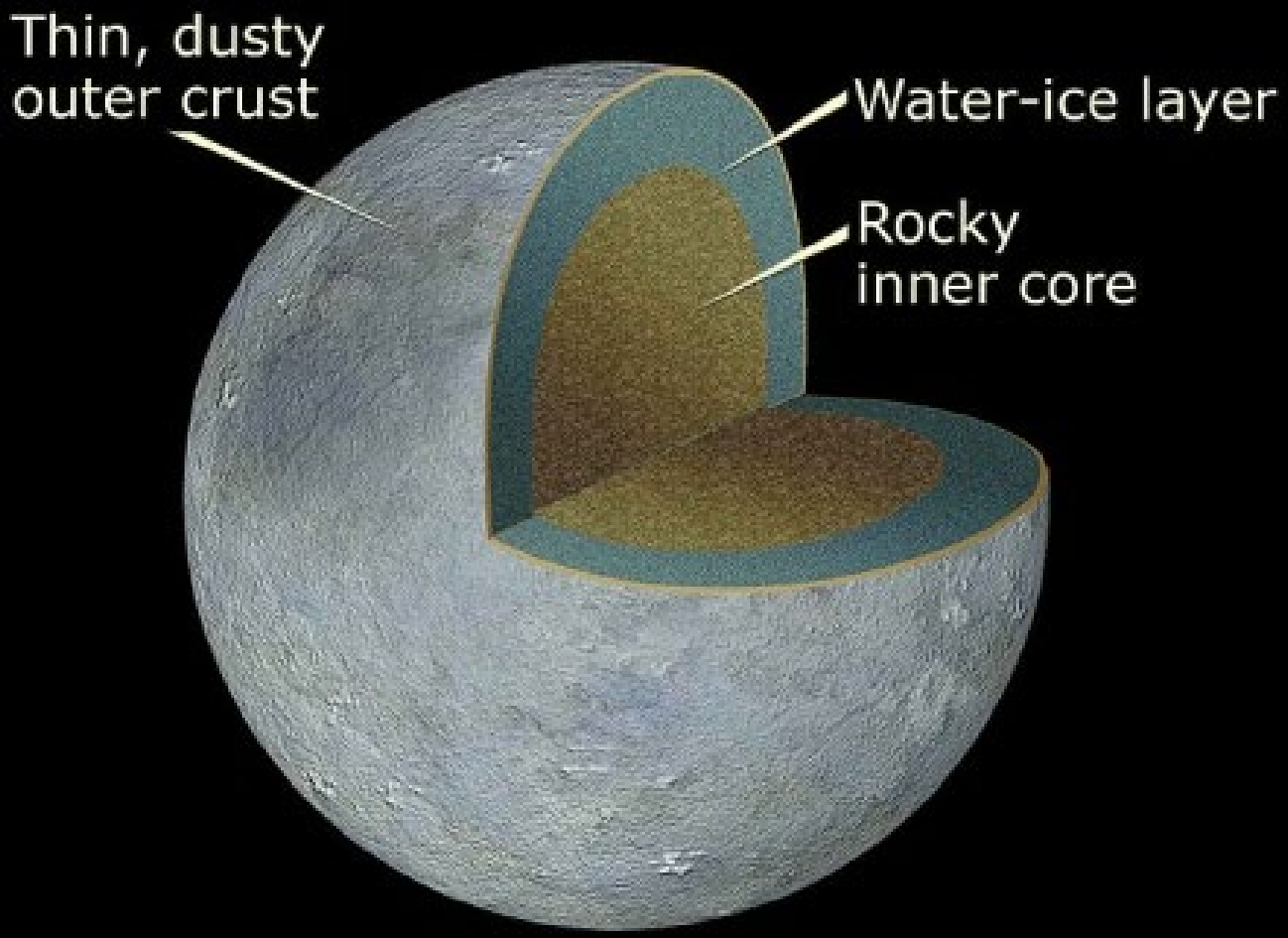




Hubble Image of the Largest Asteroid
Ceres: 400 mi Diameter



Ceres' layers

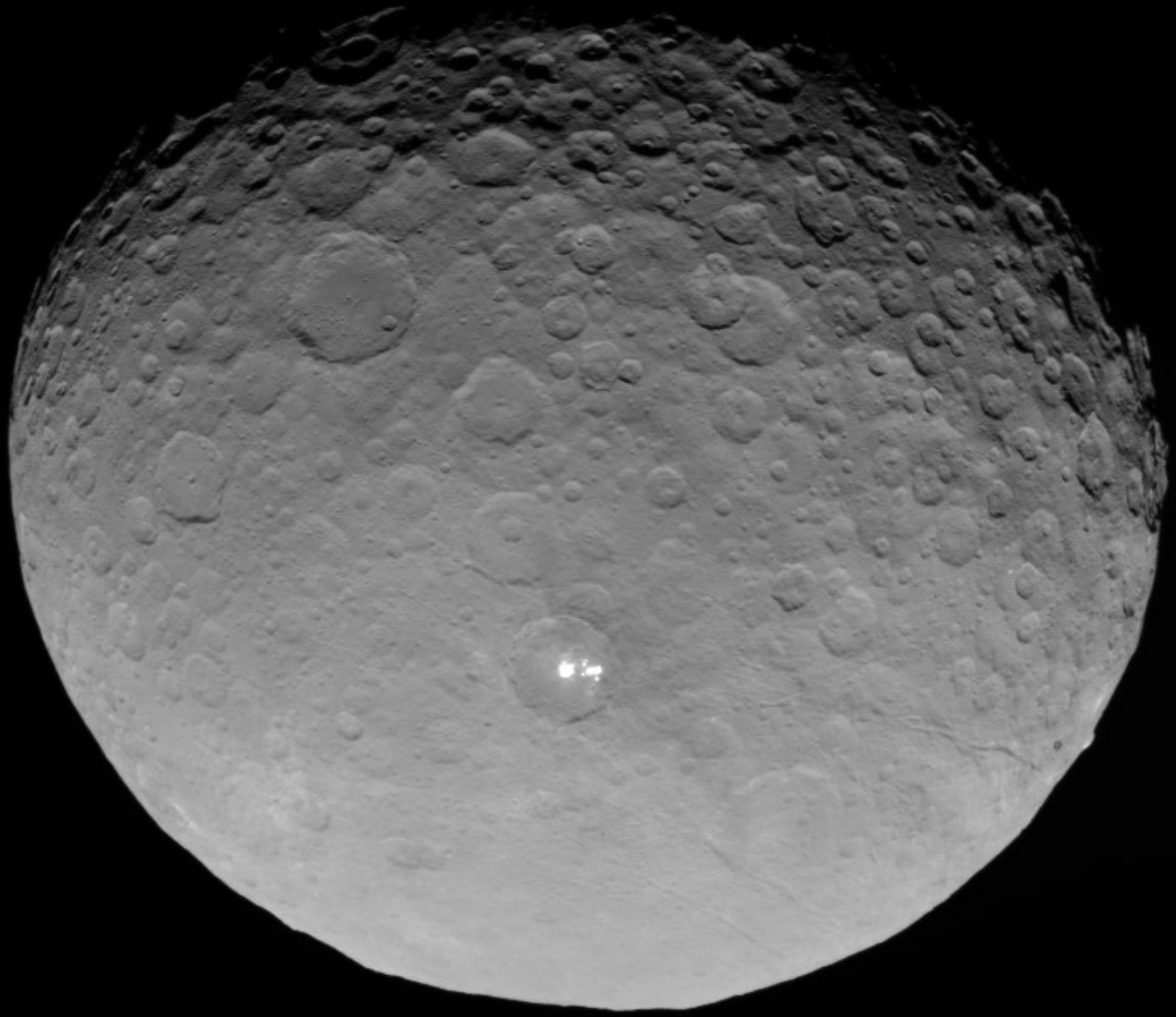


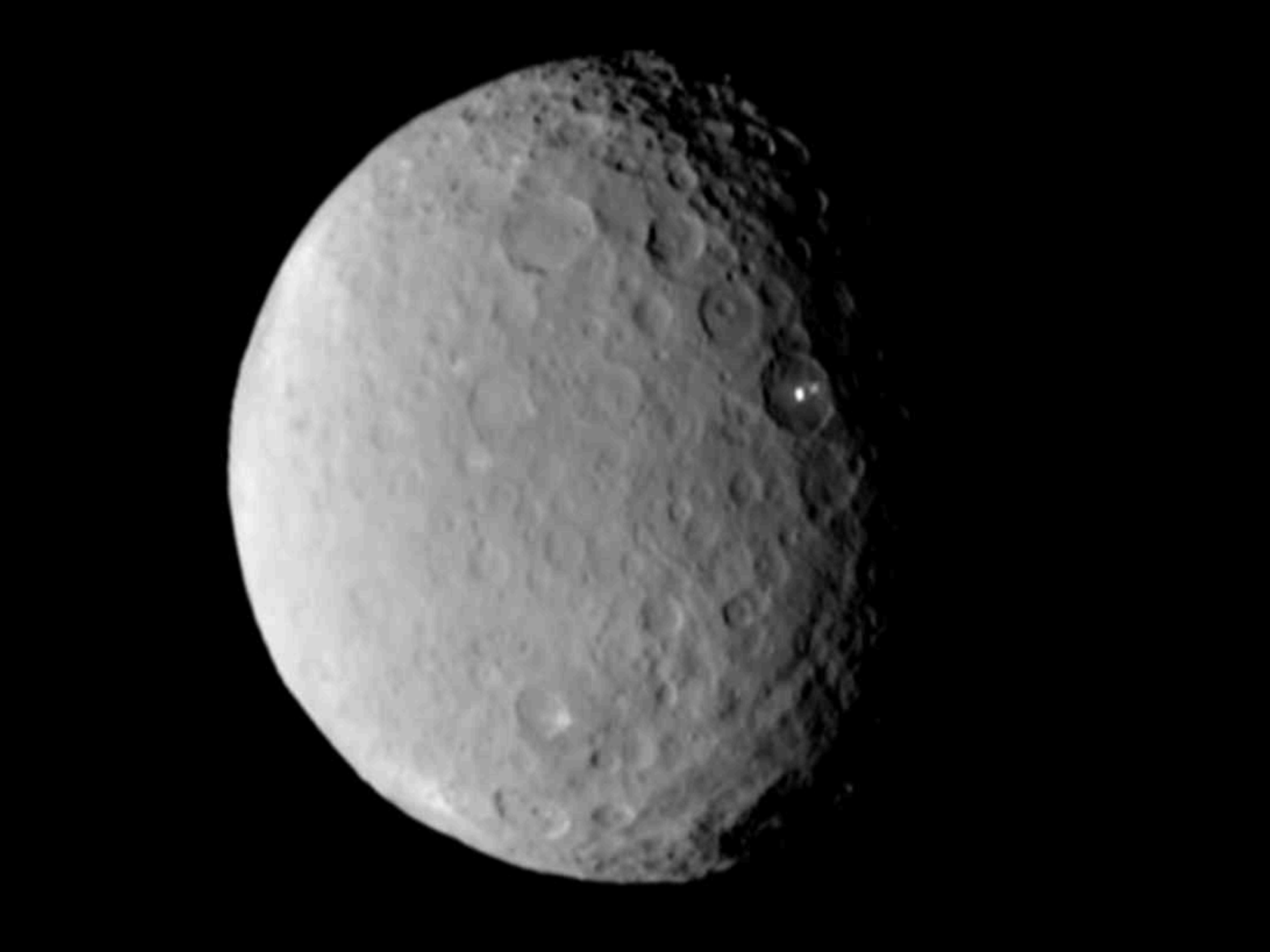
The Dawn Mission Space Probe has Moved on to Ceres

- And found a bizarre feature which we have no explanation for, yet.
- A complex of brilliant lights, at the bottom of a crater
- Not like anything we've seen before.

WHAT ARE THEY?

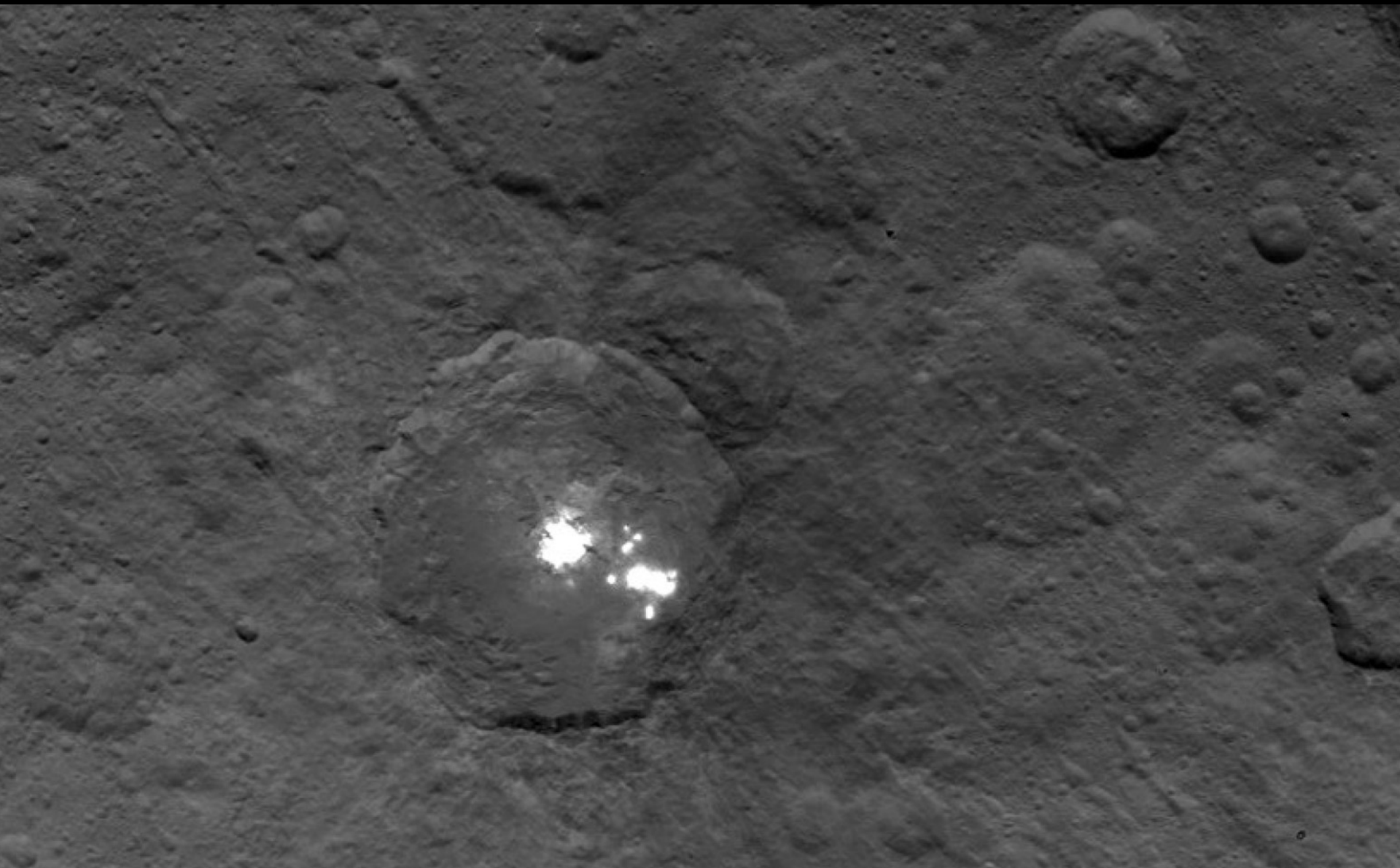
They are VERY bright



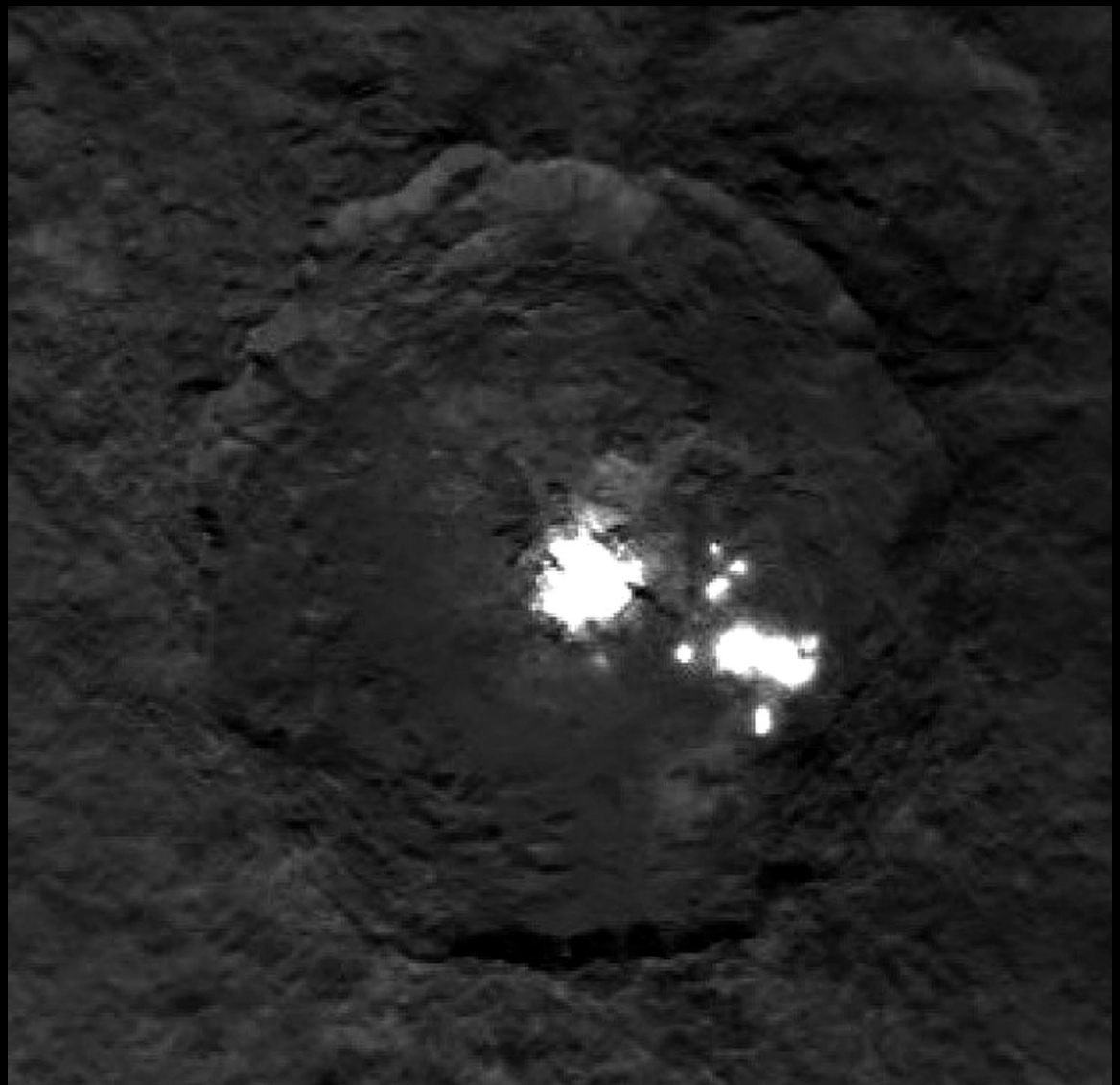


Expanded View, Before Close-ups Came Later

Latest Images from June ‘15. Almost Looks Like a Colony of Lights…



The left one is at the crater center, where there's often a central peak from rebound at formation. NOT where you'd expect to see icy basement. The scattered lights on the right are at the flat bottom, a very different geography if there is a central peak. You can see some surrounding highlands are actually illuminated by the bright lights. Very bizarre.



Shining… on the Dark Side too?!

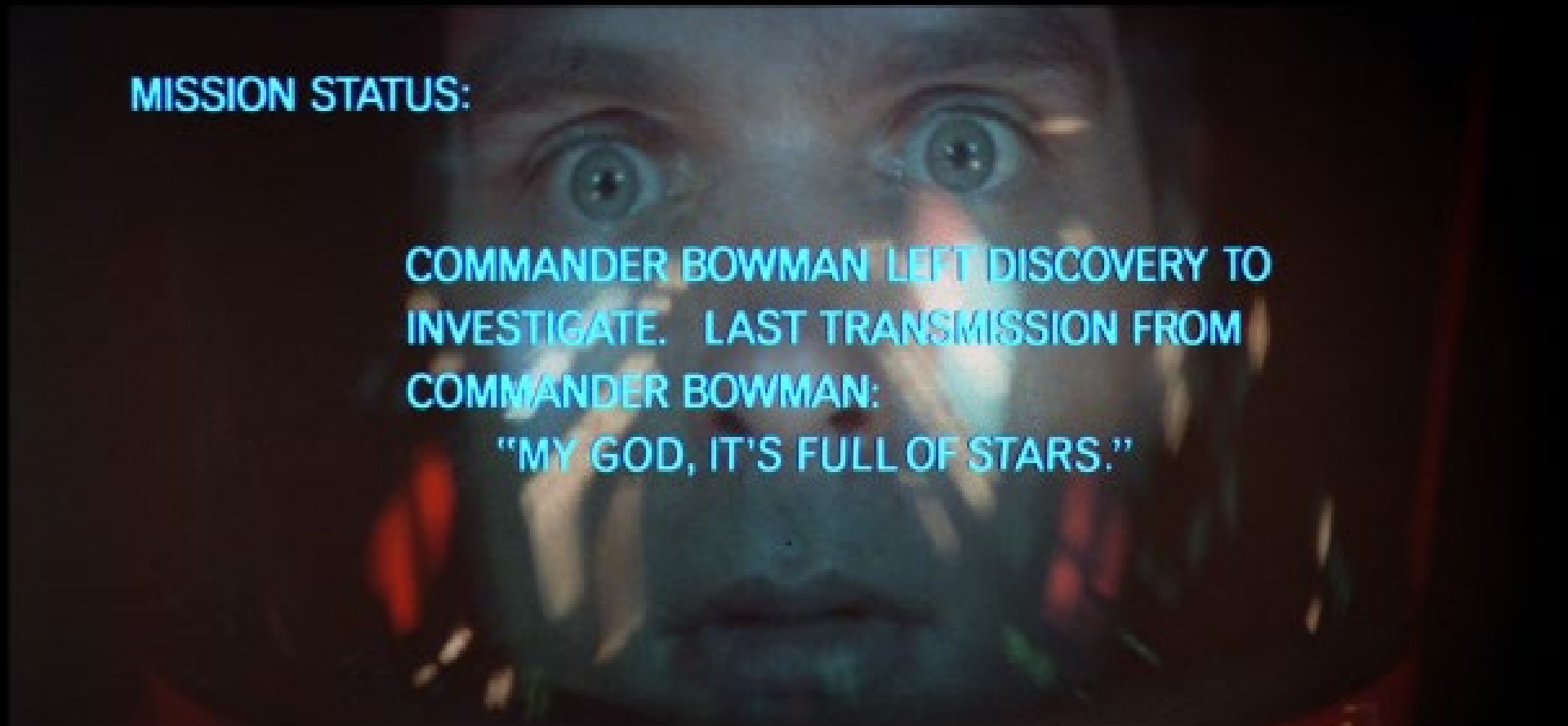

I'M NOT SAYING IT'S ALIENS
BUT IT'S ALIENS.

Maybe Ice Reflections?

- But then, why aren't they covered up with thick dust, like everywhere else? How can there be exposed ice in the two very different geographies on the crater bottom?
- Ice which is this shiny reflects with a specular aspect, but specular reflection is VERY dependent on the angle of the incident light and the observer, and these are clearly not specular reflection; they're bright from all angles
- And how could they shine on the dark side?
- I'd like to see a luminance figure, so we could guesstimate the wattage
- Scientists still have no good idea of a natural cause which fits the observations, although salts are talked about

THEY'LL BE DROPPING THE ORBIT A LITTLE CLOSER LATER THIS YEAR TO GET SOME CLOSER VIEWS. (BUT THEN, THEY TRIED THAT IN THE MOVIE "2010" AND LOOK WHAT HAPPENED THERE!

LET'S HOPE DAWN DOES NOT SUFFER THE SAME FATE!



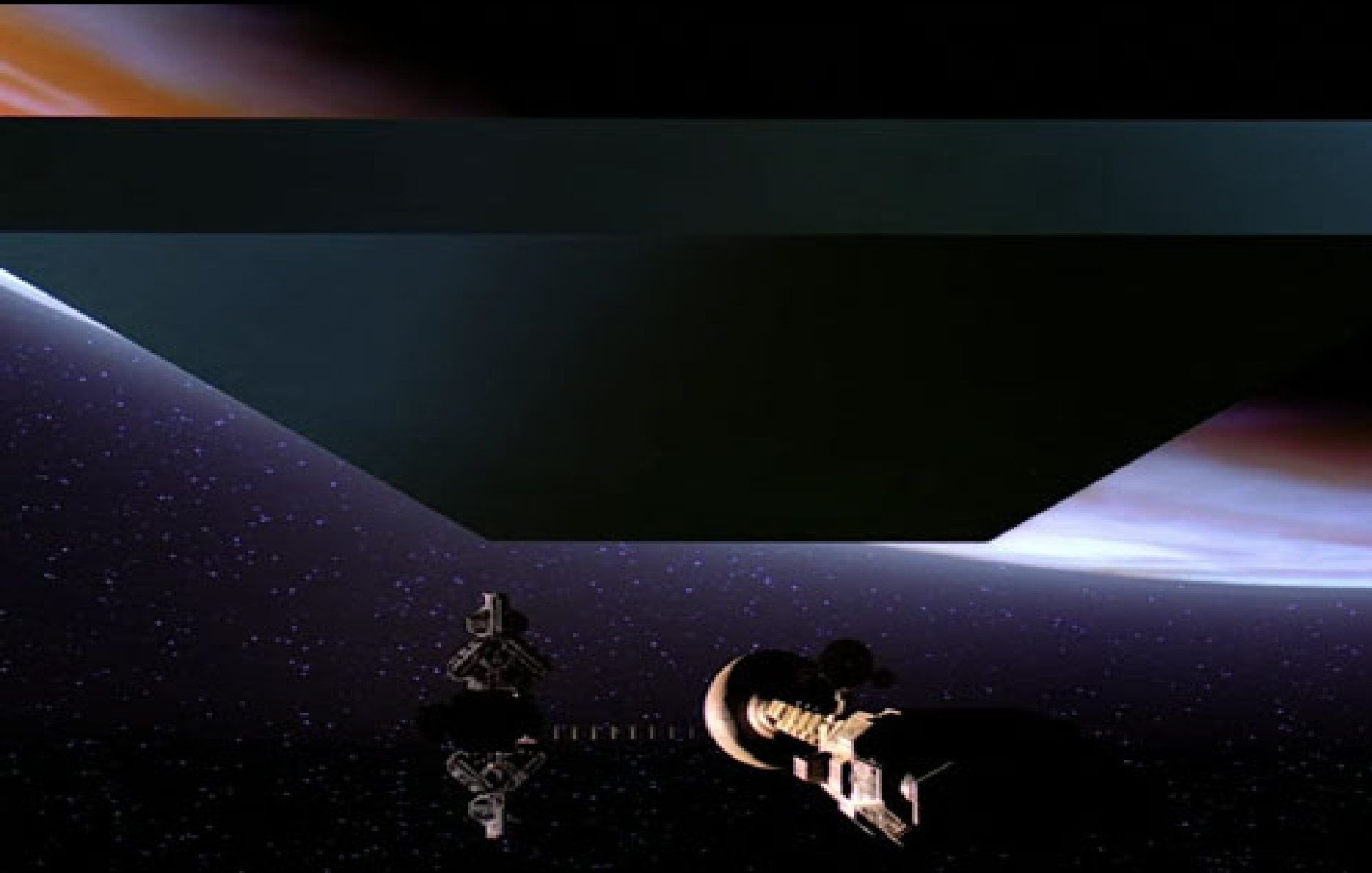
Conspiracy Theorists Are Having Fun… Still, it's definitely strange and we don't know what's going on there. We Know There's Ice Under the Surface

While We're on that subject… This Year there's Something Even More Bizarre

- Our first genuinely confirmed visitor from Interstellar Space – now named **Oumuamua**
- **Came from the direction of Vega (remember, from the movie "Contact"? Eery… but unless it changed course on it's own, it couldn't have actually launched from Vega**

Most Bizarre – it is not shaped like anything we've ever seen (well, except for the Monolith of "2001" fame)

This is about the right scale (scene from movie “2010”



Oumuamua has an aspect ratio of 10:1 (!) and is made of solid rock or metal

Artist's concept of interstellar asteroid 1I/2017 U1 ('Oumuamua) as it passed through the solar system after its discovery in October 2017. The aspect ratio of up to 10:1 is unlike that of any object seen in our own solar system.
ESO / M. Kornmesser

Rock or Metal, and not ice?!

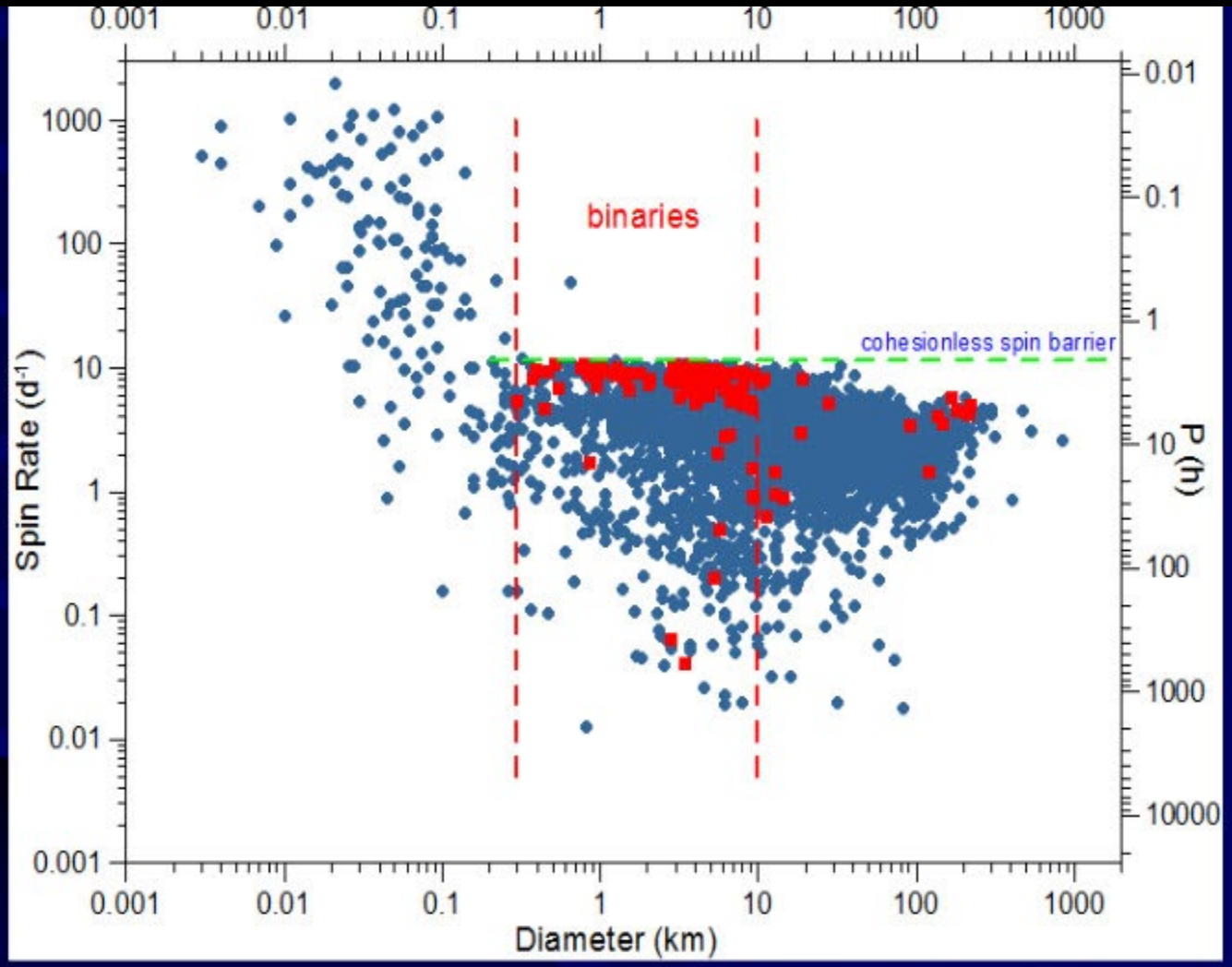
- What's more bizarre is that if this thing came from the Oort Cloud of another star system, the odds are about 250:1 that instead it would be made of almost pure ice.
- **It's not.** It sped by the sun, dipping in closer than Mercury's orbit in October of 2017 (to refuel???) and showed absolutely no vaporization or outgasing.
- It must have come from the inner solar system of another star system to have lost all trace of ices or volatiles. So how did it acquire escape velocity?
- **A new paper does some calculations of how hard it would be to try to launch a mission to catch up with it, speeding away from us now at faster than 59,000 mph**

But what if that's not such a great idea… remember what happened to those who got too close to **the Monolith in "2010"**! (I'm just sayin'…)

We Don’t Know WHAT it is

- Except it’s very weird
- OK, back to more solid science
- This time, on asteroids, not interstellar UFO’s that don’t obey the rules…

The Spin Graph – It Shows Most or All Asteroids are Solid Rock if < 300m in size, Not if Larger



At the spin barrier – balance between the gravity and centrifugal acceleration at the equator of a sphere with ρ ~ 3 g/cm^3, taking into account also

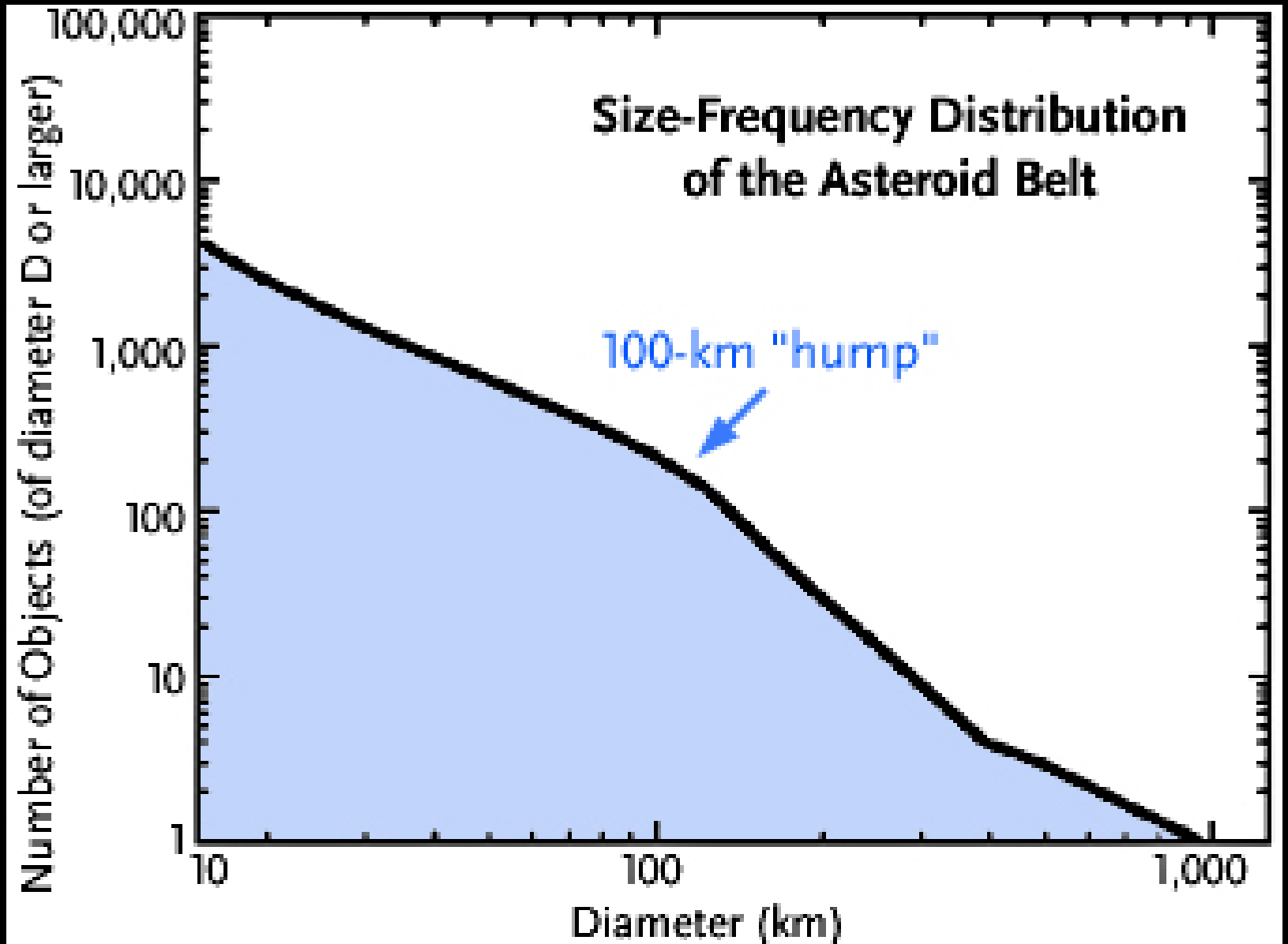
where ω_{csph} is the critical spin rate for the sphere

$$\omega_{csph} = \sqrt{\frac{4}{3}\pi\rho G},$$

Asteroid Shapes + the Spin Graph => A Good and Reasonable Theory…

- Small asteroids are mostly solid rocks, bigger ones are mostly gravity-held conglomerations and therefore round-ish
- Suggests that early on, several planets orbited between Mars and Jupiter and collisions ensued, probably because of Jupiter's strong gravity continually changing their orbits
- Collisions ground up these former planets
- This resulted in a range of fragments, from dust to gravel to boulders, but little or nothing bigger than about 300m in size.
- Then, over the eons, gravity pulled together much of this material into fewer, larger asteroids on the non-intersecting orbits. The big asteroids are all loose piles of gravel and dust as revealed by their round shapes pulled by gravity.
- The small ones (smaller than 300m) are too small to have significant gravity and, if spinning, must be held together by solid-state forces; in other words – they're rocks, covered with a thin layer of dust. You can spin them fairly fast and yet they won't fly apart.

How many asteroids are there of each size? The "100-km Hump" says asteroids are born LARGE

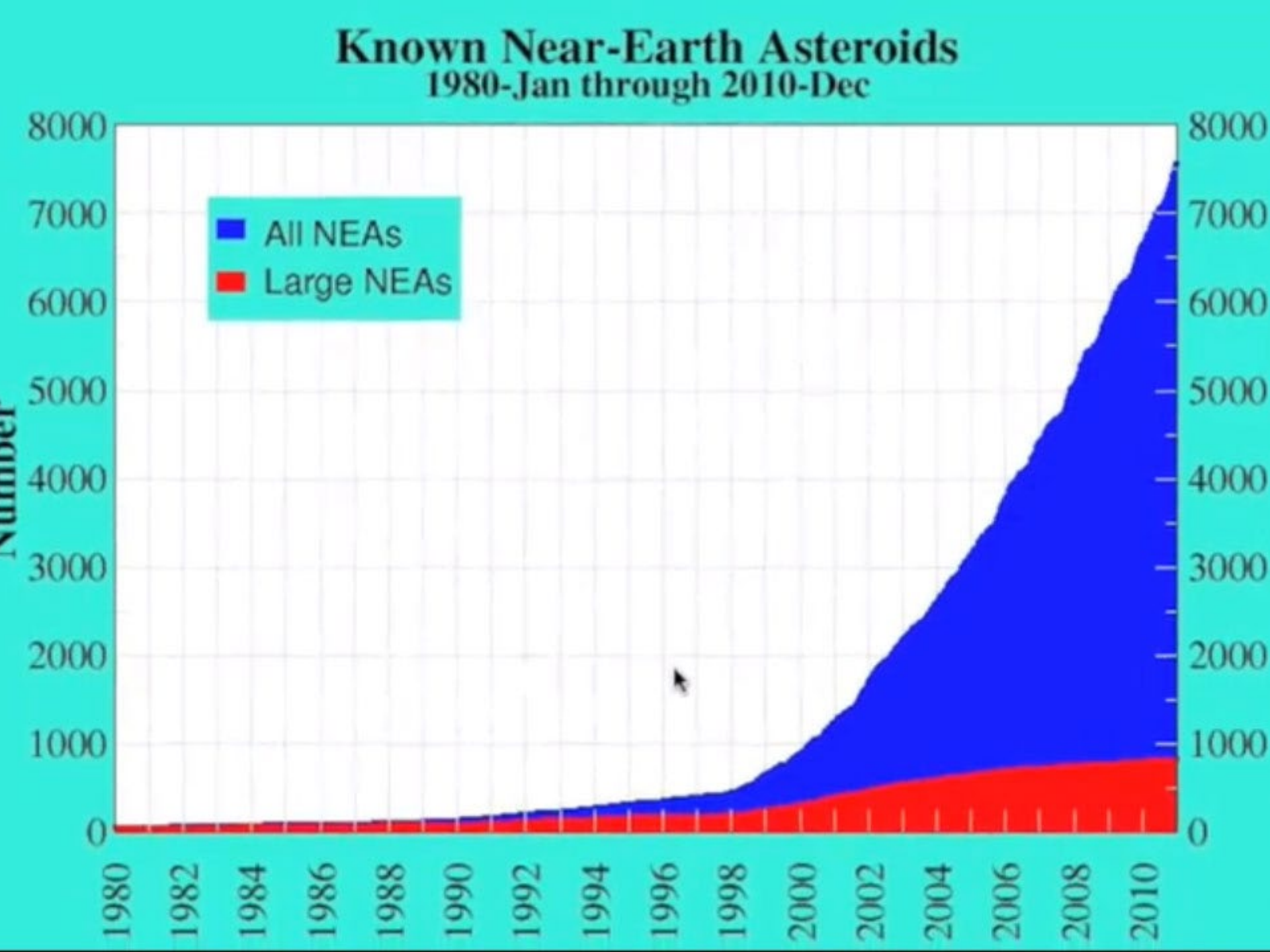


Interesting! So the Smaller Asteroids are the Tough Ones Made of Solid Rock. Is that a Good Thing?

- Not really.
- There are MANY more little ones than big ones, and …
- Would you rather be hit by a handful of dirt? …or a solid ***rock***
- Wear your hardhat at ALL times

Asteroid close encounters and Jupiter's gravity have changed some orbits, creating a population of Earth-crossing asteroids. Those that haven't already hit us, probably will, in the (hopefully distant) future, causing….

Big Trouble!


Known Near-Earth Asteroids
1980-Jan through 2010-Dec
All NEAs
Large NEAs
Number
8000
7000
6000
5000
4000
3000
2000
1000
0
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010

Teenager Michelle Knapp's Car…. Bummer.

Geologists examine a fresh crater formed when an iron meteorite about 1 meter across slammed into a freshly planted wheat field near the Russian town of Sterlitamak on May 17, 1990. The impact energy, equivalent to setting off about 1½ tons of TNT, created a hole nearly 10 meters across.

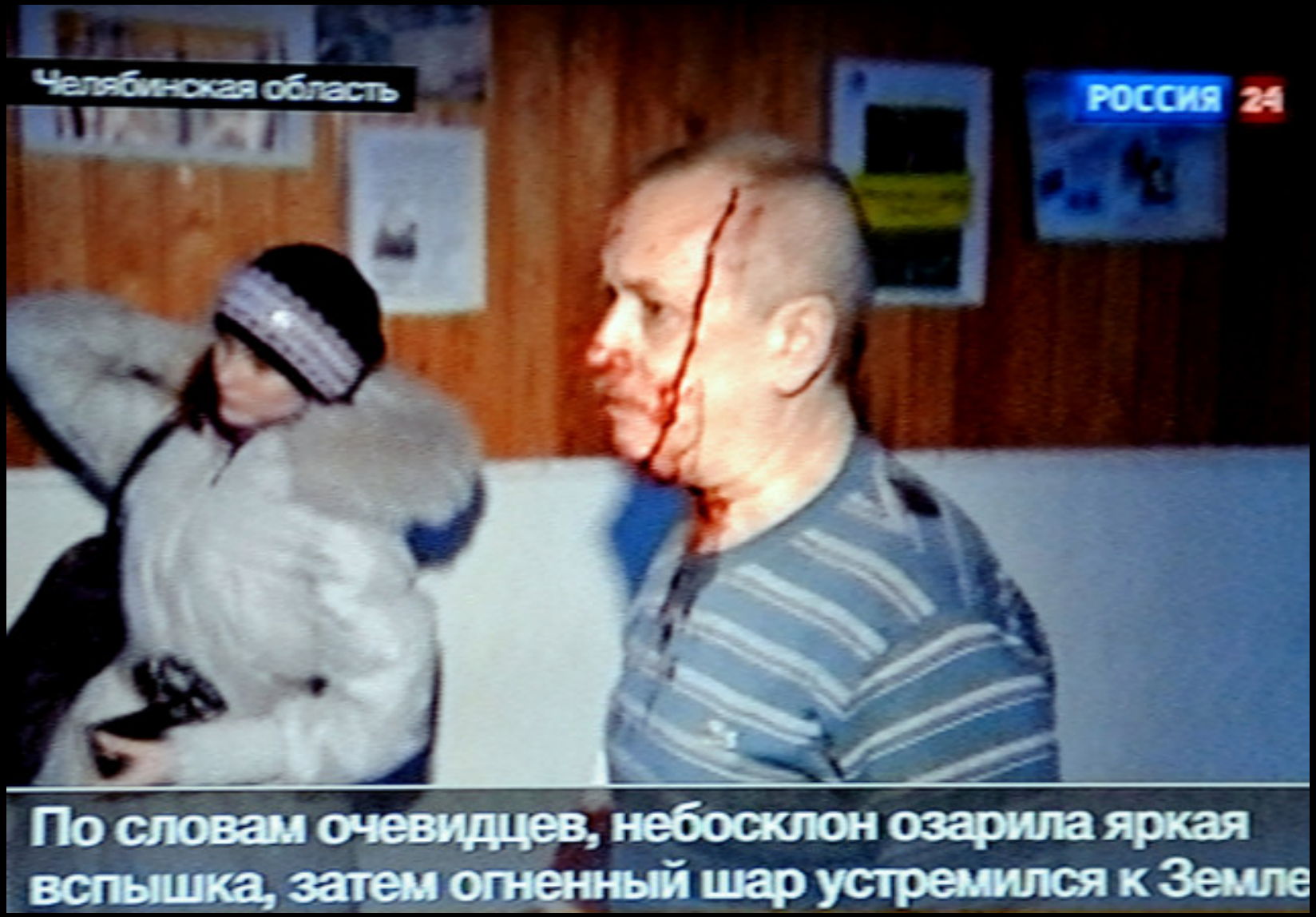
The Feb 15, 2013 Chelyabinsk Fireball and Explosion

The Chelyabinsk Impact

- Asteroid 70 feet across before entering our atmosphere
- 13,000 metric tons
- 19 km/sec speed, 50x speed of sound
- Broke up 37 km above ground
- 37x brighter than the sun!
- Explosion equivalent to 500,000 tons of dynamite; a 500 kiloton A-Bomb!
- Only ~5,900 kg of rock reached the ground

Caused $millions in damage

And a thousand injuries from shattered windows and buildings

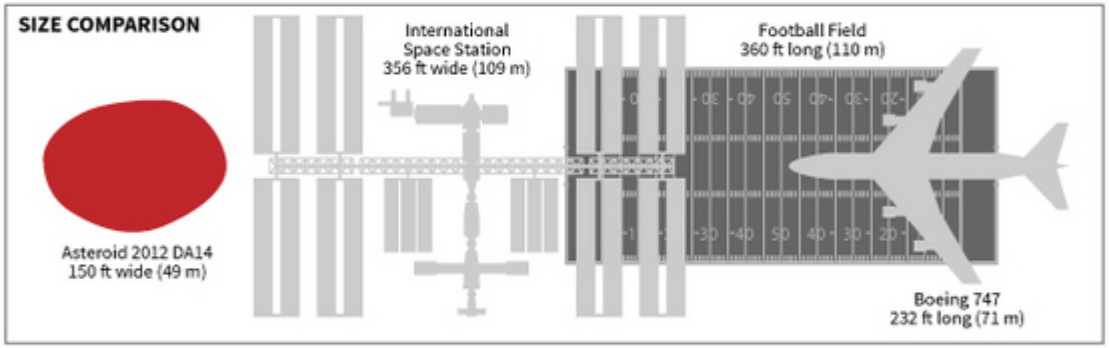


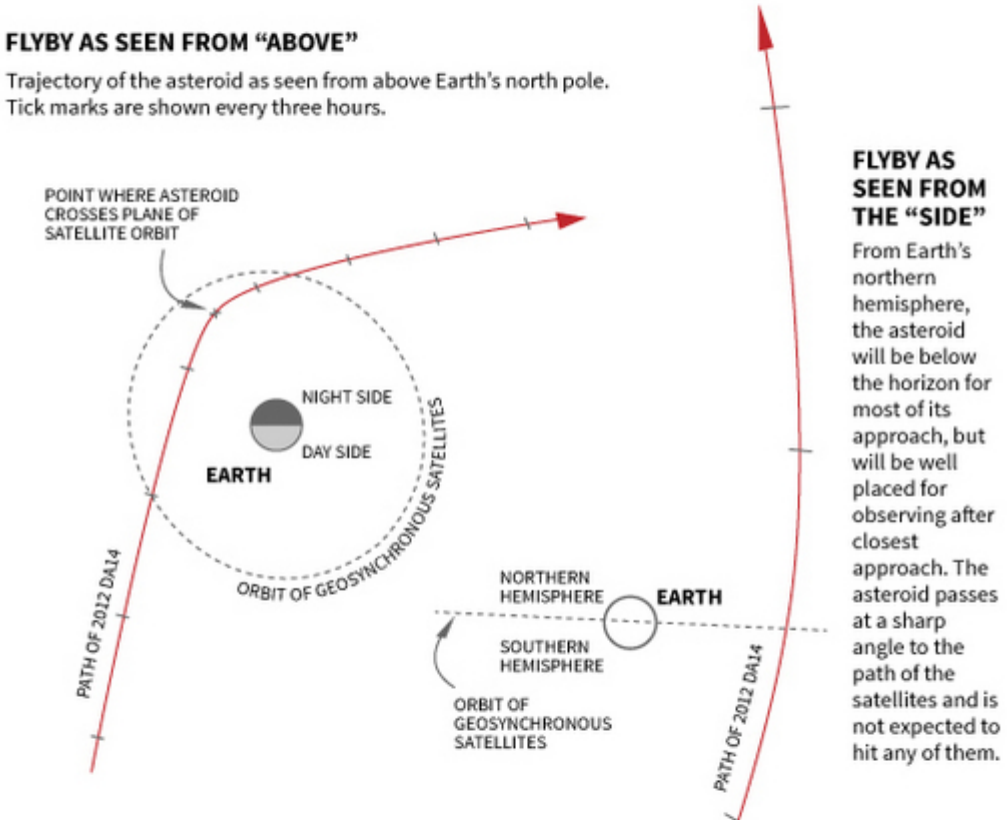
Shallow trajectory was lucky!
Exploded 7 miles above ground

A steeper trajectory might have looked like this… (Energy release of Chelyabinsk impact = 25 Hiroshima A-Bombs)

Close Flyby: Asteroid 2012 DA14

At 2:26 p.m. EST on Feb. 15, an asteroid 150 feet wide will hurtle within 17,200 miles (27,680 kilometers) of Earth. This is lower than the communications satellites that orbit 22,000 miles (35,800 km) above the equator. The asteroid will not hit the Earth on this orbital pass, but 2012 DA14 is about the size of the object that hit Siberia in 1908 (the "Tunguska Event"). The asteroid was discovered on Feb. 23, 2012, by the La Sagra Sky Survey.





FLYBY AS SEEN FROM THE "SIDE"

From Earth's northern hemisphere, the asteroid will be below the horizon for most of its approach, but will be well placed for observing after closest approach. The asteroid passes at a sharp angle to the path of the satellites and is not expected to hit any of them.

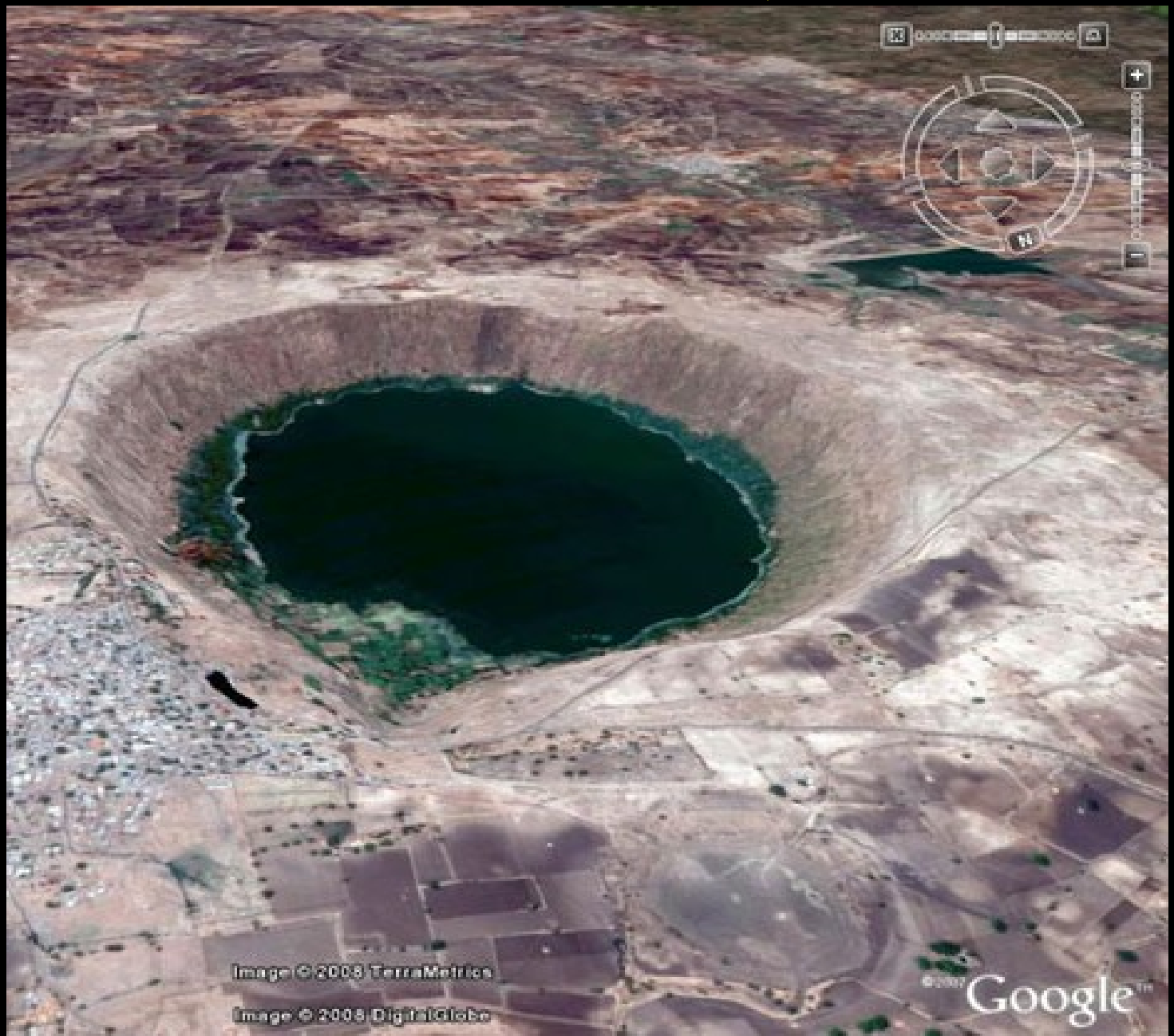
The same day as the Chelyabinsk Siberian Meteor hit, a far larger NEA missed us by just a few thousand miles

About 200 Impact Craters so far identified on Earth

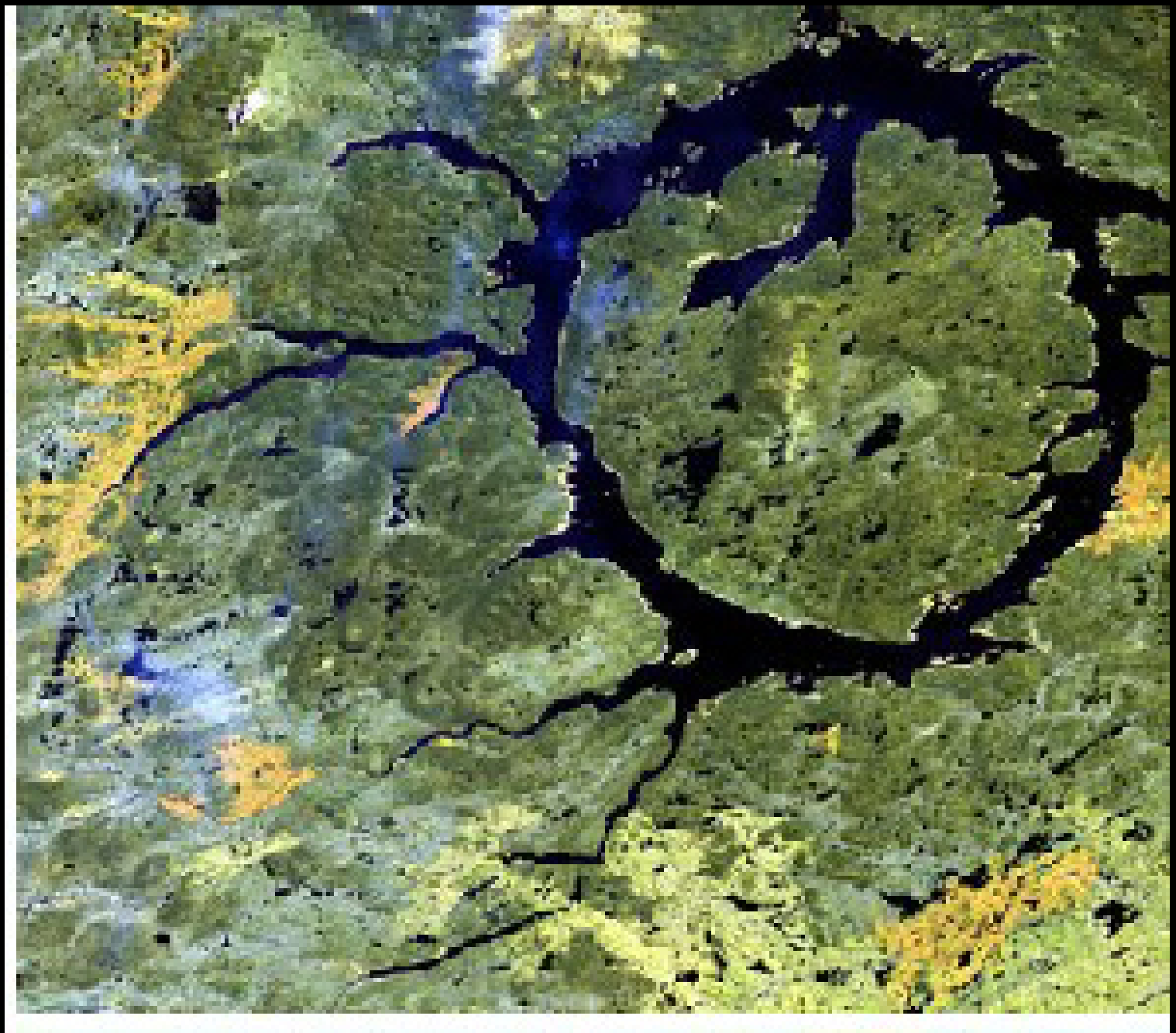
- Nice gallery of the best is here

Meteor Crater, Arizona

Lona Crater, India



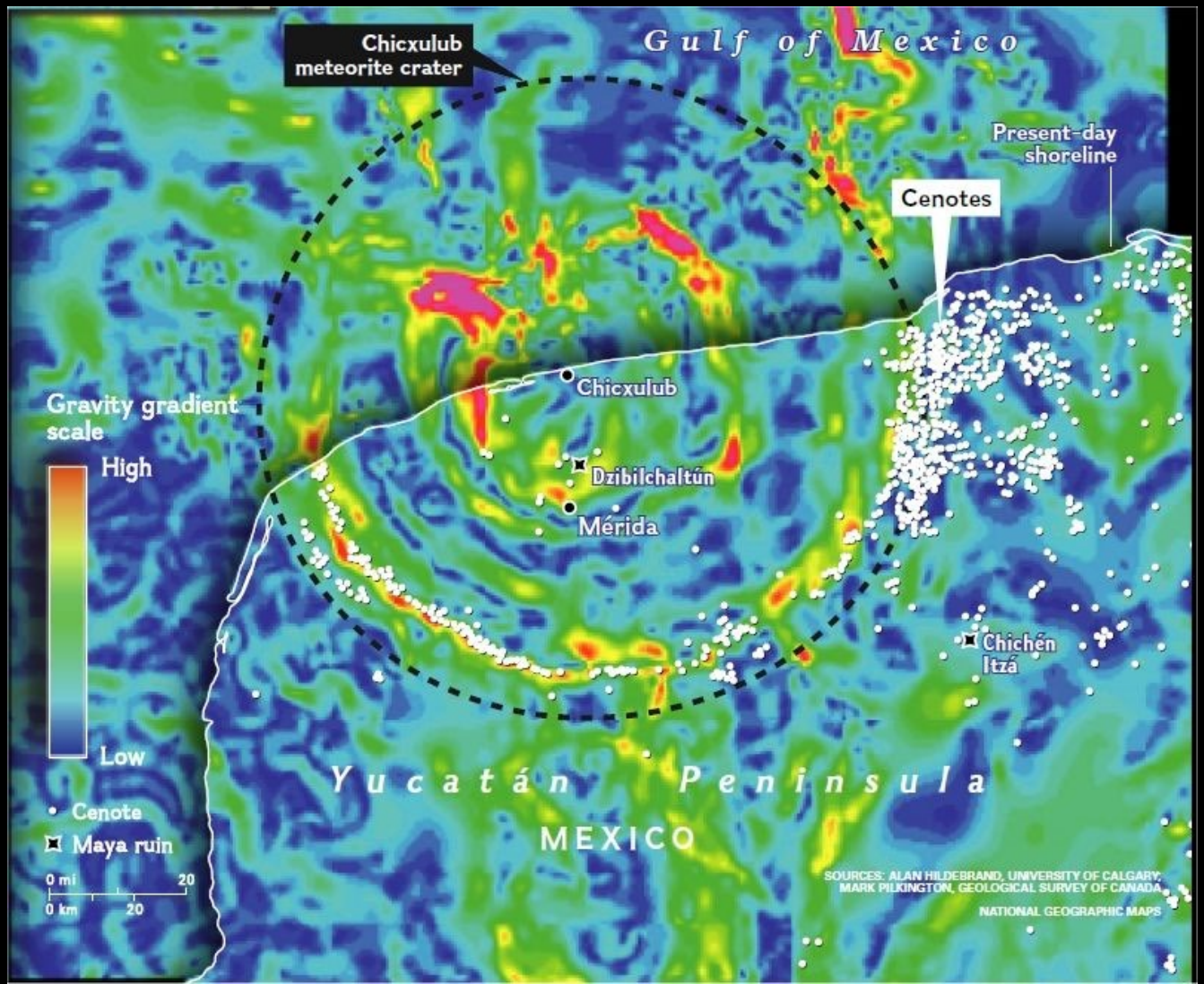
Mannicouagan Crater, Canada (40 mi diameter)



Gosse Bluffs Crater, Australia

65 Million Years Ago…One, maybe Two Major Asteroid Impacts

- A 10 km asteroid hit the Yucatan causing 180 km crater



An Even Larger, ~40km Impacting Asteroid at the Same Time?

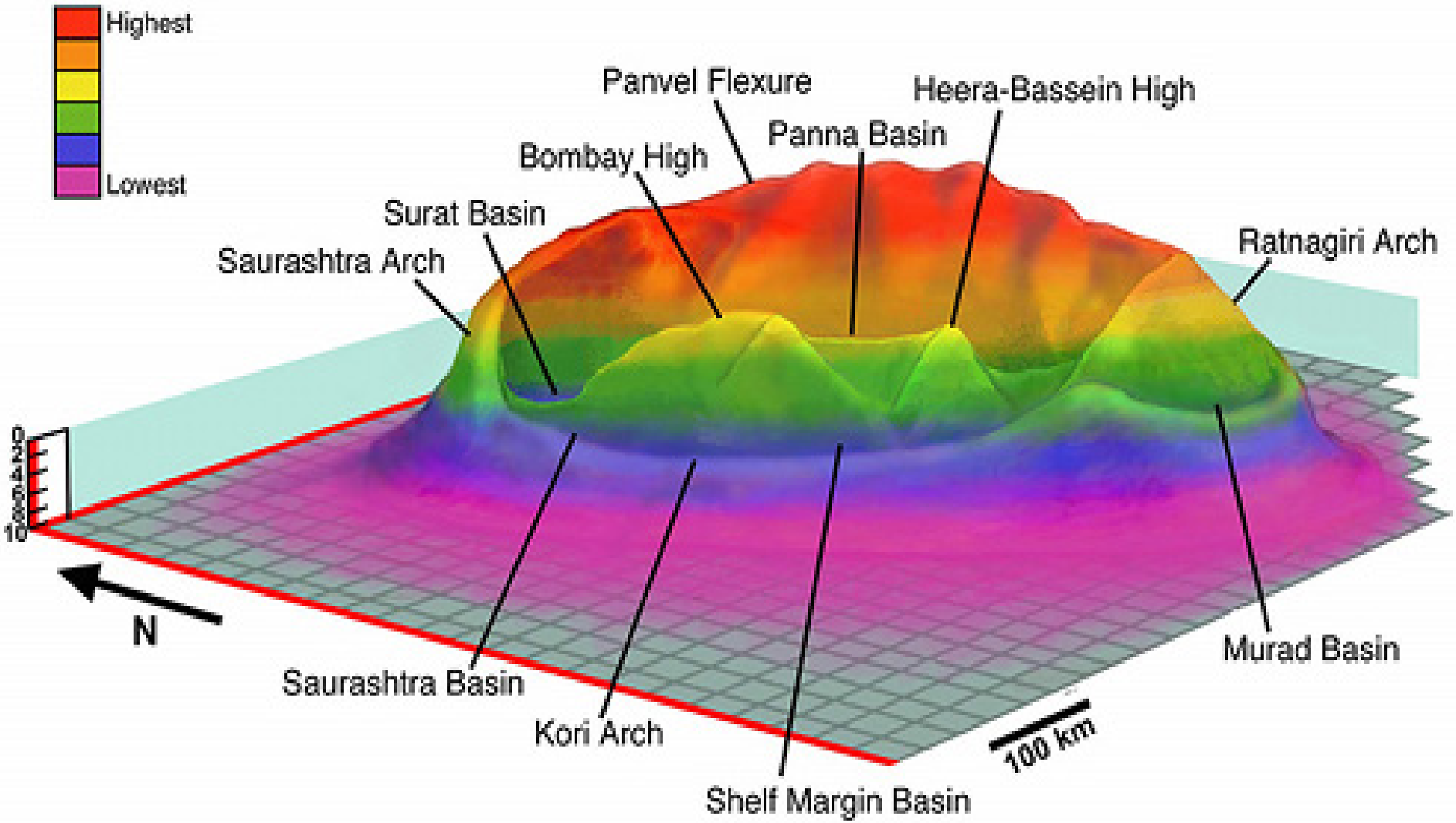
Also 65 million years ago – a suspected impact crater (the Shiva Crater 310 miles across) at the Deccan Traps in India is highly controversial, but if true, could have caused the Deccan formation, which is a huge lava formation also ~65 million years old, and thought by many geologists as co-implicated in the K-Pg Extinction.

Evidence for/against the Shiva Impact

- -- Alkaline igneous rock spires within the Deccan Traps which are rich in iridium, while Deccan lava is very poor in Iridium
- --The worldwide KT boundary layer (rich in iridium, carbon spherules, shocked quartz – all signatures of asteroid impactors) is thickest, 1 meter, in India
- -- large underwater mountain 16,000 ft tall defining the central peak.
- --- distorted by having occurred on the tectonic spreading zone, so that the crater is widely split now
- --- Need better physical evidence but the on-land portion is controlled by government and oil companies who won't allow drilling, so it remains only suggestive
- BUT – this purported crater would have delivered MUCH more energy than the Yucatan impact, and yet the timing of the Yucatan impact and the KT Extinction are now in agreement to better than 1 part in 10,000. so either this crater occurred at the same time (binary asteroid? These do exist) or it is not an impact remnant.

Binary Asteroid Impact, Clear Lakes, Canada

Shiva - Impact Crater?



The Deccan Traps

- Before the discovery of the classic signatures of extra-terrestrial impact in the K-Pg boundary layer, most paleontologists favored the huge volcanic outflows forming the Deccan traps of India as causing worldwide climate change sufficient to cause a mass extinction.
- Many geology people still feel ruffled at the astronomers coming into their field and arguing for a catastrophic end to life by asteroid impact, and cling still to this gradualist explanation.
- However, the Deccan Traps volcanic episodes took place over a period lasting well over 1 million years, while the vast majority of Cretaceous species went extinct in a tiny fraction of that interval (extinctions and impact happened at the same time, precise to 0.01% in time). (Schulte, *et al.* 2010 and refs. therein).

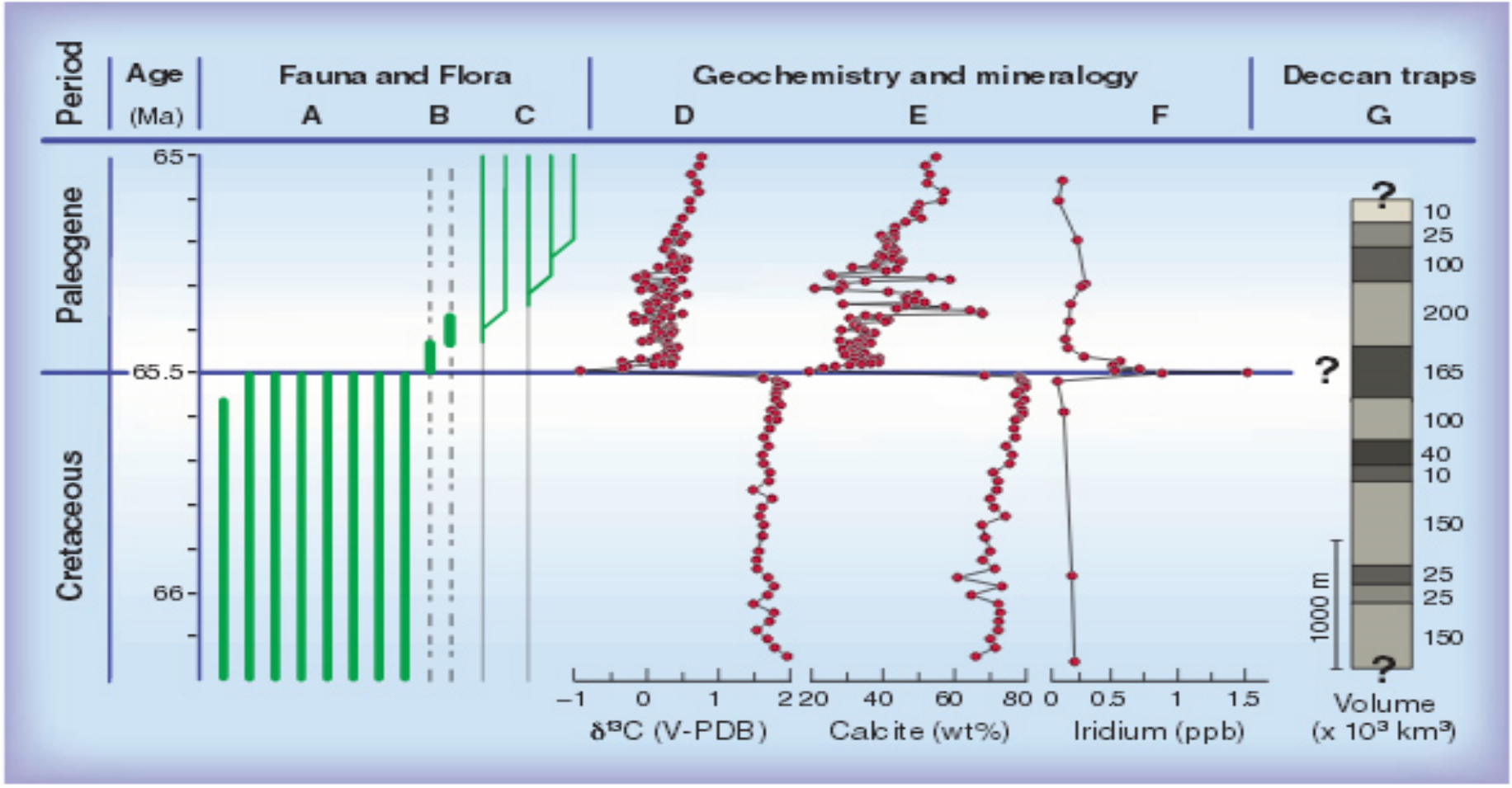


Fig. 1. Stratigraphy and schematic record of biotic events across the K-Pg boundary correlated to the chemical and mineralogical records of a core from the North Atlantic [Ocean Drilling Program (ODP) Leg 207] and the major eruptive units of the Deccan flood basalt province, India. Many (>60%) Cretaceous species experienced mass extinction at the boundary (A), whereas successive blooms of opportunistic species (B) and radiation of new species (C) occurred in the Early Paleogene. V-PDB indicates the Vienna Pee Dee Belemnite; wt %, weight %; and ppb, parts per billion. The mass extinction coincides with a major perturbation of the global carbon cycle as indicated by a negative $\delta^{13}C$ anomaly (D), a major drop of carbonate sedimentation in the marine realm (E), and the enrichment of PGEs in Chicxulub ejecta deposits (F) (*25*, *26*). Composite stratigraphic column of the formations of the main Deccan Trap flood basalt province showing their cumulative thickness and estimated basalt volumes (G) (*15*). Note that the exact stratigraphic onset and end of the main Deccan flood basalt sequence and the precise position of the K-Pg boundary in the formations have yet to be determined, as indicated by the question marks (*16*). However, the onset of the main eruption phase is ~400 to 600 thousand years before the K-Pg boundary as is also shown by Os isotope data (*38*).

So What Caused the K-Pg Mass Extinction?

- 95% of researchers find the evidence favors the Yucatan Impact as **the** cause of the mass extinctions on Earth at that time, The K-Pg boundary layer found around the entire Earth is rich in iridium, micro-diamonds, shocked quartz, and carbon spherules – all signatures of a large extra-terrestrial impact. **Nice Summary**
- Schulte *et al.* (2010) published a review paper in the journal Science, studying all the evidence from earlier published work. They make a compelling case that it was the Yucatan impact which caused the mass extinction.
- Renne *et al.* (2013) pinned down the time of the extinction event and also the impact event to within 11,000 years and find them to be the same, to an accuracy of plus or minus 30,000 years, a much tighter agreement than earlier estimates: these two very rare events in the billions of years of Earth history, happened at the **same moment to within 1 part in 10,000**. Another good summary here.

90% of all life, and 2/3 of all species, went extinct

- A local geology person has said "astronomers tend to like single-cause explanations" for the extinction. He should have checked the literature cited in the past slides.
- Volcanism did not cause the mass extinctions. Various volcanic / climate events can cause population changes. But extinction kills ALL members, and mass extinctions are very rare, and the Schulte paper shows no extinctions happening during the million-year long enhanced volcanism, only at the impact itself.
- I'll note in passing that geologists don't have a great record of fair physical evaluation of evidence coming from outsiders – it was a meteorologist who first developed the theory of plate tectonics, at which geologists scoffed for decades, right up to the 1960's.

But the science continues to add more and more confirmation of that "Single cause explanation".

- The dinosaurs were in fact expanding into new niches and additional speciation in North America, when the asteroid impact caused their sudden extinction (Chiarenza *et al.* 2019, described here)

- *Chiarenza's work falls in line with other studies that also fail to show a long-term dino decline. In 2018, a study led by Ph.D. student Klara Nordén found that based on their teeth, plant-eating dinosaurs of the late Cretaceous were as ecologically diverse as ever. "It fits really nicely with what we already know from other lines of evidence," she says.*

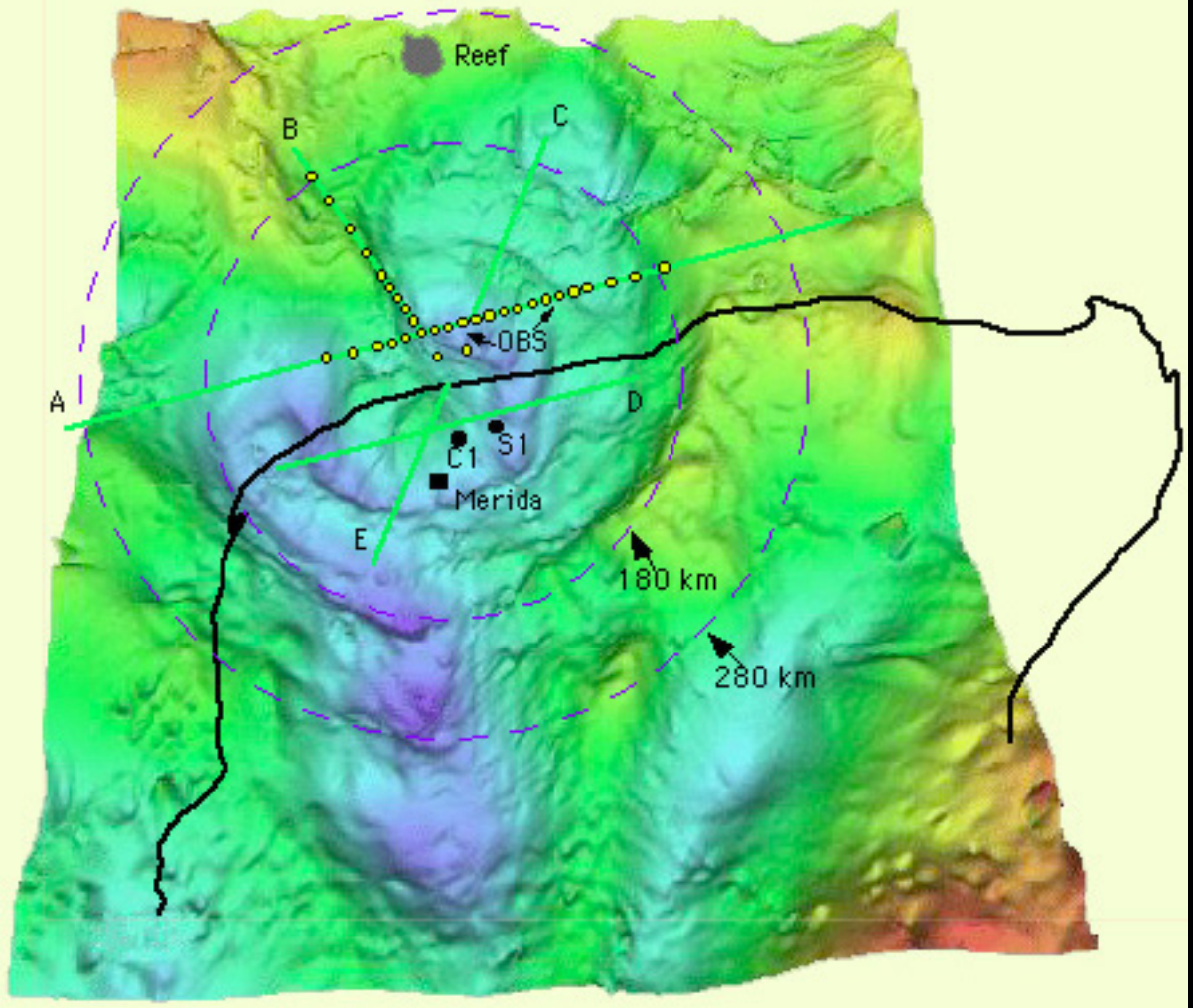
- *“Steve Brusatte, a paleontologist at the University of Edinburgh, adds that the study very clearly implicates the asteroid as the reason the dinosaurs died out. But he also notes that the study hints at what could have been if not for the sudden catastrophe.*

  ‘The most touching part of the paper [is that] it’s really clear that there was still plenty of potential niches for the dinosaurs—but the dinosaurs just weren't there, because the asteroid killed them off,’ he says. ‘You kind of get this sad sense of the dinosaurs that could have been.’” (source)

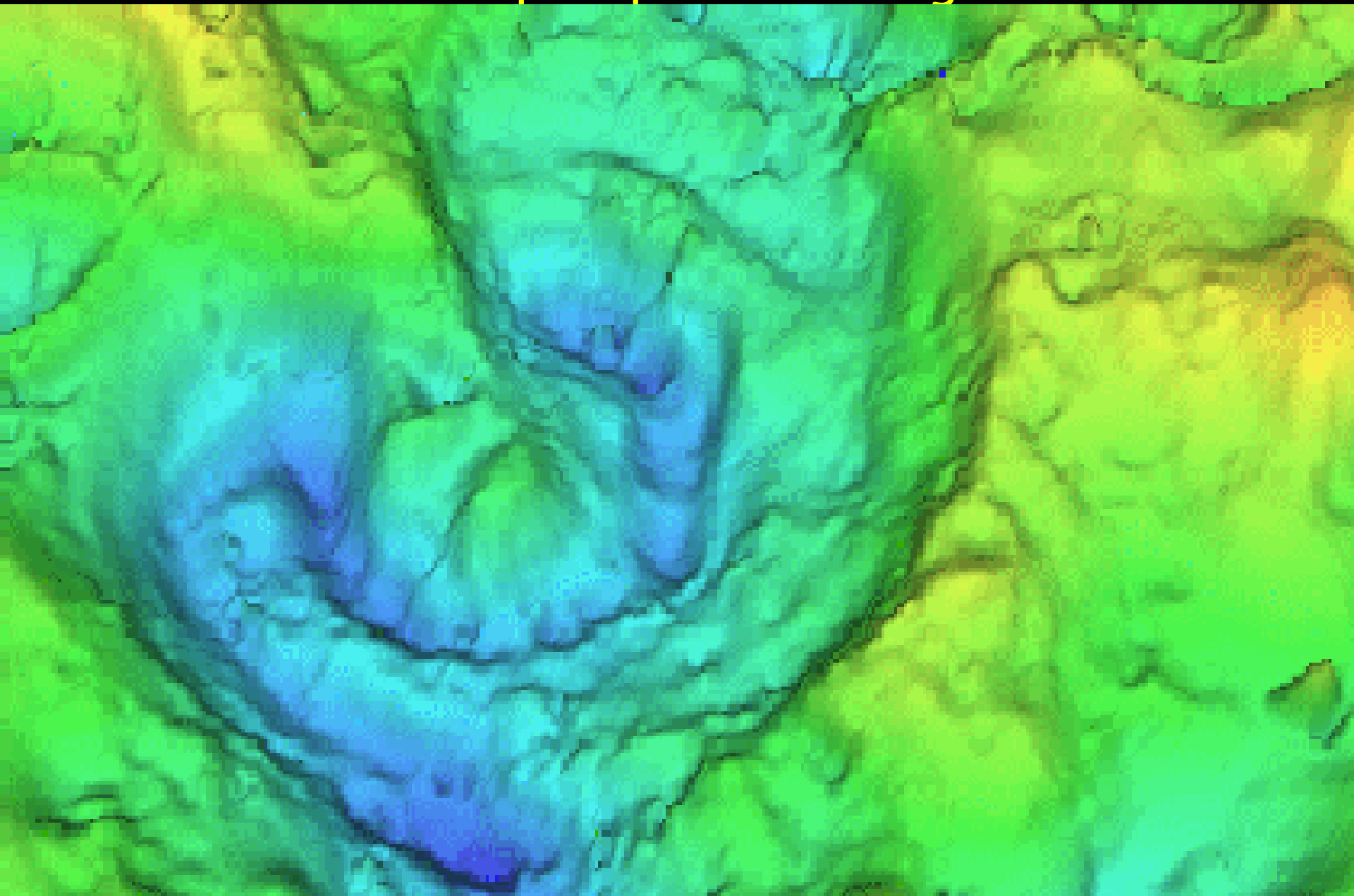
CHICXULUB SEISMIC EXPERIMENT, 1996

BIRPS/IMPERIAL COLLEGE/UNIVERSITY OF TEXAS/UNAM/LPI/GEOLOGICAL SURVEY CANADA

3 MCS LINES, 2 WITH OBS
OFFSHORE GRAVITY/MAGNETICS
2 LAND LINES (PASSIVE RECORDING)

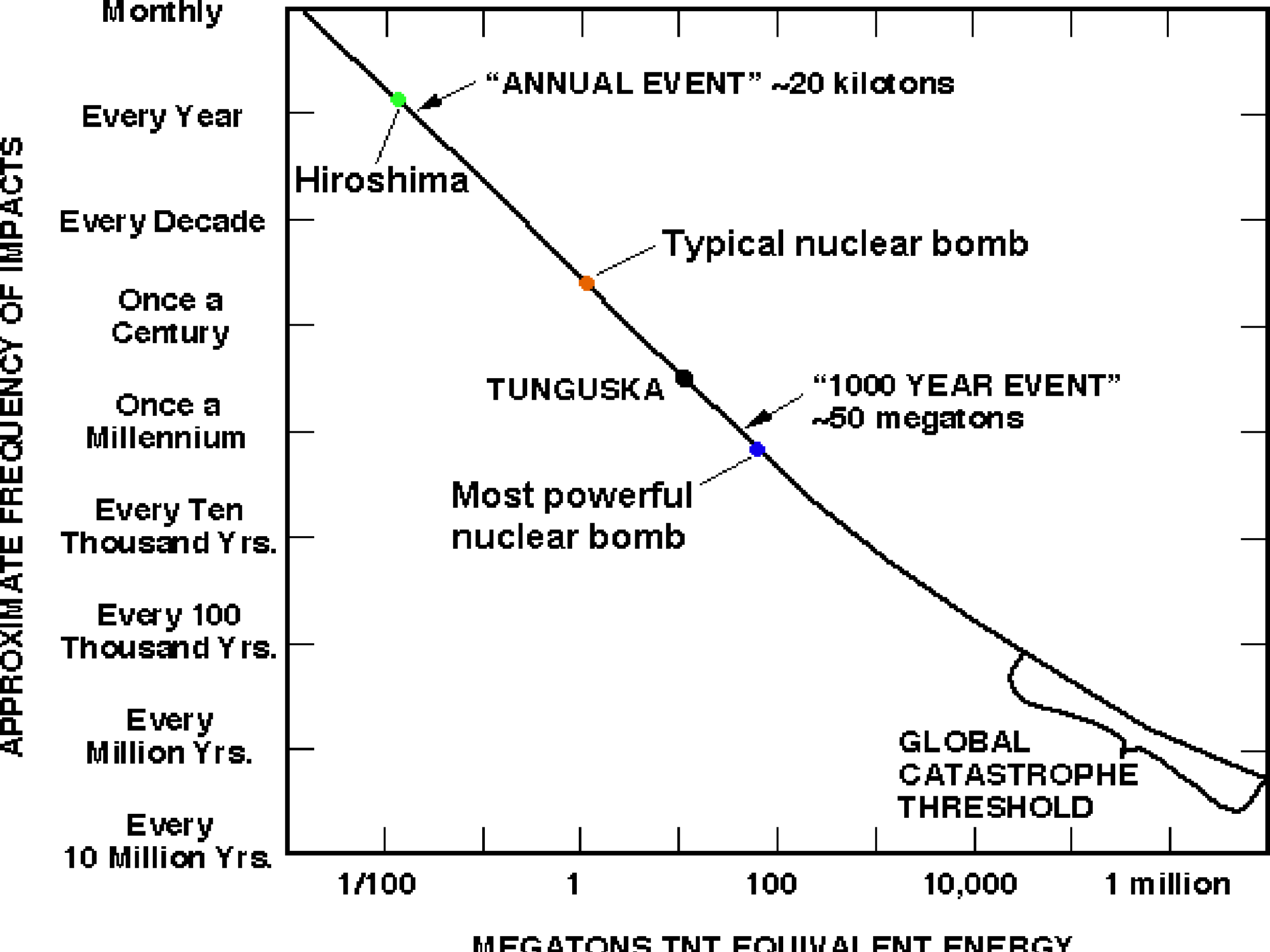


Chixilub crater on the Yucatan Peninsula, Mexico.
Close up of previous image



Impacts, Volcanic Episodes and Geologic Era Boundaries

- Glickson (2010) points out that asteroid impact clusters and volcanic events overlap at the end stages of at least 4 geologic epochs, not just the K-Pg boundary. He points out many flaws in the volcanics-only traditionalist arguments made e.g. by **(Morgan *et al.* (2004)**.
- The odds of impacts of sufficient size, as calculated from known abundances of asteroids *vs.* size *vs.* orbital characteristics, make massive impacts likely throughout Earth's history (see next slide)


Monthly
Every Year
Every Decade
Once a Century
Once a Millennium
Every Ten Thousand Yrs.
Every 100 Thousand Yrs.
Every Million Yrs.
Every 10 Million Yrs.
APPROXIMATE FREQUENCY OF IMPACTS
"ANNUAL EVENT" ~20 kilotons
Hiroshima
Typical nuclear bomb
TUNGUSKA
"1000 YEAR EVENT" ~50 megatons
Most powerful nuclear bomb
GLOBAL CATASTROPHE THRESHOLD
1/100
1
100
10,000
1 million
MEGATONS TNT EQUIVALENT ENERGY

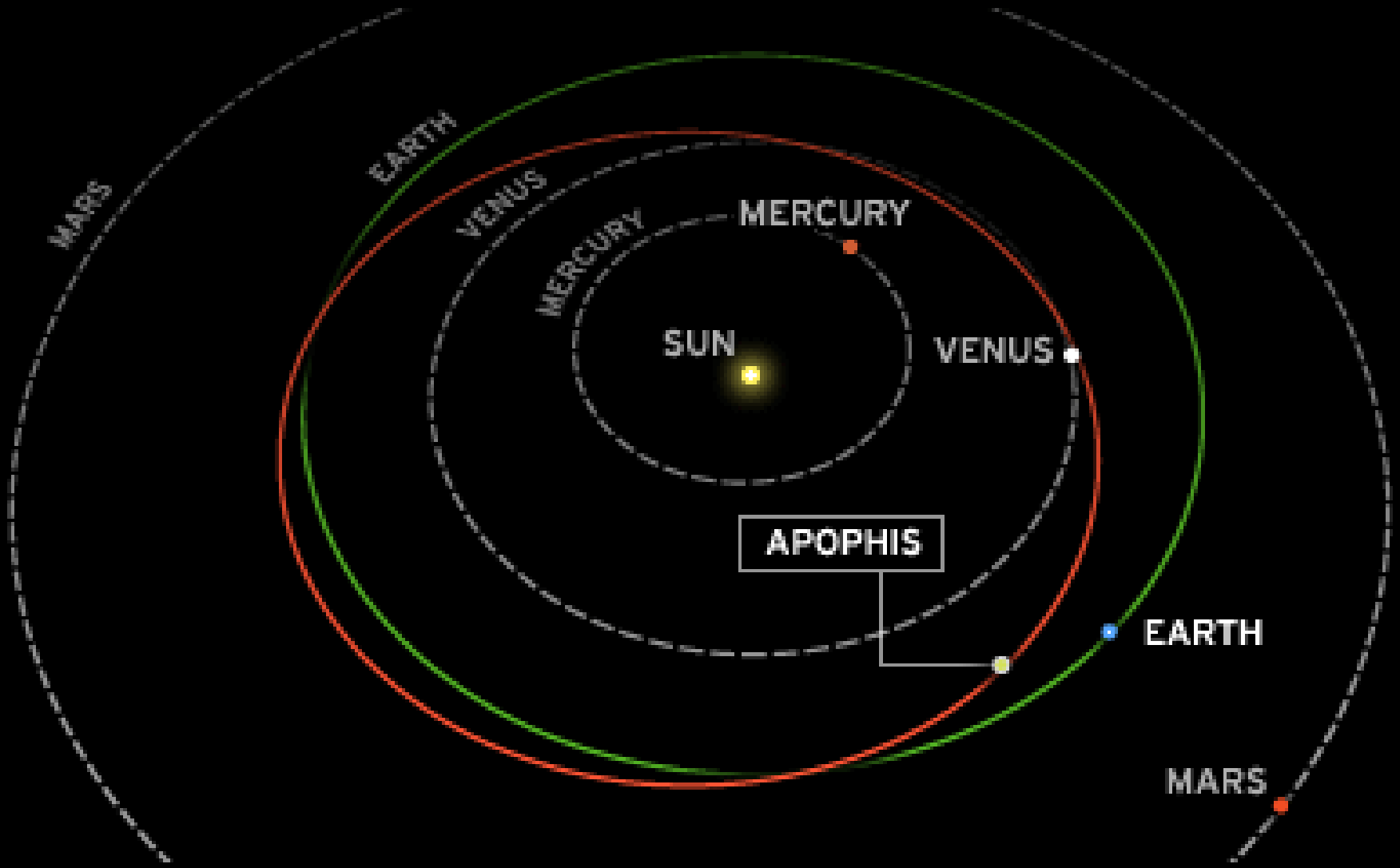
Only 12,900 years ago…

- A ~3 km asteroid or comet apparently hit North America, likely on the retreating Laurentian Ice Sheet, crater at bottom of one of the Great Lakes??
- It's now a leading explanation for what took out the wooley mammoths, saber tooth tigers, the Clovis people… and pretty much burned the continent to the ground
- This is fairly new discovery; this research was published in 2007
- High iridium, hexagonal micro-diamonds (only found in asteroids) in layer, found in Greenland as well as many places in Europe and North America, argue for an impact.
- I've been doing my own search for this tell-tale dark layer in likely locations around California – so far without luck…
- We may try again in future Astro Field Astronomy classes which go to Carrizo Plain National Monument.

Impact boundary layer in Southern Arizona, formed 12,900 years ago, showing enhanced iridium

And Soon….

- 1300 ft wide asteroid Apophis will make a near-collision with Earth on **Friday the 13th**, April 2029
- If it threads through a 600m x 600m "keyhole" during this fly-by, it'll return in 7 more years and collide with Earth.
- If so, directly facing the on-coming Apophis in 2036…. is **California**
- **(Bummer, Dude!)**


MARS
EARTH
VENUS
MERCURY
MERCURY
SUN
VENUS
APOPHIS
EARTH
MARS

What to Do? Call up Bruce Willis?

- NASA instead decided…
- 2015: Plan for space mission to launch
- 2019: craft rendezvous with Apophis and takes measurements allowing orbit to be determined to within yards
- If collision will happen, design "Son of Deep Impact" for hitting asteroid in 2024-8
- 2013: new astrometry reduces impact odds to 1 in a million – whew! We're saved!
- But, it could take out a satellite or two in 2029. A few bucks gone – not a disaster.
- Update – odds of going through "the keyhole" now less than 1 in a million and we're backing off our worries

What if we get Blind-sided by a much bigger asteroid?

- …. That would be bad.
- We almost got hit by DA14 on Feb 15, 2013 (and DID get blindsided by a smaller rock the very same day – just ask the Russians).
- Just for fun: the **End of the World (8:39)**
- Looks like Apophis will not hit us in 2029 or 2036, and even if it did, it won't be near as dramatic as this video

Chap 12 Key Points: Asteroids, KBO's, Comets

- Comets: frozen ices with black, dirty hard crust, porous interior
- Short period comets created by collisions between KBO's especially in Early Solar System
- KBO orbits suggest possible new planets far beyond Neptune
- Ices in short period comets slowly blown away or vaporized, leaving dirt, dust in same orbit as comet, causing meteor shower if crosses our orbit
- Comets have a dust tail, and a straight anti-solar ion tail
- Asteroids mostly orbit between Mars and Jupiter, formed from collisions of former planets there, and more collisions between themselves, by Jupiter's strong disturbing gravity
- Asteroids made of mostly rock, a bit of ice, some carbonaceous material farther out in asteroid belt.
- 300m asteroids and smaller, are almost all made of solid rock with dusty coatings. Larger asteroids are gravel and small pieces loosely held together by weak gravity, with icey layers inside
- Pluto; first discovered KBO. Triton is also a KBO, captured by Neptune long ago. About 100,000 KBO's 100km across or bigger.
- Comets; few, shallow craters. Asteroids: covered with craters, some are binary.
- Excess number of asteroids of ~100km size says asteroids formed large, and broke up by collisions