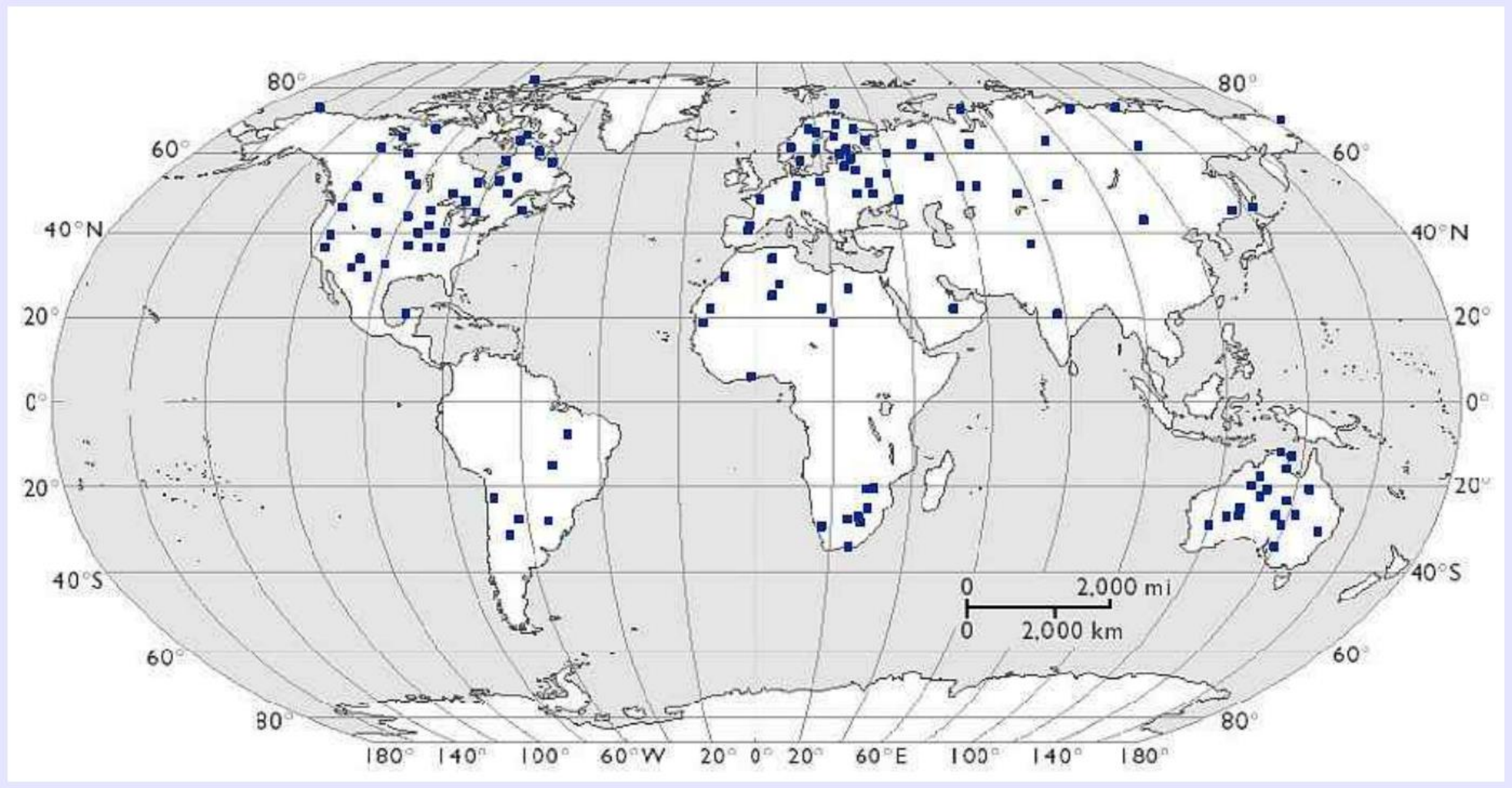
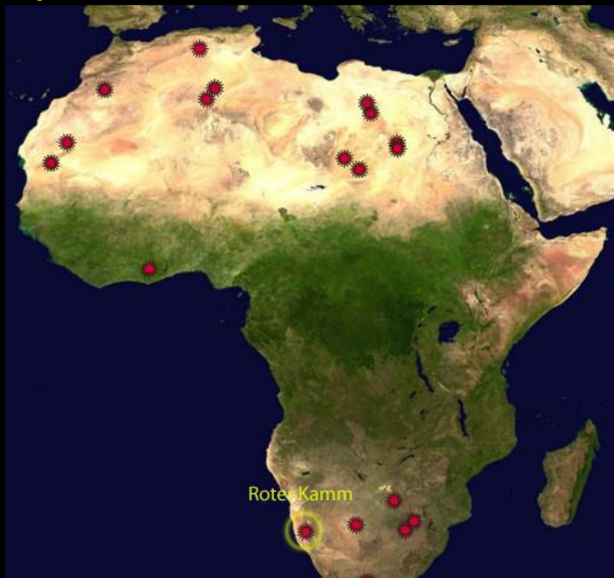
World Wide Crater Distribution



Simple Craters – Barringer (Meteor Crater), Arizona, USA

Barringer crater is 1.2 km in diameter and approximately 50,000 years old. Location is 35°2’N, 111°1’W

Simple Craters – Roter Kamm, Namibia



Roter Kamm is 2.5 km in diameter, 3.7 million years in age and located at 27°46'S, 16°18'E

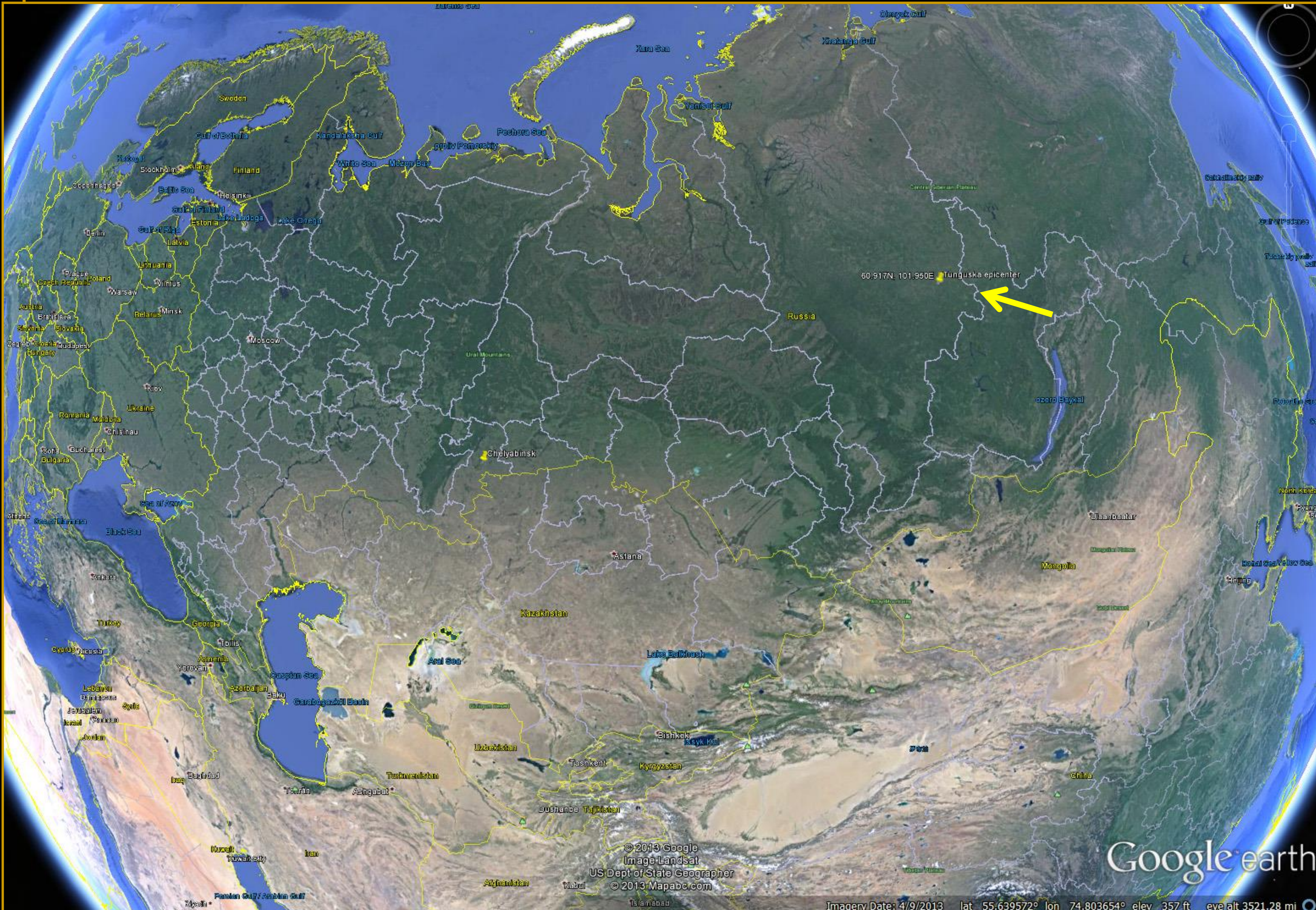
Odessa Meteorite Crater

Complex Craters – Manicouagan, Quebec, Canada

Diameter 100 km, age is 214 million years, location is 51º23'N, 68º42'W

Tunguska – June 30, 1908

- At about 0:17 UT an explosion occurred near the Podkamennaya Tunguska River in central Siberia at an altitude of about 5 – 10 km
- The energy of the explosion is estimated to have been equivalent to that of about 15 megatons of TNT
- At 5 – 16 km trees were blown over with the tops pointed away from the blast
- At 60 km people were thrown to the ground, windows were broken
- At 30 km people were blown into the air and knocked unconscious


60.917N, 101.950E
Tunguska epicenter
Russia
Chelyabinsk
Moscow
Astana
Kazakhstan
Mongolia
Ulaanbaatar
ozero Baykal
Finland
Sweden
Ukraine
Belarus
Black Sea
Caspian Sea
Aral Sea
Lake Balkhash
Uzbekistan
Turkmenistan
Kyrgyzstan
Tajikistan
Afghanistan
Bishkek
Tashkent
China
Turkey
Georgia
Iran
Iraq
Baghdad
© 2013 Google
Image Landsat
US Dept of State Geographer
© 2013 Mapabc.com
Google earth
Imagery Date: 4/9/2013 lat 55.639572° lon 74.803654° elev 357 ft eye alt 3521.28 mi

Tunguska – June 30, 1908

400 km southeast of ground zero

60 km south of ground zero

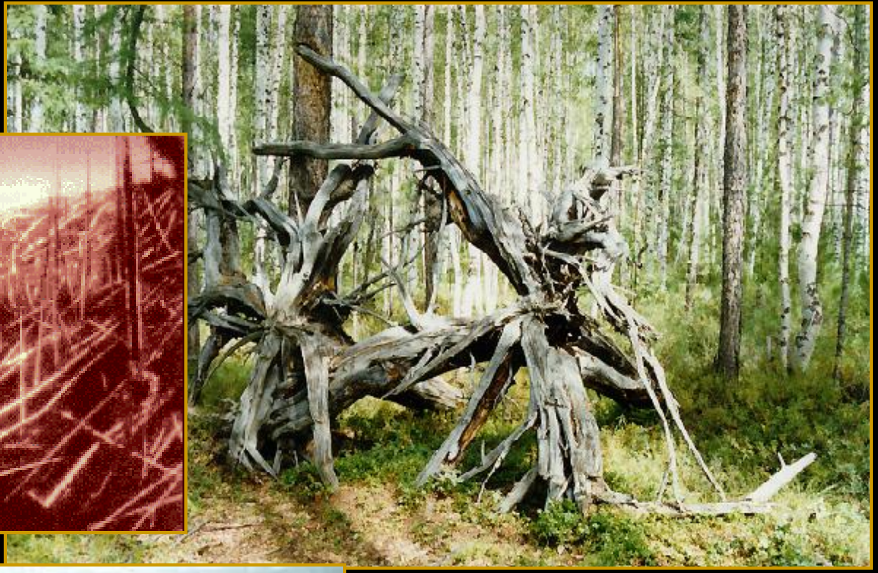
15 km from ground zero – a few minutes after the explosion

Tunguska 1920's to 2008

192

1927

1998



Actually, 1929

Southern swamp, epicenter of explosion. Photo taken 2008

1927

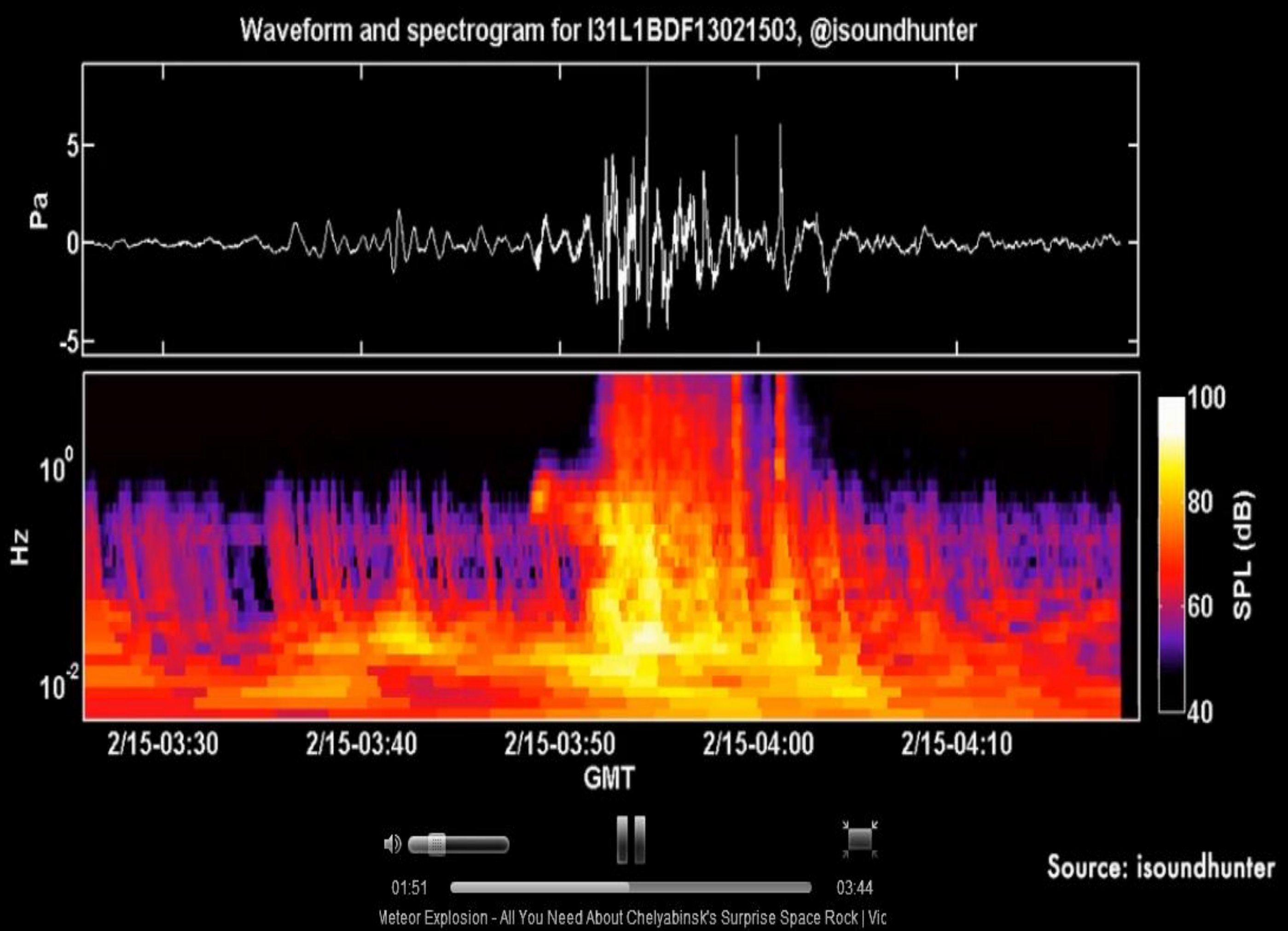
Tunguska – Final Word?

- Probably was a small asteroid (estimated to be 50 – 60 m in diameter) that exploded at about 5 to 10 km above the surface of the Earth
  - Platinum-group metal iridium and other rare elements in ratios consistent with stony meteorites were found in spheres discovered at Tunguska

Cheylabinsk Meteoroid

- Was a Near-Earth asteroid that entered the Earth's atmosphere over Russia February 15, 2013 at about 9:20 local time (sunrise) at an estimated speed of 66,960 km/hr (41,000 mph), almost 60 times the speed of sound
- Due to high velocity and shallow angle it exploded over Chelyabinsk at about 23.3 km altitude (14.5 miles)
- Blast contained 20-30 times more energy than was released from the atomic bomb detonated at Hiroshima
- Initial mass estimated to be about 12,000 – 13,000 metric tonnes and between 17 - 20 m in size – **largest known natural object to enter Earth's atmosphere since Tunguska event in 1908**
- Around 1500 people were injured, 3500 buildings were damaged

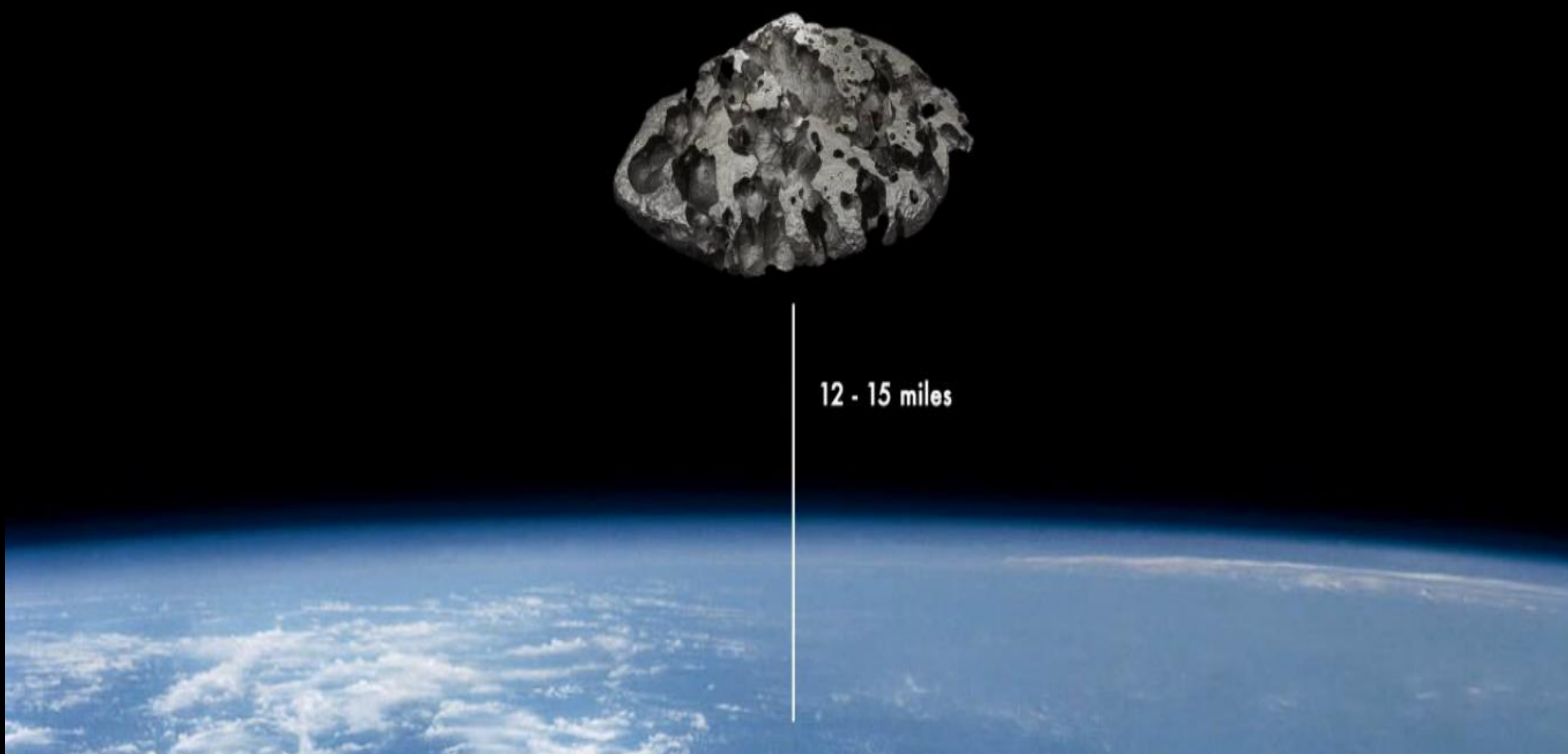

60.917N, 101.950E
Tunguska epicenter
Russia
Chelyabinsk
Moscow
Astana
Kazakhstan
Mongolia
Ulaanbaatar
China
Sweden
Finland
Stockholm
Helsinki
Ukraine
Romania
Turkey
Georgia
Tbilisi
Armenia
Azerbaijan
Baku
Caspian Sea
Aral Sea
Black Sea
Lake Balkhash
Bishkek
Tashkent
Kyrgyzstan
Uzbekistan
Turkmenistan
Ashgabat
Tehran
Baghdad
Dushanbe
Tajikistan
Afghanistan
Kabul
Iran
Kuwait
Riyadh
Saudi Arabia
© 2013 Google
Image Landsat
US Dept of State Geographer
© 2013 Mapabc.com
Google earth
Imagery Date: 4/9/2013 lat 55.639572° lon 74.803654° elev 357 ft eye alt 3521.28 mi


Waveform and spectrogram for I31L1BDF13021503, @isoundhunter
Pa
5
0
-5
Hz
10^0
10^-2
2/15-03:30
2/15-03:40
2/15-03:50
2/15-04:00
2/15-04:10
GMT
100
80
60
40
SPL (dB)
01:51
03:44
Meteor Explosion - All You Need About Chelyabinsk's Surprise Space Rock | Vic
Source: isoundhunter

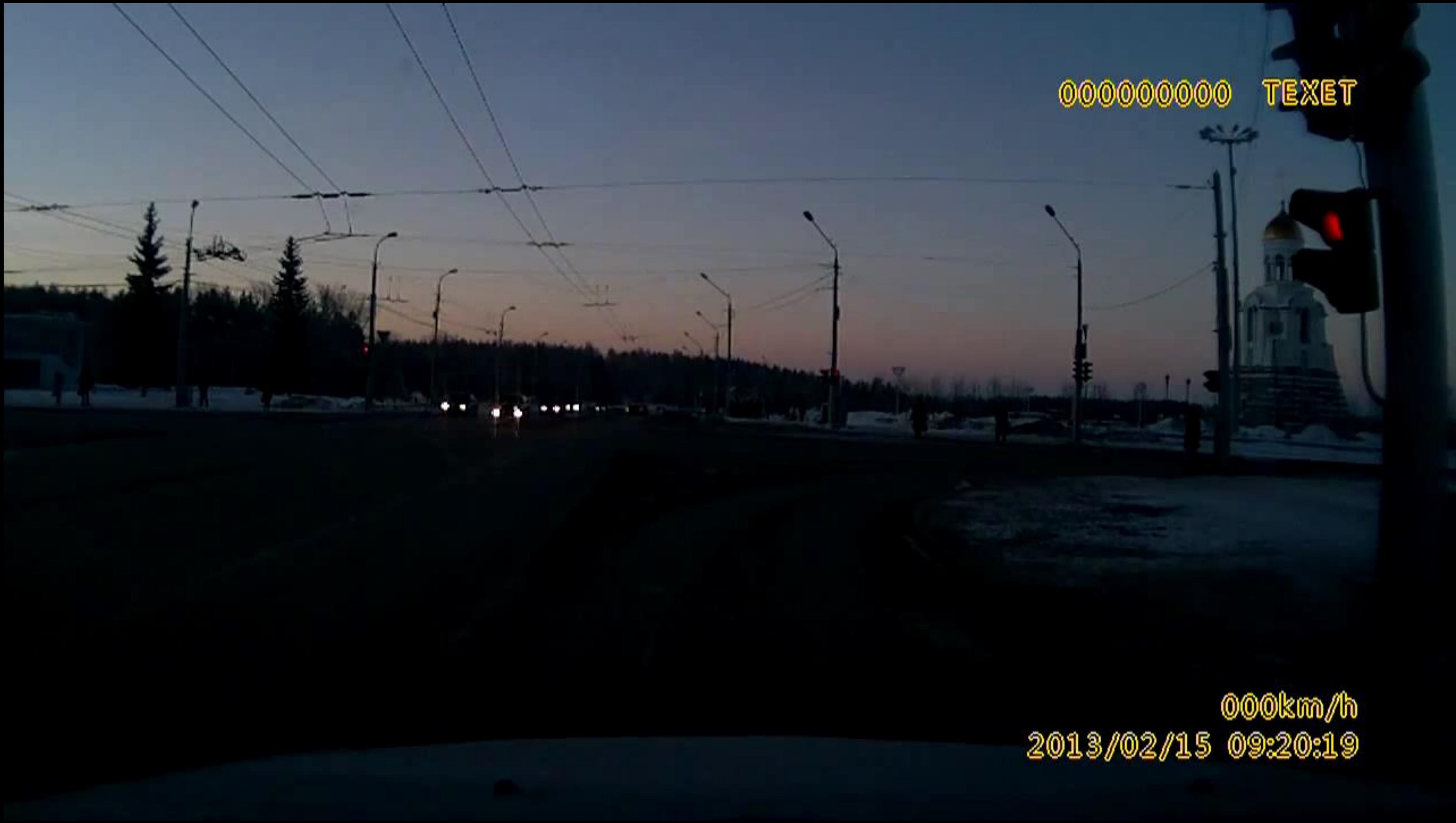
Diameter: 17 m

Weight: 10,000 T

Entry: 40,000 mph



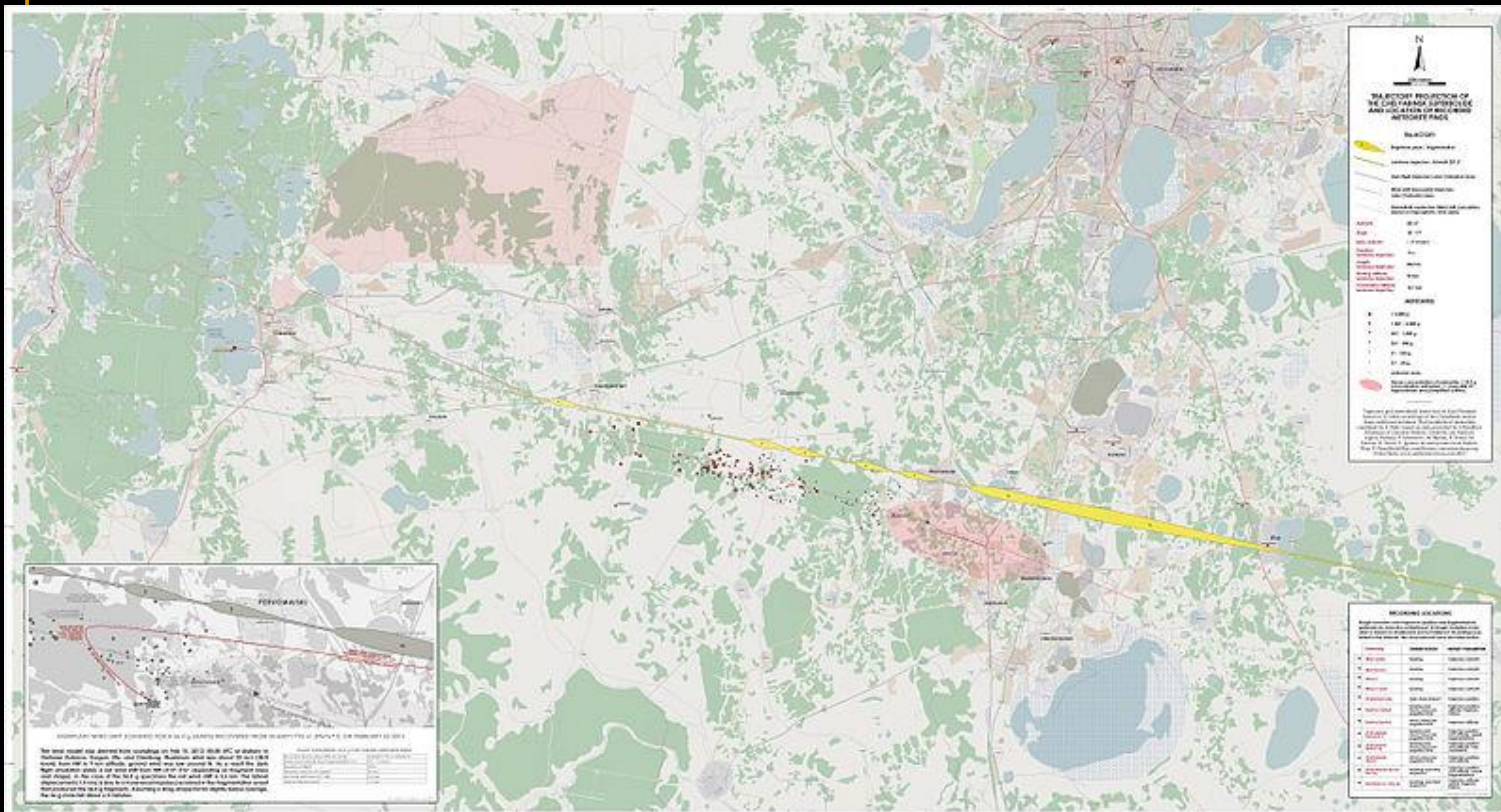

02/15/2013 09:20:11



000000000 TEXET
000km/h
2013/02/15 09:20:19

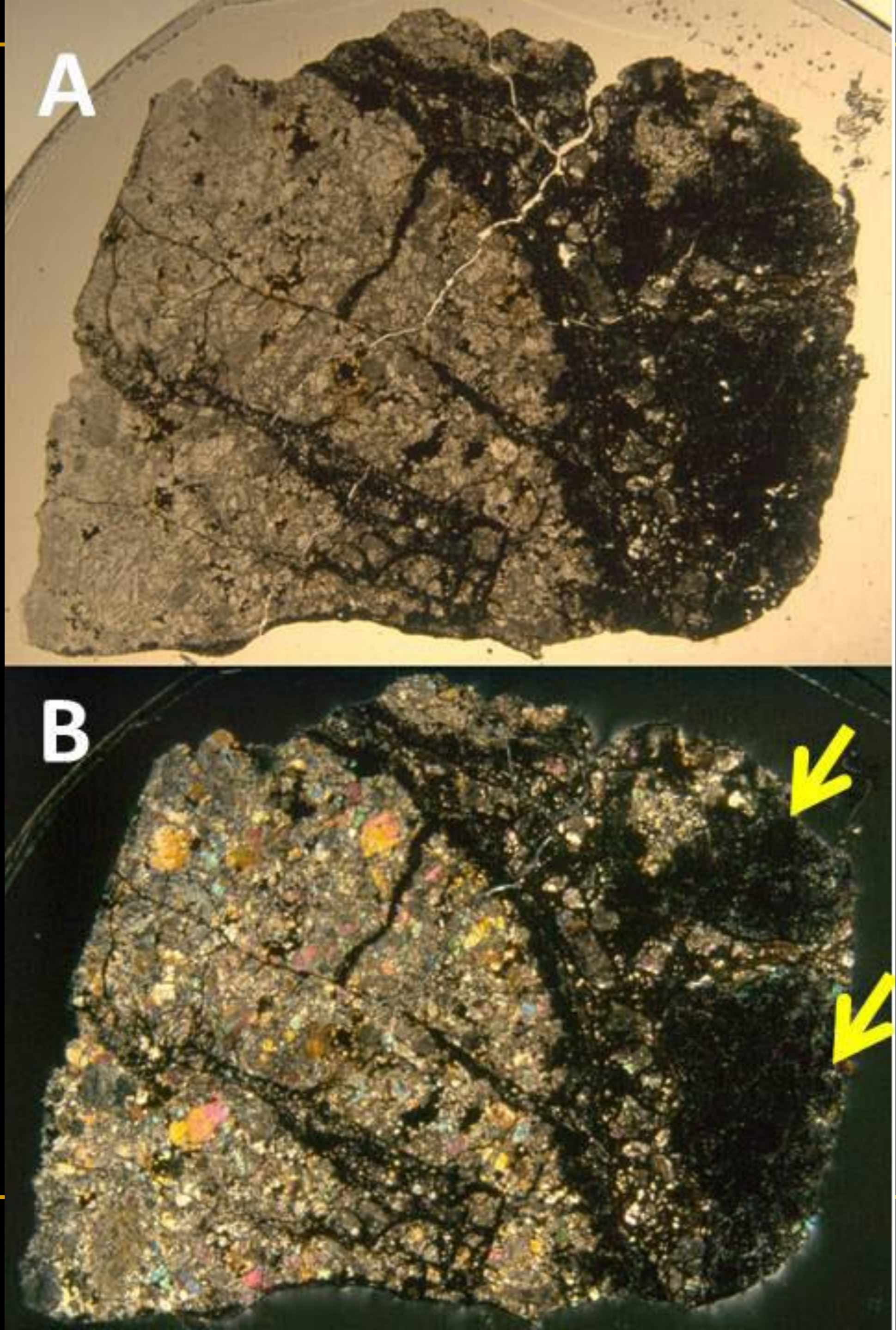

08:49:48


15/02/2013 09:22:36

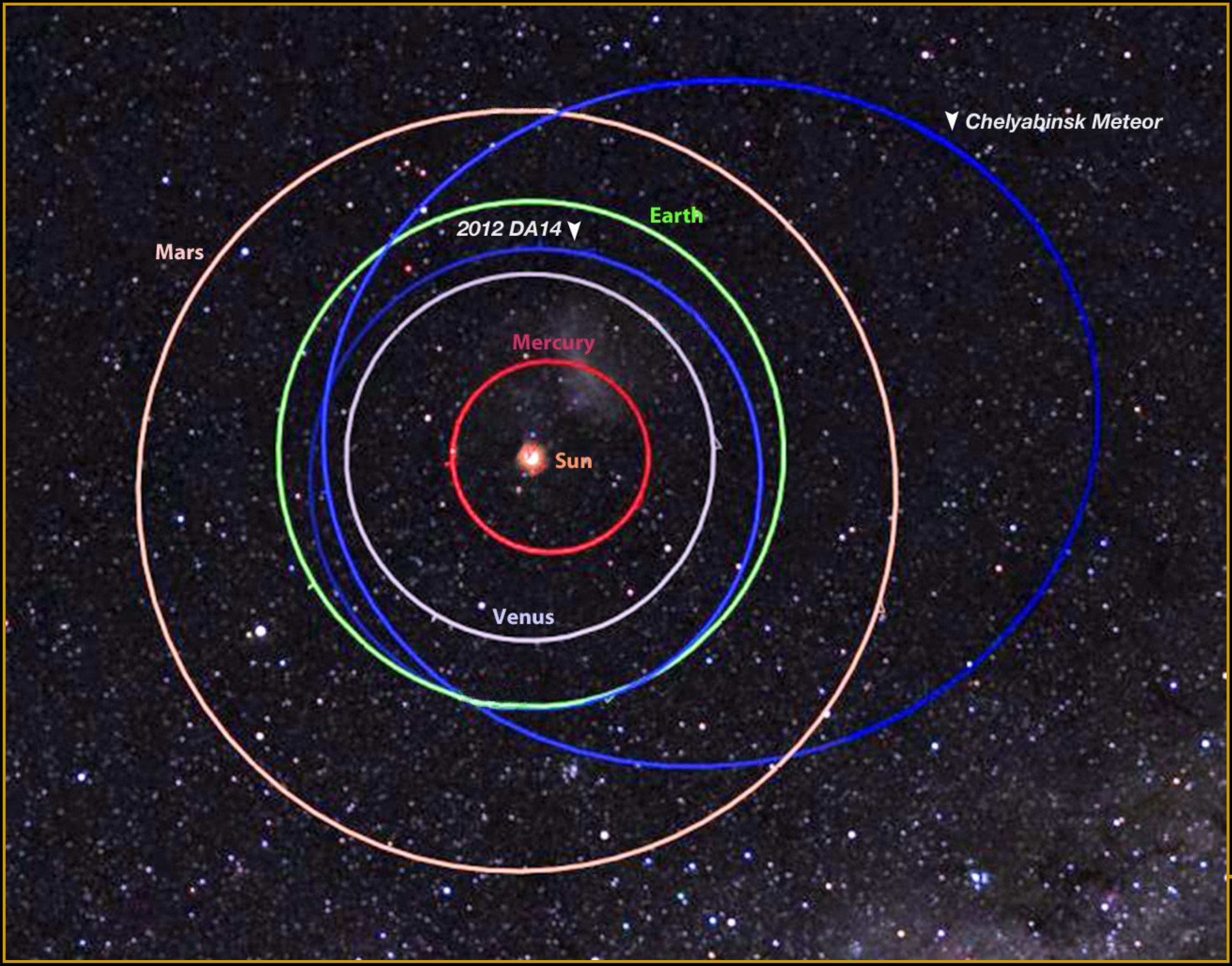


N


N


A
B

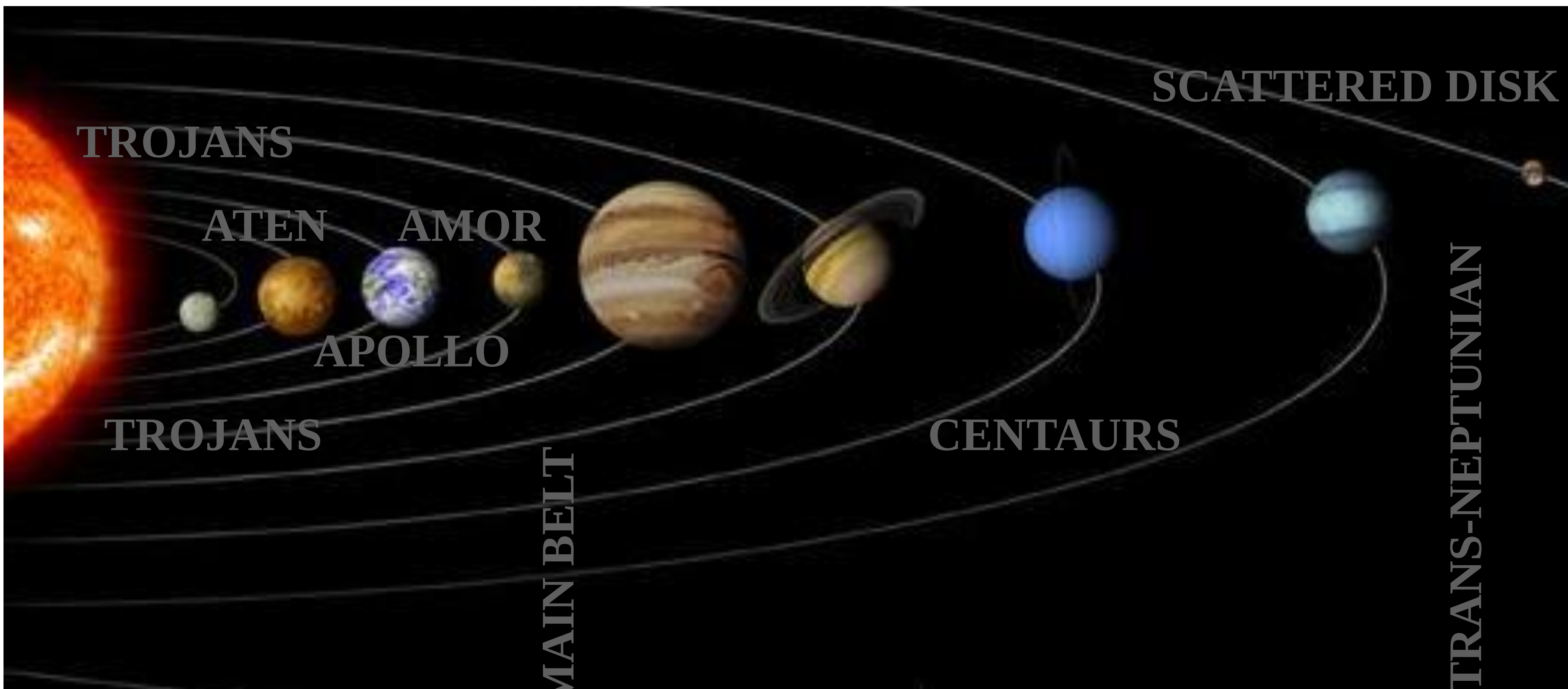
Cheylabinsk Meteoroid - Orbit



Cheylabinsk Meteor not related to Asteroid 2012 DA14 which made a close flyby of Earth 16 hours after the Cheylabinsk event.

THE REAL SOLAR SYSTEM

ASTEROIDS and COMETS!

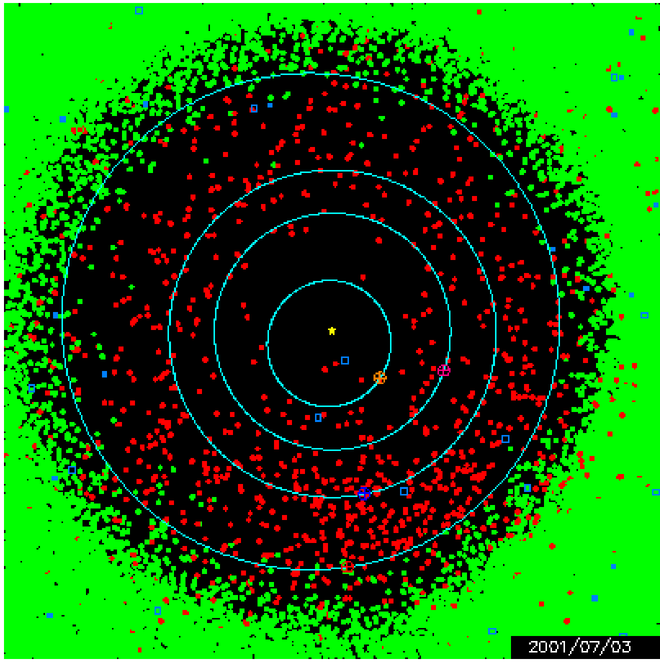


THE INNER SOLAR SYSTEM

THE INNER SOLAR SYSTEM

This animation shows the motion of the inner part of the solar system over a two-year time period. The sun is at the center and the orbits of the planets Mercury, Venus, Earth and Mars are shown in light blue (the locations of each planet are shown as large crossed circles). Comets are shown as blue squares (numbered periodic comets are filled squares, other comets are outline squares). Main-belt minor planets are displayed as green circles, near-Earth minor planets are shown as red circles.

The individual frames were generated on an OpenVMS system, using the PGPLOT graphics library. The animation was put together on a RISC OS 4.03 system using !InterGif.



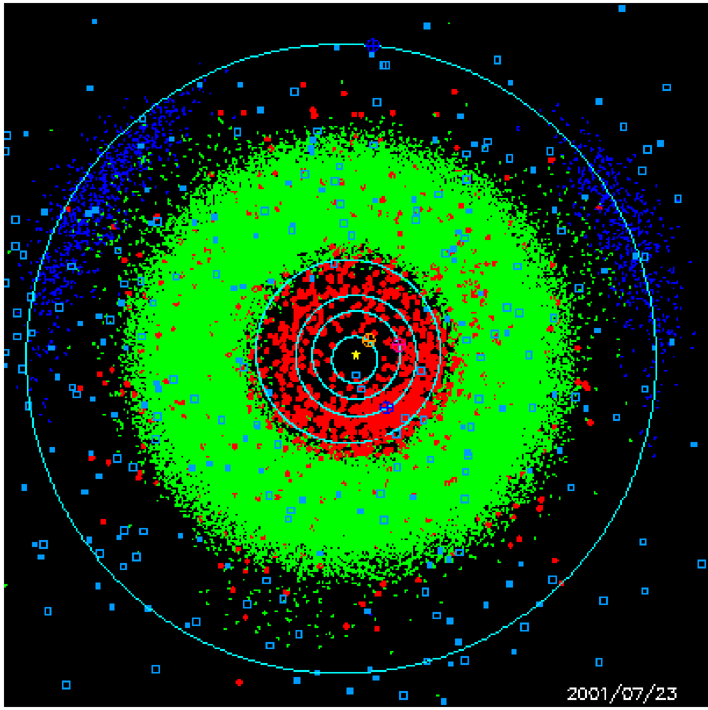
from the Minor Planet Centre
http://www.cfa.harvard.edu/iau/Animations/InnerSmall.gif

THE MIDDLE SOLAR SYSTEM

THE MIDDLE SOLAR SYSTEM

This animation shows the motion of the middle part of the solar system over a two-year time period. The sun is at the center and the orbits of the planets Mercury, Venus, Earth Mars and Jupiter are shown in light blue (the locations of each planet are shown as large crossed circles). Comets are shown as blue squares (numbered periodic comets are filled squares, other comets are outline squares). Main-belt minor planets are displayed as green circles, near-Earth minor planets are shown as red circles.

The individual frames were generated on an OpenVMS system, using the PGPLOT graphics library. The animation was put together on a RISC OS 4.03 system using !InterGif.



from the Minor Planet Centre
http://www.cfa.harvard.edu/iau/Animations/MiddleSmall.gif

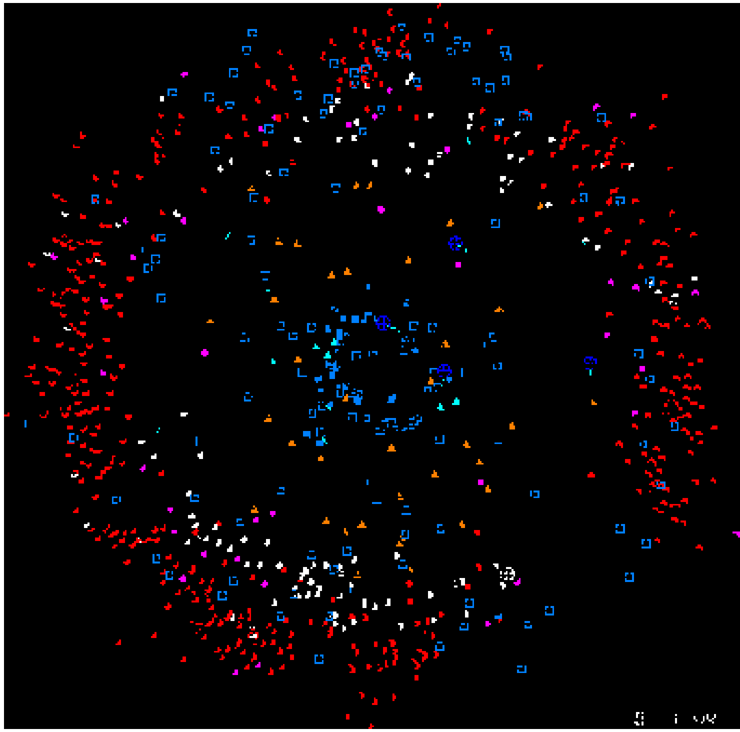
THE OUTER SOLAR SYSTEM

THE OUTER SOLAR SYSTEM

This animation shows the motion of the outer part of the solar system over a 100-year time period. The sun is at the center and the orbits of the planets Jupiter, Saturn Uranus and Neptune are shown in light blue (the locations of each planet are shown as large crossed circles).

Comets: blue squares (filled for numbered periodic comets, outline for other comets)
High-e objects: cyan triangles
Centaurs: orange triangles
Plutinos: white circles (Pluto itself is the large white crossed circle)
"Classical" TNOs: red circles
Scattered Disk Objects: magenta circles

The individual frames were generated on an OpenVMS system, using the PGPLOT graphics library. The animation was put together on a RISC OS 4.03 system using !InterGif.



from the Minor Planet Centre
http://www.cfa.harvard.edu/iau/Animations/OuterSmall.gif

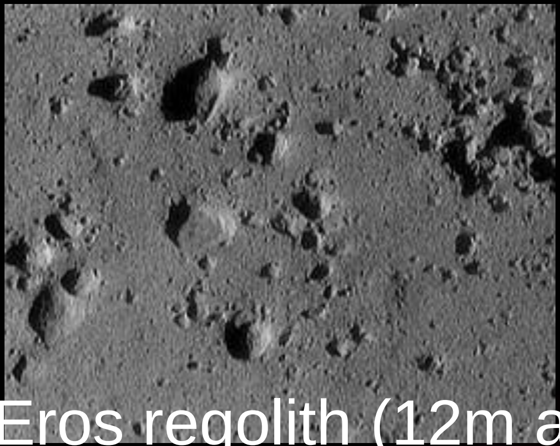
The planetesimal graveyard

- The asteroid belt is the ‘resting ground’ for most of the inner solar system planetesimals that were not incorporated into a planet
  - total mass in asteroid belt ~ 5 x 10^{21} kg (which is about 1/3rd the mass of Pluto or 1/15th the mass of the Moon)

  - Ceres the largest asteroid has
    - a diameter of 940 km and a mass of ~10^{21} kg
    - it is the only “dwarf planet” in the asteroid belt (later)
  - a planet did not form in this region because of gravitational perturbations due to nearby rapidly-formed and massive planet Jupiter


True
False colour
Gaspra: 19 x 12 x 11 kilometers

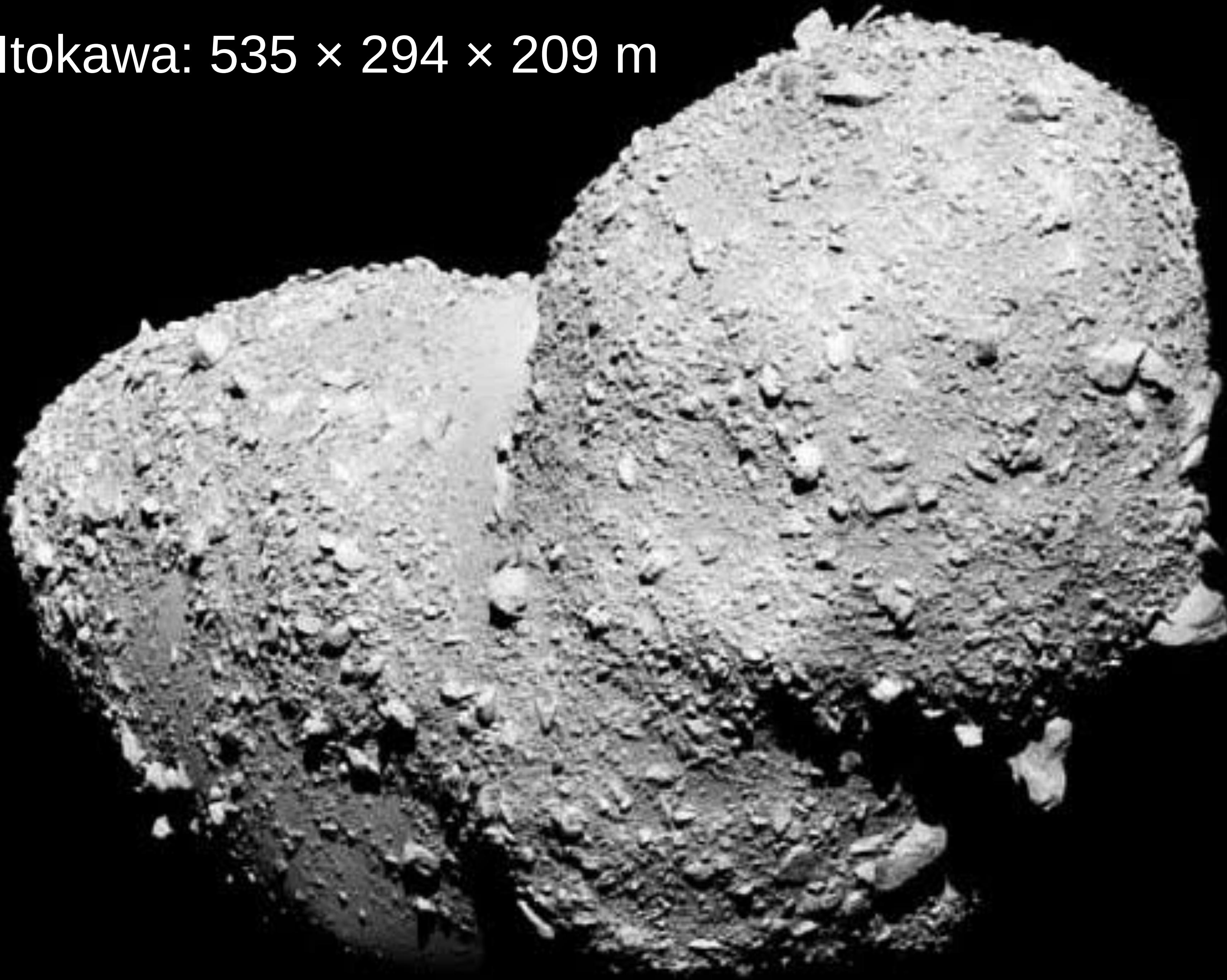
Ida (53 km) and its moon Dactyl



Eros regolith (12m across)

Eros: 34.4×11.2×11.2 km

Itokawa: 535 × 294 × 209 m



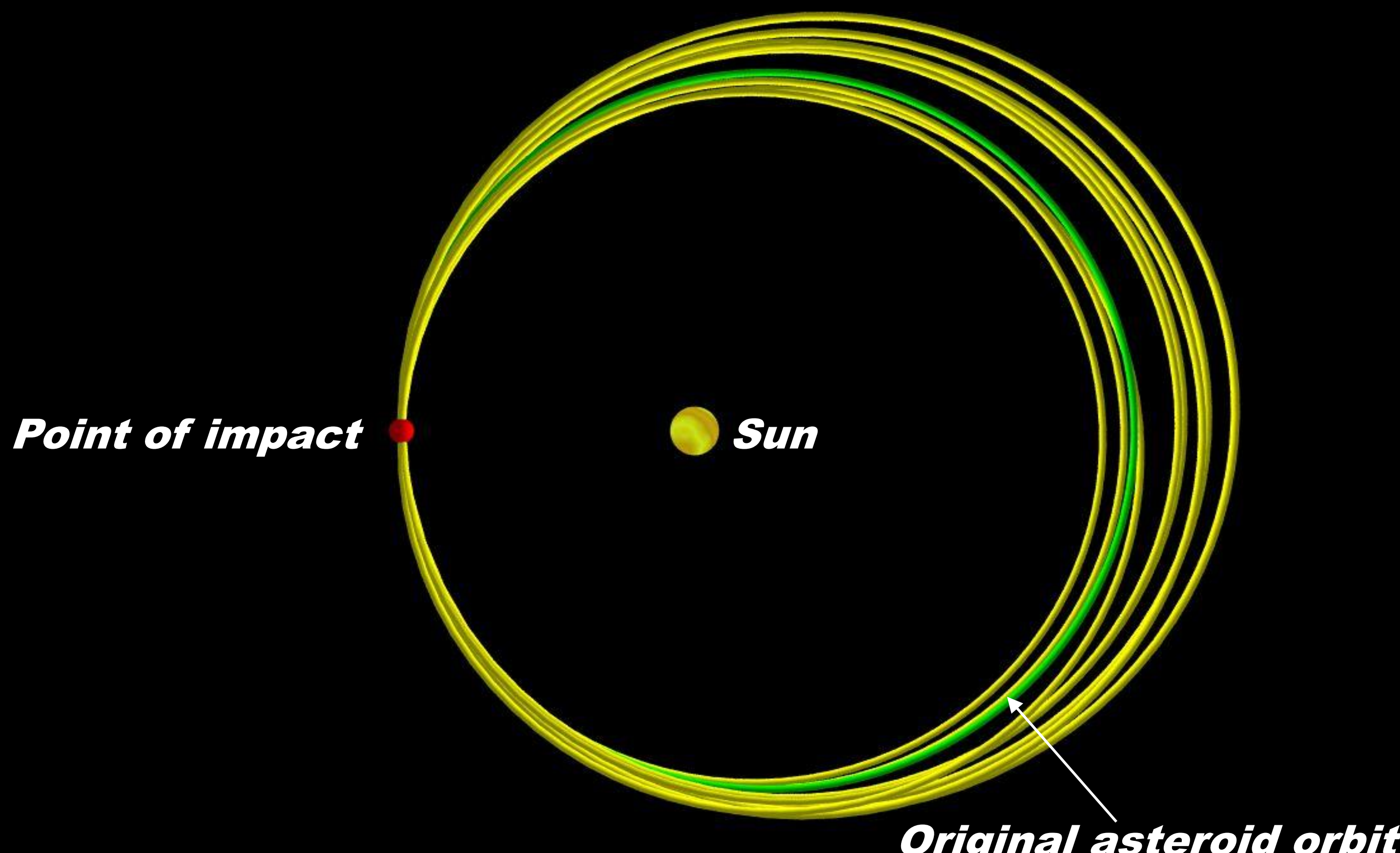
Vesta:
530 km

Asteroid collisions and families

- Though widely spaced, over the age of the Solar System, asteroids undergo frequent collisions.
- Collisions produce fragments that remain on orbits near those of the parents, producing *asteroid families.*

These families can be isolated by plotting the “proper” orbital elements, similar to the ones we’re familiar with but with some corrections for the perturbations of Jupiter.

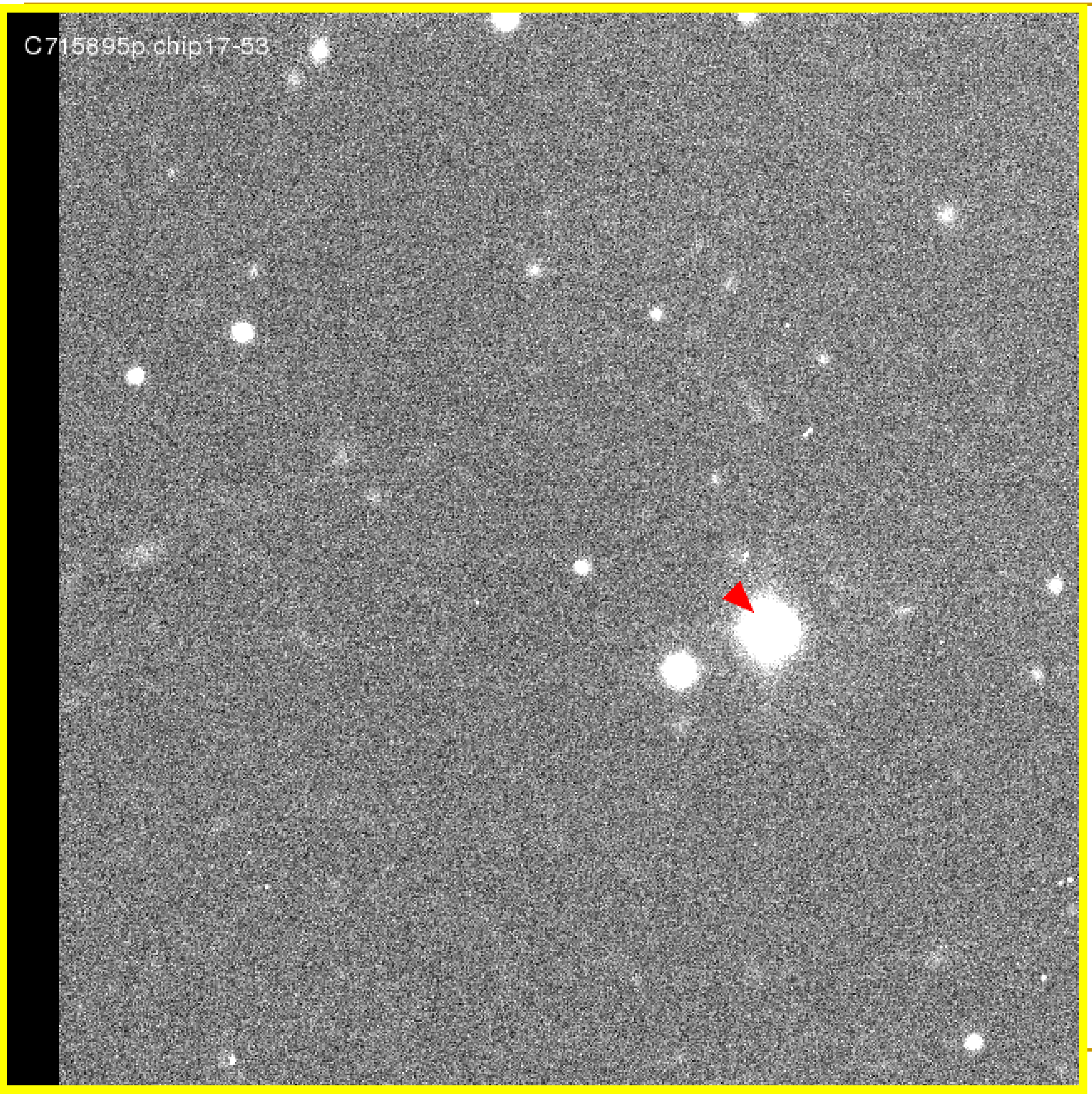
Collisions generate small changes in the fragments' orbits, though they are not violent enough to immediately send them spraying through the Solar system



So how do asteroids/meteorites get to the Earth?

Near-Earth Asteroids (NEAs)

- Smaller asteroids “escape” main-belt via resonances which change their orbits greatly
- Classes of NEAs based on orbits
  - Amor (outside Earth’s orbit)
  - Apollo (fully cross Earth’s orbit)
  - Aten (cross Earth’s orbit only near their aphelion)
- Potentially Hazardous Asteroids (PHAs) : minimum orbital distance with Earth’s orbit < 0.05 A.U.
- Note: Earth orbit is slightly eccentric, so the Earth ranges from .983 to 1.017AU from the Sun, which comes into NEA class definitions



One of the larger asteroids 832 Karin (about 20km diameter) as seen from the 3.6m Canada-France-Hawaii Telescope on Mauna Kea, Hawaii.

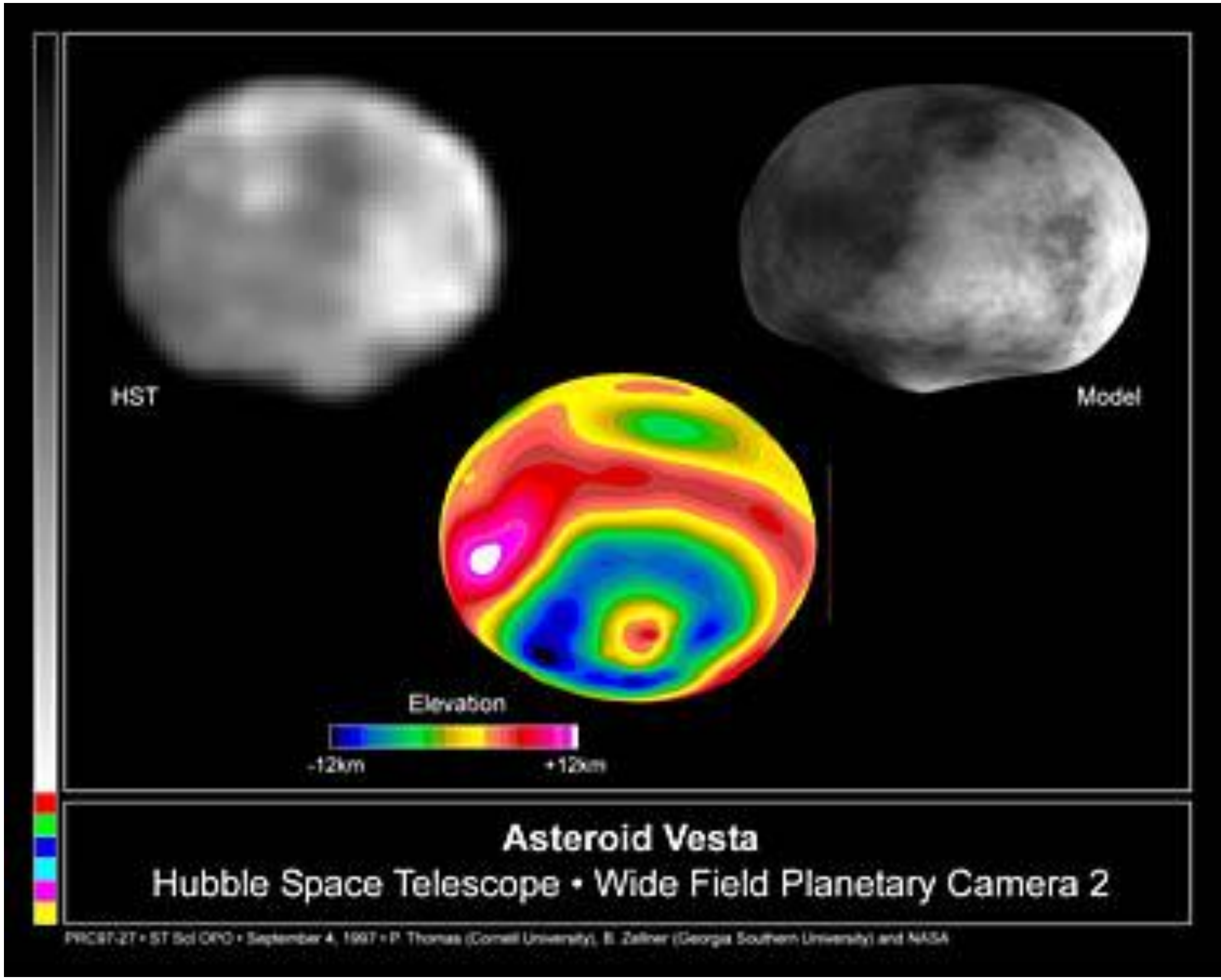
What you see is not the surface of the asteroid, but a blur due to atmospheric and optical imperfections.

So how do we know what their surfaces are like, or even how big they are?

The red arrow was added afterwards by asteroid search software

Best HST view Computer enhanced

1. The Hubble Space Telescope can only see rather minor detail on even the largest asteroids. Most asteroids show no more detail through the HST than through ground-based telescopes.



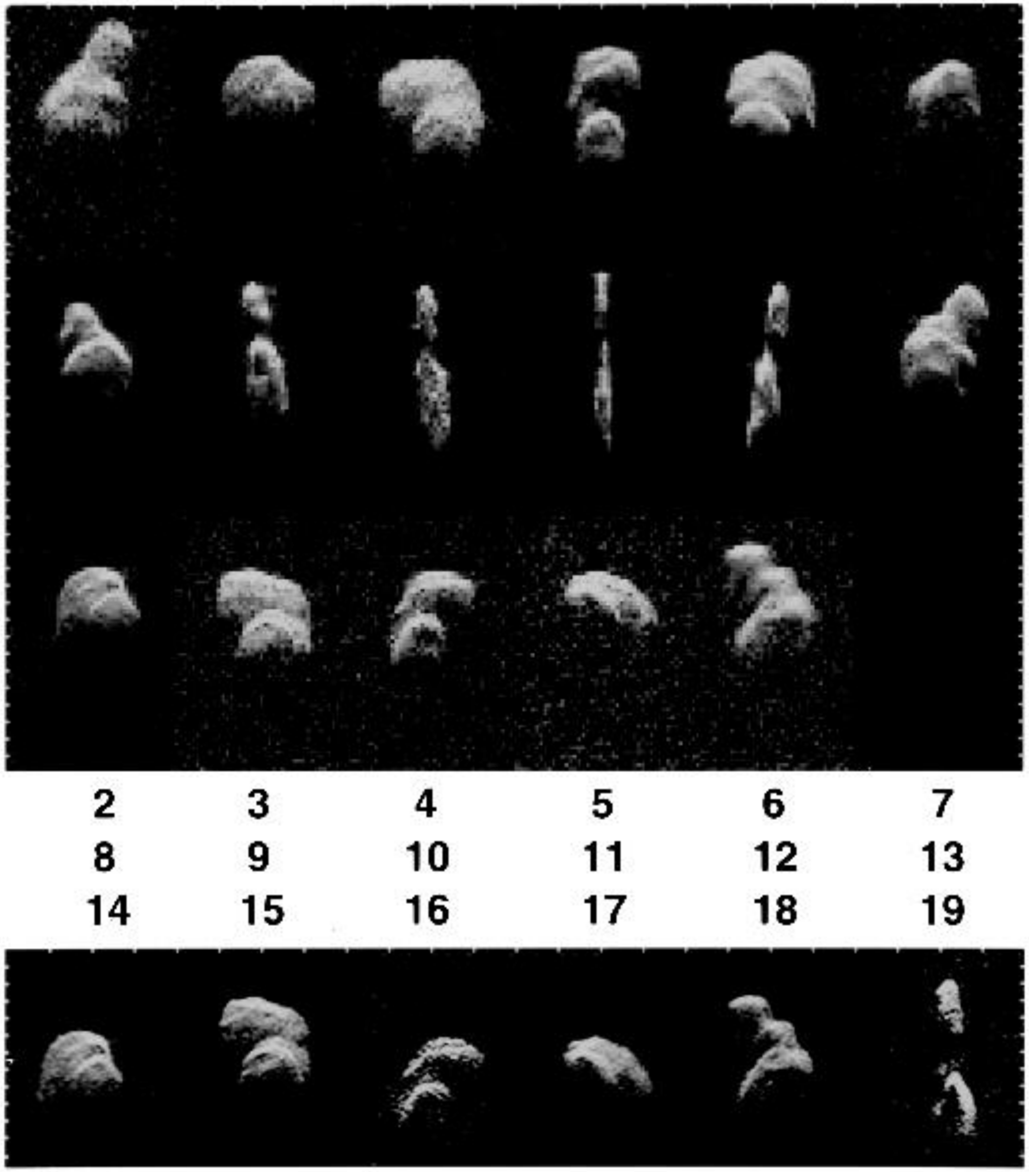
a Gaspra (16 km across)

b Ida (53 km) and its tiny moon, Dactyl

c Mathilde (59 km)

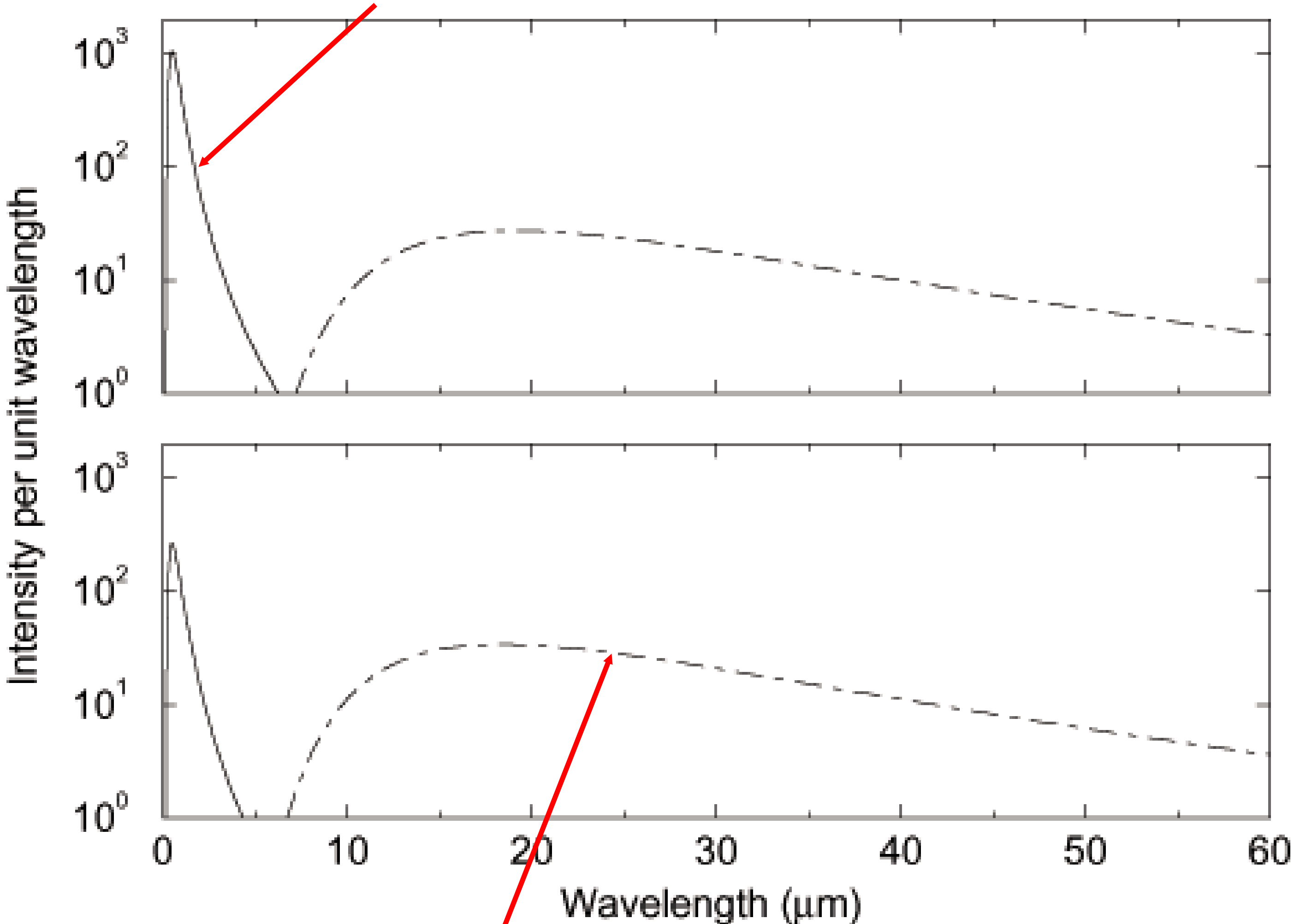
2. Another "easy" way is to send a spacecraft. They can study the asteroids in great detail, but this has only been done for a few asteroids.

Radar Observations of the NEA 4179 Toutatis



3. If an asteroid passes close enough to the Earth, radar beams can be bounced off of it to determine its shape. But this only happens for a few NEAs.

Reflected visible light

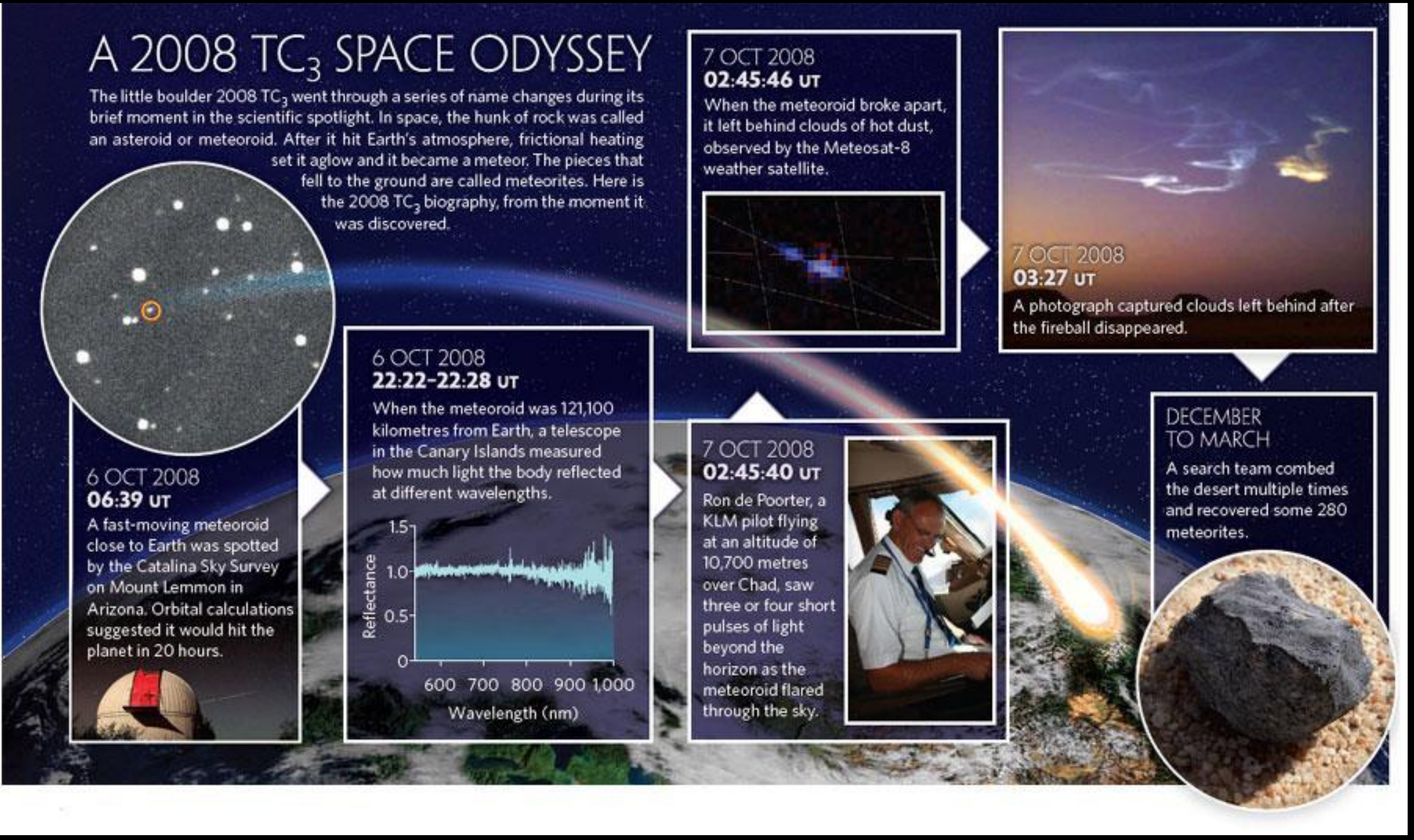


IR emission (blackbody, typically 200K for asteroids in the main asteroid belt)

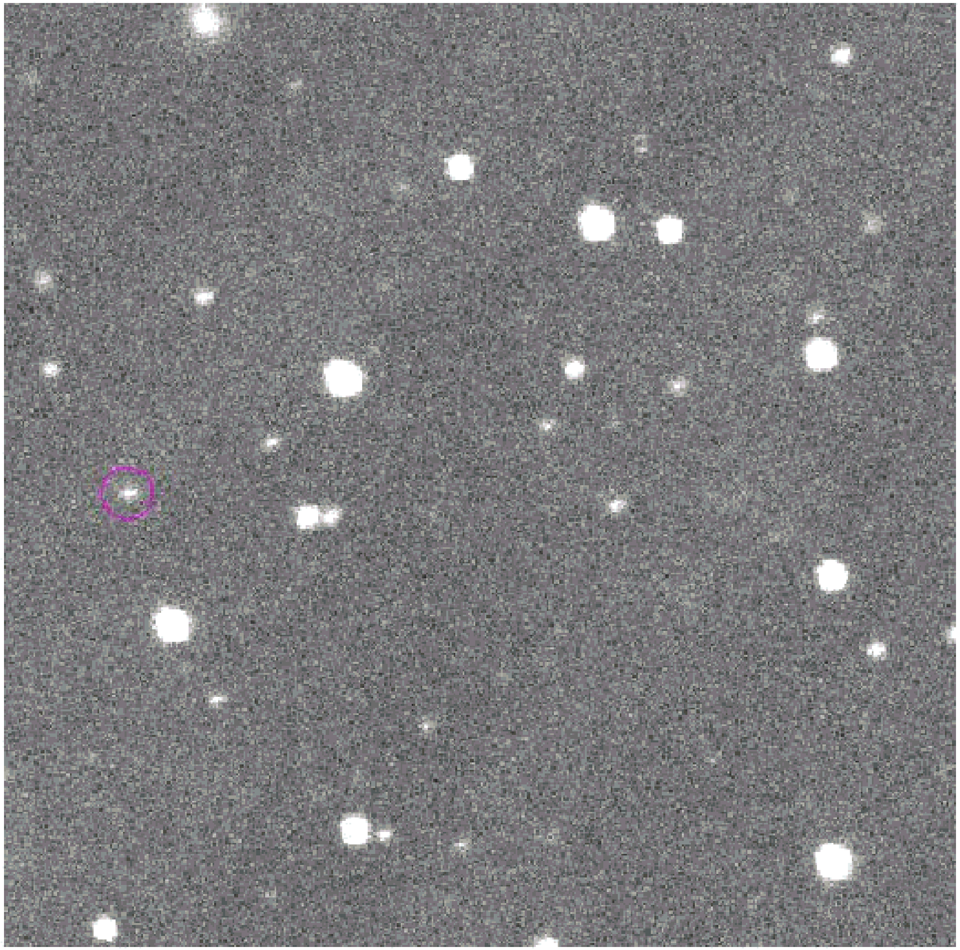
Comets vs. Asteroids

- Originally the difference between the two was observational (that is, based on their appearance in a telescope image)
  - Comets have fuzzy heads and tails
  - Asteroids are starlike with no extended emission
- Now we understand that there are substantial physical differences :
  - Comets are cold, dusty, volatile/ice-rich bodies
  - Asteroids are rocky, volatile-poor bodies

THE ALMAHATA SITTA UREILITE

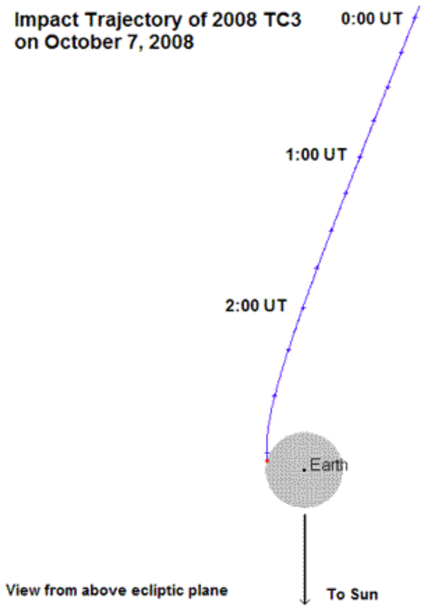


Asteroid 2008TC$_3$ was discovered by the automated Catalina Sky Survey Telescope at Mount Lemmon, Arizona on October 6, 2008



2008 TC3: First asteroid to strike!

- October 6, 6:39 UT
  - Detected in Catalina Sky Survey at Mt. Lemmon, Arizona, by Richard A. Kowalski
  - Steve Chesley, JPL, calculates the impact point in northern Sudan



- October 7, 02:45:29 UT
  - reaches 100 km point at speed 12.2 km/s
  - Radiant at: R.A. = 23h12m, Decl. = +7.6 º, Vg = 6.45 km/s
  - Azimuth 281º (WNW)

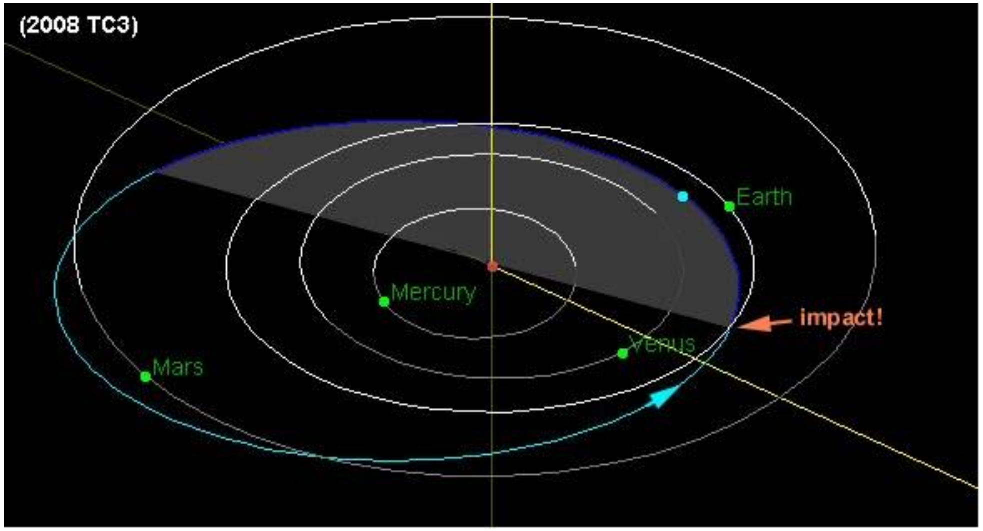

2008-10-06 279:23:48:02.460

Hours before impact: astrometry, photometry, and one spectrum

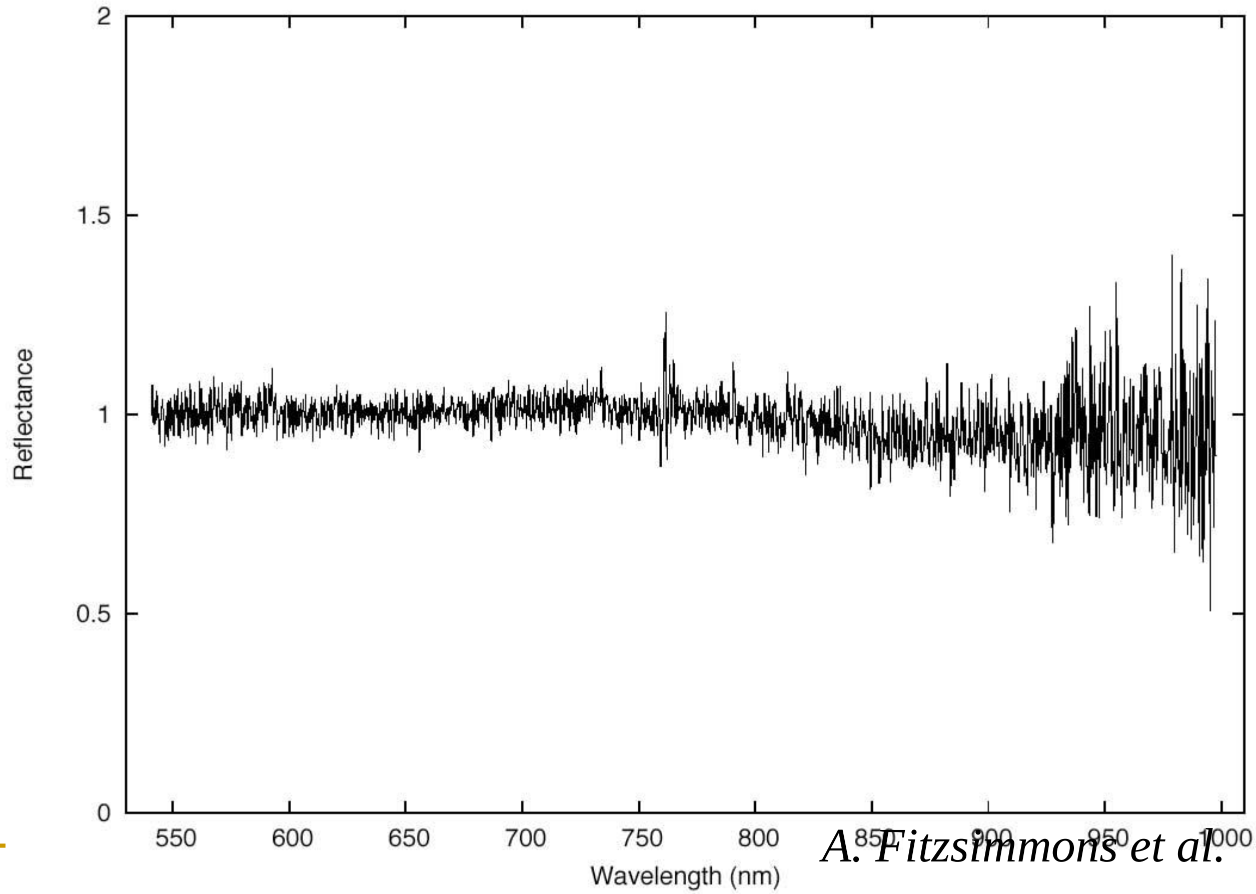
Orbit determined 10,000 times better than typical orbit derived from bolide

Steven R. Chesley (JPL):

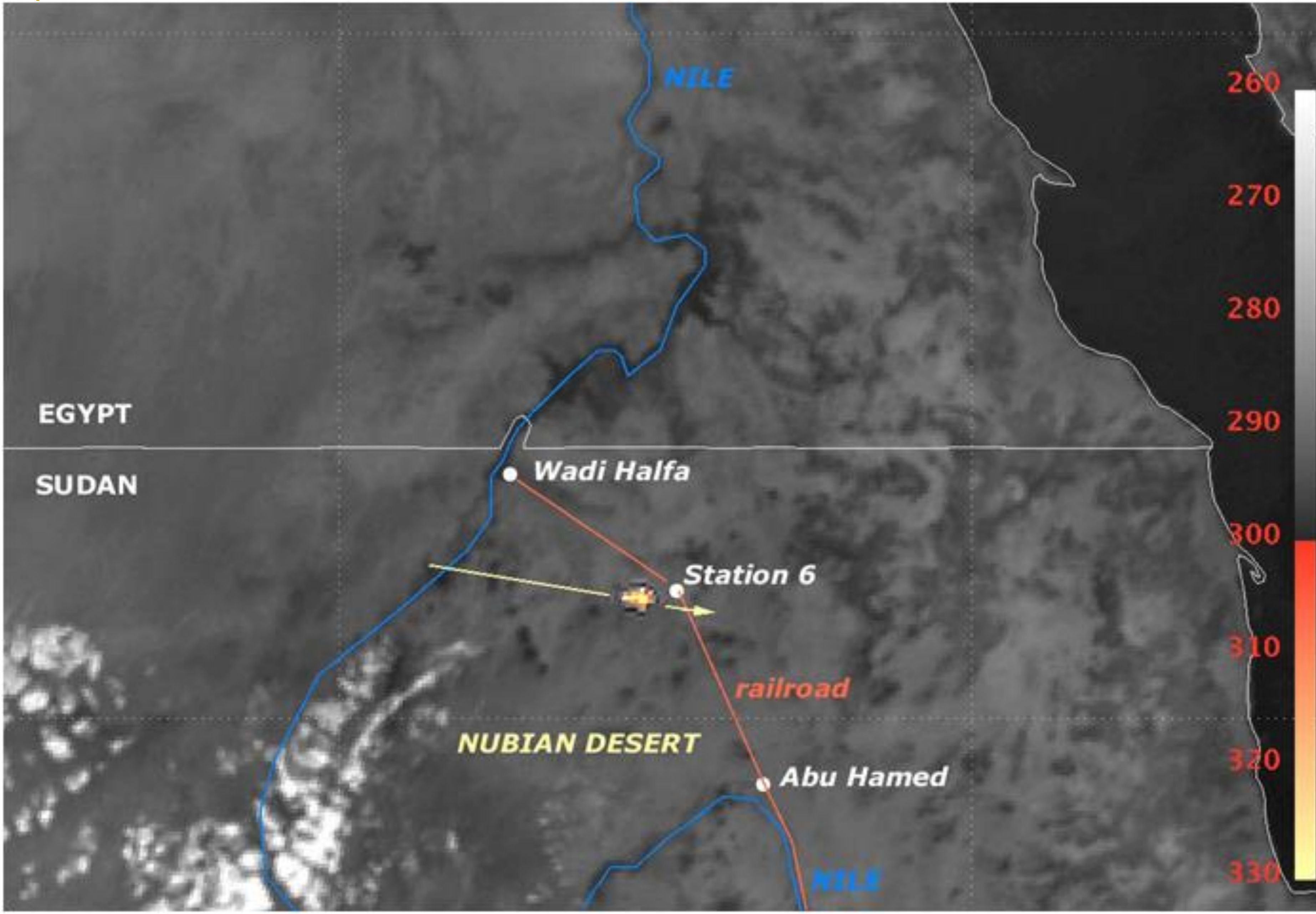
- a = 1.308201 ±0.000009 AU (P
- q = 0.899957 ±0.000002 AU
- i = 2.54220 ±0.00004º
- Ω = 194.101139±0.000002º
- ω = 234.44897 ±0.00008º

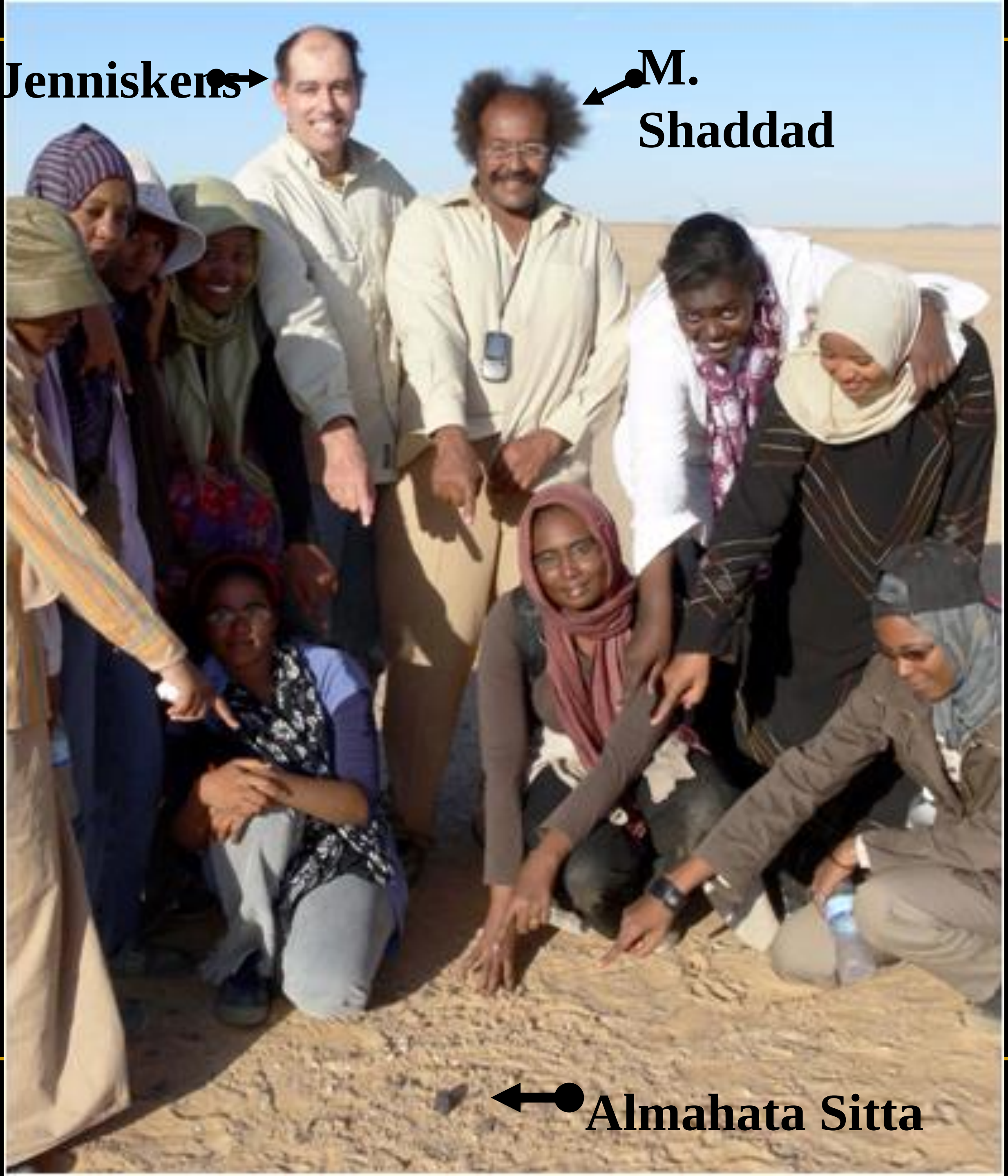


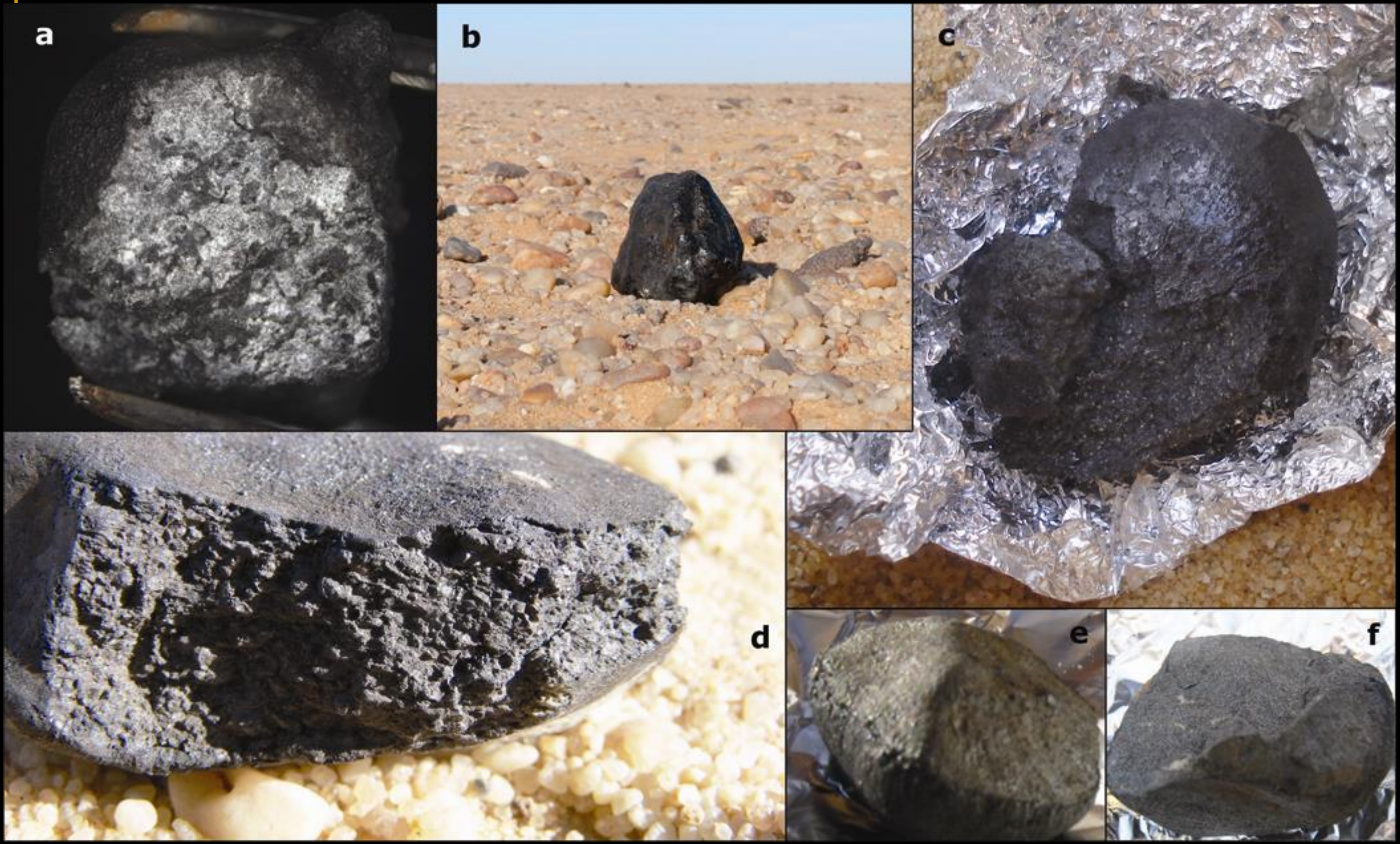
Astronomical reflectance spectrum: flat



A. Fitzsimmons et al.


NILE
EGYPT
SUDAN
Wadi Halfa
Station 6
railroad
NUBIAN DESERT
Abu Hamed
NILE
260
270
280
290
300
310
320
330


Jenniskens
M.
Shaddad
Almahata Sitta


a
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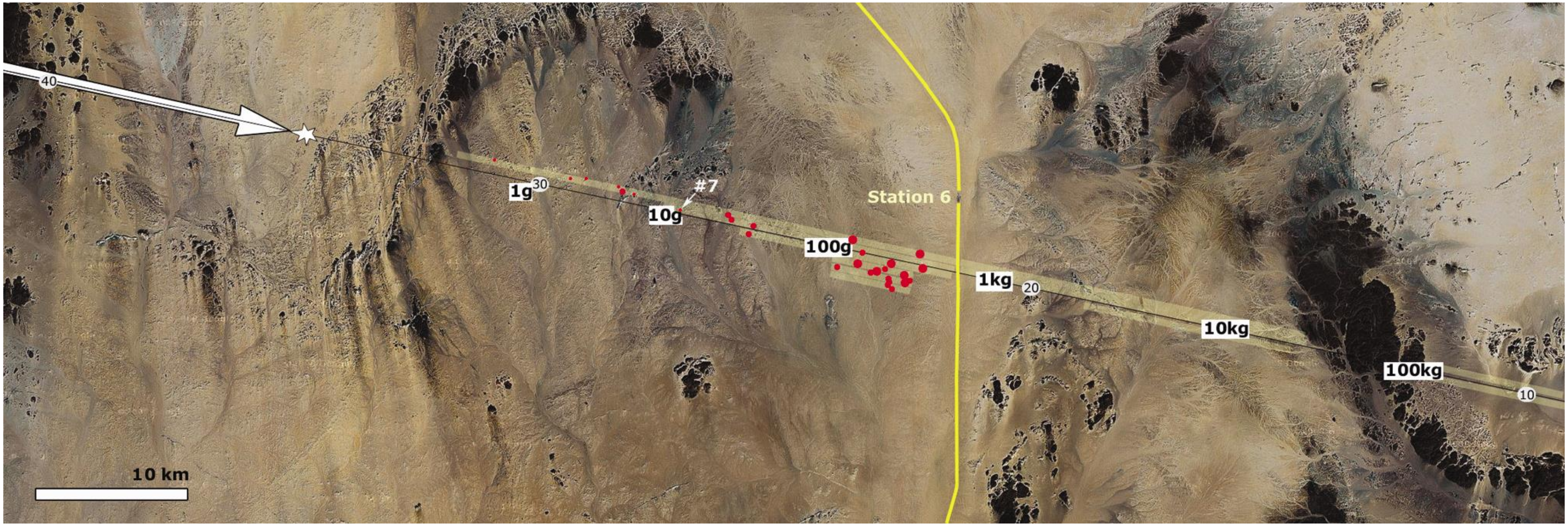
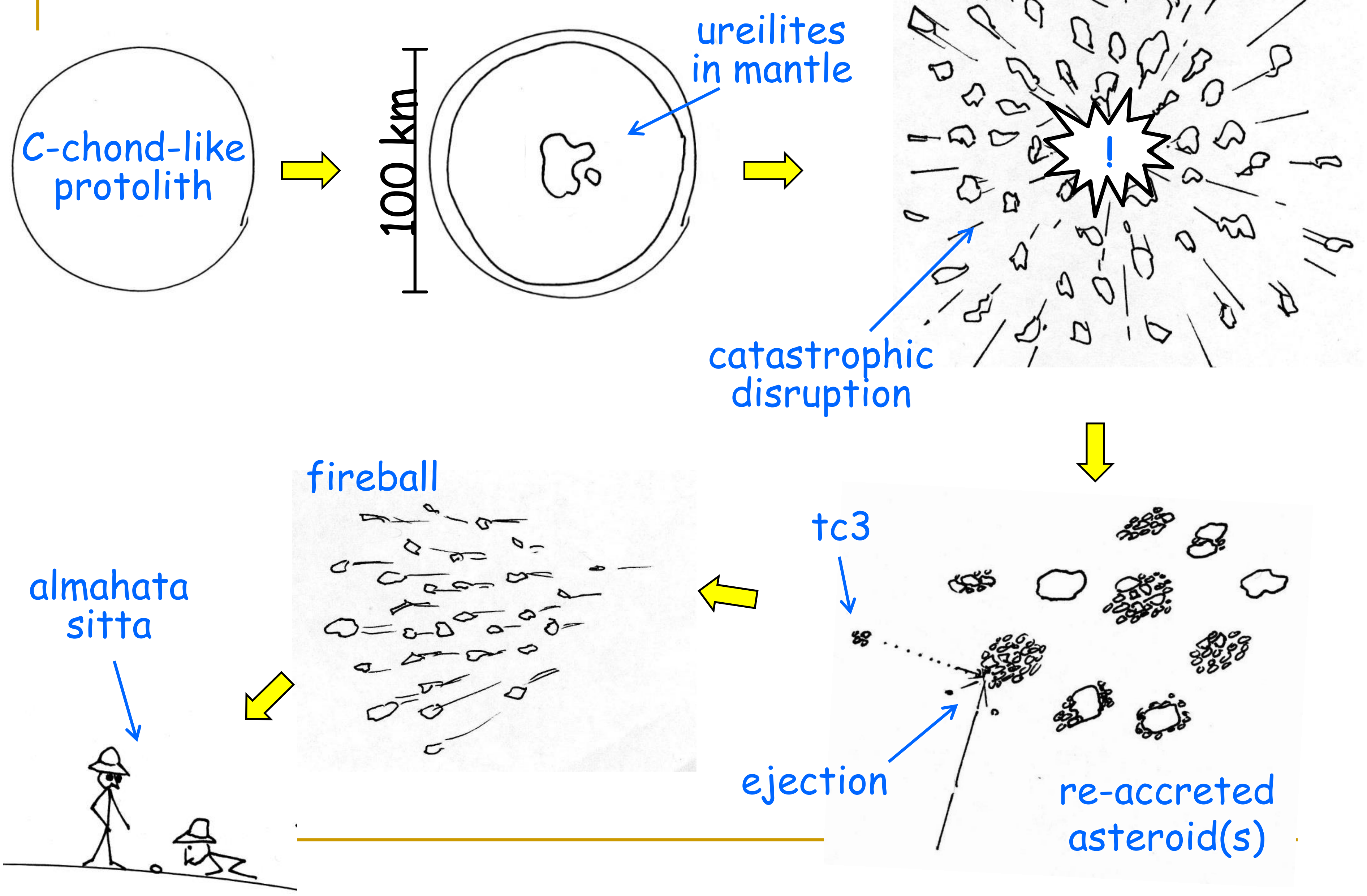
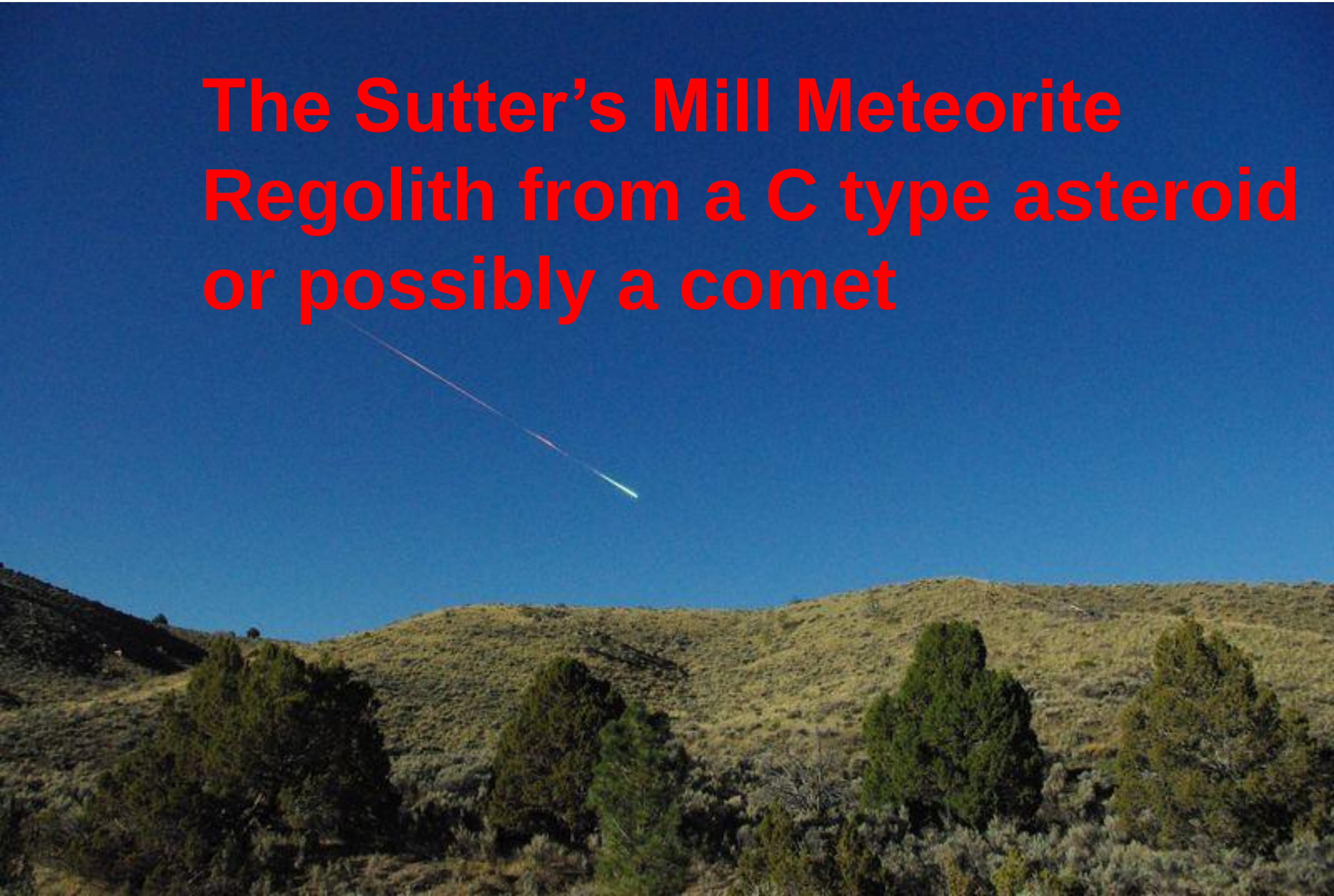


40
1g
30
#7
10g
Station 6
100g
1kg
20
10kg
100kg
10
10 km

the life of almahata sitta…

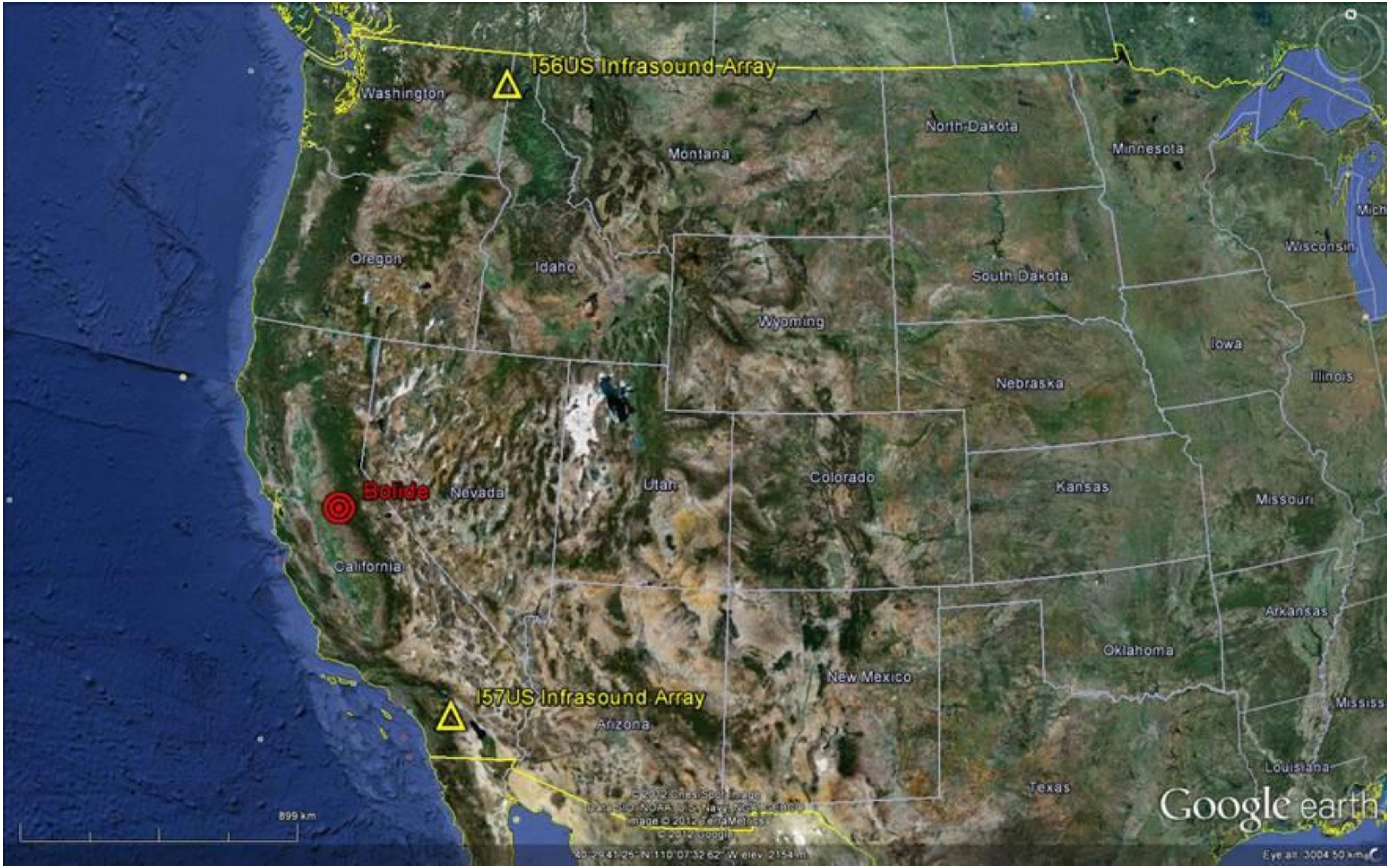


Fireball Over California - April 22, 2012



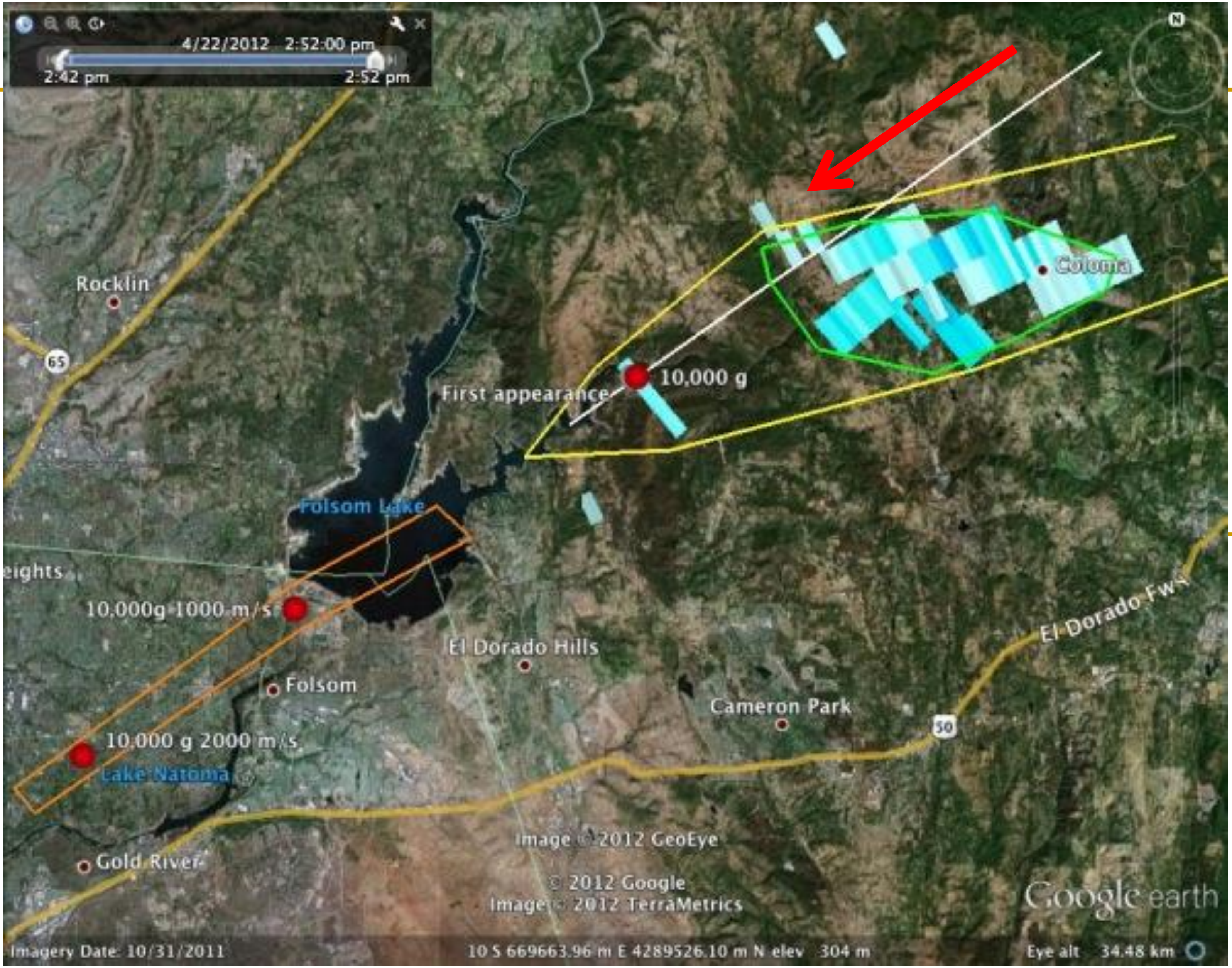
At Brush Creek near Johnsondale, CA, the fireball was filmed by Shon Bollock

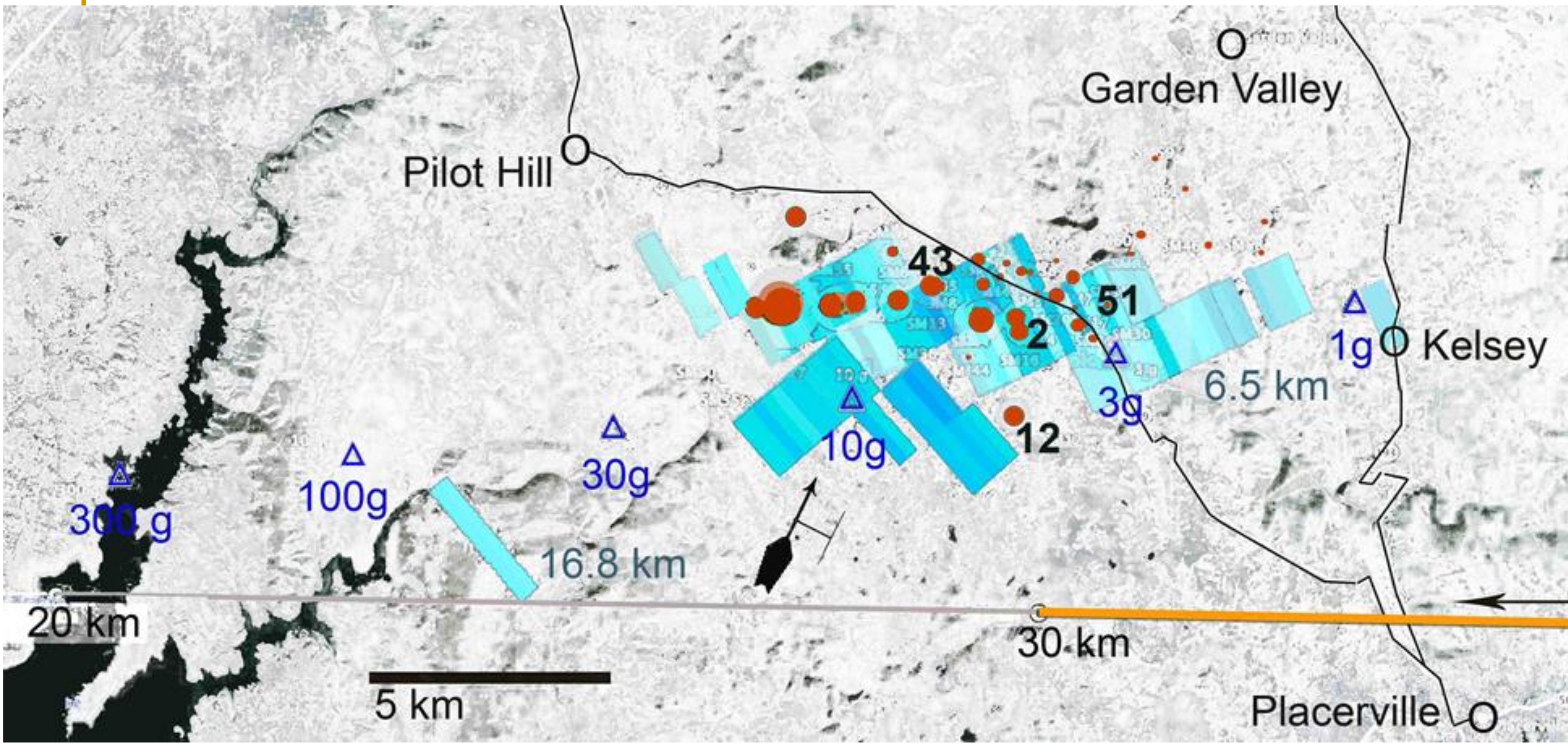
Sunday Morning April 22, 2012 Acoustic Info



Ground Track from Radar Plotting

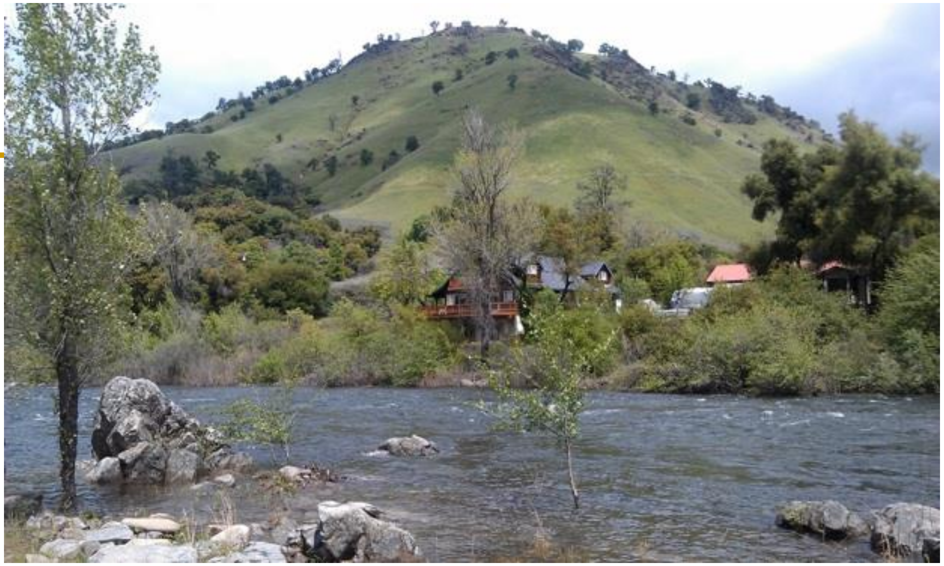
Summary of Information on Fall by Marc Fries





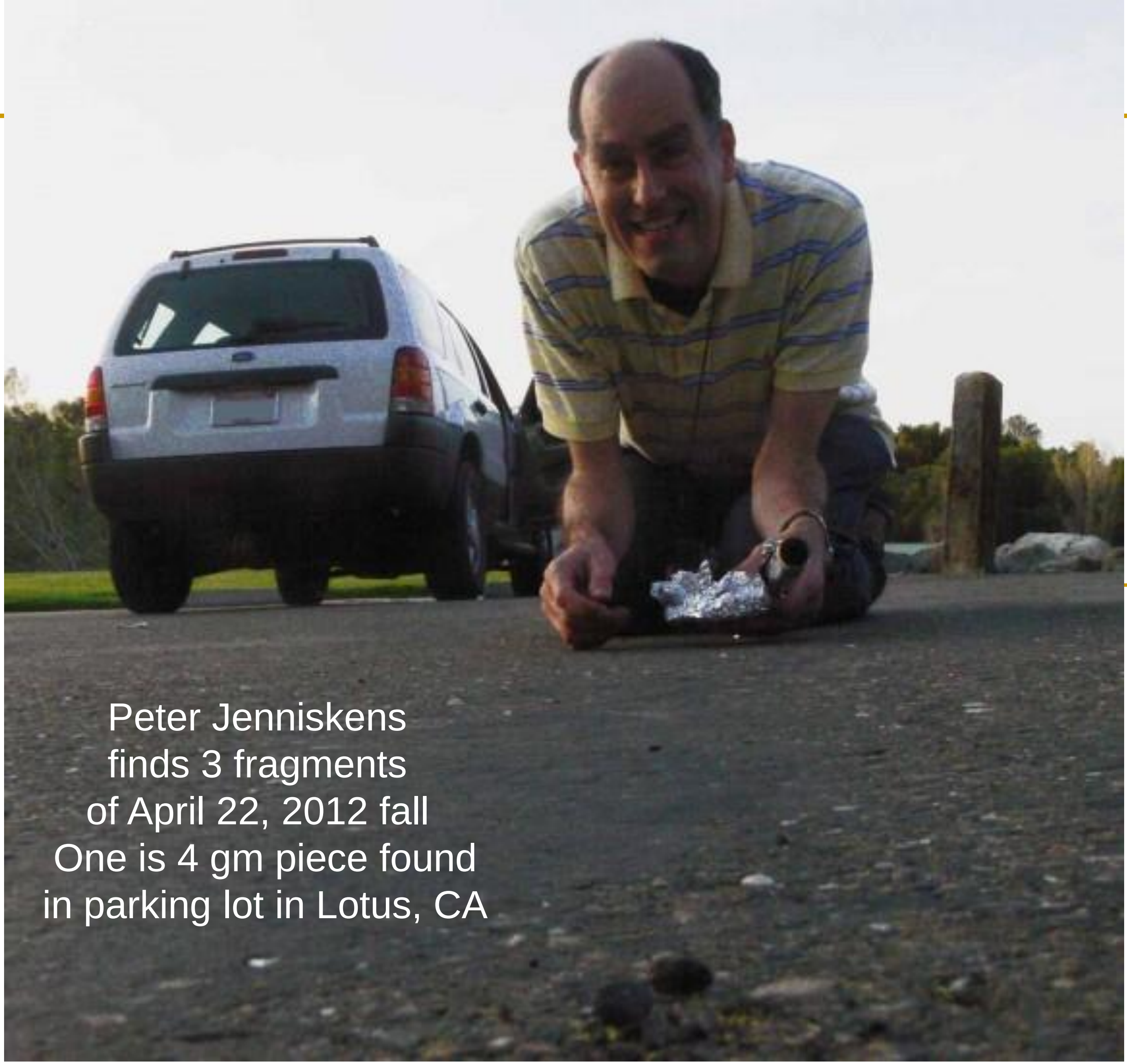
Garden Valley
Pilot Hill
43
51
2
12
1g
Kelsey
3g
6.5 km
10g
30g
100g
300 g
16.8 km
20 km
30 km
5 km
Placerville

SUTTER'S MILL AT COLOMA
A reproduction of photograph in possession of Charles B. Turrill, of San Francisco, from original daguerreotype taken on the spot by R. H. Vance in 1850.
James W. Marshall in the foreground.


Meteorite Collector Robert Ward's First Find
Tuesday April 24, 2012

Collection of Fragments in Al-Foil Lotus, CA



Interior of Broken CM2 Pieces on Road

Webelo Scout River Townsend Discovers Meteorite while on Campout near the American River

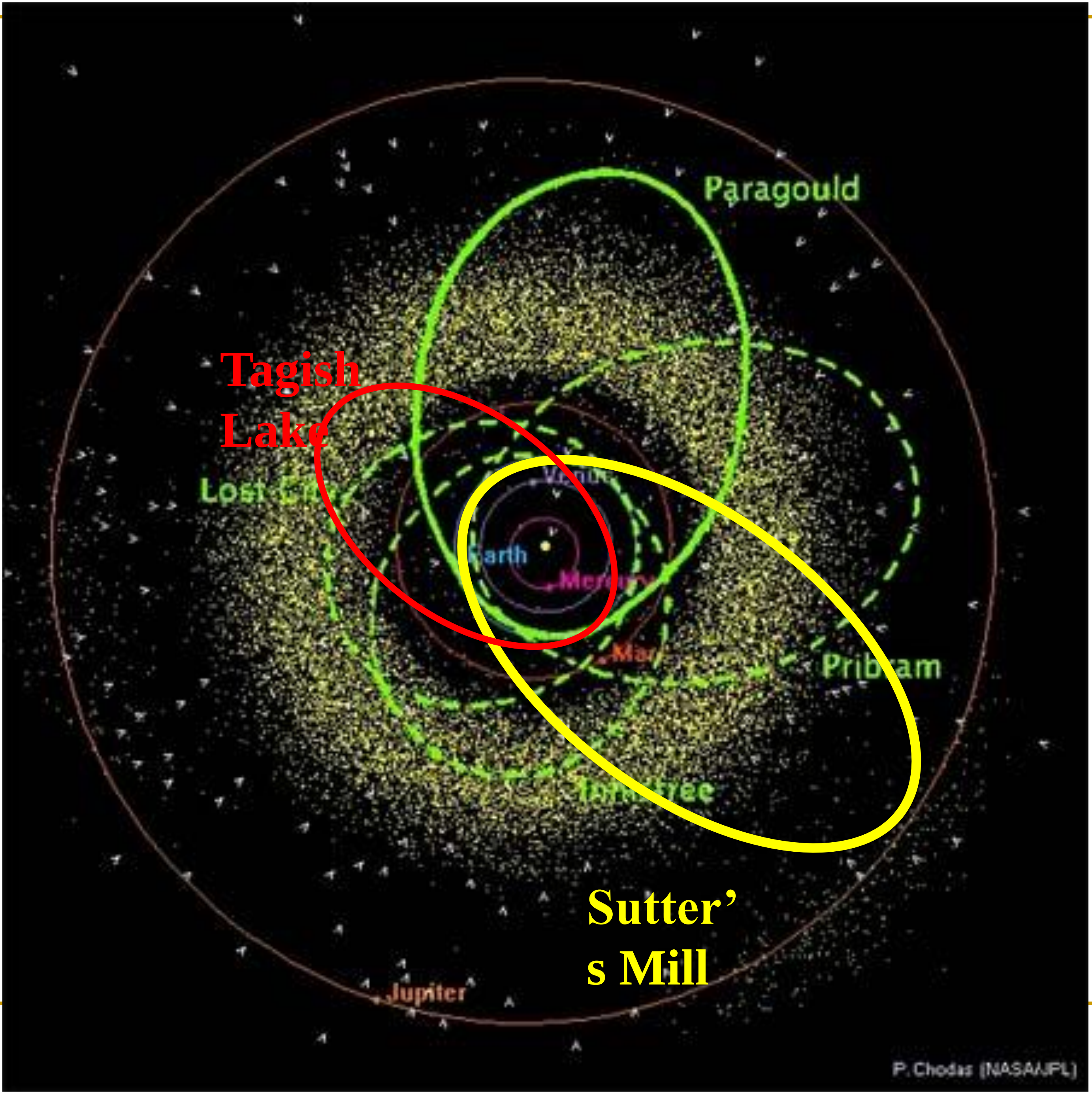

First time in Meteoritics a Blimp has been used to hunt meteorites!

Atmospheric trajectory and pre-atmospheric orbit for Sutter's Mill. Angular elements are for equinox J2000.0.

Atmospheric trajectory:		Pre-atmospheric orbit:	
H_b (beginning height)	90.2 ± 0.4 km	T_J (Tisserand's parameter)	2.92 ± 0.27
H_m (1st disruption, broad)	~56 km	a (semi-major axis)	2.45 ± 0.33 AU
H_m (2nd disruption, narrow)	47.6 ± 0.7 km	e (eccentricity)	0.817 ± 0.020
H_e (end height)	~30.1 km	q (perihelion distance)	0.448 ± 0.024 AU
V_∞ (entry speed)	28.6 ± 0.6 km/s	ω (argument of perihelion)	76.5 ± 3.5°
h (entry elevation angle)	26.3 ± 0.5°	Ω (longitude of ascending node)	32.710 ± 0.003°
a_z (entry azimuth angle)	272.5 ± 0.4°	i (inclination)	2.63 ± 1.29°
V_g (geocentric entry speed)	26.0 ± 0.7 km/s	Q (aphelion distance)	4.4 ± 0.7 AU
Ra_g (geocentric right ascension of radiant)	23.3 ±1.3°	T_p (perihelion time)	2012-03-09.1
Dec_g (geocentric declination of radiant)	12.6 ± 1.7°	Epoch	2012-04-22.3

Table XX. Overview of known meteorite falls with orbit determinations from photographic and video data.

Fall Date (UT)	Meteorite name (location)	Mv (100km)	Start Alt (km)	Initial Vel (km/s)	Entry Angle	Peak Alt.	Final Alt.	Final Vel.	D m	E kT TNT
4/22/2012	Sutter's Mill (California)	-19	90.2	28.6	26.3	47.6	30.1	19	3.0	4.0
4/13/2010	Mason Gully (Australia)	-9.4	83.46	14.53	53.9	35.8	23.84	4.1	0.3	0.001
2/28/2010	Kosice (Slovakia)	-18.3	72	15	-.-	37	-.-	-.-	1.2	0.09
9/26/2009	Grimsby (Canada)	-14.5	100.5	20.91	55.2	39	19.6	3.1	0.18	0.002
4/9/2009	Jesenice (Slovenia)	-15	88	13.78	40.6	26	15.3	3.0	0.4	0.004
11/21/2008	Buzzard Coulee (Canada)	-15	86	18.0	66.7	-.-	<17.6	-.-	1.4	0.32
7/10/2008	Almahata Sitta (Sudan)	-20	65	12.42	20	37.5	32.7	-.-	4.0	6.7
7/20/2007	Bunburra Rockhole (Australia)	-9.6	62.8	13.36	-.-	-.-	29.95	5.8	0.3	0.001
1/4/2004	Villalbeto de la Pena (Spain)	-18	47	16.9	29.0	28	22.20	7.8	0.8	0.02
3/27/2003	Park Forest (Illinois)	-21.7	82	19.5	29	28	<18	-.-	1.3	0.5
4/6/2002	Neuschwanstein (Germany)	-17.2	84.95	20.95	49.5	21	16.04	2.4	0.45	0.026
5/6/2000	Morávka (Czech Republic)	-20.0	80	22.5	20.4	33	21.2	3.7	1.0	0.1
1/18/2000	Tagish Lake (Canada)	-16	-.-	15.8	16.5	-.-	-.-	-.-	5	4.8
10/9/1992	Peekskill (New York)	-16	80	14.72	3.4	-.-	33.6	-.-	1.2	0.5
5/7/1991	Benesov (Czech Republic)	-19.5	-.-	21.0	-.-	34	19	5	1.6	0.2
2/6/1977	Innisfree (Alberta)	-12.1	>62	14.54	67.8	36	21	4.7	0.19	0.0005
1/4/1970	Lost City (Oklahoma)	-12	86	14.15	38	28	19.5	3.4	0.3	0.004
4/7/1959	Pribram (Czech Republic)	-19.2	98	20.89	43	46	13.3	-.-	1.8	0.05


Paragould
Tagish
Lake
Lost City
Venus
Earth
Mercury
Mars
Pribram
Innisfree
Sutter's Mill
Jupiter
P. Chodas (NASA/JPL)


جامعة الخرطوم
fire

Comet nuclei

An icy/rocky body a few to 10-20 km in diameter. We have size measurements of about 10 nuclei

Resolved:

Halley (Giotto 1986) 8x15km:

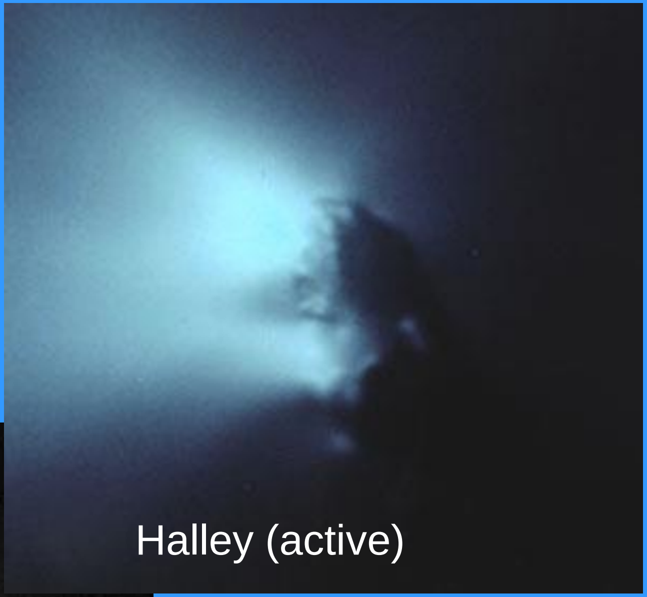
Borrelly (Deep Space 1) 8km long

Wild 2 (Stardust) 5km

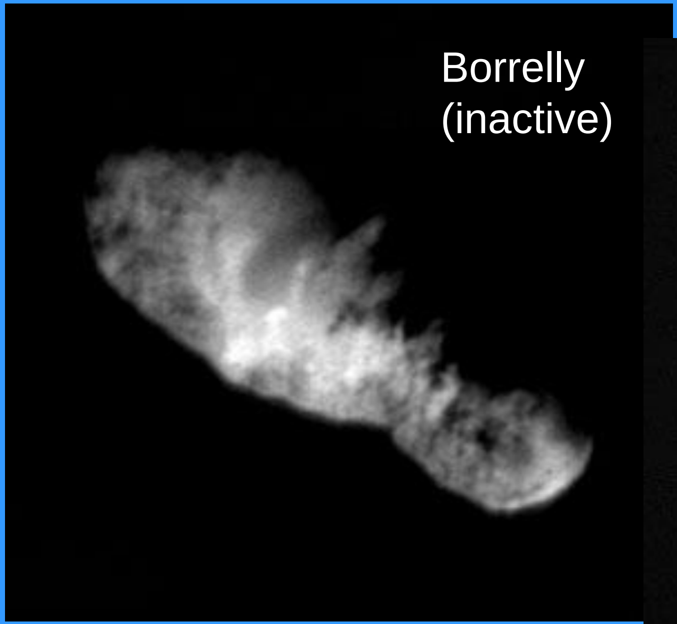
Inferred diameters:

Schwassmann-Wachmann 1: 20 km

Hale-Bopp: 40 km



Halley (active)



Borrelly (inactive)

Wild 2 (inactive)

Albedos:2-5%, darker than coal

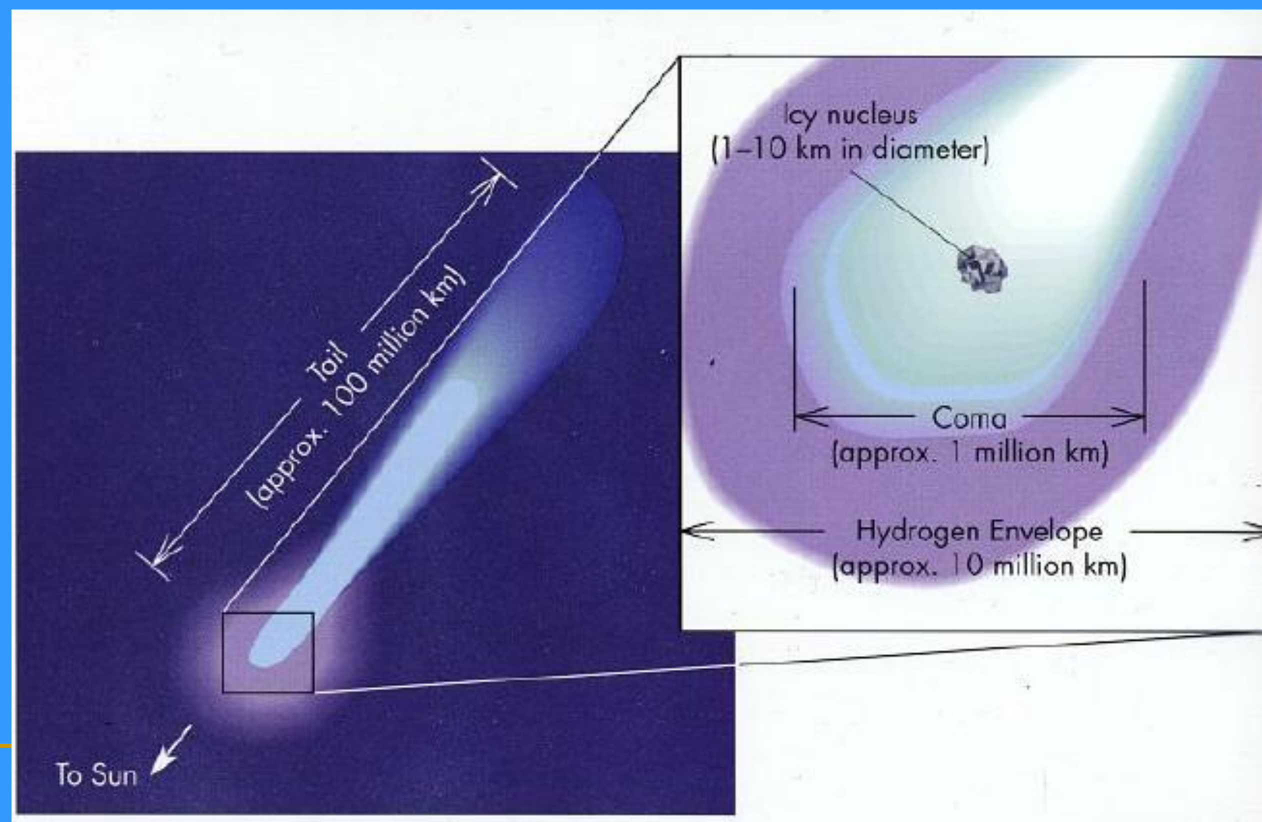
Current Nucleus concepts

- Physical makeup of nucleus may be single body or perhaps gravitationally bound rubble-pile
- Ice sublimation decreases as comet ages due to development of insulating rubble mantle
- Nucleus very dark and reddish due to complex organics (tar-like) on the surface
- Ice sublimation usually confined to jets as nucleus surface blanketed by rocky debris

When comets approach the Sun

When (if?) its orbit takes it near the Sun (r <~ 3 AU), the ice component of the nucleus begins to vaporize and produces a *tail* up to 10^8 km long. The near-spherical cloud of gas near the nucleus is the *coma* and is typically 10^4 to a few x 10^5 km across.

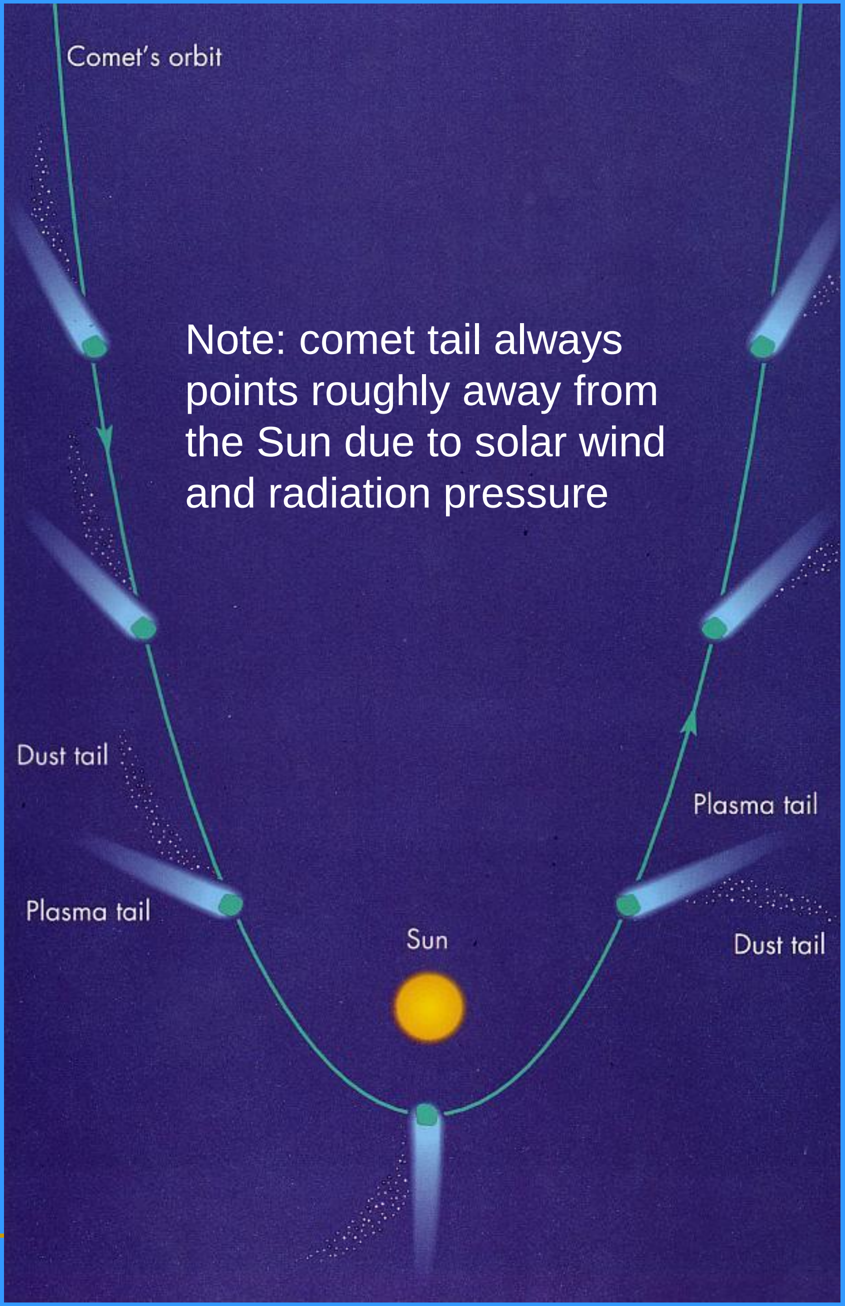
Tail to nucleus size ratio: 10,000,000 to 1



Comet orbits are often (but not always) highly elliptical.

As a result, they only spend a small fraction of their lives as active comets. Most of the time, they are frozen inert bodies, far from the Sun.

When inactive, comets are difficult to detect even with large telescopes. So the properties of these objects (including any which may remain permanently exiled in the outer Solar System), must be deduced from their brief active phases.



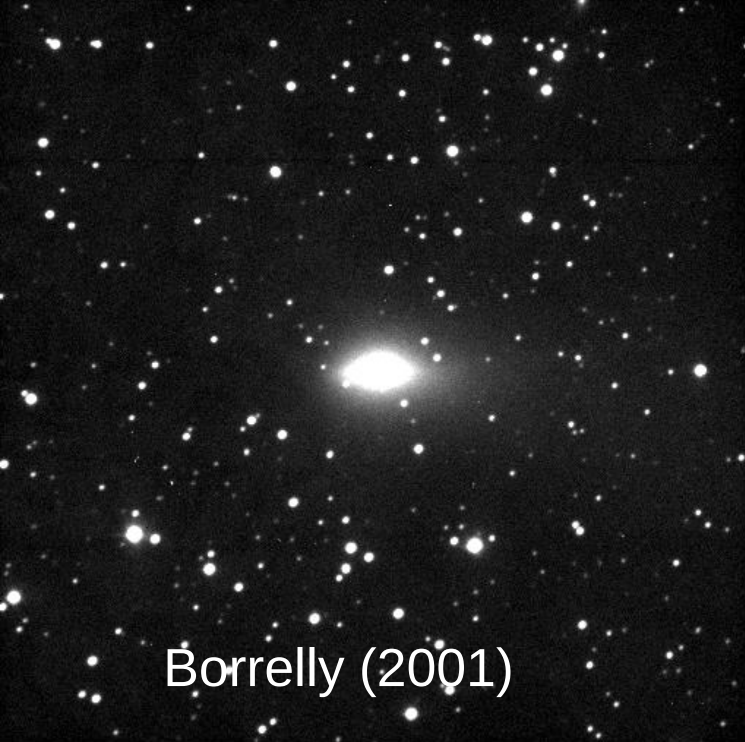
Active comets (visible to naked-eye)

Hyakutake (1998)

West (1976)

Hale-Bopp (1997)

Moderately Active comets (usually not visible to the naked-eye)



Nucleus: a dirty snowball

- Whipple (1950) proposed the “dirty snowball” theory of cometary nuclei
- This theory has stood up well though some argue comets are more like ‘snowy dirtballs”
- Densities of cometary nuclei are hard to determine, but models indicate 0.3-0.7 g/cm^3, which is less than most ices (water ice = 1g/cm^3).
- Low density points to a porous “rubble-pile” model containing significant void space
- Comet nuclei may be held together by “sintering” and other relatively weak contact forces

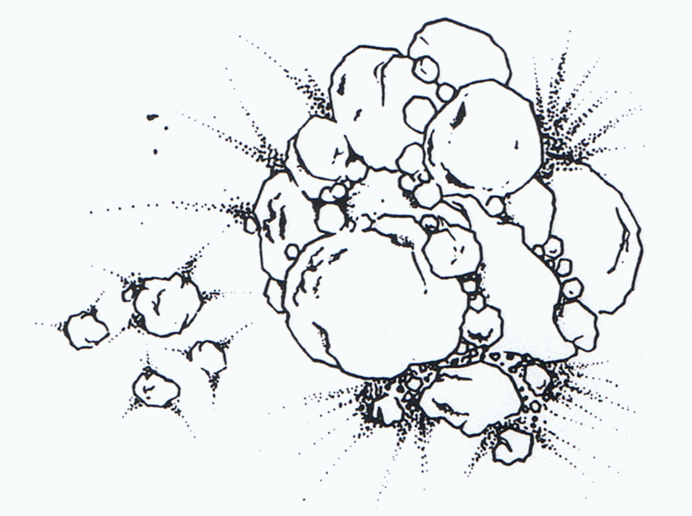
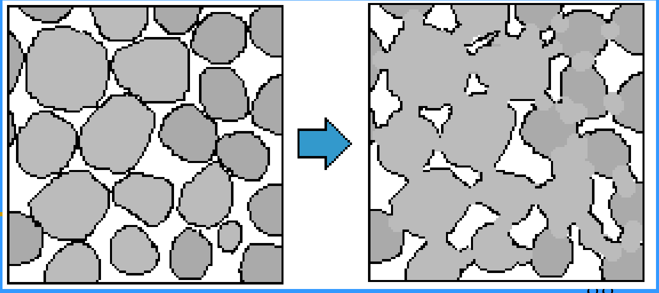
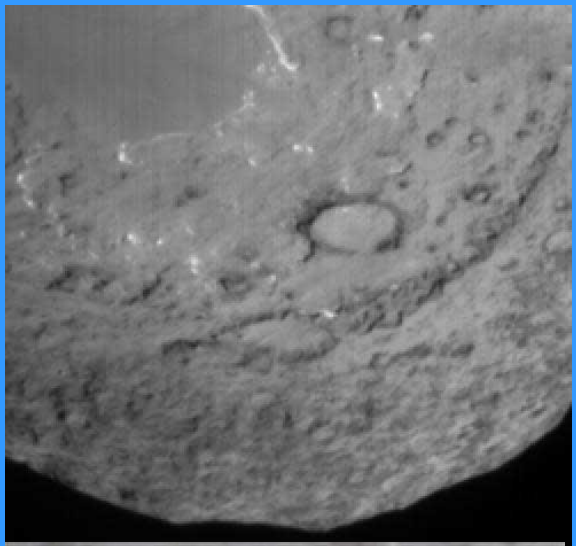


FIGURE 10.30 A schematic representation of a cometary nucleus according to the rubble-pile model, in which the individual fragments are lightly bonded by thermal processing or sintering. (Weissman 1986)



sintering

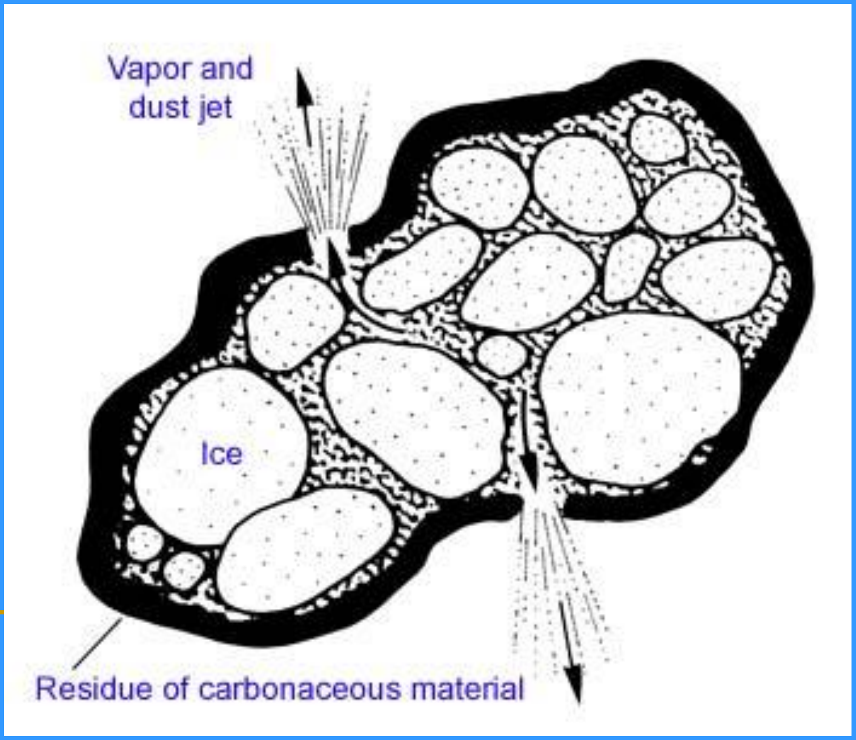
Nuclear surface layers



CometTempel 1
90 seconds
before the Deep
Impact probe hit

One of the last
images before
Deep Impact

- Comets that have passed by the Sun on many occasions are thought to have a *<u>dust crust</u>*, an accumulation of large non-volatile rocky material that builds up as the ices disappear.
- This is why their surfaces are dark rather than snowy-white

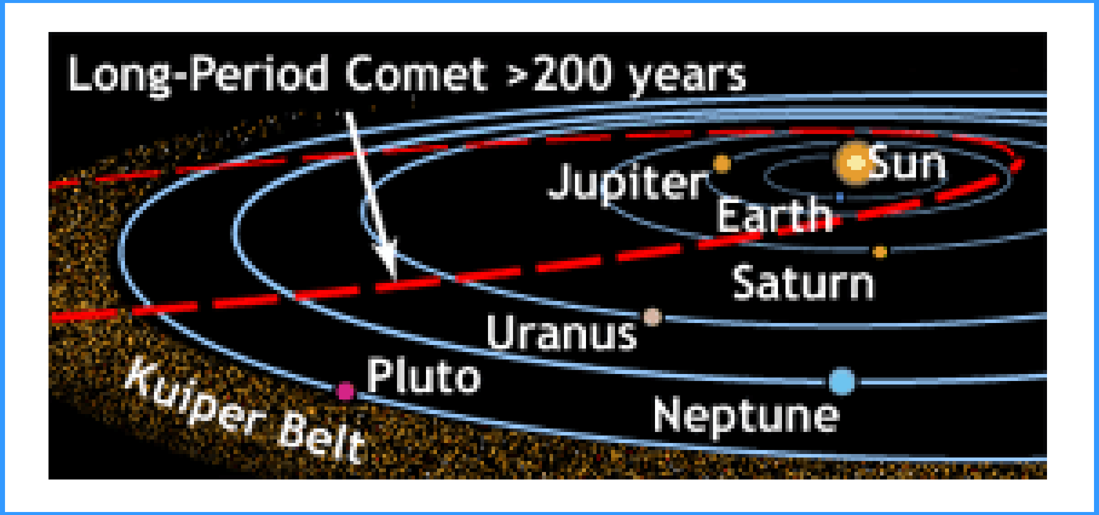


Different dynamical families of comets

A long-period comet is one with an orbital period (year) longer than 200 years.

These comets have orbits which extend beyond our planetary system.

Perhaps more importantly, the orbits of these comets are quite different from those of short-period comets, those with P < 20yrs.

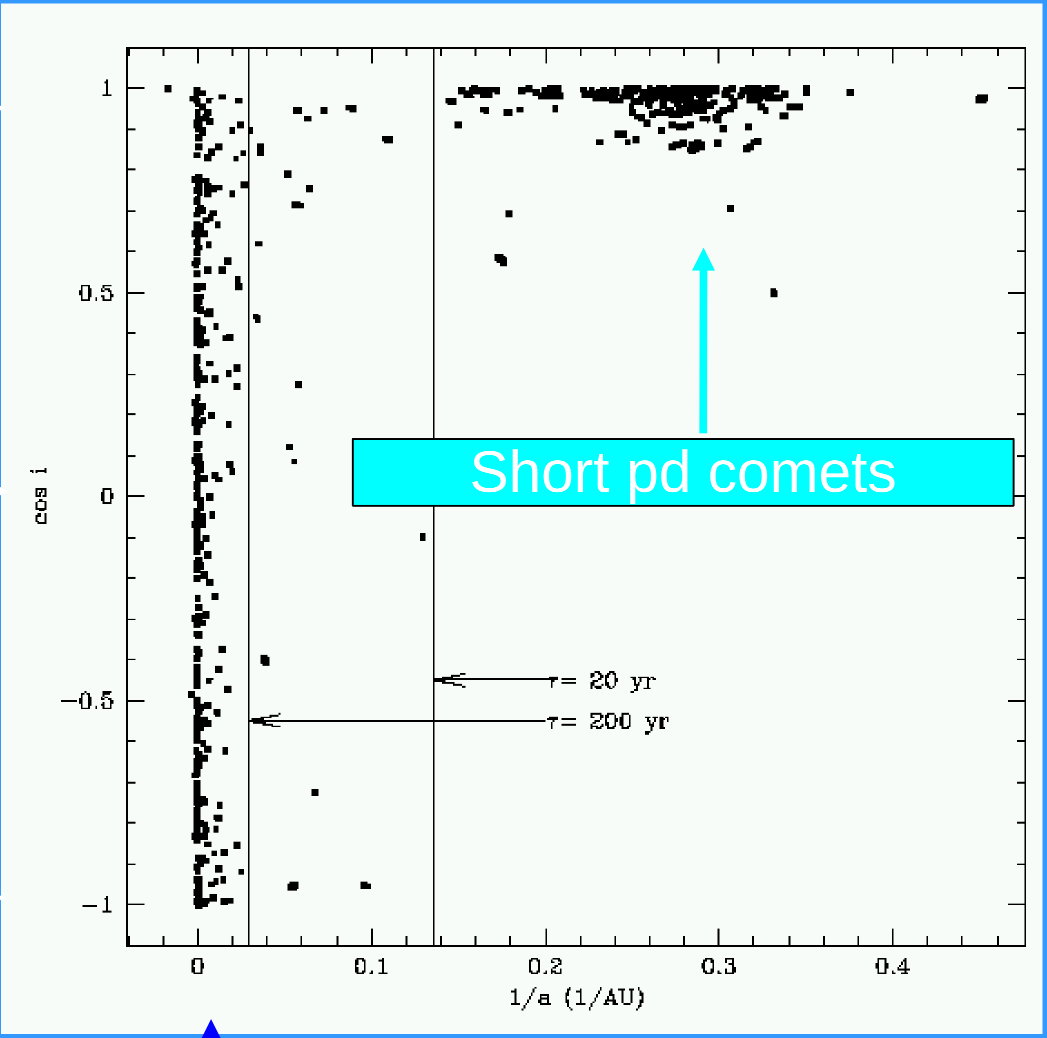


Shorter periods
Smaller orbits

Inclinations near those of the planets (prograde)

Inclinations at right angles to those of the planets

In the plane of the planets, but moving in the opposite direction (retrograde)



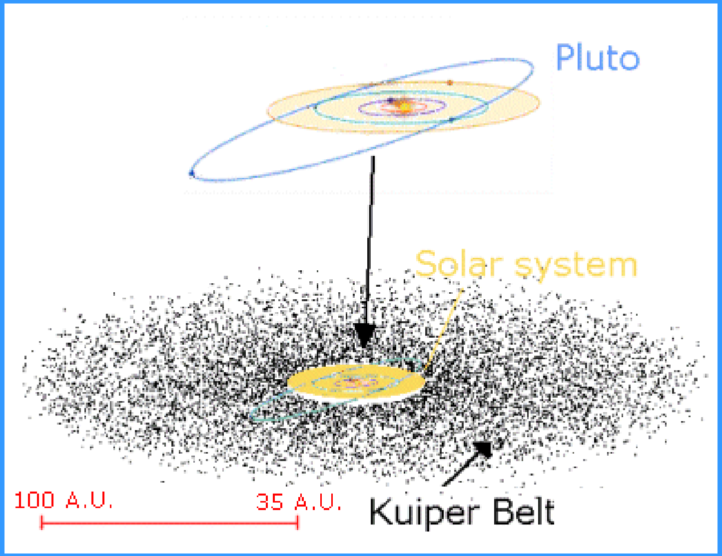
Short pd comets

Long-period comets

Q: What makes SP and LP comets different?

A: Their origin

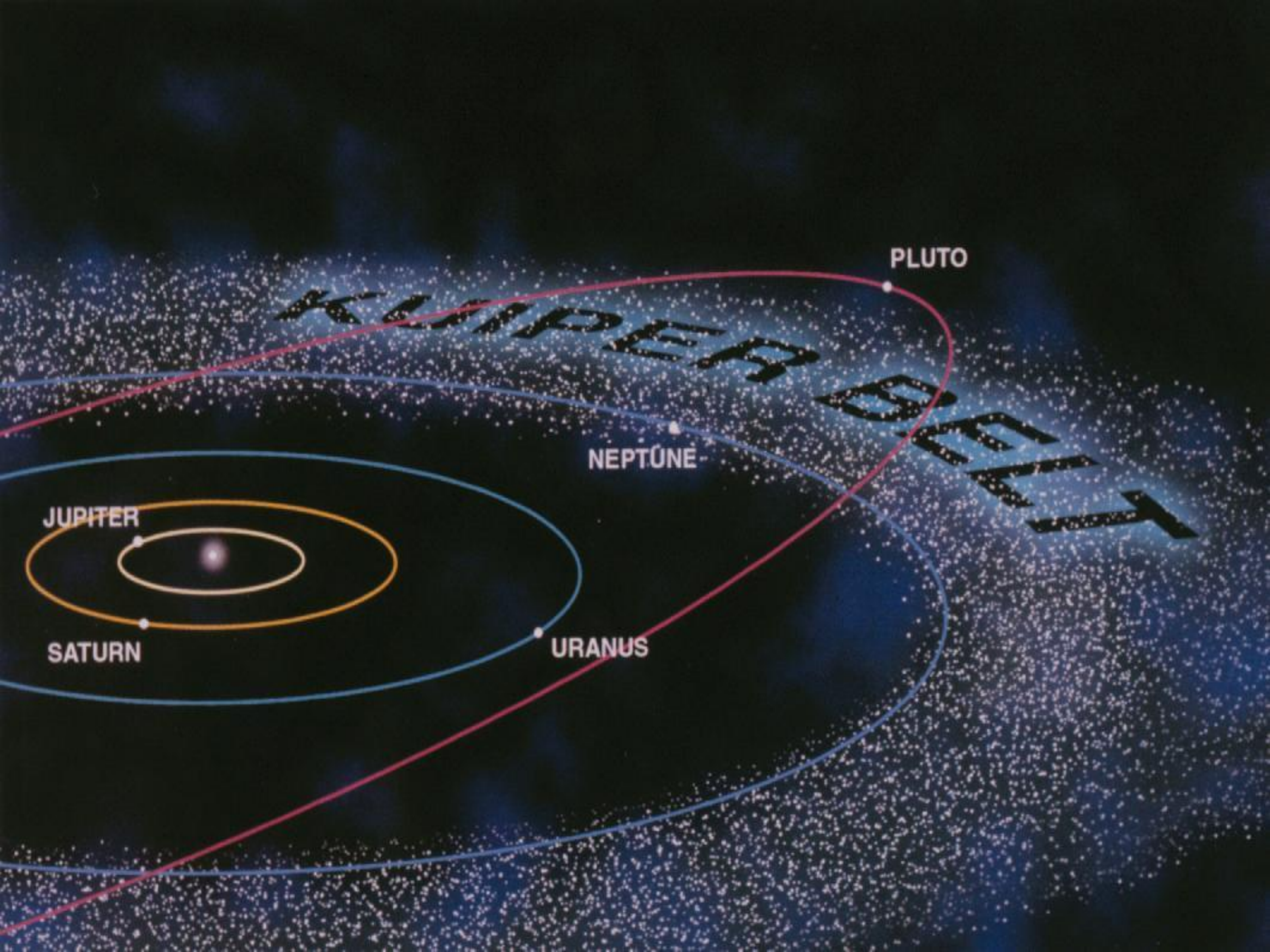
Short-period comets come from the Kuiper-Edgeworth belt, a ring of "leftovers" at the edge of our Solar System.

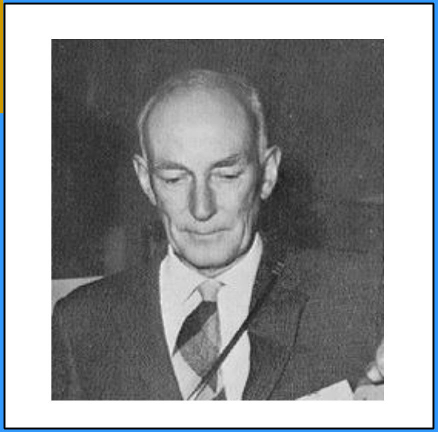


Kenneth E. Edgeworth
1880-1972

Gerard P. Kuiper
1905-1973

These remnants of planetary formation orbit in the plane of the planets out beyond Neptune, hence their low inclinations.

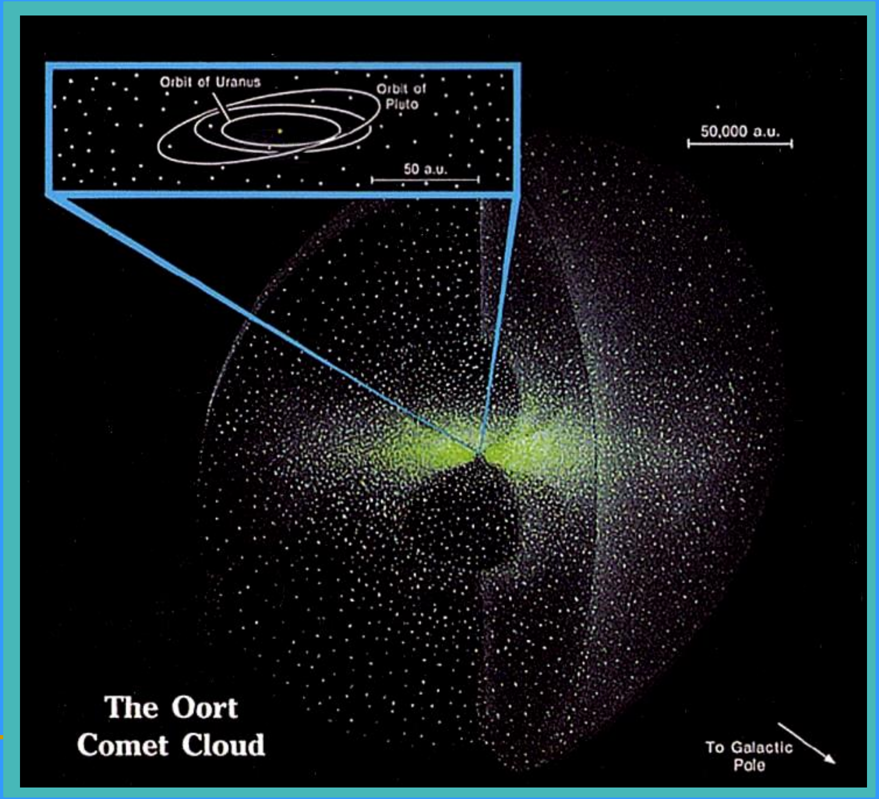

PLUTO
KUIPER BELT
NEPTUNE
JUPITER
SATURN
URANUS



Jan Oort
1900-1992

Long-period comets come from the Oort Cloud, a spherical cloud of frozen comet nuclei reaching up to half-way to the nearest stars (around 10^5 AU or 1.6 ly, closest star α Cen is 4.3 ly away).

Both the Oort cloud and the Kuiper belt are made up of icy planetesimals left over from the era of the formation of the planets.



So why are they different?

The formation of the solar system

Solid matter condensed out of the original spinning, flattened cloud of gas and dust (the "solar nebula") surrounding the proto-Sun.

Elements at the edge of what would become our planetary system were too sparse to form planets. The Kuiper Belt is what still remains of this material.

Solid bodies within the planetary system itself were all swept up into the growing planets.

Or were they?

Gravitational Slingshot

A number of space probes, including Voyager 1 and 2, have deliberately used a planet's gravity to slingshot themselves into different orbits.

Many planetesimals in the early Solar System would have, by happenstance, undergone a similar effect.

Some of these would have crashed into planets, some would have received only minor orbital changes. Still others would have been ejected into deep space, never to return.

SEGWay (UC Berkeley)

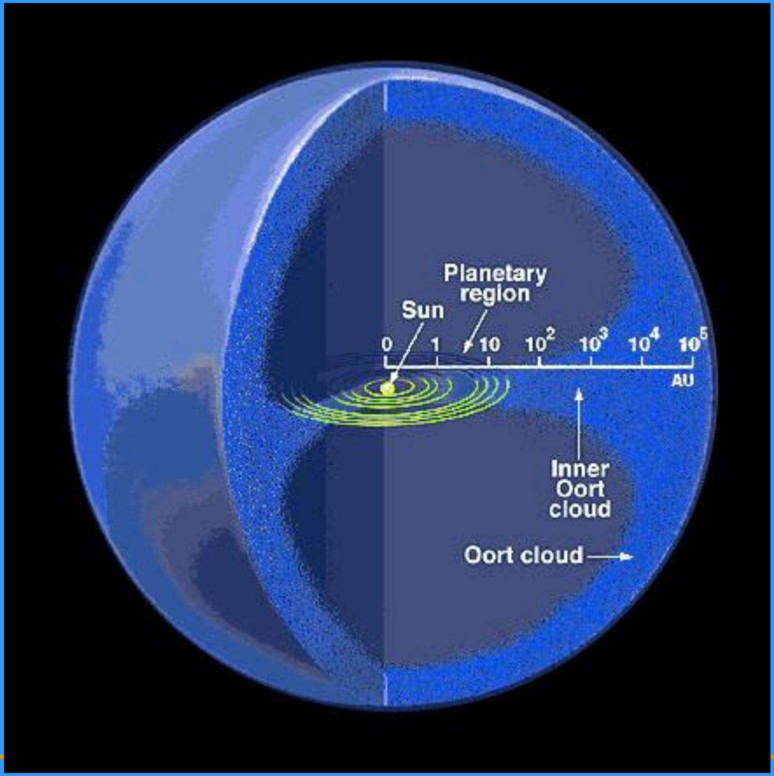
A few would have been flung far but not quite out...

The edge of the Oort cloud

Comets ejected into the Oort cloud end up on orbits with *a* at very large values. Their kinetic + potential energy is just slightly below zero (or 1/a ~ 0). These large orbits are only very weakly bound and can be removed by perturbations by passing stars for example.
Only orbits up to *a* of perhaps 50,000 AU are stable in this sense, defining the edge of the Oort cloud, which is thought to contain $\sim 10^{12}$ objects > 1 km.

$$E_{tot} = -\frac{GMm}{2a}$$

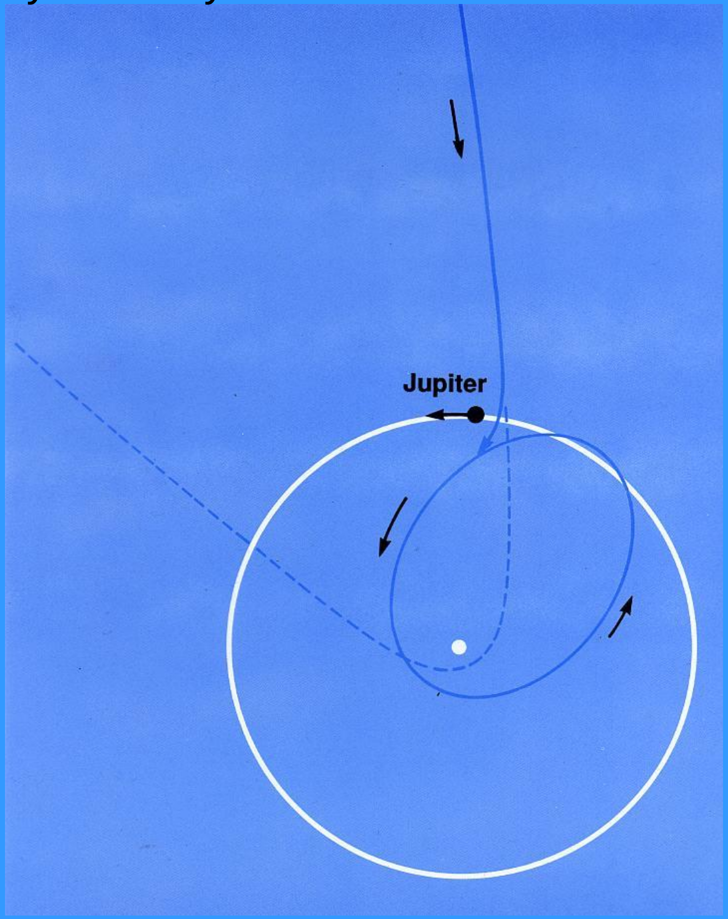
Recall from chapter on celestial mechanics



Dynamically new Oort cloud comets: one time only

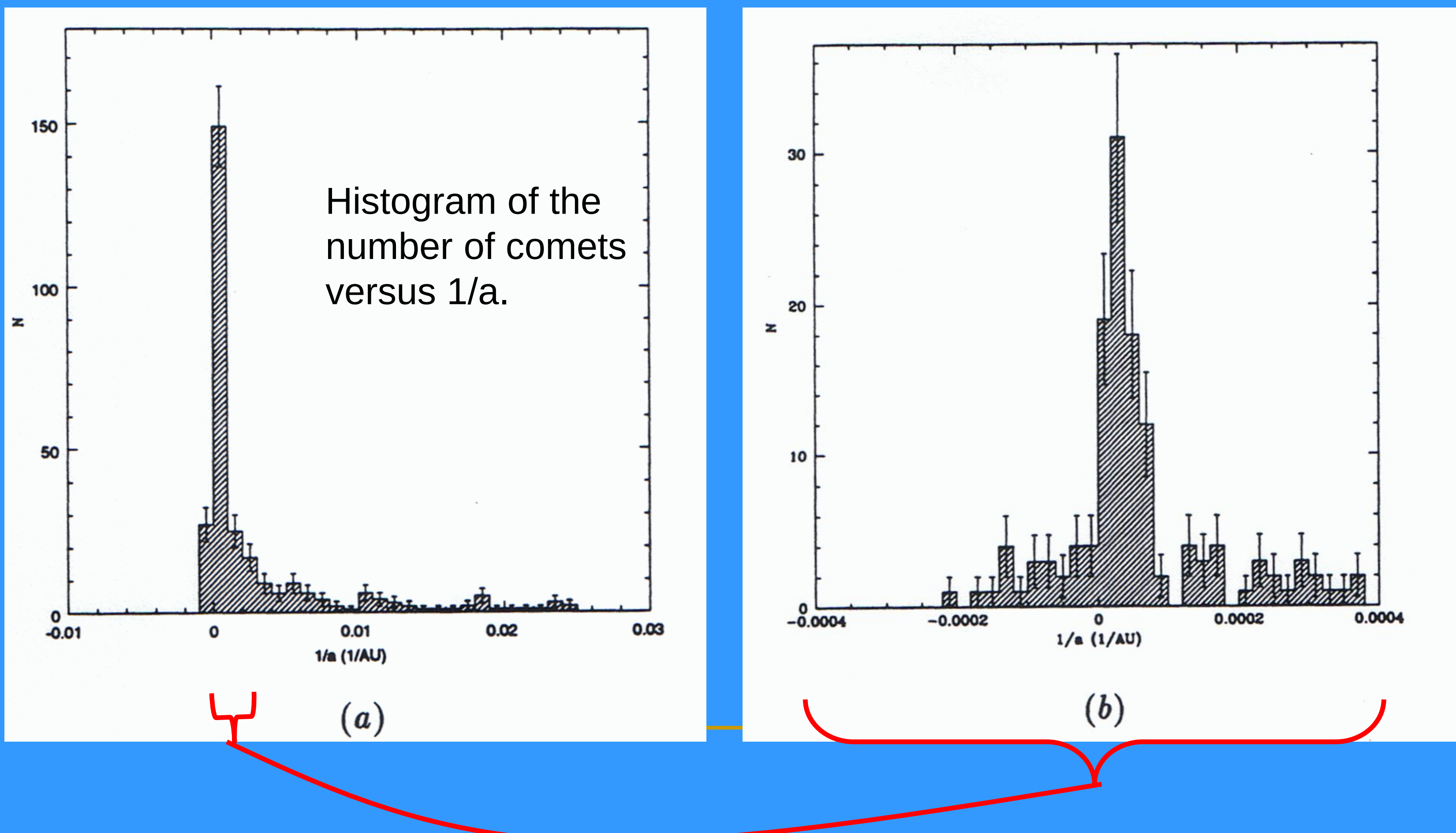
- Perturbations due to passing stars a) scramble their inclinations, making the Oort cloud rather spherical and b) may eventually place them on orbits that return them to the planetary system.
- Roughly half of *dynamically new Oort cloud comets* distinguishable by their very large *a* upon arrival) have their orbits so disturbed by the planets that they are subsequently ejected from the Solar System.
- The other half end up on various smaller, more tightly bound orbits.
- Few return to the Oort cloud.

Extreme example of a perturbed dynamically new Oort cloud comet



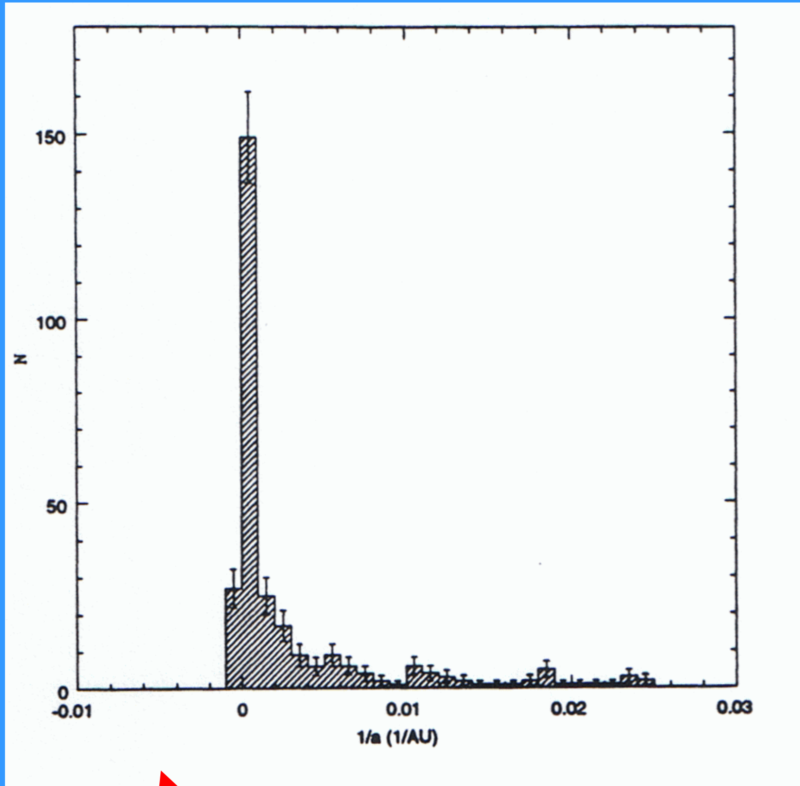
Oort cloud: the evidence

- Since Oort cloud comets cannot be imaged yet *in situ*, the measured large semimajor axis (a) values for some comets is the primary evidence for the Oort cloud’s existence.



Alien Comets?

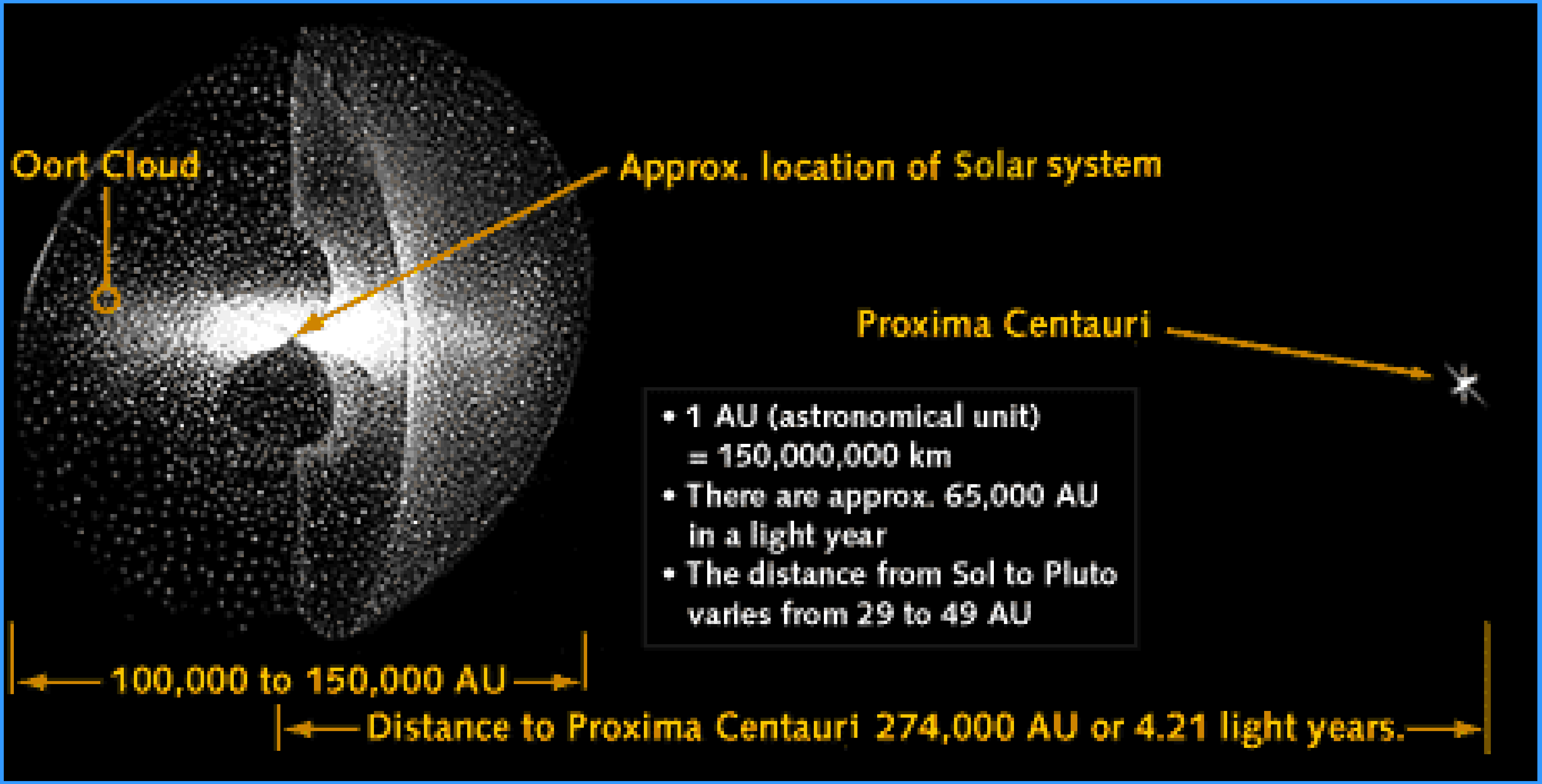
- Since so many comet nuclei are flung out into the Galaxy, in principle there are likely to be interstellar cometary nuclei “out there”
- No interstellar comets or asteroids have been detected - at least in the past ~100 years.
- At least none that are obvious from the large hyperbolic velocity relative to the Sun that would be expected.



(a)

Interstellar comets should (mostly?) appear well to the left of zero on this plot

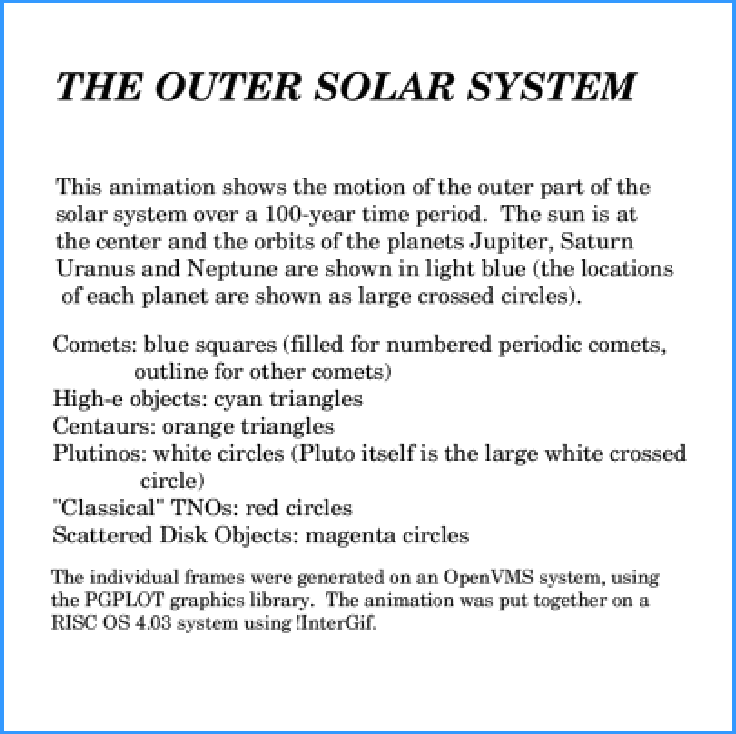
Oort cloud size relative to closest stars



Kuiper belt comets: path to visibility

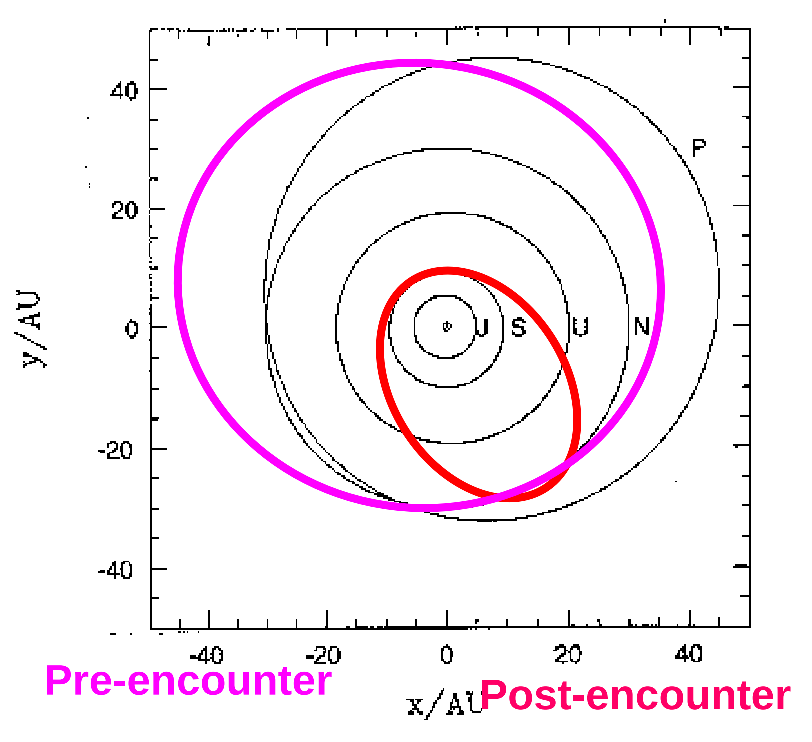
- The 10^9-10^{10} comet nuclei in the Kuiper Belt are on orbits outside Neptune, typically with
  - 30 AU> *a* > 50 AU
  - low *e* (<0.2)
  - low *i* (< 30^o)

- These orbits do not bring them near the Sun. How do these objects eventually become visible comets?

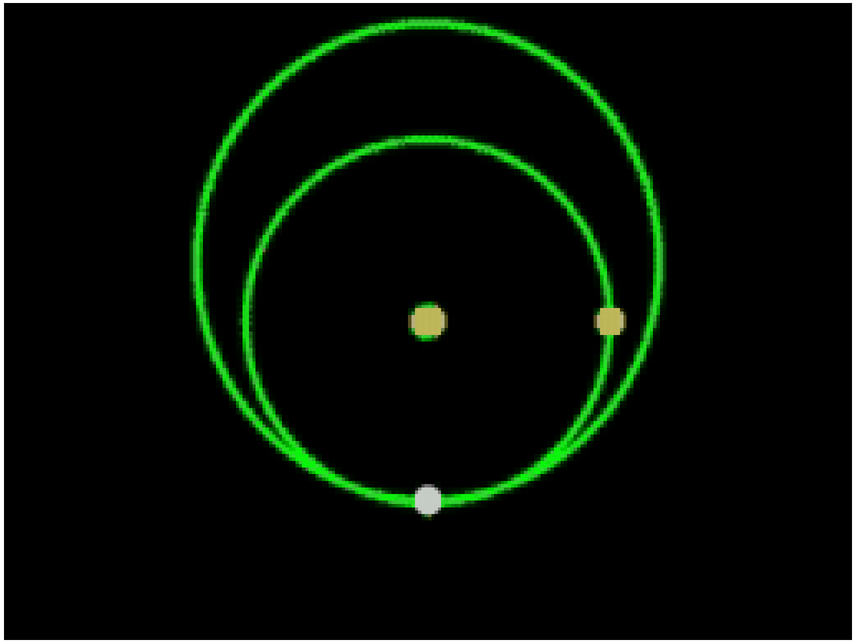


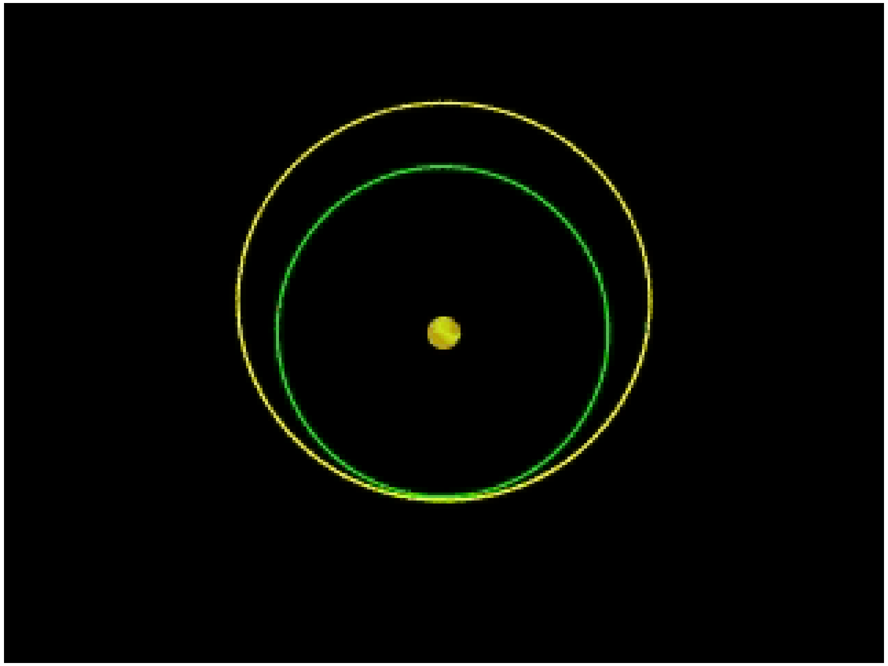
Kuiper belt comets: path to visibility

- Neptune is the dominant player out here.
- A close approach with that planet will change the comet’s orbit: if *a* is decreased the comet is “handed down” to the inner giant planets, where it “pinballs” between them, possibly eventually reaching the inner solar system, and visibility as an active comet (a short-period comet).
- Thus Kuiper Belt Objects (KBOs) are slowly “picked off” by Neptune and transferred onto different orbits.



Pluto and Neptune: a complicated relationship



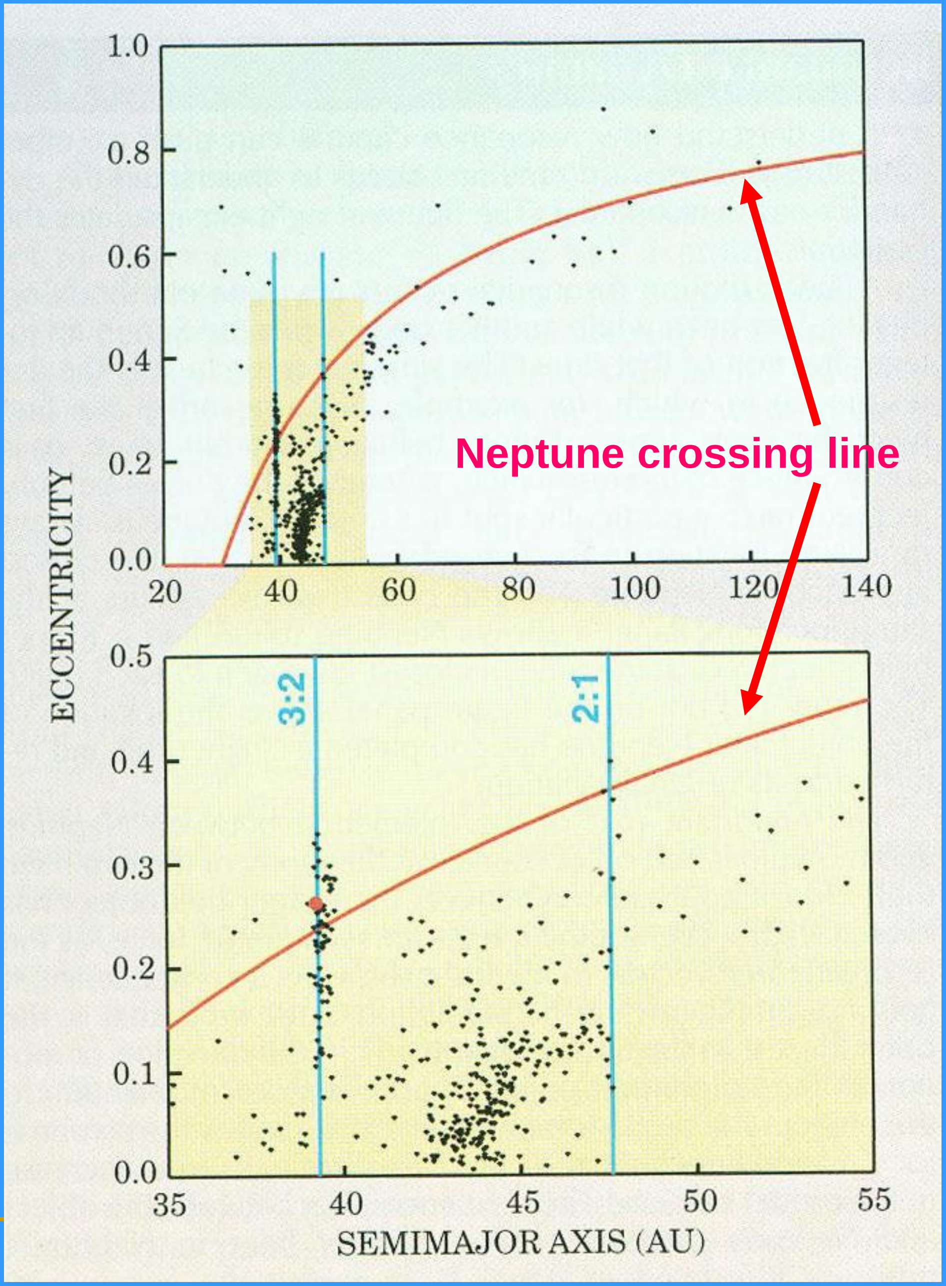


Neptune and Pluto are in 3:2 resonance: When Neptune is near the crossing point, Pluto is somewhere else.

Pluto's orbit is inclined (17º)

Neptune and Pluto never approach each other

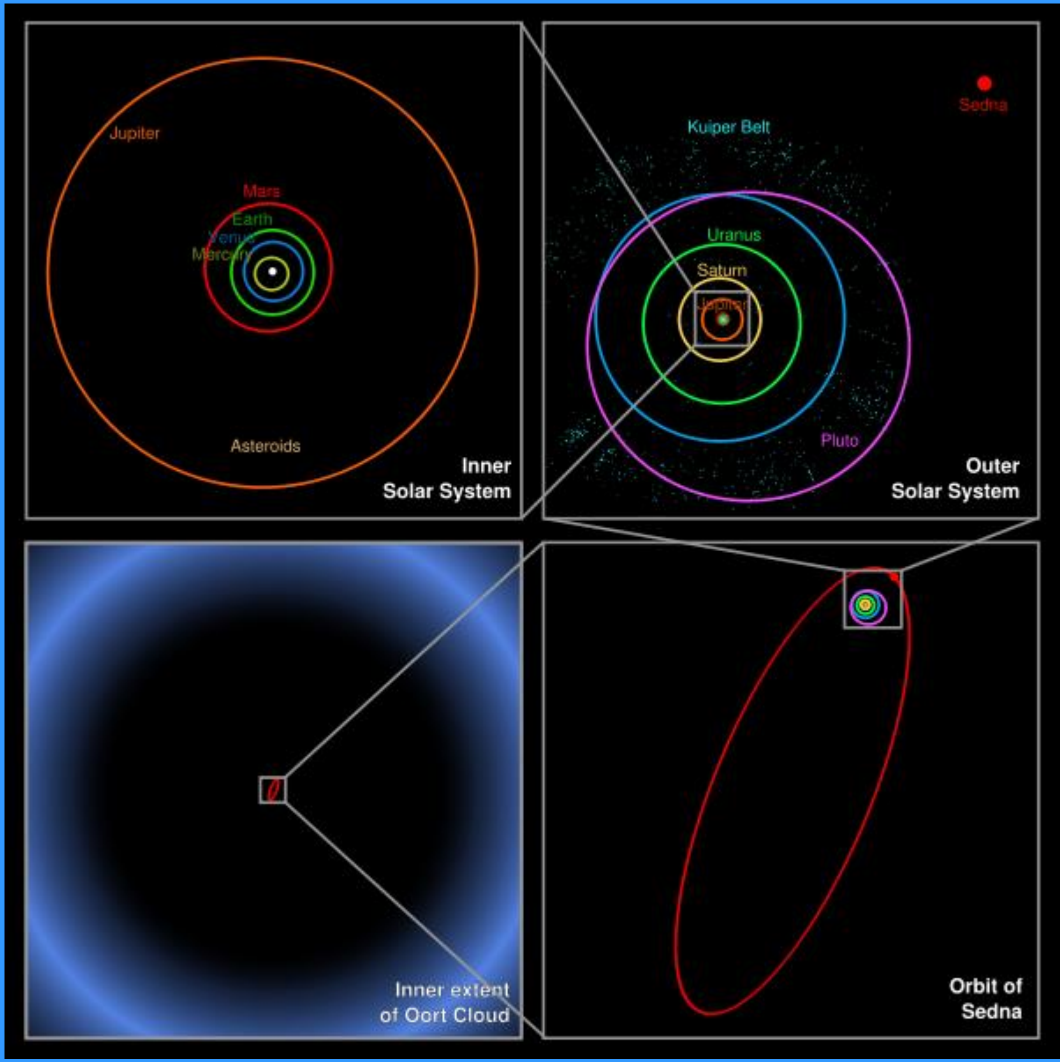
- Over 1000 KBOs have been observed (though not all have good orbits known)
- Many cluster in mean-motion resonances with Neptune (*resonant KBOs*)
- Those in 3:2 resonance with Neptune are called *Plutinos* (Pluto is also in this resonance); those in 2:1, *twotinos* (ugh!)
- Those that have been scattered onto larger orbits by Neptune have q~30 AU (near Neptune) are the *scattered disk* or *SKBOs*
- *CKBOs* or *the classical Kuiper belt* are the remainder, sometimes called *cubewanos* after 1992 QB1, the first KBO discovered



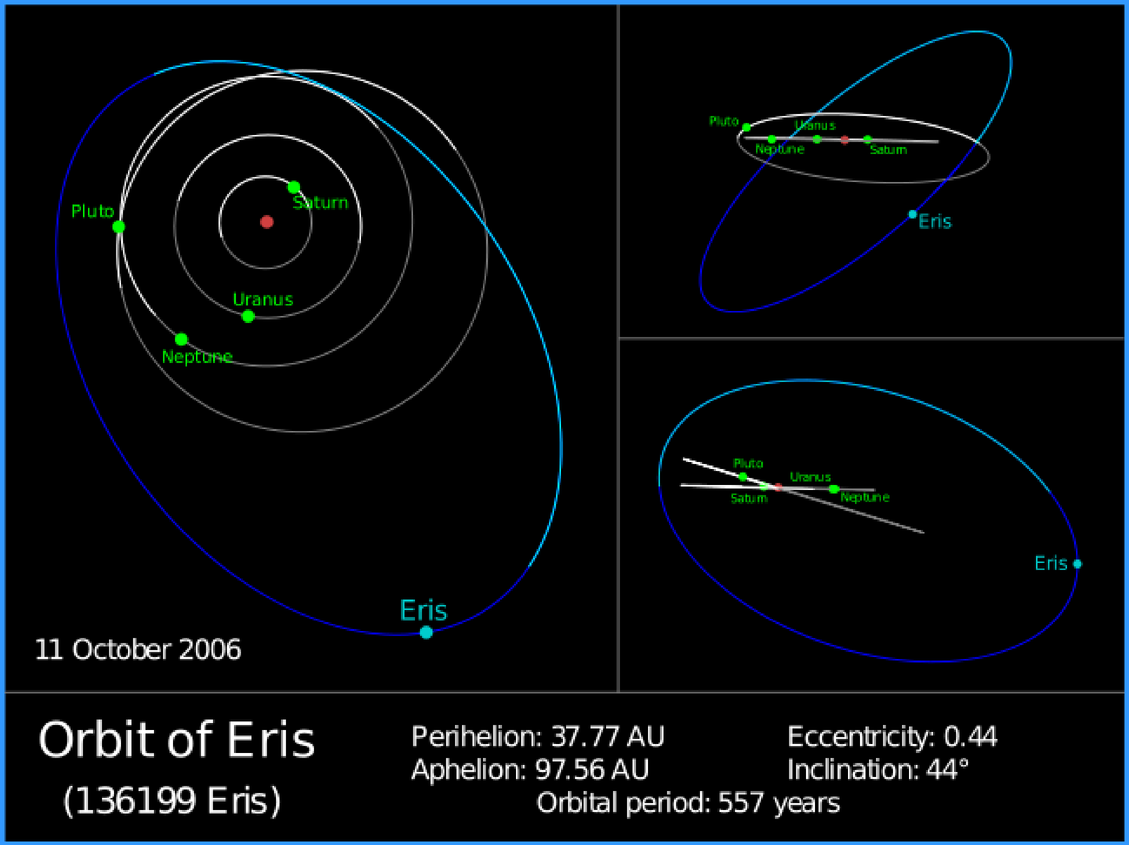
An oddball: 90337 Sedna

- ***Perihelion:*** 76 AU
- ***Aphelion:*** 975 AU
- ***Period:*** 120000 yr
- ***i:*** 11.9°

Estimated diameter: 1500 km. At the time of its discovery it was the largest object in the solar system since Pluto. It is now 5th largest known Trans-Neptunian Object.
Sedna was argued to be the first observed Oort cloud body, Kenyon and Bromley (2004) showed rather that it is probably a KBO jarred loose by a passing star, but the book is far from closed.

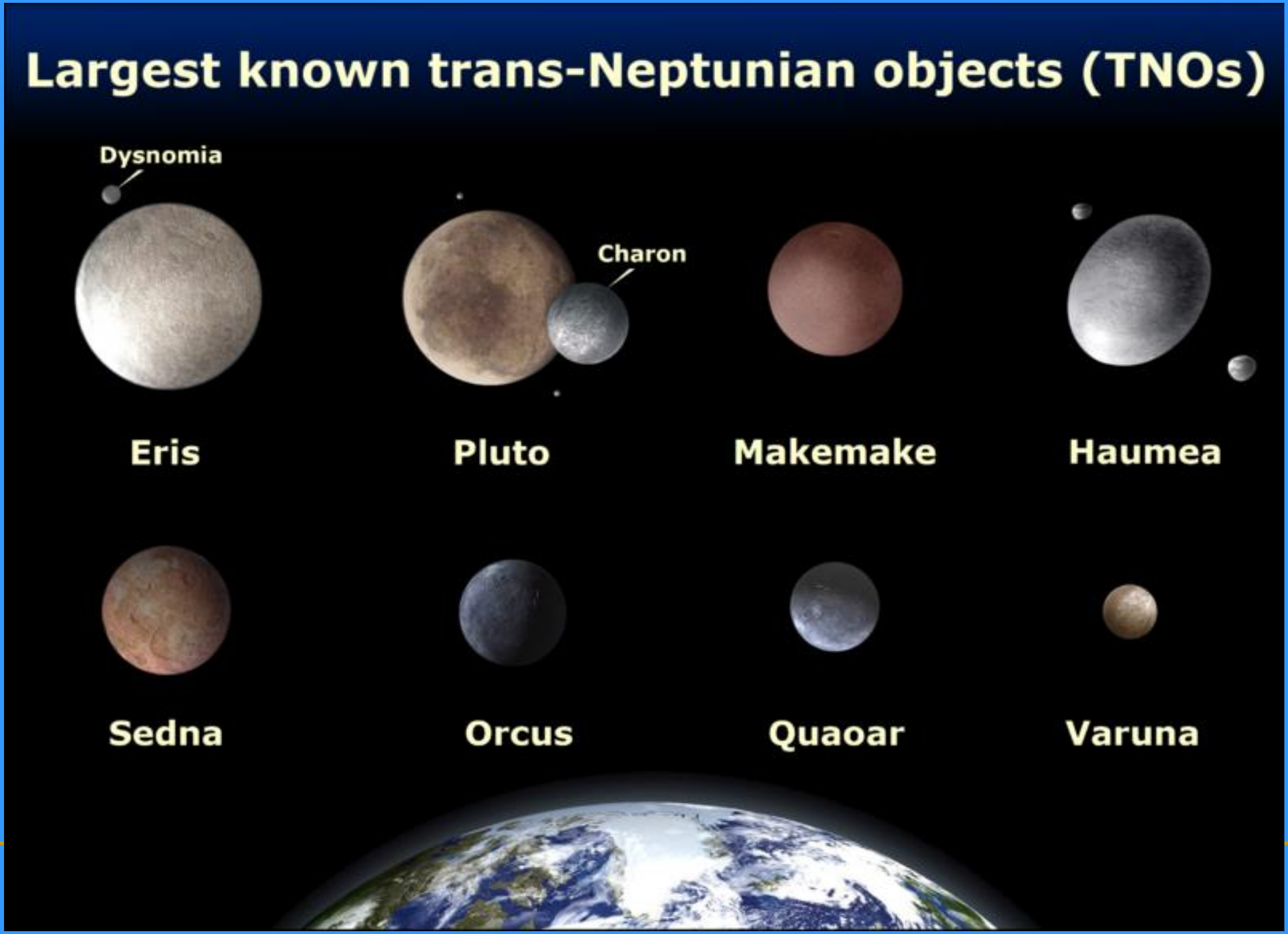


Eris: Pluto’s nemesis



- Eris has a diameter of 2,700 km, and is about 25% more massive than Pluto (some debate).
- Its discovery, along with strong suspicions that there are many more out there like it, precipitated the International Astronomical Union to demote Pluto from planet-hood and create a new category of “dwarf planet” for these objects.

So which ones of these should be called planets?



Why isn't Pluto a planet anymore?

- Pluto is not a planet because it has not cleared everything from its orbit. The rules of a planet are:
  - It orbits the Sun
  - It is large enough for gravity to squash it into a ball
  - It must have cleared everything in its orbit (Pluto did not fulfill this).
- Those objects which can satisfy the first two but not the third are now called "dwarf planets"

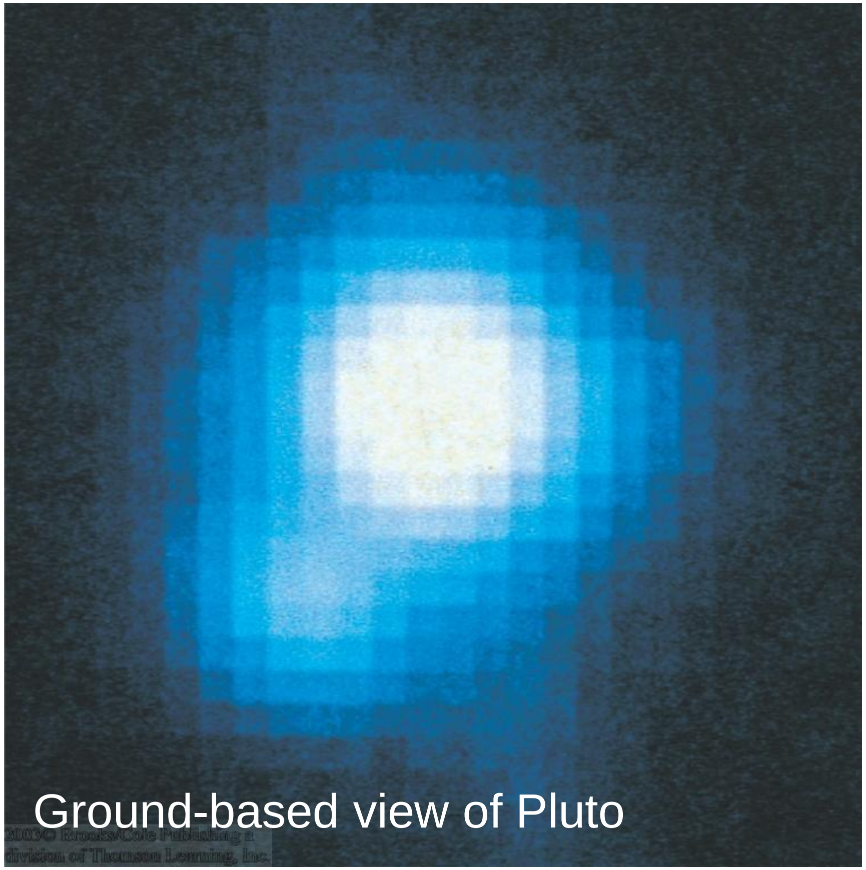
Pluto

Virtually no surface features visible from Earth.

~ 65 % of size of Earth's Moon.

Highly elliptical orbit; coming occasionally closer to the Sun than Neptune.

Very faint, only discovered in 1930.



Ground-based view of Pluto

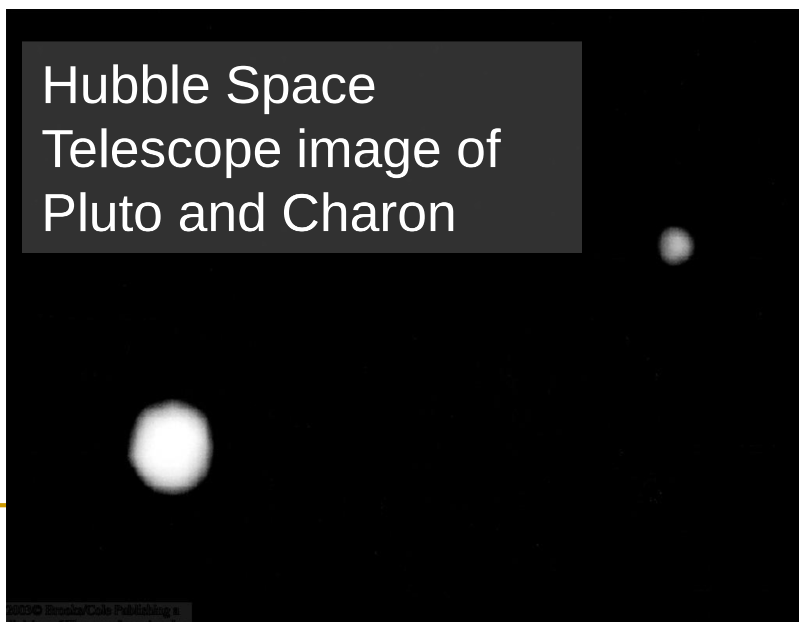
Surface covered with nitrogen (N) ice; traces of frozen methane and carbon monoxide (CO).

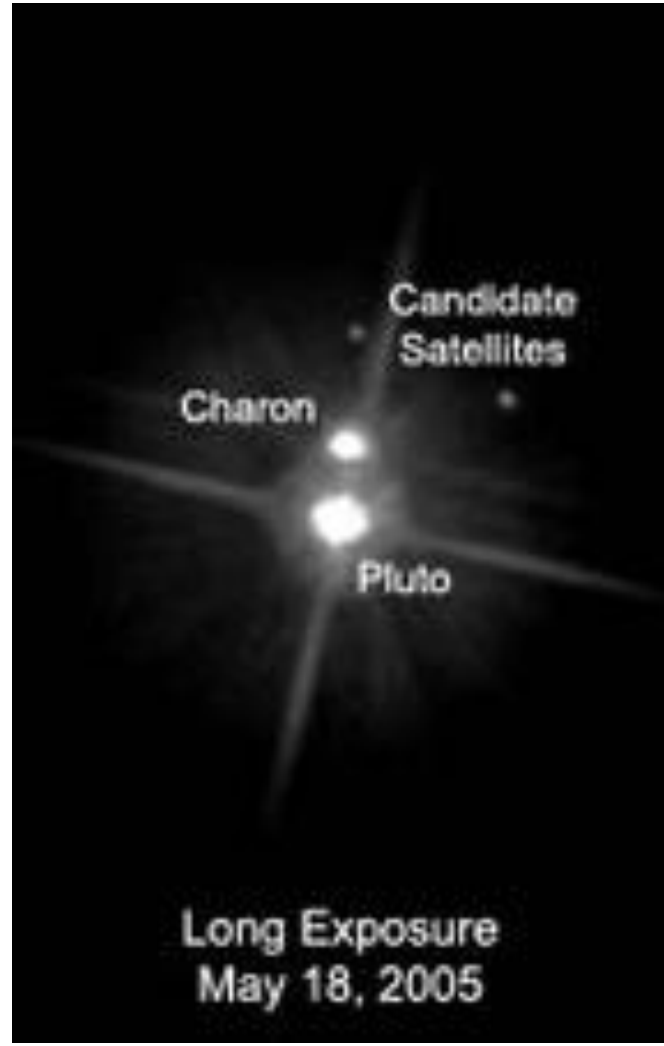
Daytime temperature (50 K) enough to vaporize some N and CO to form a very tenuous atmosphere.

Pluto’s Moons

Charon: largest, discovered in 1978; about half the size and 1/12 the mass of Pluto itself.

Both tidally locked. They always keep the same face to each other.


Hubble Space Telescope image of Pluto and Charon



Recent discovery: Pluto seems to have two more small moons, giving it three so far.

Life on Pluto?

Too darn cold…

No liquid…

Little sunlight…

Unlikely.

Artist's rendering of Sun as seen from Pluto

Cometary gas production

- Cometary activity (gas production) is triggered by proximity to the Sun (solar heating)
  - Most comets at r > 3 AU are inert, and begin to produce gas inside this distance
- The onset of activity near 3 AU is indicative of water ice on the nucleus, as this is the location at which solar heating should begin to sublimate it in significant quantities
- Some comets produce little gas even at smaller distances (e.g. Comet P/Tempel 2)
- Some produce gas at larger distances
  - 2060 Chiron (between Sat. & Ura): intermittent coma (*outbursts*)
  - Hale-Bopp displayed a coma at r > 6 AU
  - Comae at larger r are indicators of more volatile species eg CO, CO_2

Hyakutake

C/2001 Q4 (NEAT)

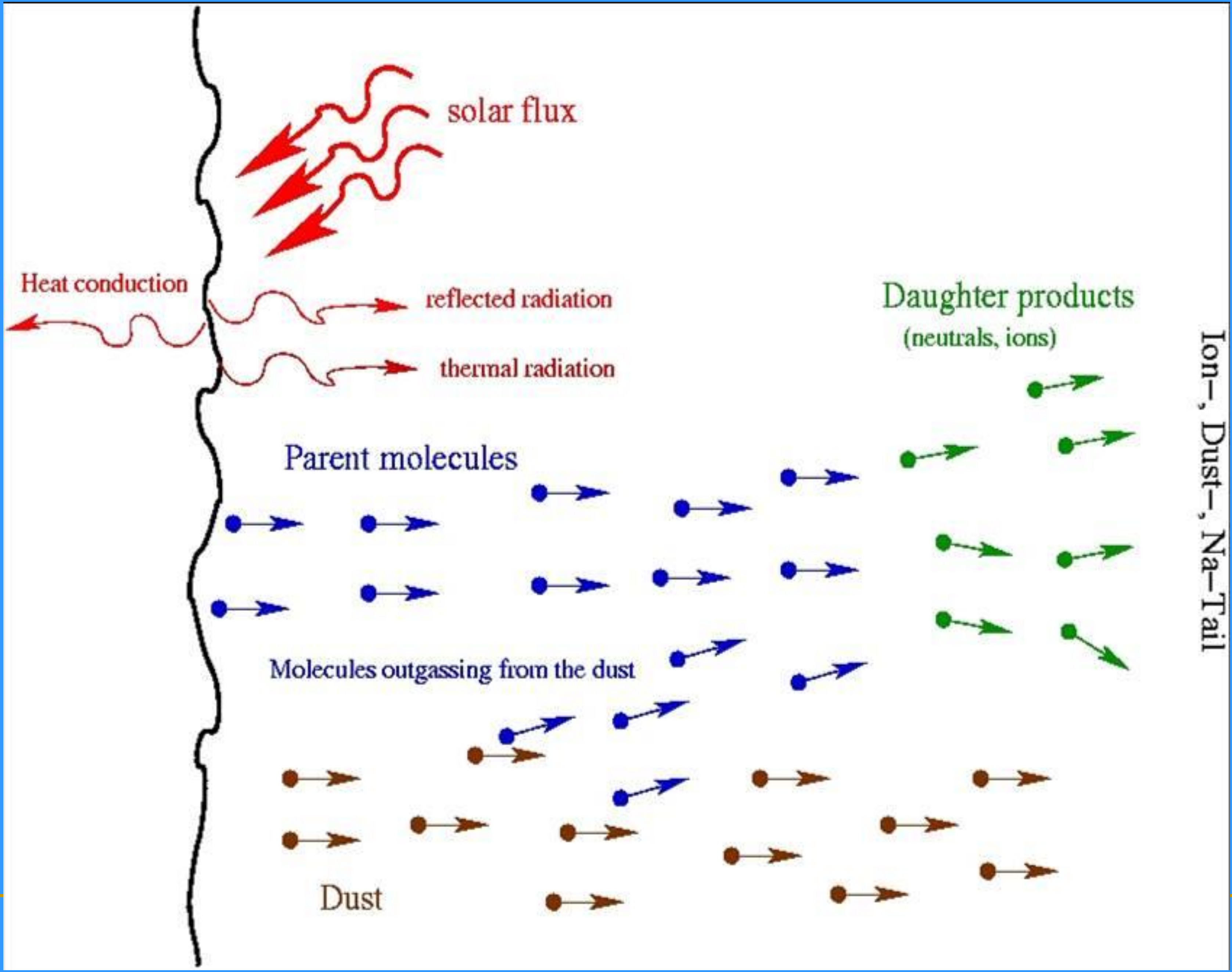
Thermal balance of the nucleus

$$(1-A_v)\frac{L_{Sun}}{4\pi r^2}\pi R^2 = 4\pi R^2 \varepsilon_{ir}\sigma T^4 + \frac{QL_s}{N_A} + 4\pi R^2 K_T \frac{\partial T}{\partial z}$$

Assuming only solar heating, the heat received must be balanced by heat lost (radiatively as well as through the loss of gas) as well as heat transmitted deeper into the nucleus.

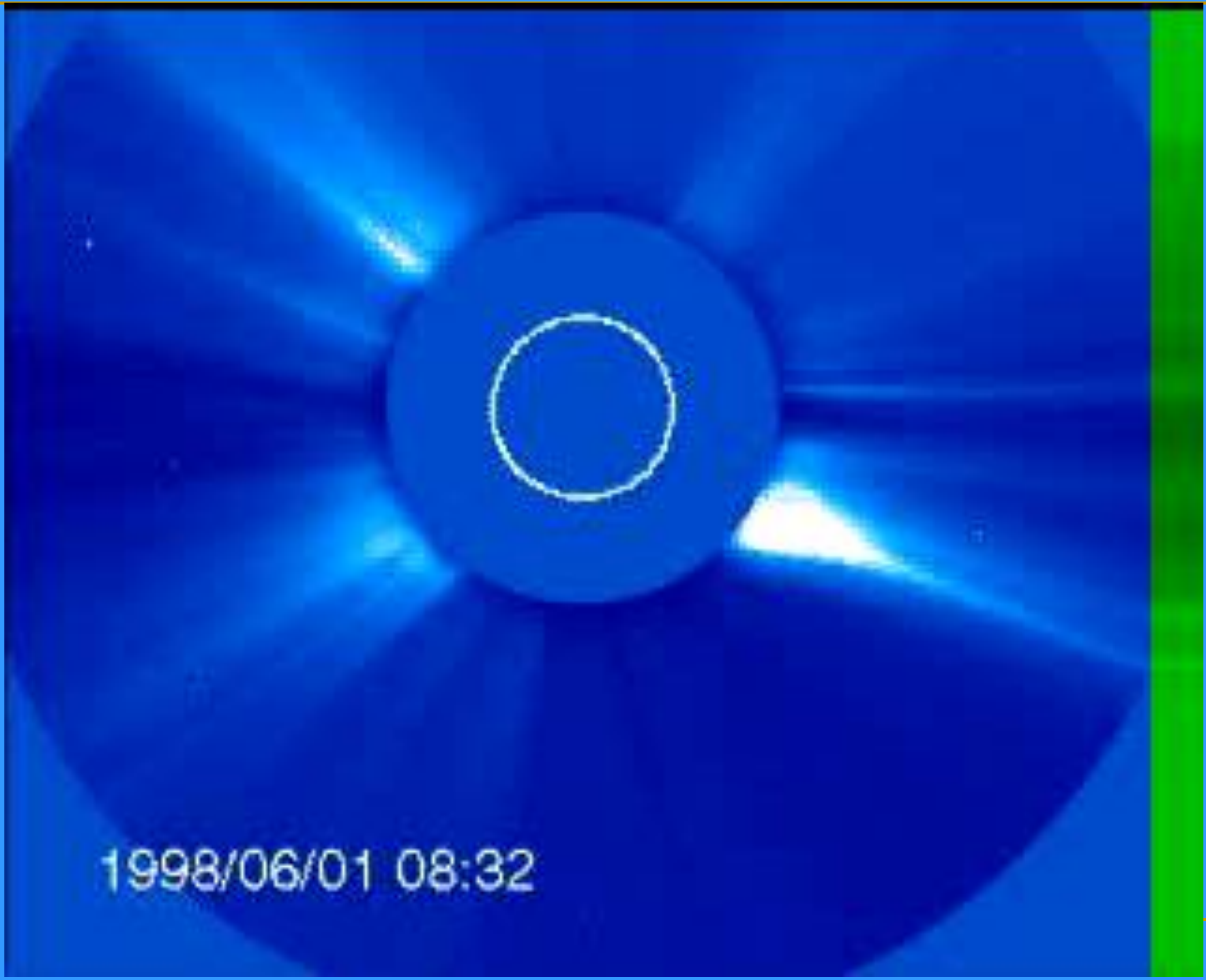
A_v = albedo
L_{Sun} = luminosity of the Sun
r = heliocentric distance
R = comet radius

ε_{ir} = infrared emissivity (~1 for most ices)
σ = Stefan-Boltzmann constant
Q = gas production rate (molecules s^{-1})
L_s = latent heat of sublimation per mole of nuclear ice
N_A = Avogadro's number
K_T = thermal conductivity of the nucleus
$\delta T/\delta Z$ = thermal gradient in the nucleus


solar flux
Heat conduction
reflected radiation
thermal radiation
Daughter products
(neutrals, ions)
Parent molecules
Molecules outgassing from the dust
Dust
Ion–, Dust–, Na–Tail

Coma composition

- The molecules that evaporate from the nucleus are broken down by solar UV light, and many “fragments” are seen.
- Water and its derived species (H,OH, H_2O^+, H_3O^+,O) are dominant
- Carbon compounds are important (C, C_2, C_3, CH, CH_2, CN, CO) with a probable origin from CO_2, HCN, CH_4, H_2CO (formaldehyde), CH_3OH (methanol)
  - CO production ~15-20% of water, CO_2 ~ 3% and others lower still
- N and S compounds are present in small amounts.
- Na is regularly seen in comets, though only Sun-grazing comets (r <0.2AU) show other metal lines such as Ca, K, Fe, Ni, Co, etc, presumably from vaporizing rock.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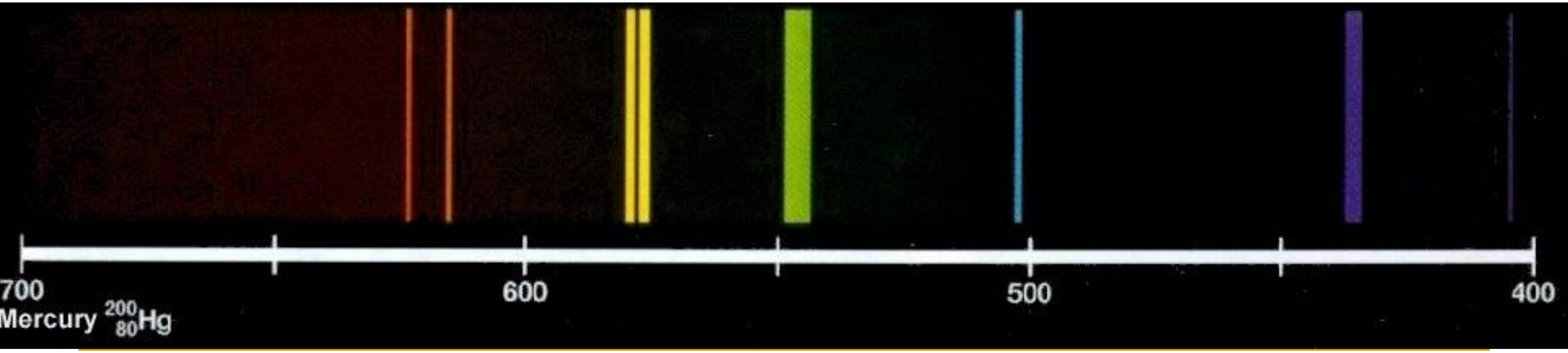
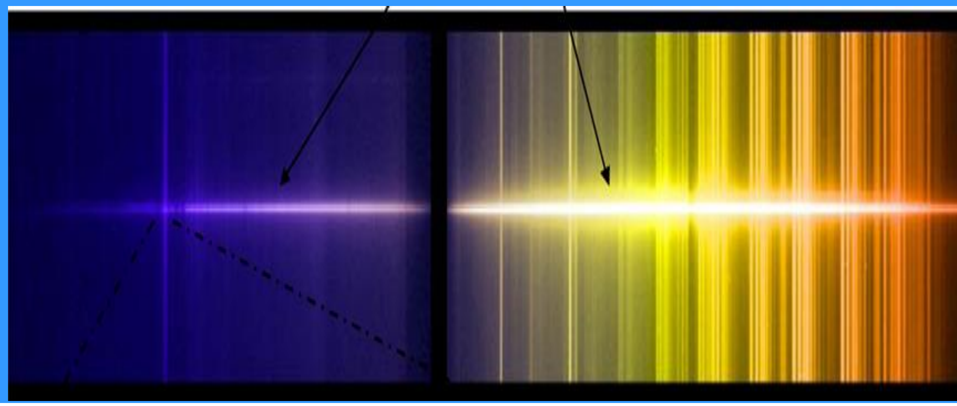
Thin gas light emission processes

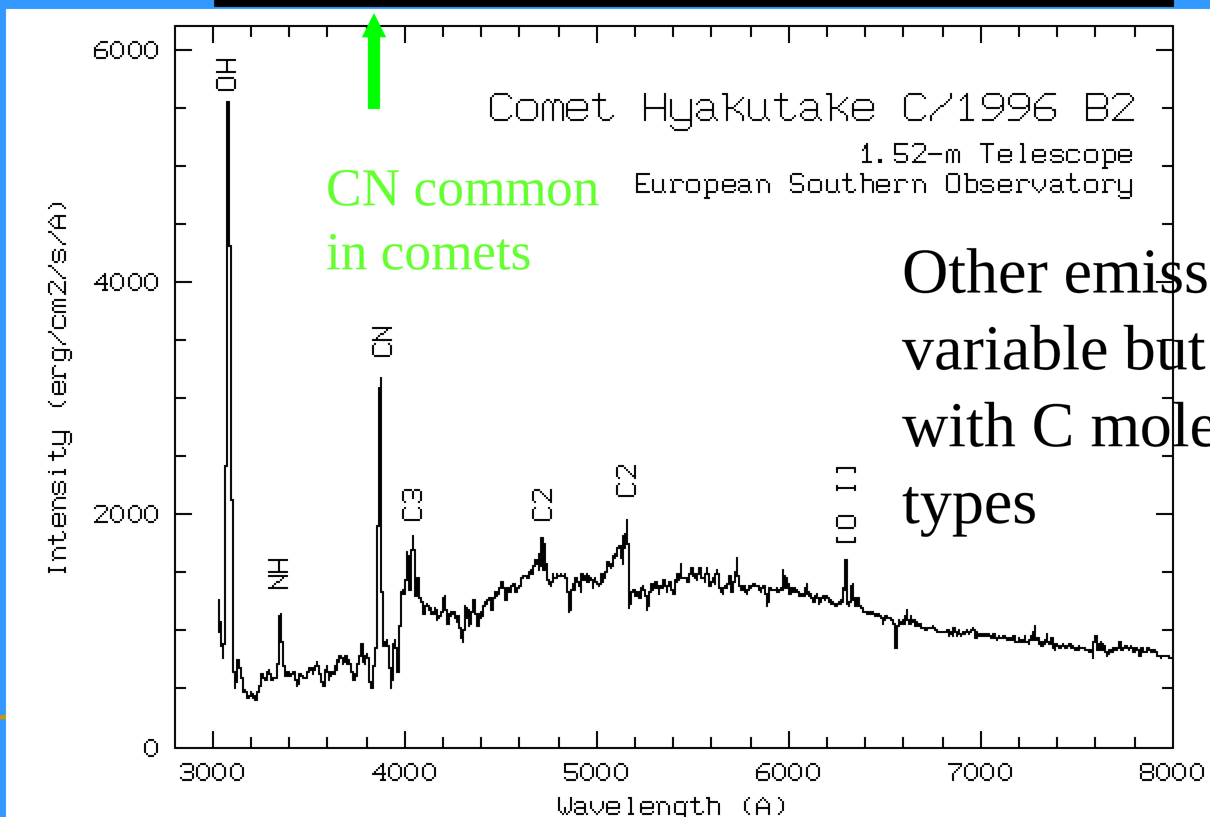
- Thin gases do not emit black-body radiation but rather emit a particular pattern of specific colours unique to the atom or molecule
- For example, passing the light from a fluorescent lamp through a prism reveals the fingerprint of mercury



Spectroscopy: fingerprinting the comet's gases



Spectrum of comet 10P/Tempel in "rainbow" format



CN common in comets

Other emission lines more variable but often associated with C molecules of different types

The Comet Cyanide Scare of 1910

- In 1910, Halley's comet passed close enough to Earth that it was thought the Earth might actually pass through its tail (it didn't ultimately)
- The astronomer Sir William Huggins had shown the presence of CN in comet tails as early as 1881 with little interest.
- But in 1910, Halley's comet drew forth the the realization that the presence of CN (cyanogen) a component of the deadly poison cyanide, in its tail might indicate the imminent doom of the Earth.
- This was unfortunately fueled by a few astronomers and astronomy popularizers that should have known better
  - the density of cometary gas is incredibly low, with too little cyanide to have any effect even if it could somehow mix into the atmosphere.
- The sale of comet "pills" and gas masks were some of the strange results of the hysteria that followed.

Dust

- Dust (rocky grains) is entrained away from the nucleus as the ices sublimate
- Dust-to-gas ratio varies: 0.1 to 10
- Small (subμm) particles can reach the gas velocity (~1km/s) but larger ones barely reach escape velocity (~1m/s)
- The dust is “blown” back into the *dust tail* which owing to the slightly different dynamics of the gas and dust, is usually separate from the *gas tail* (or *ion tail*)
- The dust tail is usually yellow-ish (reflected sunlight) with the gas tail is usually bluish (CN, C_3, C_2 lines)

Active comets

Hyakutake (1998)

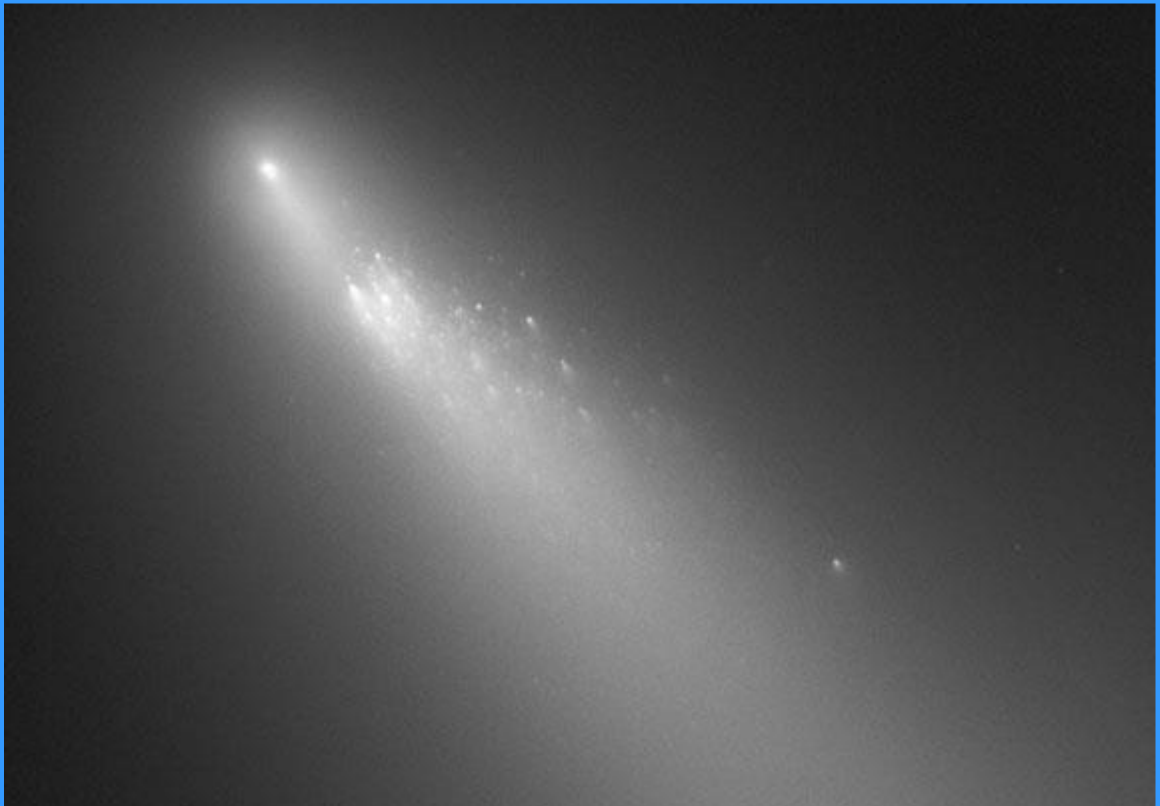
Hale-Bopp (1997)

West (1976)

Dust streamers from Comet McNaught (2007)

The end of the line: Splitting and disruption

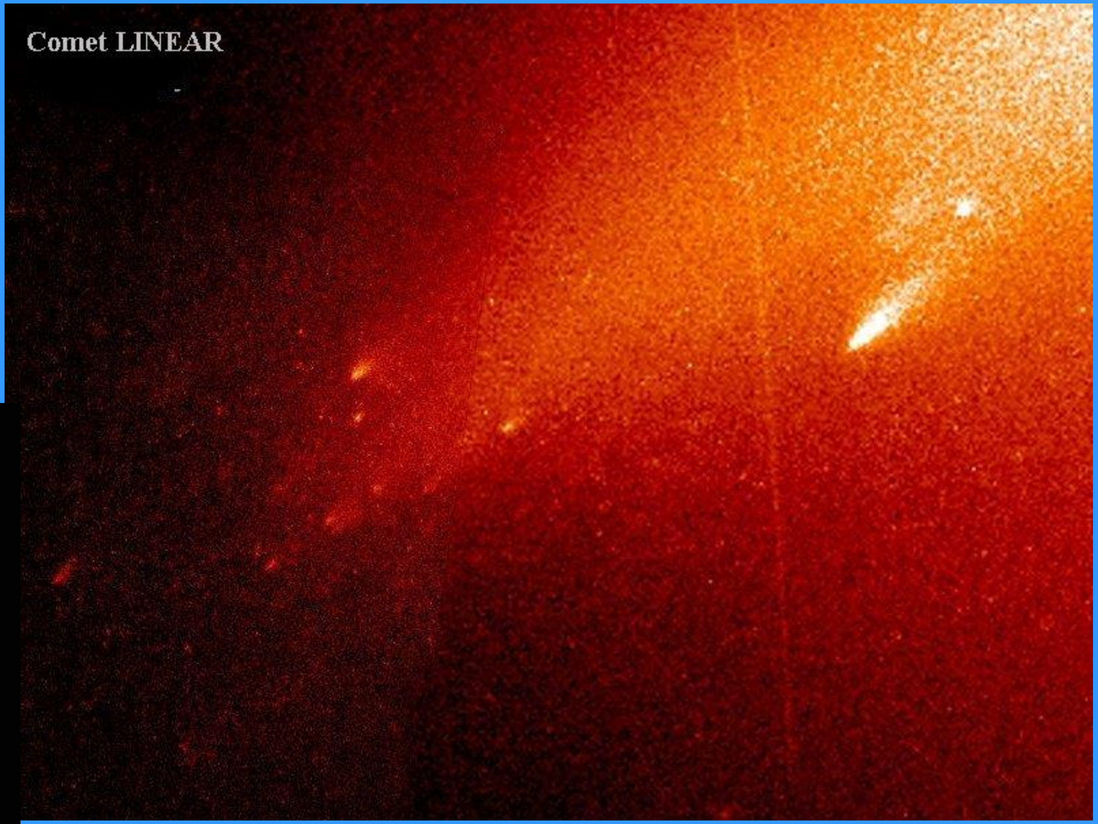
- Comets are sometimes seen to break apart (about 2 dozen cases reported so far), shedding a few small pieces, other times undergoing more dramatic breakups
- Splits are often first seen as outbursts of gas and dust from the nucleus, as it usually takes some time for the fragments to drift apart enough to become visible individually

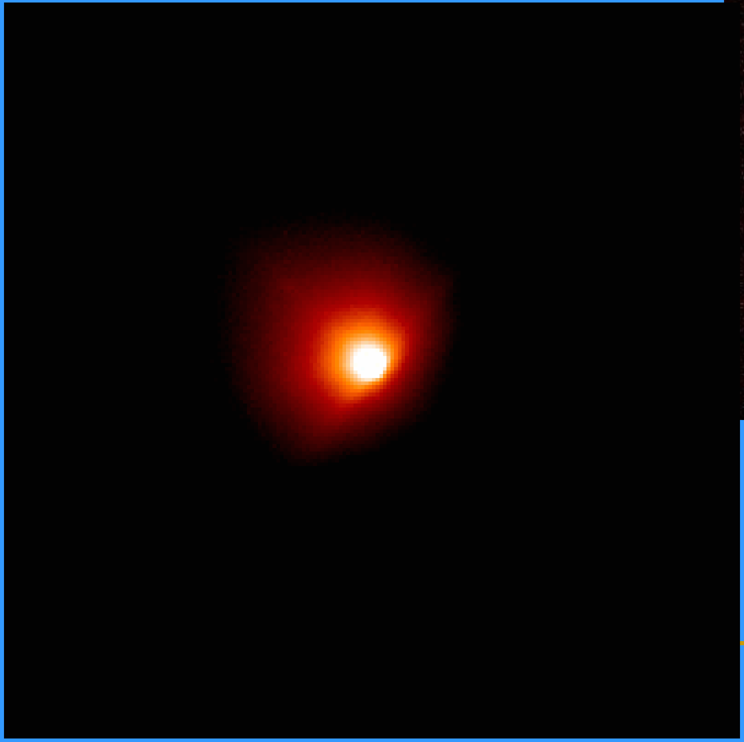


Comet Schwassmann-Wachmann 3 breaking up in 2006

Comet C/1999 S4 LINEAR

- broke into at least 16 pieces as it passed the Sun in 2000

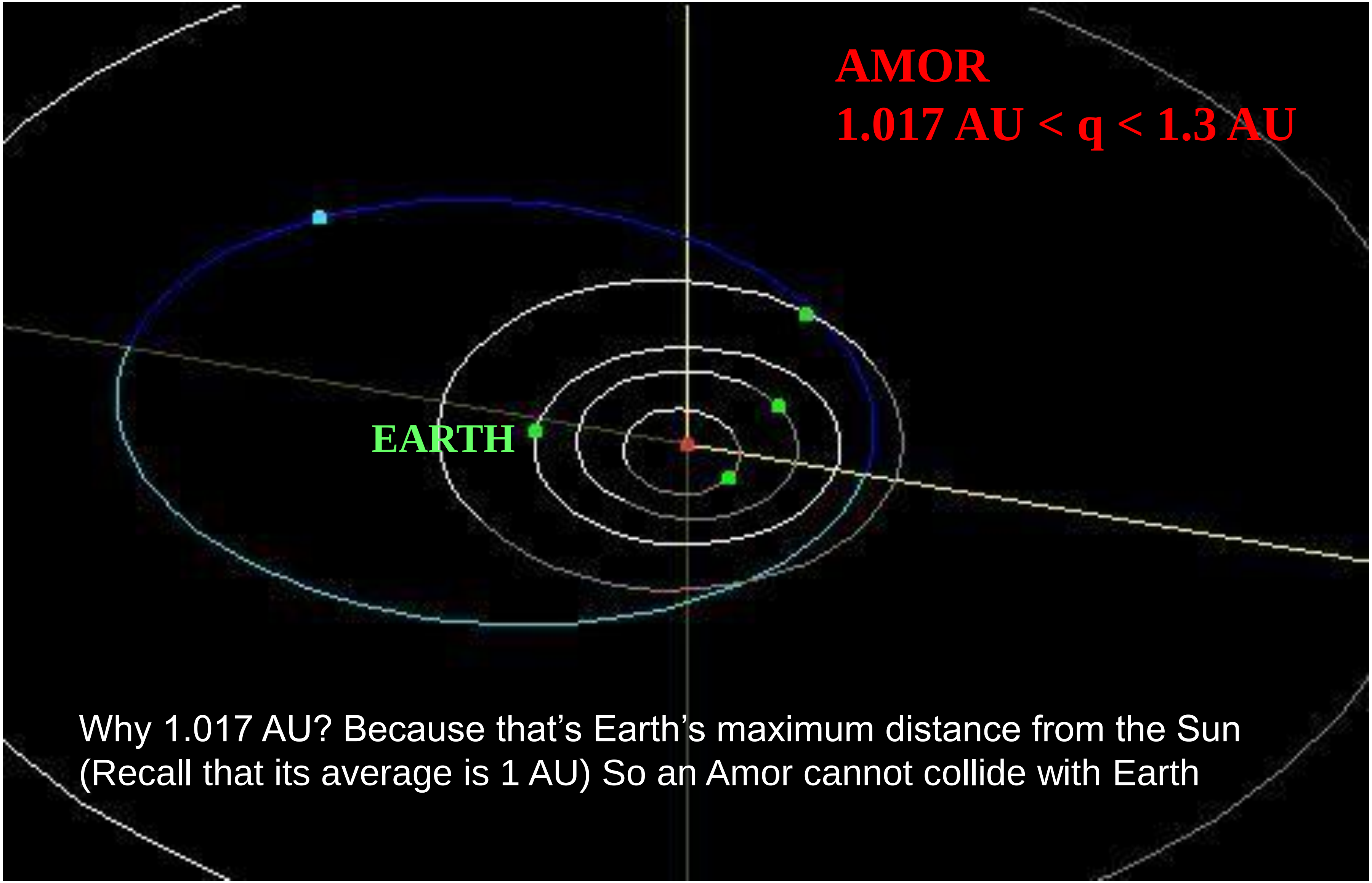




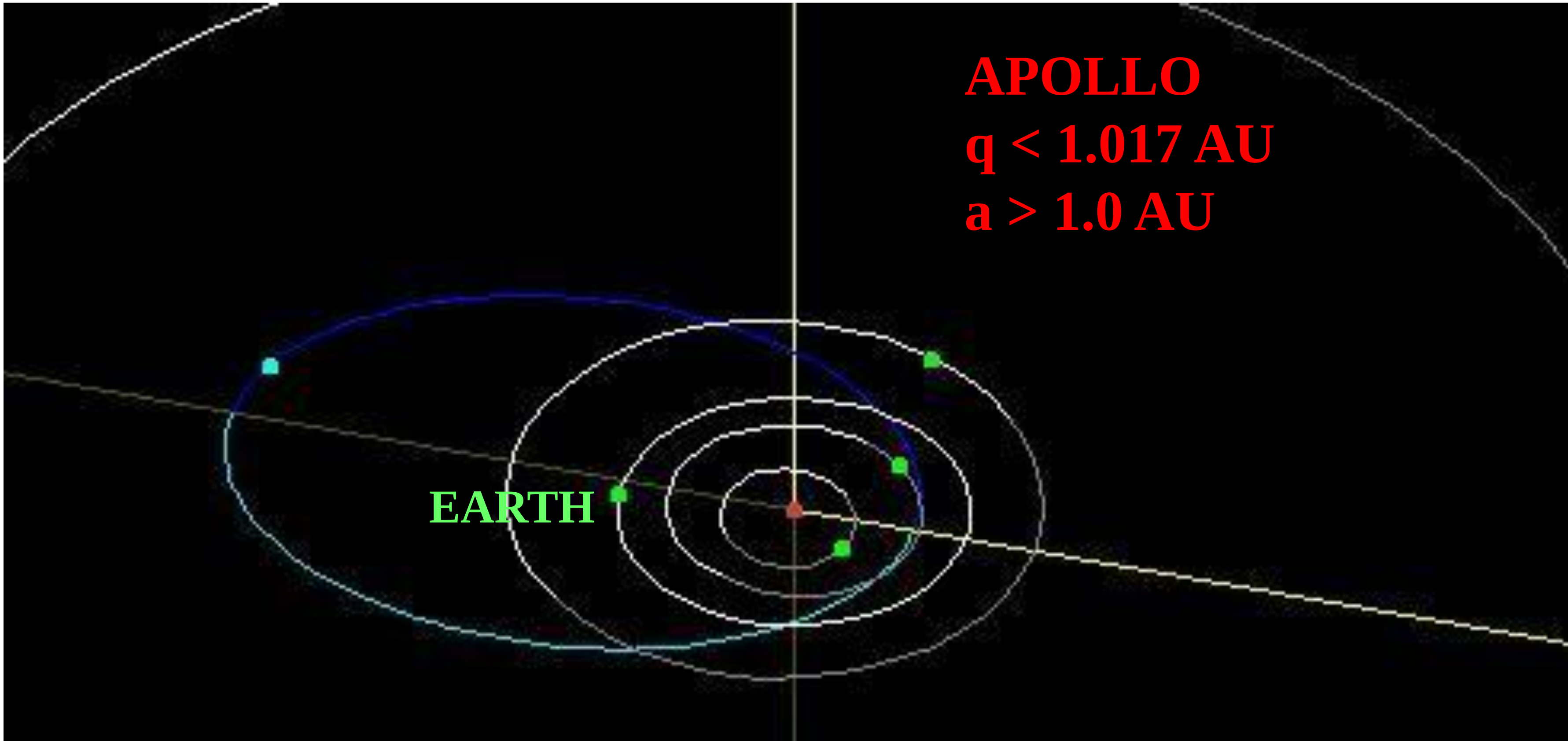
The End

For next day : Read Chapter 8 – Planetary Interiors

NEA TYPES

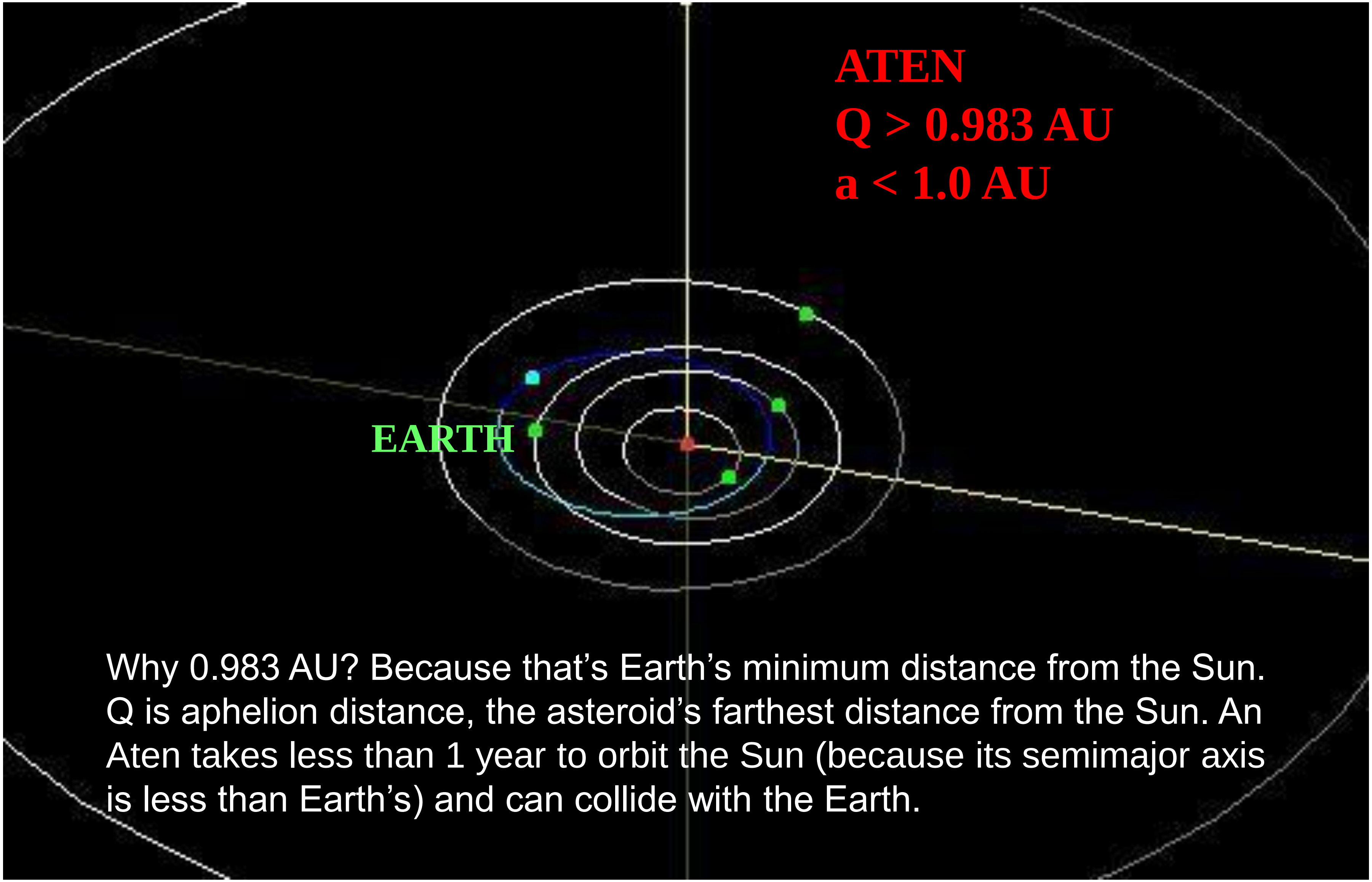

AMOR
1.017 AU < q < 1.3 AU
EARTH
Why 1.017 AU? Because that's Earth's maximum distance from the Sun (Recall that its average is 1 AU) So an Amor cannot collide with Earth

NEA TYPES



q is perihelion distance, the asteroid's closest approach distance to the Sun. An Apollo takes more than 1 year to orbit the Sun (because its semimajor axis is greater than Earth's) and can collide with the Earth.

NEA TYPES



Why 0.983 AU? Because that's Earth's minimum distance from the Sun. Q is aphelion distance, the asteroid's farthest distance from the Sun. An Aten takes less than 1 year to orbit the Sun (because its semimajor axis is less than Earth's) and can collide with the Earth.