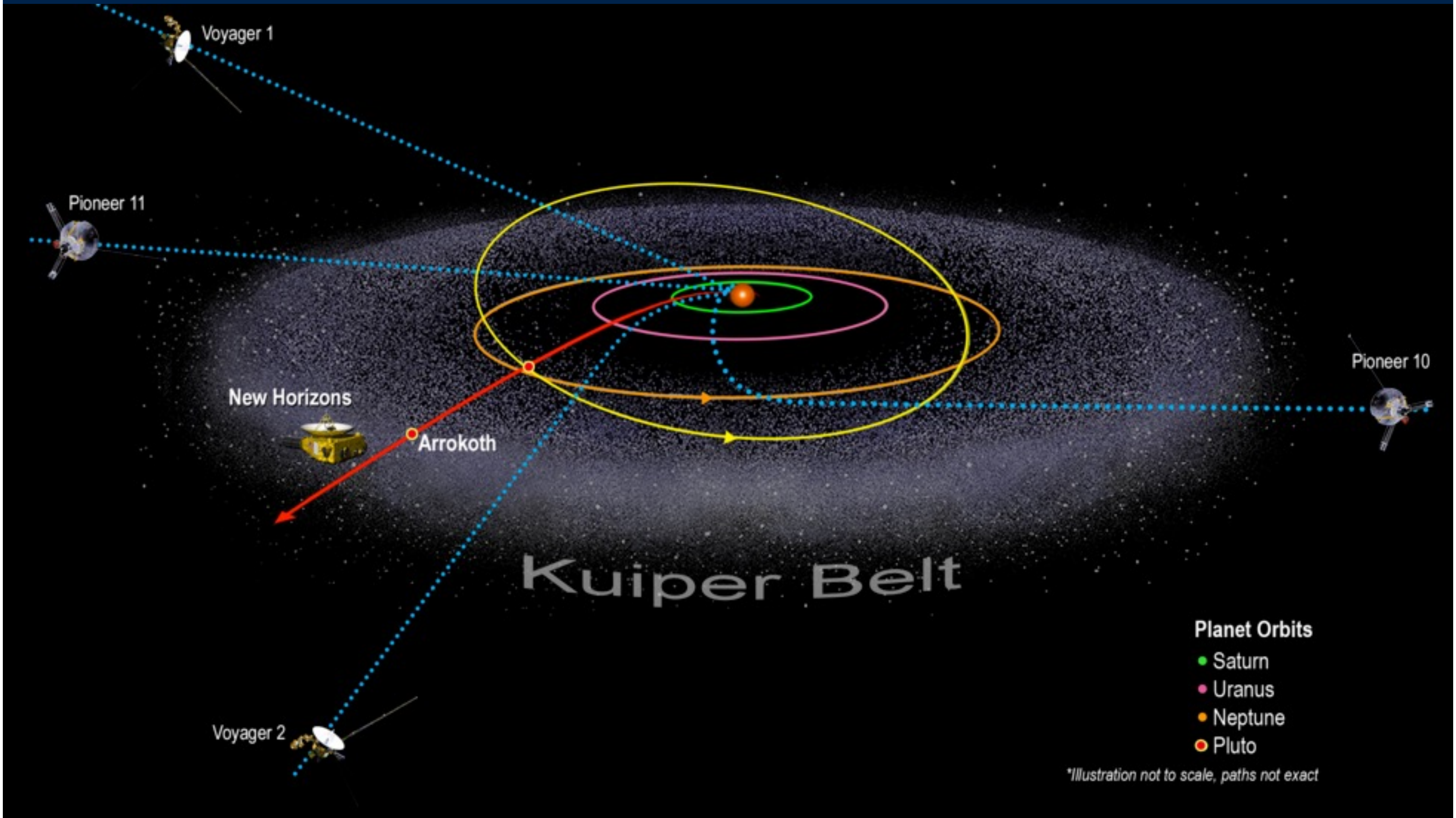
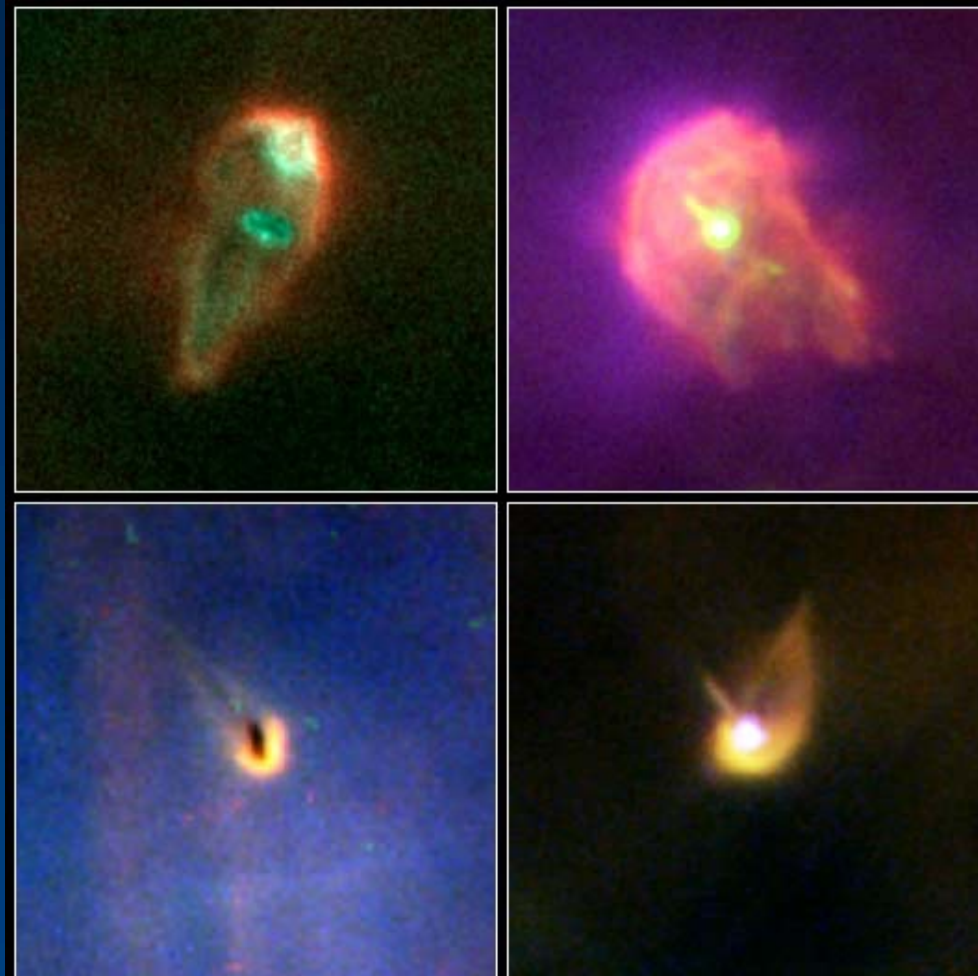
Our most distant spacecraft



Direct Images of Primordial Disks

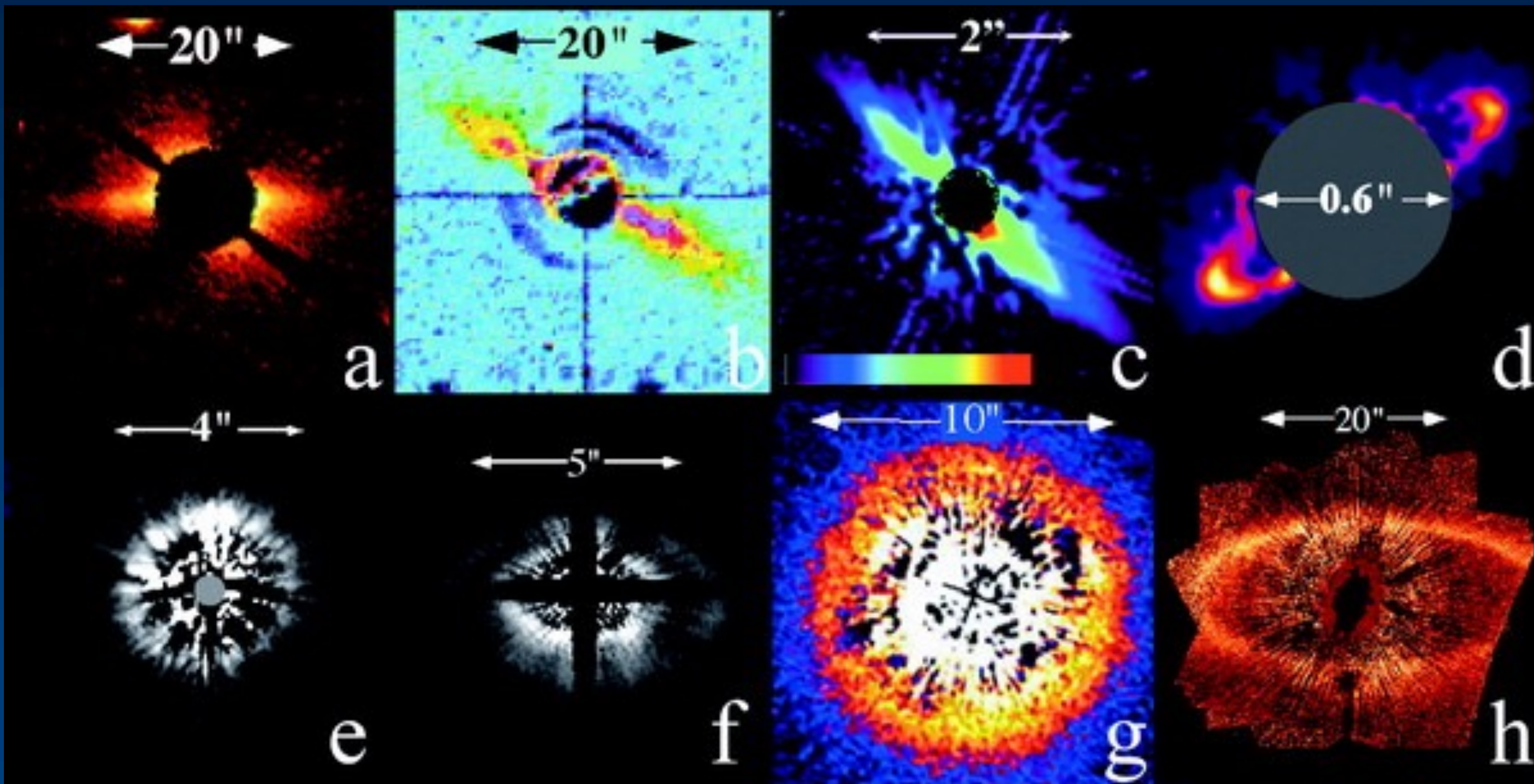
(Triggered star formation in Orion)

Edge-On Protoplanetary Disk
Orion Nebula
PRC95-45c · ST ScI OPO · November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

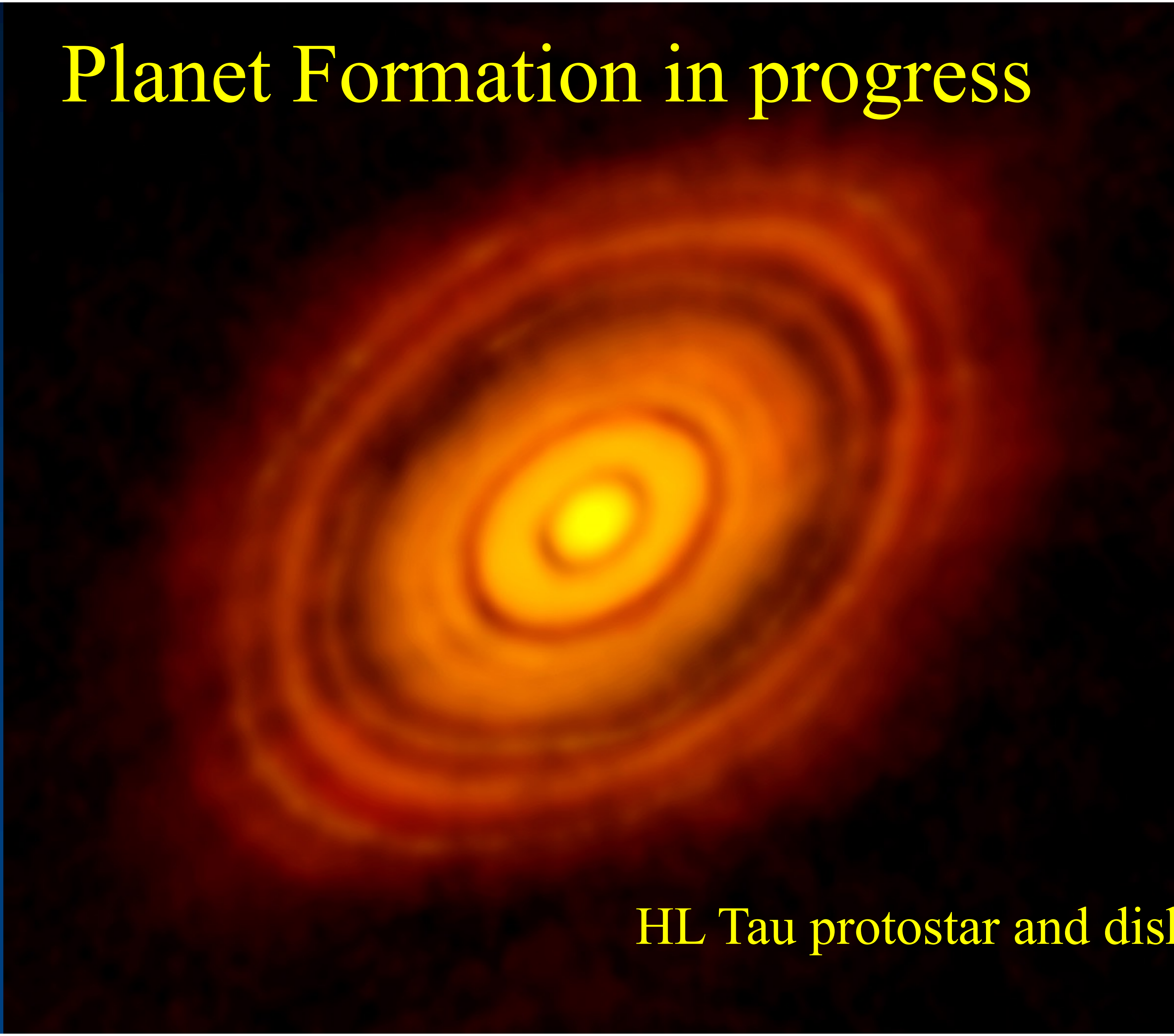


Protoplanetary Disks in the Orion Nebula
NASA, J. Bally (University of Colorado), H. Throop (SWRI), and C.R. O'Dell (Vanderbilt University) • STScI-PRC01-13

Scattered Light Images of Debris Disks

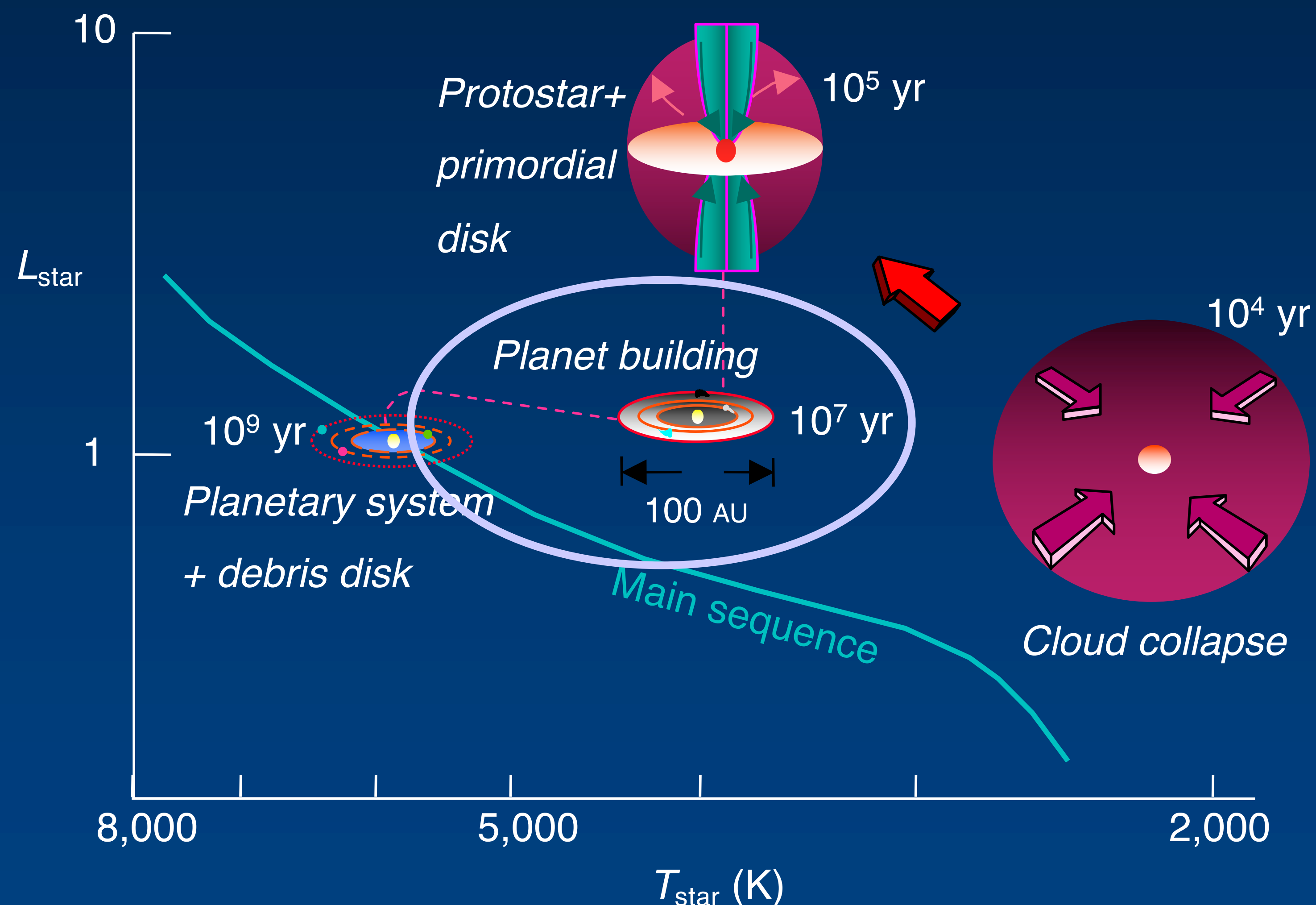


Planet Formation in progress



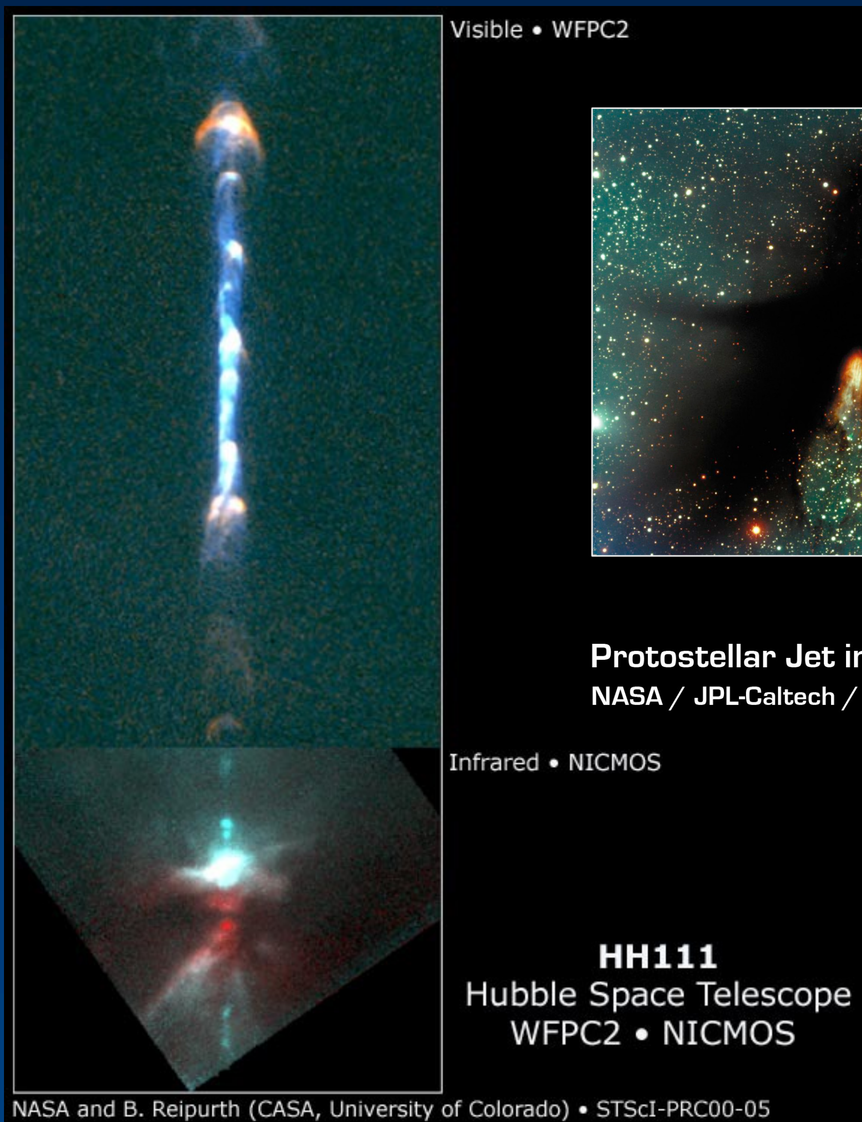
HL Tau protostar and disk

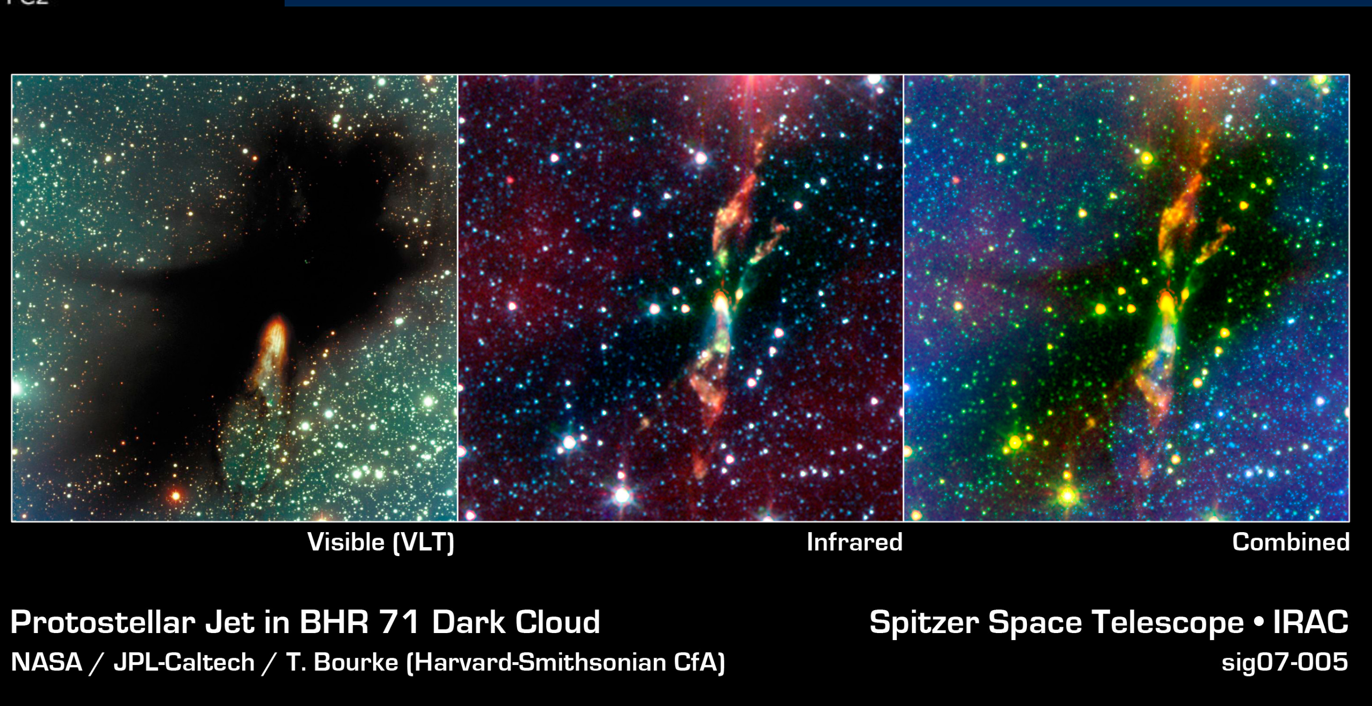
The Nebular Theory of Planet Formation



Beckwith & Sargent

Accretion & Dissipation

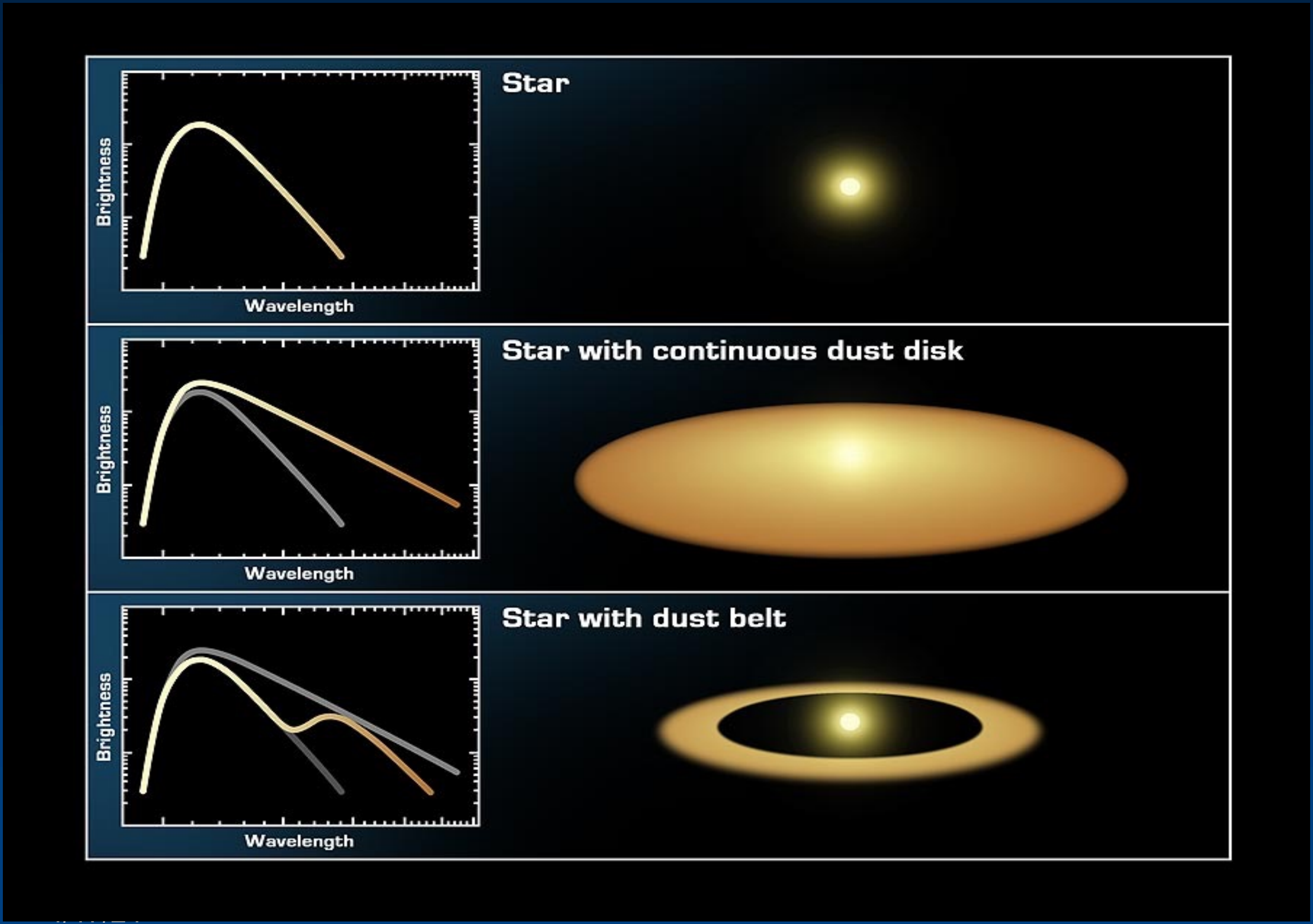




← HST

↑ Spitzer

Thermal Emission from Debris Disks

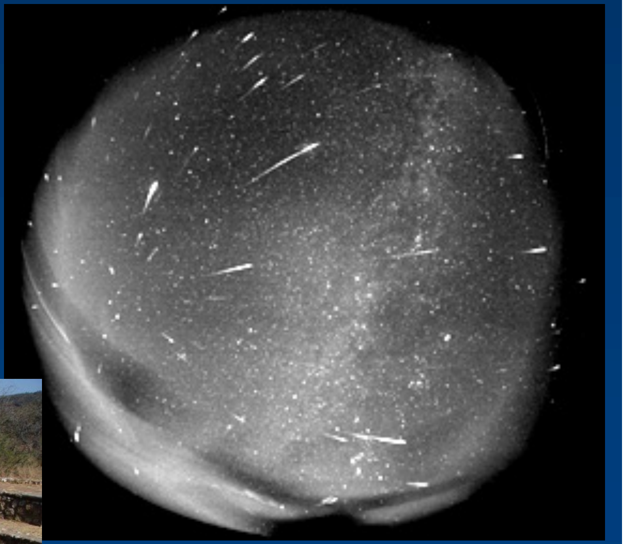


Asteroids

Comets

Meteor Showers

(Meteorites – Museum at Northrop Hall)

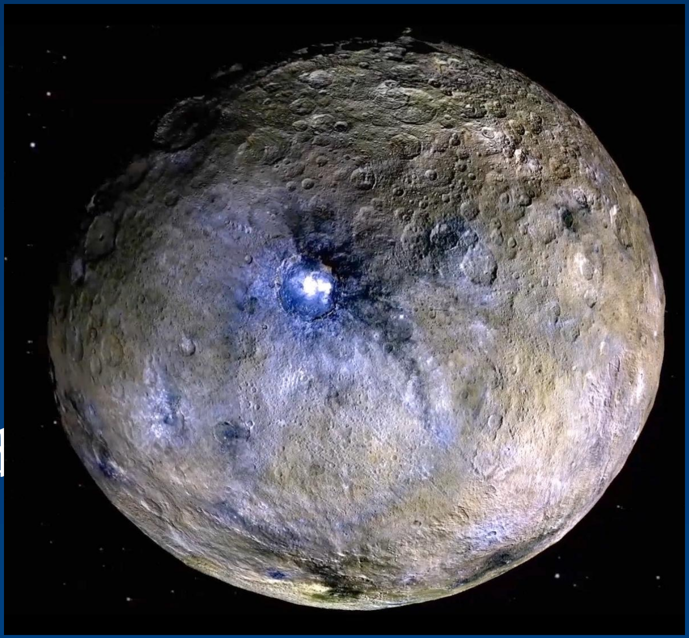


Asteroids

Discovery of Asteroids:

After discovery of Uranus, astronomers wondered if there were other "unknown" planets - anything between Mars and Jupiter?

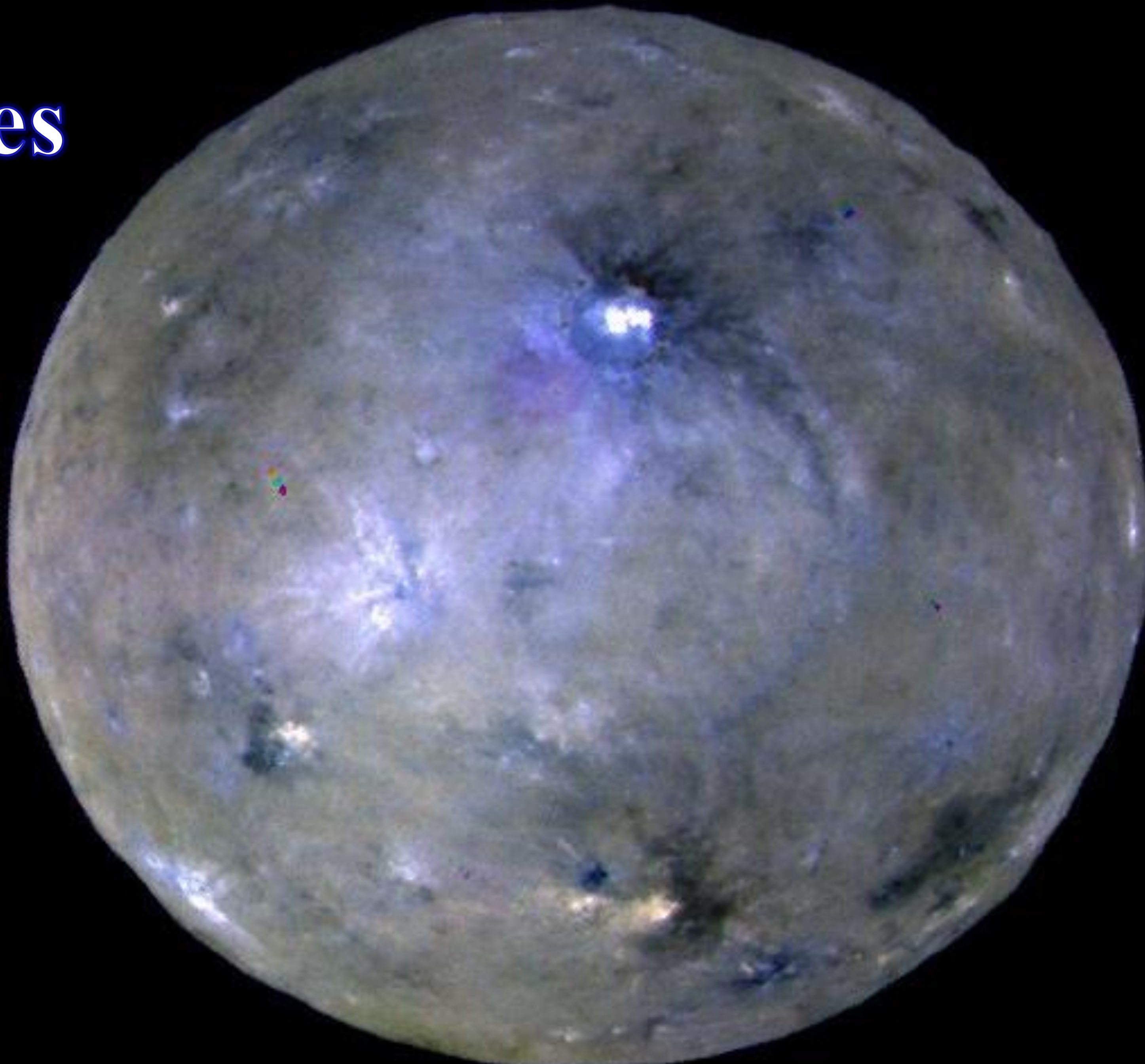
In 1801, Ceres was found at 2.77 AU, followed by others.



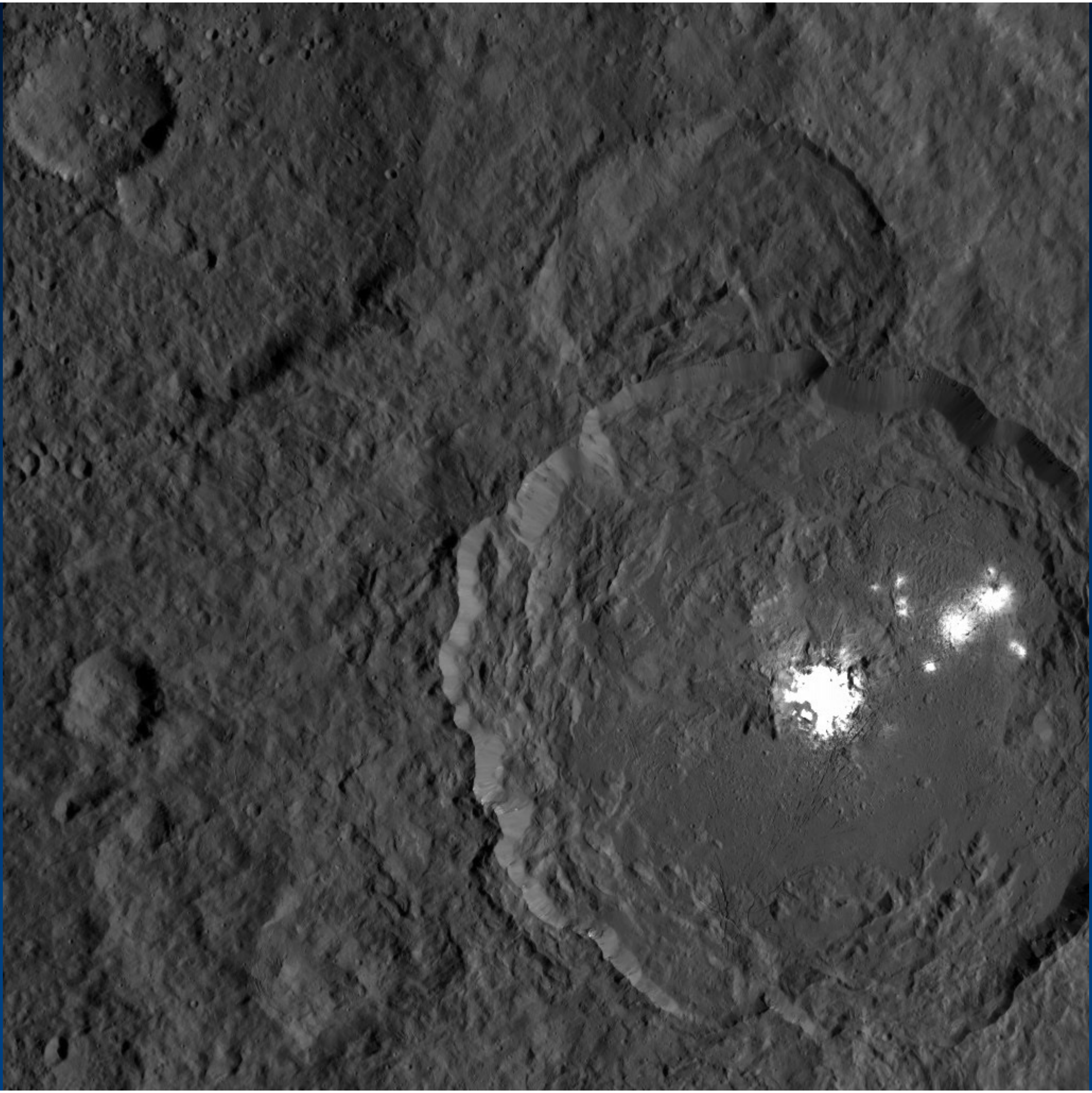
Referred to as planets, until realized that there was a large number of these.

First thought to be debris from a destroyed planet. Eventually realized mass in Asteroid Belt too small for this.

Ceres



Ceres



DAWN

spacecraft

image tracking the stars

image tracking the asteroid

What are asteroids?

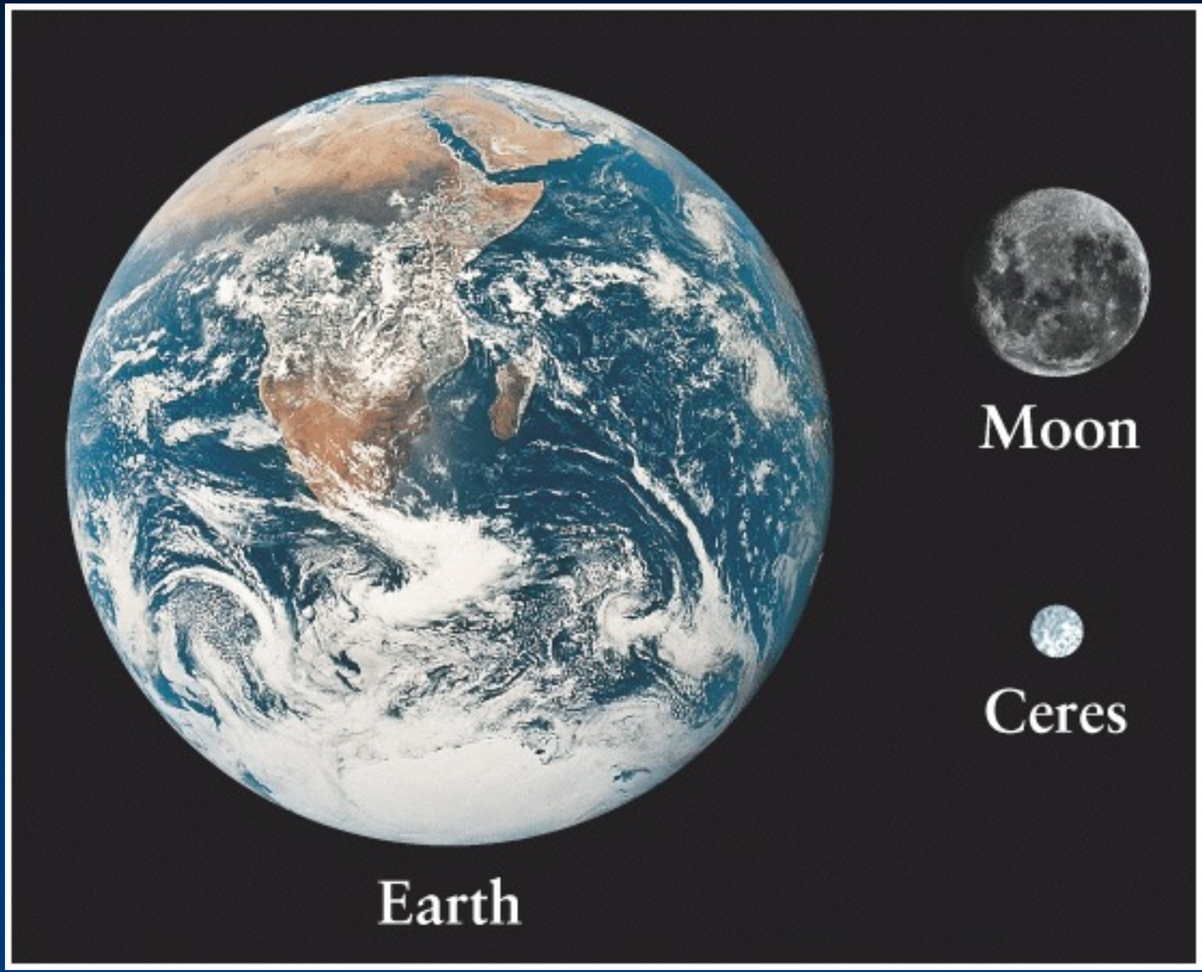
- Small, rocky objects (not planets – haven't cleared out their path. Only Ceres is spherical and is also a dwarf planet).

- Largest asteroids and naming scheme:

1 Ceres	975 km diameter
2 Pallas	522 km
3 Juno	248 km
4 Vesta	549 km

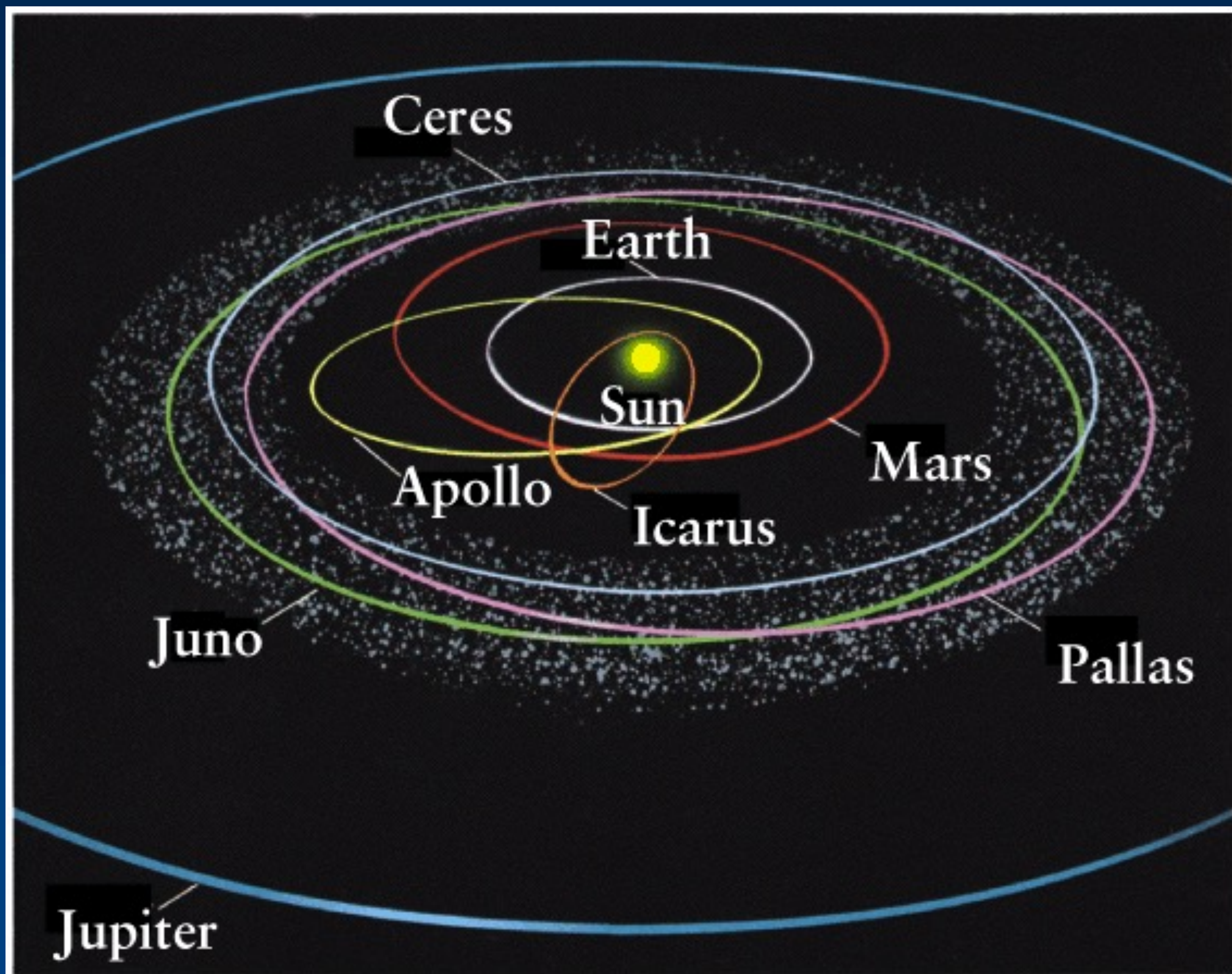
Number before name indicates order discovered.

>300,000 found. 100,000 have measured orbits. Most of the mass is in ones with D=100-200 km, but many smaller ones exist.



- Ceres alone accounts for 25% of the mass of all asteroids
- The combined asteroids don't make an Earth-size planet, would only make a small planet of 1500 km diameter
- They are *leftovers from solar system formation* – probably affected by gravitational influence of Jupiter

Most asteroids reside in the Asteroid Belt, 1.5 AU wide between Mars and Jupiter, centered at 2.8 AU



- In the 1700s, scientists tried to describe the Solar System mathematically, especially the distances of the planets from the Sun – Bode's Law
- $D_{planet}=0.4+0.3N$ where N=0,1,2,4,8 (doubles for each planet)

Planet	N	Predicted D	Real D
Mercury	0	0.4	0.39
Venus	1	0.7	0.72
Earth	2	1.0	1.00
Mars	4	1.6	1.52
Gap	8	2.8	2.77
Jupiter	16	5.2	5.20
Saturn	32	10.0	9.54
Uranus	64	19.6	19.19
Neptune	128	38.8	30.07
Pluto	256	77.2	39.53

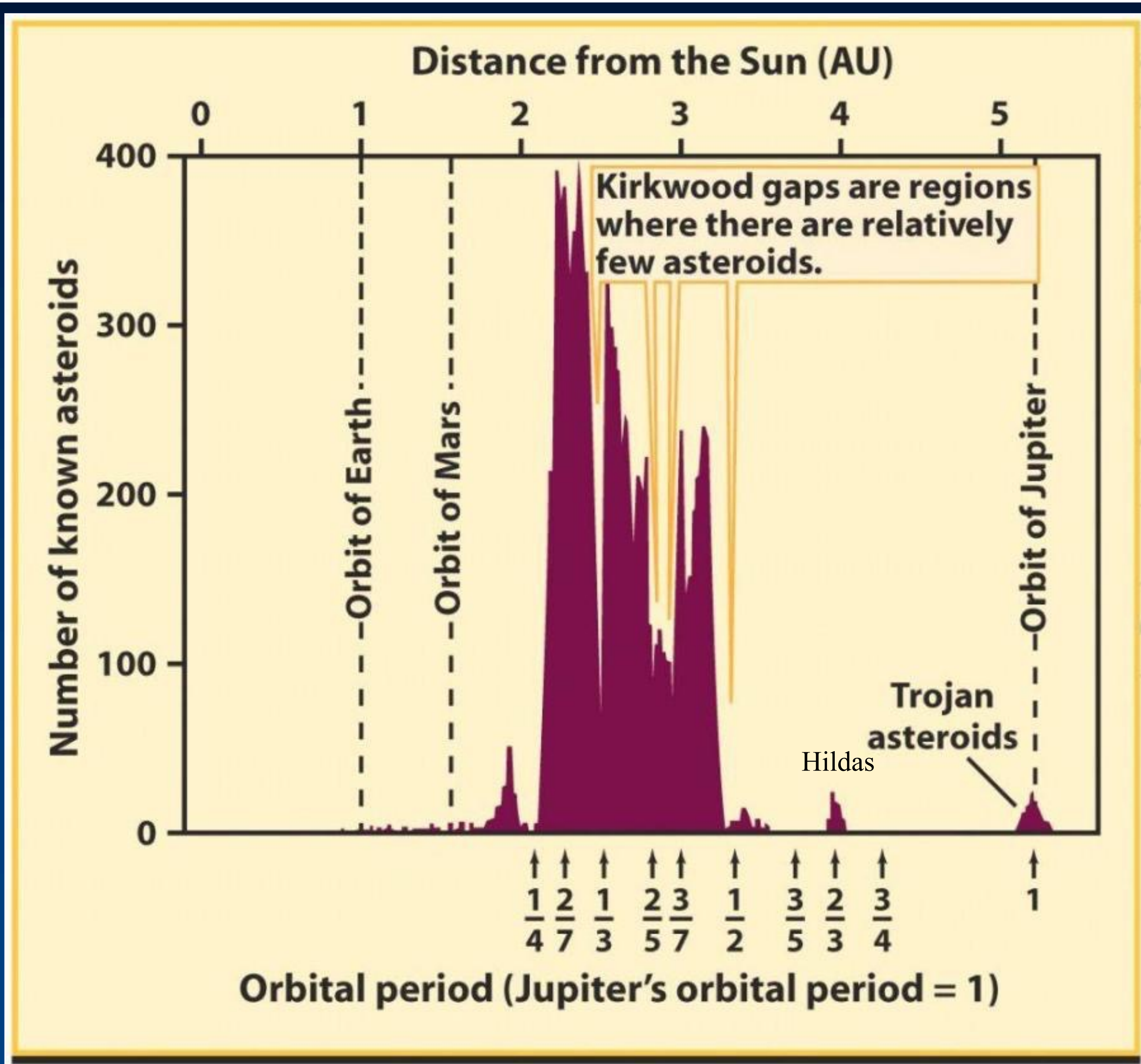
Jupiter's effect

- Perhaps a planet was going to form there, but Jupiter's pull disrupted orbits of planetesimals, ejecting some completely, preventing formation of planet. Asteroids are leftovers.
- Supported by simulations. If no Jupiter, an Earth-like planet likely to form. With Jupiter, orbits are disrupted.

Kirkwood gaps

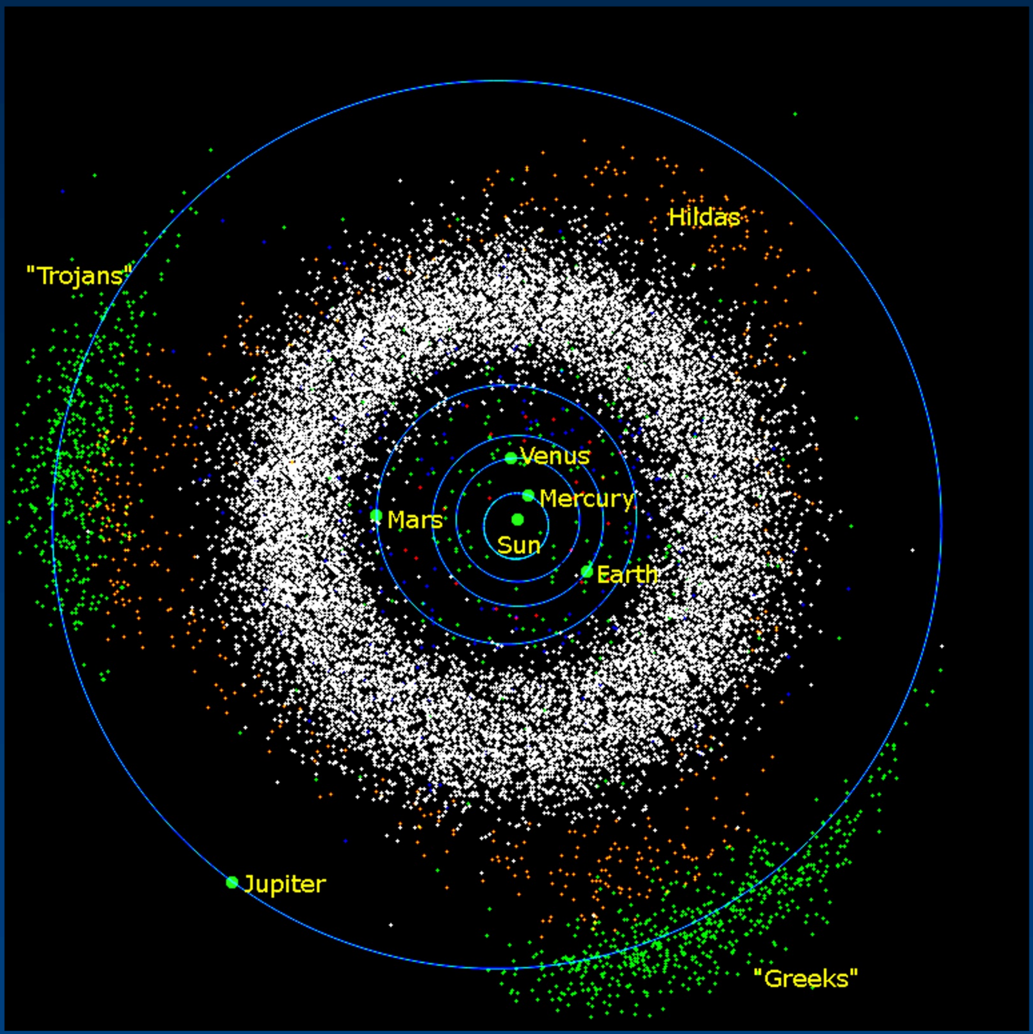
Caused by resonances with Jupiter's orbital period. Where asteroids would have periods which are in simple fractions of Jupiter's period, they are cleared out of that orbit.

Where have we seen this before?

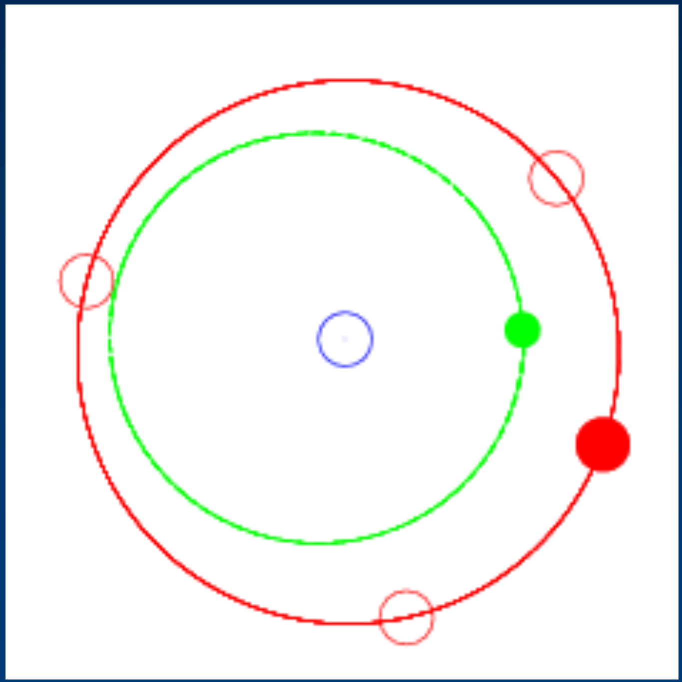


Distance from the Sun (AU)
0
1
2
3
4
5
400
300
200
100
0
Number of known asteroids
Orbit of Earth
Orbit of Mars
Orbit of Jupiter
Kirkwood gaps are regions where there are relatively few asteroids.
Trojan asteroids
Hildas
1/4 2/7 1/3 2/5 3/7 1/2 3/5 2/3 3/4 1
Orbital period (Jupiter's orbital period = 1)

Hildas Asteroids



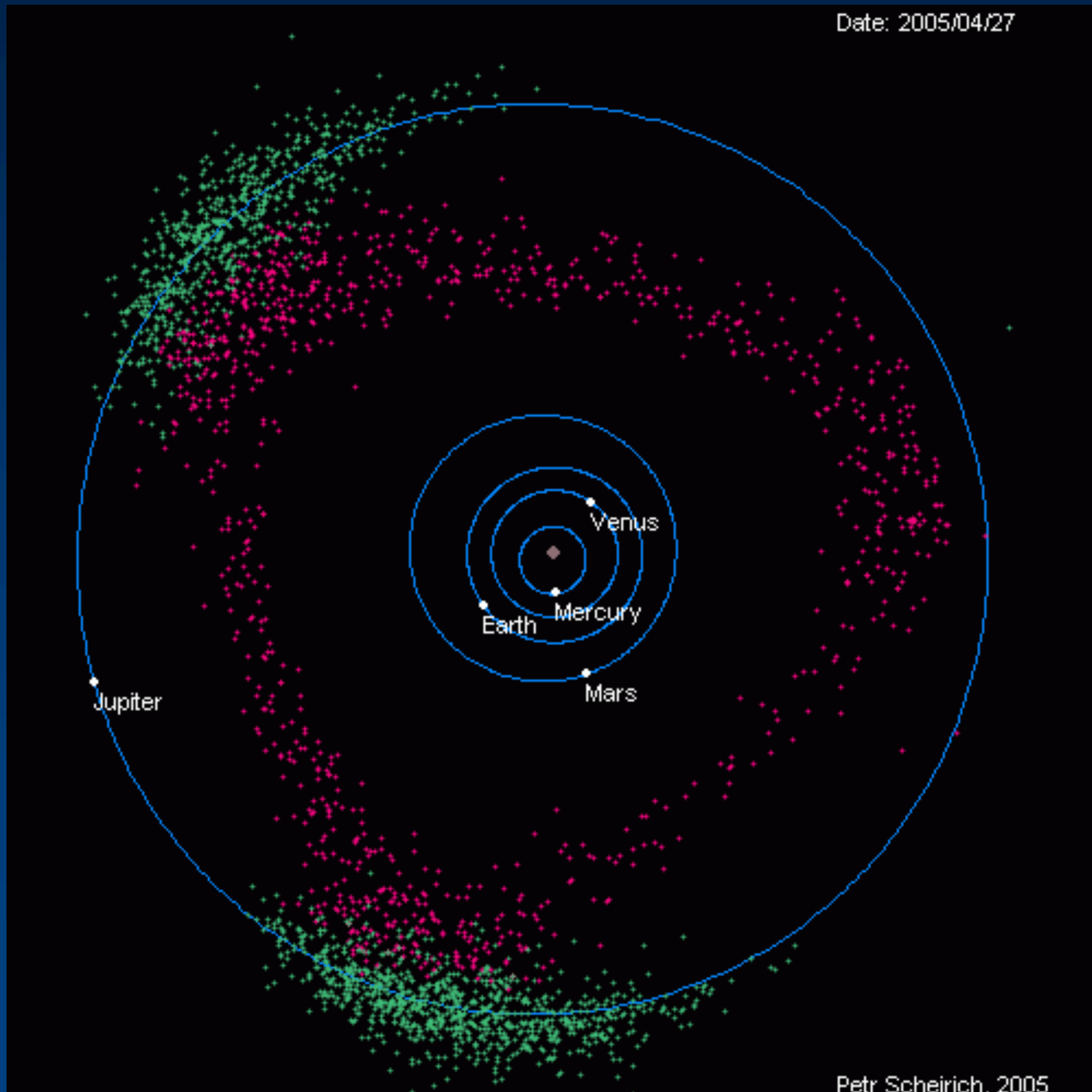
~ 5 AU



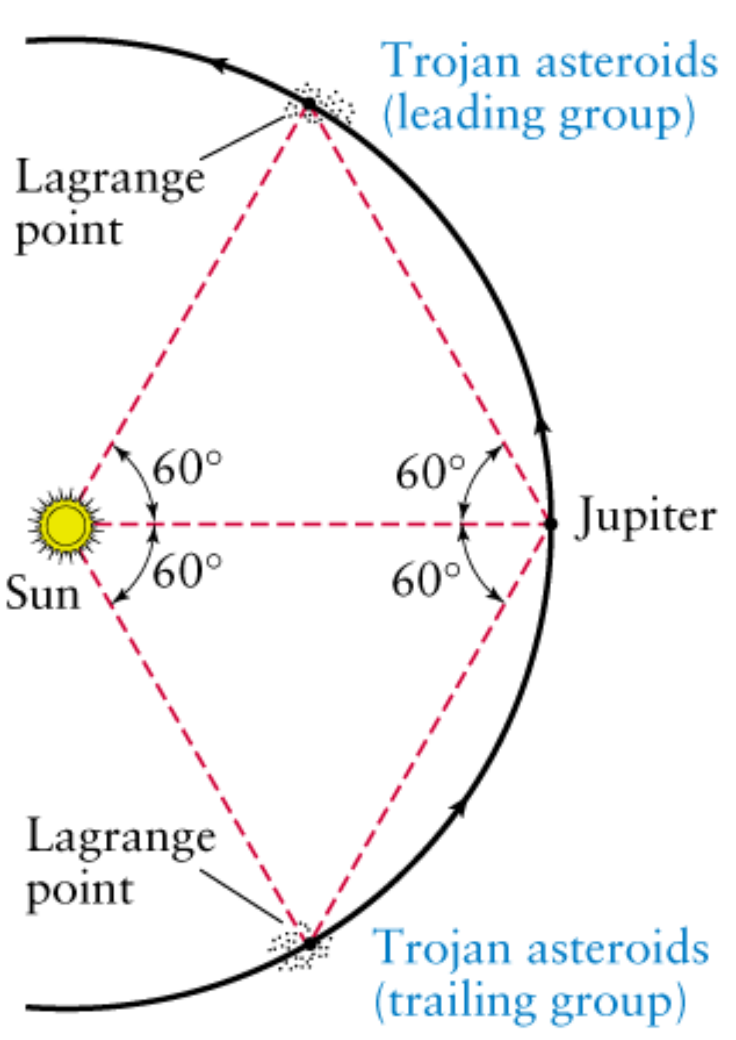
Green = 153 Hilda

Red = Jupiter

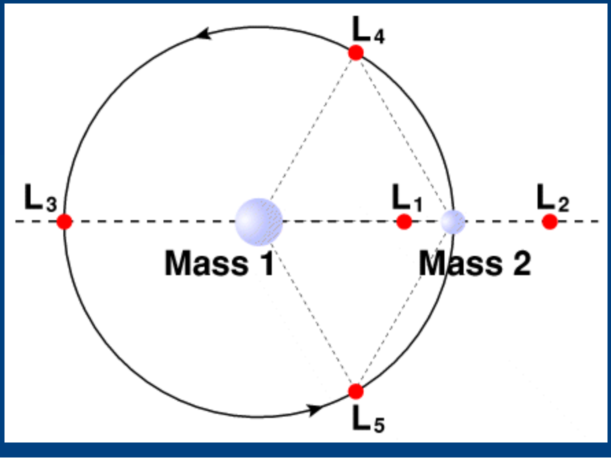
Hildas


Date: 2005/04/27
Venus
Mercury
Earth
Mars
Jupiter
Petr Scheirich, 2005

Trojan asteroids: 2000 or so, located at two Lagrange Points of Jupiter-Sun system. The five Lagrange points in an orbiting two-body system are where objects, pulled by both bodies, can orbit stably with the same period as the two bodies.



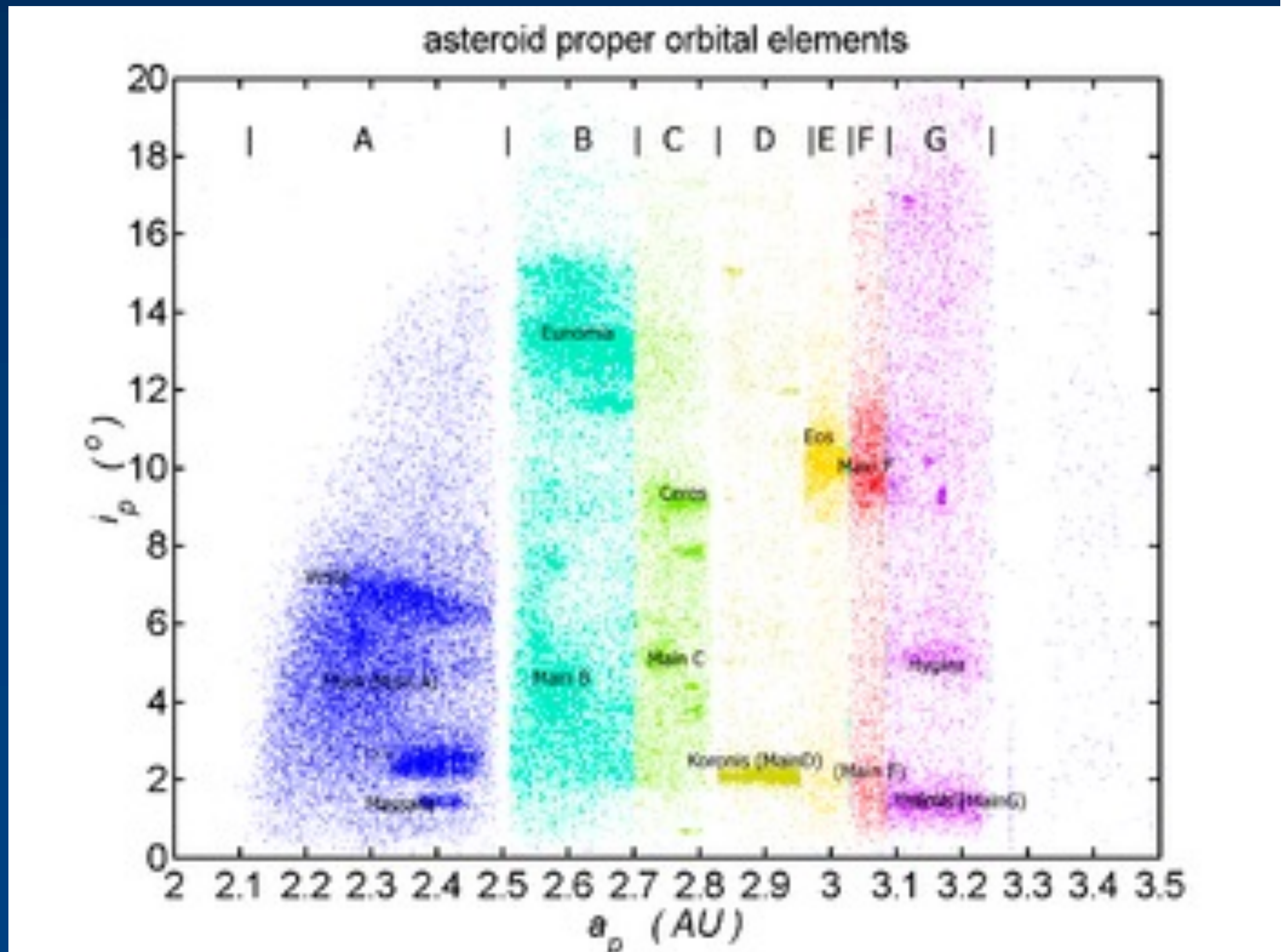
In other words, the Lagrange points mark positions where the combined gravitational pull of the two large masses provides precisely the centripetal force required to rotate with them.



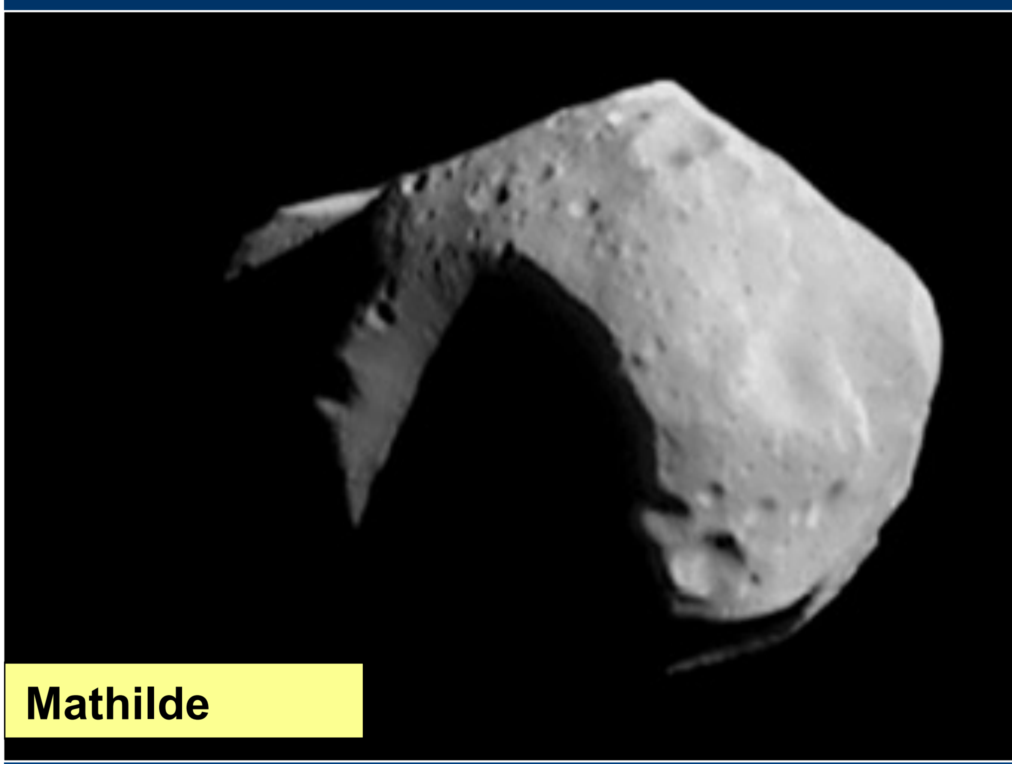
Asteroid Families

- *Hirayama families* - several groups of asteroids have nearly identical orbits. Why?

Result from the breakup of larger asteroids through high speed collisions.



Many asteroids have densities typical of rock (~3 g cm^{-3}). But many others have densities 1-2 g cm^{-3} - cannot be solid rock. Example, Mathilde (density = 1.3 g cm^{-3}). Presumably it is a porous "rubble pile" from a low speed collision. Collisions fragmented it, but gravity of fragments brought them back together. Other collisions may lead to "moons" like Dactyl around Ida.

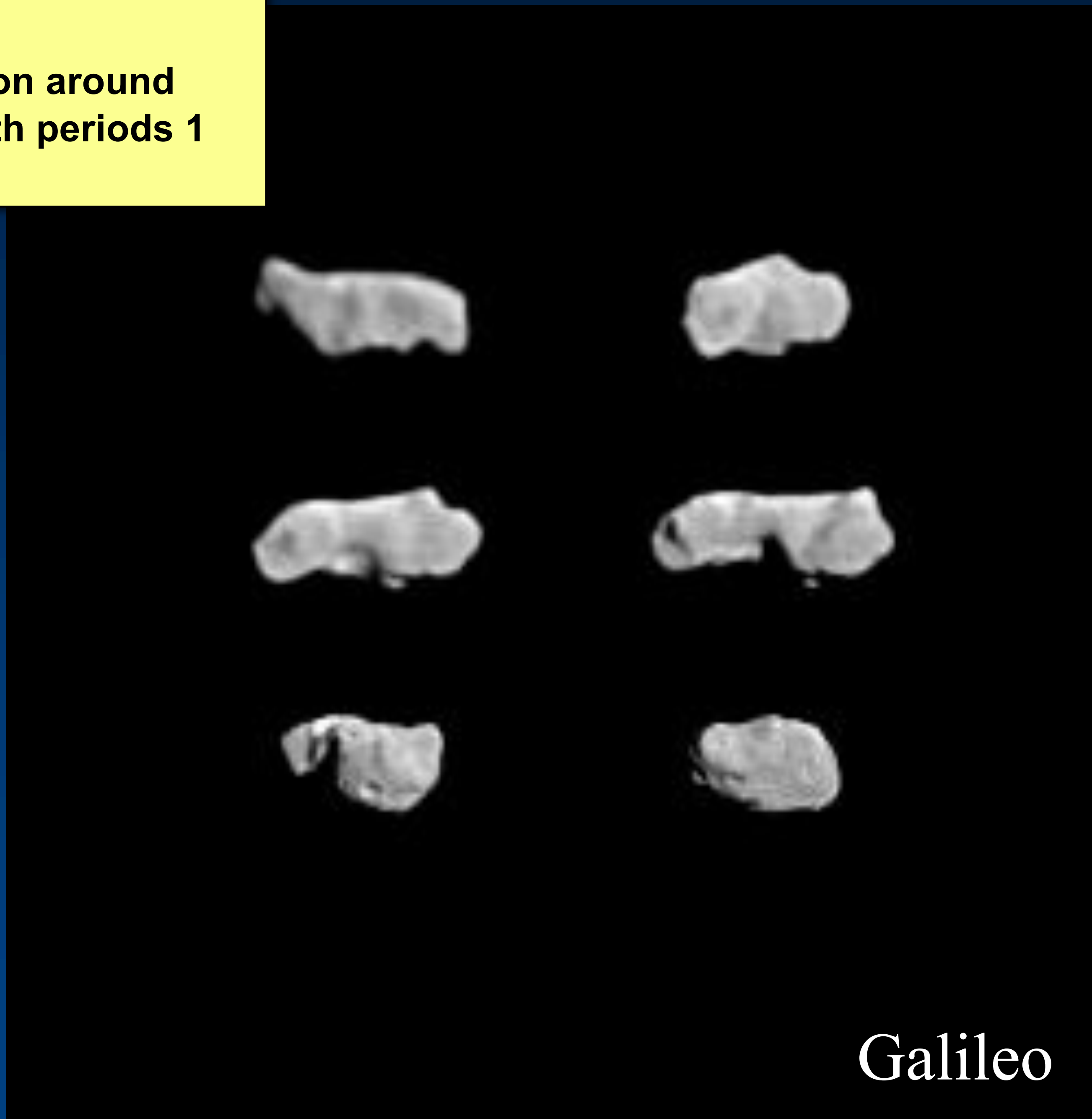


NEAR Shoemaker 1997

Galileo 1993

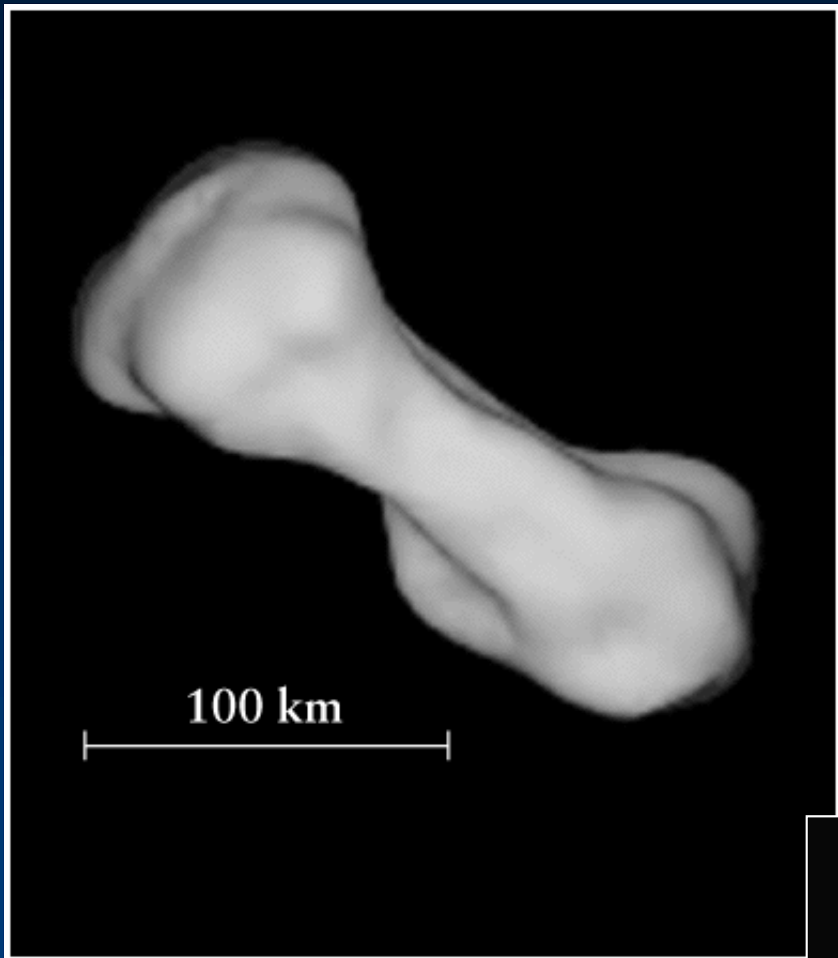
Ida rotating

Typical rotation around fixed axis, with periods 1 hour to 1 day

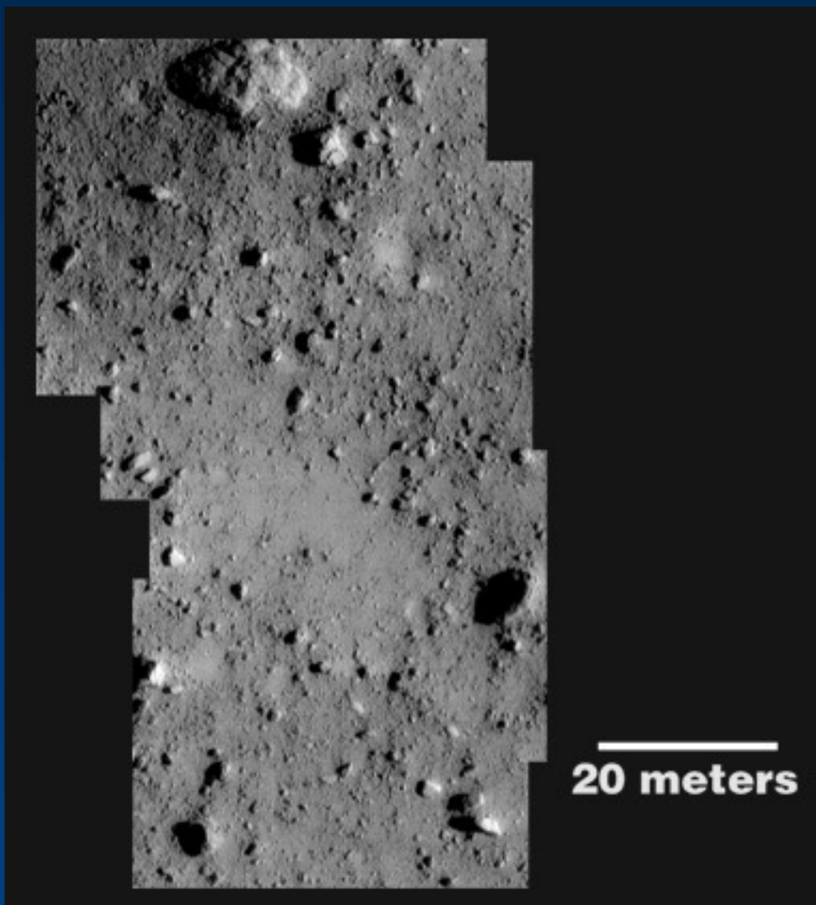


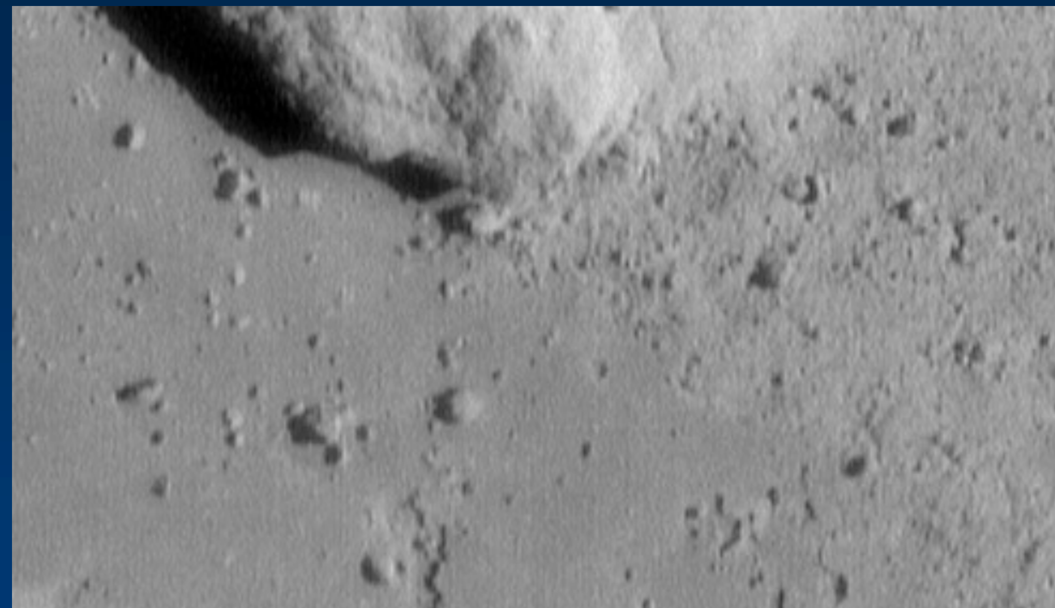
216 Kleopatra – imaged by radar

Result of gentle collision, or merger of two orbiting asteroids?



NEAR Shoemaker landed on 433 Eros in 2001.





6 m

Hayabusa mission to collect sample from asteroid Itokawa. Launched May 2003, sample returned June 2010.

Dust from Itokawa was found to be identical to material that makes up meteorites. Itokawa is an S-type asteroid whose composition matches that of an low-iron, low-metal chondrite.

Ryugu sample return on Dec 6, 2020

Spacecraft Dawn launched in 2007, to orbit Vesta (2011-2012), Ceres (2015)

Asteroids and the Earth

- Asteroids whose orbits cross the orbits of Earth and other inner planets: NEOs
- About 2500 "near-Earth asteroids" known – but collisions with Earth are rare.
- Small bits do fall to Earth as meteors or meteorites. Meteors come in two kinds – sporadic and shower. The sporadic meteors are mostly asteroid pieces. Showers are mostly related to comets (except Geminids).

Terminology

- Meteoroid – small piece of debris in the Solar System.
- Meteor – visible streak in sky caused by meteoroid burning up in atmosphere.
- Meteorite – meteoroid that survives to hit surface of Earth.

Read in text, and visit Meteorite Museum

Types of meteorites

- 85% stony silicate rocks, some from undifferentiated asteroids
- 5% Carbonaceous chondrites: possibly pre-solar
- 4% stony iron
- 6% iron, no rock, evidence for differentiation

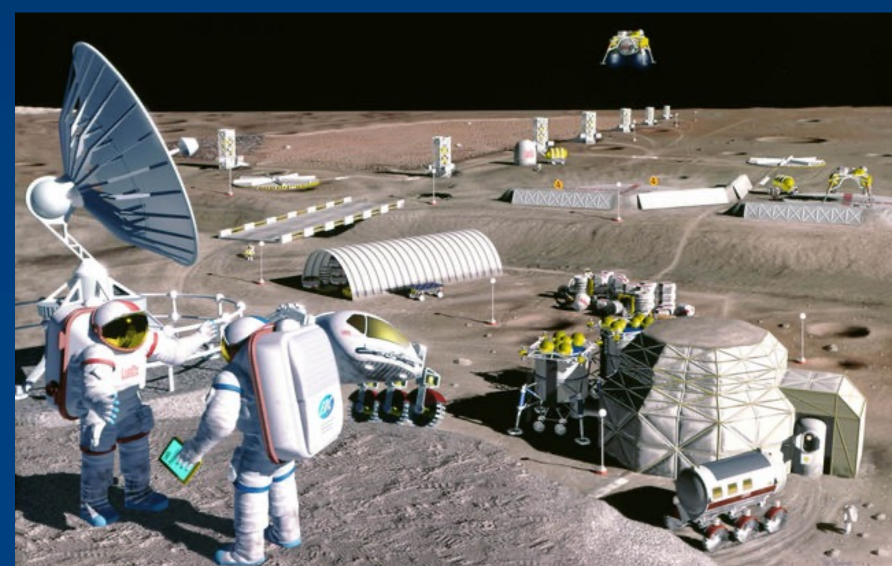
Widmanstätten patterns are evidence of very slow cooling, differentiation – large objects that later fragmented.

Go check out UNM's excellent meteorite collection at the Institute for Meteoritics – Northrop Hall

Asteroid Mining

- Planetary Resources Inc. (founded April 2012)
  - By group of tech billionaires (Page, Schmidt, etc.)
  - Fuel depot expected by 2020
  - Mining of water, platinum & gold
  - Ran out of funds in 2018, bought by ConsenSys
  - Others: Karman, TransAstra, AstroForge, Asteroid Mining Company
- A small asteroid (1 km across) could supply many years worth of metals world-wide
- Advanced technologies
  - Factories in space?
  - Self-replicating robots?

Who Owns the Asteroids?



Comet Hale-Bopp
(1997)

Comets

Historically, these were regarded as very bad omens.

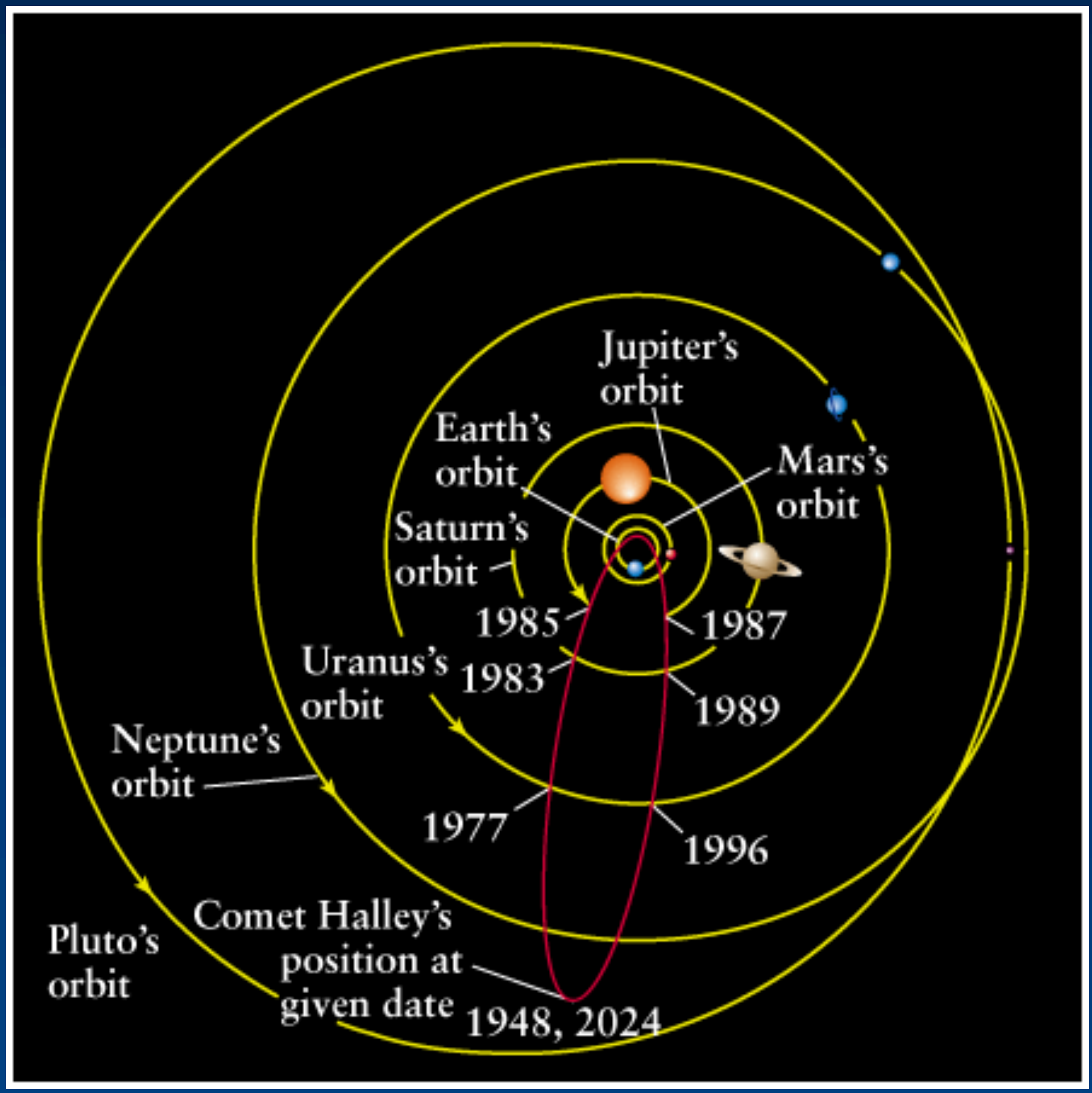
Discovery of a Comet at Greenwich Observatory

Great Comet of 1843

- Aristotle thought comets were atmospheric phenomena:
  - Unusual clouds in the Earth's atmosphere.
  - Could not be part of the perfect & unchanging heavenly realm.

- Renaissance astronomers began more systematic studies:
  - Observed that tails always point away from the Sun, suggesting cosmic phenomena.
  - Tycho Brahe measured the parallax of the great comet of 1577 & showed it orbited the Sun.

Comet orbits are very different from asteroids or planets - highly elliptical orbits, some with random orientations, and not necessarily in ecliptic.



Two types of comets

- Long-period comets (P>200 years)
  - Very elliptical orbits, random inclinations to ecliptic, equally likely to be prograde or retrograde
  - Many have periods of millions of years. Then orbit sizes are $>10^4$ AU.
  - Over 3000 known
- Short-period comets (P<200 years)
  - Elliptical orbits close to ecliptic, most have inclinations $< 30°$, mostly prograde
  - Almost 500 known
  - From periods, orbit sizes are about that of Kuiper Belt.

Origin of comets

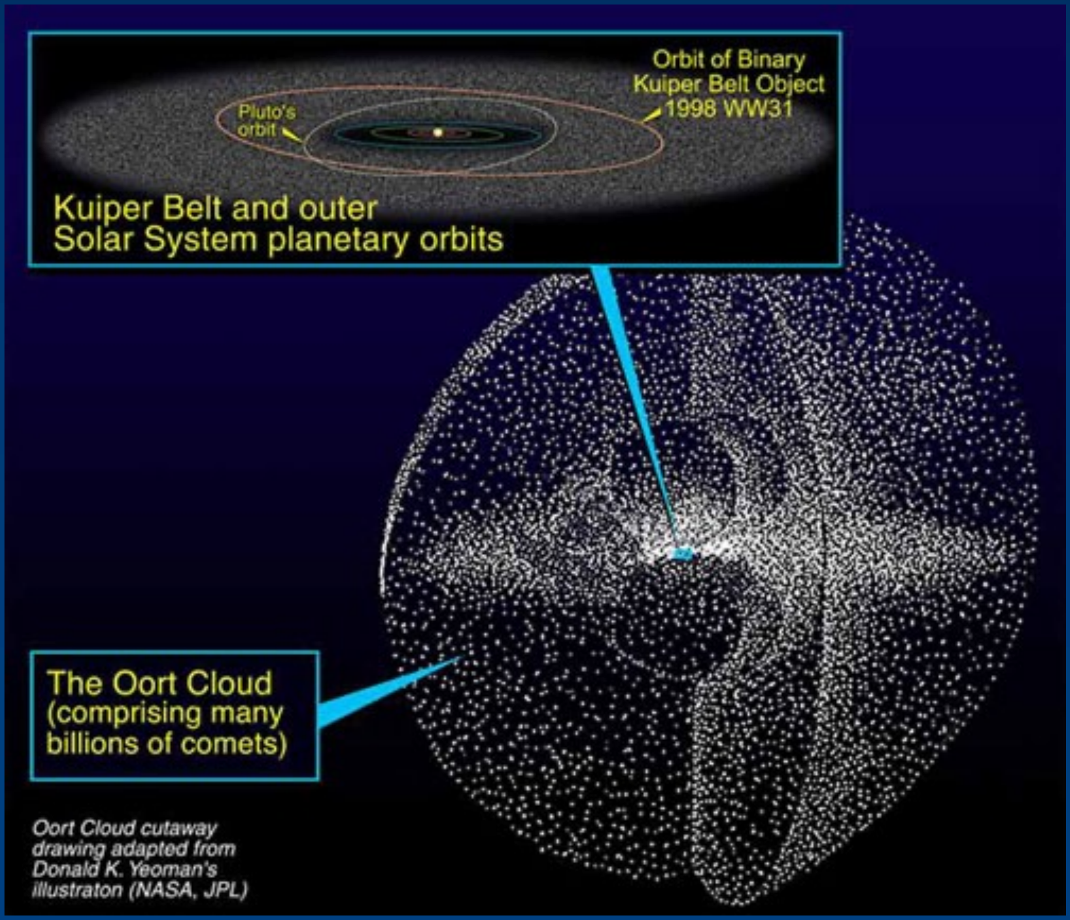
- Short period: from the Kuiper Belt (30-50AU)
  – Gravitationally deflected into inner parts of Solar System by close encounters with Neptune

- Long-period: from the hypothesized "Oort cloud"…

The Oort cloud

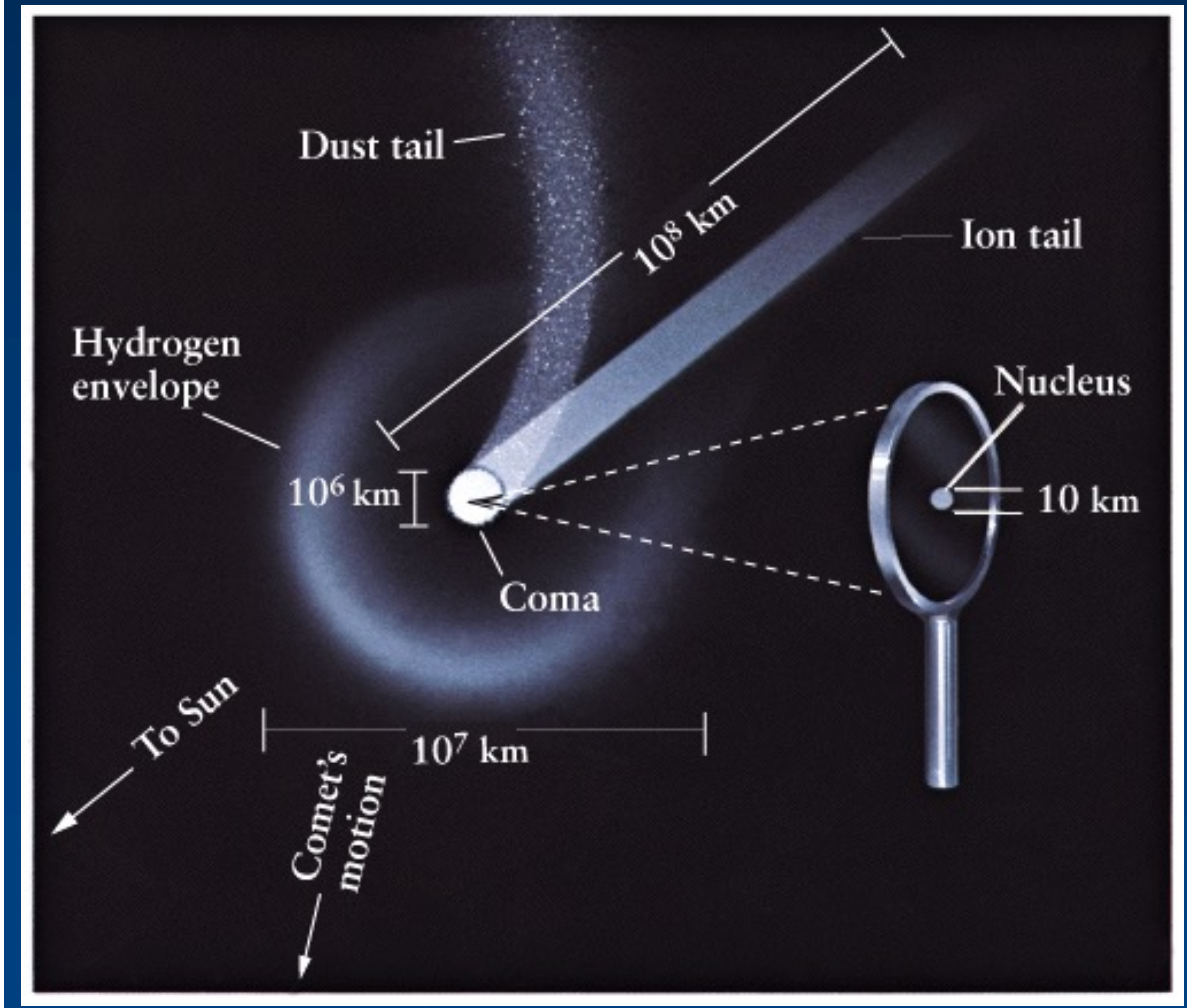
- Hypothesized spherical cloud surrounding the planetary system up to 50,000 AU across
- The edge of the Sun's gravitational influence

- Trillions of icy objects - relics of primordial solar nebula
- Occasional disturbances by passing stars, even interstellar gas clouds, launch objects towards inner Solar System



Comet Structure

Comet composition is different from asteroids. Much icier. Where do you think they formed, near or far from Sun?



Nucleus: "dirty snowball" of ices and small rocky particles. 99% of the mass. But hard to see.

Parts visible to eye or telescope:

coma - low density gas/dust cloud

H envelope (only seen in UV)

dust tail - whitish

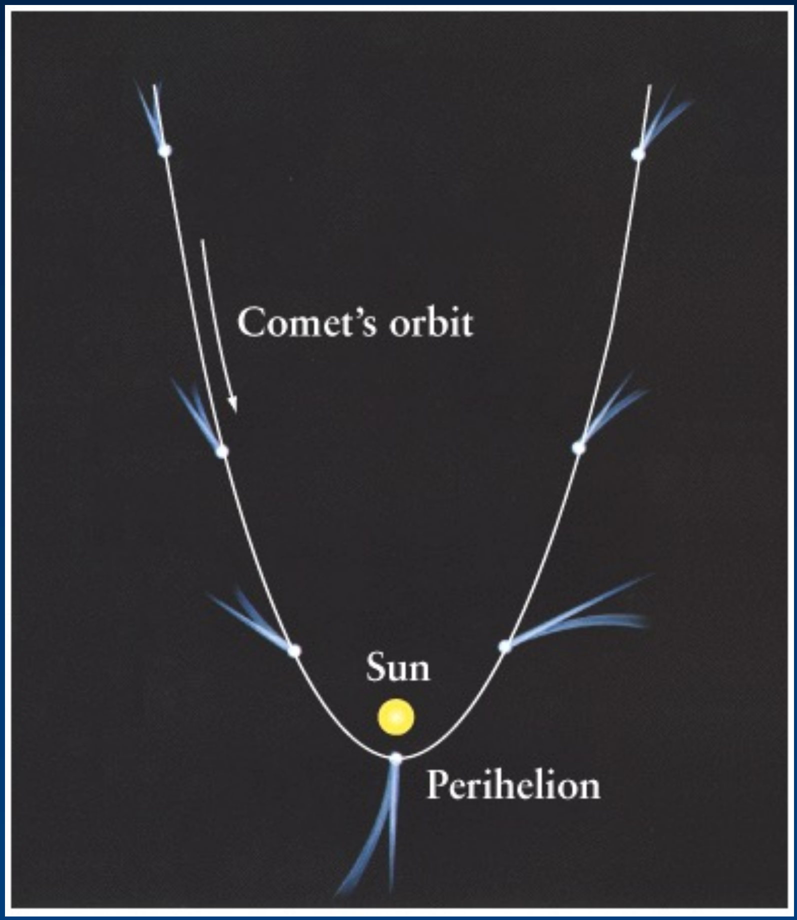
ion tail - bluish (emission from C-bearing molecules).

Coma and tails only seen when comet within about 1 AU of Sun. Most of orbit, comet is just nucleus.

Tails are produced when ices sublimate.

Gas or ion tails point directly away from sun, blown back by solar wind (this is how solar wind was initially inferred!)

Dust tails curve as the liberated particles begin their own individual orbits.



Tails can be 10^8 km long.

Comet West with gas and dust tails

Comet Hyakutake

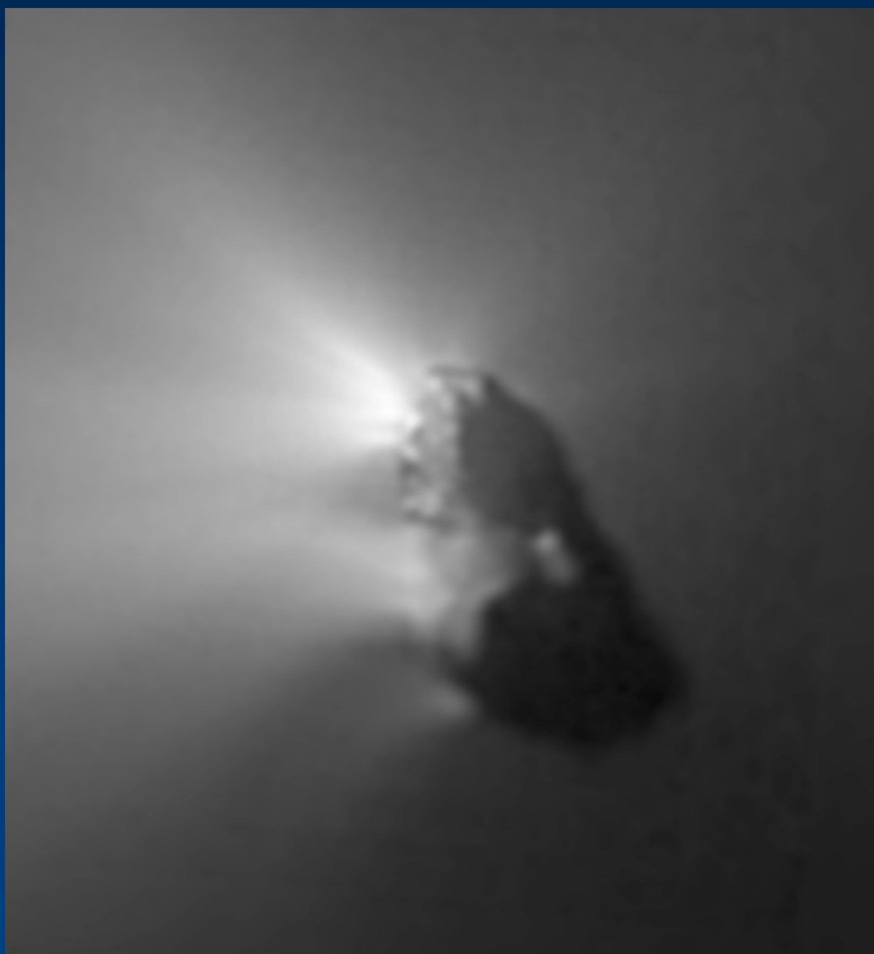
- In 1705, Edmund Halley computed orbit of the comet of 1682 using Newton's laws

- Orbit of the 1682 comet same as that for comets seen in 1531 & 1607.

- => predicted it would return in 1758.

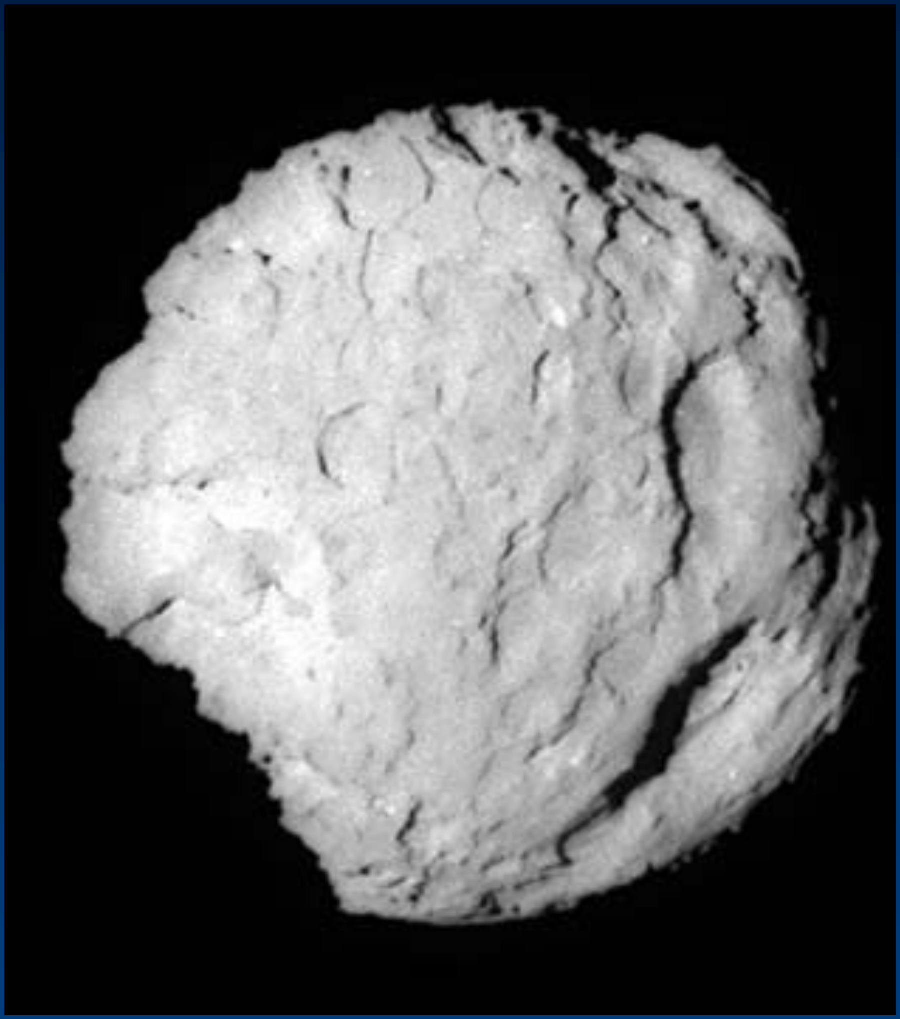
- Seen on 12/5 1758, 12 years after Halley's death.
- Orbital properties:
  - Elliptical orbit, e=0.967
  - Semimajor axis, a=17.94 AU, with aphelion at 35 AU, and perihelion at 0.6 AU.
  - Period is 74-79 years.

Dirty snowball model of nucleus verified by spacecraft visits. Typical size ~ 10 km.

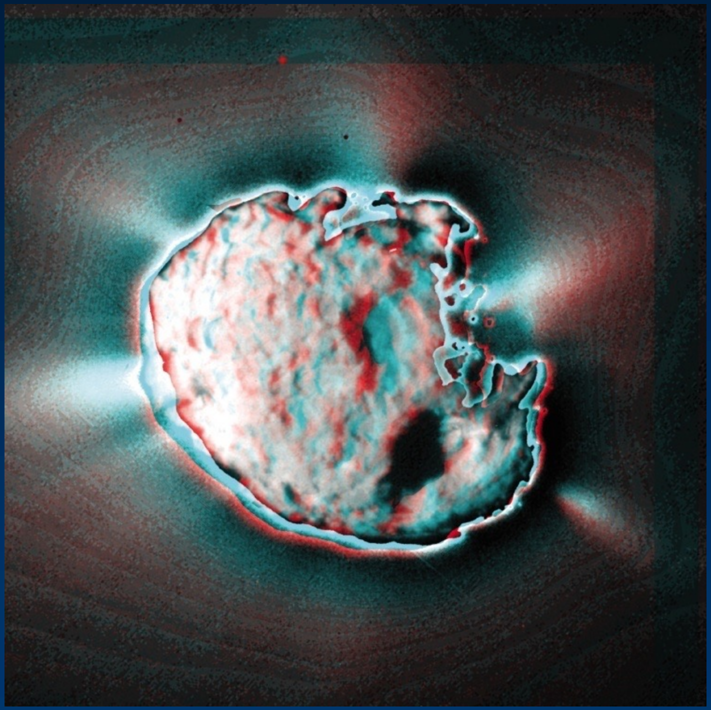


Halley

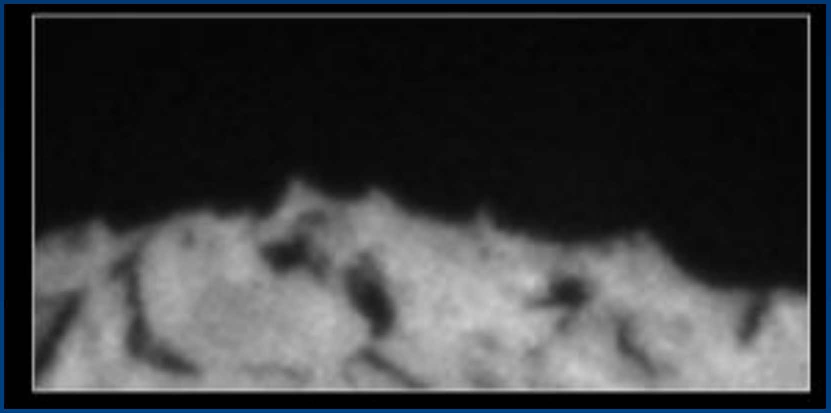
Tempel 1
(Deep Impact mission)



Wild 2
(Stardust mission)



Jets due to sublimating ices



Pinnacles 100’s of m tall.
Cliffs also seen

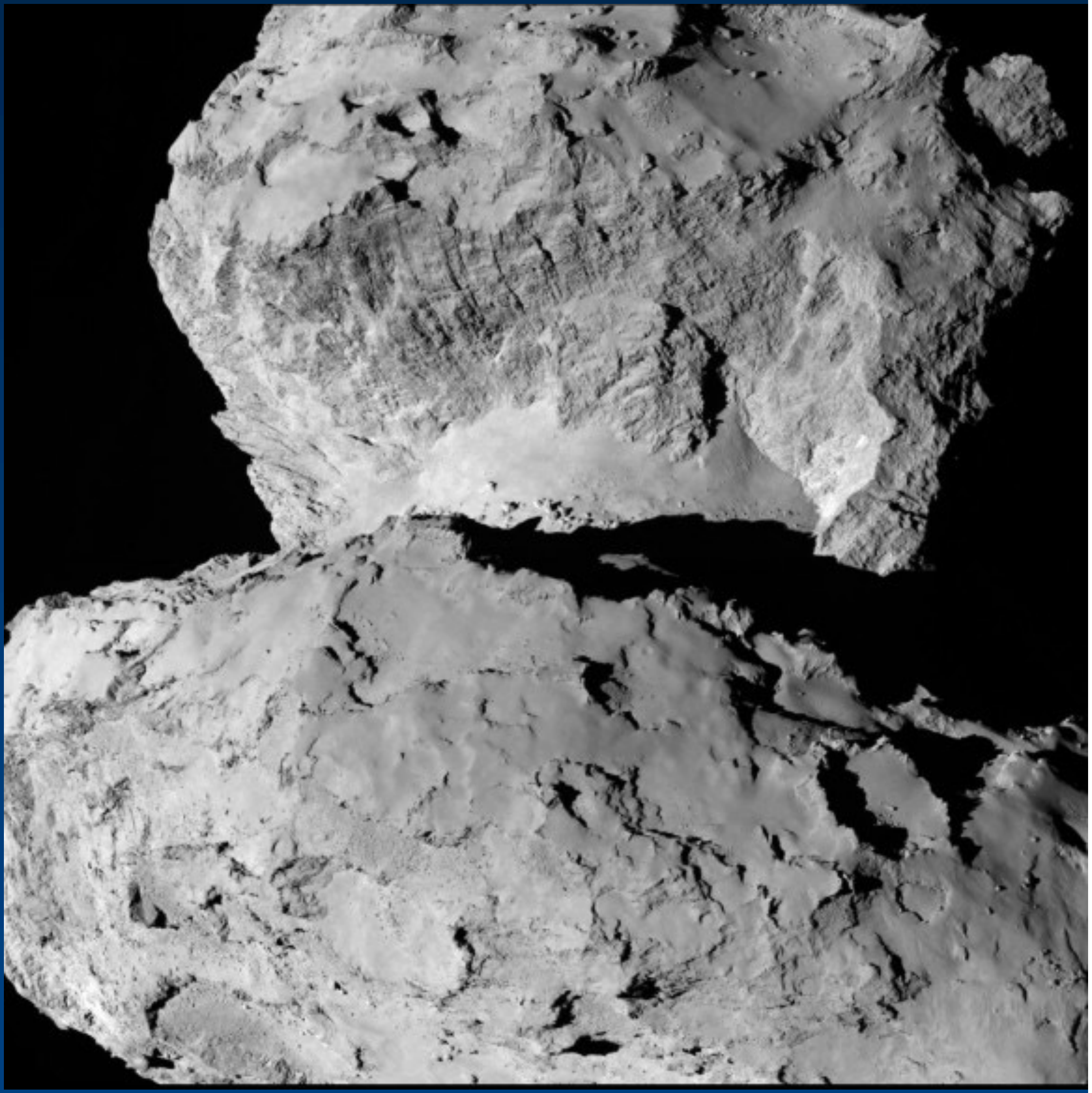
Comet nuclei are loosely packed due to outgassing of ices as a result of solar heating. Eventually should break apart into many pieces.

Comet LINEAR

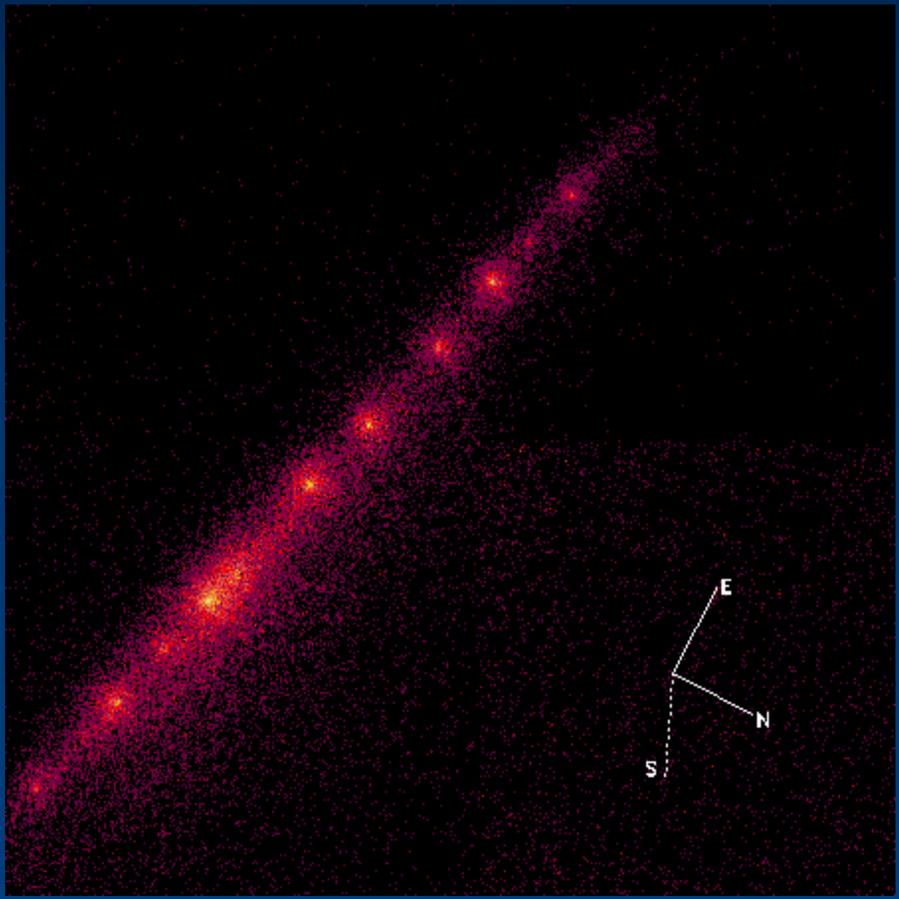
Thus lifetime of comets coming close to Sun is limited. For example, Halley loses 10 tons/sec when near Sun. Will be destroyed in 40,000 years.

Rosetta Mission (ESA)

- Launched March 2004
- Rendezvous with 67P/Churyumov-Gerasimenko
- First "soft landing" on a comet
- Study the effect of solar warming on comet

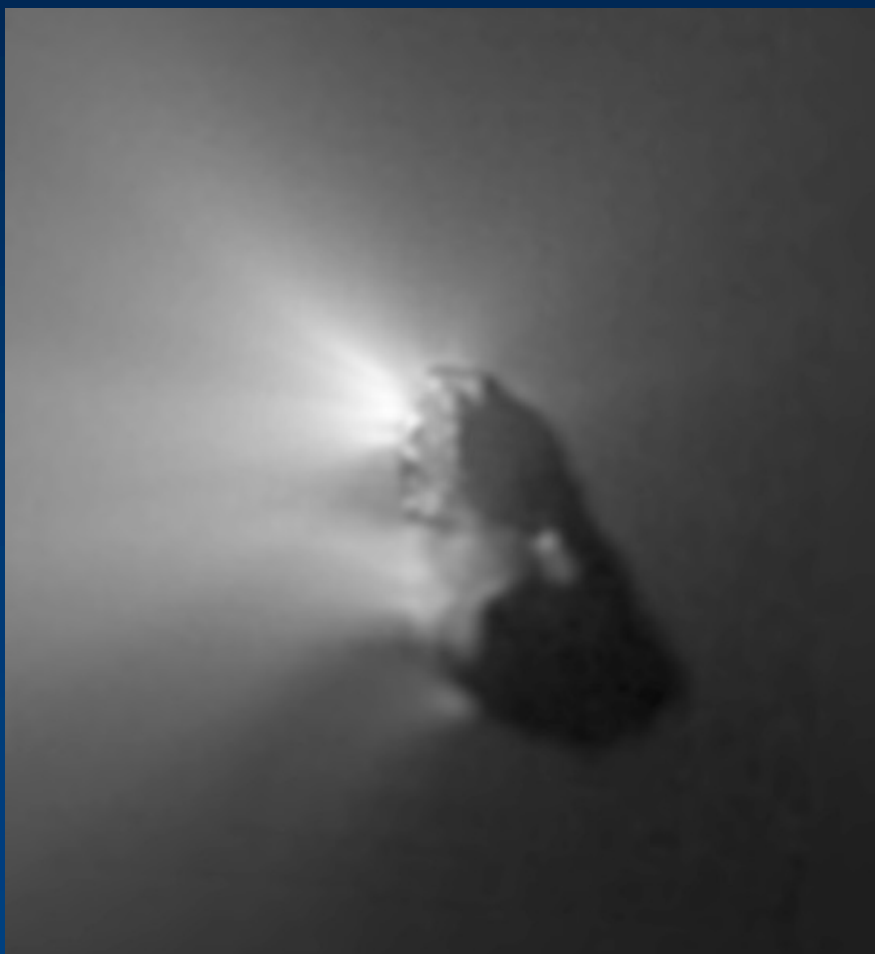


Comet Shoemaker-Levy 9 nucleus was broken apart by Jupiter's tidal force before plunging into planet



Comet Shoemaker –Levy 9

Dirty snowball model of nucleus verified by spacecraft visits. Typical size ~ 10 km.

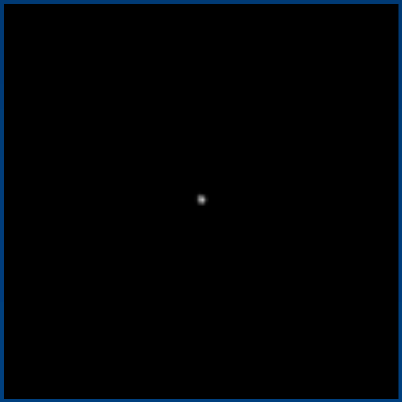


Halley

Tempel 1
(Deep Impact mission)

“Deep Impact” July 2005 – “fluffy structure” revealed by measuring expansion of ejecta. Found water ice, organic molecules, studied make-up of dusty matter.

Tempel 1: 370kg impact probe, image spectra probed from Earth and Spacecraft



Stardust mission collected sample from comet Wild 2 in January 2004, landed 15 January 2006.

Was brought to Johnson Space Flight Center for study.

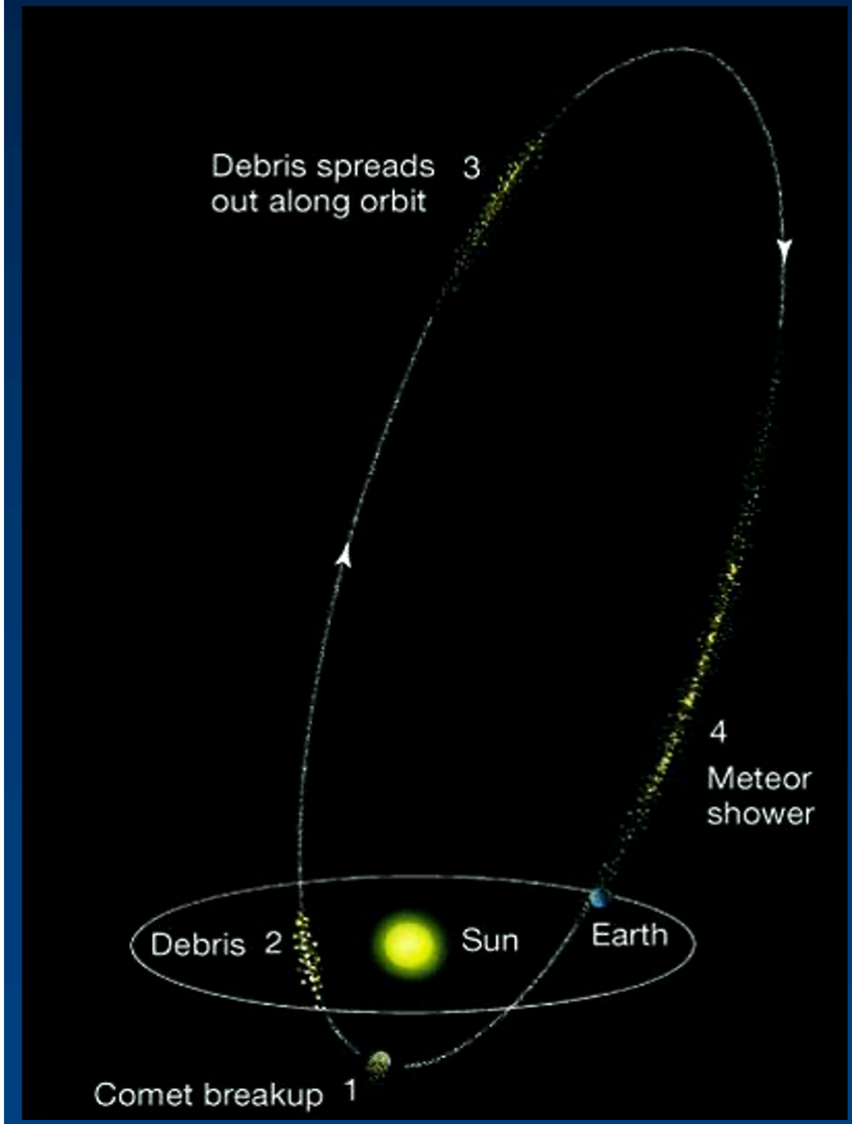
Main results:

High-temperature minerals that should form close to Sun are abundant in the tail. Somehow these were pushed to outer solar nebula.

Amino acid glycine found. Building blocks of proteins. How much in amino acids did comets deliver to Earth?

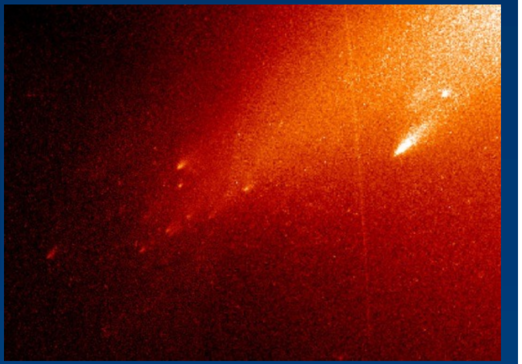
Stardust mission used an aerogel material to collect cometary material and interstellar dust.

Meteor Showers



Shredded nucleus debris eventually spreads out along orbit.

Fragmentation of Comet LINEAR



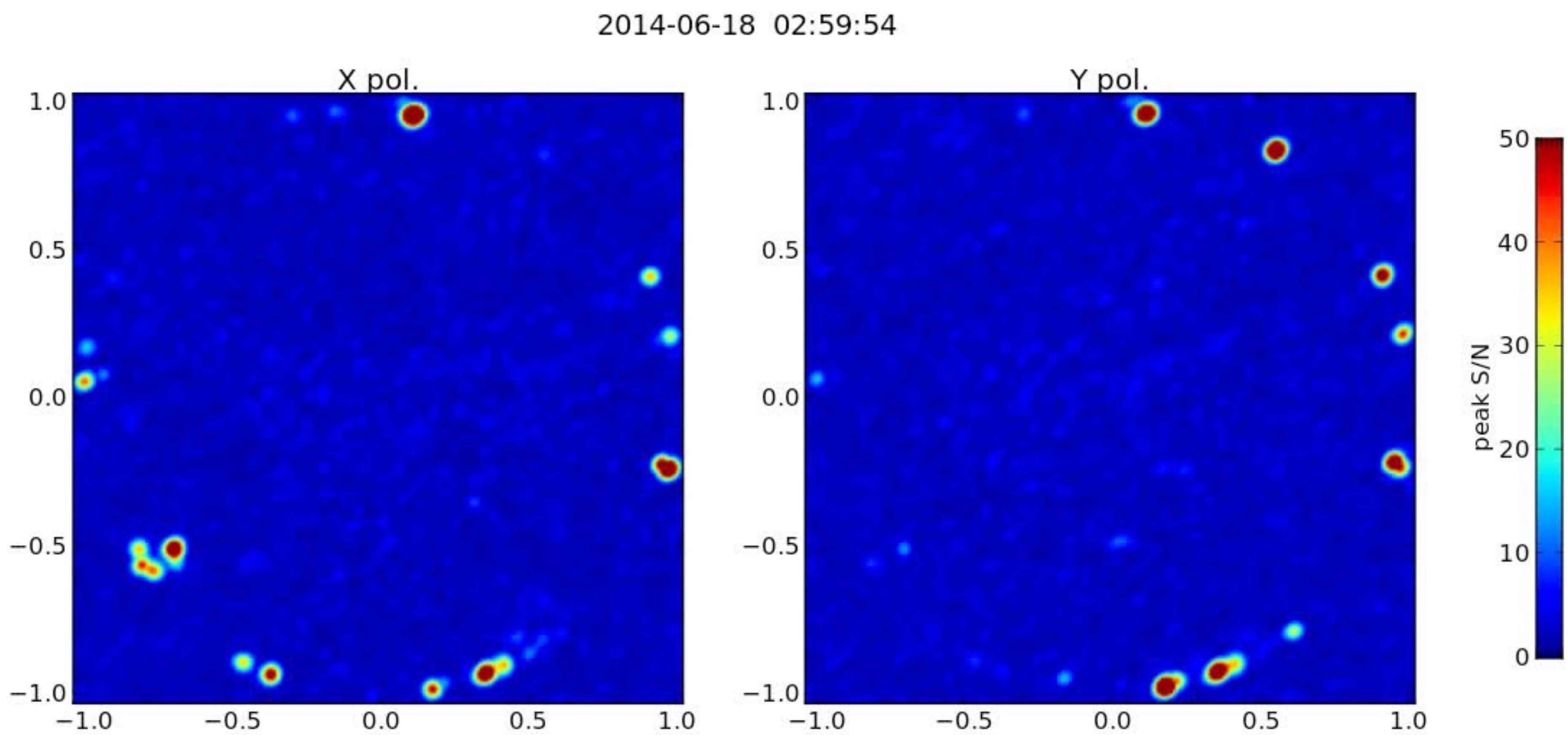
IF Earth's orbit crosses comet orbit, get annual meteor shower, as fragments burn up in atmosphere.

Table 17-1 Prominent Yearly Meteor Showers

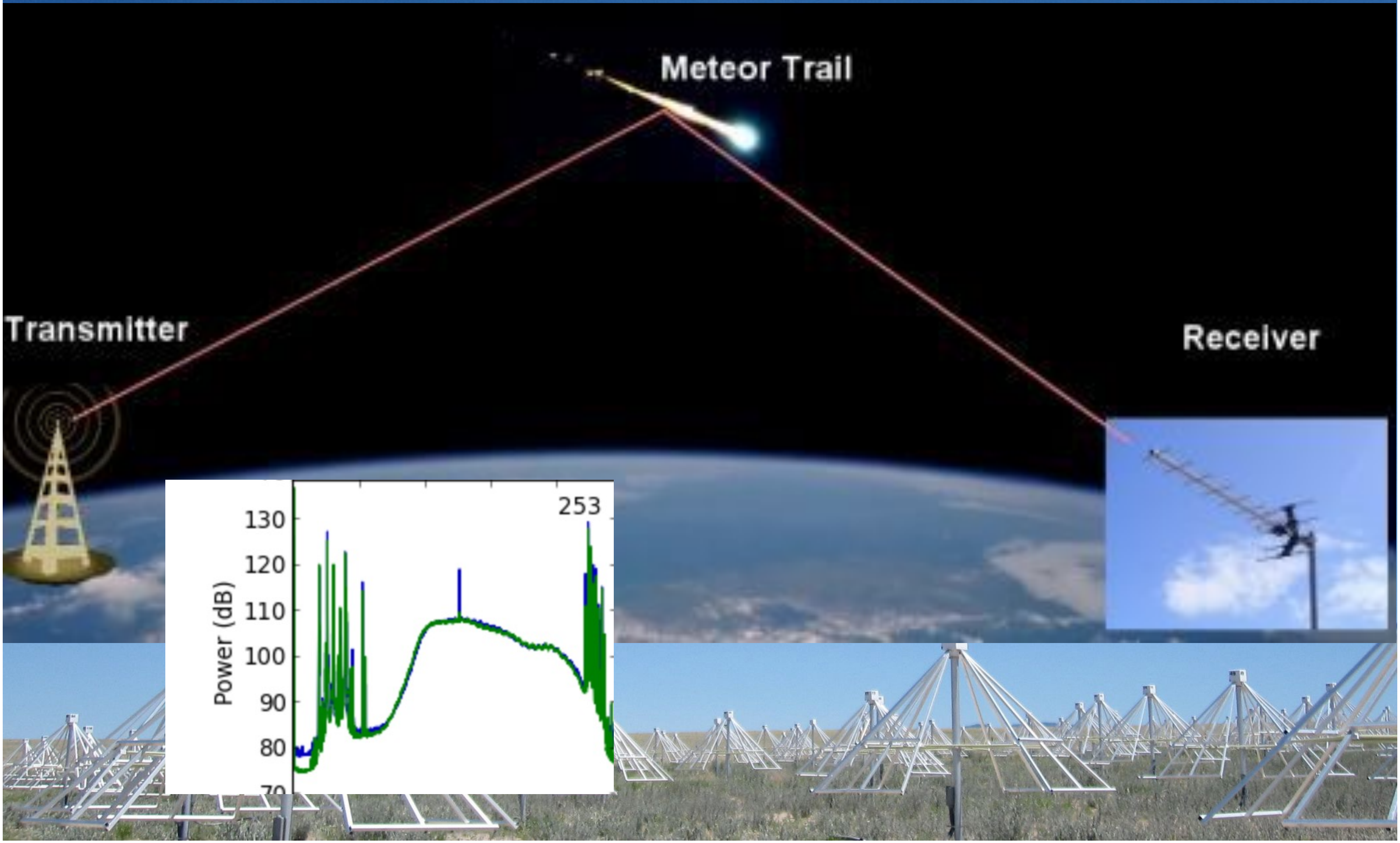
Shower	Date of maximum intensity	Typical hourly rate	Average speed (km/s)	Radiant constellation
Quadrantids	January 3	40	40	Boötes
Lyrids	April 22	15	50	Lyra
Eta Aquarids	May 4	20	64	Aquarius
Delta Aquarids	July 30	20	40	Aquarius
Perseids	August 12	50	60	Perseus
Orionids	October 21	20	66	Orion
Taurids	November 4	15	30	Taurus
Leonids	November 16	15	70	Leo
Geminids	December 13	50	35	Gemini
Ursids	December 22	15	35	Ursa Minor

The date of maximum intensity is the best time to observe a particular shower, although good displays can often be seen a day or two before or after the maximum. The typical hourly rate is given for an observer under optimum viewing conditions. The average speed refers to how fast the meteoroids are moving when they strike the atmosphere.

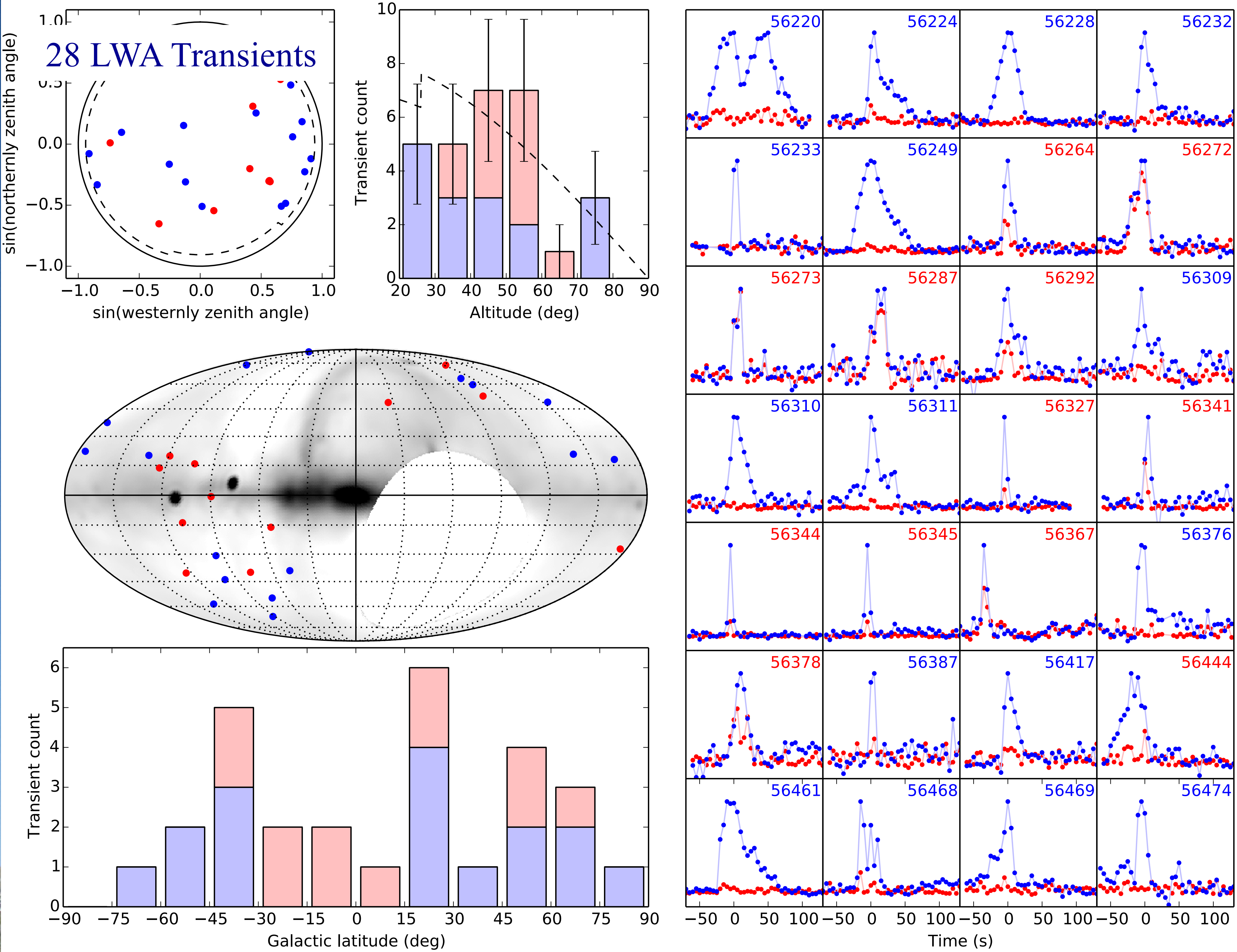
Meteors – by reflection



Meteors – by reflection

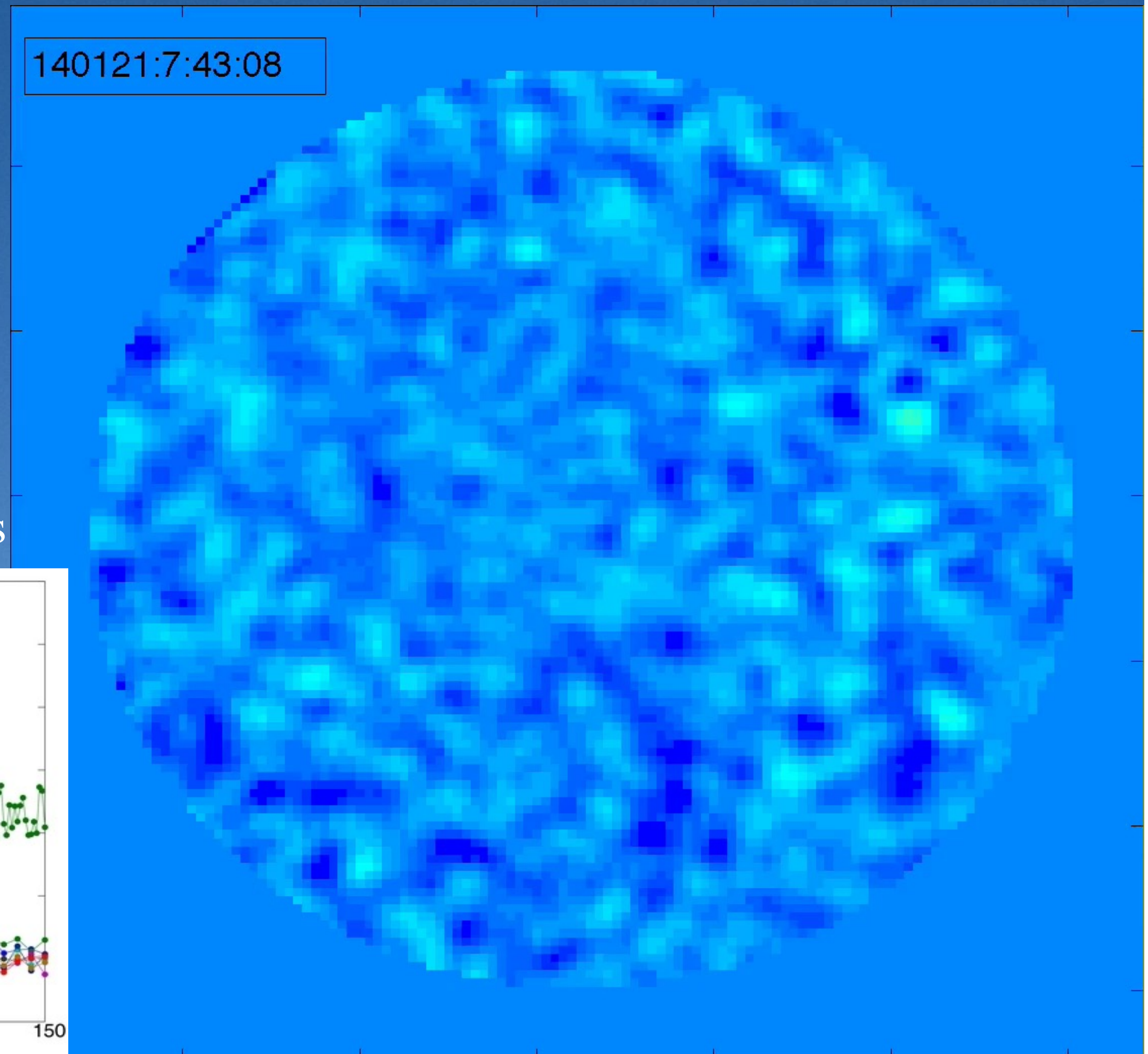


28 LWA Transients

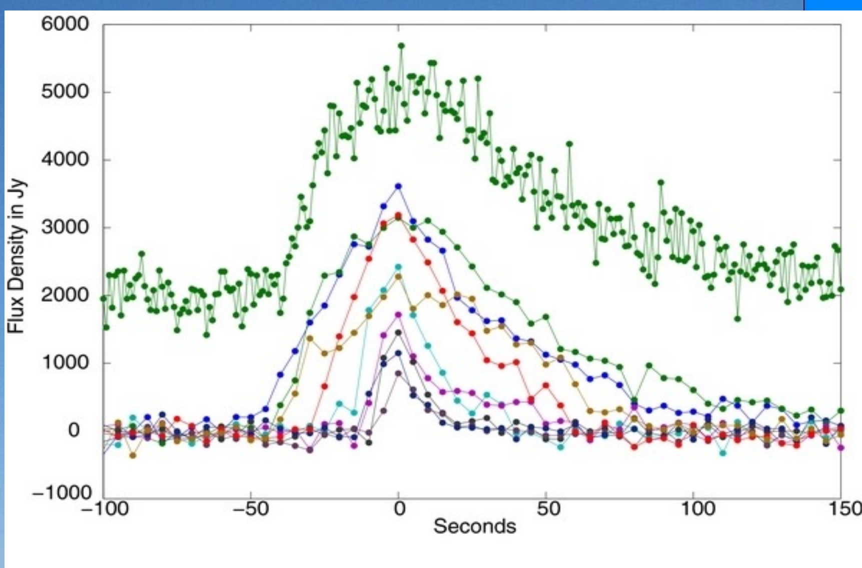


Great Balls of Fire!

Obenberger et al. 2014



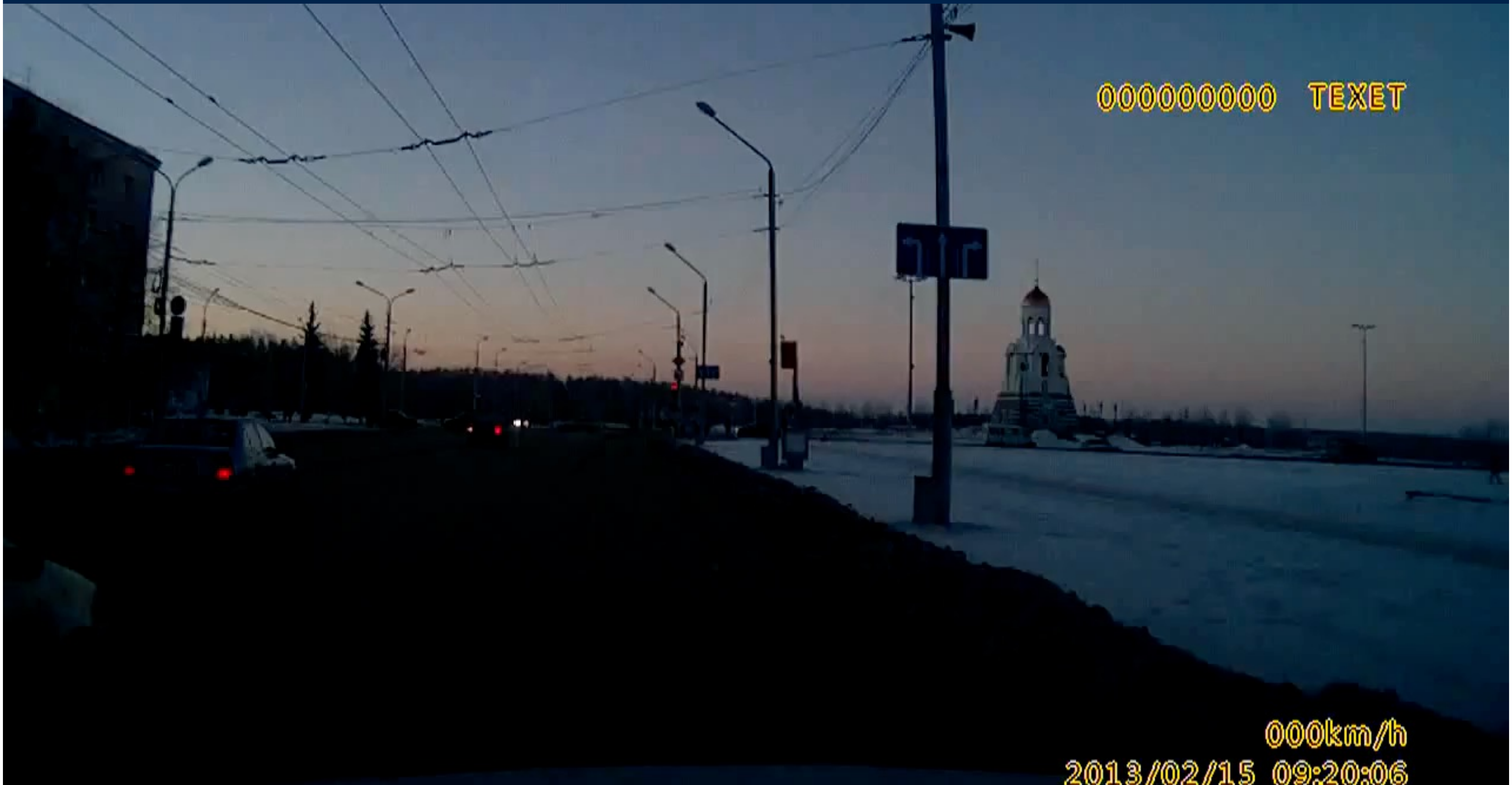
Light curves of the brightest transients



Big Fireballs do a lot of damage if they hit the Earth!

Meteor Crater in Arizona – impact about 50,000 years ago. Meteorite was about 50 m across, hit at 40,000 km/hr.

Chelyabinsk Meteor



Chelyabinsk Meteor

K-T event?

- Createaceous-Tertiary event 65Myrs ago in Yucatan impact of 11km/s of 10 km diameter asteroid
- Threw matter into the atmosphere, caused 2000ft waves
- Months of darkness interfering with photosynthesis, cooler temps globally – “nuclear winter” mass extinction