



Radar Observations of Solar System Objects

Science at (Sometimes) Negative Redshift



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Arecibo Observatory

with lots of help from the radar community

8th NAIC/NRAO Single Dish Summer School
July 8, 2015 @ Green Bank, WV

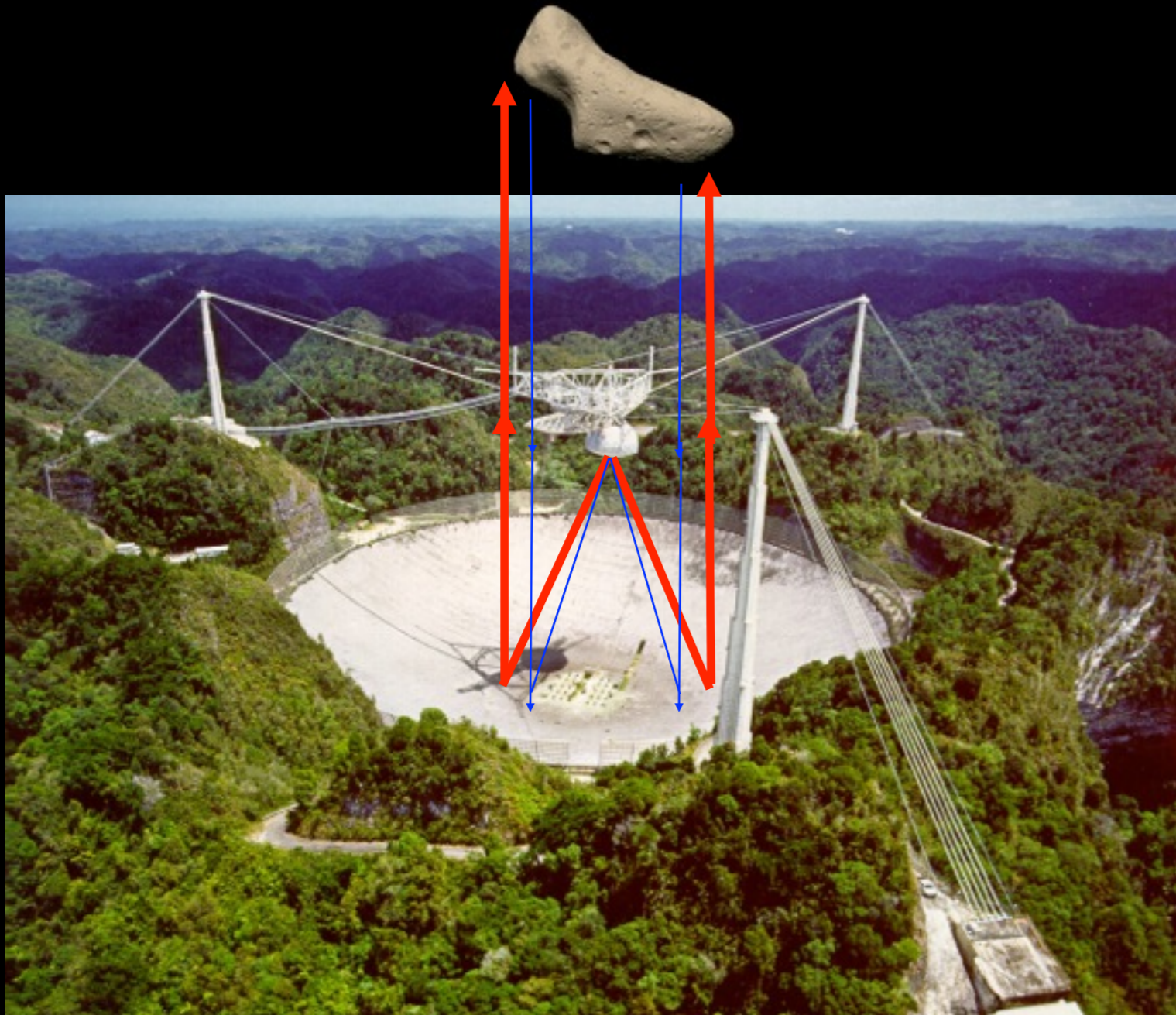


Right: Arecibo
305m diameter
1 MW transmitter
12.6 cm, 2380 MHz
Fixed dish



Left: Goldstone (DSS-13)
70m diameter
500 kW transmitter
3.5 cm, 8560 MHz
Steerable dish

Radar Basics



Create an observing ephemeris that predicts Doppler shift and range to the target.

Generate 2 MW of power with diesel generators.

Output coherent radiation from klystrons with ~50% efficiency.

Transmit a polarized signal at a known frequency for a certain time interval. Signal bounces off of the target and returns to the telescope. The receiver is moved into the focus and detects the weak echo in two polarizations.

What is Transmitted?

We control the signal!

- Continuous Wave: transmit a monochromatic tone (no frequency, amplitude, or phase modulation)
- Delay-Doppler Ranging/Imaging:
 - Transmit a signal that is phase modulated by a pseudo-random code
 - The frequency of the phase modulation translates to resolution in range, *e.g.*, 20 MHz modulation gives 0.05 us delay resolution or 7.5 range resolution

What is Received?

Any Changes are Due to the Object!

- Received signal is **very weak**: $\sim 10^{-27}$ of transmitted signal returns to the receiver!
- Signal is mixed, filtered, attenuated, amplified, etc. and the voltage is recorded as a function of time
- Continuous Wave: Fourier transform the voltage to get the component frequencies
- Delay-Doppler Imaging: Cross-correlate the voltage with the transmitted code to get delay/range information, then Fourier transform to get frequency information

Signal-to-Noise Considerations

$$\text{Signal} \propto \frac{P_{\text{tx}} A_{\text{eff,tx}} A_{\text{eff,rx}} D^2}{RTT^4}$$

Want high power, large effective area (gain);
a big and close target is best

$$\text{Noise} \propto \frac{T_{\text{sys}} B}{\sqrt{B t_{\text{int}}}}$$

Narrow bandwidths improve SNR

$$B \propto \frac{D}{P} \cos \delta$$

Bandwidth indicates rotation rate
AND/OR viewing geometry

What Do We Measure?

D = Distance (time delay)

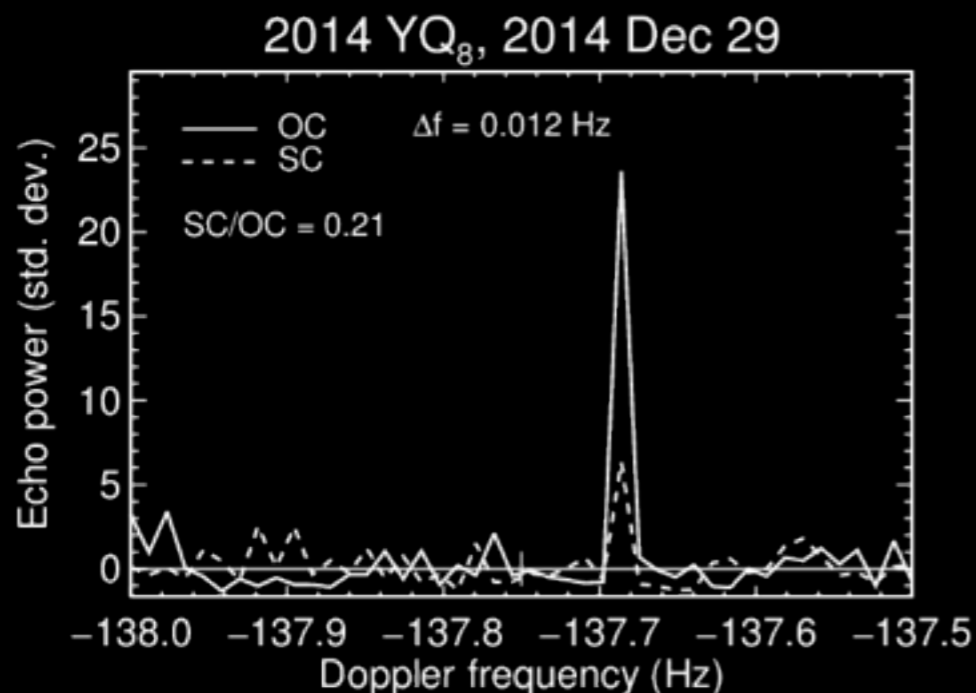
V = Velocity (Doppler shift)

- | | |
|-------------------------|-------------------|
| – Orbital D, V | Orbit improvement |
| – Object D depth | Size and shape |
| – Object V dispersion | Spin and shape |
| – Scattering properties | Surface roughness |

Observe the Moon, Mercury, Venus, Mars, the Galilean satellites, Saturn's rings, near-Earth asteroids, main-belt asteroids, and comets

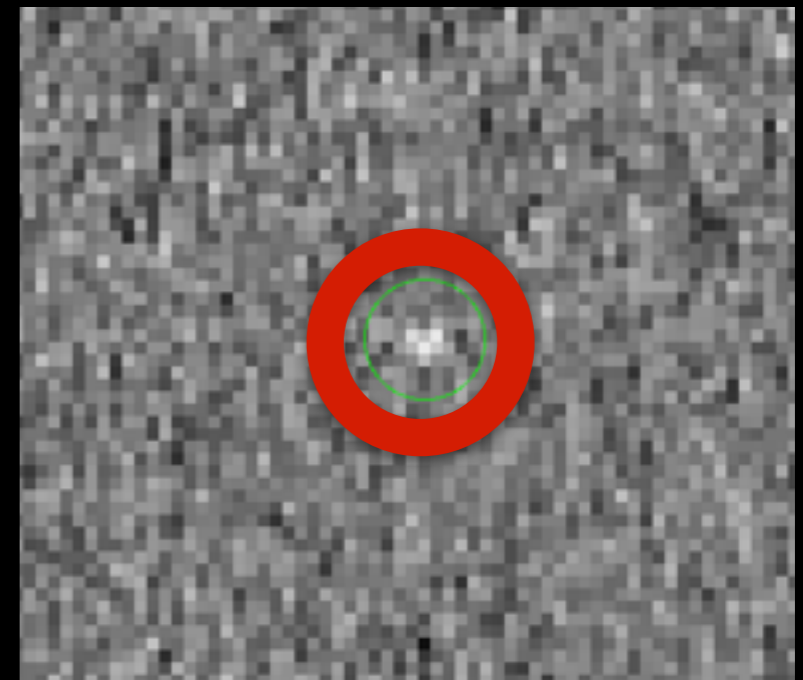
Orbit Improvement (Astrometry)

- Radar detects rather than discovers
- High-precision determination of distance to the target and line-of-sight velocity
- Orthogonal to plane-of-sky optical observations
- Reduce pre-radar orbit uncertainties by **five orders of magnitude** for newly discovered objects
- Extend Earth encounter predictions by factor of five
- Invaluable for impact hazard assessment!



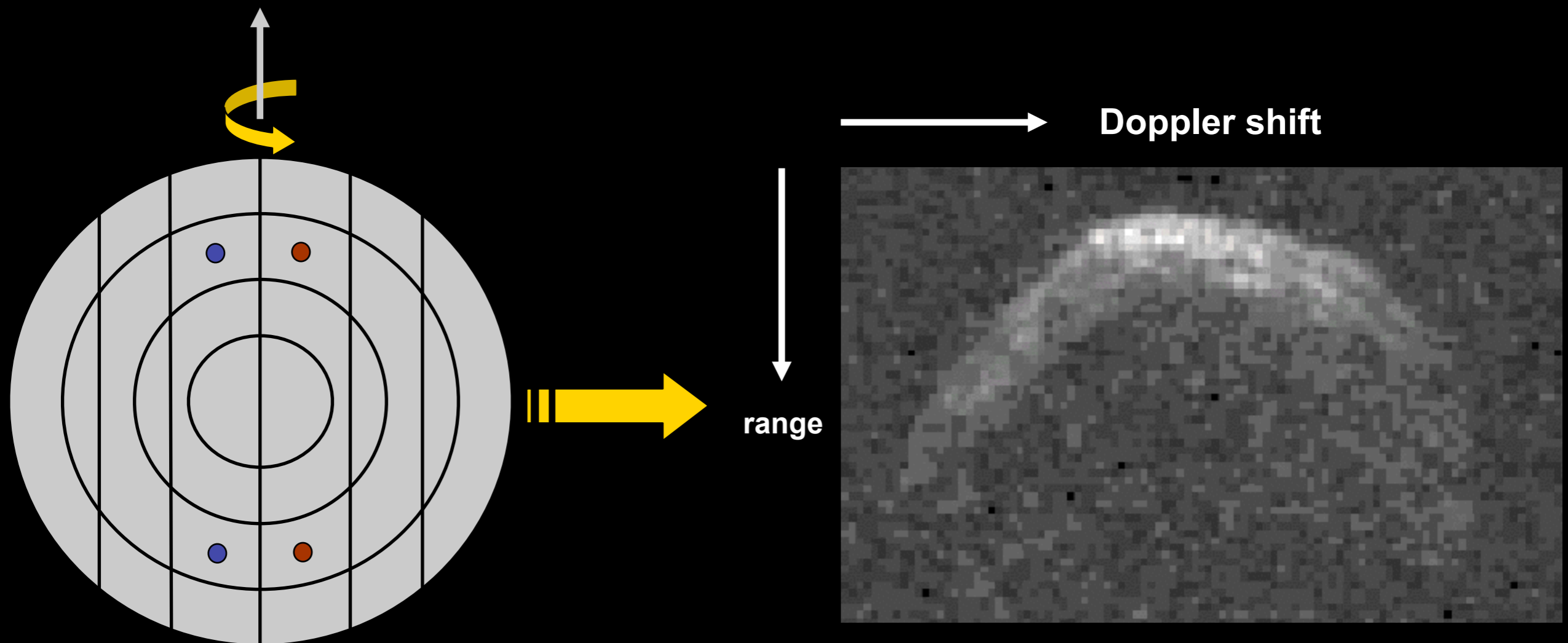
Left: 2014 YQ8

Right: Bennu



Delay-Doppler Radar Images

- Map a 3D object to a 2D image
Circles: Represent lines of constant range
Lines: Represent lines of constant Doppler shift

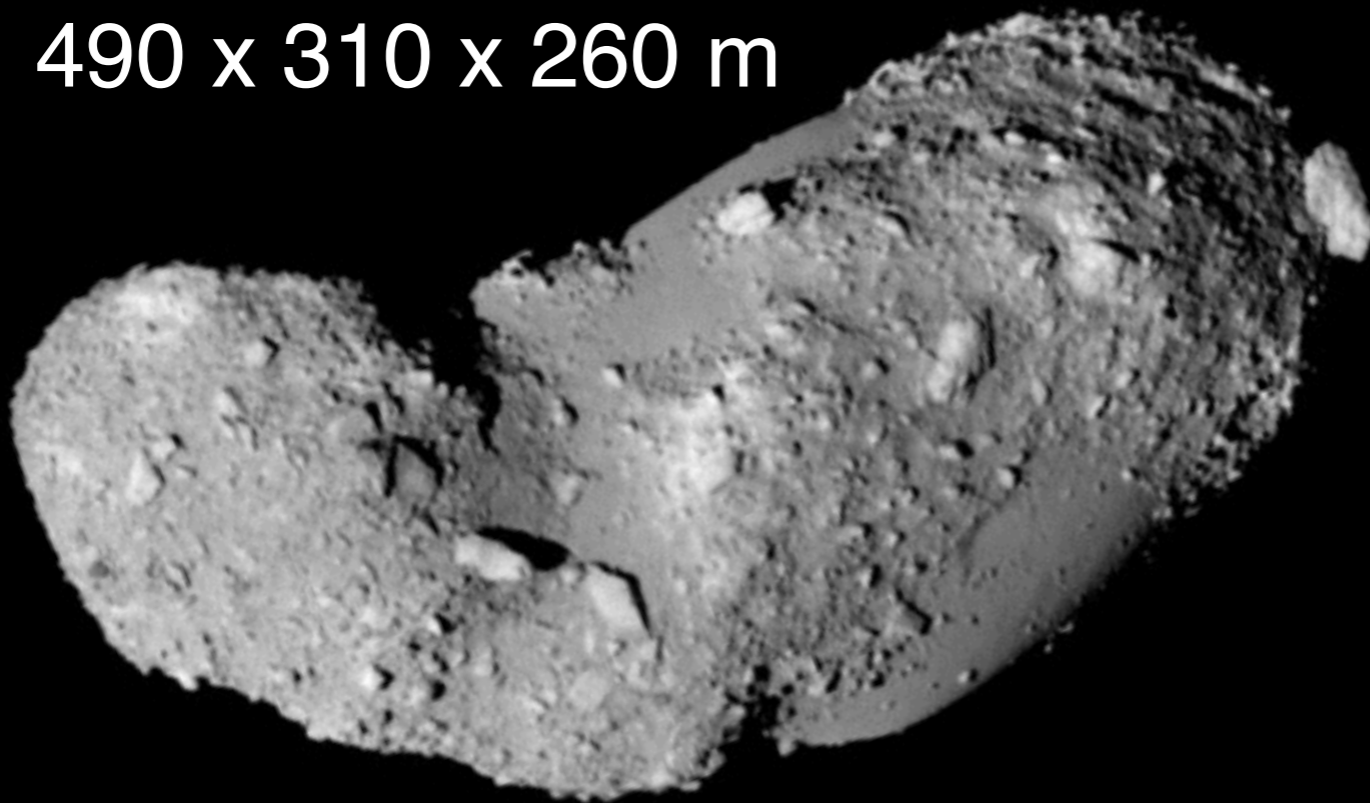


Blue dots map to same point in delay-Doppler image (N-S ambiguity)

Comparison to Spacecraft

(25143) Itokawa: Hayabusa vs. radar

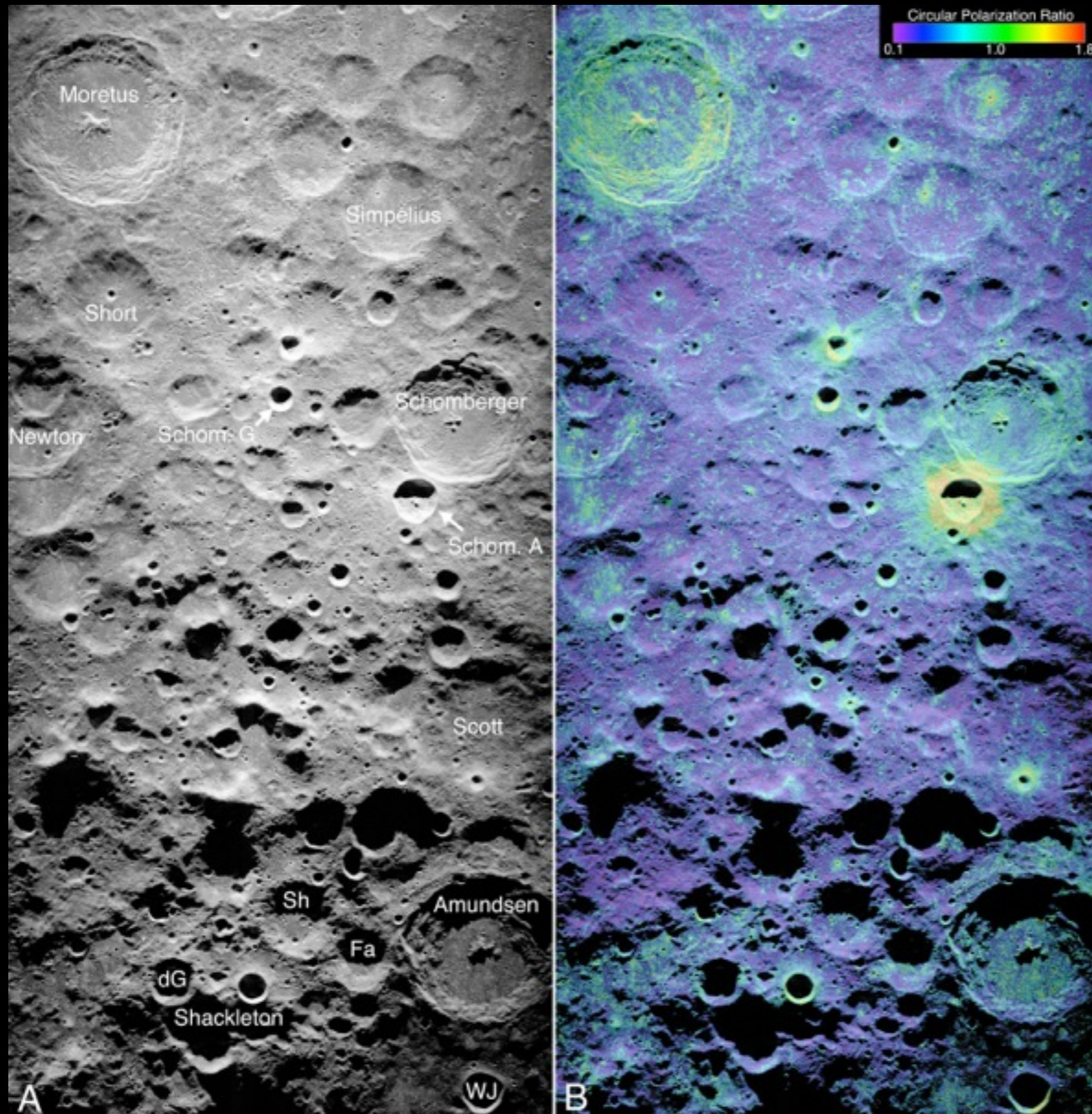
490 x 310 x 260 m



Radar is a relatively inexpensive method of studying the **population** of near-Earth asteroids, capable of reaching fine resolutions only surpassed by costly, object-specific spacecraft missions.

For Visualizations of asteroid 25143 Itokawa, Radar-Derived Shape Models, and Their Corresponding Synthetic Radar Spectra and Radar Images, see Dr. James E. Richardson's (Arecibo Observatory) YouTube Channel at:
<https://www.youtube.com/user/jerichardsonjr>

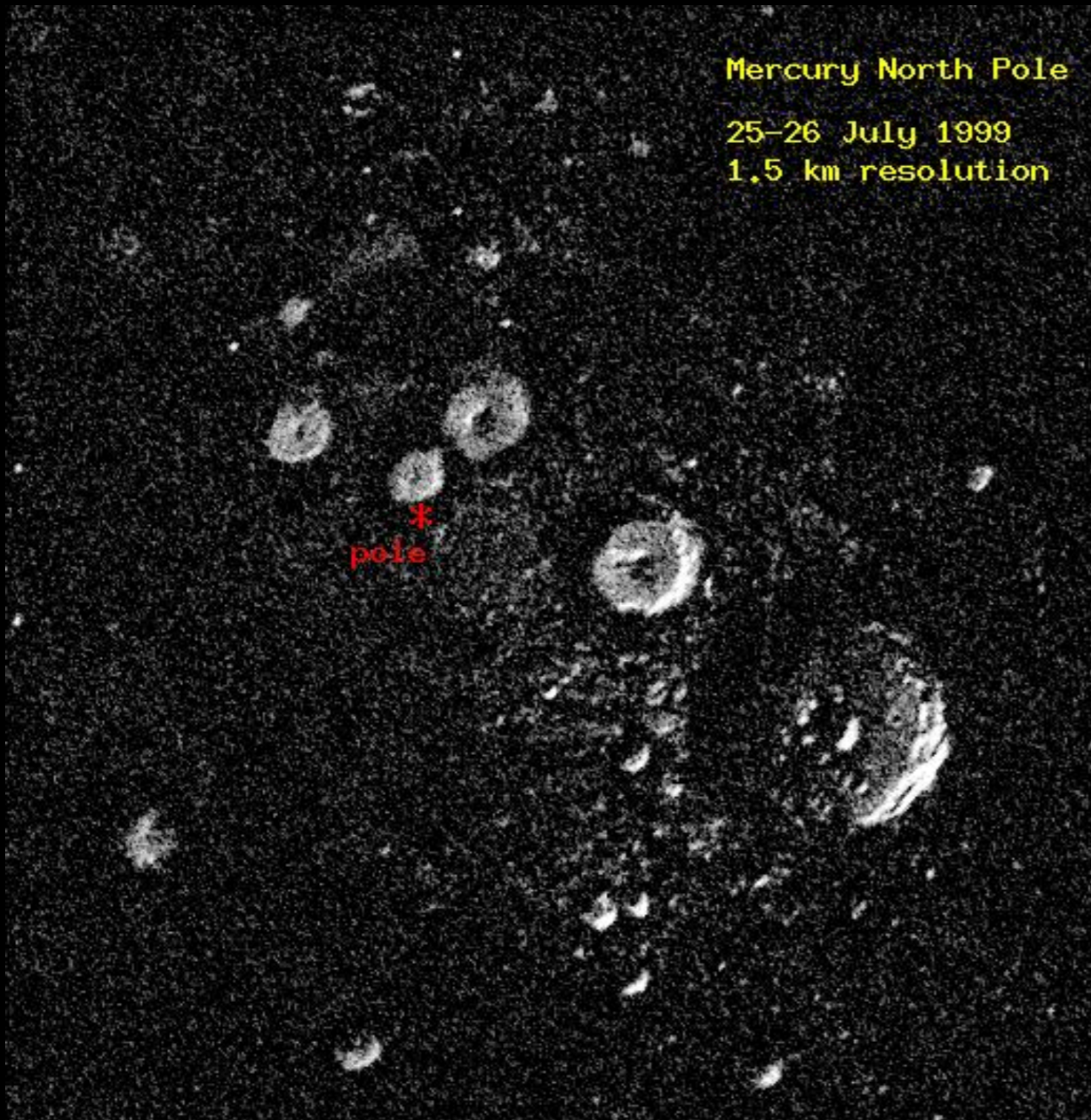
Moon



- Delay-Doppler image mapped to latitude-longitude
- 20-m resolution
- Exceeded only by recent spacecraft
- No obvious evidence for ice at the south pole
- High polarization ratio apparently due to roughness

Mercury

Mercury North Pole
25–26 July 1999
1.5 km resolution



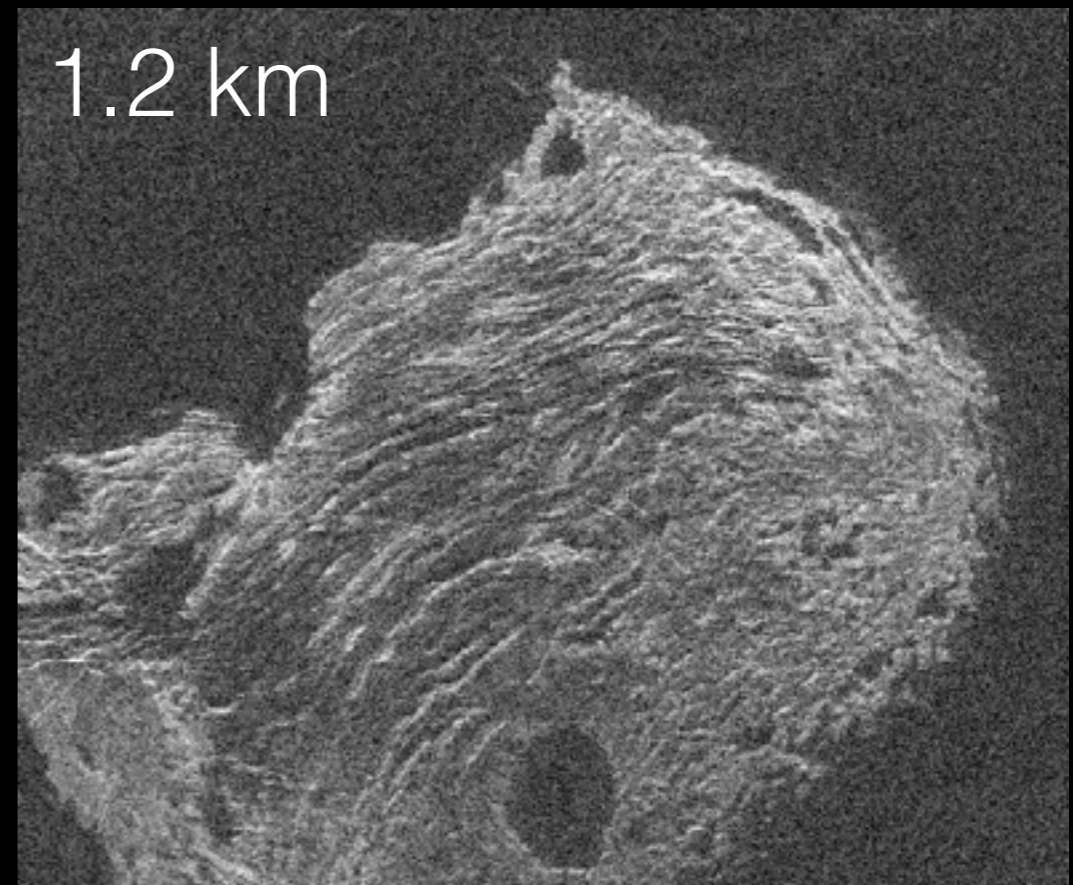
- Determination of Mercury's rotation rate and the 3:2 spin:orbit resonance (1965)
- Determination that Mercury is in a Cassini state with a partially molten core (2007)
- Detection of radar-bright material in permanently shadowed craters, presumably ice, confirmed by MESSENGER

Venus

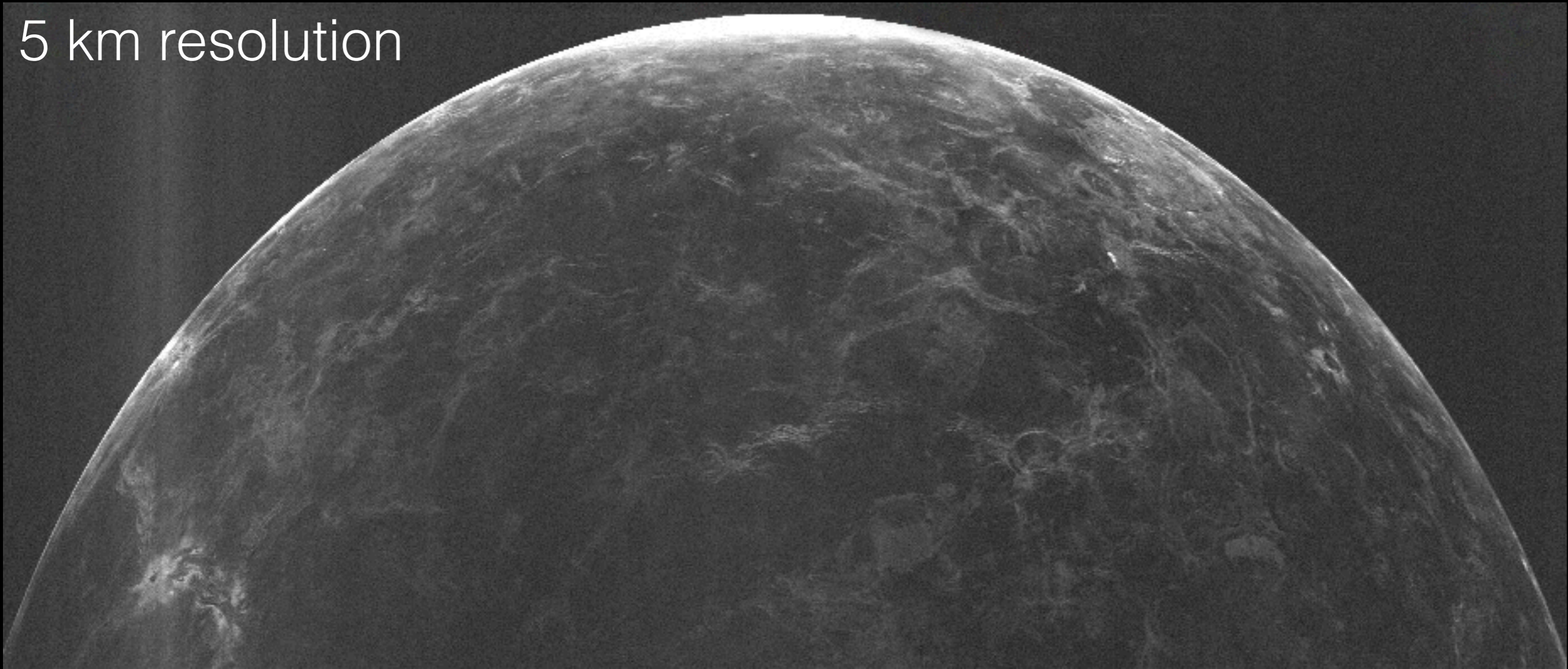
Rotation period also determined by radar
(1964; but not at Arecibo)

Below: delay-Doppler image

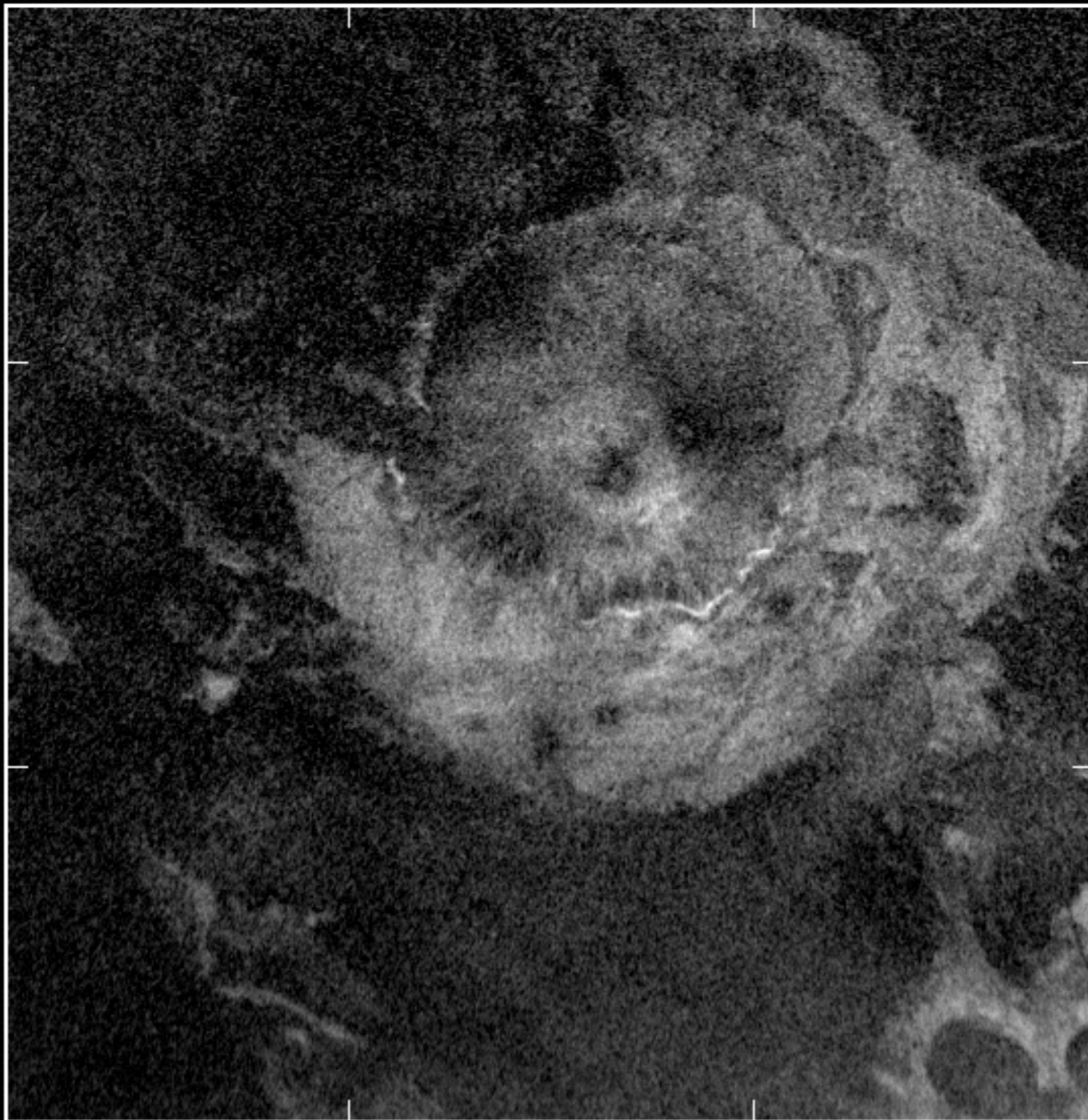
Right: lat.-lon. map of Maxwell Montes



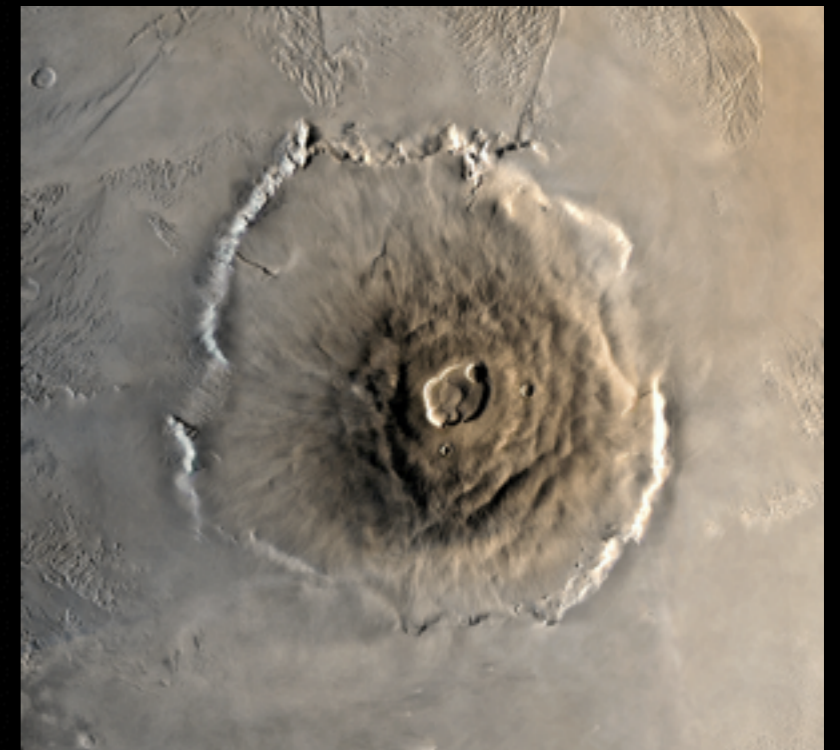
5 km resolution



Mars: Olympus Mons

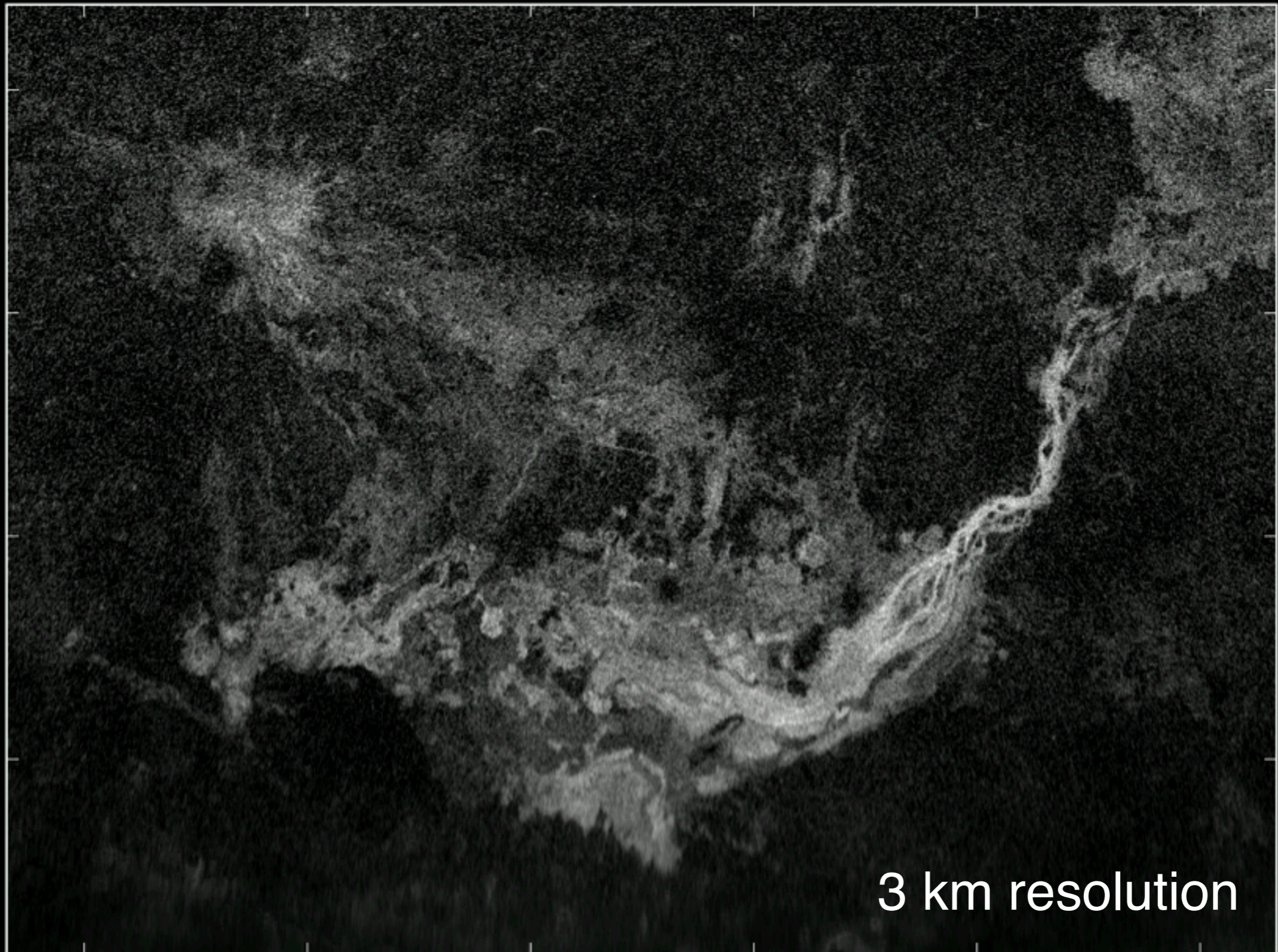


Left: 3 km resolution

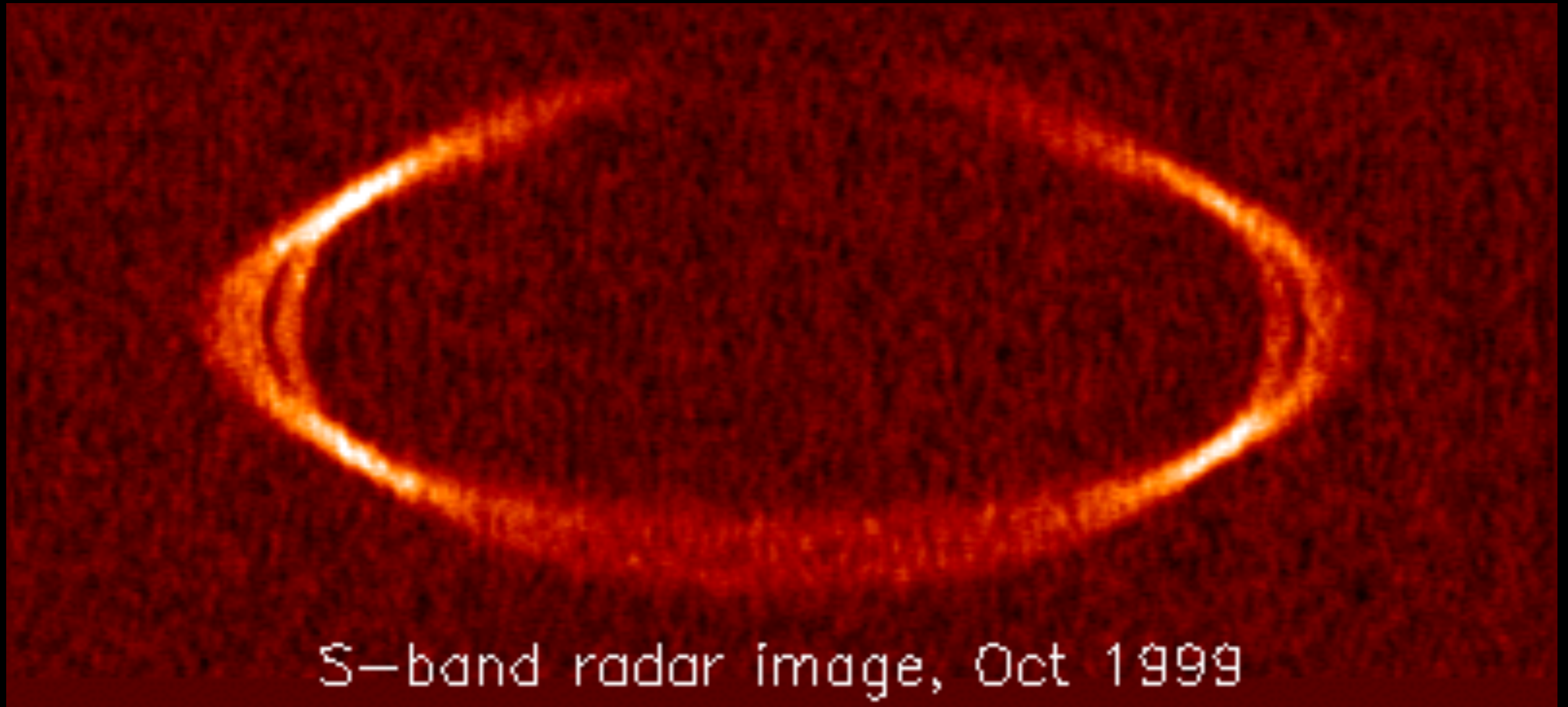


Above: Viking 1

Mars: Elysium



Saturn



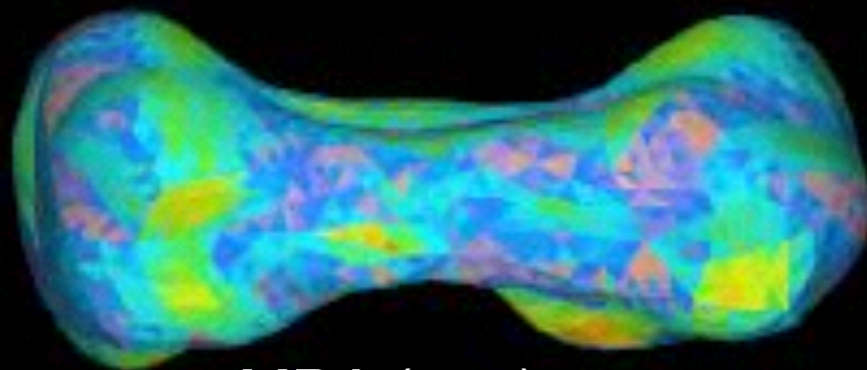
There are two strange things about this image...

Observed Asteroid Population

- Varieties of asteroids observed with radar:
 - Spheroidal
 - Irregular
 - Multiple-component systems
 - Fast rotators (minutes)
 - Slow rotators (days)



2006 SX217



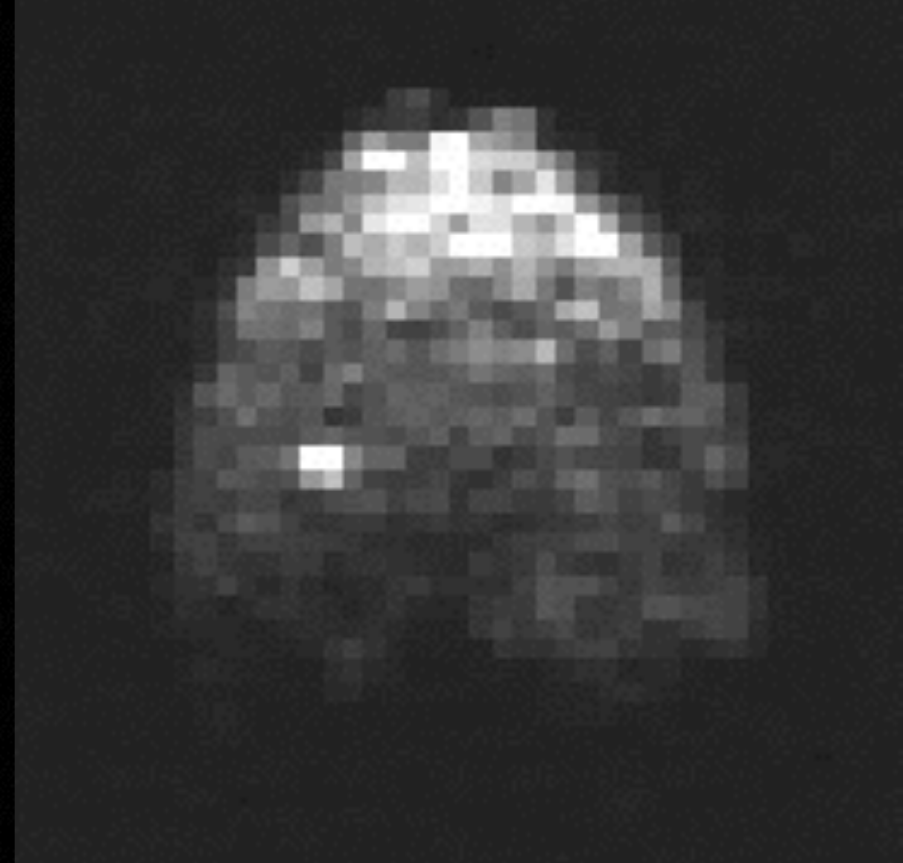
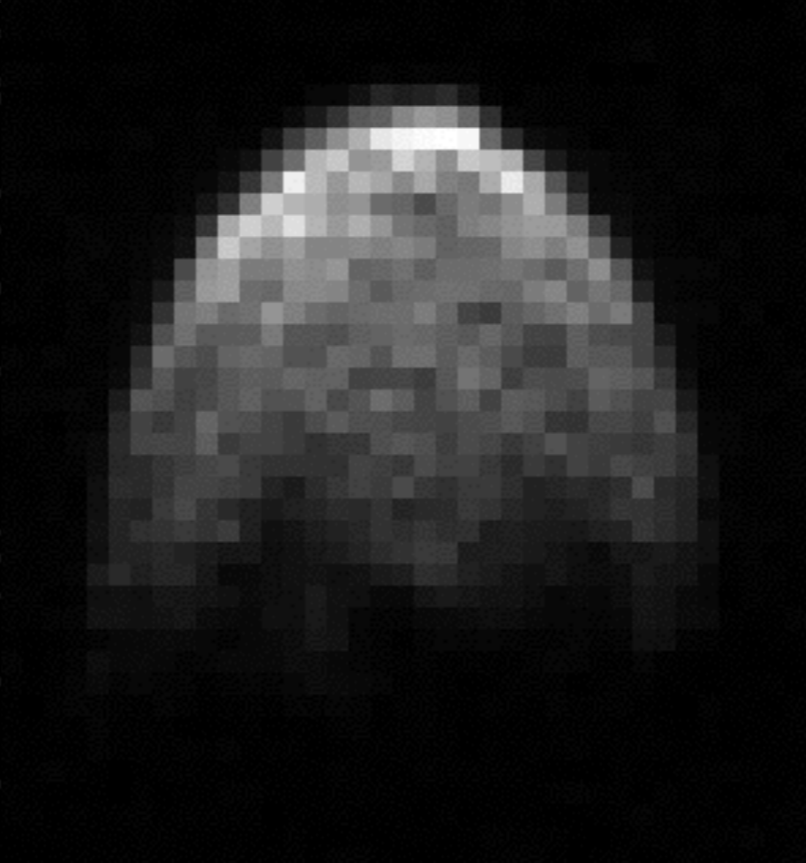
MBA (216)
Kleopatra



1999 JM8

Spheroidal 2005 YU55

- Flew by Earth at 0.85 lunar distances on November 8, 2011
- Closest known flyby from a 400-m scale object in over 30 years
- Perfect target for Goldstone (images at left), Arecibo images below had less resolution

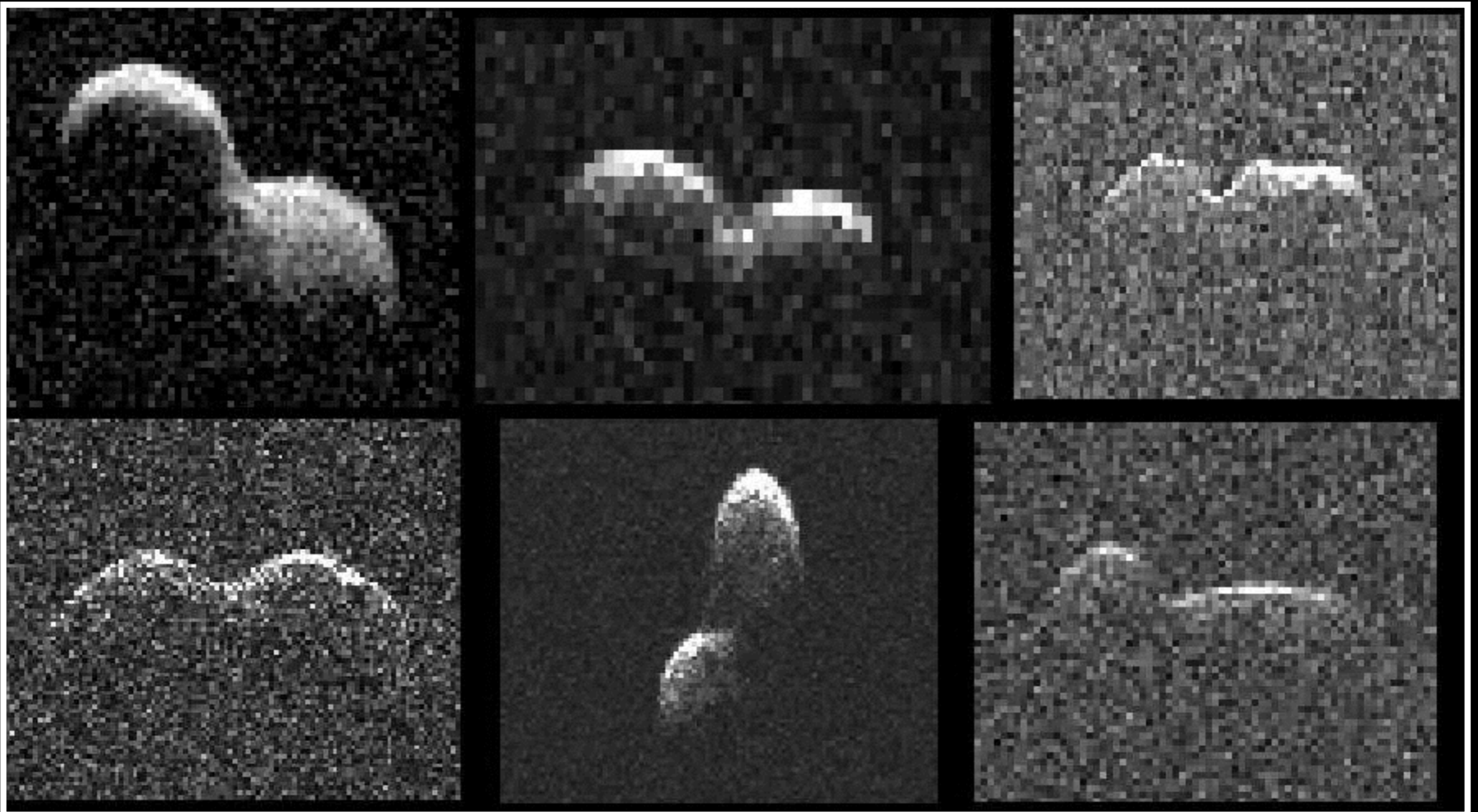


Contact Binaries ~ 1 in 7

2002 NY40

2007 VD12

(11066) Sigurd



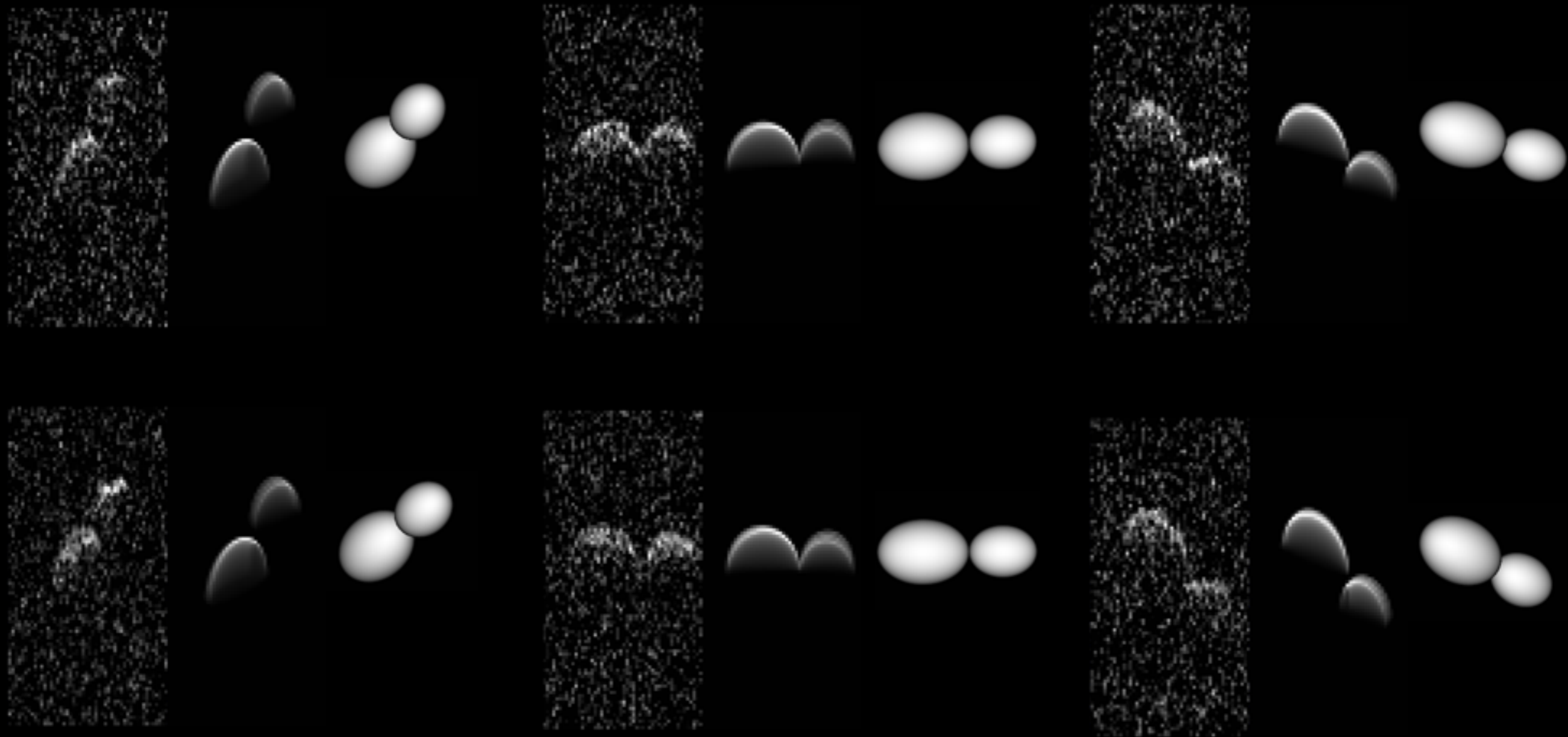
2005 CR37

(4450) Pan

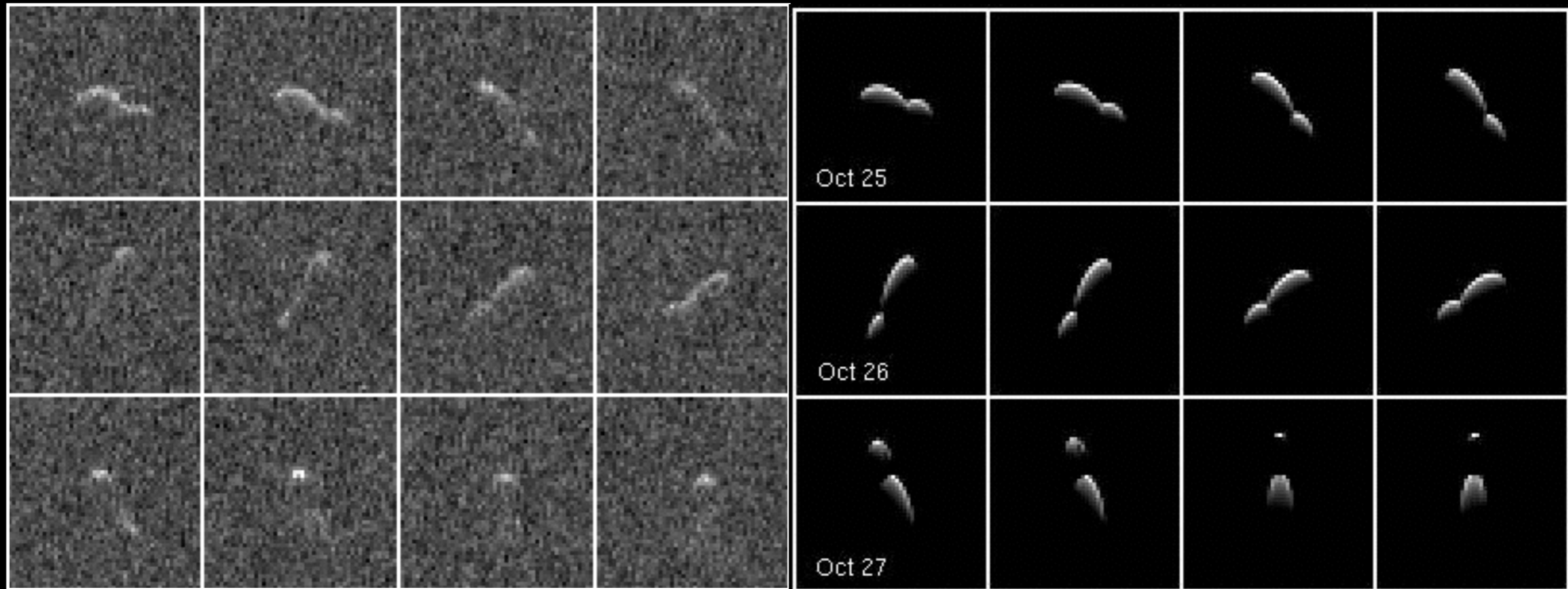
1996 HW1

Comet 8P/Tuttle

Columns are Radar Data, Synthetic Data, and Model on Plane of Sky

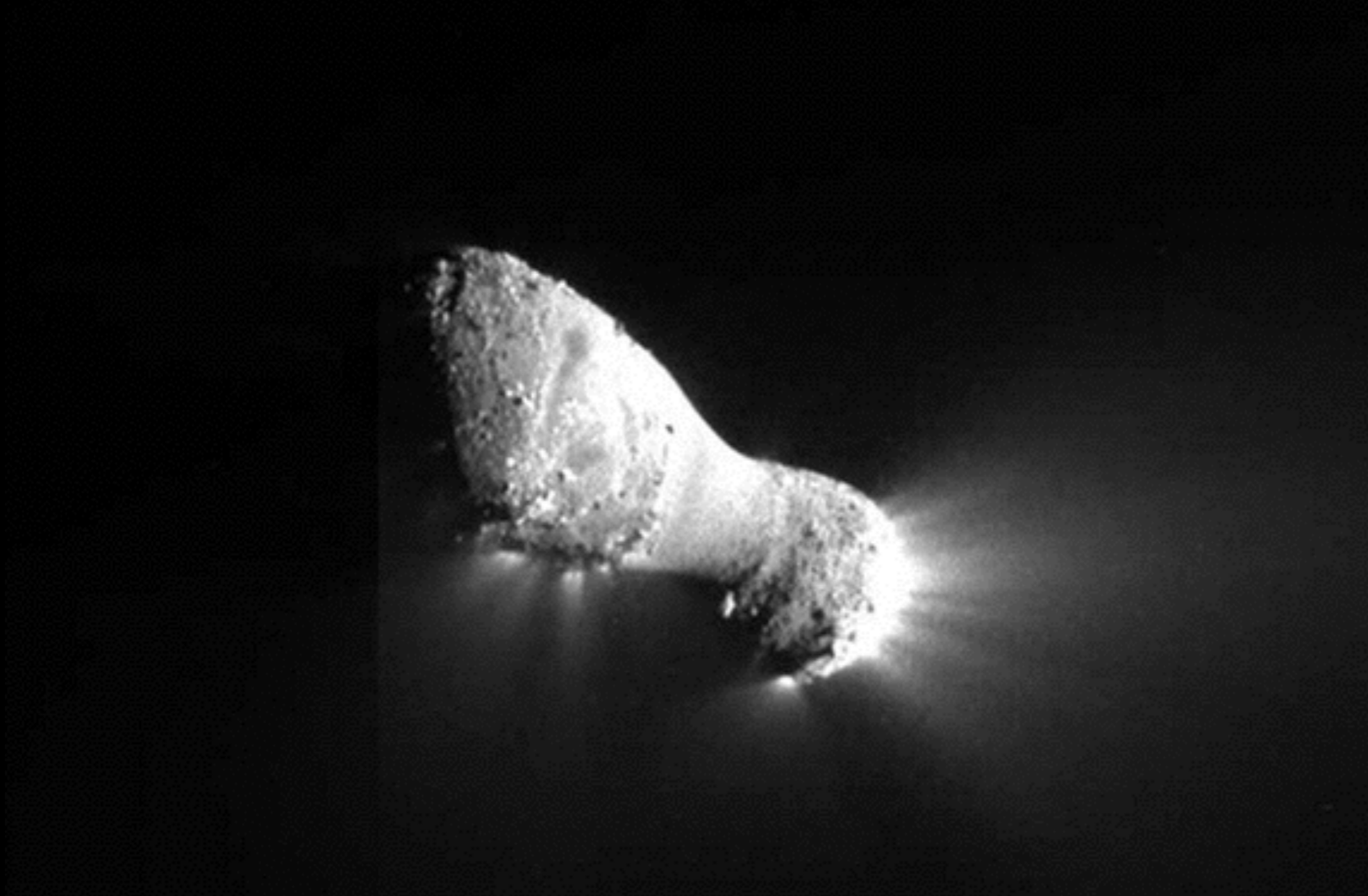


Comet 103P/Hartley 2



- Used radar to pinpoint the comet's position and velocity to help Deep Impact's navigation team prepare for the 2010 flyby
- Images reveal a bowling-pin shape with two lobes similar to 8P/Tuttle

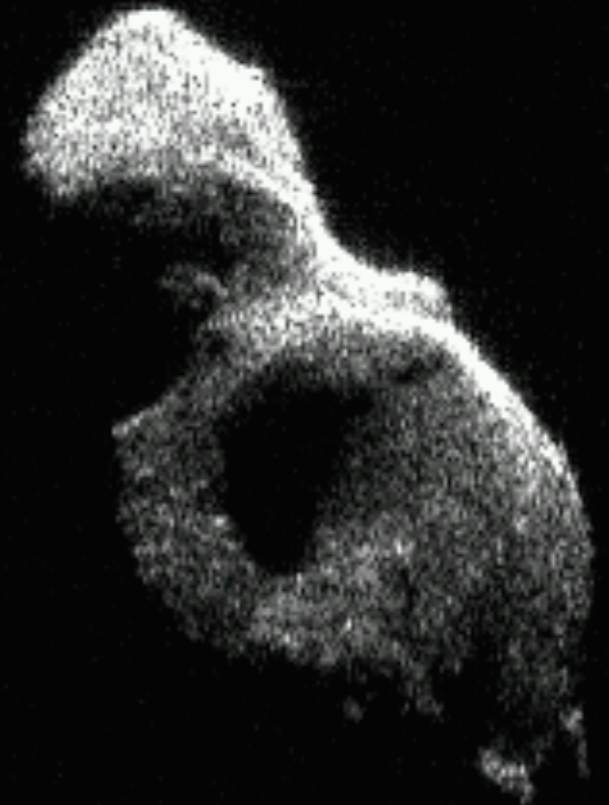
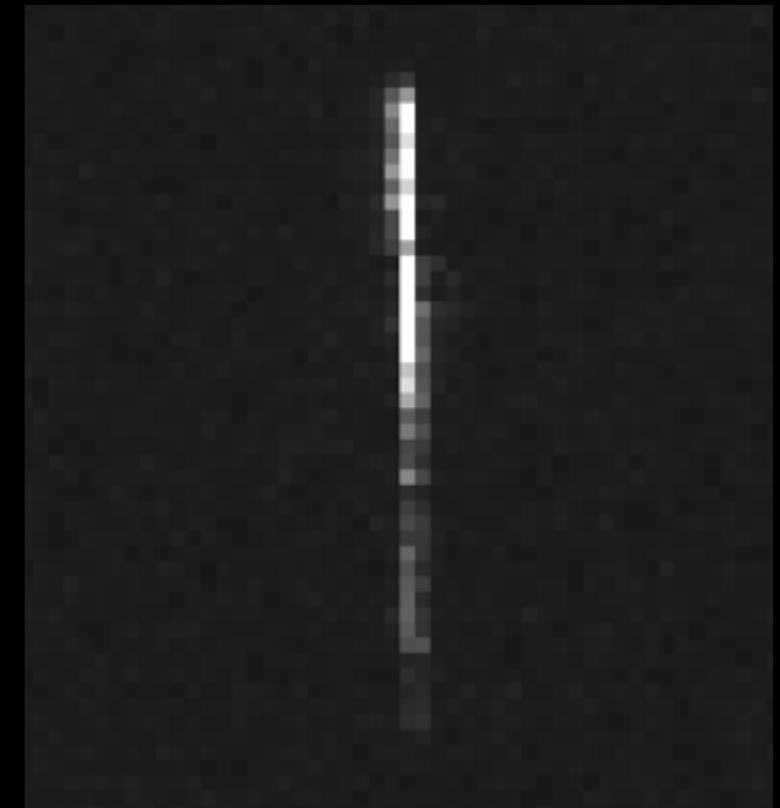
Comet 103P/Hartley 2



Nov. 4, 2010 flyby performed by NASA's Deep Impact spacecraft

2014 HQ₁₂₄

- Approached within 5 lunar distances on June 8, 2014
- Too close for Arecibo to resolve in Doppler frequency!
- Perfect target for a bistatic experiment
- Goldstone continuously transmits at X band with 3.5 meter resolution
- Arecibo continuously receives with no limitation on the Doppler resolution
- This configuration is 5x more sensitive than Goldstone working alone



Ultra-rapid Rotators

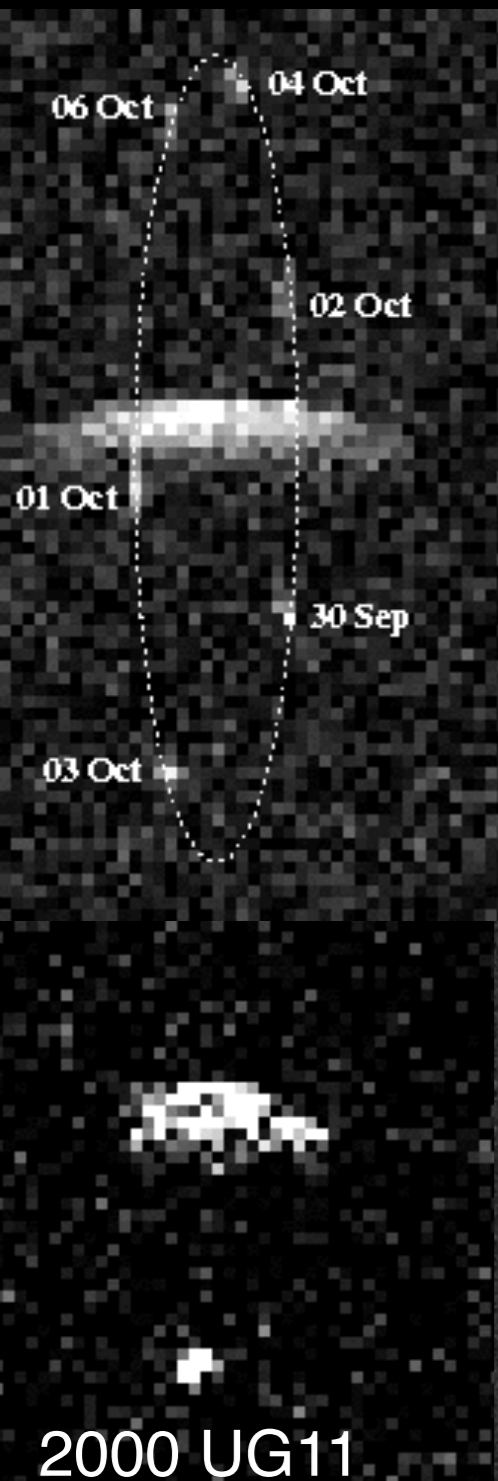
- 2006 AM4
 - diameter of 150 m
 - **5 minute** rotation!
- 2015 HM10
 - 80 x 40 m in diameter
 - **22 minute** rotation



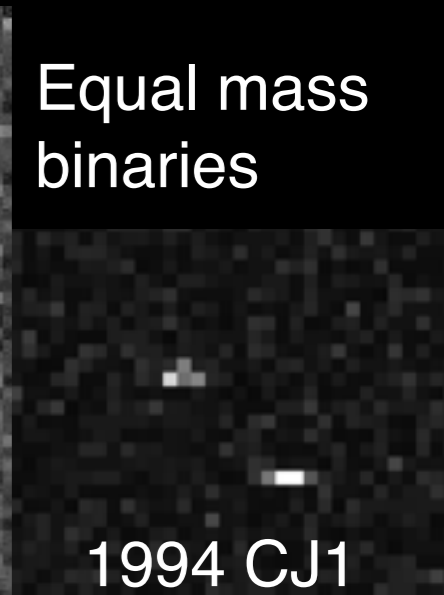
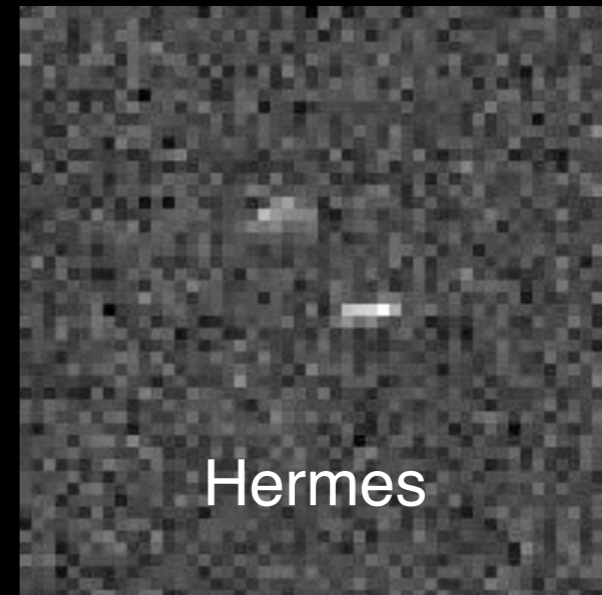
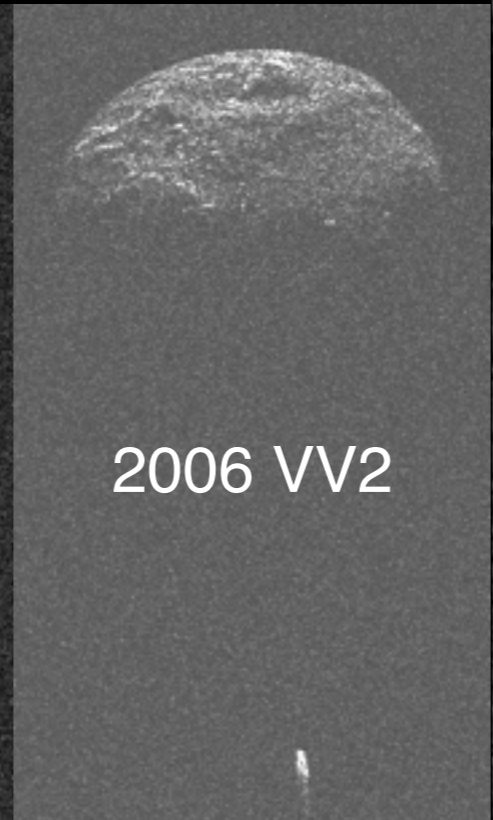
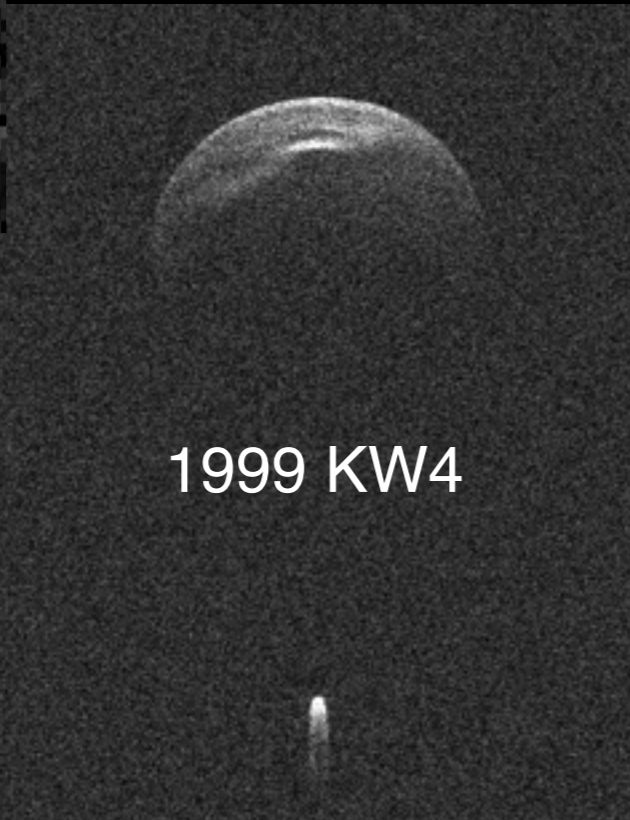
- Any loose surface material must be lost!

Binaries Everywhere!

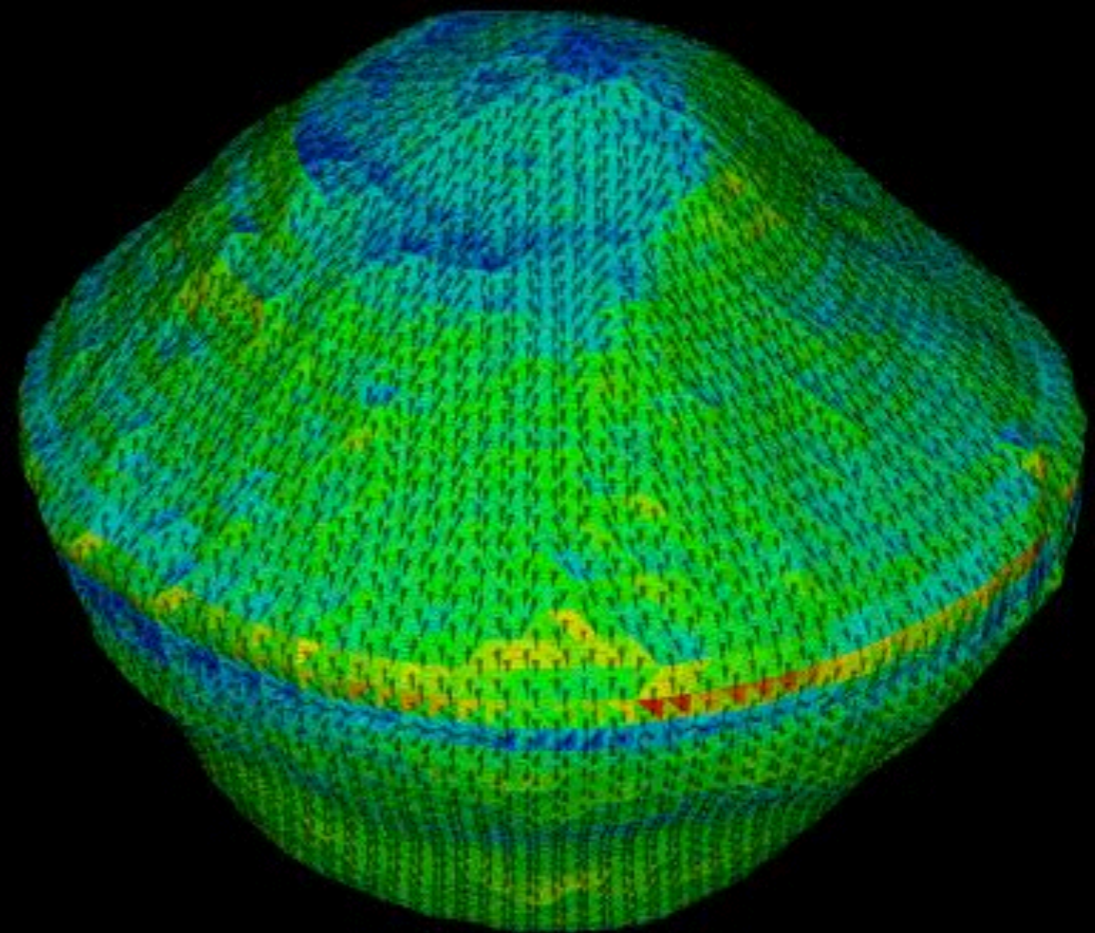
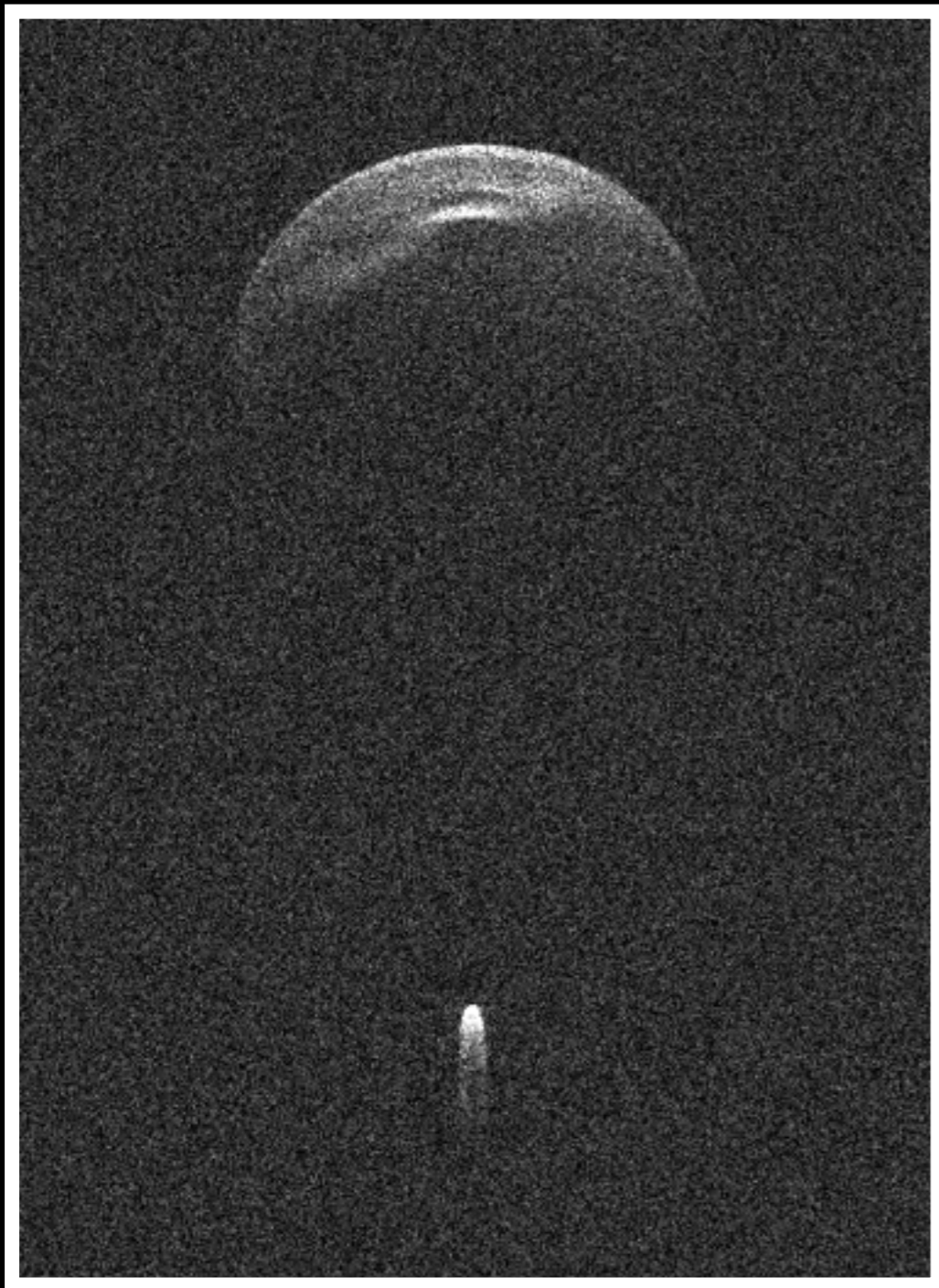
2000 DP107



- **1 in 6** observed is binary
- Rapidly rotating primaries
- Primaries roughly spheroidal
- Circular, equatorial orbits
- Secondaries likely tidally locked (like Earth's Moon)

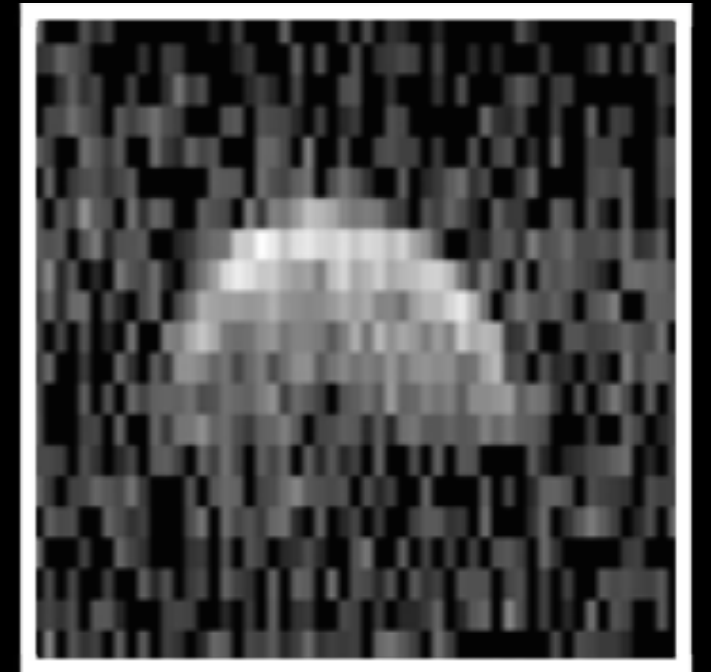
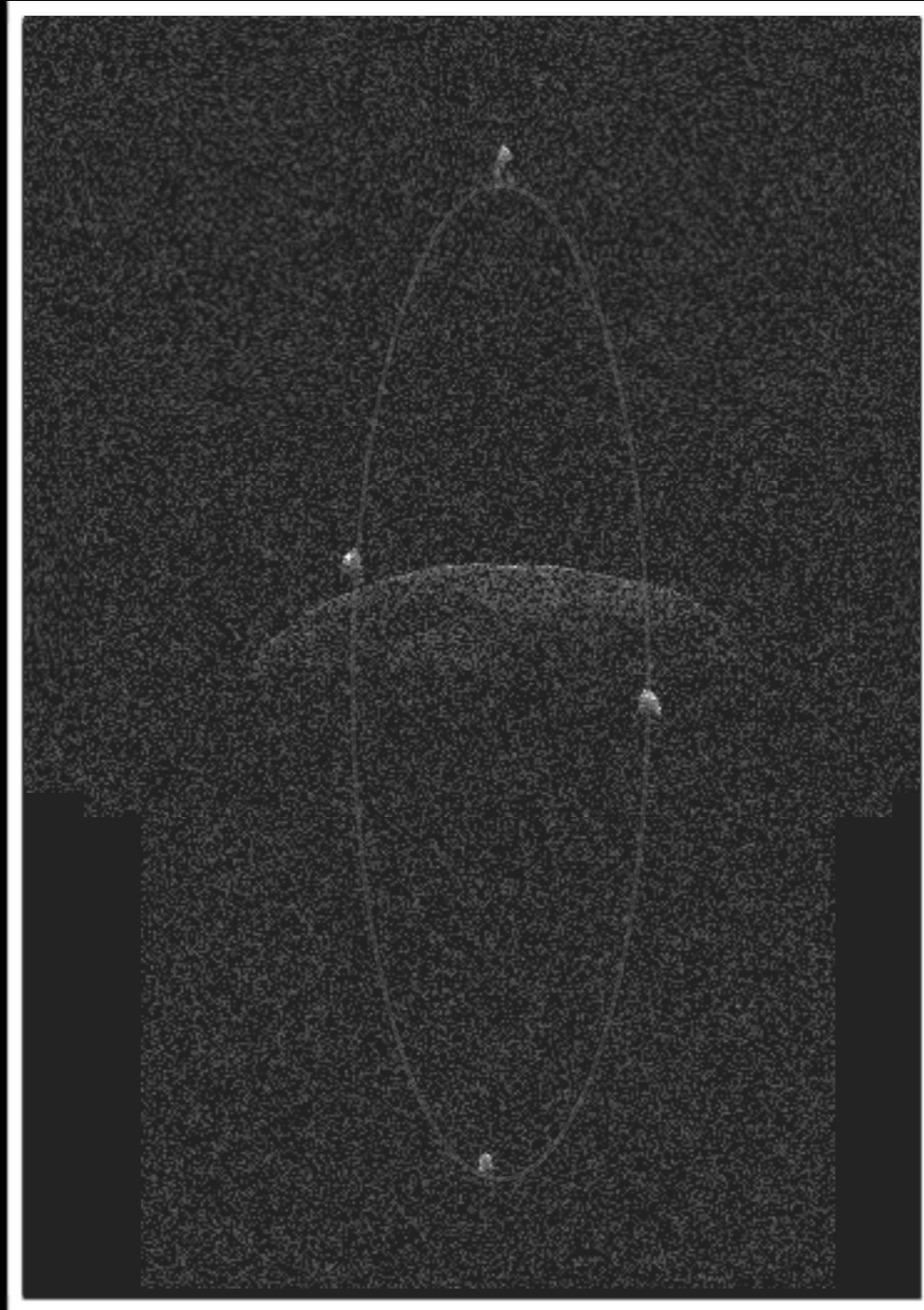
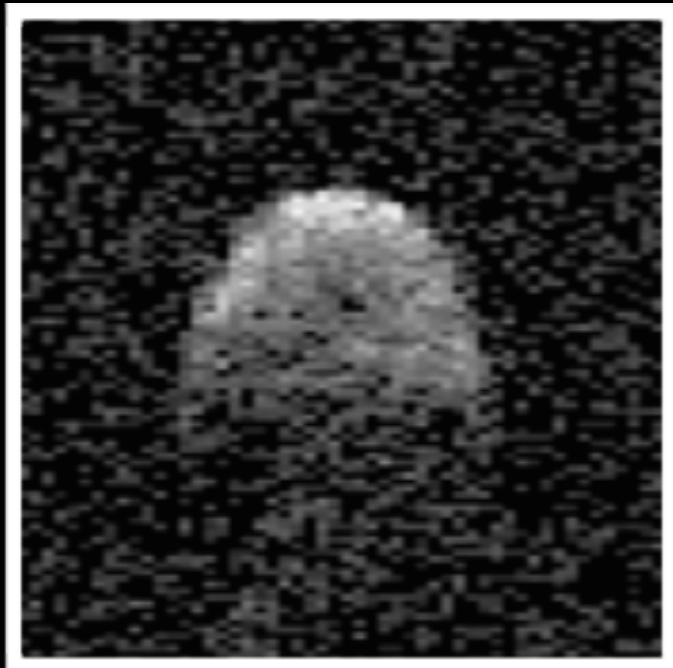
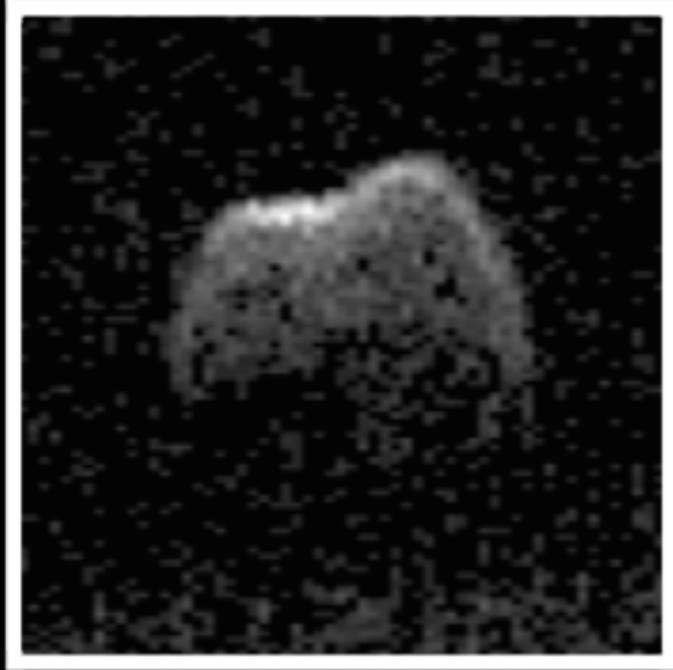


Binary NEA 1999 KW4

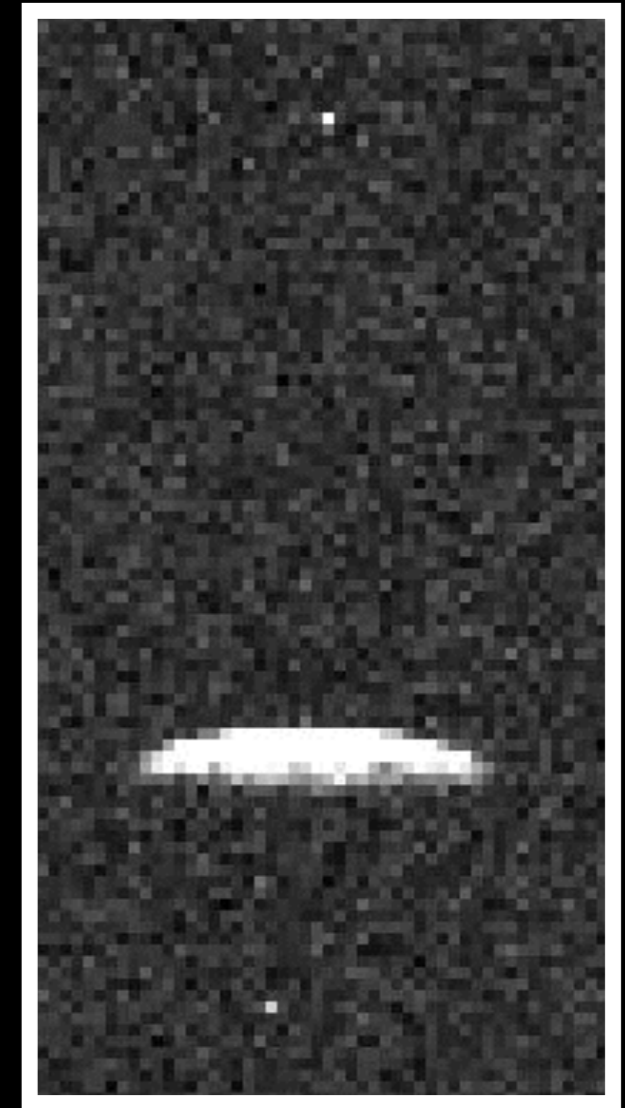
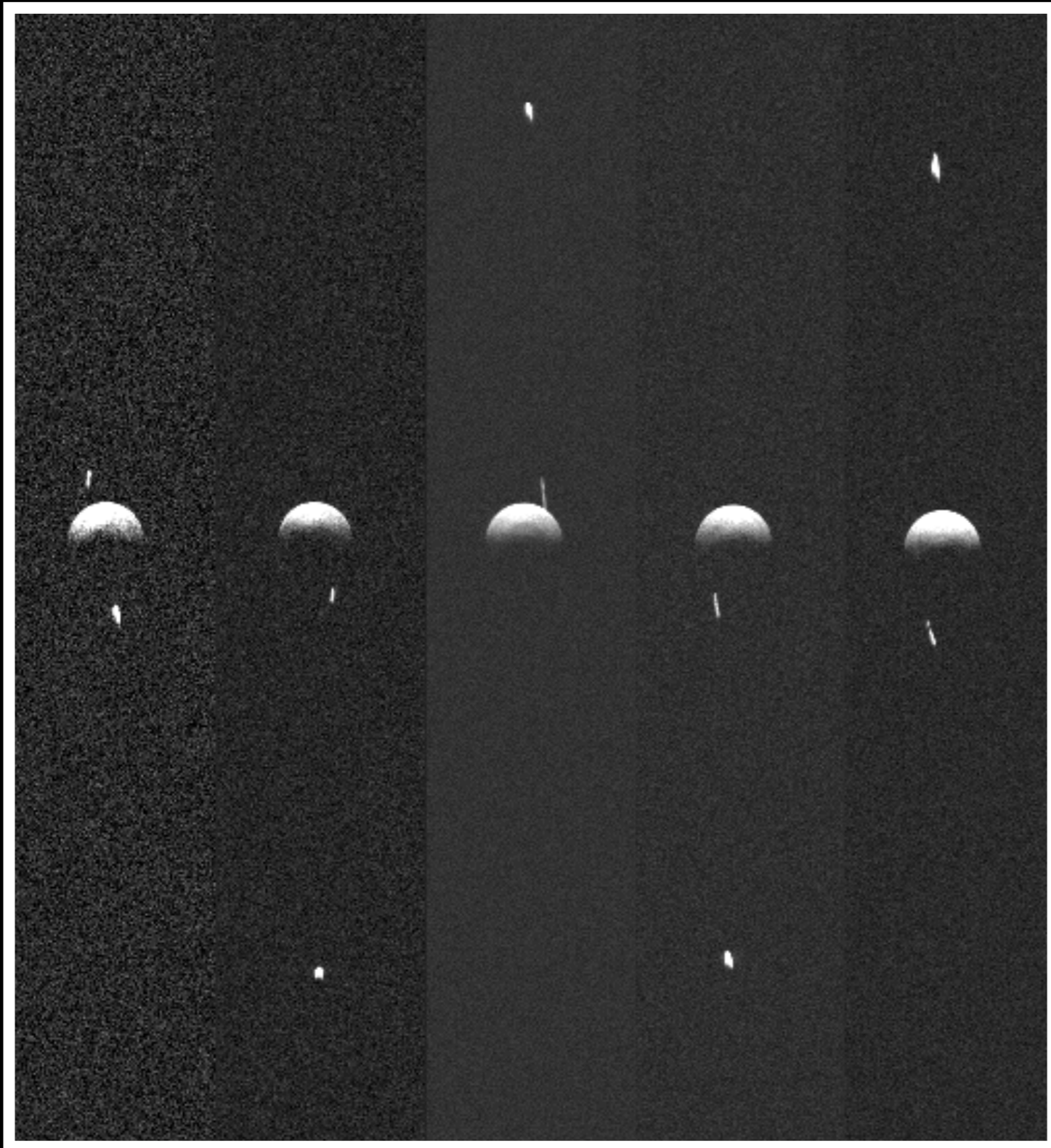


For Visualizations of the 1999 KW4 Binary Asteroid System,
Radar-Derived Shape Models, and Their Corresponding Synthetic
Radar Spectra and Radar Images, see Dr. James E. Richardson's
(Arecibo Observatory) YouTube Channel at:
<https://www.youtube.com/user/jerichardsonjr>

1998 QE2 Mutual Orbit and Secondary Shape



Triple Asteroid Systems



Above: 1994 CC
Left: 2001 SN263

Radar Astronomy Summary

- Radar is a unique method of studying solid objects from Mercury out to Saturn's rings
- Image resolution surpassed only by dedicated spacecraft
- Radar is a vital tool for impact hazard assessment
- Efficiency compared to spacecraft allows us to describe the asteroid **population**
- Near-Earth asteroid population is **heterogeneous**
- Binaries (~16%) + Contact Binaries (~14%) + Triples (~1%) ~ **one-third** of NEAs!