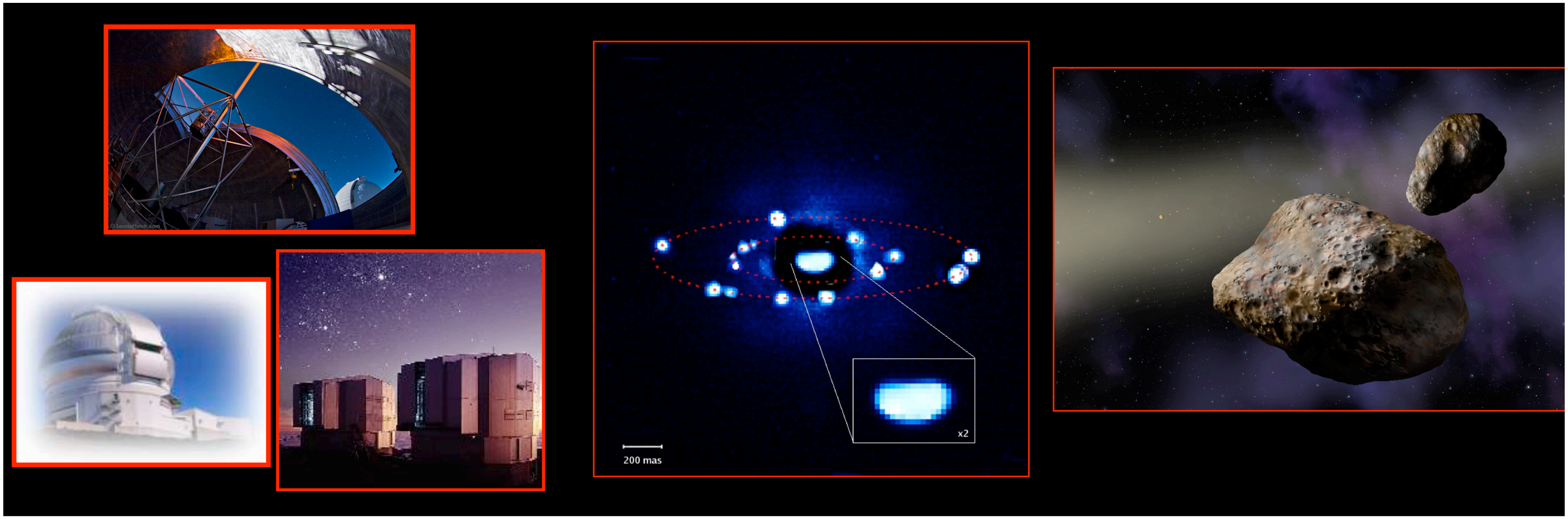


Multiple Asteroid Systems
Search Programs and Studies with AO

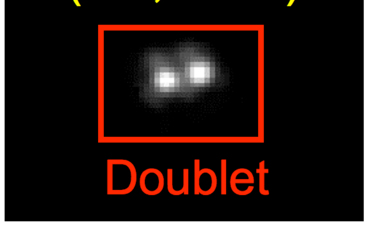
Franck Marchis
SETI Institute & University of California Berkeley
June 9 2009, AAS Conference Pasadena, CA, USA

SETI INSTITUTE

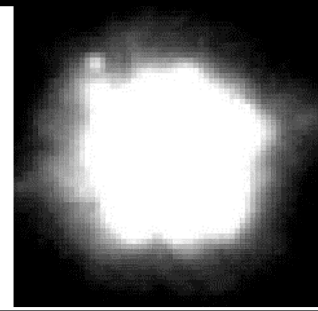
Binary Asteroids
A Family Portrait

MB Ida and Dactyl (Galileo 1993)

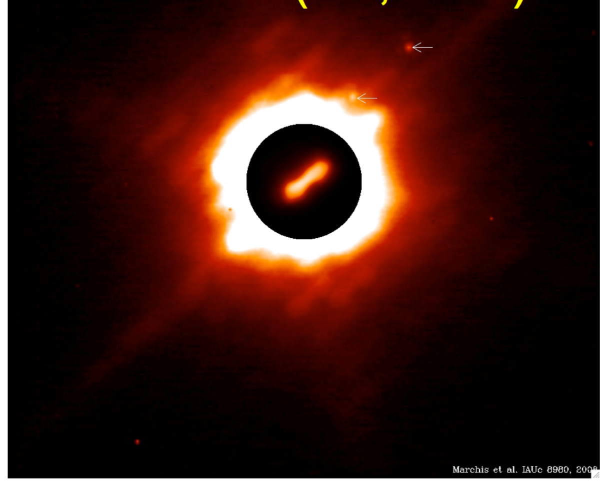
MB 90 Antiope
(AO, 2001)



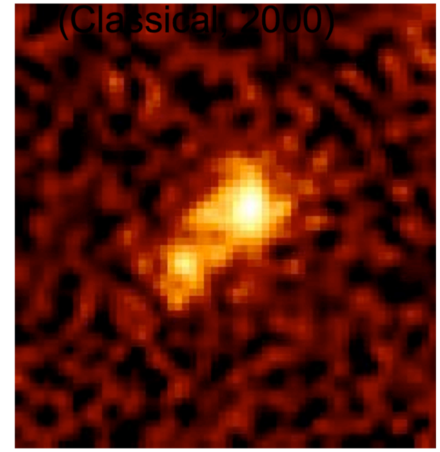
MB 45 Eugenia &
Petit-Prince
(AO, 1998)



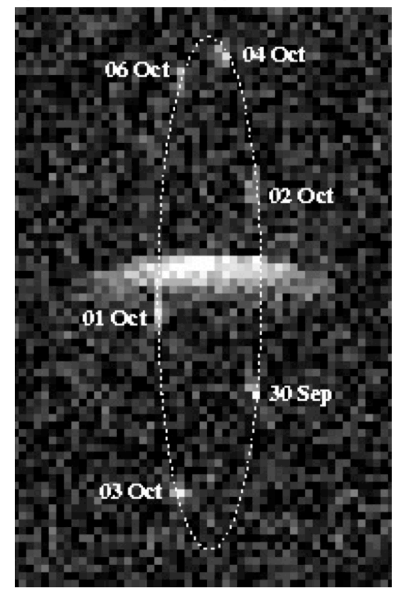
MB 216 Kleopatra and its
2 moons (AO, 2008)



TNO 1998WW31



NEA 2000DP107
(2002, radar)



~172 are known (MB, NEA, Trojans, TNOs)

~80 can be visualized with AO,HST, or Radar

~20 observable with current NGS, ~20 with LGS on 8-10m class telescopes

⇒ Mass, density -> formation of solar system

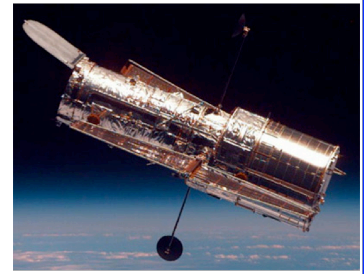
Virtual Observatory Binary Asteroid Database (VOBAD)

VLT 8m-ESO
Paranal (Chile)
2003-2008

Keck II 10-m
Mauna Kea (Hawaii)
2002-2009

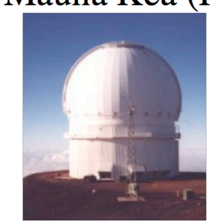
Gemini-North 8m
Mauna Kea (Hawaii)
2005-2007

HST 2m
2000-2008



Lick 3m-UC
Hamilton (CA)
2000-2001

CFHT 4m
Mauna Kea (HI)
1999-2000



VOBAD

- AO ~1340 observations of 501 SSSBs
34 NEAs, 402 MBAs, 62 Jupiter-Trojan, 1 Centaur, 2 KBOs

- HST ~612 observations of 378 SSSBs
1 NEA, 79 MBAs, 34 Jupiter-Trojan, 19 Centaurs, 245 KBOs

Virtual Observatory Binary Asteroid Database (VOBAD)

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Paranal (Chile)

2003-2008

Keck II 10-m
Mauna Kea (Hawaii)

2002-2009

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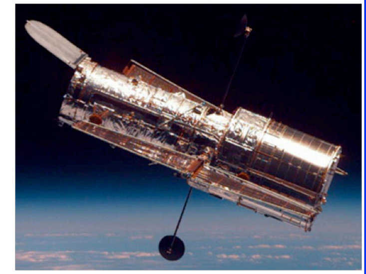
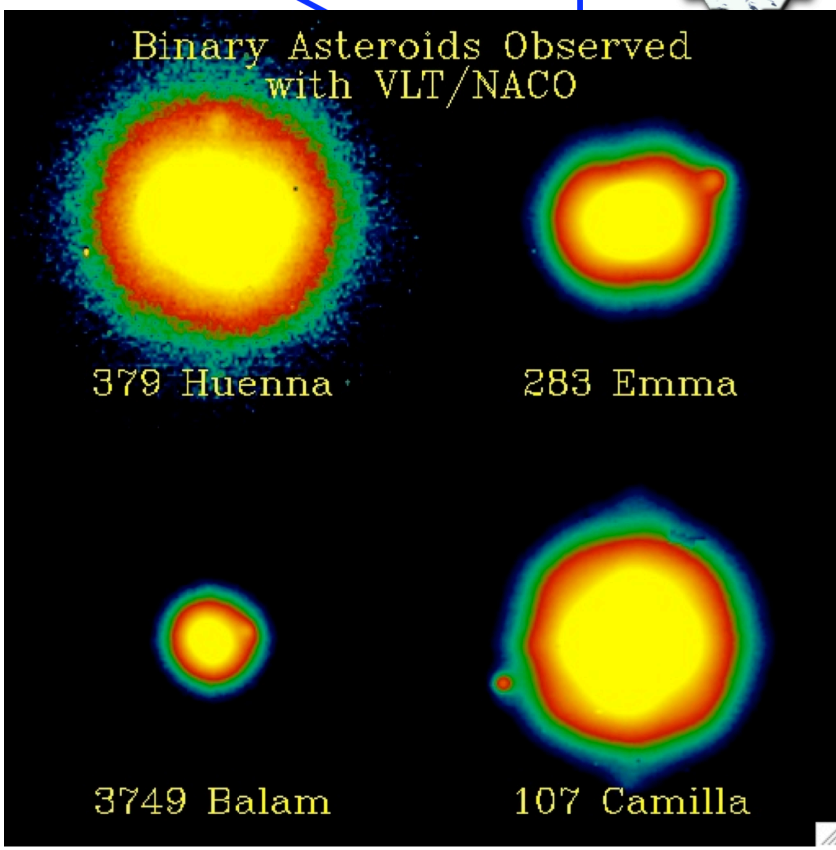


2000-2008



VOBAD

bservations of 501 SSSBs
MBAs, 62 Jupiter-Trojan,
BOs

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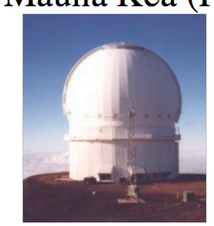
As, 34 Jupiter-Trojan, 19
KBOs

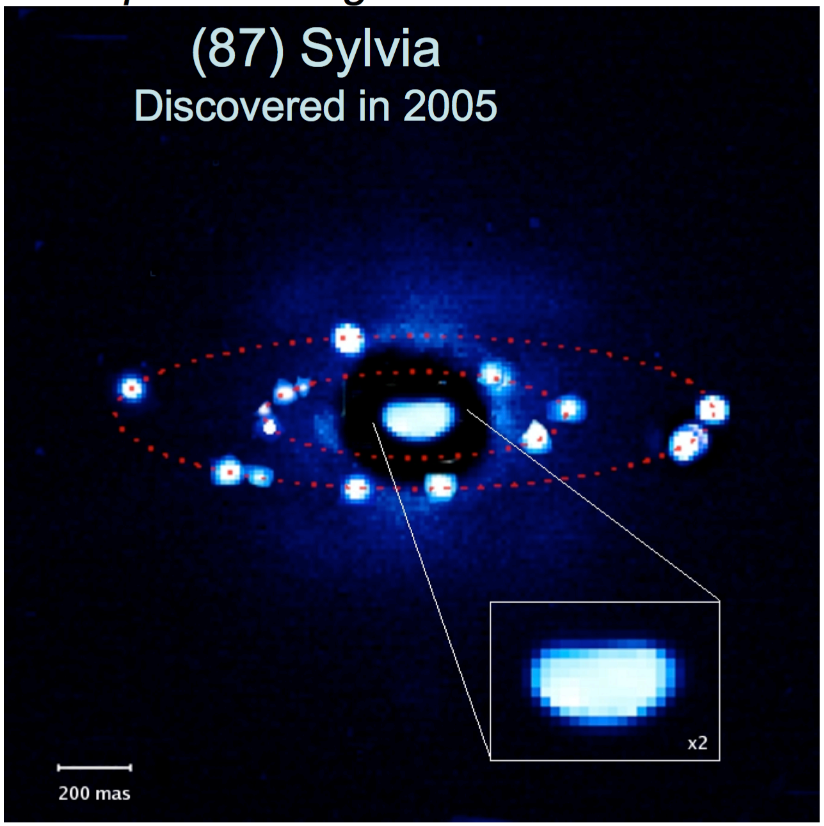
CFHT 4m
Mauna Kea (HI)



1999-2000

The first triple asteroid system: 87 Sylvia

Composite images



S/2001 (87)1 - Romulus

- $D_1 = 18 \pm 4$ km
- $a_1 = 1356 \pm 5$ km = 1/50 x R_{hill}
- $P_1 = 3.6496 \pm 0.0007$ days

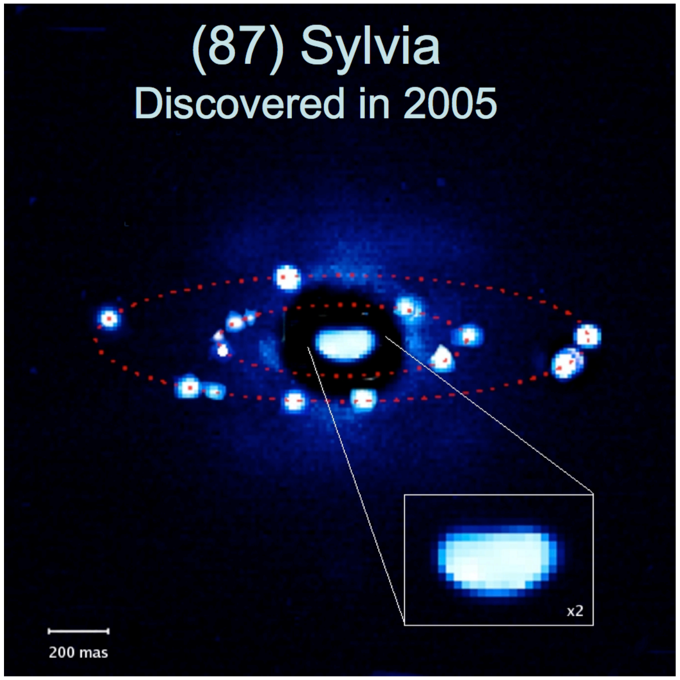
S/2004 (87)1 - Remus

- $D_2 = 7 \pm 2$ km
- $a_2 = 706 \pm 5$ km = 0.52 x a_1
- $P_2 = 1.3788 \pm 0.0007$ days

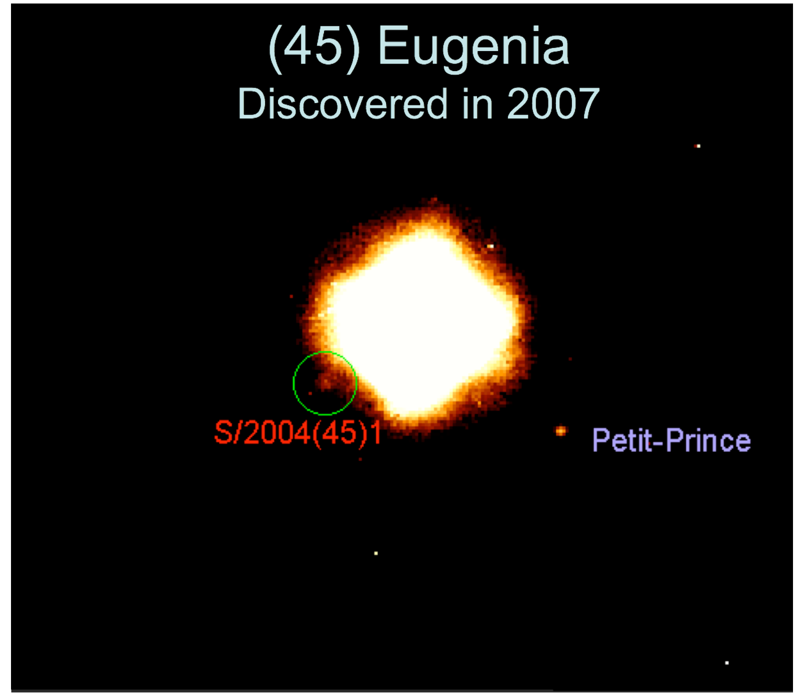
-> coplanar, prograde and equatorial orbits
-> damped by tidal effect
-> precession of the inner moon observed due to oblateness (elongated shape) of the primary

- 5-body numerical simulation showed that the system is stable because of the oblateness of the primary (Winter et al., 2009)
- We discovered new triple systems (45 Eugenia in 2006, 3749 Balam in 2007, and 216 Kleopatra in 2008)

Discovery of Triple Asteroid Systems



Triplicity rate in VOBAD: **~1%**



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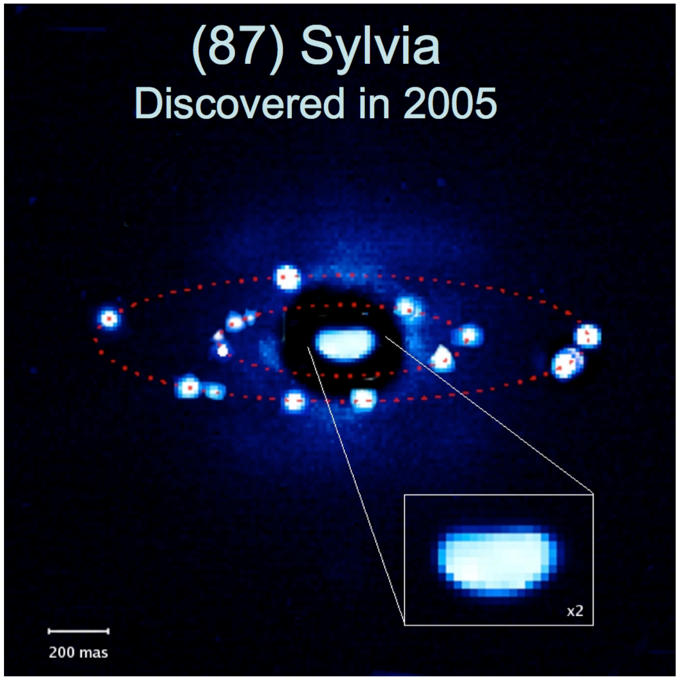
From reanalysis of Feb. 2004 VLT data
4 detections only (orbit is very preliminary…)

$D_{\text{"Princesse"}} \sim$ 5-6 km
$D_{\text{Petit-Prince}} = 7 \pm 3$ km

Preliminary orbit: a_2 = 0.49 x a_1
same relative ratio to (87) Sylvia moonlets
by design or coincidence?

Discovery of Triple Asteroid Systems



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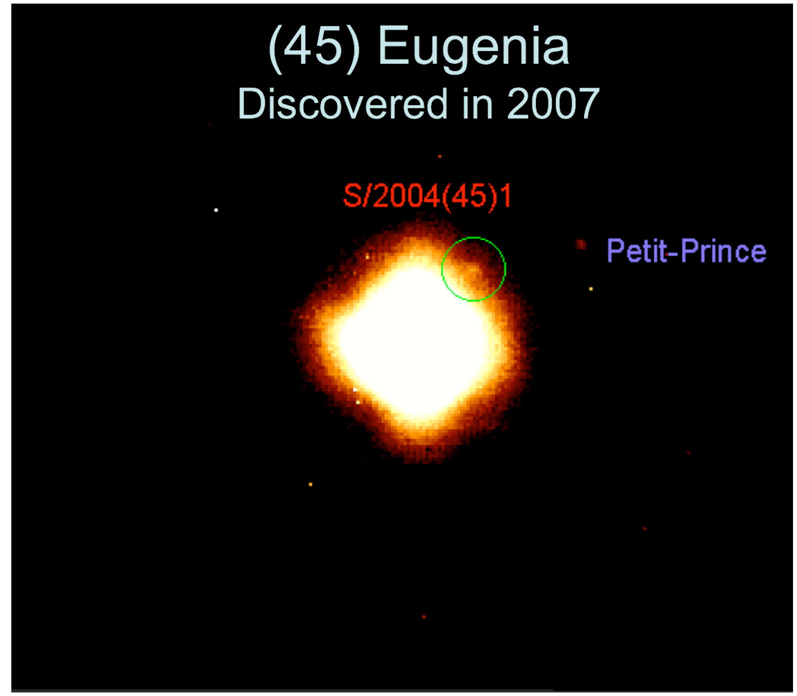

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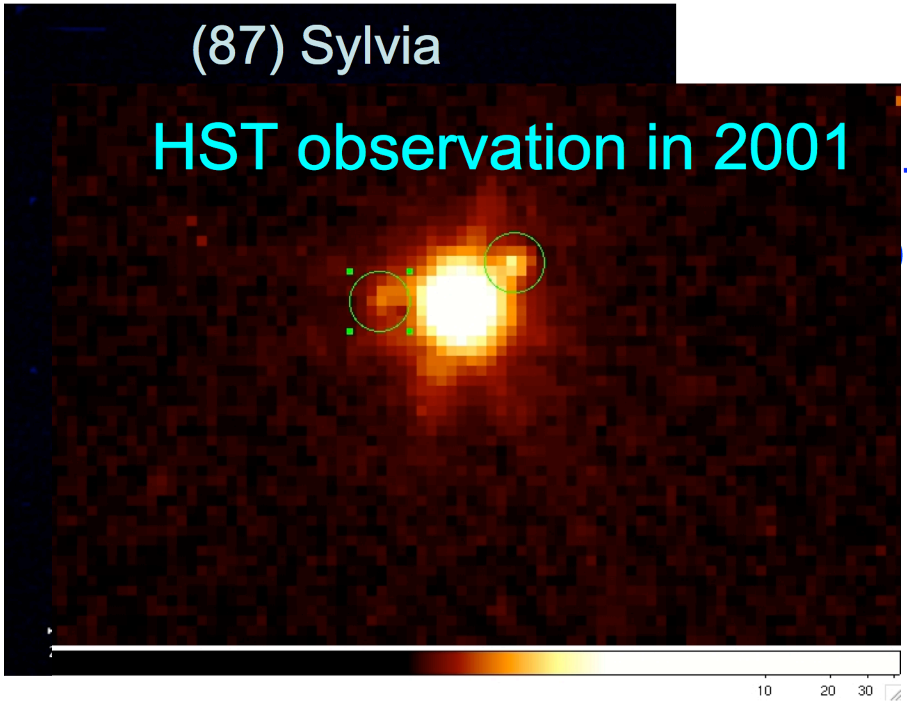
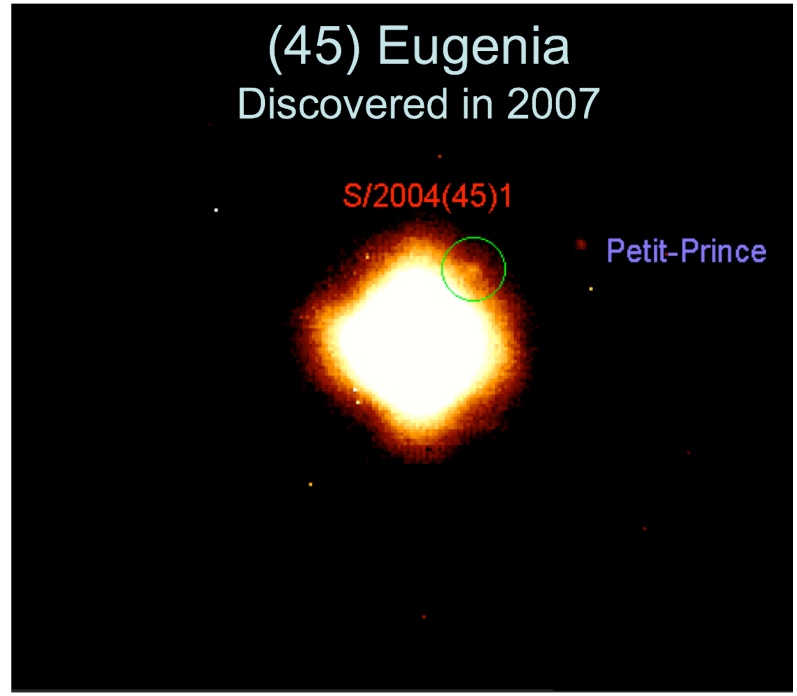


ty rate
BAD:
%



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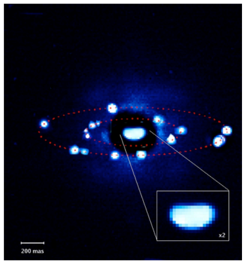
Mass, Bulk Density & Porosity of 87 Sylvia

• From 3rd Kepler law ⇒ Mass=1.48 × 10^{19} kg (Keplerian model + precession due to Sylvia primary oblateness)

• Shape and Size of the primary refined based on AO observations ellipsoid with a=192km, b=132 km, c=116 km



⇒ **Bulk density = 1.2± 0.2 g/cm^3**

Porosity of 25-60% (C-type) CI-CM or CR-CV meteorite analogs?

Rubble-pile internal structure of the primary

+

Circular, prograde, and equatorial orbits of the moonlets

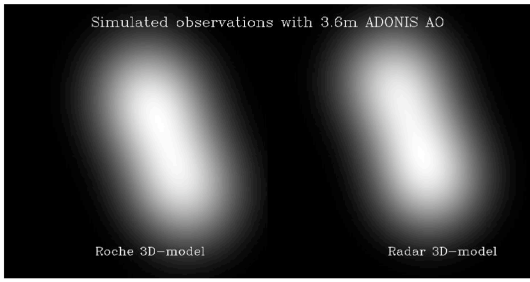
⇓

Origin of the system?

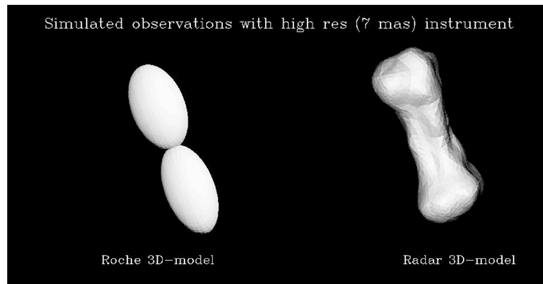
216 Kleopatra: a new triple system

Two models

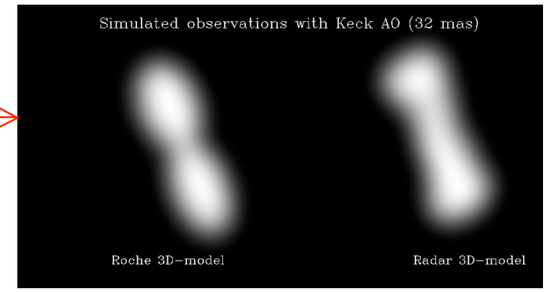
May 1999 with
AO-ADONIS 3.6m

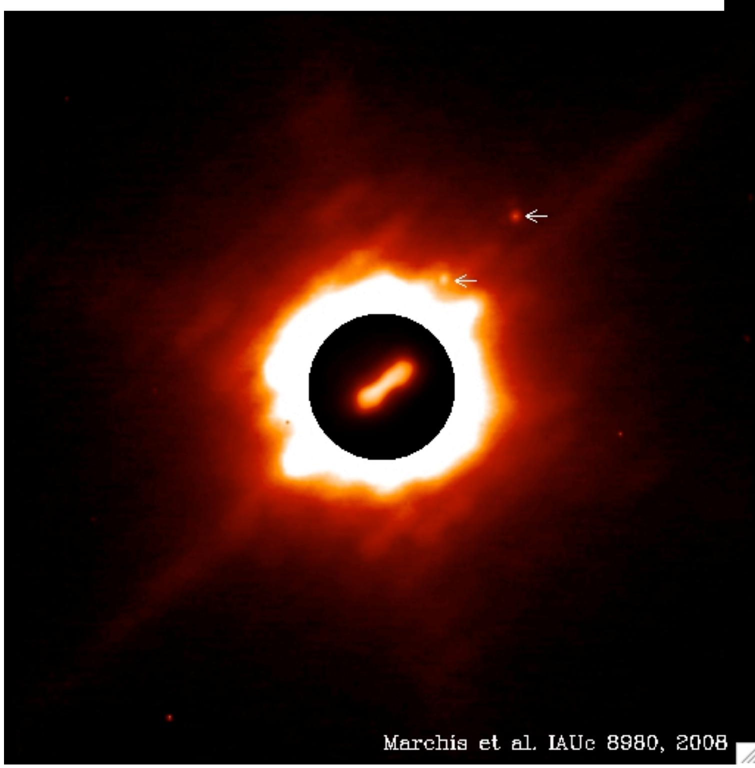


Hestroffer vs Ostro
AO-3.6m vs Radar

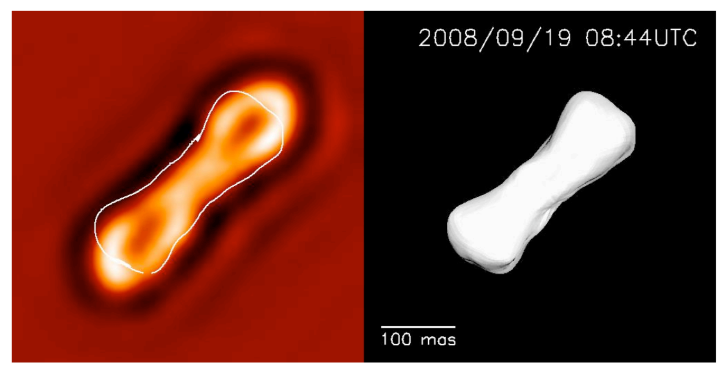


September 2008
Simulation Keck





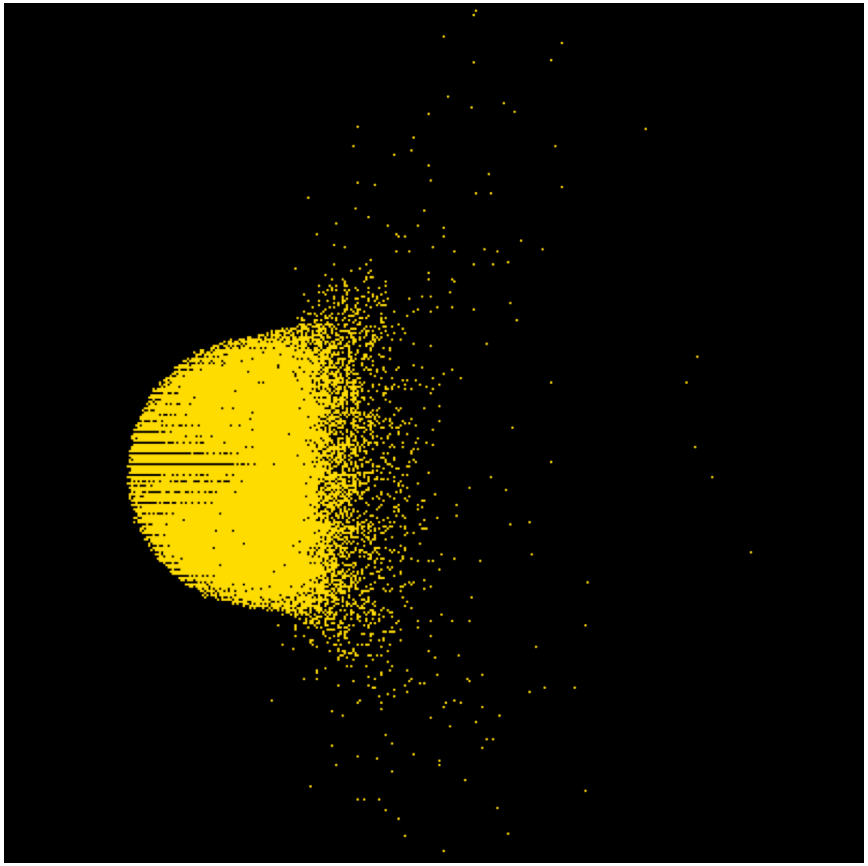
M-type asteroid
Two 3 and 4 km moons discovered
Preliminary orbits -> ρ =2.5-3.0 g/cm^3
3D-shape model in construction



Formation of triple asteroid systems

A catastrophic impact produced the disruption of a parent asteroid, follow by gravitational reaccumulation

->Simulation by 3D particle hydrodynamics, then N-body code



•Outcome of the simulation:

✓Irregular primary with rubble-pile structure $R_p \sim 100$ km

✓Small moonlet $R_s \sim$ a few km close to the primary (3-6x R_p) describing a circular and equatorial orbit (due to damping by tidal effect)

✓Multiple systems (less than 5%)

Binary asteroids in other populations?

AO systems are limited to m_v=13.5 stars, so we can observe:

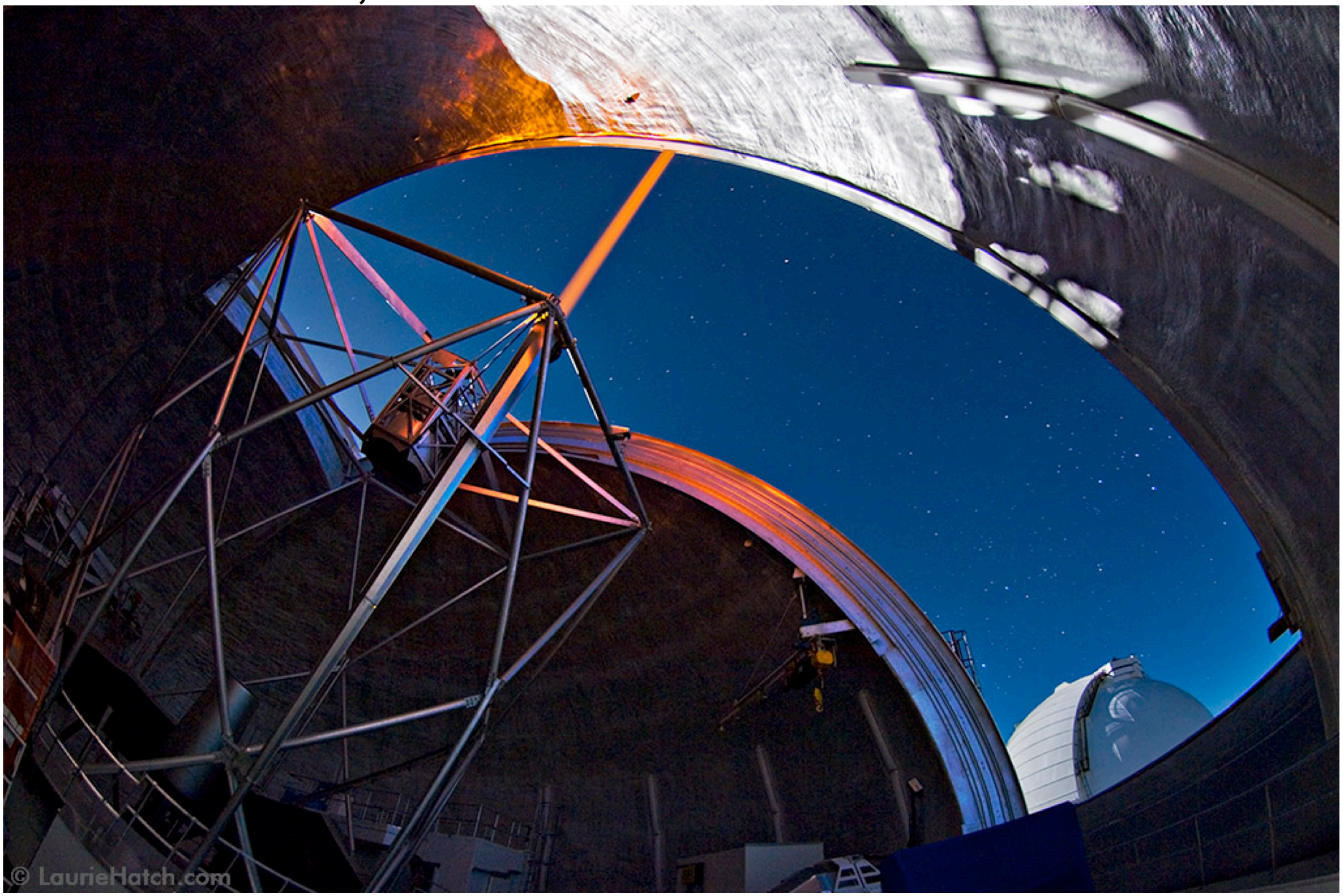
- Only 5% of the sky (in average)
- Only ~400 main-belt asteroids
- No Trojan, No NEAs, No TNOs (Kuiper Belt objects)

- How can we observe Fainter/Further Objects (TNOs, NEAs, Trojan) ?

✓ Improvement of AO systems (more sensitive, better quality)
✓ Appulse Observations
✓ **Laser Guide Star (LGS) observations**

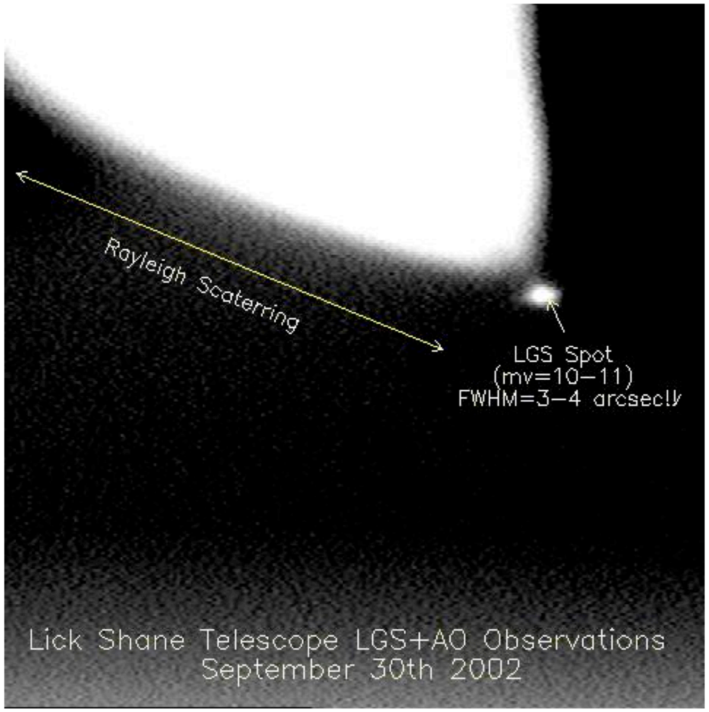
Laser Guide Star and AO

© Laurie Hatch, Keck LGS seen in the dome



Keck Laser Guide Star Adaptive Optics System

- Laser Guide Star AO commissioned in 2004-2005
- Sodium dye laser creates a m_V~12 artificial star
- Angular resolution ~0.060 arcsec on m_V=17.5 target
- Comparable to Hubble Space Telescope (HST) in visible



Binary Trojan Asteroids?

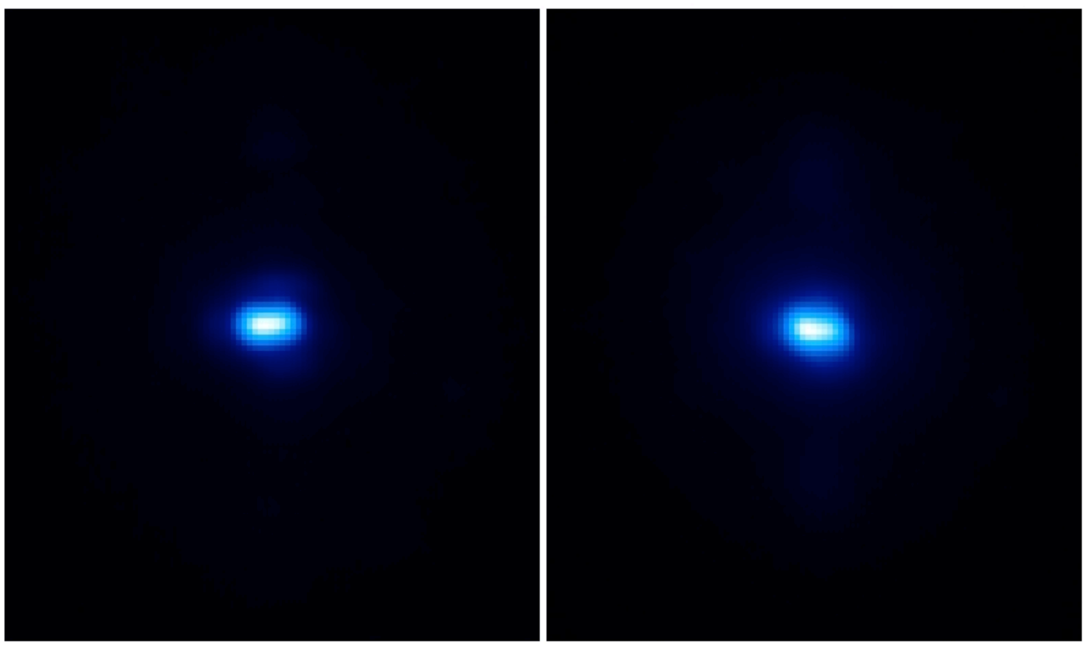
Only two binary Trojan Asteroids are known

(617) Patroclus (P-type) a double similarly-sized binary discovered in 2001 by Merline et al. (2001). Mutual orbit from Keck LGS in Marchis et al. (2006)

(624) Hektor (D-type) a large bilobated primary (D=210 km) and a 10-km moonlet discovered with Keck LGS AO (Marchis et al., 2006)

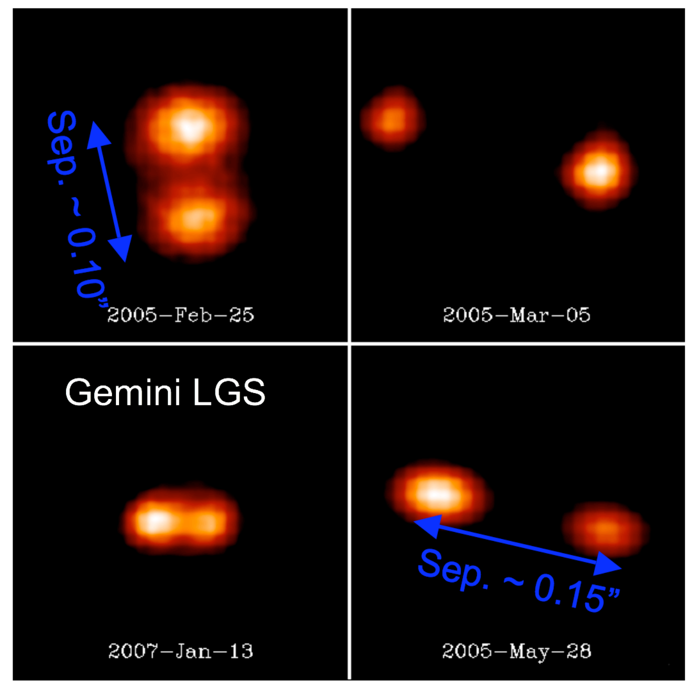
(624) Hektor

$\rho_{Hektor} = 2.1 \pm 0.3$ g/cm^3



(617) Patroclus

$\rho_{orbit} = 0.8 \pm 0.2$ g/cm^3



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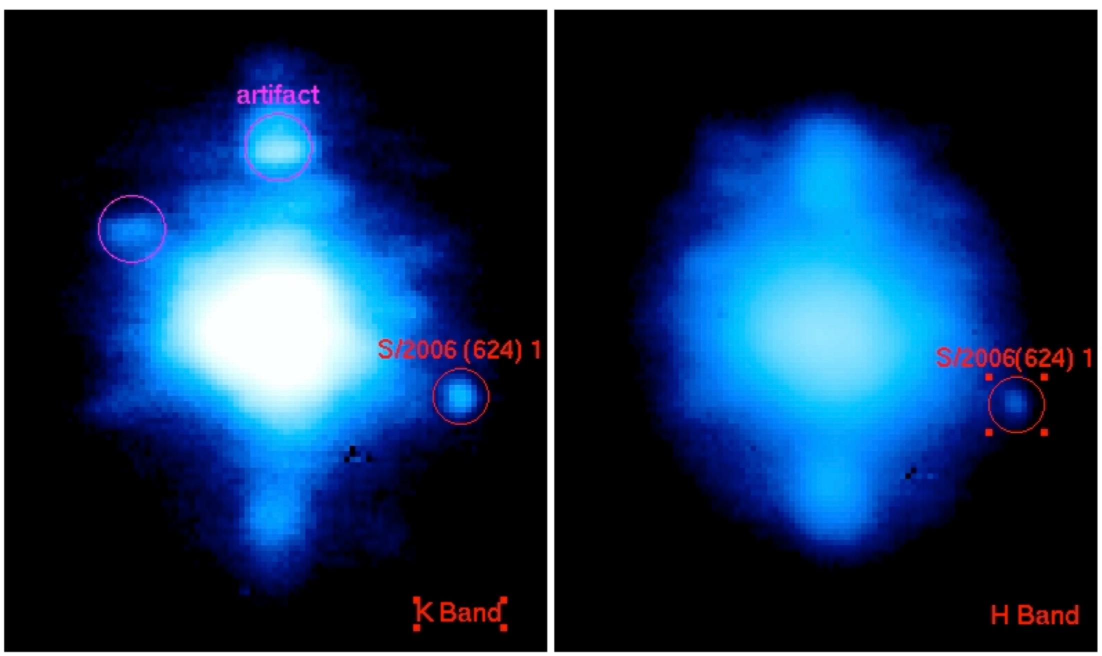

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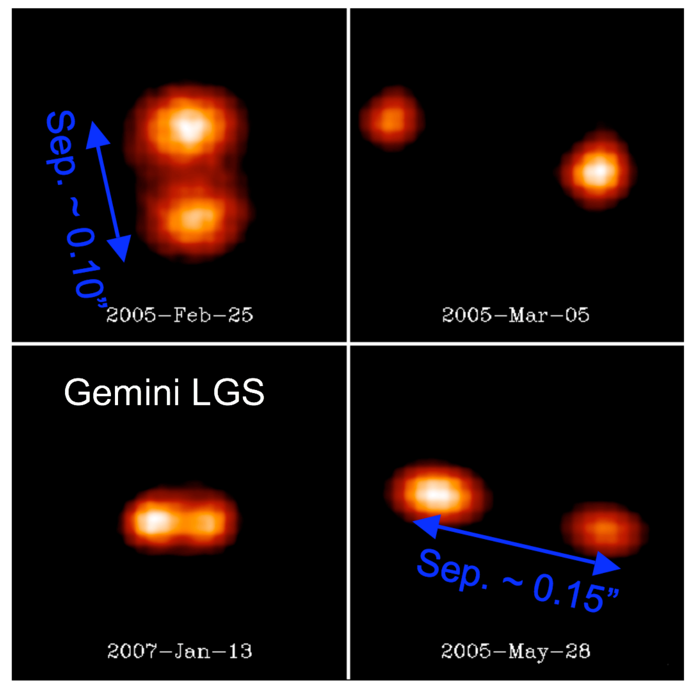
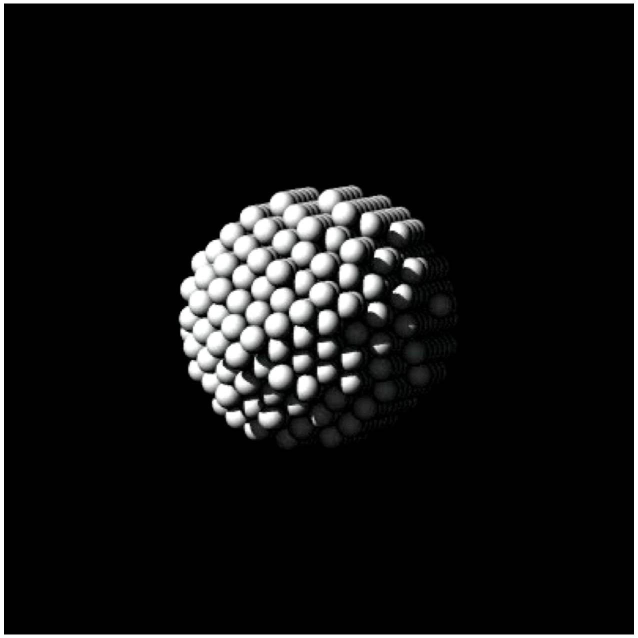


Trojan Asteroids: a dual population?

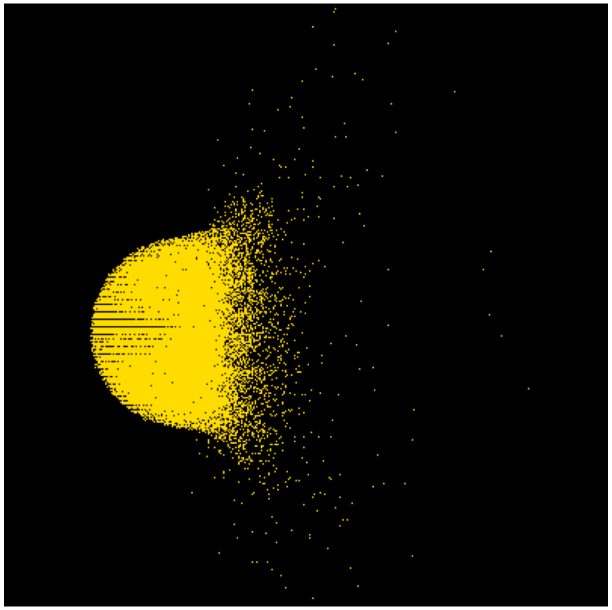
ρ(L4-Hektor) ~ 2-3 × ρ(L5-Patroclus)

617 Patroclus is a captured icy doublet asteroid ⇒ result of tidal splitting after a close encounter with Jupiter.



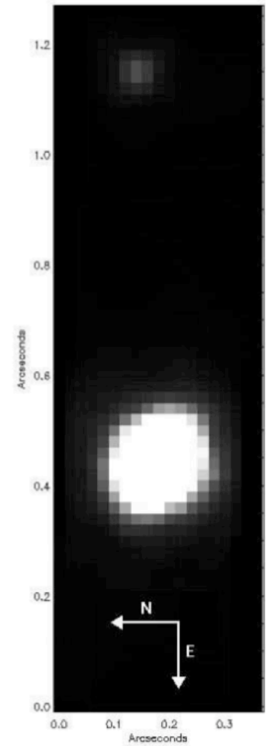
Tidal Splitting Simulation (Walsh & Richardson, 2005)
- 110,500 simulations
- a ~ 5-10 x R_p
- Δmag~0.1-0.2
- e>0.1 (but e~0 by damping)

- 624 Hektor is a rocky, fractured/rubble pile, and bilobated asteroid with a 10 km-moonlet ⇒ result of a catastrophic disruption of a parent asteroid



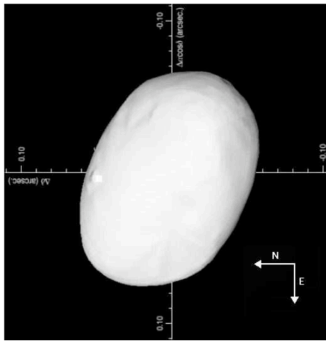
Catastrophic Disruption Simulation (Michel et al. 2000)
✓Irregular primary with rubble-pile structure R_p ~ 100 km
✓Small moonlet R_s~ a few km close to the primary (3-6 x R_p)

The Origin of Binary asteroid by comparative spectroscopy



if the moon and the asteroid formed from a parent body (catastrophic disruption or fission) they should have the same spectra. First attempt: 22 Kalliope and its satellite Linus

- Observations performed with Keck/OSIRIS IFU on March 25 2008
- data taken in Zbb, Jbb, Hbb, Kbb with R~3800
- First successful observations for (22) Kalliope, a binary asteroid with Δm=3.7 (Laver et al., 2009)



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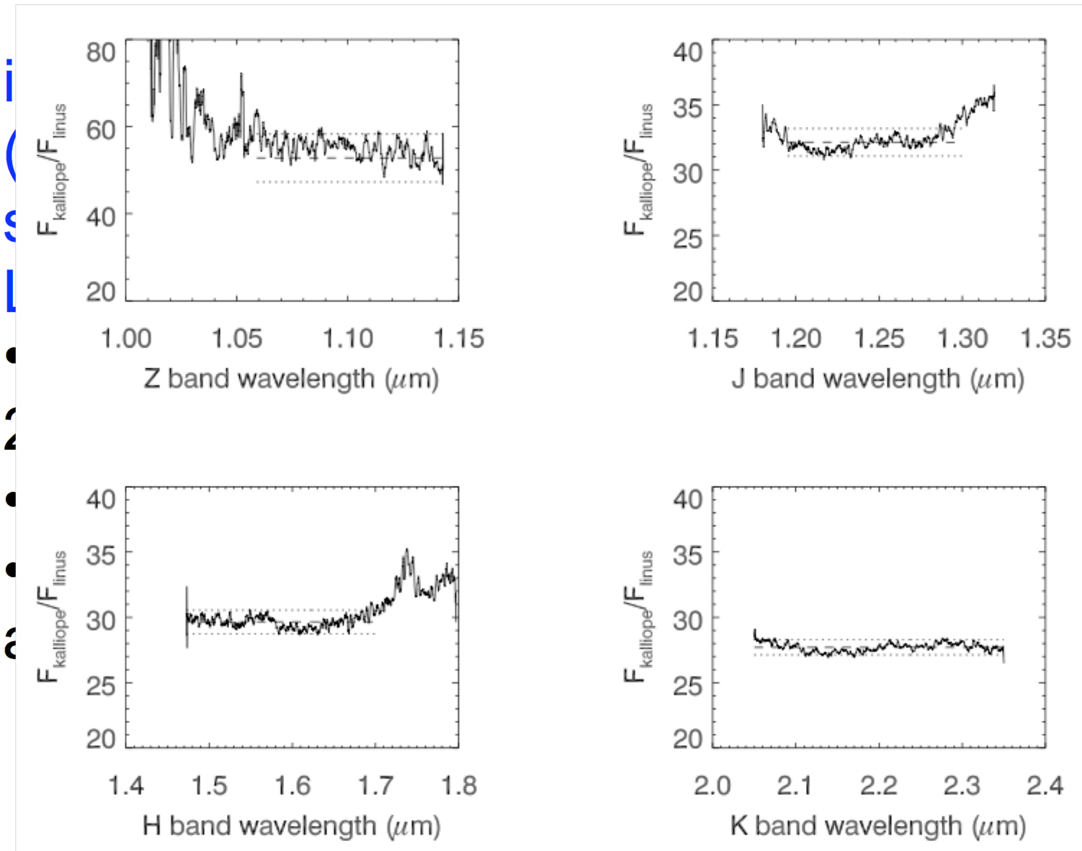
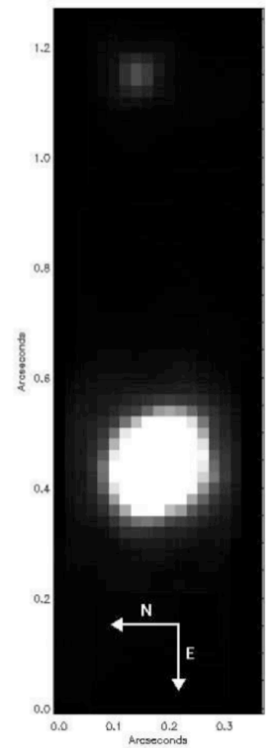
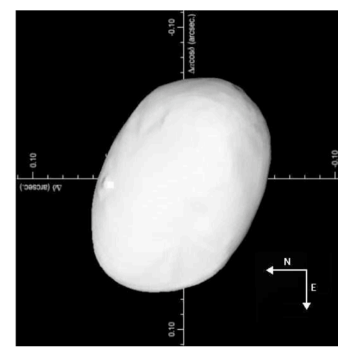


a parent body
ould have the
nd its satellite

- IS IFU on March 25
- ~3800
- lliope, a binary

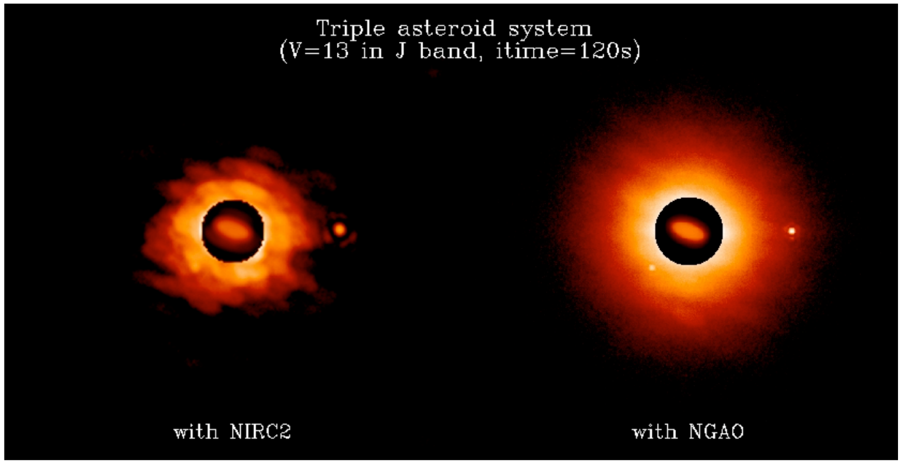


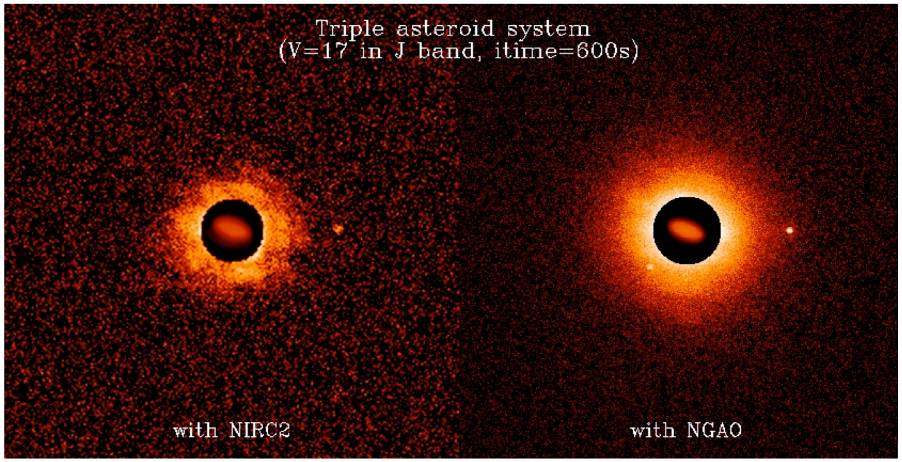


Spectra are remarkably similar implying that the two bodies formed at the same time from the same material

Next Generation of AOs for Planetary Science

- Future AO instruments
  - Better angular resolution (Visible AO or larger aperture)
  - Better sensitivity (high SR ~70-80%)
  - Enhance sky coverage
  - Imaging and spectroscopic observations





Conclusion: The Wedding Cake of the Multiple Asteroid Study

Space Missions?

?

Mid-IR telescopes

Thermal Inertia

1 measurement only
-> surface characteristic, age

Combined effort
Lab

Bulk Density & Porosity

20% have bulk estimate (30% accuracy)
-> Interior and formation

AO with IFS

Comparative spectroscopy

Only 1 (Kalliope & Linus), color measurements
->Formation mechanism

1-8m spectro

Integrated spectroscopy

24% have taxonomic class, 14% have NIR spectra
-> Composition, meteorite analogs

LC
Stellar occ.
NGAO/TMT

Size and shape of the companion

Rough estimate (50% accuracy) for 60% of them
-> Evolution due to Tidal effect, Formation

AO
LC
Radar

Size and shape of the Primary

Work in progress ~20% have size estimate, <5% shape
-> Formation and Bulk density

AO
LC
HST

Mutual orbits of multiple asteroid systems

40% have estimated Mutual orbits -> Mass
Constraints on Formation, age, and evolution

AO
LC
Radar
HST

Existence of multiple asteroid systems

Multiplicity rate: 10-15% for NEAs, 6% for D>40km MBA, 4% for Jupiter Trojan
172 multiple systems known, including 4 triple MBA, 1 triple NEA, 1 triple TNOs