AO4ELT meets the Solar System:

The coming interplay between adaptive optics on ELT, space telescopes, and spacecraft missions.

Al Conrad, Christian Veillet, Antonin Bouchez, Warren Skidmore, Fraser Clarke, Carmelo Arcidiacono

Outline of the Talk

- Mission support for spacecraft probes –
  - Motivation for using HAR from the ground
- Two examples – past and current with 8-10m apertures
  - ***Rosetta***: (21) Lutetia
  - ***Journey to a Metal World:*** (16) Psyche
- Three possibilities for future 23-39m apertures
  - ***Lucy***: 5 Trojans
  - ***Io Volcano Observer***: Io
  - ***Europa Clipper:*** Europa
- Conclusions

Case Study

Motivation

Space agencies (NASA, ESA, etc) often fund high angular resolution at large observatories.

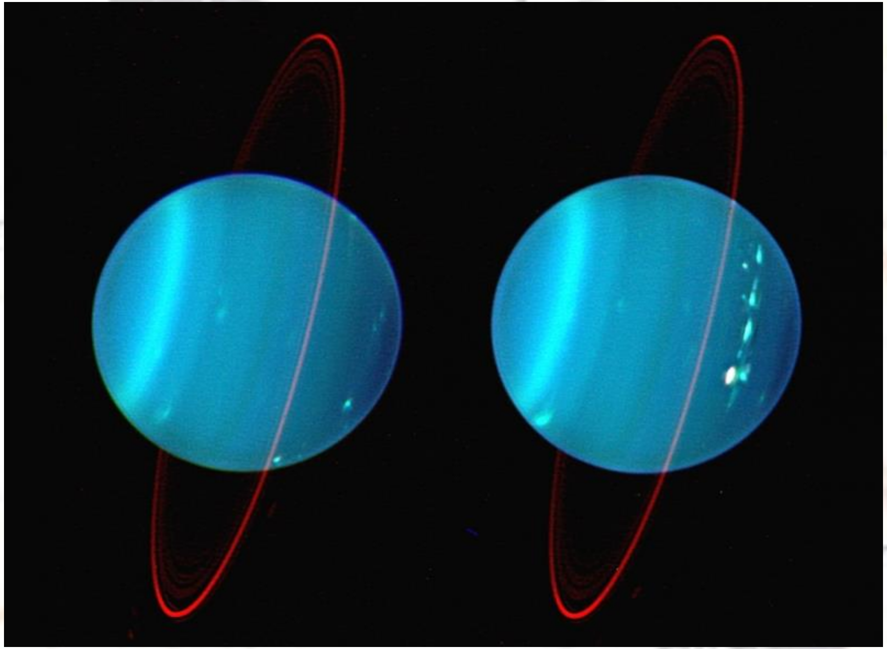
- NASA funded GB/HAR for TPF target survey
  - Keck II AO system
  - KI
  - LBTI HOSTS
- NASA funded and gave nights for hazard study for Deep Horizons pre-Pluto arrival
- Numerous Planetary Astronomy Grants to use HAR for small bodies research
- Many others …

Motivation

The number of missions for which NASA funding for ground-based support of spacecraft missions to small bodies has grown.

Mission	Number	Target	Vmag	Size (mas)
LUCY	3548	Eurybates	16.8 to 17.7	13 to 20
	15094	Polymele	18.9 to 19.8	5 to 7
	11351	Leucus	17.8 to 18.8	7 to 11
	21900	Orus	16.9 to 17.9	11 to 16
	617	Patroclus	15.9 to 16.5	33 to 39
	52246	Donaldjohanson	18.3 to 20.1	2 to 4
DAWN	145	Adeona	11.0 to 13.6	56 to 133
DESTINY	3200	Phaethon	10.2 to 19.1	4 to 101
Psyche	16	Psyche	10.9 to 12.2	85 to 156
TBC (Not U.S.)	469219	HO3 2016	21.5 to 26+	0.5
Osiris-Rex	101955	Bennu	21 to 23	2 to 3

Motivation



Adaptive Optics images of Solar System objects are usually used for early press releases

Rosetta visit to (21) Lutetia

About the mission

- Mission Name: *Rosetta*
- Agency: ESA
- Year: Launch – 2004; Encounter - 2010
- Target: Lutetia (fly-by en route to Comet C-G)

Science Goals:

- Satellite search
- Volume (for density)
- taxonomic type

Rosetta visit to (21) Lutetia

Physical properties of ESA Rosetta target asteroid (21) Lutetia:

The tri

Jack I

4. Rosetta flyby of (21) Lutetia

Finally, we investigate the regions of Lutetia that will be observed by Rosetta during the upcoming flyby on 2010 July 10. We used the shape model and spin solution described in section 3 and the spacecraft trajectory (obtained using the most recent spice kernels) to derive the relative position (SPK[6]) and orientation (PCK[7]) of Rosetta and Lutetia. This provides the relative distance between Rosetta and (21) Lutetia, the coordinates of the Sub-Rosetta Point (SRP) and Sub-Solar Point (SSP), the illuminated fraction of Lutetia surface, and the Solar phase angle as function of time.

At the time of the flyby, the northern hemisphere will

March 2, 2004
Launch

10

Rosetta visit to (21) Lutetia

- The ESA mission team used the HAR results for missioning planning.
- Shape models continued to use the HAR results after the flyby since the south was the space short flyb

Sierks et al. 2011). At the time of the Rosetta flyby, the southern hemisphere was in seasonal shadow, and observations at optical/near-infrared wavelengths were not possible south of -40° latitude. The detailed 3-D shape model derived from flyby

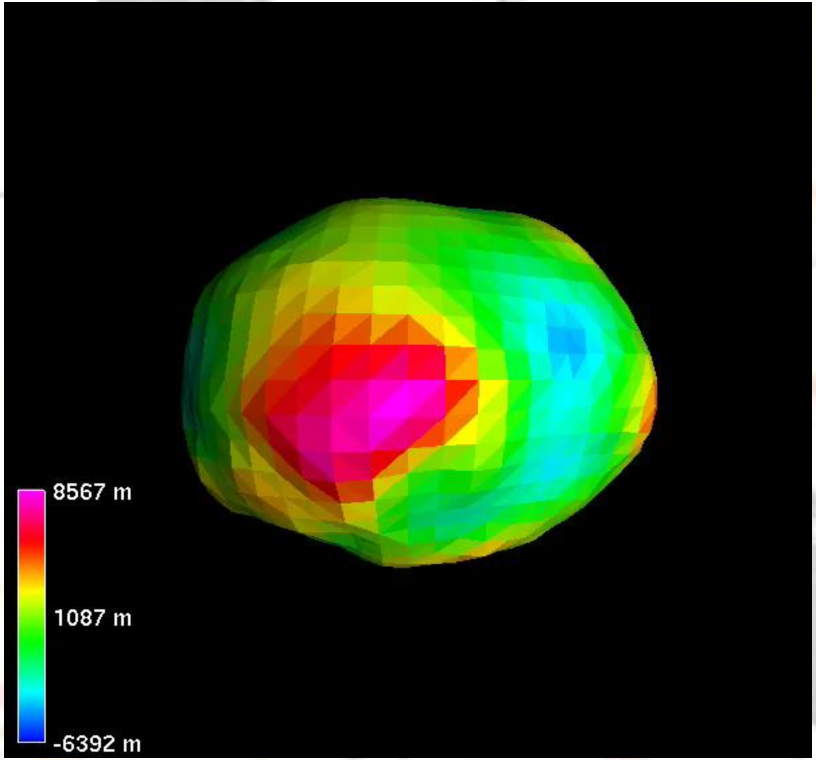
Discovery Mission to Psyche visit to (16) Psyche

About the mission

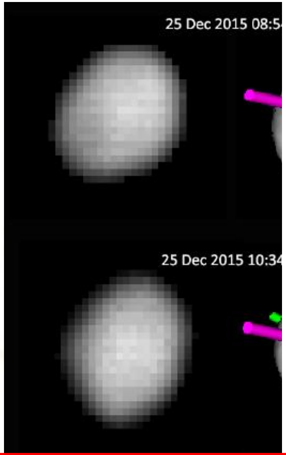
- Mission Name: *Psyche: Journey to a Metal World*
- Agency: NASA/ASU
- Year: Launch – 2022; Encounter - 2026
- Target: (16) Psyche – Orbit for 21 months

- Science Goals:
  - Planet core? Yes or no
  - Age
  - (Unusual) Composition

Discovery Mission to Psyche visit to <u>(16) Psyche</u>

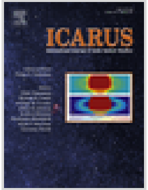


Discovery Mission to Psyche visit to (16) Psyche



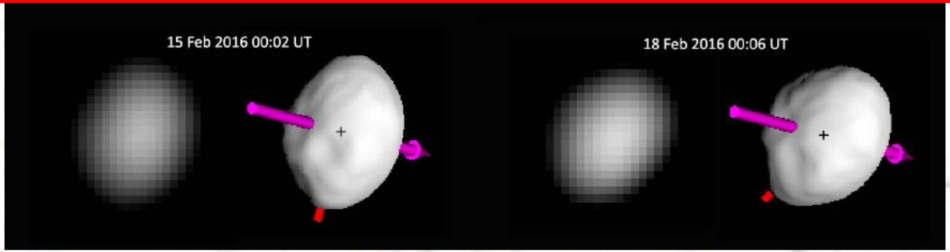
Icarus

Volume 281, 1 January 2017, Pages 388–403



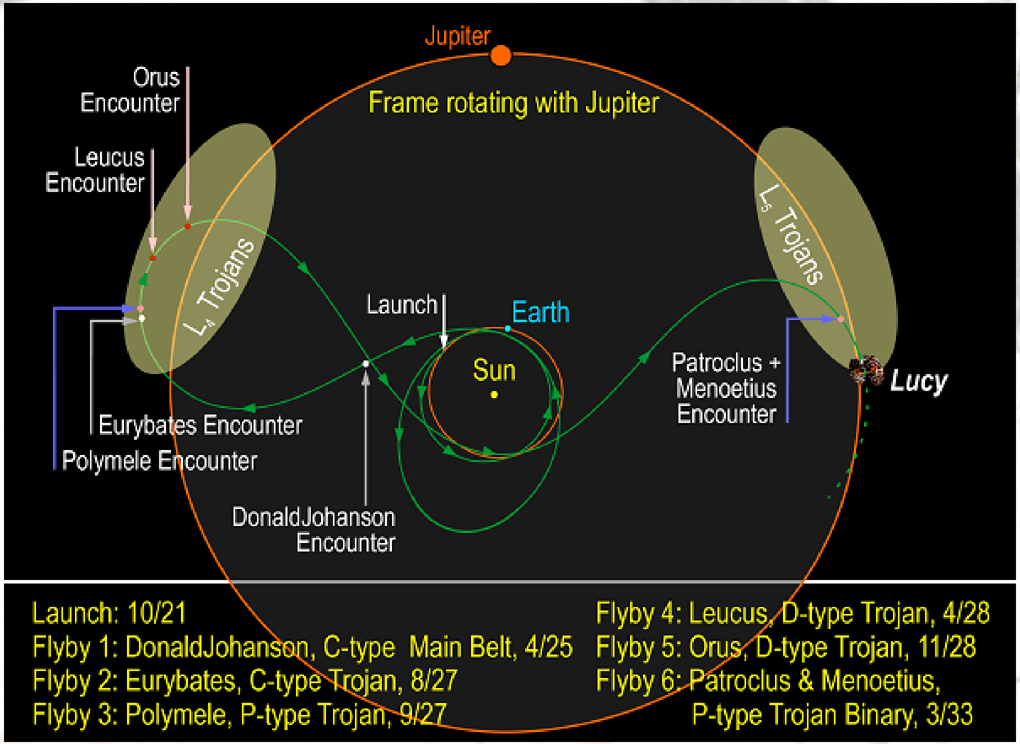
Radar observations and shape model of asteroid 16 Psyche

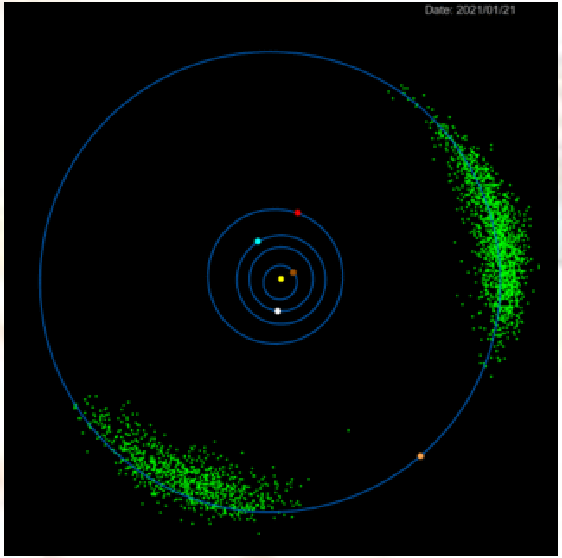
Michael K. Shepard[a], James Richardson[b], Patrick A. Taylor[b], Linda A. Rodriguez-Ford[b], Al Conrad[c], Imke de Pater[d], Mate Adamkovics[d], Katherine de Kleer[d], Jared R. Males[e], Katie M. Morzinski[e],



First published example of AO-in-the-visible on an asteroid.

Lucy visit to Trojans





Science Goals:

- Source of Trojan differences
- History of the Solar System

Lucy visit to Trojans

The probability that one of these is observable via appulse on a given night is ~20%, i.e.; one object per week.

Vmag	Size (mas)
16.8 to 17.7	13 to 20
18.9 to 19.8	5 to 7
17.8 to 18.8	7 to 11
16.9 to 17.9	11 to 16
15.9 to 16.5	33 to 39
18.3 to 20.1	2 to 4

The size and brightness range of the LUCY targets puts them out of reach for today's AO systems on 8-10m telescopes with NGS

With visible AO on GMT, TMT, and E-ELT we will measure:

- Measure shape and pole of the larger (10 to 20 mas) bodies
- Search for satellites around all 6

This will be starting 2023.

What might be done in the meantime?

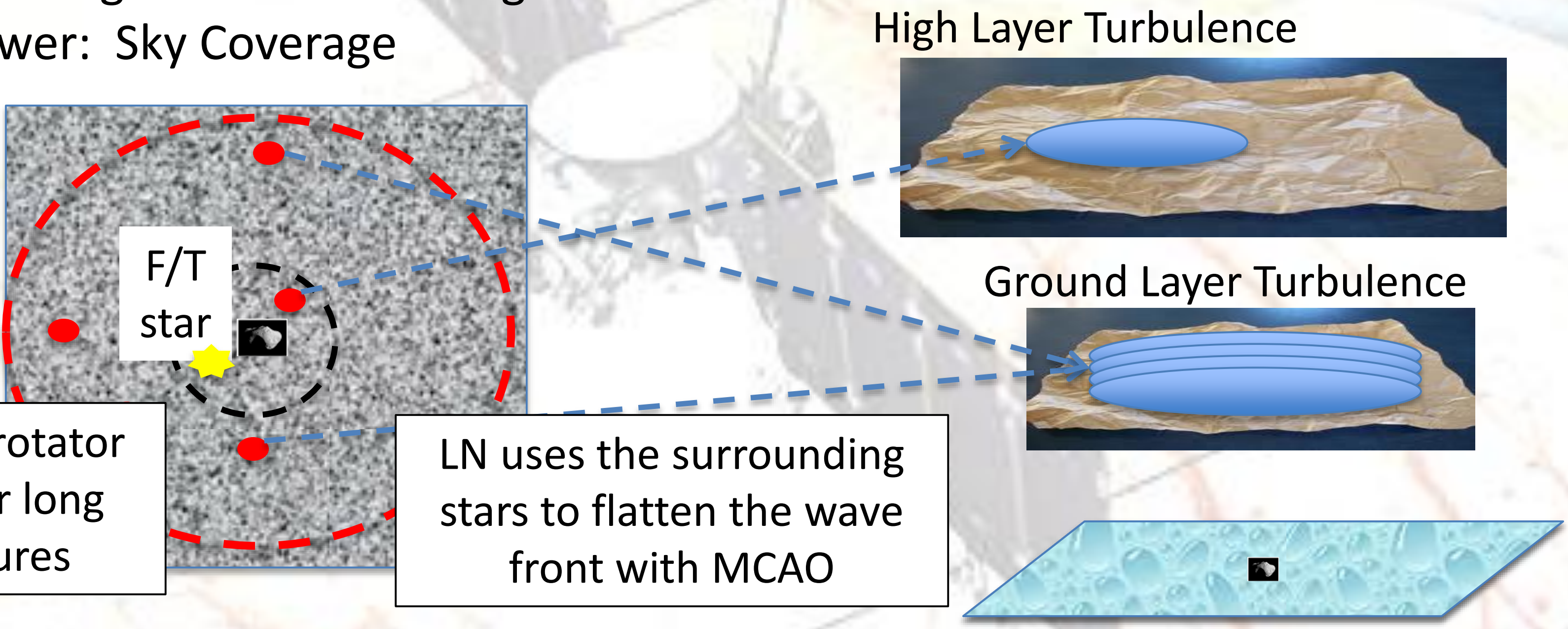
Vmag	Size (mas)
16.8 to 17.7	13 to 20
18.9 to 19.8	5 to 7
17.8 to 18.8	7 to 11
16.9 to 17.9	11 to 16
15.9 to 16.5	33 to 39
18.3 to 20.1	2 to 4

- 23m Fizeau Imaging on the *Large Binocular Telescope* could fill the 2018 to 2023 gap for observing the LUCY mission targets.
- With queue observing, 10 to 20 observations per semester.
- Approx. 5 to 10 hours total observing time.

- Two points about appulse observations:
  - Please future ELT designers: Provide smooth tracking AO probe for differential motion
  - At LBT, a goal for the other 23m imager, LINC-NIRVANA, is to provide greater grasp of appulse stars via MCAO

MCAO = Greater Sky Coverage

- What might be the advantage of LN?
- Answer: Sky Coverage



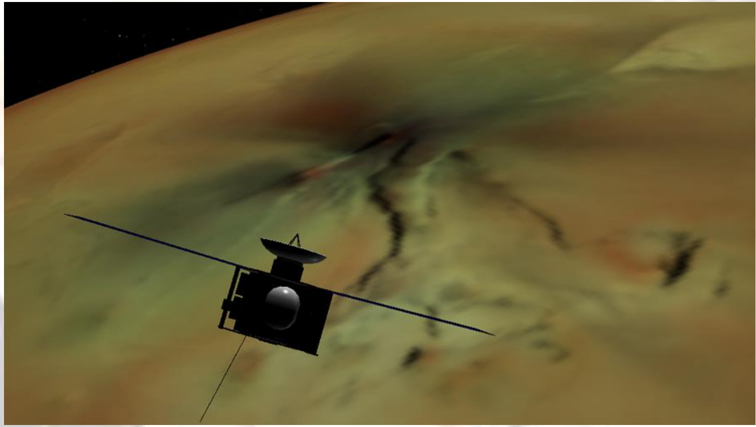
Also the rotator helps for long exposures

LN uses the surrounding stars to flatten the wave front with MCAO

Theoretically, this allows the fringe tracking star to be up to 45” distant.

IVO visit to Io

About the mission



- Mission Name: *Io Volcano Observer*
- Agency: NASA/UofA
- Year: Launch – ??; Encounter – 6 years to encounter
- Target: Io (from 22-month Jupiter orbit)

Science Goals:

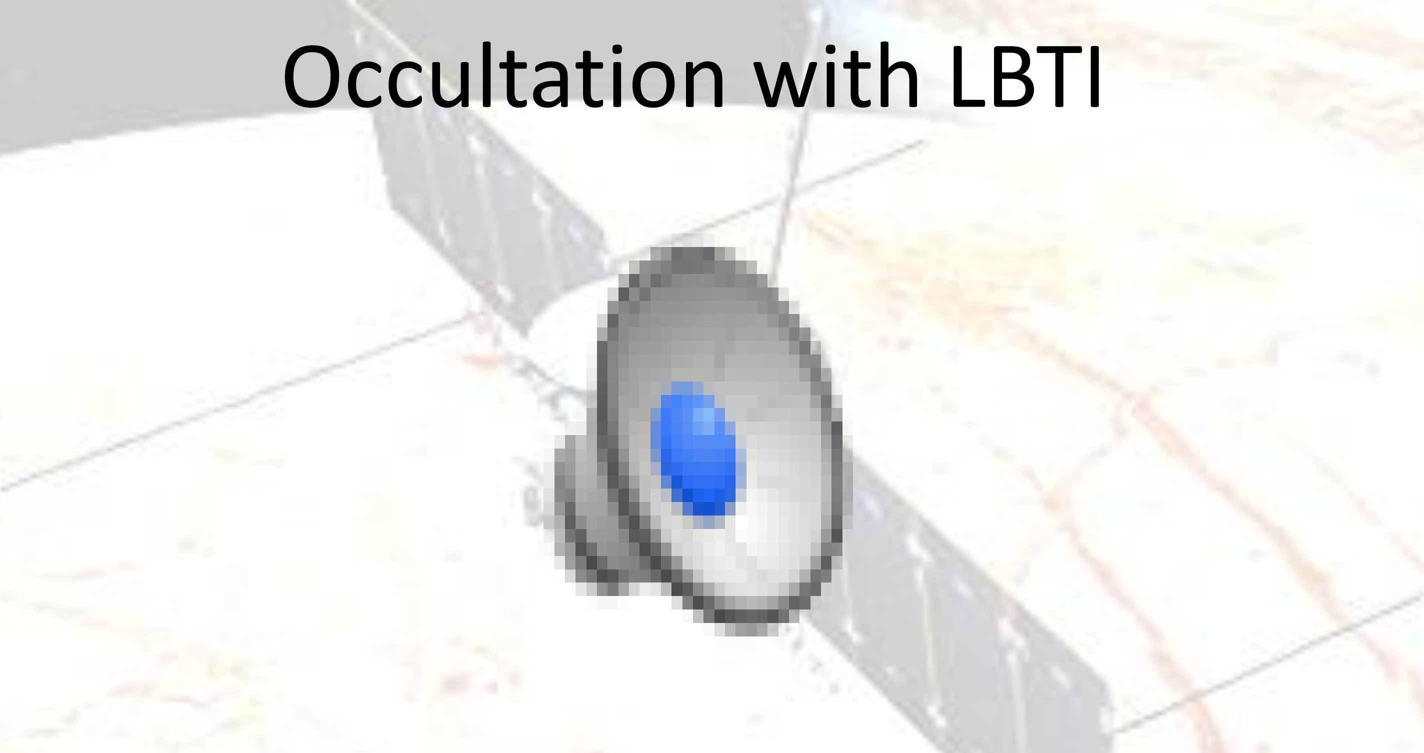
- Understand volcanism
- Understand interior
- Effects on Jovian system

How will we observe Io at HAR using ELT?

- In sunlight at M-band
  - Occultation
  - Normal imaging
- In eclipse at K-band

With LBTI we have performed each of these.
(Nature, de Kleer+ & AJ, Conrad+)

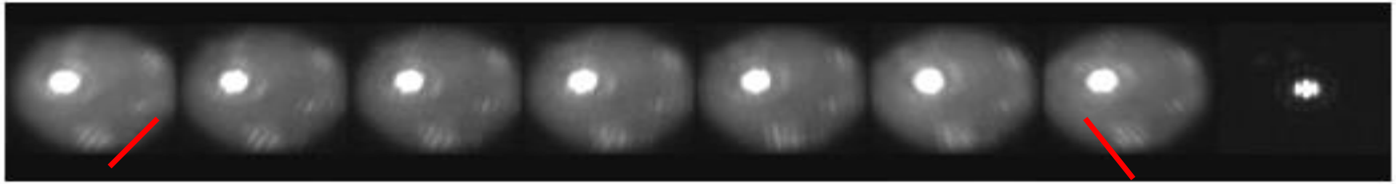
Occultation with LBTI



- 4.8-µm
  - Water ice on Europa absorbs sunlight
  - Io's surface is reflective
- Phased 23m fringes allowed rapid sampling

De Kleer et al., *Nature* **545** (2017)

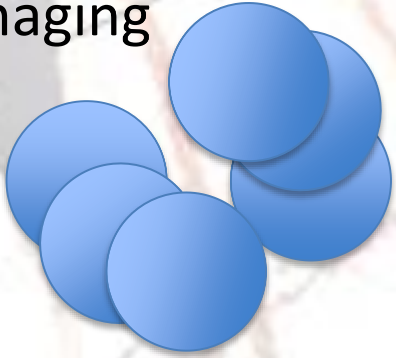
Fizeau Imaging with LBTI



We observed Io with LBTI for ~~one hour~~ on Christmas Eve 2013

Epoch	Time (UT)	Hour Angle	Air-mass	SEL	Mean Parang
1	07:53	−0.47	1.022	286.59	−30.0
2	07:59	−0.37	1.020	287.44	−22.2
3	08:06	−0.25	1.018	288.43	−15.9
4	08:13	−0.13	1.016	289.42	−07.5
5	08:24	+0.05	1.016	290.97	+04.1
6	08:35	+0.23	1.017	292.53	+16.3
7	08:47	+0.43	1.021	294.22	+29.1

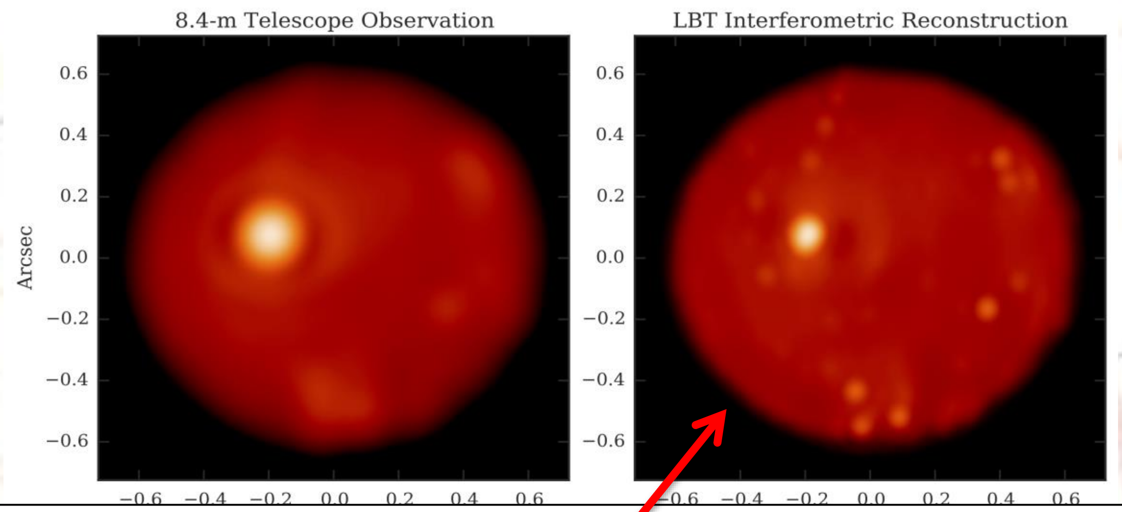
This value is critical for Fizeau imaging



Conrad, et al *AJ* **149** 175 (2015)

Fizeau Imaging with LBTI

The resulting image provides better than twice the resolution achievable on a telescope with a single 8.4 meter aperture.

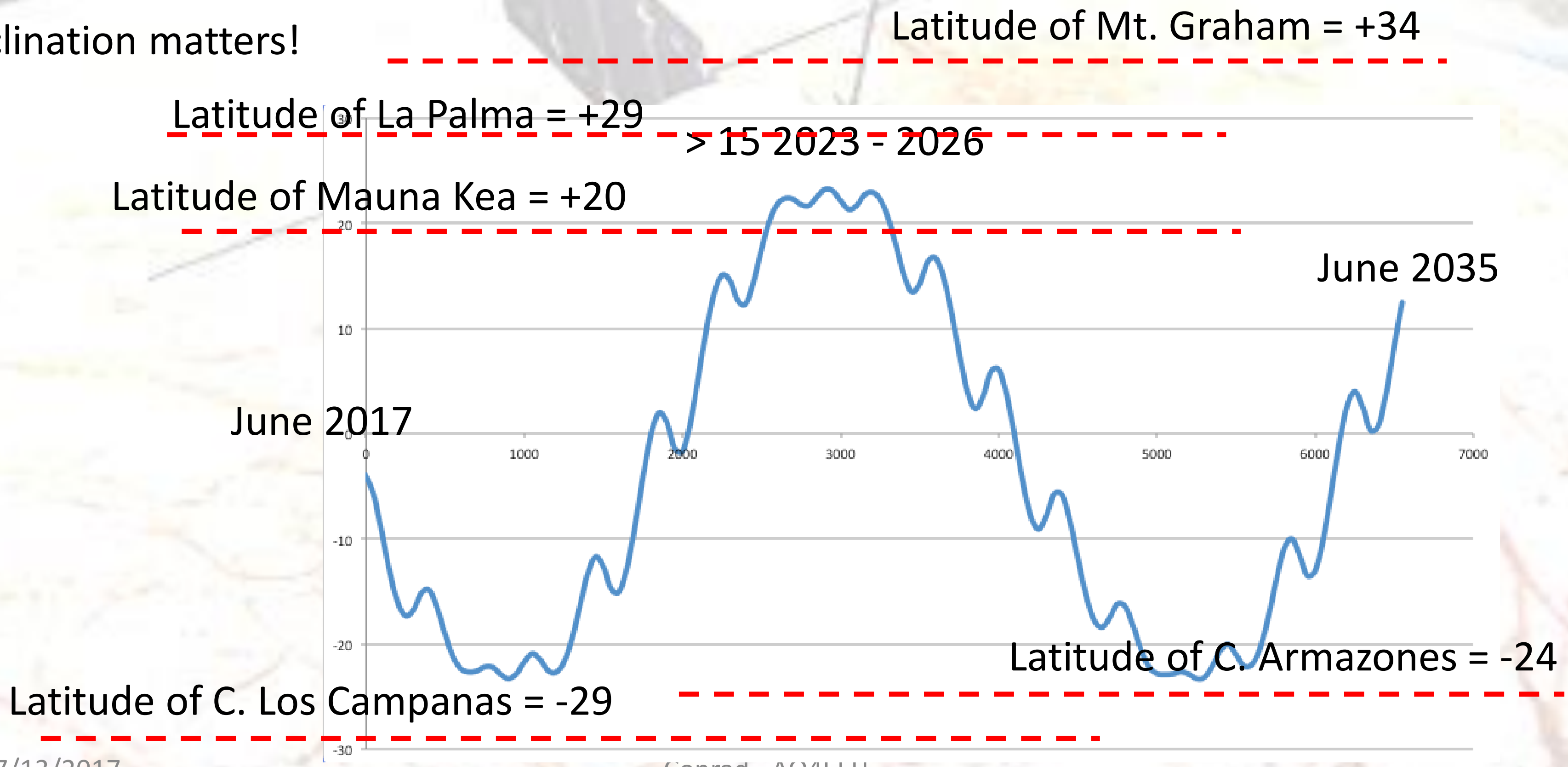


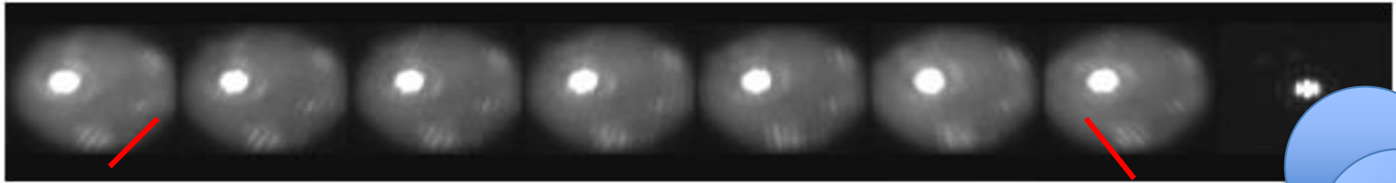
The resolution in this M-band image is like K-band on 8-10 meter telescopes (at K-band most volcanoes are invisible)

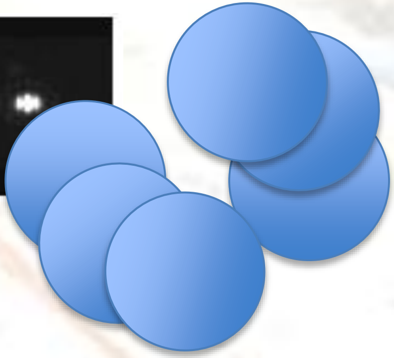
Conrad, et al *AJ* **149** 175 (2015)

How might Io be observed with 23-39m apertures in the future?

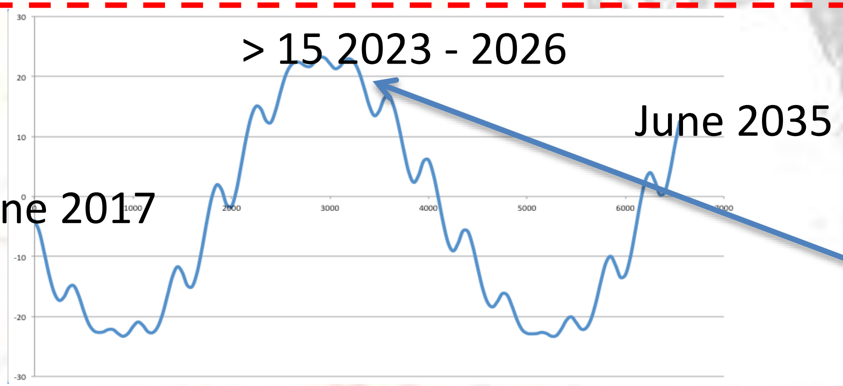
Declination matters!



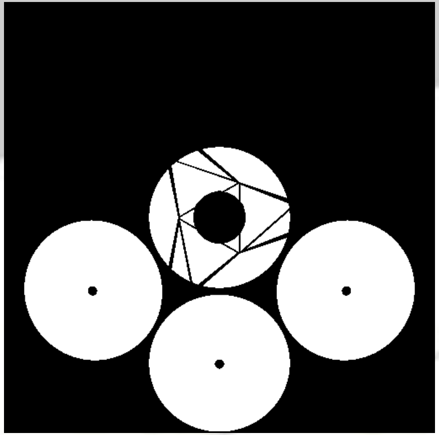


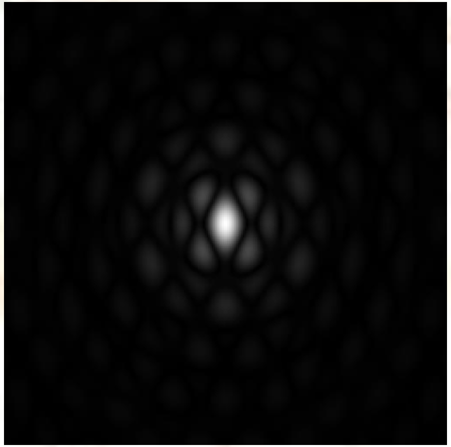


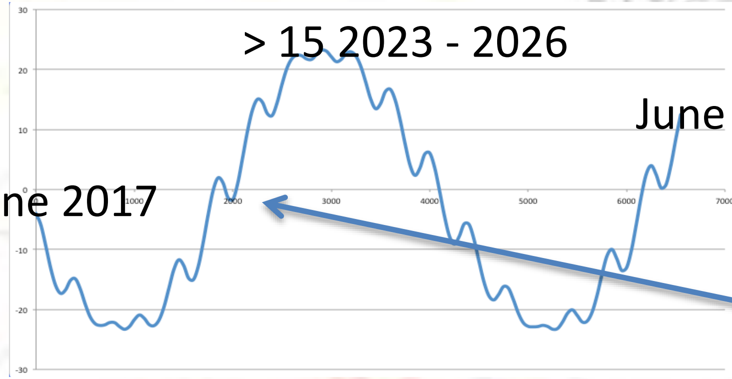
Latitude of Mt. Graham = +34



To make a complete image with LBTI we must observe here





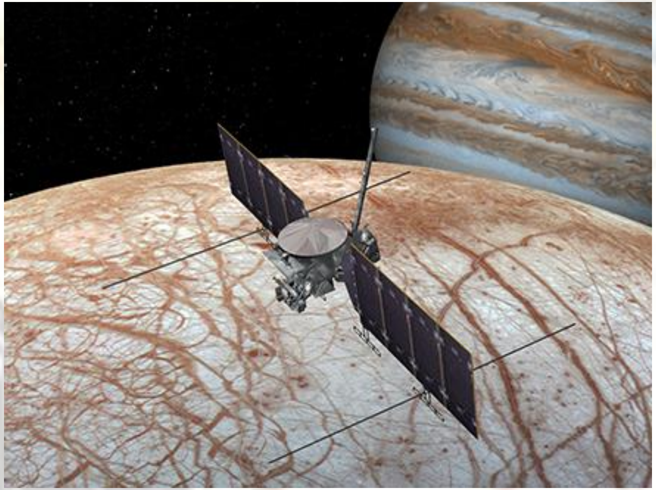


Latitude of C. Los Campanas = -29

Perhaps GMT could use this window with their first light configuration?

Europa Clipper visit to Europa

About the mission



- Mission Name: *Europa Clipper*
- Agency: NASA
- Year: Launch – ~2025; Encounter – ~2030
- Target: Europa

Science Goals:

- Understand the ice shell
- Understand formation processes
- Determine habitability

!!!!! →

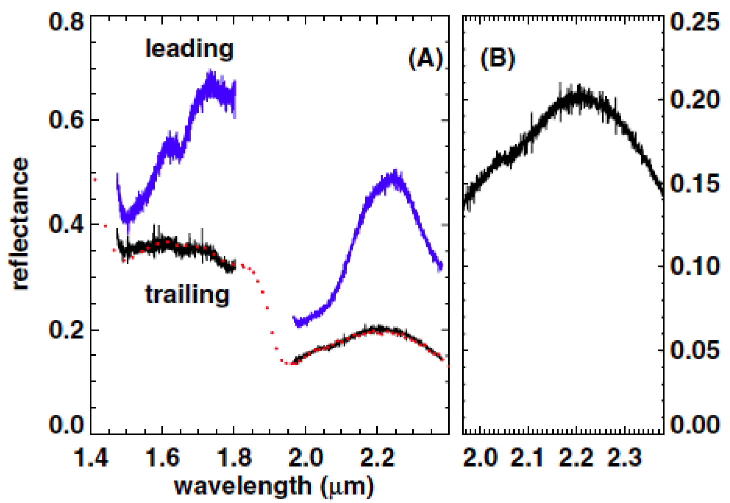
NASA is now, for the first time, directed to search for life and Europa is one of the targets of interest for this search.

How Congress Sneakily **Directed NASA** to **Look** for Alien **Life**
Inverse - 13 jun. 2017
Back in May, when President Donald Trump signed a bill to authorize funding for **NASA** over the 2017 fiscal year, the takeaway was that the ...

So that why is Europa an ideal case study?
Could all four 23-39m facilities observe Europa?

The ideal capability would provide spectra, at moderate spectral resolution, but at ***high spatial resolution***

Ground-based HAR result: *Salts are confined to the trailing hemisphere of Europa.* (Brown and Hand, AJ, 2013)



How might the four facilities make a concerted effort to provide NASA with key data for mission planning ahead of the 2025+ EC launch window?

Can our meeting here in Tenerife become the beginning of a collaborative effort to observe Europa in time for "the Clipper"??

- GMTIFS on GMT, IRIS on TMT, ELT-IFU on E-ELT
- With AO fed systems using natural guide stars and LGS for MCAO.

Conclusions

- Non-sidereal observations at high angular resolution benefit first light AO systems.
- The Rosetta mission and mission to Psyche stand as good examples of collaboration between space- and ground-based missions.
- For the future, the LUCY and IVO missions are both naturals for ground-based support.
- With the new direction to NASA to search for life, the Europa Clipper mission provides an especially good opportunity for the developers of ground-based AO systems to capitalize on resources going into that effort.

Hidden Slides Follow

What can be learned about Europa from the ground with high spatial resolution imaging, and maybe also low resolution spectroscopy,between now and the arrival of Europa Clipper (~ 2035 (??)) using 23m to 39m aperture?

what might be specialized time frames for individual facilities.

For example, for LBTI there are 2-3 year intervals every 11 years when the Jovian system is far enough north in the sky to offer a good zenith distance for the rotational coverage needed.

That's not relevant for the filled aperture ELT, but there might be similar considerstions based on the latitude of the site, arrival of adaptive M2/M4,

Planned Examples w/26-39m (TMT)

<table>
<tr>
<td>Measuring the chemical composition of main belt asteroids</td>
<td rowspan="3">Science goal: Determine maps of the chemical composition of asteroids and satellites and create spatially resolved maps for larger targets.</td>
<td>Angular sizes of main belt asteroids are between <0.007” to about 0.6”.
Target brightness is 8 to 24 Mag.</td>
<td>AO fed near-IR medium resolution (>4,000) spectroscopy between 1 to 2.4 microns using natural guide stars and LGS for MCAO.</td>
</tr>
<tr>
<td rowspan="2">Determining the properties of asteroid satellites and primaries</td>
<td>Angular sizes of asteroid primaries between 0.01” to 0.35” at closest approach (~0.05 AU), brightness from V~8 to 20.</td>
<td rowspan="2">IFU observations of satellite(s) at Sloan z’ and JHK with R<8000. Satellite orbital periods are 10 to 40 hours. Integration times <2 min keep smearing to <<1 spatial resolution element.</td>
</tr>
<tr>
<td>Satellites separation from the primaries from 0.15” to 1.3” and angular sizes from <0.007” to 0.17”.</td>
</tr>
</table>

Solar system science with ELT+HARMONI

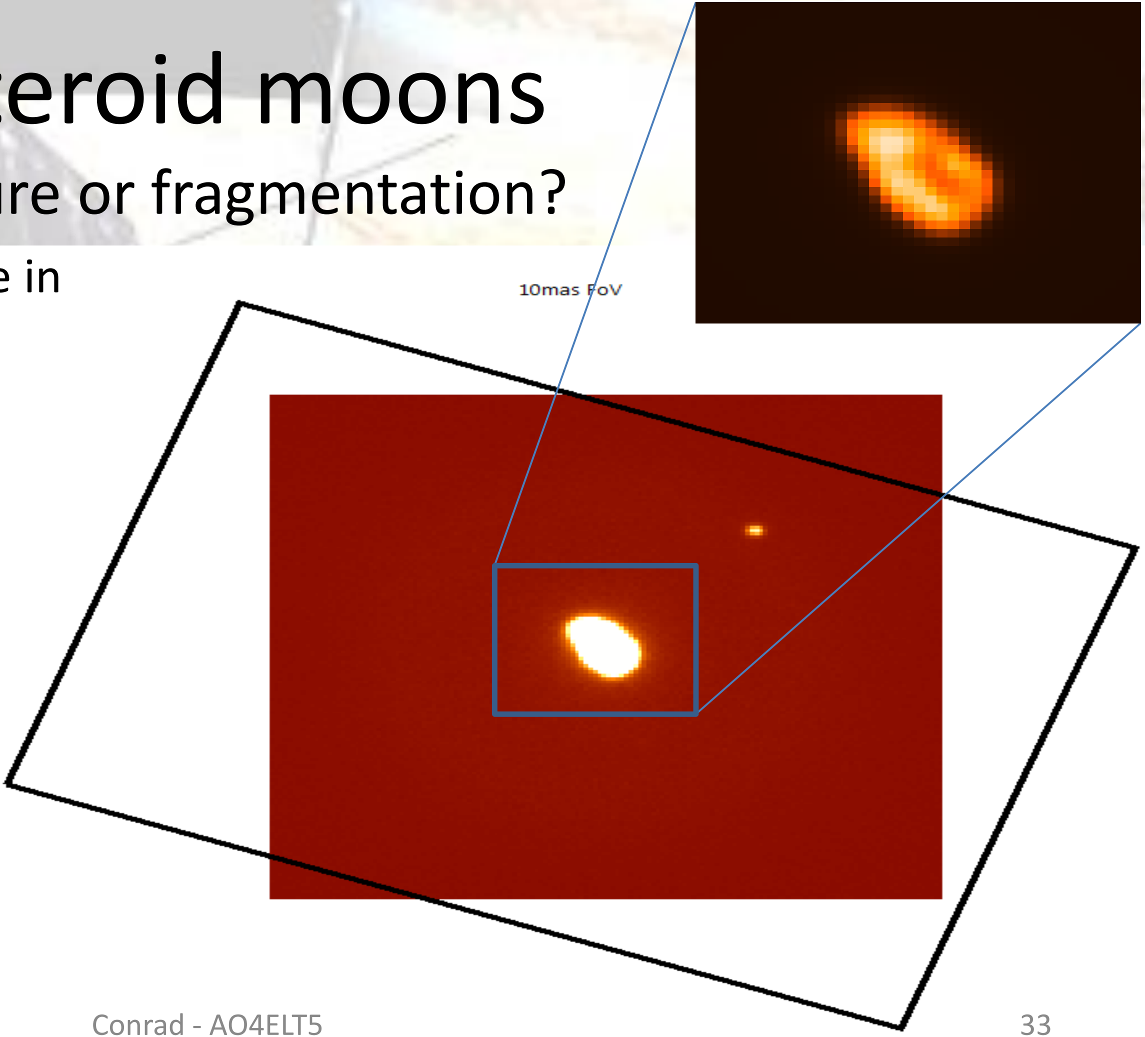
- Simulations based on model of HARMONI+AO performance
  - Asteroids + moons
  - Kuiper belt spectroscopy
  - Jovian moons
- Simulations using the “HSIM” tool [1]. Available for others to use

[1] http://www-astro.physics.ox.ac.uk/instr/HARMONI/Simulator/simulator.html

Asteroid moons

Capture or fragmentation?

- Simulation of 121 Hermione in August 2027
  - V=11.87
  - Dia=0.18”
- Known moon
  - ~5.3 mag fainter
  - 0.5” away
- Example observation with 1x120s exposures
  - Single channel in the K-band
  - 10mas scale

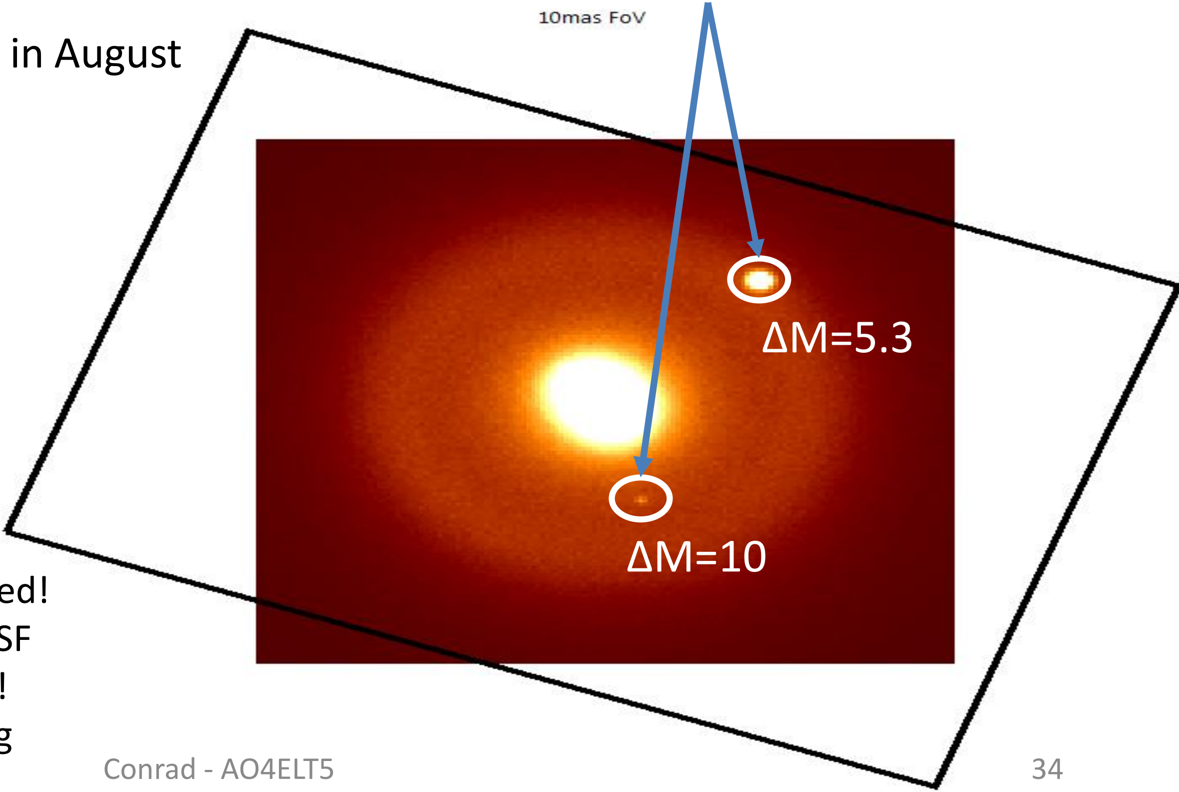


Asteroid moons

Capture or fragmentation?

Still to do: Extract spectra and see if we can recover the spectral types!

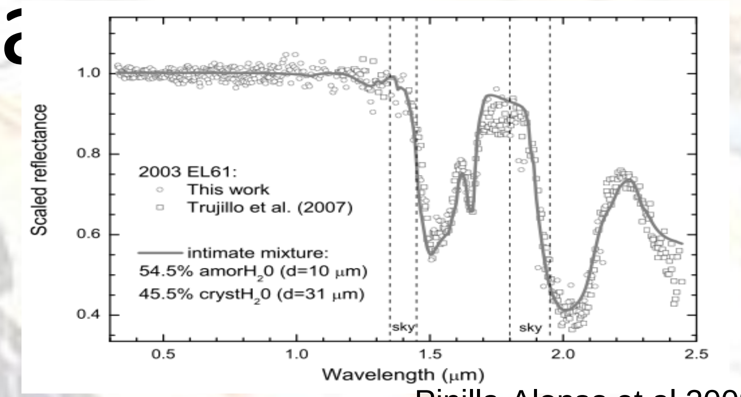
- Simulation of 121 Hermione in August 2027
  - V=11.87
  - Dia=0.18”
- Un-known moon perhaps??
  - ~10 mag fainter
  - 0.3” away
- Example observation with 20x120s exposures
  - Single channel in the K-band
  - Healthy pinch-of-salt needed!
  - Simulator uses a smooth PSF
  - No speckles included at all!
  - But also no post-processing



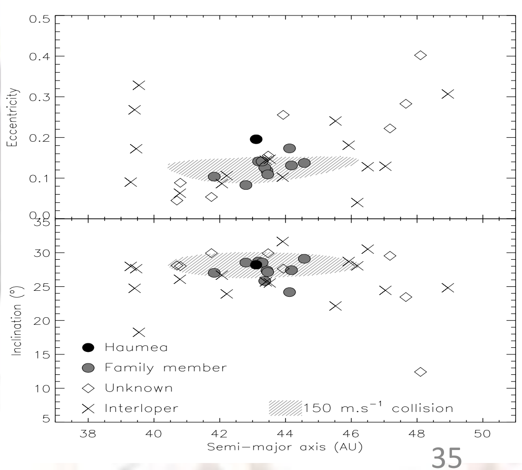
Courtesy of Colin Snodgrass

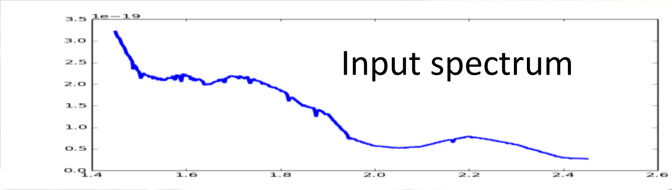
Haumea

- 136108 Haumea (or 2003 EL61) is one of the largest TNOs, but a strange one:
  - Two satellites
  - Fast spin
  - Elongated
  - (Almost) pure water ice surface
- May be the result of a collision, and discovery of dynamically / compositionally linked objects support this
- Most are too faint for spectroscopy on 8m
- Limited to follow-up via photometry

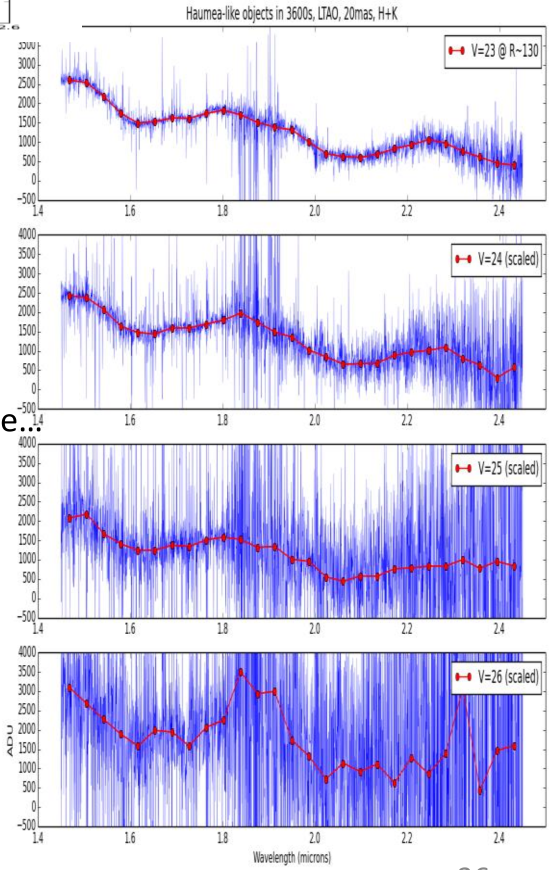


Pinilla-Alonso et al 2009





Observed sky subtracted spectra



V=23

V=24

~20km size object
Comet nucleus size…

V=25

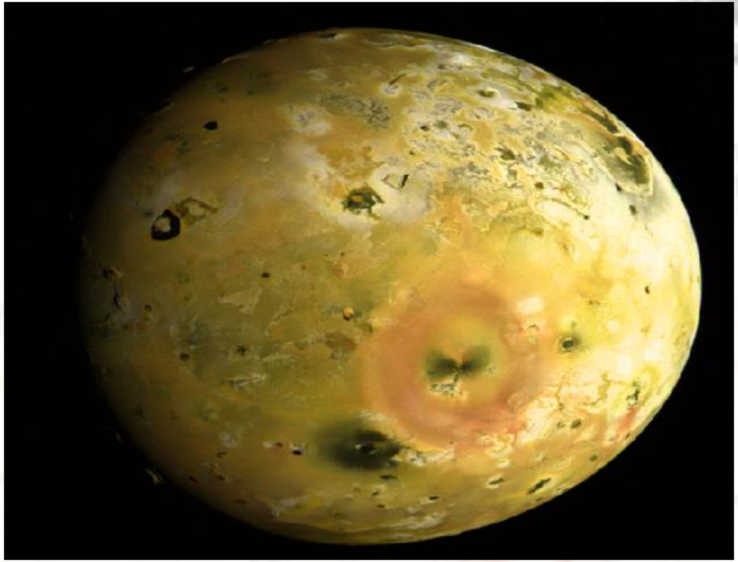
V=26

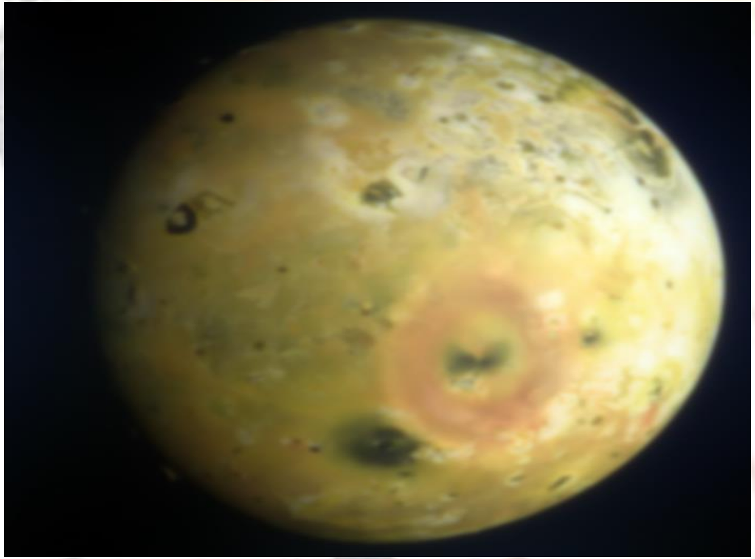
- 1 hour observation of Haumea spectrum scaled to V=23-26 magnitude
  - 20 mas spaxel scale
  - LTAO PSF
  - H+K R~3500 spectrum (blue line)
  - Rebinned down to R~130 (red line)
  - Simple 3 spaxel aperture extraction

- Feasible to measure surface compositions down to V~24-25

- Comparable to comet nuclei sizes in the Kuiper belt (depending on Albedo!)

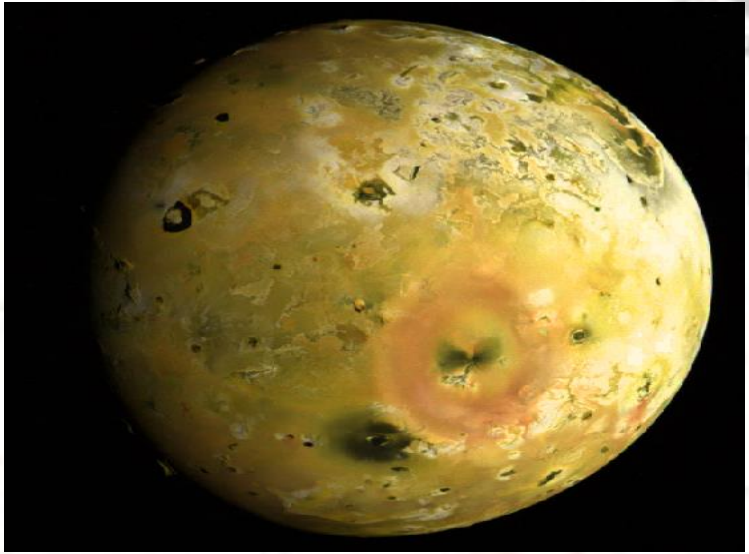
Galilean moons –

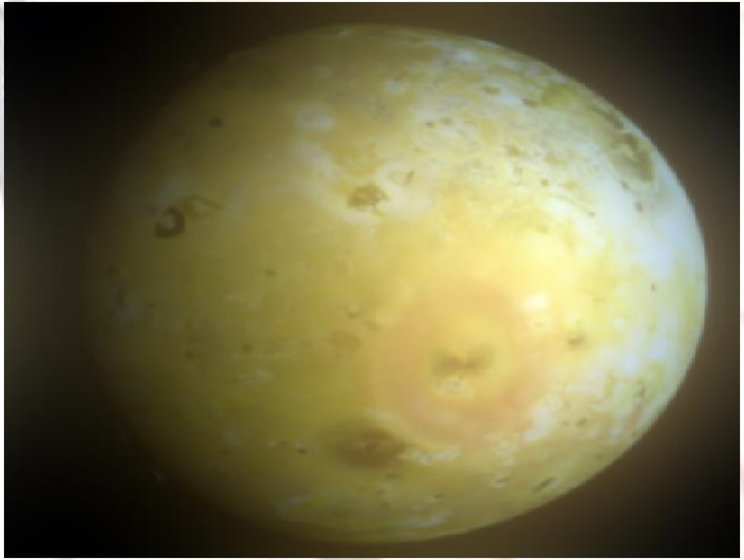




Galilean moons –

km / sp





Rosetta visit to (21) Lutetia

How was it observed from the ground with HAR …

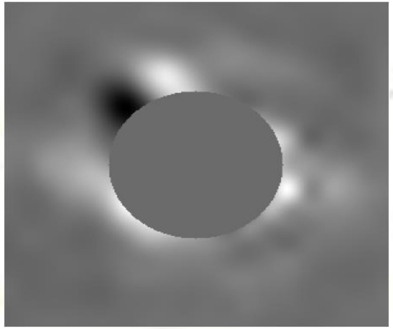
- HAR GB facilities: Gemini-N, Keck, HST
- HAR GB participants: Carry, Merline, …
- Non sidereal tracking method: ‘non-sidereal sidereally’
- Other special-for-nonsid caps needed? No

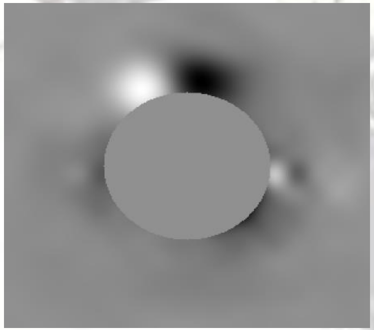
Pix of facilities go here (?)

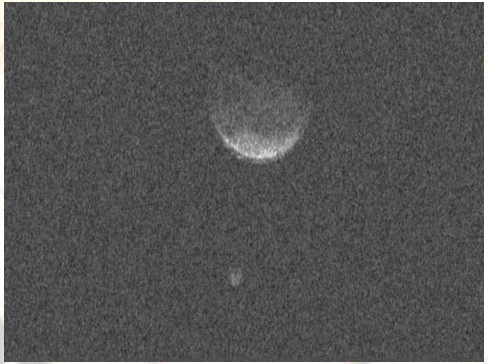
Past & Current Examples w/8-10m

Near-Earth Binary Asteroid 2003 YT1 30 Oct 2016

LBT direct imaging and radar



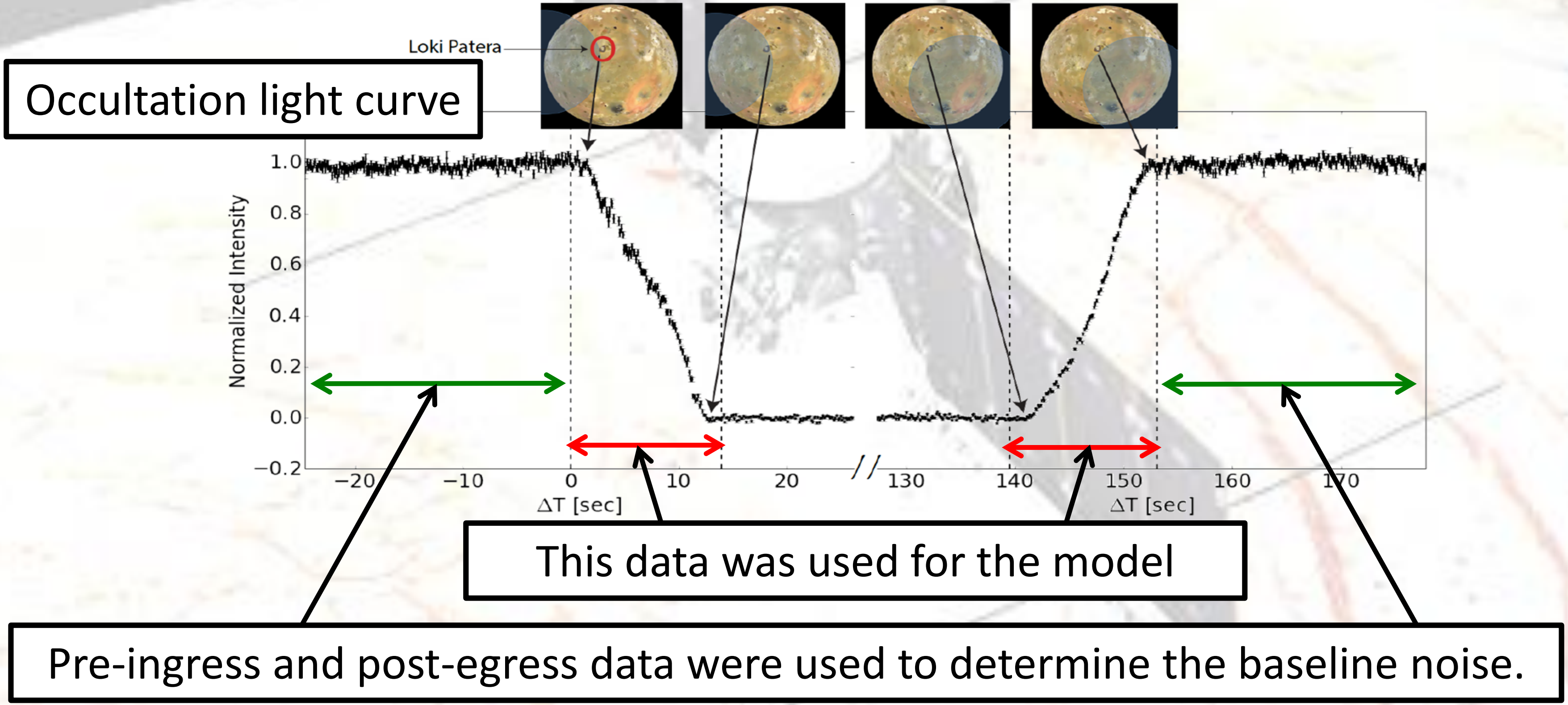




AO images of satellite, primary masked out for clarity. Left image shows mid-time image minus first image, right shows mid-time minus last image. Motion is combination of parallactic angle and satellite motion in its orbit.

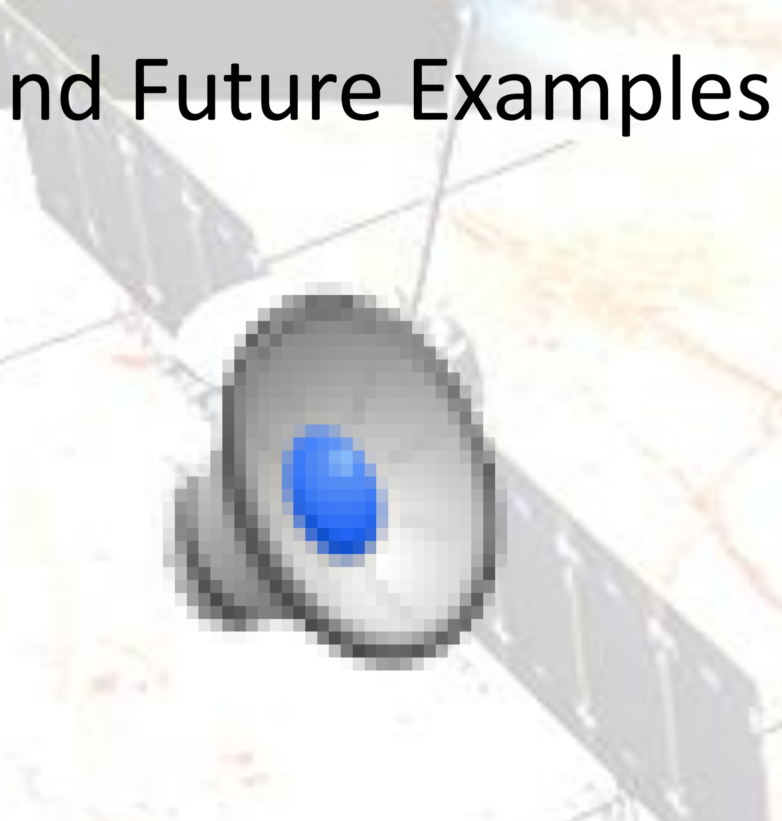
Arecibo Radar images from 30 October showing primary (top) rotation and satellite motion in the line of sight. Delay-Doppler image with distance from observer increasing bottom to top, Doppler velocity increasing left to right.

Current and Future Examples w/23m



De Kleer et al., *Nature* **545** (2017)

Current and Future Examples w/23m

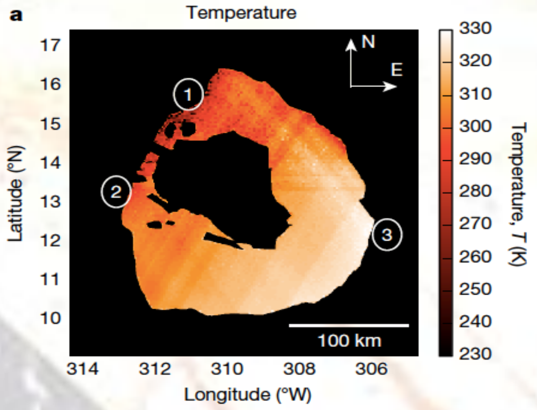


The model that will be shown in the subsequent slides fits well to the actual data as shown in this animation

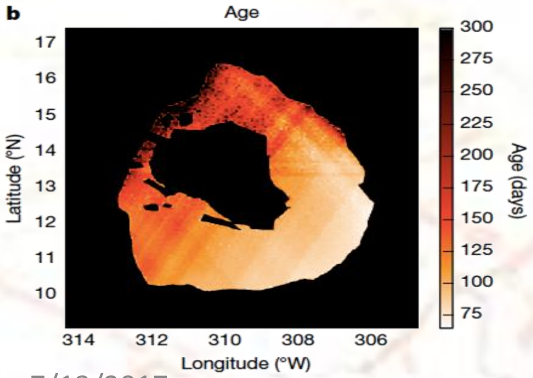
De Kleer et al., *Nature* **545** (2017)

Current and Future Examples w/23m

Through modeling, a temperature map was produced.



The surface is hottest when the magma is newly exposed, and gradually cools as a lava crust forms and thickens.

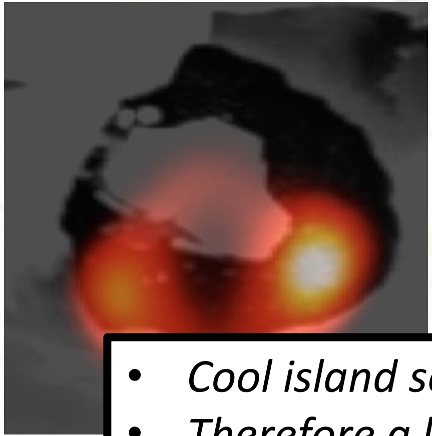


When this effect is quantified, a map of the resurfaced "age" (in days) can be produced.

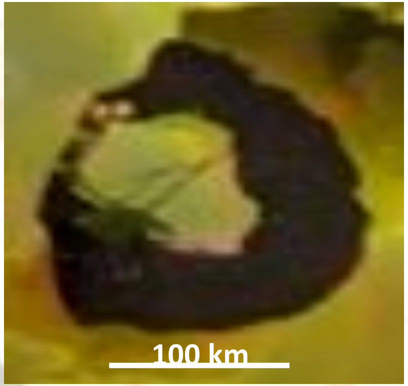
De Kleer et al., *Nature* **545** (2017)

Current and Future Examples w/23m

This is one of the best high resolution images we have from the *Voyager* mission



This is our M-band measurement overlaid on that image and smoothed to better indicate the achieved resolution



Credit: NASA PIA00320
March 1979

- *Cool island seen for first time since Voyager 36 years ago.*
- *Therefore a long-term fixture persisting for at least the 36 years.*
- *A result used in the following paper.*

Conrad, et al *AJ* **149** 175 (2015)

Current and Future Examples w/23m

A Contemporaneous JWST/LBTI Observation of Io

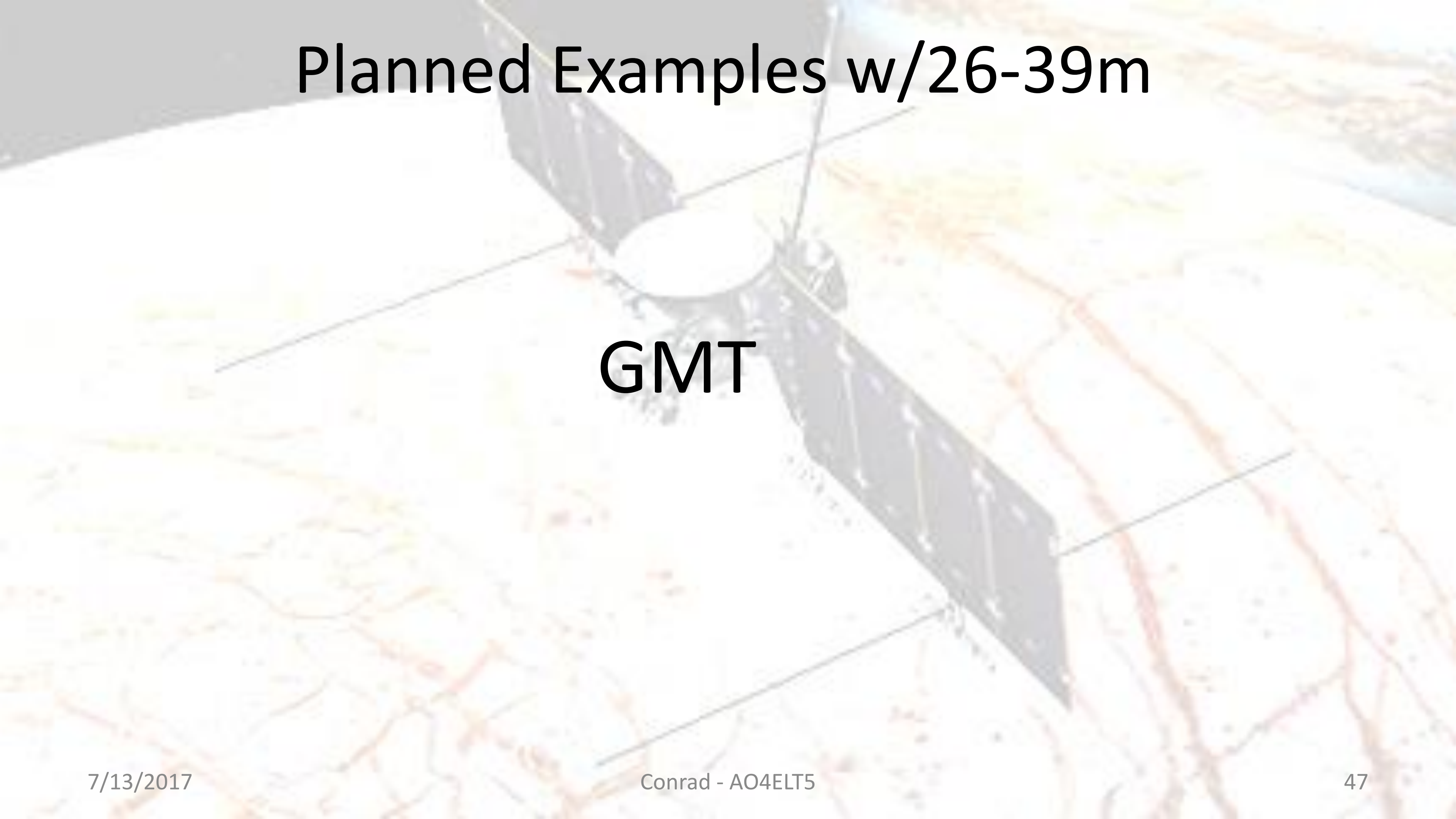
- Space-based apertures are historically about one third the diameter of ground-based
- They provide lower angular resolution, but excellent PSF stability (e.g., for photometry)
- Absolute photometry using any ground-based AO is accurate only to about 10%.

Current and Future Examples w/23m

A Contemporaneous JWST/LBTI Observation of Io

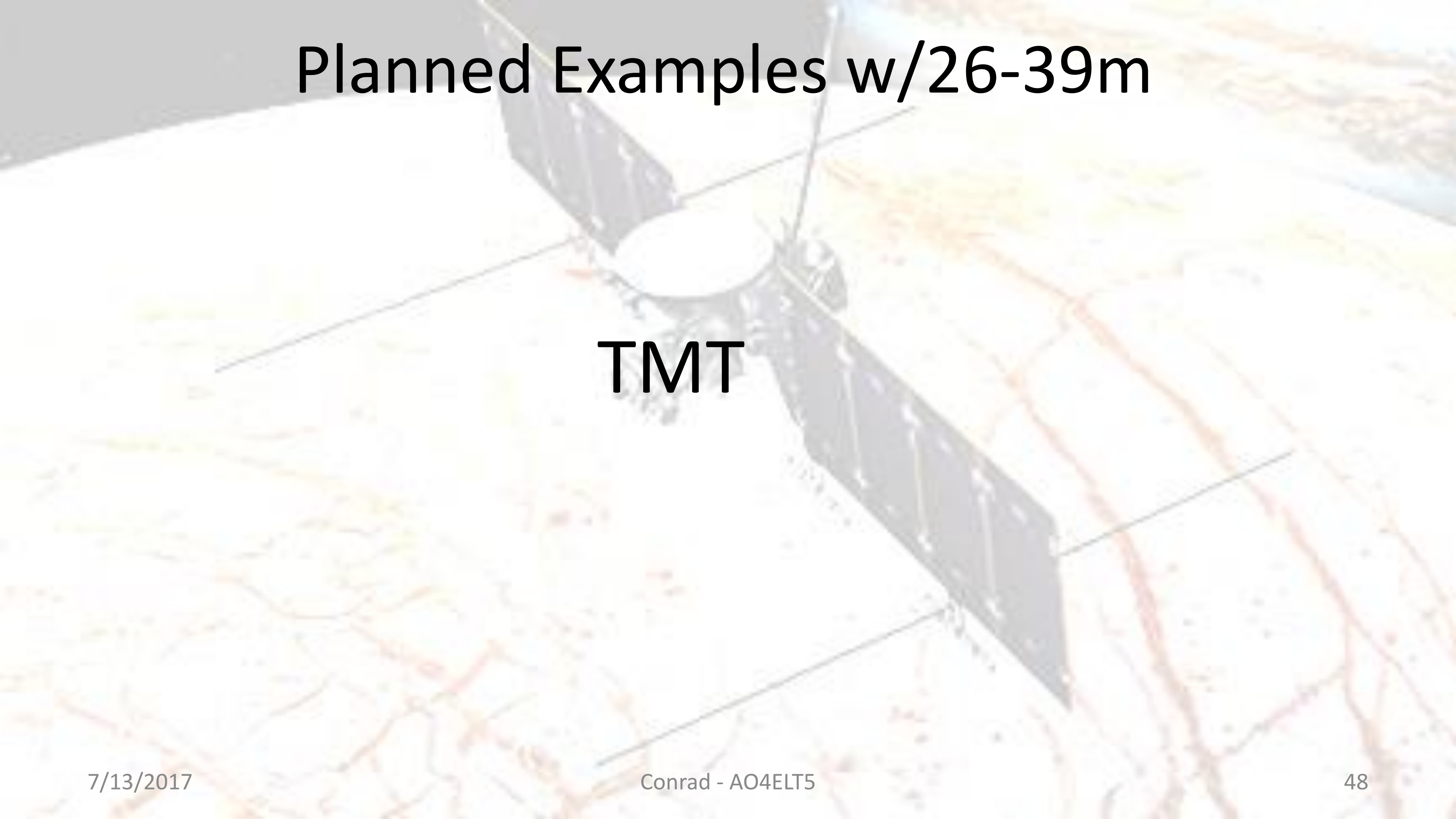
- We will propose for time to observe Io with LBTI contemporaneously with JWST
- We intend to get the best of both worlds: larger aperture and stable PSF
- Result: more hot spots at finer scale ***<u>and</u>*** with accurate photometry of each.

Planned Examples w/26-39m



GMT

Planned Examples w/26-39m



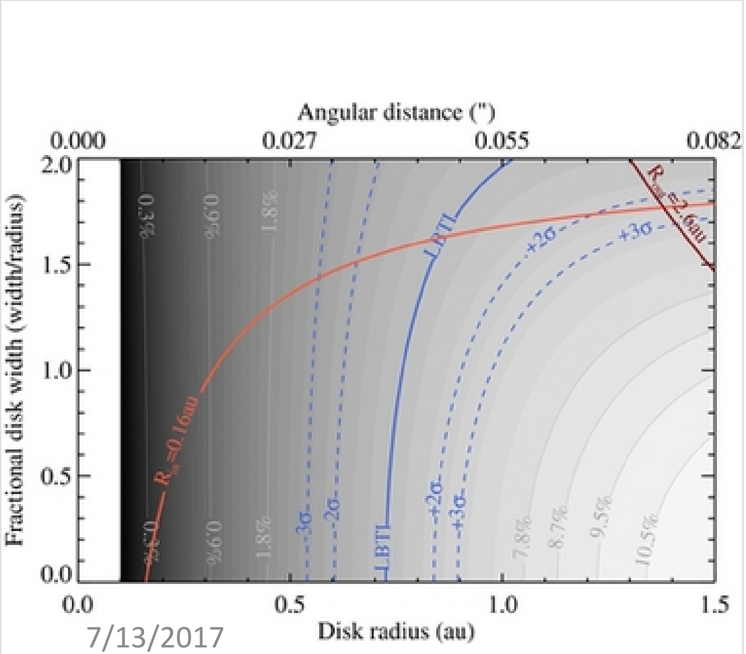
TMT

Planned Examples w/26-39m

E-ELT

Current and Future Examples w/23m

LBTI/HOSTS

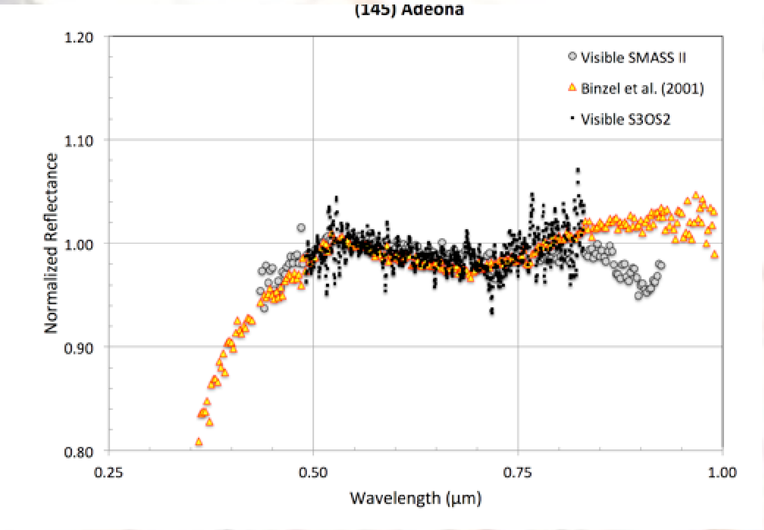


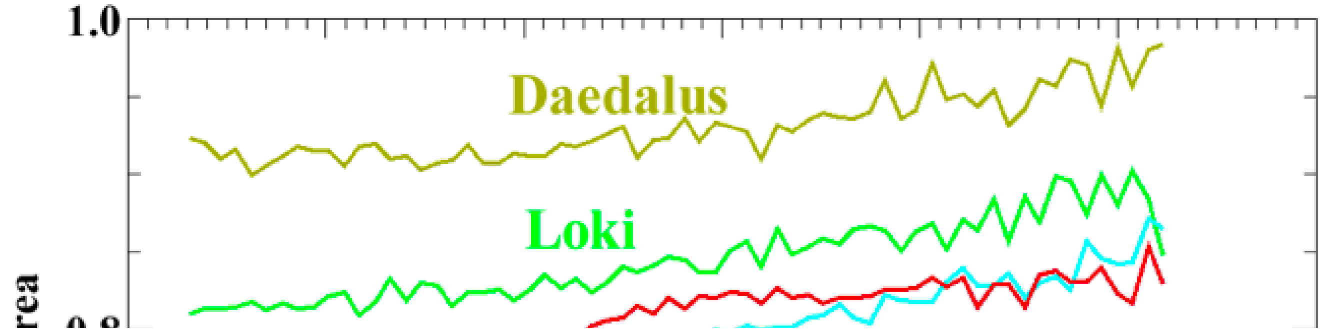
First-light LBT Nulling Interferometric Observations: Warm Exozodiacal Dust Resolved within a Few AU of η Crv

Authors: D. Defrère, P. M. Hinz, A. J. Skemer, G. M. Kennedy, V. P. Bailey, W. F. Hoffmann, B. Mennesson, R. Millan-Gabet, W. C. Danchi, O. Absil, P. Arbo, C. Beichman, G. Brusa, G. Bryden, E. C. Downey, O. Durney, S. Esposito, A. Gaspar, P. Grenz, C. Haniff, J. M. Hill, J. Lebreton, J. M. Leisenring, J. R. Males, L. Marion, T. J. McMahon, M. Montoya, K. M. Morzinski, E. Pinna, A. Puglisi, G. Rieke, A. Roberge, E. Serabyn, R. Sosa, K. Stapeldfeldt, K. Su, V. Vaitheeswaran, A. Vaz, A. J. Weinberger, and M. C. Wyatt

Defrère *et al.* 2015 *The Astrophysical Journal* **799** 42.

Provider: AAS Journals

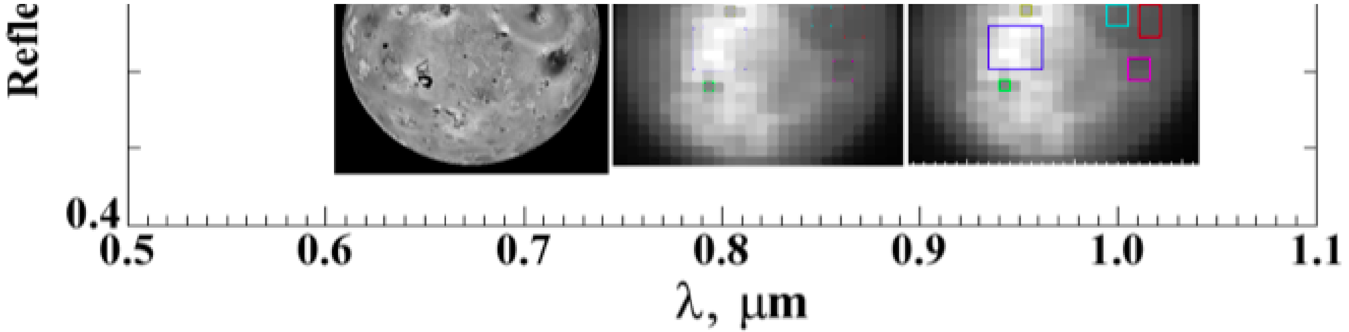

(145) Adeona
Visible SMASS II
Binzel et al. (2001)
Visible S3OS2
Normalized Reflectance
1.20
1.10
1.00
0.90
0.80
0.25
0.50
0.75
1.00
Wavelength (µm)



The Astronomical Journal, 145:110 (7pp), 2013 April doi:10.1088/0004-6256/145/4/110

SALTS AND RADIATION PRODUCTS ON THE SURFACE OF EUROPA

M. E. Brown[1] and K. P. Hand[2]
[1] Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA; mbrown@caltech.edu
[2] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
Received 2012 December 18; accepted 2013 February 9; published 2013 March 14



Destiny+ visit to <u>(3200) Phaethon</u>

One fancy graphic

Info about the mission goes here

- Dates: xxx
- Agency:
- Year:
- Science Goals:

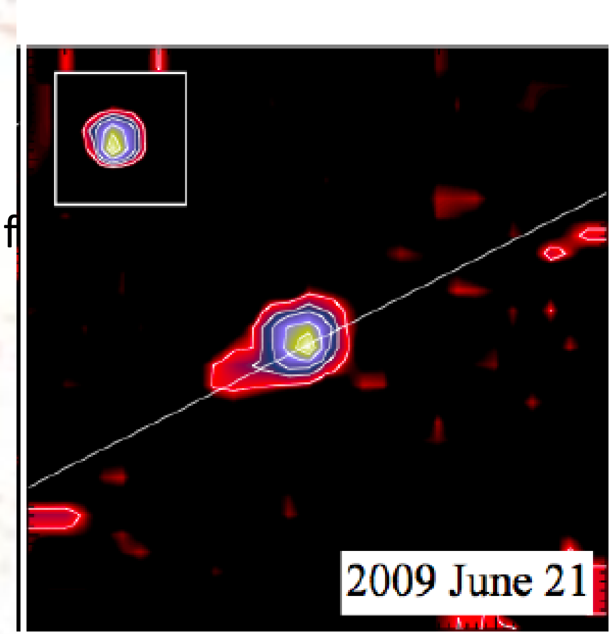
How was it observed from the ground with HAR …

We gave 3 examples, but there are many more for which we don’t have time:

- Pluto
    - Related: WG/KBO (good nonsid tracking example)
- Other 2 dawn
- HOSTS
- Maybe adeona too (See spec on last Hidden slide) = DAWN 3rd trgt

Destiny+ visit to (3200) Phaethon

Stuf



here

Probability to find a 15th or brighter star within 30 arcsec of a non-sidereal

Assume:

- Nonsid moving 100 arcsec/hour
- 100 stars <15 Rmag per sq degree
- Nonsid observable for 4 hours

Nonsid neighborhood with radius 30 covers 100 x 4 x 60 in 4 hours

(100 x 4 x 60) / 3600^2 = .002 => 0.2%

List of 100 objects of interest, 20% chance of appulse per night

Approx. one per week