Small Bodies Near And Far

Pablo Santos-Sanz
& the
SBNAF team

Project baseline & strategy

Topic: COMPET-05-2015 - Scientific exploitation of astrophysics, comets, and planetary data
Project Title: Small Bodies Near and Far (SBNAF)
Proposal No: 687378 - SBNAF - RIA
Duration: Apr 1, 2016 - Mar 31, 2019 (3 yr)
Budget: ≈1.6 M€

Grant Agreement no 687378

- A benchmark study that will address critical points in reconstructing physical and thermal properties of NEAs, MBAs and TNOs
- Combination of data from ground (visual, radar, radio, ...), from astrophysics missions (Herschel, Spitzer, (NEO)WISE, ISO, Akari), and interplanetary missions (NEAR-Shoemaker, Rosetta, Dawn, Hayabusa, New Horizons) is key to improving the scientific understanding of these objects
- Development of crucial tools/techniques/database for the interpretation of much larger data sets from (NEO)WISE, Gaia, JWST, or NEOShield-2, but also for Hayabusa-2, OSIRIS-REx, or AIM

SBNAF team

- Project coordinator: Thomas Müller (MPE)
- Participants:
  - Max Planck Gesellschaft zur Förderung der Wissenschaften e.V. (MPG), Germany (DE)
  - Agencia Estatal Consejo Superior de Investigaciones Cientificas (CSIC), Spain (ES)
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  - Uniwersytet im. Adama Mickiewicza w Poznaniu (UAM), Poland (PL)
- Team members (alphabetically):

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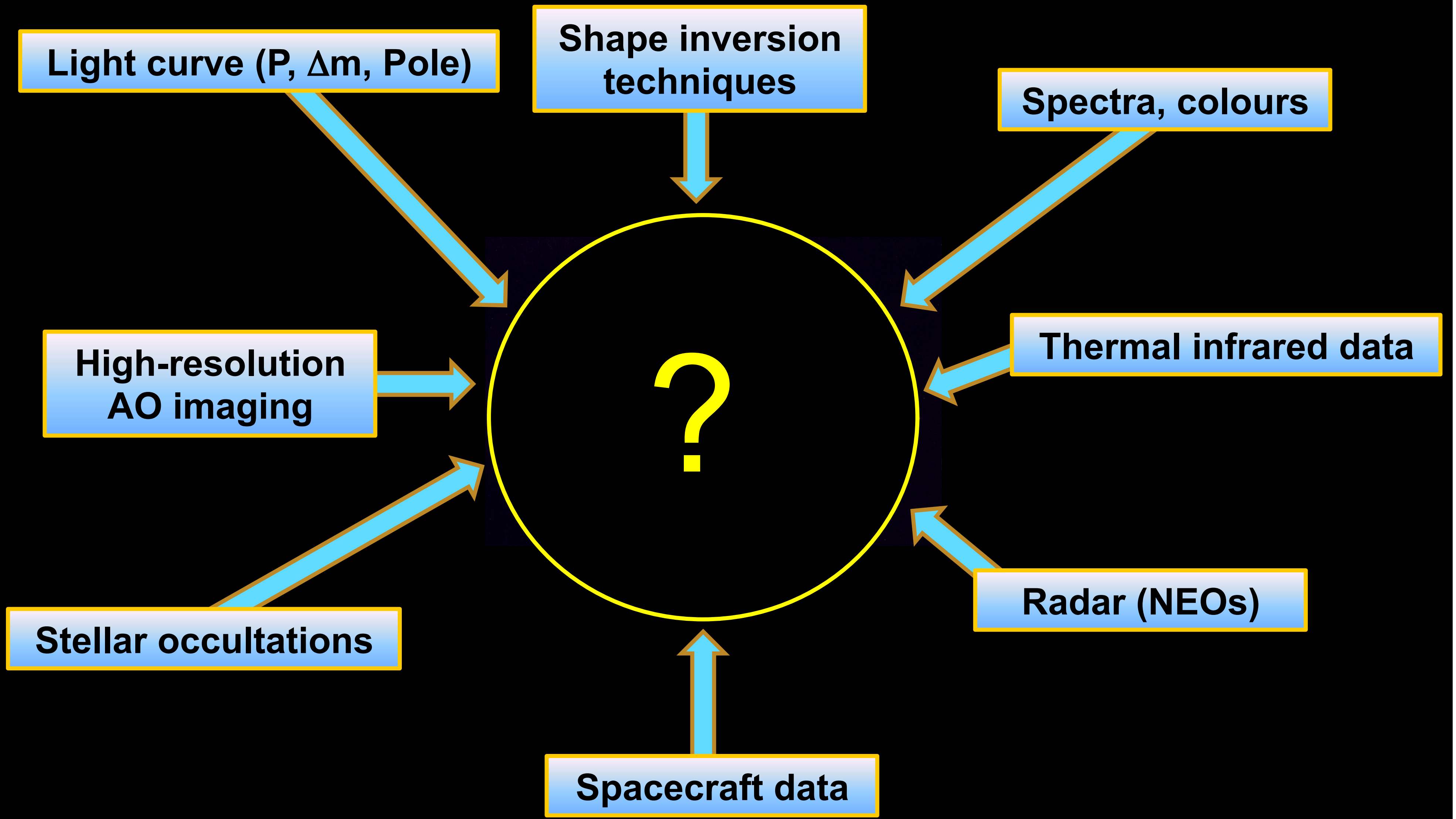
(*): not officially specified in proposal;

Total: about 15 scientists (PhD, postdoc, staff), 6 female, one open position at MPE

Criteria for target selection



NEAs

Target	Available data
433 Eros (NEAR-Shoemaker mission)	• Shape, size, spin (NEAR) • Thermal data: Spitzer-IRS, IRAC, MIPS; WISE; Herschel, Akari; Ground-based N-band • HST • Ground-based light curves, spectra, auxiliary data
25143 Itokawa (Hayabusa mission)	• Shape, size, spin (Hayabusa) • Ground-based light curves • Thermal data: Akari, multi- epoch,-instrument, ground-based N-/Q-band
162173 Ryugu (Hayabusa-2 target?)	• Ground-based light curves • Thermal data: Spitzer IRS, IRAC ligth curves, Herschel, ground-based N-band

MBAs

Target	Available data
1 Ceres 4 Vesta 21 Lutetia	• In-situ information from DAWN & Rosetta • Wide range of thermal data, including high-quality Herschel measurements, data from Planck, ALMA, APEX, Akari, IRAM, ISO • HST images • Ground-based lightcurves, spectra, stellar occultations, auxiliary data
2 Pallas 7 Iris 9 Metis 10 Hygea 14 Irene 16 Psyche 27 Euterpe 46 Hestia 52 Europa 64 Angelina 88 Thisbe 114 Kassandra 145 Adeona 721 Tabora…	Gaia sample: **large main-belt asteroids where mass determination will be possible using Gaia data -up to 50 MBAs- (selected from Mouret et al 2006) . Sub-sample of objects w/ some good LCs (and no previous models) obtained from a larger list of 140 objects by the Gaia team** (Gaia Perturbers) • Wide range of thermal data, including high-quality Herschel measurements, Akari, IRAS, partially Planck • Ground-based light curves, stellar occultations, spectra, auxiliary data

Calibrators (MBAs)

Target	Available data
3 Juno 6 Hebe 7 Iris 8 Flora 10 Hygiea 18 Melpomene 19 Fortuna 20 Massalia 29 Amphitrite 37 Fides 40 Harmonia 47 Aglaja 52 Europa 54 Alexandra 65 Cybele 88 Thisbe 93 Minerva 173 Ino 360 Carlova 372 Palma 423 Diotima	Calibration sample: large main-belt asteroids useful for far-IR/ Submm/mm calibration (10-20 MBAs) • Wide range of thermal data, including high-quality Herschel measurements, partially Planck, ALMA, APEX, SOFIA, ISO, Spitzer, Akari • Ground-based light curves, spectra, stellar occultations, auxiliary data

Trojans and Centaurs

Trojans	Available data
911 Agamemnon	• Thermal data from IRAS, ISO, Akari, Spitzer, WISE, ground-based mid-IR • Ground-based light curves, spectra • Stellar occultation measurements

Centaurs	Available data
2060 Chiron 10199 Chariklo 54598 Bienor 60558 Echeclus (145486) 2005 UJ_{438} 8405 Asbolus 5145 Pholus	• Stellar occultation measurements • High-quality thermal Herschel, in some cases also Spitzer measurements

TNOs

Target	Available data
134340 Pluto 136199 Eris 136472 Makemake 90482 Orcus 20000 Varuna 50000 Quaoar 136108 Haumea 90377 Sedna (84922) 2003 VS_2 (208996) 2003 AZ_{84} (55636) 2002 $TX3_{00}$ (229762) 2007 UK_{126} (119951) 2002 KX_{14}	• Stellar occultation measurements • High-quality thermal Herschel, in some cases also Spitzer measurements

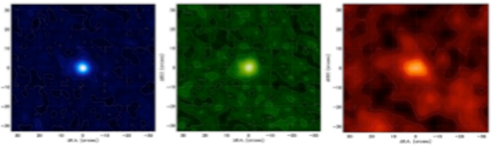
Work Packages

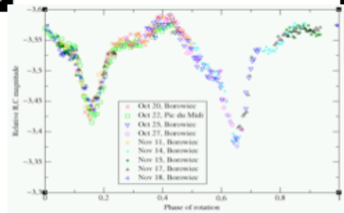
WP1: thermal data from ground and space

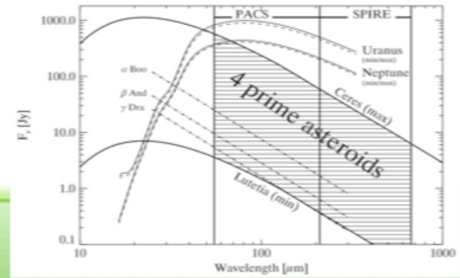
WP2: lightcurves: collections & inversion

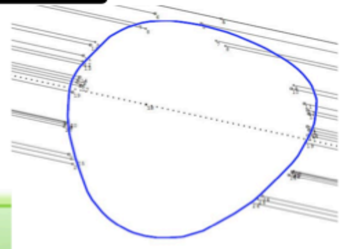
WP3: asteroid calibration from ISO, Herschel, Akari

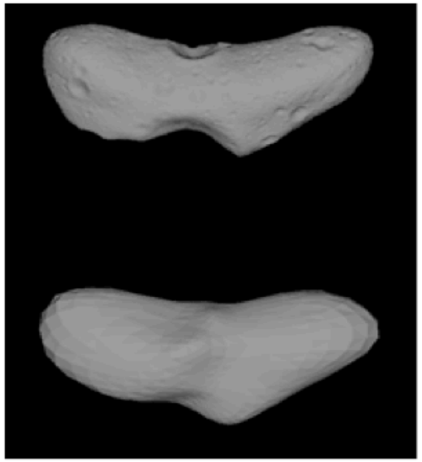
WP4: occultation campaigns, auxiliary groundbased observations





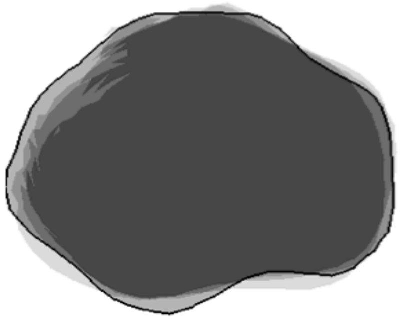






WP5: Synergy

combination of lightcurves, thermal observations, occultations, auxiliary groundbased observations; development of new tools and methods; addressing critical questions by direct comparison with in-situ results



Trojans/Centaurs/TNOs: main scientific goals

- Shape and spin-axis reconstruction from light curves, occultations, and thermal measurements.

- Development of methods to reconstruct 3D information for remote objects.

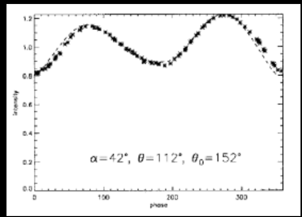
- Completion of auxiliary data from the ground (light curves, absolute photometry, additional occultations).

- Testing sub-surface emission effects to validate radiometric methods for future ALMA observations.

Observational techniques: Light curve inversion

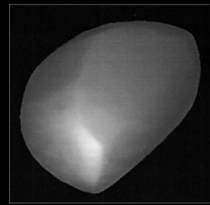
- Lightcurve inversion technique (Kaasalainen & Torppa 2001; Kaasalainen at al. 2001)

From light curves



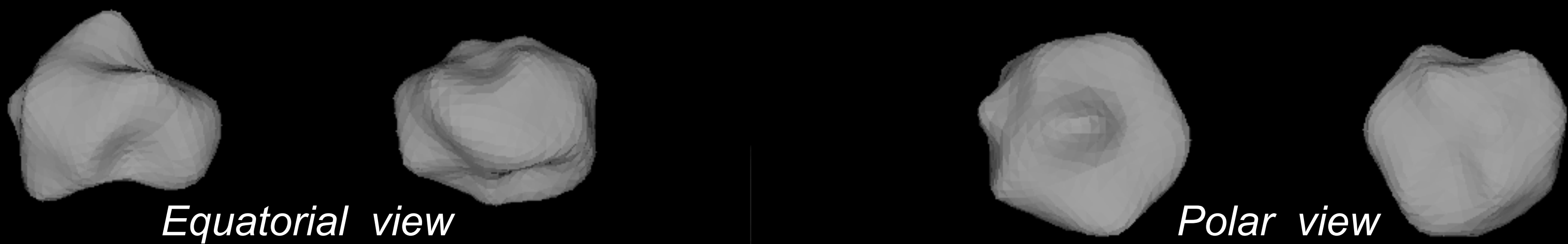
to

433 Eros



Spin and shape models

- >400 Spin and shape models published (e.g. Hanus at al. 2013; Marciniak et al. 2012)
- 1st attempts multi-data inversion: KOALA (Carry et al. 2012); ADAM (Viikinkoski et al. 2015)
- Previously shape models size-scaled using stellar occultations results (Durech et al. 2011)
- Recently: LCs alone enough for reliable non-convex models (SAGE, Bartczak et al. 2014)



Shape models of the binary asteroid (90) Antiope obtained from the SAGE algorithm for non-convex shapes (Bartczak et al. 2014).

Observational techniques: Radiometry

Exploitation of thermal data in the mid/far-IR (space) and data in the visible (ground)

Radiometric techniques:

- -Standard Thermal Model (STM)
- -Fast Rotating Thermal Model (FRM)
- -near-Earth asteroid ther model (NEATM)

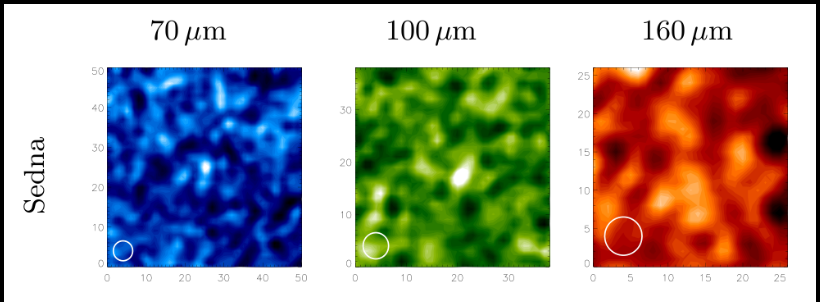
Size, albedo (unc ~10%)

Preferred wavelengths (T-depending)

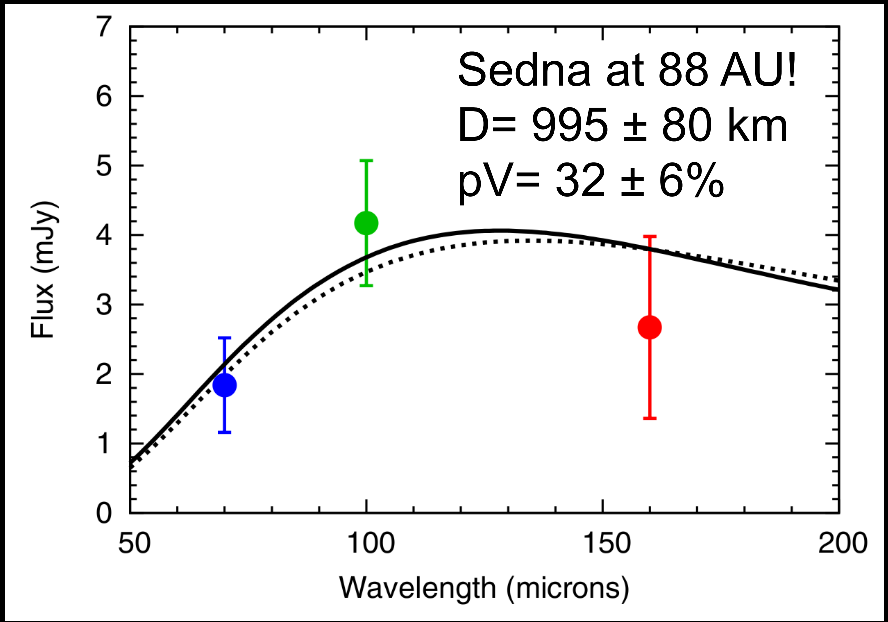
- MBAs (T~ 300 K) → 10 µm
- TNOs (T~ 30–40 K) → 70-100µm

The most productive way of determining sizes and albedos (e.g. "TNOs are cool" Herschel Key project ~ 370h, >130TNOs: Mueller et al.2010; Santos-Sanz et al.2012; Kiss et al.2013; Duffard et al. 2014)

Thermo-physical models (TPM): Size, albedo + T.I., roughness…(e.g. Muller et al. 2010)



(Pál et al. 2012)

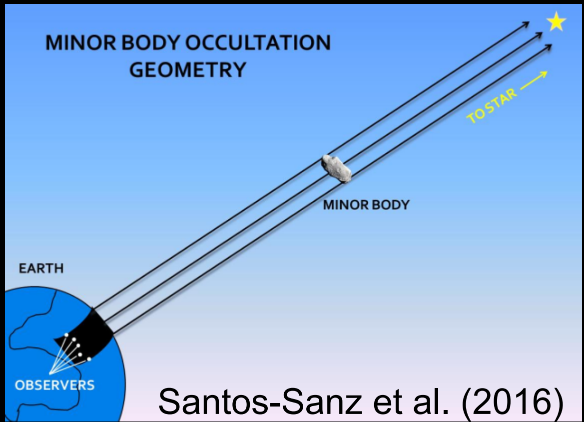


Pablo Santos-Sanz

Observational techniques: Stellar occultation

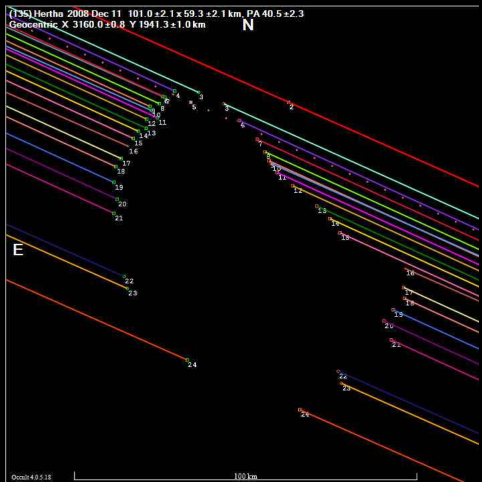
Small Bodies Near And Far

- Another way to determine sizes, shapes & albedos (Elliot 1979; Elliot & Young 1992)
- The most accurate & powerful technique, D ~ km. Allows to determine shape, to detect/characterize atmospheres (P ~ nbar), satellites, rings, other fine details.



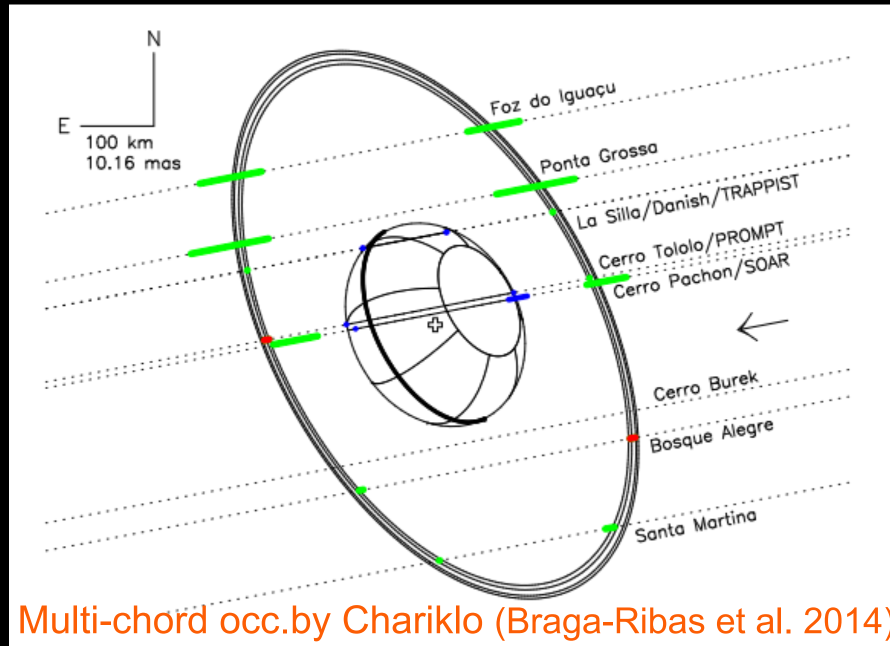
Santos-Sanz et al. (2016)

- Well developed for planets, satellites, MBAs is an emerging field for TNOs: Predicting and observing stellar occultations by TNOs is extremely difficult → very small angular diameters + uncertain orbits + uncertainties in stellar catalogues → difficult get reliable predictions well in advance



Multi-chord stellar occ. by 135 Hertha

A multi-chord stellar occultation by a minor body allows to determine the projected shape and orientation of the body in the plane of sky at the moment of occultation.



Multi-chord occ.by Chariklo (Braga-Ribas et al. 2014)

Observational techniques: Direct imaging (HST, AO)

• Direct measurements of physical properties for largest asteroids (HST / AO-systems in large ground-based telescopes) → Size, Shape, & Pole orientation.

• AO-systems: images~ diffraction limit at shorter wavelengths (<1.6 μm), res.~ 33 mas

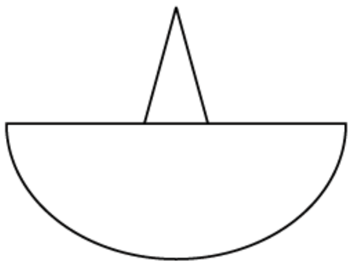
• Also possible to discover binary systems → invaluable to study internal structure & composition through density (mass not easy to determine for single objects)

AO images of two multiple-system asteroids. Figure adapted from Descamps et al. (2007).

Observational techniques: Radar Doppler delay

- Measure the distribution of echo power in time delay (range) and Doppler frequency (radial velocity) → two-dimensional images w/ spatial resolution as fine as ~10 m.
- For MBAs w/ well known orbits (unc. ~ 1”), Doppler uncertainties small compared to frequency dispersion of echoes, & delay uncertainties ~ object’s diameter → only echo strength limited the delay-Doppler resolution.

- For NEAs less accuracy of ephemeris (in particular for newly discovered objects)
- Radar has revealed: stony & metallic objects, principal-axis & complex rotators, smooth & extremely rough surfaces, monolithic & rubble pile objects, spheroids and highly elongated, contact-binary shapes, & binary systems.



Credit: Emily Lakdawalla

Credit: NASA / JPL-Caltech / GSSR

Triple asteroid 1994 CC from Arecibo radio telescope.

How to put all the data together?

Light curve inversion models can be beneficiary of thermal data and TPM (& viceversa)

Goal: to develop an applicable spin and shape modelling technique based on such varied sources (optical and thermal data)

Stellar occultations, rotational light curves and thermo-physical models

Goal: to combine stellar occultation results w/ optical LCs and thermal data to determine a full 3D shape and spin axis. This will allow to obtain accurate bulk densities.

Direct imaging and light curve inversion models

Radar Doppler delay, light curve inversion models, rotational LCs and TPMs

Goal: to use direct imaging and radar Doppler delay results to improve and refine the light curve inversion models, the ground-based rotational light curves and the TPMs.

How to put all the data together?

Small Bodies Near And Far

NEAs | **Main Belt** | **Trojan/Centaurs** | **TNO Belt**

Lightcurve inversion

standard **Stellar occultations** new

Thermal/Infrared data

WISE, IRAS, Akari, Spitzer, ground-based

Spitzer, Akari, **Herschel**, ALMA

Spacecraft visits

Radar

High-resolution AO imaging (large MBAs)

Asteroids for calibrations

THANK YOU!

Contact: psantos@iaa.es

Grant Agreement no 687378

NEAs | **Main Belt** | **Trojan/Centaurs** | **TNO Belt**