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SPHERE Unveils the True Face of the Largest Main Belt Asteroids

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Over the past 2.5 years, we have been carrying out disc-resolved observations of a substantial fraction of all large (*D* > 100 km) main-belt asteroids, monitoring them at high angular resolution throughout their rotation, and sampling the main compositional classes, using the Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE) instrument on the VLT. These observations enable us to characterise the internal structure of our targets from their density as well as their cratering record down to ~ 30 km in diameter. Such information, in turn, places unprecedented constraints on models of the formation of the Solar System and the collisional evolution of the main belt.

Scientific context

Asteroids are minor planets ranging in size from a few metres to a few hundred kilometres which are located between Mars and Jupiter (typically between 2 and 3.3 astronomical units [au]). The diversity in their surface composition (for example, metallic iron, basalt, mixtures of silicates such as olivine and pyroxene, water-rich silicates, water ice) — as inferred from spectroscopic observations — and their orbital distribution across the main belt (see, for example, Vernazza & Beck, 2017 for a review) have provided unique constraints to Solar System formation models which could not have been derived from observations of the giant or telluric planets themselves.

It is now understood that the present-day asteroid belt hosts bodies that were formed at large heliocentric distances (> 10 au) as well as bodies that may have formed close to the Sun (< 1.5 au) and that they have ended up at their current location following giant planet migration (see, for example, the Nice and Grand Tack models; Levison et al., 2009; Walsh et al., 2011) as well as gravitational interaction with the embryos of the telluric planets (Bottke et al., 2006). Broadly speaking, the idea that the asteroid belt is a condensed sample of the primordial Solar System has gradually emerged.

Whereas our understanding of the surface composition of asteroids and its distribution across the asteroid belt has improved enormously over the last decade, see recent reviews by Burbine (2014) and Vernazza & Beck (2017) the same cannot be said regarding their internal structure, which is best characterised by their density. To constrain the density, one needs to fully reconstruct the 3D shape of a body, to estimate its volume and to determine its mass from its gravitational interaction with other asteroids, preferably (whenever possible) with its own satellite(s).

This is due to the fact that disc-resolved observations of asteroids — contrary to disc-integrated observations of these same bodies (from light curves and/or visible and infrared spectroscopy) — have so far been obtained with sufficient spatial resolution for only a few bodies, either from dedicated interplanetary missions (for example, Galileo, Near Earth Asteroid Rendezvous (NEAR), Rosetta, Dawn, Origins-Spectral Interpretation-Resource Identification-Security-Regolith Explorer [OSIRIS-Rex], Hayabusa 1 & 2) or from remote imaging with the Hubble Space Telescope (HST) and adaptive-optics-equipped ground-based telescopes (for example, the VLT and the Keck Observatory) in the case of the largest bodies.

The drastic increase in angular resolution (by about a factor of three) with respect to the HST that is possible with the new generation of adaptive optics using the Zurich imaging polarimeter (ZIMPOL) on SPHERE indicates that the largest main-belt asteroids become resolvable worlds and are thus no longer extended point sources. To place this in context, these asteroids have diameters greater than 100 km and angular sizes typically greater than 100 milliarcseconds (mas). With the SPHERE instrument, craters with diameters greater than approximately 30 km can now be identified on the surfaces of main-belt asteroids and the shapes of the largest asteroids can be accurately reconstructed (for example, Marsset et al., 2017).

To maximise the science return of the SPHERE instrument in the field of asteroid studies, we proposed an ESO Large Programme with the aim of characterising the shape, density, internal and compositional structure, and surface topography of a statistically significant fraction of *D* > 100-kilometre main-belt asteroids (~ 35 out of ~ 200 asteroids). Our sample covers the major compositional classes (S, B/C, Ch/Cgh, X, P/D; DeMeo et al., 2009; DeMeo & Carry, 2013). The survey started in April 2017 and ended successfully in September 2019.

Methods

To achieve our science objectives, we image our targets with SPHERE/ZIMPOL throughout their rotation (we collect images every ~ 60 degrees in planetocentric longitude). These images are subsequently reduced and deconvolved with the MISTRAL algorithm (Fusco et al., 2003; Mugnier, Conan & Fusco, 2004) using a point spread function (PSF). At the beginning of our observing programme, we were observing a stellar PSF either before or just after every asteroid observation. However, because the deconvolution with the stellar PSF did not produce systematically satisfactory results, we investigated alternative methods to increase the sharpness of the image. We noticed that in several cases we achieved a better result by using stellar PSFs acquired on different nights. We therefore tested the deconvolution process with synthetic PSFs modeled by a 2D Moffat function. The deconvolution using a Moffat PSF always converged towards an acceptable solution by varying the Moffat parameters (Fétick et al., 2019). We therefore started systematically using a parametric PSF to deconvolve our images (for example, Viikinkoski et al., 2018; Fétick et al., 2019). Notably, the case of Vesta (Figure 1) has confirmed the accuracy of our image deconvolution algorithm. Nevertheless, it is clear that our programme provides a strong motivation for further development of deconvolution algorithms in order to limit artefacts with additional priors, incorporate non-axisymmetric features of the stellar PSF, and improve convergence and stability.

The deconvolved images serve as input to a 3D shape reconstruction algorithm (ADAM; Viikinkoski, Kaasalainen & Durech, 2015 or MPCD; Jorda et al., 2016). Even though we already have low-resolution, convex, shape models from existing light curves for all our targets, the SPHERE data allow us to drastically improve those models by producing more realistic non-convex shape models, revealing the topography of individual craters ($D \geq 30$ km). Thus, thanks to SPHERE's unique angular resolution, we have been able to open an entirely new window on asteroid exploration. Cratering records that are now available for our targets allow us to address their global geology, as in the case of (7) Iris for instance (Hanus et al., 2019).

The methods we employ to derive the physical properties of our targets have been validated in the case of the asteroid (21) Lutetia (Carry et al., 2010, 2012), which is a relatively small object (D ~ 98 km) compared to our targets. The asteroid was visited by the ESA Rosetta mission in 2010 (Sierks et al., 2011). With our methods, the inferred spin coordinates were accurate to one degree and the absolute dimensions to within 2 km with respect to those derived from the Rosetta fly-by data.

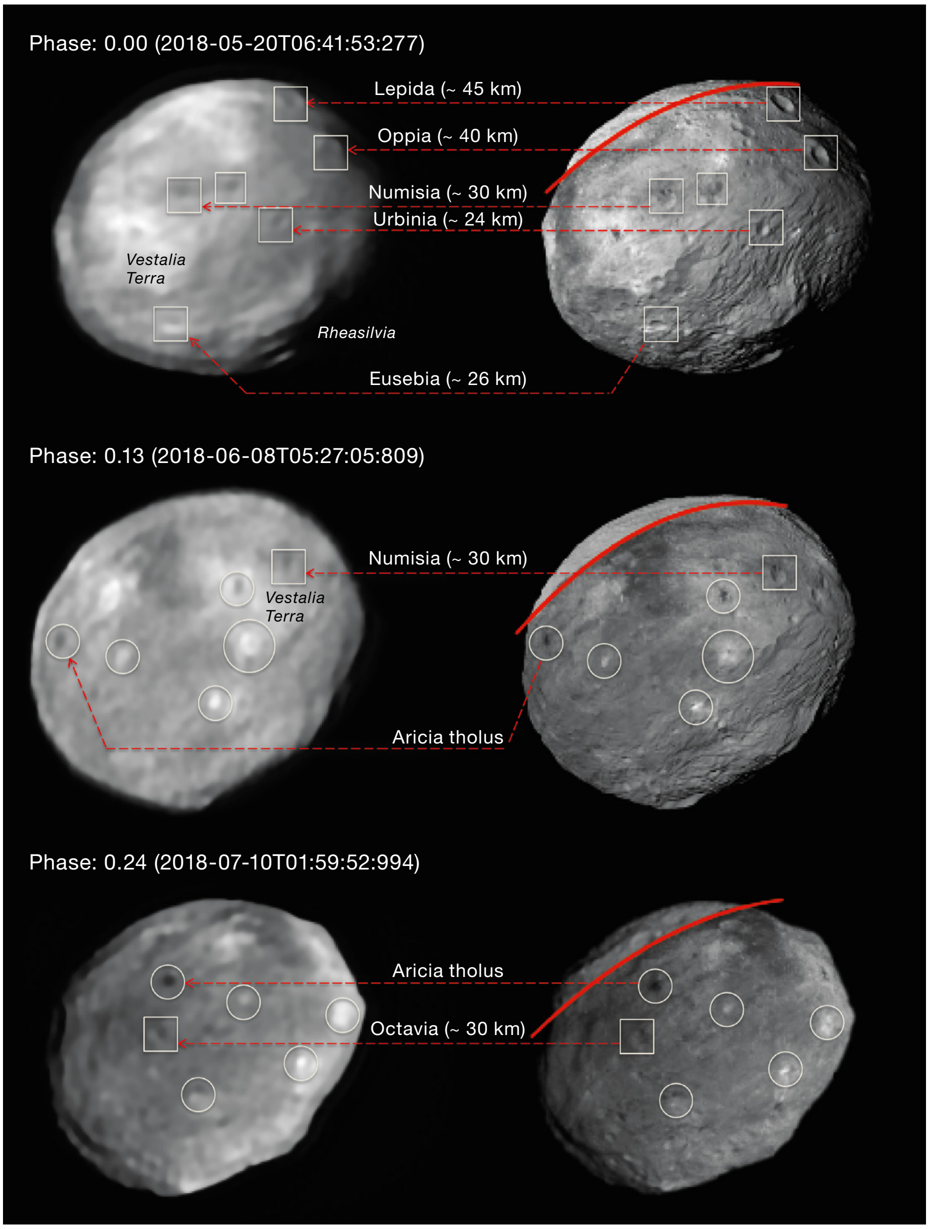

Figure 1. Comparison of the VLT/SPHERE deconvolved images of Vesta (left column) with synthetic projections of the Dawn model produced with OASIS and with albedo information (right column). The main structures that can be identified in both the SPHERE images and the synthetic ones are highlighted: craters are outlined by squares and albedo features by circles. Reproduced from Fétick et al., 2019.

Hereafter, we summarise some of the main results obtained so far. These results illustrate well the diversity of the science questions that can be investigated via such an imaging survey.

A bluffing view of (4) Vesta

With a mean diameter of 525 km (Russell et al., 2013), (4) Vesta is the second largest body in the asteroid belt. In the early 1990s, telescopic observations of small asteroids on similar orbits revealed the presence of numerous bodies with spectral properties similar to those of Vesta (Binzel & Xu, 1993). It was understood that these bodies originated as fragments from Vesta that had been excavated in one or more giant impacts. A few years later, observations performed with the HST revealed the presence of an impact crater 460 km in diameter near the south pole of Vesta (Thomas et al., 1997), thus confirming the collisional origin of the Vesta-like bodies. Later on, the NASA Dawn mission characterised the surface topography of Vesta in detail, revealing the existence of two overlapping basins in the south polar region and a central peak whose height rivals that of Olympus Mons on Mars (for example, Russell et al., 2012; Jaumann et al., 2012; Marchi et al., 2012; Schenk et al., 2012).

Our SPHERE images have recovered the surface of Vesta in great detail (Figure 1; Fétick et al., 2019). Most of the main topographic features present across Vesta's surface can be readily recognised from the ground. These include the south pole impact basin and its prominent central peak, several $D \geq 25$ kilometre-sized craters and also Matronalia Rupes, including its steep scarp and its small and big arcs. On the basis of our observations, it follows that next-generation telescopes with mirror sizes in the range 30–40 m (for example, ESO's ELT) should in principle be able to resolve the remaining major topographic features of (4) Vesta (i.e., equatorial troughs, north-south crater dichotomy), provided that they operate at the diffraction limit in the visible.

A bright future for asteroid family studies

Our SPHERE observations of asteroid (89) Julia (Vernazza et al., 2018; Figure 2), a $D \sim 140$ km S-type asteroid and the parent body of a small collisional family that consists of 66 known members with $D < 2.5$ km, have revealed the presence of an impact crater (~ 75 km wide) that could be the origin of this family. In addition, we studied both the impact event by means of smoothed particular hydrodynamic simulations and the subsequent long-term orbital evolution of the asteroid family, to determine its age (30–120 Myr). It follows that the same type of science investigation that could be performed 20 years ago with the HST in the case of (4) Vesta and the discovery of its south pole impact basin at the origin of the Vesta family (Thomas et al., 1997) can now be performed for many $D > 100$ km main-belt asteroids with VLT/SPHERE. In the field of asteroid-family studies, the future will only get brighter with the resolving power of the extremely large telescopes (ESO's ELT, the Thirty Meter Telescope [TMT], and the Giant Magellan Telescope [GMT]). All-sky surveys using the Vera C. Rubin Observatory will surely discover many new small families. The follow-up with adaptive optics observations of their parent bodies may allow us to reconstruct the respective impact craters at the origin of these families.

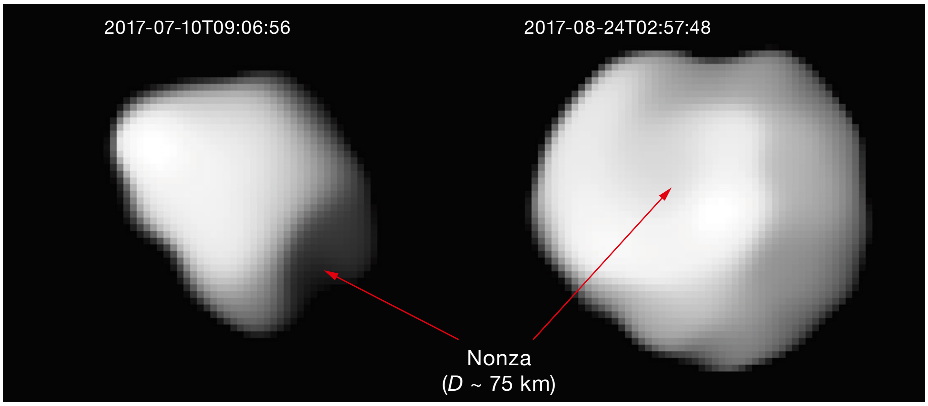

Figure 2. SPHERE/ZIMPOL images of (89) Julia deconvolved with the MISTRAL algorithm. Nonza, the likely impact crater at the origin of a small collisional family, is highlighted.

At the same time, such investigations may help to establish new meteorite-asteroid connections. Indeed, asteroid families likely constitute a major source of meteorites. The case of Vesta supports such a hypothesis, it being likely that the howardite-eucrite-diogenite (HED) meteorites — achondrite meteorites which account for about 6% of falls — are derived from its family. In the near future, it will therefore become possible to search for the origin locations of individual meteorite falls using their cosmic ray exposure ages — which indicate the time they have been traveling in space since being excavated from their parent body — in conjunction with the estimated asteroid family ages and high-angular-resolution imaging observations of the presumed parent bodies.

Asteroids with satellites

Multiple-asteroid systems (binaries, triples) are important because they represent a sizable fraction of the asteroid population and because they enable investigations of properties and processes that are often difficult to probe by other means. In particular, Earth-based observations of binaries and triples provide the most powerful way of deriving precise masses and thus densities for a substantial number of objects (for example, Descamps et al., 2011; Marchis et al., 2013). The only other way to constrain asteroid masses with similar precision is with dedicated interplanetary missions, either a fly-by for the largest ones (as in the case of (21) Lutetia) or a rendezvous (for example, the Dawn mission, OSIRIS-Rex and Hayabusa 1 & 2).

Direct imaging performed in the course of our Large Programme is a very efficient way of discovering new moons, constraining their orbital parameters and hence the total mass of the system (primary + secondary). In the case of a small secondary (which is always the case for our targets), the total mass is dominated by the primary, implying that the mass of the primary can be well constrained (usually with < 10% uncertainty).

Our programme has allowed us to discover a moon around the C-type asteroid (31) Euphrosyne (Vernazza et al., 2019). With an estimated diameter of ~ 270 km, Euphrosyne is so far the largest known main-belt asteroid with a companion. We have also investigated the compositional structure of the binary asteroid (41) Daphne (Carry et al., 2019; Figure 3). Our observations imply a density similar to that of CM chondrites, and thus a homogeneous internal structure for that object, in agreement with numerical models simulating the early thermal evolution of the parent bodies of CM chondrites.

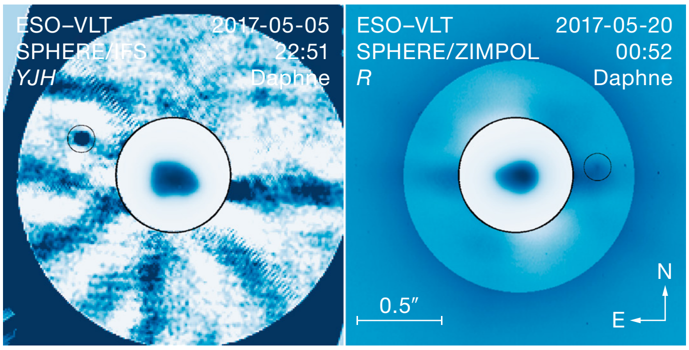

Figure 3. Images of (41) Daphne and its satellite. Daphne's image is displayed in the inner circle and the outer region shows the satellite after halo removal (highlighted by a small circle). Reproduced from Carry et al. (2019).

Perspectives

New opportunities for ground-based asteroid exploration, namely geophysical and geological studies, are becoming available thanks to SPHERE's unique capabilities. Also, the present work represents the beginning of a new era of asteroid-family studies. Notably, our SPHERE observations using the VLT have demonstrated in a striking manner how the gap between interplanetary missions and ground-based observations is getting narrower (Fétick et al., 2019). With the advent of extremely large telescopes (ESO's ELT, GMT, TMT), the science objectives of future interplanetary missions will have to be carefully thought out so that these missions will complement, rather than duplicate, what will be achieved via Earth-based telescopic observations. For instance, future ELT adaptive-optics imaging of main-belt asteroids will allow us to resolve craters down to ~ 2–5 km in size implying that we shall be able to characterise their global geological history from the ground. Consequently, missions performing cosmochemistry experiments, landing and eventually returning a sample, should be preferred at the forefront of *in-situ* exploration.

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Paranal Observatory at sunset.