DOI: 10.18727/0722-6691/5035

SPHERE Sheds New Light on the Collisional History of Main-belt Asteroids

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The Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE) instrument has unveiled unprecedented details of the three-dimensional shape, surface topography and cratering record of four medium-sized (~ 200 km) asteroids, opening the prospect of a new era of ground-based exploration of the asteroid belt. Although two of the targets, (130) Elektra and (107) Camilla, have been observed extensively for more than fifteen years by the first-generation adaptive optics imagers, two new moonlets were discovered around these targets, illustrating the unique power of SPHERE. In the next two years SPHERE will continue to collect high-angular-resolution and high-contrast measurements of about 40 asteroids. These observations of a large number of asteroids will provide a unique dataset to better understand the collisional history and multiplicity rate of the asteroid belt.

Context

Disc-resolved imaging is a powerful tool with which to investigate the origin and collisional history of small bodies in the Solar System; for example, the recent *in-situ* visits of the comet 67P/Churyumov-Gerasimenko by the Rosetta mission, the asteroids Vesta and Ceres with the Dawn mission, and the dwarf planet Pluto with New Horizons. However, fly-by and rendezvous space missions are rare and only a very limited number of objects have been visited to date.

In the late 1990s, observations of (4) Vesta with the Hubble Space Telescope (HST) demonstrated the capability of remote observations to spatially resolve impact features on the surface of some of the largest asteroids. Specifically, HST observations led to the discovery of the "Rheasilvia basin" at the south pole of Vesta, and allowed the origin of the V-type asteroids (Vestoids) and howardite-eucrite-diogenite (HED) meteorites to be established as collisional fragments from Vesta (Thomas et al., 1997).

In the 2000s, a new generation of adaptive optics (AO) imagers installed on the largest ground-based telescopes, such as the NAOS-CONICA (NACO) instrument on the Very Large Telescope (VLT), and the Near-InfraRed Camera 2 (NIRC2) on the W. M. Keck II Telescope, made disc-resolved imaging possible from the ground for a large number of medium-sized asteroids (~ 100–200 km in diameter). In turn, these observations triggered the development of methods for modelling the three-dimensional (3D) shapes of these objects (Carry et al., 2010a; Viikinkoski et al., 2015a) which were validated by in situ measurements during the Rosetta fly-by of asteroid (21) Lutetia (Carry et al., 2010b). In parallel, these AO imagers allowed the discovery and study of satellites of asteroids by direct imaging from the ground (see the Asteroids IV chapter of Margot et al., 2015).

More recently, the newly commissioned SPHERE instrument on the VLT (Beuzit et al., 2008) revealed the surfaces of four medium-sized asteroids in even greater detail: (3) Juno; (6) Hebe; and the two binary systems (107) Camilla and (130) Elektra. This remarkable achievement opens the prospect of a new era of exploration of the asteroid belt and its collisional history.

Internal structure and collisional history

High-angular-resolution images were collected with SPHERE at several epochs to provide full longitudinal coverage of the asteroids' silhouettes. Observations were acquired with the InfraRed Dual-band Imager and Spectrograph (IRDIS) in the broad *Y*-band, using the asteroid as a natural guide star for AO corrections. After each asteroid observation, images of a nearby star were acquired under exactly the same AO configuration to estimate the instrumental point spread function (PSF). These stellar calibration images were subsequently used to restore the optimal angular resolution of the asteroid images through image deconvolution techniques.

The IRDIS images of (3) Juno and (6) Hebe are shown in Figure 1, together with the corresponding geometric views of the 3D-shape models derived for these objects. The achieved angular resolution, $\theta = \lambda/D \sim 0.026$ arcseconds, corresponds to a projected distance of only ~ 20–25 km on the asteroid's surface. Compared to earlier images provided by HST and high-contrast imagers on 10-metre telescopes, including NACO and NIRC2 on Keck, SPHERE improves the spatial resolution of the available images of those asteroids by a factor of two to four.

The analysis of the SPHERE images, together with that of optical light curves, allows a precise 3D reconstruction of the asteroid's shape (Figure 2). Combining such measurements with the asteroid's mass estimate returns a highly accurate determination of its density and, therefore, information on its internal structure. Excellent agreement is found for asteroids Juno and Hebe between their measured density and that of their associated meteorites, respectively the ordinary L- and H-type chondrites (~ 3.4–3.5 g cm^{-3}), implying a homogeneous and intact interior for these objects. Camilla and Elektra, on the other hand, have very low densities (~ 1.4–1.7 g cm^{-3}; see Pajuelo et al., 2017 and Hanuš et al., 2017), lower in fact than any known meteorite found on Earth. This result implies either a very

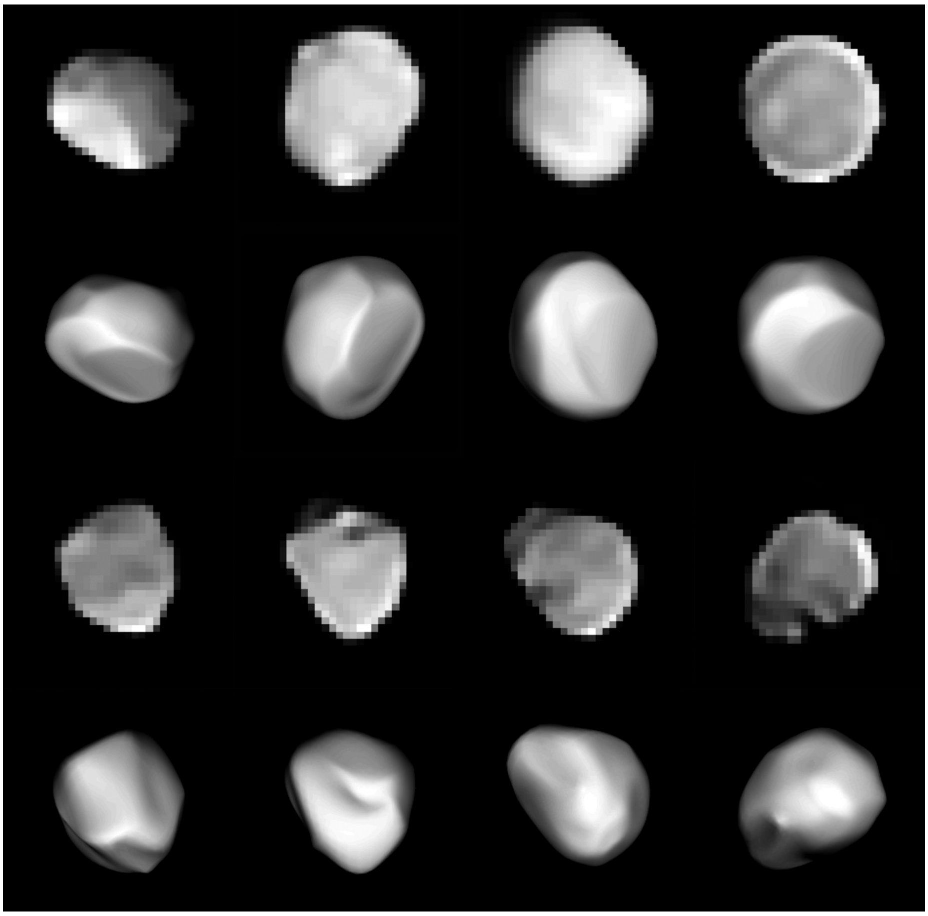

Figure 1. Deconvolved SPHERE images compared with the projections of their corresponding 3D models, for asteroids (3) Juno (top two rows respectively) and (6) Hebe (bottom two rows). Adapted from Viikinkoski et al. (2015b) and Marsset et al. (2017).

porous structure or an interior made from a high fraction of volatiles. Such a discrepancy may also indicate that Juno and Hebe formed in situ, whereas Camilla and Elektra formed in a volatile-rich environment, far from their current location.

A common feature among all four asteroids is the presence of large depressions on their surfaces, likely remnants of large impacts. In the case of Hebe, the largest depression encompasses a volume roughly a fifth of that of nearby asteroid families with similar composition. This could be evidence that Hebe is not the main source of ordinary H chondrites (Marsset et al., 2017), in contrast to some proposed scenarios.

The formation of asteroid binaries through collisional excavation

Simultaneous spectro-imaging observations of the primary and its moon for the two binaries, (107) Camilla and (130) Elektra, were further obtained using the Integral Field Unit (IFU). IFU observations were carried out in the IRDIFS_EXT mode, where the IFU covers 39 spectral channels between 0.95 and 1.65 microns (*YJH*-bands), while IRDIS performs broad-band imaging simultaneously in *K*-band. A solar analogue star was observed after each asteroid observation in order to remove the solar colour from the asteroid's spectrum.

The known satellites of Camilla and Elektra are clearly detected in the IRDIS and IFU images after subtracting the central halo of each of the primaries (Figure 3). The same process also unveiled the presence of a new smaller companion around Elektra (Yang et al., 2016) and also one around Camilla (Marsset et al.,

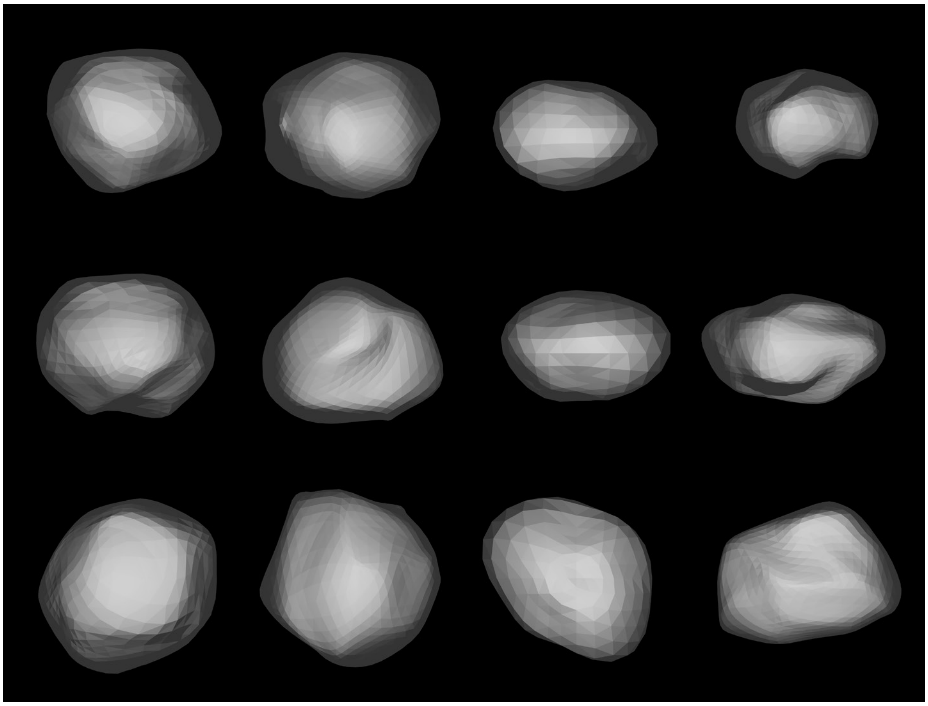

Figure 2. 3D shape models reconstructed from a combination of SPHERE images and optical light curves. Viewing directions are two equator-on views rotated by 90 degrees (first two rows) and a pole-on view (last row). Adapted from: Viikinkoski et al. (2015b); Hanuš et al. (2017); Marsset et al. (2017); and Pajuelo et al. (2017).

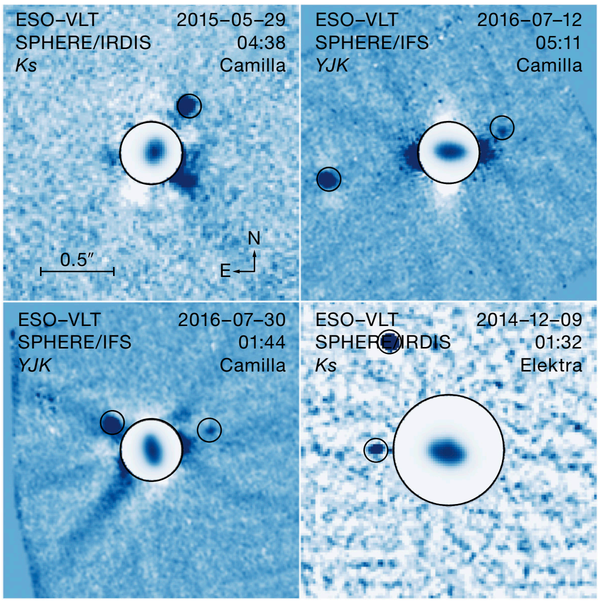

Figure 3. (Left) Halo-removed, SPHERE inverted-colour images of (107) Camilla and (130) Elektra. The small circles highlight the positions of the satellites. The central circle shows the primary. Adapted from Yang et al. (2016) and Pajuelo et al. (2017).

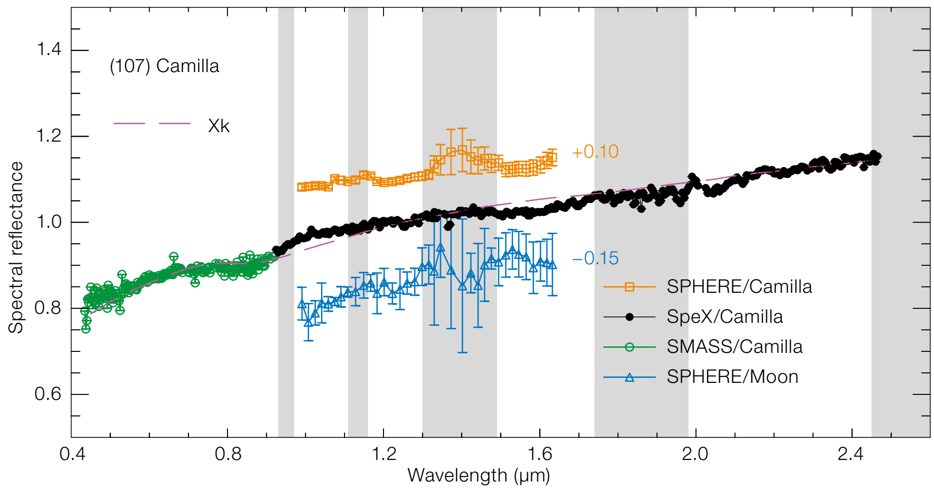

Figure 4. (Lower) SPHERE IFU spatially-resolved near-infrared spectrum of Camilla (orange) and its main moon (light blue). The IFU spectra are compared to a long-slit spectrum obtained with the Infrared Telescope Facility (IRTF), in black, and complemented with publicly available visible data retrieved from the SMASS database (green). The IFU data reveal no colour variation between the two bodies within the accuracy level of our measurements. From Pajuelo et al. (2017).

2016), making these two objects the fifth and sixth triple systems discovered in the asteroid belt after (45) Eugenia, (87) Sylvia, (93) Minerva, and (216) Kleopatra.

It is worth noting that both Camilla and Elektra have been extensively studied in the past using the first-generation high-contrast imagers. Specifically, more than 60 observations of Camilla were acquired between 2001 and 2016 with HST, NACO, NIRC2 and the Near-InfraRed Imager and spectrograph (NIRI) at the Gemini Observatory. The discovery by SPHERE of additional companions around these two heavily studied asteroids illustrates its outstanding performance in terms of contrast and angular resolution compared to earlier-generation instruments.

This performance also translates to the spectral data extracted from the IFU cubes. Component-resolved measurements of binaries usually suffer from the scattered light of the primary, which contaminates the photometry of the moon. Using SPHERE, the achieved contrast and resolution allow a clear separation of the two components, which indicate that the primary body and its moons share very similar properties and hence composition in each triple system (see Figure 4 and Yang et al., 2016; Pajuelo et al., 2017). This finding supports the hypothesis that multiple systems in the main asteroid belt formed through collisional processes. This formation scenario is also consistent with the presence of large surface depressions on both Camilla and Elektra. An estimate of their volume shows that these excavations can easily account for the creation of the two satellites of Camilla (Pajuelo et al., 2017) and Elektra (Hanuš et al., 2017).

The future exploration of the asteroid belt

In the next two years, our team will collect a set of volume, shape and topographic measurements for a substantial fraction of all > 100 km diameter main-belt asteroids (approximately 40) sampling the main compositional classes via a large SPHERE programme (ID: 199.C-0074, PI: P. Vernazza). These observations will allow us to determine the bulk density of these objects and hence to characterise their internal structure. In turn, this information will allow us to determine: (a) the nature of the initial building blocks (rock only, or a mixture of ice and rock); and (b) which compositional classes experienced differentiation. Our survey will also provide elements of answers to the following questions:

- What is the diversity in shapes among and within the main compositional classes? Space missions have revealed a variety of shapes among the few visited small bodies (for example, Ceres: spherical; Vesta: ellipsoidal, 67P: bilobed). We anticipate that our survey will make new discoveries in this domain.
- What is the multiplicity rate of large asteroids and is it related to their surface composition? It is understood that collisions are at the origin of the existence of multiple (binary and triple) asteroids. Answering this question will provide key constraints on models simulating asteroid collisions. In particular, it will allow us to understand whether rocky bodies have the same response to impacts as the ice-rich ones.

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