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OBSERVATION OF ASTEROIDS WITH GRAVITY - PHYSICAL CHARACTERIZATION OF BINARY SYSTEMS

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Abstract. Density and internal structures are among the most important characteristics of asteroids, yet these properties are also some of the least known. For distant asteroids (in the Main Belt and beyond) these properties were up to now accessible only for the largest (>100 km in size) asteroids. Going to smaller and fainter asteroids can revolutionize our understanding because we will be sampling a new regime in physical properties. Here we discuss how ground-based optical interferometry with the GRAVITY instrument can be used to observe the motion of asteroid satellites to determine the mass of small binary systems. Following the expected sensitivity performances in K-band of GRAVITY, we present a sample of binary targets potentially observable in single-field mode. The feasibility of such observations will strongly be dependent on the ability of the control software of GRAVITY to track objects moving at high rate on the sky (differential motion $\sim$ 10 mas.s^{-1}). Although the dual-field mode could allow to increase the sample of small binary asteroids observable, it seems to be currently unfeasible given the high differential motion of asteroids.

Keywords: interferometry, asteroids, internal structure, density

1 Introduction

Density and internal structure are probably the most fundamental and at the same time the least constrained characteristics of asteroids. They indeed reflect the accretional and collisional environment of the early solar system. Moreover, because some asteroids are analogs to the building blocks that formed the terrestrial planets 4.56 Gy ago, the density and internal structures of minor bodies inform us about the formation conditions and evolution processes of planets and the solar system as a whole. Any deviation of the asteroids bulk density from its potential meteorite analogs grain density provides an estimate of the bulk porosity of the asteroid. Such a bulk porosity is directly linked to the past collisional evolution of the asteroid belt and the solar system. For instance, current collisional models (Benz & Asphaug 1999; Jutzi et al. 2010) predict that most asteroids larger than a few 100 m are fractured aggregates held together by gravity only ('rubble-pile'). Their gravitational reaccumulation follows the catastrophic disruption of a larger parent body (Michel et al. 2001). Models of formation of binary systems also predict particular configuration and bulk porosities. For instance, close and small similar-sized components are expected to have formed by a rotational breakup of a parent porous body, due to spin-up effects, thus leading to a rubble-pile structure (Walsh et al. 2012).

Testing these models is highly needed because our knowledge of the collisional process is still poor and needs to be confronted to a large variety of validation tests (e.g. impact experiments at small scale, asteroid family formation at large scale, and comparison with bulk porosity measurements).

Mass and volume are required to determine the bulk density of an asteroid and infer its bulk porosity. Volume determination is often affected by large uncertainties when the object shape is approximated with a sphere, or when a radiometric diameter (obtain from thermal modeling of the infrared flux) is taken at face value. This can lead to a relative error on the bulk density of at least 60% (see e.g., Carry 2012). Masses of asteroids are also poorly determined and biased towards the very large asteroids. The most used method, which consists in

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tracking the motions of asteroids that gravitationally interact with one another, requires modeling the orbits of multiple asteroids over long periods of time and high accuracy astrometry. The best data are for the largest asteroids (1) Ceres, (2) Pallas, and (4) Vesta (Carry 2012). It is expected that Gaia will enable us to derive the masses of the largest 100 asteroids (Mouret et al. 2007). An approach that is not biased towards large objects is the observation of asteroid satellites. This is the most productive method of asteroid mass determination. It can provide accurate masses of asteroids since, by Kepler's third law ($P^2/a^3 = 4\pi^2/(GM)$), the orbital period P and semimajor axis a of the satellite uniquely determine the mass of the system. The best observations yield typical errors of $\sim$ 10% (Carry 2012). The challenge is to determine the semimajor axis of the system, and in general this requires spatially resolving the secondary from the primary. In particular, interferometry offer unprecedented high angular resolution to measure (1) the size of an asteroid projected along the interferometer baseline and (2) the semimajor axis of the orbits of asteroid satellites. The orbital elements (period, anomaly, ...) of the binary asteroid targets are in general well known and constrained from photometric lightcurve observations. We can note that a good lightcurve coverage during mutual eclipsing events can also offer the possibility of constraining the shape of the binaries and the relative size of the components. In principle, their absolute size and density can also be derived (Scheirich et al., 2009) but only under strong assumptions on the shape, that one should avoid if a low uncertainty on density is needed. Also, this method is shown to work best for asteroids visible at high phase angles - such as near-Earth asteroids. Main Belt photometric binaries remain essentially out of reach of a purely photometric approach.

Using the VLTI/MIDI instrument (Leinert et al. 2003), we have already demonstrated the potential of long-baseline interferometry for the determination of physical properties of asteroids, including size, basic shape, and surface properties (Delbo et al. 2009; Matter et al. 2011, 2013). We also demonstrated recently the capabilities of the MIDI instrument to observe small photometric binary asteroids and derive, in combination with optical lightcurves, their physical properties (Carry et al., submitted to Icarus). In the following, we discuss how ground-based optical interferometry can be used to observe the motion of asteroid satellites to determine the mass of small binary systems. We then focus on the case of the GRAVITY instrument and present a sample of binary targets potentially observable according to the expected sensitivity performances in K-band of GRAVITY. Finally, the feasability of both the single-field and dual-field modes is discussed.

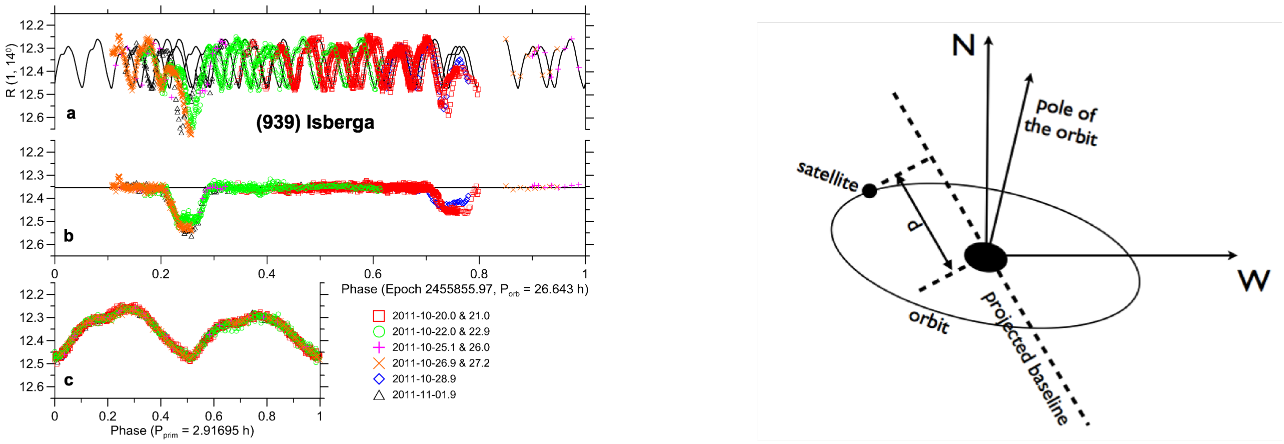

Fig. 1. Left: Example of lightcurves of the small main-belt binary asteroid (939) Isberga, taken from Carry et al. (submitted), showing the mutual eclipses and photometric variability induced by the primary rotation. a) All the lightcurves acquired between 20 October 2011 and 11 November 2011 folded over the synodic orbital period of 26.643 h; b) the same as above, with the orbital component of the lightcurve only; c) the rotation component of the lightcurve only, folded over the rotation period of 2.91695 h. **Right:** Geometry of the orbit of a binary asteroid on the plane of the sky at the time of an interferometric measurement.

2 The method

Studying the density and internal structure of asteroids requires the determination of mass and volume. One one hand, measurements of asteroid interferometric signals along different baselines and at different epoch - exploiting the rotation of the body about its axis and change in obliquity - allow to refine asteroids size measurements and calculate more accurate volumes then those based on a spherical approximation. On the other hand, the observation of asteroid satellites can provide very accurate masses since, by Kepler's third law, the orbital period and semi-major axis of the system uniquely determine the mass of the bodies. When combined with lightcurve observations, a single interferometric measurement can, in principle, be sufficient to determine the semi-major axis of the binary orbit (see right panel of Fig.1). Indeed, the lightcurve of a binary system at the epoch of its discovery already provides its orbital period and basic information about the orientation of the orbit in space (orbit pole) and the orbital anomaly (simply by the detection of the eclipse and occultation events). Then, the amount of available lightcurve data usually increase in the years following the binary system discovery because of the follow up of the asteroid by photometric observations (see left panel of Fig.1). The increasing amount of data allows orbital and physical parameters of the system to be refined. However, several interferometric observations of the systems are preferred in order to measure more accurately the motion of the components, the evolution of their apparent separation, and ultimately the semi-major axis. The separation and the sizes of the components along different directions (the system orbital period is of the order of the day, so during one night the components will significantly rotate under the baseline) can be obtained by fitting a binary model to the interferometric data (see Delbo et al. 2009). Given the orbital period, the orbit, and the semi-major axis, masses can be determined. From the masses and the shapes we can infer bulk densities, which will be compared to its potential meteorite analogs grain density to provides an estimate of the bulk porosity.

3 The targets

With more than 200 binary systems including about 100 main belt objects, and more discoveries announced almost monthly, the study of mutual orbits can provide numerous mass determinations. Figure 3 shows a sample of asteroids with satellites known today in the Main Belt. Only asteroids in the upper left corner (in red), bright and with primary-secondary separation in excess of 100 mas, can be resolved today using direct imaging with adaptive optics (AOs) at 8m-class telescopes. Ideal targets for interferometric observations are those asteroids, with separation << 100 mas, that can not be easily resolved by AOs. These asteroids are known to have a satellite from photometric lightcurve studies (green spots in Fig.3). With nominal spatial resolution down to ~ 2 mas in K-band, the new VLTI instrument GRAVITY can be used to characterize binary asteroids that are too compact to be imaged with other techniques. The measurement of the separation of a binary astronomical source is a classical application of interferometry, and Delbo et al. (2009) and Carry et al. (submitted) describe

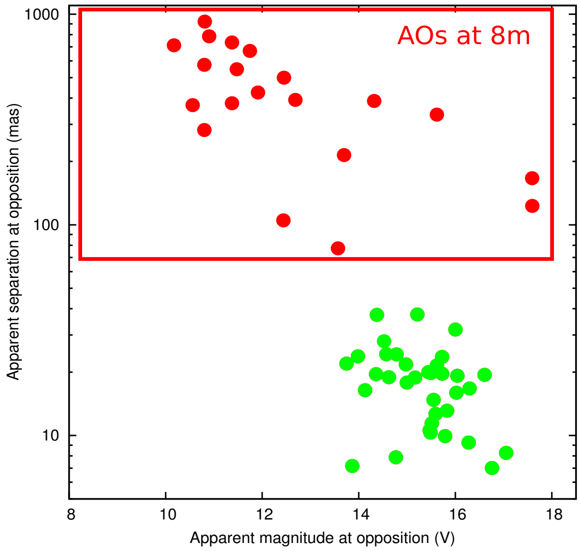

Fig. 2. Sample of binary asteroids in the Main Belt; red spots indicate binary systems discovered and spatially resolved by adaptive optics direct imaging with 8m-class telescopes, while green spots indicate binary systems detected by photometry only (transits/eclipses). This plot shows the separation of the two components vs the system magnitude under best observing conditions (the object apparent separation is computed at its average opposition distance). For photometric binaries, the separation is guessed from a fit of the photometry itself combined to reasonable assumptions on the density or on the albedo.

Name	Apparition	V range
(317) Roxane	2015,2016,2017,2018,2019	11.8-13.9
(809) Lundia	2015	11.8-13.9
(854) Frostia	2015	13.9-14.0
(1052) Belgica	2015	13.8-13.9
(1089) Tama	2016,2019	13.1-13.9
(1139) Atami	2016,2017	13.0-13.9
(1453) Fennia	2019	13.7-13.9
(1717) Arlan	2019	13.9-14.0
(1727) Mette	2018	13.9-14.0
(1866) Sisyphus	2019	12.8-14.0
(2121) Sevastopol	2016	13.9-14.0
(2044) Wirt	2016	13.7-13.9
1999 kw4	2018,2019	12.7-13.4
2003 yt1	2016	11.8-13.3

Table 1. Sample of photometric binary asteroids observable with GRAVITY in single-field mode (V $\leq$ 14) in the next 3-4 years.

the application of this technique in the case of asteroids observed with MIDI at the VLTI. In particular, a binary source produces a visibility that depends on the square root of cos $\left(2\pi\frac{B}{\lambda}\rho\right)$, where B is the projected length of the interferometer baseline, λ the observing wavelength, and ρ the angular separation of the binary components in the plane of the sky projected along B. Given the long baseline length allowed by the VLTI (up to 200m), one can in principle measure the separation of very compact systems ($<< 50 - 100$ mas). However, one of the major limitations of the first generation of ground based interferometers was the target magnitude. For instance the limiting magnitude with the near-infrared VLTI instrument AMBER is V$\sim$10 when used the 8m UTs, which prevents the observation of all of the more interesting binaries, with V>10. Bright binary asteroids have usually large separations such that they can be resolved by means of adaptive optics at 10m class telescopes. We think that the real challenge for interferometric observation of solar system minor bodies is the spatial resolution of compact and faint binary asteroids. These objects are routinely discovered by lightcurve observations performed with CCD photometric campaigns at smaller (1-2m) telescopes.

4 Observation of binary asteroids with GRAVITY

GRAVITY is the near-infrared focal instrument of the VLTI (Eisenhauer et al. 2011). It will operate in K-band (i.e. from 2.0 to 2.4 μm) combining the light from four Unit Telescopes (UTs) or Auxiliary Telescopes (ATs); (light is injected into optical fibers before recombination), and measuring fringes from six baselines simultaneously. Aside from classical visibility and closure phase measurements, this instrument will provide high precision narrow-angle astrometry and phase-referenced interferometric imaging. In single-field mode, where fringe tracking is performed 'on-axis' namely on the science target, the expected GRAVITY limiting magnitude is K=11 (correlated flux). Up to this limiting magnitude, GRAVITY should provide high signal-to-noise ratio ($\sim$ 10) visibilities and 2° accuracy on closure phases for a few minutes of integration (Eisenhauer et al. 2011). As asteroids are usually rather dark and red objects, their typical color V-K is $\sim$ 2.5. Therefore, considering a limiting magnitude of V=14, we calculated the observability from Paranal, namely the different periods of apparition, of all the photometric binaries brigther than V=14 in the next 3-4 years. This is shown in Table 1. About 15 objects would be potential binary targets for GRAVITY in single-field mode. We mention that the assumed limiting magnitude is expected to lead to high signal-to-noise ratio visibilities and accurate closure phases. To increase the sample of potential binary targets for GRAVITY in single-field mode, we could think of relaxing such a constraint on the V magnitude once the instrument will be optimized; this should lead to lower but still decent signal-to-noise ratios ($\sim$ 3).

Another way to increase the number of potential targets would be to consider the dual-field mode of GRAVITY. In this mode, fringe tracking and reference phase measurement are performed 'off-axis' on a reference star with K=10-11 located within 2" from the science target. In this case, the expected GRAVITY limiting magnitude would be K=16 (correlated flux), which translates to V$\simeq$ 19. As asteroids are moving targets, close encounter events with reference stars are possible at different epochs and can be calculated from softwares available from the Internet (e.g., WinOCCULT).

However, a critical aspect that could affect the feasibility of both the single-field and dual-field modes is the differential motion rate of asteroids. Indeed, for typical main-belt asteroids orbiting the Sun between ~ 2 and 3 AU, the orbital keplerian velocity ranges from 30 to 21 km.s^{-1}. As seen from the Earth, this translates to an apparent differential motion of 20 to 10 mas.s^{-1}, respectively. With such a differential motion, the asteroid would cross the interferometric field-of-view of 70 mas of GRAVITY, which corresponds to the injection cone of the optical fibers, in a few seconds. The global field-of-view of 2", which includes the reference star, would be crossed in about 3 minutes. This appears to be too fast to allow dual-field mode with a sufficient integration time (at least 1 min) on the science target. In single-field mode, the tracking on the science target at such apparent rate ($\sim$ 10 mas.s^{-1}) seems problematic with the first version of the control software of GRAVITY. Nevertheless, it should be possible to include, in a future version of the control software, a functionality of high speed tracking on sources with high differential motion. It should allow to follow directly the asteroids with the 'science fiber' and acquire fringes during a sufficient integration time.

5 Conclusions

Binary and multiple systems have been discovered in all populations of asteroids and other solar system small bodies. Furthermore, it is expected that about 15% of asteroids smaller than 10 km in diameter have a satellite. This latter population of binary asteroids is especially important because the observations of the motion of the components allows one to derive the dynamical mass of the system from Keplers third law. Combined to information on their size, and thus volume, bulk density and then porosity can be derived. Such an information on the asteroids internal structure is fundamental to constrain the models of collisional evolution including the formation of multiple systems. Here we discussed how ground based optical interferometry can provide the required sensitivity and spatial resolution to measure the size and separation of the components of faint and distant small binary asteroids; a population that is not spatially resolvable by direct imaging with current 8m-class telescopes. Finally, we show that the GRAVITY instrument be used for the observations of a significant sample ($\sim$ 15) of small binary asteroids in the next 3-4 years. However, the feasibility of such an observation in single-field mode will be dependent on the ability of GRAVITY to track moving objects with high differential motion. Indeed, with a typical differential motion of 10 mas.s^{-1} for the Main-Belt asteroids, the control software of GRAVITY will have to include an additional functionality of high speed tracking to follow directly the asteroids with the 'science fiber' and acquire fringes during a sufficient integration time. As to the dual-field mode, it currently seems unfeasible given the high differential motion of Main-Belt asteroids, which will not allow sufficient integration time on the target while passing close to the reference star.

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