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A dynamical solution of the triple asteroid system (45) Eugenia ☆

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ABSTRACT

We present the first dynamical solution of the triple asteroid system (45) Eugenia and its two moons Petit–Prince (diameter ~ 7 km) and S/2004 (45) 1 (diameter ~ 5 km). The two moons orbit at 1165 and 610 km from the primary, describing an almost-circular orbit ($e \sim 6 \times 10^{-3}$ and $e \sim 7 \times 10^{-2}$ respectively). The system is quite different from the other known triple systems in the main belt since the inclinations of the moon orbits are sizeable (9° and 18° with respect to the equator of the primary respectively). No resonances, neither secular nor due to Lidov–Kozai mechanism, were detected in our dynamical solution, suggesting that these inclinations are not due to excitation modes between the primary and the moons. A 10-year evolution study shows that the orbits are slightly affected by perturbations from the Sun, and to a lesser extent by mutual interactions between the moons. The estimated J_2 of the primary is three times lower than the theoretical one, calculated assuming the shape of the primary and an homogeneous interior, possibly suggesting the importance of other gravitational harmonics.

1. Introduction

The study of asteroids, remnants of the formation of the planets, is key to understanding the past of our Solar System. Binary asteroids, asteroids with a satellite, are particularly interesting since they provide a window into the collisional history of our Solar System, and are natural laboratories to study surface alteration processes and evolution for asteroids with different sizes, shapes, densities and environments. Since the discovery of the first binary asteroid system, Dactyl orbiting around (243) Ida in 1993 (Chapman et al., 1995), we have learned of ~192 companions of small Solar System bodies, including eight multiple systems composed of more than one companion. The asteroid (87) Sylvia, orbiting in the Cybele part of the main belt, was the first asteroid known to have two companions. Its larger moon (87) Sylvia I Romulus was discovered in 2001 (Brown et al., 2001) whereas the closer and smaller moon named (87) Sylvia II Remus was discovered 4 years later (Marchis et al., 2005a). These two moons orbit well inside the Hill sphere of the primary and describe circular, direct, and equatorial orbits (Marchis et al., 2005b). Using adaptive optics technology available on 8–10 m class ground-based telescopes, three more triple asteroid systems located in the main belt have been discovered recently: (45) Eugenia (Marchis et al., 2007), (216) Kleopatra (Marchis et al., 2008a), and (93) Minerva (Marchis et al., 2009a). Like (87) Sylvia, we know that these systems have a large primary ($D \sim$ 100–200 km) and two kilometer-sized satellites, but their mutual orbits are not yet defined.

The main-belt asteroid (45) Eugenia is an interesting system in the broad and diverse family of multiple small Solar System bodies. A first moonlet officially named (45) Eugenia I Petit–Prince (hereafter called "Petit–Prince") was discovered using a ground-based adaptive optics system available on the Canada–France–Hawaii Telescope in 1999 (Merline et al., 1999). Its orbit was well constrained using a large set of adaptive optics (AO) data collected from November 1998 to August 2006 based on a Keplerian model (Marchis et al., 2008b). This work revealed that its mutual orbit is direct with respect to the primary and almost circular like those of other binary asteroid systems such as (22) Kalliope, (107) Camilla and (762) Pulcova. However, they reported a significant inclination (~12°) for this satellite with respect to the equator of the primary. More recently, Marchis et al. (2007) announced the discovery of a second moon after careful reanalysis of data recorded in February

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2004 with the European Southern Observatory (ESO) Very Large Telescope (VLT) adaptive optics (AO) system. (45) Eugenia is located roughly in the middle of the asteroid main belt with semi-major axis of about 2.721 AU, eccentricity of 0.083 and 6.61° of orbital inclination.

We propose in this work to estimate the mutual orbits of both known satellites of (45) Eugenia. Additional observations were collected in 2007, shortly after the discovery of S/2004 45 1 (the placeholder name used in the rest of this work will be "Princesse") and are presented in Section 2. In Section 3, we show how we used a dynamical model to derive the osculating elements of the two moon orbits. A long-term temporal analysis of the orbital elements is described and discussed in Section 4.

2. Observations

2.1. Adaptive optics data from 1998 to 2007

Today several adaptive optics systems are available on 8–10 m class telescopes. Thanks to real-time correction of atmospheric turbulence effects, images and spectra recorded with these innovative instruments reach an angular resolution close to the diffraction limit of the telescopes. The images also have better contrast, permitting the detection of faint features around bright sources such as satellites of large asteroids. (45) Eugenia is an excellent target for AO observation since (i) the asteroid is bright enough at opposition (apparent visual magnitude $V\sim 11$–12) to be used as a wavefront reference for the AO correction, (ii) its proper motion is relatively small (~70 arcsec/h at its opposition), (iii) the primary is not resolved without AO correction providing an excellent source for the wavefront sensor. The data described in this work were essentially collected using two telescopes:

- The Yepun telescope, one of the four ESO 8 m-telescopes located at Mount Paranal in Chile, part of the Very Large Telescope. It has been equipped with NaCo which stands for NAOS–CONICA (Lenzen et al., 2003; Rousset et al., 2003), an adaptive optics systems offered since 2003. The near-infrared camera CONICA was used in direct imaging mode with the S13 camera corresponding to a pixel size of 13.27 milli-arcsec (mas) in the Ks band filter (central wavelength 2.18 μm and bandwidth of 0.35 μm).
- the Keck-II 10 m telescope located on the top of Mauna Kea, a dormant volcano on the Big Island of Hawaii, equipped with an AO system since 2001 (Wizinowich et al., 2000; van Dam et al., 2004). The data listed in Table 1 were recorded using the near-infrared camera (NIRC2) with a pixel scale of 9.96 mas in the Kp band filter (central wavelength 2.124 μm and bandwidth of 0.336 μm) and the H band filter (central wavelength 1.633 μm and bandwidth of 0.300 μm).

Additional data collected in 1998 using the Canada–France–Hawaii Telescope (CFHT) and its PUEO AO system, retrieved and reanalyzed by Marchis et al. (2008b), are also used for this work.

Table 1
Summary of AO observations taken in 2004 and 2007 which reveal the presence of Princesse. This table completes the AO observations listed in Table 2b of Marchis et al. (2008b).

ID	Name	Date	UT	Total exp. (s)	Filter	Telescope
45	Eugenia	14-February-04	03:41:49	300	Ks	VLT
45	Eugenia	15-February-04	03:30:32	300	Ks	VLT
45	Eugenia	16-February-04	03:42:16	300	Ks	VLT
45	Eugenia	19-October-07	12:05:30	900	Kp	Keck
45	Eugenia	19-October-07	12:54:38	360	H	Keck
45	Eugenia	19-October-07	13:29:59	180	Kp	Keck

Data taken from 1998 to 2006 are listed in Table 2b of Marchis et al. (2008b). More recent data taken in 2007 and not used in this previous work are listed in Table 1. These nine additional observations expand the temporal baseline of the Keplerian model of Petit–Prince and provide six astrometric positions of Princesse, allowing us to derive the orbital elements of its orbit.

Reanalysis of the 2004 data collected with the VLT/NACO revealed the presence of a second fainter satellite (~5 km in diameter), closer (~0.4″, corresponding to a projected distance of ~600 km) to the primary as shown in Fig. 1 (Marchis et al., 2008b). Additional observations were collected with the Keck AO system in 2007 that confirm the genuineness of this new satellite (Fig. 2). The rate of detection of this small satellite, which is defined as the number of observations with the detected satellite divided by the total number of observations, was quite low (12%), but it increased by 5% since 2007. The recent data taken with the W.M. Keck-II telescope have better sensitivity due to an improvement in quality of the AO system, increasing the detection rate of the fainter and closer satellite of (45) Eugenia. Even if the intensity of the inner satellite is close to the intensity of the artifacts in the case of the observations taken on October 19, 2007, it can be easily identified due to its motion around the primary. Additionally, the artifacts visible around the PSF are "ghosts" of the central peak, meaning that they are extended like the resolved primary. In contrast, the moons are circular sources with a full width at half-maximum close to the diffraction limit of the telescope (~45 mas in Kp band).

2.2. Data-processing, photometry and astrometry

Each image was basic-processed following the same procedure. The observations of the asteroid were recorded at different locations on the detector (with an individual integration time of ~1 min). An estimate of the sky, calculated by a median average of these frames, was subtracted from each individual observation. A flat-field frame and a bad-pixel map of the detector with the relevant filter were calculated using observations of the sky at sunset or sunrise (VLT) or of a uniform light projected on the dome (Keck). Each frame was divided by a normalized flat-field frame to correct for the heterogeneity of the pixel-to-pixel response. The bad pixels in the frames were replaced by the average of their neighborhood pixels. We used the *eclipse* data reduction package to perform the basic data processing (Devillard, 1997). The final frames taken over a time span of less than 10 min were combined into one single average image after applying an accurate shift-and-add process.

We describe in Marchis et al. (2005b, 2008b) how we measure the position of the satellites with respect to the primary. Our algorithm is based on a Moffat–Gauss profile in two dimensions, which is adjusted to fit the position of the satellites and the primary. An estimate of the background due to the residual of the wavefront correction is also added. The astrometric positions relative to the primary in arcsec, labeled X and Y in Table 2, correspond to the projected separation on the celestial sphere between the primary and the satellites. X is positive when the satellite is located to the astronomical East of the primary and Y is positive when it is located to the North. The 1-σ errors of the positions, which depend on the brightness of the satellite, its relative position, and the AO correction quality, are estimated to be 20 mas (VLT) and 17 mas (Keck) for Princesse and 9 mas (VLT) and 6 mas (Keck) for Petit–Prince. The 1-σ error for the data recorded in 1998 with the CFHT AO system is larger (~70 mas) since the telescope has a modest aperture size of 3.6 m. We did not apply any phase correction to correct for the illumination geometry since the observations were taken close to the opposition with an average phase angle of 13.5°. Assuming a spherical shape for the primary, this phase angle would introduce a shift of the centroid of roughly $\sin(phase/2)\times R_{eq}$ (R_{eq} = 108.5 km, the mean radius of the