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Characteristics and large bulk density of the C-type main-belt triple asteroid (93) Minerva

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ABSTRACT

From a set of adaptive optics (AO) observations collected with the W.M. Keck telescope between August and September 2009, we derived the orbital parameters of the most recently discovered satellites of the large C-type asteroid (93) Minerva. The satellites of Minerva, which are approximately 3 and 4 km in diameter, orbit very close to the primary (∼5 and ∼8 × R_p and ∼1% and ∼2% × R_{Hill}) in a circular manner, sharing common characteristics with most of the triple asteroid systems in the main-belt. Combining these AO observations with lightcurve data collected since 1980 and two stellar occultations in 2010 and 2011, we removed the ambiguity of the pole solution of Minerva's primary and showed that it has an almost regular shape with an equivalent diameter D_{eq} = 154 ± 6 km in agreement with IRAS observations. The surprisingly high bulk density of 1.75 ± 0.30 g/cm^3 for this C-type asteroid, suggests that this taxonomic class is composed of asteroids with different compositions, For instance, Minerva could be made of the same material as dry CR, CO, and CV meteorites. We discuss possible scenarios on the origin of the system and conclude that future observations may shine light on the nature and composition of this fifth known triple main-belt asteroid.

1. Introduction

The serendipitous discovery of Dactyl, a companion of the main-belt asteroid (243) Ida, seen during the Galileo spacecraft voyage to Jupiter (Chapman et al., 1995), gave birth to a new field of study for small Solar System bodies. Today, using techniques such as high angular resolution imaging with the Hubble Space Telescope (HST), adaptive optics (AO) on ground-based telescopes, radar observations and photometric studies, about 200 multiple asteroids (asteroids with one or several moons) are known in all populations of small Solar System bodies, from the near-Earth asteroids to the Kuiper Belt Objects. The study of these multiple asteroids is an opportunity for planetary astronomers to obtain insights on the asteroids such as their masses and densities and how these quantities possibly relate to their compositions, see e.g. Marchis et al. (2012a). Their existence and the understanding of their formation and evolution also provide a direct window to the history of our Solar System.

In this work, we describe a study of one of these recently discovered triple asteroid systems. (93) Minerva is a large (H_v = 7.7, P_{spin} = 5.97909 h in Tungalag (2002)) asteroid discovered by J.C. Watson at Ann Arbor, MI, USA in 1867. Located in the middle of the main-belt ($a_{Minerva}$ = 2.75 AU, $e_{Minerva}$ = 0.14, $i_{Minerva}$ = 9°), it was initially classified as a member of an old collisional family (1.2 ± 0.4 Gyr) named "Gefion" consisting of 973 members based on Nesvorný et al. (2005). Because most of the members of this family are identified as S-type, and (93) Minerva is known to be a C_b-type (Lazzaro et al., 2004) or C-type (deMeo et al., 2009), the large Minerva is likely to be an interloper in the Gefion family.

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The size and geometrical albedo of Minerva were reported in several mid-infrared surveys such as IRAS ($D = 142 \pm 4$ km, $p_v = 0.073 \pm 0.004$ in Tedesco et al. (2002)), MSX ($D = 157 \pm 3$ km, $p_v = 0.060 \pm 0.002$ in Price et al. (2001)), AKARI ($D = 147 \pm 2$ km, $p_v = 0.068 \pm 0.003$ in Usui et al. (2011)) and in a reanalysis of IRAS and MSX data ($D = 165 \pm 8$ km, $p_v = 0.0597 \pm 0.0021$ in Ryan and Woodward (2010)). There is a clear discrepancy in the sizes of Minerva derived from mid-infrared catalogs (up to ~23 km), indicative of different viewing geometries of the asteroid at the time of the observations, but also linked to a slightly different modeling in these works. The disparate diameters could be due to the use of different absolute magnitudes (H_v) for Minerva, assumptions on the thermal model and distinctive wavelength bands of observations between these surveys.

In the next section of this work, we describe observations of (93) Minerva from different sources. The key finding of this work is the discovery of two satellites around the large asteroid, which was made possible by W.M. Keck AO observations. We also combined our analysis with a large set of lightcurve data and stellar occultation data already published in the literature. Section 3 describes how a coherent analysis of these disparate sets of data allowed us to constrain the pole orientation, size and shape of the primary of the system. The mutual orbits of the satellites are determined in Section 4 and compared to other known triple asteroid systems. We discuss the composition and the origin of the system based on the first direct measurement of its density in Section 5. In Section 6 we discuss the origin of the system based on the orbital parameters and contrast our study with other multiple asteroids. A summary of our findings and future work is discussed in Section 7.

2. Observations and data processing

2.1. Adaptive optics observations

Observations of (93) Minerva were collected on August 16, 2009 using the W.M. Keck II telescope located atop Mauna Kea on the Big Island of Hawaii. The Nasmyth platform of this 10 m telescope has been host to the NIRC2 infrared camera equipped with an AO system since 2001 (Wizinowich et al., 2000; van Dam et al., 2004). Thanks to the large aperture size of the telescope and the potential of AO, the angular resolution expected on these images for a $V \sim 12$ bright target (see Table 1) is ~40–50 milli-arcsec (mas), very close to the diffraction limit of the telescope in Fe II ($\lambda_c = 1.6455$ μm, $\Delta\lambda = 0.0256$ μm) and Kcont ($\lambda_c = 2.2706$ μm, $\Delta\lambda = 0.0296$ μm). The first images were taken in these broadband filters (Table 1) from 13:38 to 13:45 UT using the narrow camera with a pixel scale of 9.94 mas. A final image was obtained using our automatic pipeline while observing at the telescope by shift-adding 3–6 frames with an exposure time of 60 s (30 s × 2 coadds). These frames were flat-field corrected, and we used a bad-pixel suppressing algorithm to improve the quality before shift-adding them. After this basic data processing, the final images revealed the presence of one small satellite at 3 o'clock at 0.42 arcsec (see Fig. 1). Additional observations taken at 13:56 UT revealed the existence of an even closer (~0.26 arcsec) companion at 5 o'clock on the image. These existence of these satellites was corroborated by additional data taken 1 h later (after 14:40 UT), which confirmed that these companions are gravitationally linked to the primary and orbit around the primary in the clockwise direction.

Additional data were collected from September 6 to September 28, 2009 when the asteroid was approaching its opposition (elongation reached 160° on September 28). Because the asteroid was brighter ($V \sim 11.7$) and closer (distance to Earth $d \sim 1.80$ AU), the AO correction was significantly better and the two satellites were easily detectable in the images after the basic processing described above. (Fig. 2). These additional observation runs confirmed the genuineness of our discovery and allowed us to derive the characteristics of this multiple asteroid system.

(93) Minerva is the fifth triple asteroid discovered among the main belt asteroids (Marchis et al., 2009), after 87 Sylvia (Marchis et al., 2005), 45 Eugenia (Marchis et al., 2007), 3749 Balam (Marchis et al., 2008c) and (216) Kleopatra (Marchis et al., 2008d). For the sake of clarity we adopt from now on the designation *(93) Minerva* for the whole system and *Minerva* for the primary alone. Minerva's companions are 5–6 magnitudes fainter than the primary body and are separated by about 0.26 and 0.42 arcsec respectively (Fig. 1). They are the smallest and closest satellites of a large asteroid ever seen. This discovery illustrates the improvement in image quality and sensitivity achieved with the AO technology over the past 15 years (Marchis et al., 2012b).

The size of the satellites can be estimated by assuming that both the moons and the primary have the same albedo and comparing their flux ratios (ϕ). In Table 2, we list the effective diameters of satellites ($D_{eff}(satellite)$), derived in each image with the equation

$$D_{eff}(satellite) = \phi^{1/2} \times D_{eff}(primary)$$

where $D_{eff}(primary)$ is the measured effective diameter on the resolved adaptive optics observations. For Minerva I, the outer moon, and Minerva II, the inner moon, we derived the following diameters by averaging $D_{eff}(satellite)$ measurements: $D_I = 3.6 \pm 1.0$ km and $D_{II} = 3.2 \pm 0.9$ km.

A single star (BD+11 229), with a brightness similar to (93) Minerva ($V = 11.06$) and located at ~0.4° from the asteroid, was observed shortly after the August 16, 2009 observation of (93) Minerva. This additional set of observations is useful to estimate the quality of the data, check for possible artefacts in the Point Spread Function (PSF) of the instrument and deconvolve the data during further analysis. This PSF image was observed at 13:50 UT using an Fe II filter with the narrow camera and a total exposure time of 25 s per frame (5 s × 5 coadds) and was processed in a manner similar to the asteroid observations. We estimated the angular resolution on the Minerva data (~41 mas) by measuring the full width at half maximum (FWHM) of the PSF. Interestingly, the FWHM measurement of the Minerva observations varies from 0.10 to

Table 1
Conditions of the Keck II AO observations of (93) Minerva collected in 2009.

Date (UT)	Time (UT)	Filter	Airmass	Predicted (V)	Elongation (°)	α Phase (°)	Δ distance to Earth (AU)
16-August-09	13:38:24	Fe II	1.03	12.47	114.69	19.95	2.110850
16-August-09	13:45:02	Kc	1.03	12.47	114.70	19.96	2.110799
16-August-09	13:56:12	Fe II	1.02	12.47	114.71	19.96	2.110719
16-August-09	14:25:02	Fe II	1.01	12.47	114.72	19.95	2.110509
16-August-09	14:40:54	Fe II	1.01	12.47	114.73	19.95	2.110401
16-August-09	15:29:45	Fe II	1.04	12.47	114.77	19.94	2.110048
06-September-09	15:30:58	Fe II	1.23	12.13	135.32	15.07	1.916779
12-September-09	15:10:47	Fe II	1.26	12.02	141.72	13.17	1.874003
15-September-09	15:11:48	Fe II	1.32	11.96	145.02	12.15	1.855197
28-September-09	13:34:08	Fe II	1.18	11.71	159.74	7.22	1.797652