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Dynamics of the binary asteroid (379) Huenna

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ABSTRACT

We aim at studying the dynamical system of the asteroid (379) Huenna and its satellite, for which a discrepancy between its predicted and observed position was reported by DeMeo et al. (2011, Icarus, 212). We compile all the available images of the system acquired with large ground-based telescopes equipped with adaptive-optics fed camera. Based on these 40 observations covering 11 years, we determine the orbit of the satellite which is strongly affected by the gravitational influence of the Sun, as opposed to most satellites of large main-belt asteroids. Combining the mass of Huenna with a compilation of diameter estimates from the literature, we revise the estimate of its bulk density to $1491 \pm 249 \text{ kg}\cdot\text{m}^{-3}$, consistent with its spectral classification as a P-type asteroid.

11 **1. Introduction**

12 Owing to their small size, asteroids had little, if
13 any, geophysical evolution over the history of the Sol-
14 ar system after their initial accretion phase some 4.6
15 Gyr ago. Their orbital environment, dominated by col-
16 lisions, however led to an important evolution of their
17 physical properties such as spin, shape, and internal
18 structure via shock-induced fractures. Asteroids are
19 nevertheless the most pristine remnants of the early
20 stages of the inner Solar system, and as such, they are
21 used to constrain the models of formation and evolution
22 of planetesimals from which terrestrial planets formed
23 (Morbidelli et al., 2015; Clement et al., 2020)

24 Understanding their compositions, and how these
25 distribute is key in that respect (DeMeo and Carry,
26 2014). The composition of asteroids is generally derived
27 from photometry and spectroscopy compared with labo-
28 ratory samples (Reddy et al., 2015). These are, how-
29 ever, sensitive to a thin surface layer only, which com-
30 position may or may be not related to the bulk com-
31 position of the asteroid. An obvious example is the
32 differentiated asteroid (4) Vesta (McCord et al., 1970),
33 but partially differentiated bodies could be common
34 (Elkins-Tanton et al., 2011; Bryson et al., 2019). As-
35 teroid bulk density is the sole remote-sensing quantity
36 that can tell us about asteroid interiors, and provide
37 hints on bulk composition (Scheeres et al., 2015).

38 The first and most difficult quantity to measure to
39 derive an asteroid density is its mass. The only ex-
40 ception is the modeling of lightcurves of mutual events
41 (eclipses and occultations) which provides the density
42 without measuring the asteroid mass (nor volume, see
43 Pravec et al., 2006; Scheirich and Pravec, 2009; Carry
44 et al., 2015). In all cases, the most precise mass esti-
45 mates (few percent accuracy) have been derived study-
46 ing binary asteroids, or during spacecraft encounters
47 (Pätzold et al., 2011; Pajuelo et al., 2018). Other deter-
48 minations, relying on the modeling of the long-distance

gravitational influence of the target asteroids on other
small asteroids, have provided many more determina-
tion but with **low** precision to date (Zielenbach, 2011).
There are currently about 300 small bodies with a mass
determination (Carry, 2012).

We focus here on the asteroid (379) Huenna, around
which a satellite was discovered in 2003 by Margot
(2003). A dynamical solution for the orbit of the satel-
lite was published by Marchis et al. (2008), provid-
ing the mass of Huenna. However, the observation in
2009 of Huenna's satellite for spectroscopic purposes
revealed a clear offset (0.5", about 680 km) between
the predicted and observed positions (DeMeo et al.,
2011), requiring an updated dynamical solution. **A dy-
namical solution has indeed been recently published by
Emelyanov and Drozdov (2020) based on the aforemen-
tioned observations. Aware of additional observations
present in archives, we** collected images of Huenna's
system as acquired by large ground-based telescopes in
Section 2. **We then** describe the dynamical solution in
Section 3, and discuss its implications in Section 4.

2. Observations and data reduction

We collect all the high angular-resolution images of
Huenna taken with ground-based telescopes equipped
with adaptive-optics (AO) cameras: ESO VLT and W.
M. Keck. The data span **27** different epochs, with mul-
tiple images each, over **11** years from **August 2003**
to **December 2014**. **This data set includes the dis-
covery observations of Margot (2003), those used by
Marchis et al. (2008), the discrepant observation re-
ported by DeMeo et al. (2011), and public data from
the archives of the Keck (Keck engineering time and
programs C257N2L, C192N2, PI M. Brown) and VLT
telescopes (program 089.C-0944, PI F. Marchis).**

The images from the VLT were acquired with NACO
(NAOS-CONICA, Lenzen et al., 2003; Rousset et al.,
2003), and those at Keck with NIRC2 (Near-InfraRed

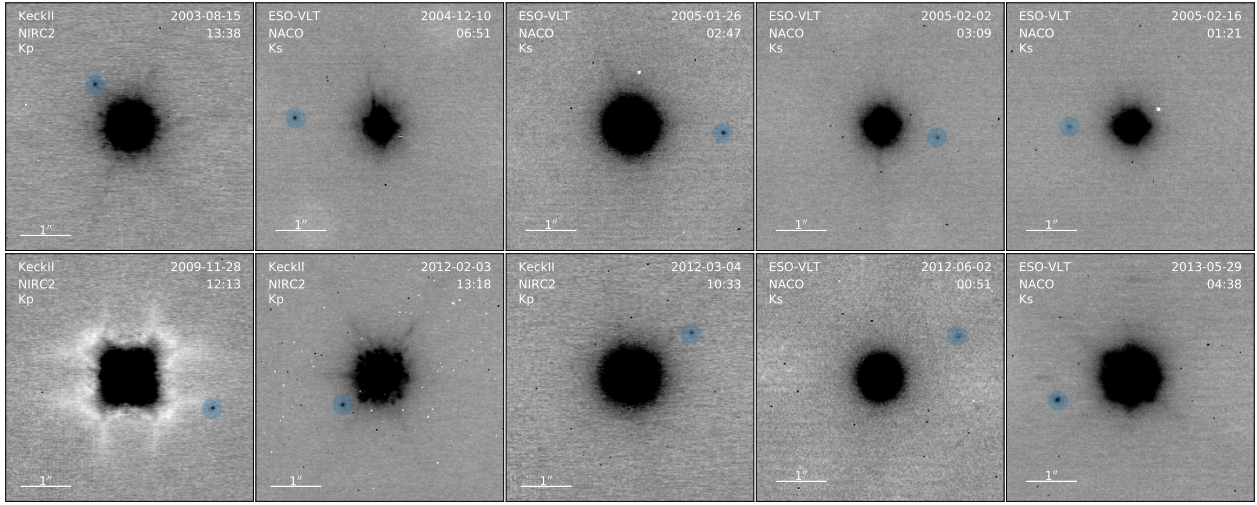


Figure 1: Examples of AO images. The small blue circles indicate the position of the satellite. North is up and East is left.

86 Camera 2, van Dam et al., 2004; Wizinowich et al.,
 87 2000). We reduce the AO imaging data with a standard
 88 data processing protocol (sky subtraction, bad-pixel
 89 identification and correction, and flat-field correction),
 90 using in-house routines (see Carry et al., 2008). The
 91 reduced images were processed to subtract the bright
 92 halo surrounding Huenna to enhance the detectability
 93 of its satellite (see Pajuelo et al., 2018, for details). The
 94 measured positions of the satellite are listed in Table 1,
 95 and we present a few examples in Figure 1.

96 3. Orbit of the satellite

97 We use all 40 positions of the satellite with respect
 98 to Huenna on the plane of the sky to characterize its
 99 orbital properties. We use the **Genoid** algorithm to
 100 find the set of dynamical parameters (mass, semi-major
 101 axis, eccentricity, inclination, longitude of the node, argu-
 102 ment of pericenter, and time of passage to pericenter)
 103 that best fit the observations (see Vachier et al., 2012;
 104 Berthier et al., 2014; Carry et al., 2019, 2021, for a de-
 105 tailed description of the algorithm and application to
 106 different systems).

Genoid explores the parameter space by successive
 generations of suites of test solutions (called individu-
 als). Each test solution consists in the set of dynamical
 parameters, and is compared with observations through
 numerical integration of the system, with the following
 metric:

$$\chi^2 = \sum_{i=1}^N \left[\left(\frac{X_{o,i} - X_{c,i}}{\sigma_{x,i}} \right)^2 + \left(\frac{Y_{o,i} - Y_{c,i}}{\sigma_{y,i}} \right)^2 \right] \quad (1)$$

107 where N is the number of observations, and X_i and
 108 Y_i are the relative positions between the satellite and
 109 Huenna along the right ascension and declination, re-
 110 spectively. The indices o and c stand for observed and

111 computed positions, and σ are the measurement uncer-
 112 tainties.

113 At each generation, the individuals with the lowest
 114 χ^2 are used to generate the individuals of the following
 115 generation, by randomly mixing their parameters (like
 116 sexual reproduction mixes genes). At each generation,
 117 the best solution is also used as initial condition to
 118 search for the local minimum by gradient descent. The
 119 algorithm stops after a given number of generations, or
 120 when the χ^2 achieved by several generations does not
 121 evolve anymore.

122 The combination of both a large grid search and
 123 a gradient descent ensures finding the best global dy-
 124 namical solution. The numerical integration is handled
 125 by **eproc**, the library of ephemerides computation be-
 126 hind all the Virtual Observatory Web services of the
 127 IMCCE (e.g., **SkyBoT**, **Miriade**, Berthier et al., 2006,
 128 2008, 2016). As such, it is a one body integrator per-
 129 turbed by N-bodies and has been extensively tested.

130 The numerical model used here consists in Huenna
 131 and its satellite, and the Sun. The case of Huenna **dif-**
 132 **fers from** other large asteroids with satellite for which
 133 the perturbation by the Sun (or any planet) is negligi-
 134 ble. Recent studies revealed purely Keplerian motions
 135 around (22) Kalliope, (31) Euphrosyne, (41) Daphne,
 136 (87) Sylvia, (107) Camilla, (130) Elektra, and (317)
 137 Roxane (Drummond et al., 2021; Yang et al., 2020;
 138 Carry et al., 2019, 2021; Berthier et al., 2014; Beauvalet
 139 and Marchis, 2014; Pajuelo et al., 2018; Yang et al.,
 140 2016). Considering the distribution of the separation
 141 between asteroids and their satellites (Fig. 2, data from
 142 Johnston 2019), only the outer satellite of (3749) Balam
 143 and the satellite of (379) Huenna are distant. The satel-
 144 lites of other bodies are located much deeper into their
 145 respective Hill spheres.

146 The influence of the Sun on the position of the satel-
 147 lite of Huenna is well above the typical precision of

Table 1

Astrometry of the satellite of Huenna. Date, mid-observing time (UTC), telescope, camera, filter, astrometry (X is aligned with Right Ascension, and Y with Declination, and o and c indices stand for observed and computed positions), uncertainty (σ), and photometry (magnitude difference ΔM with uncertainty δM) are reported.

Date	UTC	Tel.	Cam.	Filter	X_o (mas)	Y_o (mas)	X_{o-c} (mas)	Y_{o-c} (mas)	σ (mas)	ΔM (mag)	δM (mag)
2003-08-14	13:04:25.9	Keck-II	NIRC2	H	501	737	1	3	10.00	8.14	0.56
2003-08-14	14:07:52.8	Keck-II	NIRC2	H	506	737	-2	0	10.00	7.76	0.27
2003-08-15	13:34:46.6	Keck-II	NIRC2	Kp	693	838	1	0	10.00	6.98	0.07
2003-08-15	13:38:59.6	Keck-II	NIRC2	Kp	696	841	3	3	10.00	7.13	0.06
2003-08-17	14:53:55.0	Keck-II	NIRC2	Kp	1070	1028	1	-7	10.00	7.10	0.11
2003-08-18	14:19:56.0	Keck-II	NIRC2	Kp	1243	1116	2	-6	10.00	6.94	0.03
2004-12-08	07:08:31.3	ESO VLT	NACO	Ks	1783	130	4	4	13.30	7.43	0.80
2004-12-09	06:29:18.8	ESO VLT	NACO	Ks	1759	147	14	-2	13.30	6.55	0.41
2004-12-09	06:41:52.7	ESO VLT	NACO	Ks	1743	146	-1	-3	13.30	6.88	0.03
2004-12-10	06:45:20.8	ESO VLT	NACO	Ks	1702	176	1	1	13.30	6.37	0.56
2004-12-10	06:51:28.8	ESO VLT	NACO	Ks	1697	174	-2	0	13.30	6.67	0.03
2004-12-14	05:28:42.9	ESO VLT	NACO	Ks	1447	264	-1	2	13.30	6.65	0.07
2004-12-14	07:08:56.9	ESO VLT	NACO	Ks	1448	266	5	2	13.30	6.73	0.05
2004-12-15	05:20:24.8	ESO VLT	NACO	Ks	1370	285	1	3	13.30	6.87	0.13
2004-12-28	05:36:53.1	ESO VLT	NACO	Ks	-21	396	3	3	13.30	7.06	0.32
2004-12-28	07:41:12.8	ESO VLT	NACO	Ks	-41	397	-6	4	13.30	6.96	0.43
2004-12-29	05:13:34.3	ESO VLT	NACO	Ks	-141	391	0	0	13.30	6.28	0.00
2005-01-18	03:58:33.8	ESO VLT	NACO	Ks	-1924	65	4	7	13.30	7.03	0.07
2005-01-18	06:17:33.1	ESO VLT	NACO	Ks	-1931	56	0	1	13.30	6.72	0.13
2005-01-21	02:25:25.0	ESO VLT	NACO	Ks	-1991	-15	-4	0	13.30	6.79	0.51
2005-01-25	04:51:31.4	ESO VLT	NACO	Ks	-1916	-110	-2	0	13.30	7.44	0.00
2005-01-26	02:47:39.2	ESO VLT	NACO	Ks	-1868	-127	0	2	13.30	6.88	0.03
2005-01-26	05:10:41.1	ESO VLT	NACO	Ks	-1860	-127	3	3	13.30	7.42	0.28
2005-01-27	03:10:50.5	ESO VLT	NACO	Ks	-1799	-146	7	2	13.30	7.13	0.20
2005-01-28	03:04:35.7	ESO VLT	NACO	Ks	-1734	-166	-1	1	13.30	6.74	0.34
2005-01-28	03:13:54.0	ESO VLT	NACO	H	-1735	-159	-3	7	13.30	7.37	0.15
2005-02-02	03:09:16.2	ESO VLT	NACO	Ks	-1147	-222	1	0	13.30	7.09	0.03
2005-02-02	05:09:29.4	ESO VLT	NACO	Ks	-1134	-225	2	-3	13.30	7.00	0.08
2005-02-04	02:41:04.7	ESO VLT	NACO	Ks	-823	-223	5	0	13.30	7.02	0.20
2005-02-04	04:05:56.8	ESO VLT	NACO	Ks	-819	-224	0	0	13.30	6.84	0.12
2005-02-16	01:21:08.5	ESO VLT	NACO	Ks	1221	-4	-3	-2	13.30	6.72	0.27
2009-11-28	12:13:35.1	Keck-II	NIRC2	Kp	-1672	-616	-4	4	10.00	7.16	0.08
2009-11-28	12:51:36.2	Keck-II	NIRC2	Kp	-1673	-615	-7	3	10.00	6.97	0.03
2012-02-03	13:18:43.9	Keck-II	NIRC2	Kp	740	-551	-7	-3	10.00	6.94	0.43
2012-02-03	13:33:28.7	Keck-II	NIRC2	Kp	739	-552	-8	-5	10.00	6.98	0.09
2012-03-04	10:33:13.8	Keck-II	NIRC2	Kp	-1225	894	4	19	10.00	7.37	0.28
2012-03-29	07:16:52.3	Keck-II	NIRC2	Kp	-1881	656	0	5	10.00	6.93	0.03
2012-06-02	00:51:58.5	ESO VLT	NACO	Ks	-1568	825	-12	-16	13.30	7.01	0.31
2014-11-10	07:16:10.7	Keck-II	NIRC2	Ks	3079	1085	-5	-16	10.00	1.65	0.06
2014-12-07	05:38:57.2	Keck-II	NIRC2	Ks	-554	-585	-2	-2	10.00	6.65	0.01
Average							0	0		6.86	0.18
Standard deviation							4	6		0.90	0.17

148 measurements, around $0.01''$ (Table 1). By compar-
 149 ing the best-fit solution (see below) including the Sun
 150 and a simple Keplerian orbit, we find a root mean-
 151 square residual of $0.477''$ over the period of 11 years
 152 covered by the observations, the two orbit diverging
 153 with time (Figure 3). The second-largest external per-
 154 turer is Jupiter, but only contributes at the level of
 155 $0.0001''$ and we neglect it in our dynamical model.

156 We present in Table 2 the best-fitting orbital solu-

157 tion, providing a root mean-square deviation of only
 158 **5.4** milli-arseconds (mas). This orbit significantly dif-
 159 fers from the **original** dynamical solution of **Marchis**
 160 **et al. (2008)**. While the orientation of the orbit (node,
 161 inclination, pericenter) is similar within a few degrees,
 162 the orbital period strongly disagree: **80.2 ± 0.01** d here,
 163 compared to the previous value of **87.6 ± 0.26** d ; i.e.,
 164 an increase of **9%**, at more than **28** σ .

165 **Four** arguments argue in favor of the revised solu-

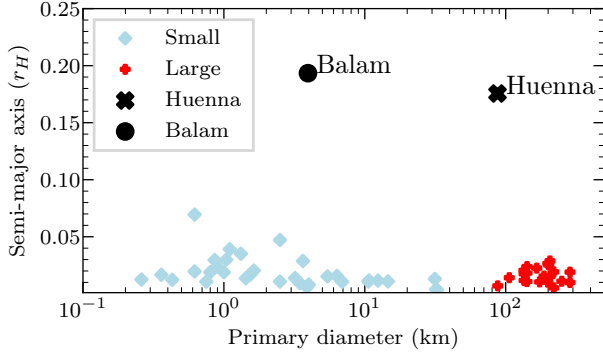


Figure 2: Semi-major axes of binary asteroids (expressed in radius of the Hill's sphere: r_H) as function of the diameter of the main component. The population is split into small (blue) and large (red) systems, using a diameter of 30 km to separate them.

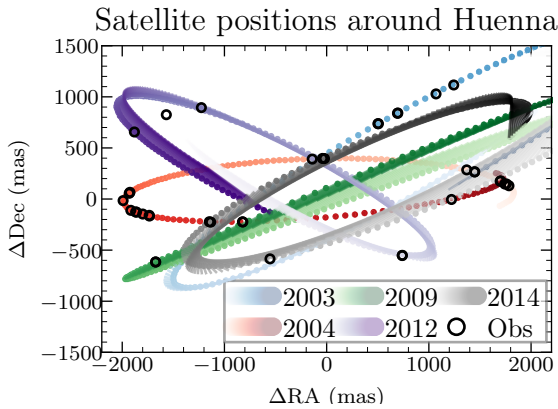


Figure 3: Comparison of the predicted position from a Keplerian orbit (fit over all 31 positions between 2003 and 2005 with a RMS of 3.6 mas only) and the orbit including the influence of the Sun. The black dots are the observations. The predictions of the two orbits are connected by lines, color-coded by epoch. The later the epoch the larger the difference.

among estimates, resulting in 10% uncertainty. This is expected for estimates based on the analysis of mid-infrared fluxes using a spherical assumption on the shape of asteroids (Mainzer et al., 2011; Carry, 2012; Usui et al., 2014; Herald et al., 2020). The updated mass and diameter estimates imply a bulk density of $1491 \pm 249 \text{ kg}\cdot\text{m}^{-3}$. This density is typical for a P-type (see, e.g., Carry, 2012; Berthier et al., 2014; Pajuelo et al., 2018; Carry et al., 2021; Vernazza et al., 2021). The diameter estimates are, however, only based on disk-integrated measurements, and the density estimate should hence be interpreted with caution.

Assuming that Huenna and its satellite have the same albedo (a reasonable assumption considering their similar spectra, see DeMeo et al., 2011), their apparent magnitude difference of 6.9 ± 0.9 (Table 1) implies a diameter of 3.72 ± 0.60 km only for the satellite. It is thus one of the smallest satellites of large (50+ km) asteroids known to date, with Daphne, Elektra, and Minerva (Marchis et al., 2013; Yang et al., 2016; Carry et al., 2019).

Small satellites of large asteroids are thought to form in giant collisions (Durda et al., 2004; Margot et al., 2015), and share common properties. Their orbits tend to be equatorial, circular, in the direct sense, and deep within their Hill spheres (0.017 ± 0.002). The peculiar properties of the satellite of Huenna, especially its eccentricity and large semi-major axis, questions its origin, or evolution. While the likelihood of an origin by capture is low (Weidenschilling et al., 1989), what excited its orbit and increased its eccentricity and semi-major axis if formed like other satellites of large asteroids? The spin axis of Huenna is not known, and lightcurve observations of Huenna to determine it will help understanding the geometry of the system: whether the mutual orbit is equatorial or tilted.

5. Conclusion

We searched for adaptive-optics images of the asteroid (379) Huenna in the archives of large ground-based telescopes. We measured 40 positions of the satellite with respect to Huenna taken over 11 years. From these positions, we determined the dynamics of the satellite, solving the miss-match between previously published orbit and an observation in 2009. We derived a new estimate of the mass of Huenna. Combined with its average diameter computed from estimates reported in the literature, we determined a density of $1491 \pm 249 \text{ kg}\cdot\text{m}^{-3}$, typical of the P-types asteroids like Huenna. The satellite is on an eccentricity orbit, far from Huenna, which contrasts with the properties of most known satellites around large main-belt asteroids. A physical characterization of Huenna, and in particular of its spin axis, is required to study further the origin of this system.

tion: the agreement within 3σ between our dynamical solution and the recent study by Emelyanov and Drozdov (2020), the small residuals obtained here, the poor prediction of previous solution for the 2009 observation reported by DeMeo et al. (2011), and the time coverage of only 70 d used by Marchis et al. (2008), i.e., shorter than an orbital period.

4. Discussion

The revised dynamical solution implies a significantly larger mass (36%) compared to the previous determination (Marchis et al., 2008). In what follow, we assume that all the mass of the system is in Huenna, owing to the small size of its satellite (see below). We compile all the diameter estimates available in the literature in Table 3, and estimate an average diameter of 87.5 ± 8.2 km. There is a significant spread

Table 2

Orbital elements and state vector (centered on Huenna) of the satellite of Huenna, expressed in EQJ2000: orbital period P , semi-major axis a , eccentricity e , inclination i , longitude of the ascending node Ω , argument of pericenter ω , time of pericenter t_p . The number of observations and RMS between predicted and observed positions are also provided. Finally, we report the system total mass M , the ecliptic J2000 coordinates of the orbital pole (λ_p, β_p) , and the equatorial J2000 coordinates of the orbital pole (α_p, δ_p) . Uncertainties are given at $3\text{-}\sigma$.

Observing data set		
Number of observations	40	
Time span (days)	4133	
RMS (mas)	5.4	
Orbital elements EQJ2000		
P (day)	80.216	± 0.015
a (km)	3487.9	± 41.4
e	0.283	± 0.010
i ($^\circ$)	151.19	± 0.68
Ω ($^\circ$)	204.53	± 1.19
ω ($^\circ$)	278.9	± 1.5
t_p (JD)	2452930.961	± 0.31
State vector EQJ2000		
x (m)	-3 228 767.0	
y (m)	-621 087.4	
z (m)	426 401.0	
v_x (m/s)	-1.2471	
v_y (m/s)	2.6316	
v_z (m/s)	1.6019	
Derived parameters		
M ($\times 10^{17}$ kg)	5.23	± 0.19
α_p, δ_p ($^\circ$)	114.5, -61.2	$\pm 1.2, 0.7$
λ_p, β_p ($^\circ$)	161.8, -77.8	$\pm 3.4, 0.5$

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Table 3

Diameter estimates of Huenna compiled from the literature.

Diameter (km)	Method	Reference
92.33 \pm 1.70	STM	Tedesco et al. (2001)
103.01 \pm 4.31	NEATM	Ryan and Woodward (2010)
82.02 \pm 2.56	STM	Ryan and Woodward (2010)
87.47 \pm 2.36	NEATM	Masiero et al. (2011)
104.56 \pm 1.88	NEATM	Masiero et al. (2012)
87.34 \pm 9.06	NEATM	Pravec et al. (2012)
82.35 \pm 1.08	NEATM	Hasegawa et al. (2013)
88.00 \pm 9.00	NEATM	Alí-Lagoa et al. (2013)
84.79 \pm 1.56	NEATM	Masiero et al. (2014)
85.70 \pm 8.57	NEATM	Alí-Lagoa et al. (2016)
85.82 \pm 23.24	NEATM	Nugent et al. (2015)
71.59 \pm 18.01	NEATM	Nugent et al. (2016)
86.18 \pm 25.86	NEATM	Nugent et al. (2016)
75.77 \pm 15.15	NEATM	Alí-Lagoa et al. (2018)
87.25 \pm 17.45	NEATM	Alí-Lagoa et al. (2018)
95.95 \pm 9.59	NEATM	Alí-Lagoa et al. (2018)

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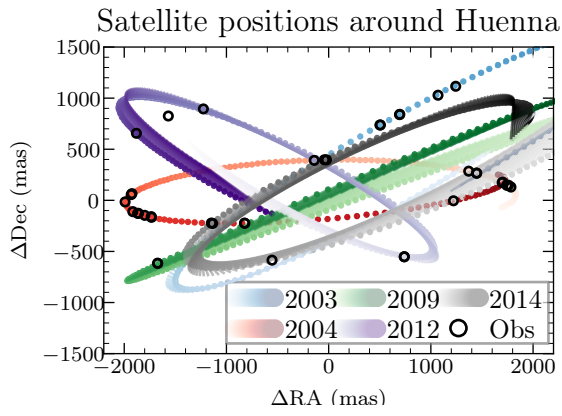
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Dynamics of the binary asteroid (379) Huenna

Frédéric Vachier, Benoit Carry, Jérôme Berthier



4 Highlights

5 Dynamics of the binary asteroid (379) Huenna

6 Frédéric Vachier, Benoit Carry, Jérôme Berthier

- 7 • We gather 40 observations of Huenna and its satellite
- 8 • We revise the published orbital elements of the satellite
- 9 • The satellite is distant from Huenna, **differing from** other satellites of large asteroids
- 10 • The density of Huenna is $1491 \pm 249 \text{ kg}\cdot\text{m}^{-3}$