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Discovery of the First Known Asteroid Confined within the Orbit of Venus

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Abstract

We report on the discovery by the Zwicky Transient Facility of an asteroid orbiting entirely within the orbit of Venus, the first known example of this orbital class. The asteroid's perihelion is closer to the Sun than the aphelion of Mercury, and its diameter is estimated at about 1.8 km assuming an albedo of 0.2. The object was first observed on 2020 January 4 in four exposures obtained 7 minutes apart during an evening twilight survey. Its IAU-recognized designation is 594913 'Ayló'chaxnim.

Unified Astronomy Thesaurus concepts: Small Solar System bodies (1469); Near-Earth objects (1092); Asteroids (72)

1. Introduction

Asteroids in the inner solar system are classified according to their orbit locations and include (1) Amors that orbit outside of Earth's orbit and most of which cross the orbit of Mars; (2) Apollos and Atens that cross the orbit of Earth; and (3) Atiras that orbit interior to Earth's orbit and all of which cross Venus's orbit. Only a few Atiras had been identified by 2019. Asteroids with orbits completely inside the orbit of Venus have been predicted by theoretical models (Greenstreet et al. 2012; Granvik et al. 2018), but none had been found by the end of 2019. This is not surprising as such objects are hard to detect from the ground because their solar elongation cannot exceed Venus's 45°, requiring them to be observed at elevations lower than 33° during twilight with the Sun just 12° to 18° below the horizon. T. B. Bolin et al. (2022, in preparation) list half a dozen surveys dedicated to finding Atiras, and more are being undertaken from the ground (Pokorny et al. 2020; Sheppard et al. 2021) and from space (Tanga et al. 2022).

The Zwicky Transient Facility (ZTF; P.I. S.R. Kulkarni, Caltech) is an optical time-domain survey (Bellm et al. 2019; Graham et al. 2019) that started operations in 2018. Using a new camera with a field of view of 47 deg^2 on the Palomar 1.2 m Oschin Schmidt telescope, ZTF surveys the sky at a rate of about 4000 deg^2 per hour with 30 s integrations yielding a median r or g 5σ sensitivity of 20.5 mag, providing a powerful capability for the detection of astrophysical transients and minor planets in the solar system (Dekany et al. 2020). The data are processed and analyzed for static sky, variable sources, transient alerts, and moving objects with a ZTF Science Data System (ZSDS; Masci et al. 2019) that yields an absolute photometric accuracy better than ∼25 mmag and repeatability of 8 to 25 mmag (airmass dependent). The absolute astrometric accuracy with respect to Gaia is typically ⩽80 mas (1σ per axis) for extractions down to a signal-to-noise ratio of 10 in a ZTF filter, corresponding to a limiting magnitude of ∼20 in either g or r. The astrometric precision in the bright (unsaturated) limit inferred from ZTF extractions with magnitudes ⩽16 at airmass ⩽1.1 is typically better than 30 mas. ZTF provides excellent characterization of the moderate depth (r, g <20.5 mag) variable sky and thus paves the way for the Vera Rubin Observatory deeper survey.

ZTF observing consists of several components, including an all-sky monitoring campaign and localized surveys with tailored cadences. One of the latter is a Twilight Survey (TS) aimed at searching for asteroids in orbits closer to the Sun than Earth's orbit (Ye et al. 2020).

A new asteroid was spotted in ZTF TS data with an orbit completely contained within that of Venus. This paper reports that discovery and the orbital parameters.

2. Observations

2.1. The ZTF Twilight Survey

The potential for the discovery of new Atiras was the motivation for initiating a TS at the inception of ZTF to take advantage of the wide-field capability of the newly installed CCD camera system. In practice, most TS observations were carried out at solar elongations between 35° and 50° and elevations between 20° and 35°.

The ZSDS includes processing branches dedicated to the detection of asteroids in ZTF data. Two branches, ZSTREAK and ZMODE, are designed to detect fast-moving and slow-moving objects, respectively (Masci et al. 2019). These processing branches are run on all ZTF data, including data collected during the TS.

As reported by Ye et al. (2020), TS was carried out during both evening and morning twilight time with the Sun between 12° and 18° below the horizon. The first phase of TS ran from 2018 November to 2019 June and was followed by the second

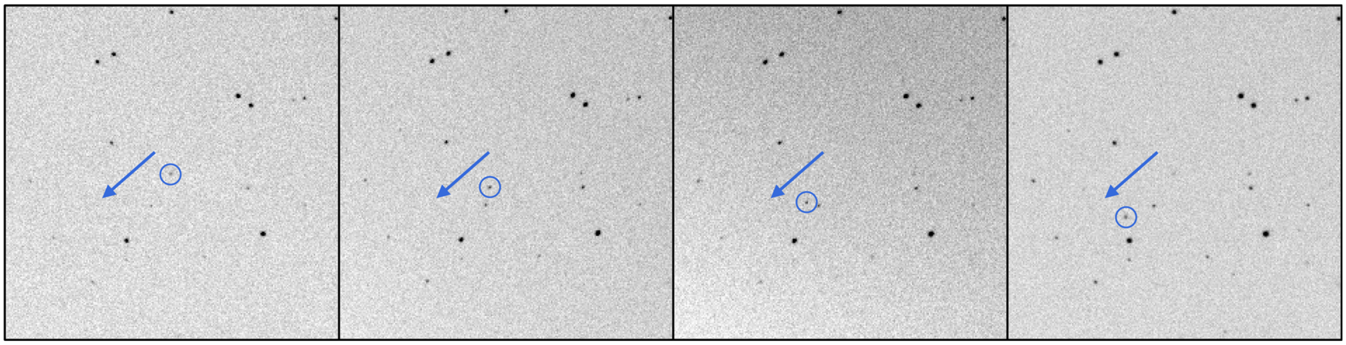

Figure 1. Discovery images in ZTF data of ‘Ayló’chaxnim obtained on 2020 January 4 during the TS. The object of interest is circled in each exposure, and the arrow indicates the apparent direction of motion. The times and coordinates of the asteroid in each image are given in Table 1 in the order of left to right.

Table 1
Data from the Initial Four Observations Leading to the Discovery Of Asteroid ‘Ayló’chaxnim

Observation Time (yr, mo, day, hour)	R.A. (hh mm ss.ss)	Decl. (dd mm ss.s)	Magnitude (*r* mag)
2020-01-04T01:50:59Z	21 24 49.90	−06 08 41.8	17.96
2020-01-04T01:58:10Z	21 24 50.67	−06 08 31.5	17.95
2020-01-04T02:05:22Z	21 24 51.46	−06 08 21.0	18.13
2020-01-04T02:12:32Z	21 24 52.22	−06 08 10.7	18.01

phase starting in 2019 September. During the first phase, TS detected six Atiras including two new discoveries, namely 2019 AQ3 and 2019 LF6. Then early in the second phase, the first asteroid in an orbit internal to that of Venus was discovered and reported to the Minor Planet Center (MPC) by Bolin et al. (2020).

2.2. Discovery Observations

The new asteroid was flagged by the ZSDS/ZMODE (Masci et al. 2019) in ZTF data collected in the evening twilight sky on 2020 January 4 and available from IRSA (2022). Four detections spaced about 7 minutes apart were connected by ZMODE into a candidate arc, which was then validated and reported to the MPC. The object was followed up by many observers, then released by the MPC as MPEC 2020-A99: 2020 AV_2 (Bolin et al. 2020) on 2020 January 8, based on 98 observations of the asteroid from observatories around the world. The original four detections are illustrated in Figure 1 and summarized in Table 1. The elevation of the asteroid from Palomar Observatory ranged from 26° to 22° during these observations. The data for these images are available as FITS files from the ZTF Archive at IRSA (IRSA 2022; https://irsa.ipac.caltech.edu/Missions/ztf.html), along with the subsequent ZTF sightings of the object in 119 distinct exposures obtained between 2020 July 27 and 2020 February 20, of which 99 are included in the MPC database.

2.3. Numbering and Naming of the Asteroid

The object was originally designated 2020 AV_2 then assigned asteroid number 594913 by the MPC in their circular dated 2021 September 24. In recognition of the peoples originally inhabiting the lands that include Palomar Observatory, we have consulted with the Pauma Band of Luiseño Indians about naming this asteroid. They suggested the Luiseño name ‘Ayló’chaxnim, meaning “Venus Girl.” This was proposed to the International Astronomical Union Working Group on Small Bodies Nomenclature and formally adopted by that Working Group on 2021 November 8 (Tichá et al. 2021). We have searched the ZTF Archive but did not find any instances of ‘Ayló’chaxnim falling within the ZTF field of view that predate the discovery images of 2020 January.

Table 2
Orbital Parameters of 594913 ‘Ayló’chaxnim (2020 AV2)

	MPEC 2020-A99: 2020 AV2 [2020-01-08]	JPL Small-body Database[a] Solution [2022-06-30]
Period (years)	0.41	0.413939241 (64)
Aphelion distance (AU)	0.654	0.653765975 (67)
Perihelion Distance (AU)	0.456	0.45706742 (51)
Inclination (deg)	15.898	15.868573 (61)
Eccentricity	0.1780	0.17707296 (90)
Absolute magnitude	16.5	16.21 (78)

Note.
[a] See the Appendix for the details of the JPL Small-body Database (2022) solution.

3. Orbital Parameters

The initial determination of orbital parameters on MPEC 2020-A99: 2020 AV_2 had the aphelion distance of the object at 0.654 au, i.e., well within the orbit of Venus, which has a perihelion of 0.718 au (Table 2). On 2022 June 30, the JPL Small-body Database provided the orbital parameters given in Table 2, based on 248 observations made since the initial ZTF discovery observations (JPL Small-body Database 2022). Note that the perihelion of ‘Ayló’chaxnim is slightly smaller than the

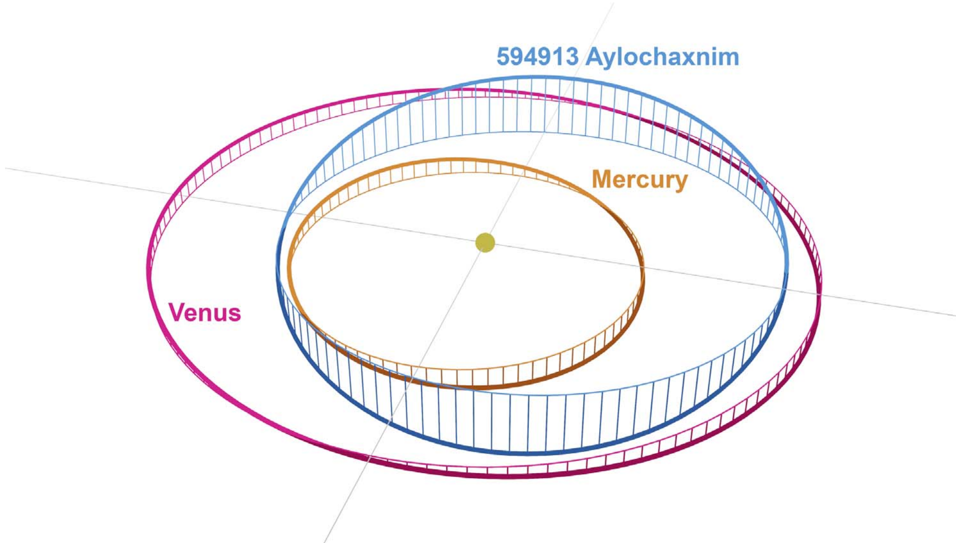

Figure 2. Orbital diagram showing the orbits of the asteroid 'Ayló'chaxnim, Mercury, and Venus corresponding to the JPL Small-body Database solution in Table 2. The vertical lines connect points on the orbit to their projection in the Ecliptic Plane.

aphelion of Mercury, 0.4667 au. While the estimates of orbital elements changed little between 2020 January and 2022 June, the best-estimate absolute magnitude became 0.34 mag brighter, though the 1σ uncertainty on the updated value is more than twice that difference. For illustration, an absolute magnitude of $H = 16.2$ corresponds to a size of 1.8 km for an albedo of 0.2, typical of S-type asteroids.

The orbit of 'Ayló'chaxnim is shown in Figure 2, based on data available at the NASA/JPL Small-body Database (2022) service at https://ssd.jpl.nasa.gov/. The Appendix provides more detail about these data.

The orbital evolution of 'Ayló'chaxnim will be discussed in T. B. Bolin et al. (2022, in preparation), but we point out here two papers that have started that discussion (de la Fuente Marcos & de la Fuente Marcos 2020; Greenstreet 2020).

4. Conclusion

The discovery of 'Ayló'chaxnim marks a significant milestone in the inventory of asteroids in the inner solar system and confirms the existence of the hypothesized class of objects internal to the orbit of Venus. A more detailed discussion of relations to models and implications is presented in T. B. Bolin et al. (2022, in preparation).

Based on observations obtained with the Samuel Oschin Telescope 48 inch and the 60 inch Telescope at the Palomar Observatory as part of the Zwicky Transient Facility project. ZTF is supported by the National Science Foundation under grant N0. AST-1440341 and a collaboration including Caltech, IPAC, the Weizmann Institute for Science, the Oskar Klein Center at Stockholm University, the University of Maryland, the University of Washington, Deutsches Elektronen-Synchrotron and Humboldt University, Los Alamos National Laboratories, the TANGO Consortium of Taiwan, the University of Wisconsin at Milwaukee, and Lawrence Berkeley National Laboratories. Operations are conducted by COO, IPAC, and UW.

Following the final acceptance of this paper for publication Dr. Bryce Bolin elected to withdraw his name from the author list. We note that Dr. Bolin played a critical role in this discovery by recognizing the uniqueness of this object in the pipeline output and triggering timely follow-up. We thank him for his contributions to this paper.

The development of ZMODE and ZSTREAK and the search for asteroids in ZTF data are made possible by NASA grants 80NSSC19K0780 and 80NSSC21K0659. We acknowledge Dr. Robert Hurt's significant contribution to the generation of figures.

The authors wish to recognize and acknowledge the cultural significance that Palomar Mountain has for the Pauma Band of the Luiseño Indians, as well as the importance of the night sky to the Luiseño people. We are most fortunate to have the opportunity to conduct observations of the sky from this mountain.

Appendix
JPL Small-body Database Solution for 'Ayló'chaxnim

The JPL Small-body Database orbital elements and absolute magnitude listed in Table 2 for the epoch 2022 August 09.0 are taken from the solution generated on 2022-02-14T04:50:02Z. A screen capture of this solution is reproduced in Figure A1. See also the URL for the JPL Small-body Database in the References section.

Osculating Orbital Elements

Epoch 2459800.5 (2022-Aug-09.0) TDB
Reference: JPL 37 (heliocentric **IAU76/J2000** ecliptic)

Element	Value	Uncertainty (1-sigma)	Units
e	0.1770729600217089	9.0402E-7	
a	0.5554166967366642	5.7049E-8	au
q	0.4570674182000232	5.131E-7	au
i	15.86857312139687	6.0855E-5	deg
node	6.702397633329228	.00025815	deg
peri	187.3290147423875	.00030984	deg
M	327.2155378117368	.00045243	deg
tp	2459814.268682538455 2022-Aug-22.76868254	.00019166	TDB
period	151.1913078024549 0.4139392410744829	2.3294E-5 6.3775e-8	d y
n	2.38108926520017	3.6686E-7	deg/d
Q	0.6537659752733052	6.7151E-8	au

Miscellaneous Details

solution date	2022-Feb-14 04:50:02
# obs. used (total)	248
data-arc span	772 days (2.11 years)
first obs. used	2020-01-04
last obs. used	2022-02-14
planetary ephem.	DE441
SB-pert. ephem.	SB441-N16
condition code	2
norm. resid. RMS	.34178
source	JPL
producer	Otto Matic
Earth MOID	.346252 au
Jupiter MOID	4.29845 au
T_jup	9.987

Figure A1. Screen capture of the orbital solution for 'Ayló'chaxnim presented by the JPL Small-body Database on June 30, 2022.

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