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Occultation evidence for a satellite of the Trojan asteroid (911) Agamemnon

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ABSTRACT

On 2012 January 19, observers in the northeastern United States of America observed an occultation of 8.0-mag HIP 41337 star by the Jupiter–Trojan (911) Agamemnon, including one video recorded with a 36 cm telescope that shows a deep brief secondary occultation that is likely due to a satellite, of about 5 km (most likely 3–10 km) across, at 278 ± 5 km (0.0931″) from the asteroid's center as projected in the plane of the sky. A satellite this small and this close to the asteroid could not be resolved in the available VLT adaptive optics observations of Agamemnon recorded in 2003. The outline of Agamemnon is fit well by an ellipse with dimensions 190.6 ± 0.9 km by 143.8 ± 1.5 km. The angular diameter of HIP 41337 was found to be 0.5 ± 0.1 milli-arcsec. After (624) Hektor, this could be the second Jupiter Trojan asteroid known to possess a small satellite.

1. Introduction

As early as 1977 (Dunham and Maley, 1977), claims were made that asteroids probably had satellites, based on observations of occultations of stars by asteroids. But these early claims, mostly based on visual observations with no recordings of the event, were dismissed by most astronomers at the time. One intriguing claim, based on independent observations by two observers at separate locations during a 1980 occultation by the asteroid (216) Kleopatra (Dunham, 1981), was found to be consistent with the currently known orbital elements of one of the now known two satellites of that asteroid (Descamps et al., 2011), that is, the position of the 1980 secondary event closely matched the projection of the now-known orbit of the satellite in the plane of the sky as computed for the 1980 event. By the end of 2006, 42 suspected satellite occultations had been reported out of a total of over 1029 asteroidal occultations, about 1 for every 25th occultation, but only 9 of these were regarded as reasonably credible at the time (Maley and Dunham, 2007). In 1982, the first video recording was obtained at Meudon Observatory of a "secondary occultation" that was likely caused by a satellite of (146) Lucina (Arlot et al., 1985). But the field of view for that observation was too narrow to include any other field stars bright enough to be recorded. In this paper, we report a good video observation of a secondary occultation that gives strong evidence that (911) Agamemnon, probably the second-largest Jupiter Trojan asteroid, likely has a small satellite.

The history of asteroidal occultation observations was reviewed in (Timerson, 2009). Successful predictions (Preston, 2013) and observations have increased dramatically, especially since 1997, aided by high-accuracy star catalogs and asteroid ephemerides (Dunham et al., 2002).

Asteroidal occultations are now usually video recorded using small sensitive security cameras attached to telescopes; the techniques and equipment needed to make these observations are described in the IOTA observer's manual (Nugent, 2012), with basic information also given by (Degenhardt, 2009). Planning software called *OccultWatcher* allows observers to space themselves across the predicted path of the occultation to gather as many unique chords as conditions allow (Pavlov, 2012a). Observations are reported to a regional coordinator who gathers these observations and uses a program called *Occult*4 (Herald, 2012) to produce a sky-plane profile of the asteroid at the time of the event (Timerson,

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2013). These asteroidal occultation data are officially deposited and archived, and made available to the astronomical community through the NASA Planetary Data System (Dunham et al., 2012).

2. Occultation results

2.1. Observing stations

On 2012 January 19 at 11:31 UT asteroid 911 Agamemnon occulted the V magnitude 8.0 star HIP 41337=SAO 60804=BD=+37° 1857=HD 70920, spectral type K0, in the constellation of Lynx over a path which moved onshore along the mid-Atlantic USA, passed through the central Great Lakes, Canada, and Alaska. The maximum duration was predicted to be 10.4 s on the basis of the AKARI AcuA spherical diameter of 185 km (Usui et al., 2011). For this event, 5 observers set up telescopes located at 8 sites across the predicted path of the occultation, using 29.97 frame s^{-1} NTSC video to record the event. Five well-spaced chords were obtained across Agamemnon, while two stations reported no occultation, and one station mal-functioned. One observer (S. Conard) used a 36 cm Schmidt–Cassegrain telescope at his Willow Oak Observatory in Gamber, Maryland, recording the analog video signal from the video camera directly to a lossless.avi file on a computer, while the other 4 positive observations were made with 0.5 cm binocular-based video systems called "mighty mini" systems (Degenhardt, 2009). The video was recorded digitally to MiniDV tapes using camcorders, and the digital files were later captured in a lossless manner to.avi files via a Firewire interface to a computer using Windows Moviemaker (thus, all of the video recordings of the occultation were not compressed, to avoid the distortions that compression can introduce). Two of these small systems were pre-pointed to the occultation altitude and azimuth, and run as stationary (non-tracking) remote unattended stations, with the video recorders turned on and off at the right time with timers, set up by Dunham. No filters were used for the observations. The cameras used are more sensitive in the red than visual observation, with some sensitivity in the near-infrared range. The occultation timings were determined by analysis of the avi video files using Limovie (Miyashita, 2008), Tangra (Pavlov, 2012b), and Occular software (George, 2009).

The observations are detailed in Table 1. After the location column, distances are given from the predicted central line, with positive values northeast of the central line. In the events column, "miss" indicates that no occultation occurred at that station. Most of the video recordings used video time inserters that wrote the UTC time on each video frame; the times for them should be accurate to 1 frame (±0.03 s). However, the two successful remote stations, chords 3 and 4, determined UTC from the camcorder clock as calibrated before and after the occultation with short GPS video time-inserted recordings using an "IOTA–VTI" video time inserter; their times should be accurate to 2 frame (±0.06 s). The last column gives the signal-to-noise (S/N) ratio for the positive observations. For the miss stations, the S/N is less important, and more difficult to measure, without an occultation period. The station locations, and the predicted path (Preston, 2012) are shown in Fig. 1.

2.2. Stellar diameter, Fresnel diffraction

The lightcurves for all observed events were "gradual", indicative of the effects of stellar diameter and/or Fresnel diffraction. The star is not listed in either the CHARM2 (Richichi et al., 2005) or CADARS (Pasinetti Fracassini et al., 2001) catalogs of stellar diameters. However its apparent diameter can be estimated using either the B or V magnitude with the K magnitude (van Belle, 1999). The V magnitude derived from the Hipparcos Vt and Bt magnitudes is 7.79, while the B magnitude is 9.02. The K magnitude from the 2MASS catalog is 4.94. The star is not known to be a variable star, nor a giant or supergiant star. Accordingly the stellar diameter estimated using equations (6) and (7) of van Belle is about 0.6 mas. Fig. 2 shows our analysis of the lightcurves for the occultation by the primary body to determine the stellar diameter. The average of the best fit in each of the 10 light curves (optimized by aiming for a minimum in chi-squared) is $0.46+/-0.03$ mas. But the Conard lightcurve has by far the highest S/N; the gradual nature of the occultation events is barely noticeable in the other recordings. Consequently, we prefer to use only Conard's observation, which gives a stellar diameter of 0.5 ± 0.1 mas – fully consistent with the estimated diameter. We have neglected limb darkening in the analysis; including it could increase the stellar diameter. At the 4.1 AU distance to Agamemnon, 0.5 mas subtends 1.5 km, almost 4 times the Fresnel diffraction fringe spacing, which is about 400 m at Agamemnon's distance. This fact, and the consistent result that we obtained neglecting diffraction, we believe justifies our neglect of the latter effect; including Fresnel diffraction in the analysis would not significantly change the results, considering the quality of the observations.

2.3. Primary chords and shape

The resulting chords and least squares ellipse from *Occult*4 are shown in Fig. 3. The chords are well-fit with an ellipse with dimensions of $190.6\pm0.9\times143.8\pm1.5$ km; the RMS of the fit is 1.9 km. This gives an average diameter of 165.6 km, in good agreement with the diameter of 167±4 km determined for Agamemnon by the Infrared Astronomy Satellite (IRAS, see Tedesco et al., 2002), but smaller than the 185±3 km size given in AKARI AcuA (Usui et al., 2011) that was used for the predicted path shown in Fig. 1. This discrepancy could be due to the rotation of the asteroid. No photometry is known of Agamemnon in January 2012, but a month later, the asteroid was observed and its rotational lightcurve was

Table 1
The occultation observations.

Chord	Observer	Location	Distance from centerline (km)	Longitude (degrees west)	Latitude (degrees north)	Elevation (m)	Disappearance time (UT)	Reappearance time (UT)	Time standard	Signal to noise ratio
1	B Timerson	Newark, NY	238.6	77.1183	43.0067	165	Miss	Miss	A	NA
2	D Dunham	Wrangle Hill, DE	59.4	75.6574	39.5743	13	11:31:42.81	11:31:47.50	A	0.98
3	D Dunham	Summit Airport, DE	51.4	75.7136	39.5159	19	11:31:42.06	11:31:48.03	B	1.27
4	D Dunham	Price, MD	4.7	75.9526	39.1077	17	11:31:39.29	11:31:48.95	B	1.46
5	Centerline		0							
6	S Conard -primary	Gamber, MD	−26.9	76.9517	39.4692	214	11:31:40.61	11:31:51.13	A	9.4
7	S Conard -secondary	Gamber, MD	−26.9	76.9517	39.4692	214	11:32:01.32	11:32:01.50	A	9.7
8	A. Tolea	Forest Glen, MD	−69.2	77.0532	39.0192	110	11:31:40.30	11:31:48.67	A	1.98
9	J. Brooks	Winchester, VA	−120.8	78.2333	39.2667	213	Miss	Miss	A	NA

Time Standard: A=GPS time inserted video, B=UTC calibrated time video at remote station, see text.