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The mass, orbit, and tidal evolution of the Quaoar–Weywot system

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ABSTRACT

Here we present new adaptive optics observations of the Quaoar–Weywot system. With these new observations we determine an improved system orbit. Due to a 0.39 day alias that exists in available observations, four possible orbital solutions are available with periods of ~11.6, ~12.0, ~12.4, and ~12.8 days. From the possible orbital solutions, system masses of $1.3–1.5 \pm 0.1 \times 10^{21}$ kg are found. These observations provide an updated density for Quaoar of 2.7–5.0 g cm^{-3}. In all cases, Weywot's orbit is eccentric, with possible values ~0.13–0.16. We present a reanalysis of the tidal orbital evolution of the Quaoar–Weywot system. We have found that Weywot has probably evolved to a state of synchronous rotation, and has likely preserved its initial inclination over the age of the Solar System. We find that for plausible values of the effective tidal dissipation factor tides produce a very slow evolution of Weywot's eccentricity and semi-major axis. Accordingly, it appears that Weywot's eccentricity likely did not tidally evolve to its current value from an initially circular orbit. Rather, it seems that some other mechanism has raised its eccentricity post-formation, or Weywot formed with a non-negligible eccentricity.

1. Introduction

Large Kuiper Belt Objects with diameters $D \gtrsim 1000$ km exhibit a broad range of densities, with values typically larger than 1.5 g cm^{-3} (Buie et al., 1997; Rabinowitz et al., 2006; Brown et al., 2010; Fraser and Brown, 2010). In addition, many of the larger objects are found with small satellites only a few percent the size of the primary (Brown et al., 2005; Brown and Schaller, 2007; Fraser et al., 2010) and that are icy in nature (Barkume et al., 2006; Brown et al., 2006; Fraser and Brown, 2009). A natural explanation is one in which during the early phases of planetesimal growth, these large bodies accreted a large enough mass sufficiently rapidly to heat up and differentiate, producing silicate rich cores surrounded by icy mantles. Subsequent collisional evolution then stripped predominantly icy material, raising their densities above their primordial values. The range of densities exhibited by each object would then reflect the relative amounts of collisional bombardment that object suffered. Another bi-product of this process are the satellites of the larger objects which are just collisional fragments from the mantle which were not ejected with a high enough velocity to escape, and remained bound to their primaries.

The large object Quaoar is an extreme case. Observations of its satellite, Weywot, presented by Fraser and Brown (2010) suggest it is the densest known KBO. The observed density of $\rho = 4.2 \pm 1.3$ g cm^{-3} implies that Quaoar may consist almost entirely of silicate material surrounded by a very thin icy veneer (Schaller and Brown, 2007). Such a result would imply that the amount of collisional bombardment suffered by Quaoar was significantly higher than that experienced by other large KBOs.

The Quaoar–Weywot system presented a further peculiarity; Weywot appeared to be on an eccentric orbit (Fraser and Brown, 2010). This was unexpected, as it seemed most likely that tidal evolution would circularize the orbits of the small satellites on short timescales consistent with the satellite of Eris, Dysnomia, which is found on a nearly circular orbit (Brown and Schaller, 2007). These two strange properties of the Quaoar–Weywot system warrant further investigation.

Here we present new observations of Quaoar and its satellite Weywot. In Section 2 we present our observations of this binary system made with the Keck 2 telescope and the data reduction steps to identify Weywot within the images. In Section 3 we present a new determination of Weywot's orbit and size, along with a more accurate determination of the Quaoar–Weywot system mass. In Section 4 we present a re-analysis of the tidal evolution the Quaoar–Weywot and Eris–Dysnomia binaries. Specifically, we present eccentricity and semi-major axis evolution which considers tides raised on both bodies and an eccentric orbit of the satellite. In

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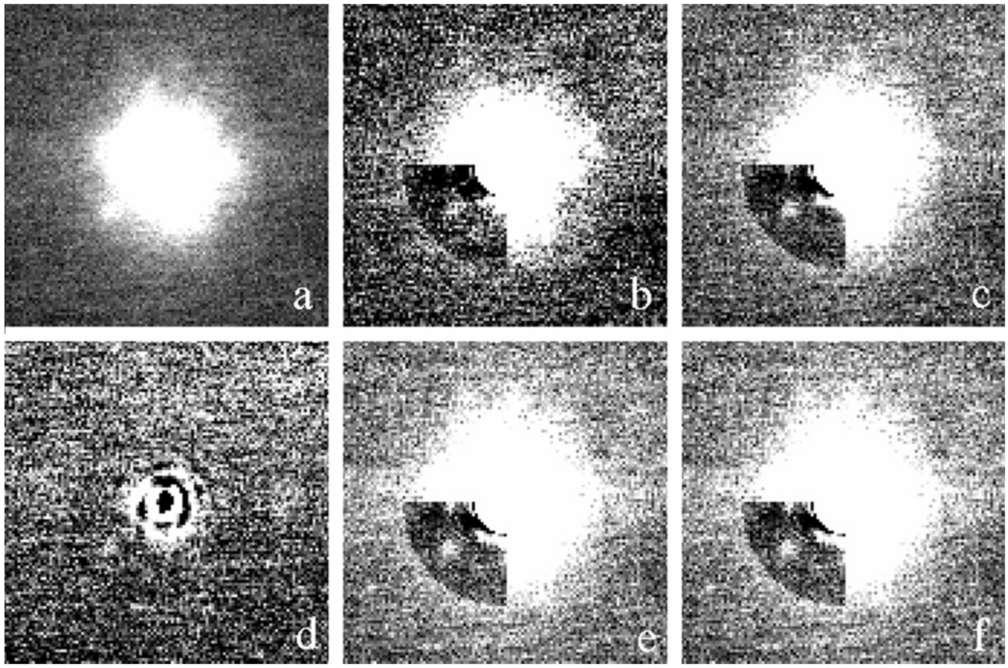

Fig. 1. (a) Median stack of all images centred on Quaoar. (b) Median stack of first quarter of the images. The radial profile of Quaoar's image has been removed in the lower quadrant containing Weywot. (c) As in (b), but for the second quarter of the images. (d) Stack of all images for which PSF subtraction was possible. (e) As in (b), but for the third quarter of the images. (f) As in (b), but for the fourth quarter of the images. In all images, North is up, East is to the left.

addition, we present some tidal evolution simulations of the Quaoar–Weywot system. We discuss possible evolution of the orbital parameters of Weywot and Dysnomia. Finally, we finish with a short discussion of the results in Section 5.

2. Observations and data reductions

Observations of the Quaoar–Weywot system were taken on June 7th, 2011 UT. During that night, Quaoar experienced an appulse with a 10.5″ closest separation to a $R = 12.1$ magnitude star. This allowed excellent adaptive optics image correction in natural guide star mode using the Keck 2 adaptive optics facility, resulting in image cores that had Full-Width at Half-Maxima of 55–66 marcsec and a Strehl between 0.13 and 0.37, with 10–25% of the light in the narrow core. Observations were taken with the Near Infrared Camera 2 (NIRC2) in the narrow camera mode resulting in a 0.01″ pixel scale. Observations were taken in the K′ filter using 15 s exposure times and a fixed sky position angle was maintained throughout the observations. The camera position angle was offset by 0.7° from zero to account for a slight rotation that exists between the telescope FOV and the camera. A 3 point dither pattern was utilized to avoid the bad quadrant of NIRC2 and 15 images were taken at each dither point.

Images were reduced with standard techniques. Appropriate darks, biases, and dome flats were used to remove instrumental flat-field and bias patterns. Median stacks of the 15 images at each dither point were created from the de-biased and flat-fielded images. Background levels at a particular dither position and in the quadrant containing Quaoar were made by averaging the stacks of that quadrant before and after that particular dither. The result was a flat image with zero background to within the noise of the images.

Identification of Weywot was made possible during a portion of the observations during which Quaoar passed close to a nearby star. Subtraction of Quaoar's point-spread function of sufficient quality for Weywot's easy identification was achieved when Quaoar was within 1.2″ of the star, roughly 1/4 of the total of the time in which Quaoar was observed. In addition, the observations were taken in fixed sky position angle mode. As a result, the PSF and associated speckle pattern rotated by roughly 90° demonstrating that the image of Weywot is real and not a PSF artifact. The image subtraction results along with a median stack of all images centred on Quaoar's position are shown in Fig. 1. Weywot is easily seen south-east of Quaoar.

To determine accurate astrometric positions of Weywot with respect to Quaoar, four median stacks with equal equivalent exposure times were produced. For each stack, a radial profile of Quaoar's image was subtracted to reveal Weywot within the PSF wings. The radial profiles were generated using 15° wide radial slices separated by 15° centred on Weywot's position. The resultant centroids in each image were not significantly altered by large variations in the radial slice parameters. The results are presented in Fig. 1.

Astrometric positions were determined in three separate ways, PSF matching using the central 9 pixels of Quaoar's image, using

Table 1
Quaoar and satellite positions. ΔRA and ΔDEC are the differences in position between the Quaoar and the satellite. The first seven rows are from Fraser and Brown (2010).

Epoch	Satellite-Quaoar Offsets[a]	
(JD + 2453000)	ΔRA (arcsec)	ΔDEC (arcsec)
781.38031	0.328 ± 0.01	−0.119 ± 0.01
1179.12990	0.303 ± 0.03	−0.135 ± 0.03
1535.70263	−0.49 ± 0.04	−0.02 ± 0.04
1540.56061	0.34 ± 0.04	−0.08 ± 0.04
1546.18353	−0.45 ± 0.04	0.09 ± 0.04
1550.31485	–	–
1556.44075	–	–
2719.82856	0.17 ± 0.01	−0.16 ± 0.01
2719.89737	0.18 ± 0.01	−0.16 ± 0.01
2719.95760	0.19 ± 0.01	−0.17 ± 0.01
2720.01759	0.20 ± 0.01	−0.16 ± 0.01

[a] Values quoted in Fraser and Brown (2010) corrected to include cos Dec term.