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The mutual orbit, mass, and density of the large transneptunian binary system Varda and Ilmarë

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ABSTRACT

From observations by the Hubble Space Telescope, Keck II Telescope, and Gemini North Telescope, we have determined the mutual orbit of the large transneptunian object (174567) Varda and its satellite Ilmarë. These two objects orbit one another in a highly inclined, circular or near-circular orbit with a period of 5.75 days and a semimajor axis of 4810 km. This orbit reveals the system mass to be $(2.664 \pm 0.064) \times 10^{20}$ kg, slightly greater than the mass of the second most massive main-belt asteroid (4) Vesta. The dynamical mass can in turn be combined with estimates of the surface area of the system from Herschel Space Telescope thermal observations to estimate a bulk density of $1.24^{+0.50}_{-0.35}$ g cm^{-3}. Varda and Ilmarë both have colors similar to the combined colors of the system, $B\text{–}V = 0.886 \pm 0.025$ and $V\text{–}I = 1.156 \pm 0.029$.

1. Introduction

The Kuiper belt, an enormous region beyond Neptune's orbit, is populated by icy planetesimals left over from the formation of the giant planets. Roughly a quarter million transneptunian objects (TNOs) larger than 100 km are estimated to reside in this region (e.g., Petit et al., 2011; Gladman et al., 2012). The largest few are planet-sized bodies such as Pluto, Eris, and Makemake, massive enough to retain atmospheres in vapor pressure equilibrium with volatile surface ices (e.g., Elliot et al., 1989; Schaller and Brown, 2007). Numerous slightly smaller TNOs are large enough to relax into spherical shapes, and could have had some degree of geological activity in the past, or even still be active today (e.g., Desch et al., 2009; Malamud and Prialnik, 2015). The scope for comparative planetological studies of these bodies is tremendous, since they come in a range of sizes, occupy a variety of heliocentric orbits, and likely accreted at different heliocentric distances within the protoplanetary nebula, drawing on chemically distinct compositional reservoirs of solid materials. Despite this scientific promise, much has still to be learned about these bodies. For the best characterized among them, their sizes, albedos, surface colors and compositions, masses, densities, and spin states are known, but prior to spacecraft exploration, knowledge of surface geology, interior structure, and bulk composition will remain largely conjectural. For many, even the most fundamental parameters have not yet been determined. Efforts to measure them continue.

Transneptunian object (174567) Varda, the subject of this paper, was discovered in 2003 by J.A. Larsen et al. at Steward Observatory's 0.9 m Spacewatch telescope on Kitt Peak (Larsen et al., 2007), and initially assigned a provisional designation of 2003 MW_{12}. Varda orbits the Sun on an inclined ($i_\odot = 21°$) and eccentric ($e_\odot = 0.15$) orbit that would be classified as "Scattered Extended" in the Deep Ecliptic Survey system (e.g., Elliot et al., 2005; http://www.boulder.swri.edu/~buie/kbo/desclass.html) and "Classical" in the Gladman et al. (2008) system. The high inclination excludes membership of the dynamically cold core of the Classical belt, where, at least among the brighter objects, binary rates are especially high and colors are especially red (e.g., Noll et al., 2008, 2014; Gulbis et al., 2010; Petit et al., 2011).

Being among the brighter transneptunian objects, Varda has been an attractive target for subsequent observational study. Fornasier et al. (2009) reported a featureless, reddish spectrum between 0.44 and 0.93 µm, with a slope of 19.2 ± 0.6% rise per

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100 nm. Perna et al. (2010, 2013) used visible color photometry to classify the object as belonging to the "IR" spectral group of Barucci et al. (2005). A near-infrared spectrum presented by Barucci et al. (2011) showed no evidence of the H_2O ice absorptions at 1.5 and 2 μm that appear in some TNO spectra, but a decline in albedo over the 2.05–2.3 μm wavelength range was tentatively attributed to absorption by methanol ice. Thirouin et al. (2010, 2014) presented photometric evidence for a low-amplitude single-peaked lightcurve with a period of 5.91 h, although 4.76 and 7.87 h periods were not formally excluded. For a double-peaked lightcurve, these would correspond to rotational periods of 11.82, 9.52, or 15.74 h.

Varda's companion Ilmarë was discovered in 2009 at a separation of about 0.12 arcsec by K.S. Noll et al., using the Hubble Space Telescope (HST; Noll et al., 2011). Follow-up observations of the pair were done through a subsequent HST program, and additional near-infrared wavelength observations were obtained using laser guide star adaptive optics on ground-based telescopes Keck II and Gemini North, both located at the summit of Mauna Kea on the big island of Hawai'i. The next section describes, in chronological order, these observations and how they were processed.

2. Observational data

The HST observation that discovered Varda's companion Ilmarë was part of Cycle 16 program 11113, led by K.S. Noll. It used the planetary camera (PC) of the Wide Field and Planetary Camera 2 (WFPC2; McMaster et al., 2008). The observing sequence (or "visit") consisted of four consecutive 260 s exposures using the *F606W* filter, a wide filter with a nominal effective wavelength of 606 nm. The images were dithered by non-integer pixel offsets to improve spatial sampling of the scene, since at those wavelengths, the pixel scale of the WFPC2/PC (46 mas/pixel) under-samples HST's point spread function (PSF). Thanks to the exceptionally stability of HST's PSF and the ability of the Tiny Tim software package to model it (e.g., Krist et al., 2011), this under-sampling is less of a problem than it otherwise would be. For each image frame, we simultaneously fit a pair of Tiny Tim PSFs representing Varda and Ilmarë. The scatter of the measurements from the four frames was used to estimate uncertainties on their relative positions and brightnesses. Additional details of our WFPC2 data processing pipeline are provided by Grundy et al. (2009) and Benecchi et al. (2009).

Our next opportunity to obtain spatially resolved images of the system was with the Keck II telescope's NIRC2 near-infrared camera. Under reasonable seeing conditions, the telescope's laser guide star adaptive optics (LGS AO) system enables NIRC2 to achieve spatial resolutions comparable to HST (e.g., Le Mignant et al., 2006). To use LGS AO for faint targets like Varda and Ilmarë, a nearby (<30 arcsec) and moderately bright ($R < 18$ mag) star is required as a reference for tip-tilt correction. Our observations were done in H band (1.49–1.78 μm), using stacks of three consecutive 100 s integrations followed by a dither, three more integrations, another dither, and then three final integrations. Astrometric reduction of each stack of three frames was done by means of PSF fitting, using an azimuthally symmetric Lorentzian PSF. Its width was fitted simultaneously with the positions of the two components of the binary. We assumed a mean plate scale of 9.952 mas/pixel and an orientation offset of 0.252° (e.g., Konopacky et al., 2010; Yelda et al., 2010). Based on experience from other binary observations with this system, we assumed a 1-σ uncertainty floor of ±2 mas on the relative astrometry. A second, identical visit was done 1.8 h later. The observed change in relative positions between the two visits enabled us to determine that the sense of Ilmarë's orbital motion was clockwise on the sky plane, and also that the orbital period must be relatively short. No photometric standards were observed, and no effort was made to compute H band magnitudes from these data, which were taken solely for astrometric purposes.

Further HST observations of the system were obtained during four visits as part of Cycle 18 program 12237, led by W.M. Grundy. By then, the fourth servicing mission to HST had replaced WFPC2 with the Wide Field Camera 3 (WFC3; Dressel, 2015). Each visit consisted of four dithered *F606W* images using the UVIS1 CCD detector. Thanks to the greater efficiency of WFC3 compared with WFPC2, we were able to use almost as long integration times in the *F606W* images, and still have time left over for four additional images using another filter to obtain some spectral information. To minimize effects of potential lightcurve variability on derived colors, these were sequenced with the *F606W* images being split into two groups of two, bracketing the other filter (except for the last visit where the final two *F606W* frames were lost). The other filter was *F438W* in the first visit and *F814W* in the second visit (with nominal central wavelengths of 438 nm and 814 nm, respectively). In the third and fourth visits, we used the infrared camera instead of UVIS1, obtaining two *F110W* images and two *F160W* images in each of those two visits, with central wavelengths 1.1 and 1.6 μm, respectively. The infrared data will be presented in a separate paper. As described in Grundy et al. (2012), PSF-fitting procedures for WFC3 data were similar to those used for WFPC2, with a pair of Tiny Tim PSFs being fitted to each frame independently. Within each visit, the scatter in modeled relative positions and fluxes between frames was used to estimate the uncertainties in the combined measurements of those parameters for the visit. The flexibility of the HST scheduling process allowed us to use optimal scheduling techniques (e.g., Grundy et al., 2008) to exploit the growing pool of astrometric information to inform scheduling of each successive visit.

A final series of observations was obtained with the Near-Infrared Imager (NIRI) camera at the Gemini North telescope (Hodapp et al., 2003), thanks to three-year NOAO survey program number 11A-0017, led by W.M. Grundy. Like the Keck II observations, the NIRI observations were done at near infrared H band wavelengths, with the use of a laser guide star with the Altair adaptive optics system (Herriot et al., 2000) being enabled by stellar appulses closer than 25 arcsec for stars brighter than $R < 16.5$. The Gemini observations were scheduled in queue mode, but the combination of NIRI with Altair and LGS was sparsely scheduled, so there was little scope for optimal scheduling. NIRI images were obtained in sets much like the Keck NIRC2 images, with a series of three to four exposures of 90–150 s in each of four dither positions. The larger/longer numbers were used for fainter targets, and for particularly faint targets, the entire pattern would be repeated a second time, but the Varda system being relatively bright for a Kuiper belt object, each observation of that system was done using the smaller numbers. The telescope was tracked at ephemeris rates. We used Lorentzian PSF profiles, but for some images had to include an ellipticity component where the PSFs were clearly elongated. The World Coordinate System (WCS) information in the image headers was used to convert from pixel coordinates to sky coordinates, via the xyad routine in the Astronomy User's Library (available from http://idlastro.gsfc.nasa.gov). We assumed a 1-σ uncertainty floor of ±3 mas for NIRI data. As with the Keck observations, we made no effort to do photometric calibration.

Example images from all four instruments are shown in Fig. 1, scaled to a common spatial scale and orientation. Also shown are the PSF models fitted to each image along with the residual images. The relative astrometry is compiled in Table 1.

The HST observations were processed to derive separate photometry of Varda and Ilmarë as shown in Table 2. The data reduction pipeline for PSF fitting photometry and conversion to standard