# DETECTION OF A SATELLITE OF THE TROJAN ASTEROID (3548) EURYBATES – A *LUCY* MISSION TARGET.

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**Introduction:** Satellites and binaries occur in most small body populations and can trace unique physical formation mechanisms including collisions and spin-fission [1]. Starting in 2018 we conducted the first deep satellite search of a diverse set of Trojans that are targets of NASA's *Lucy* mission. Deep searches are required to detect small satellites and we carried out observations with the Hubble Space Telescope (HST) to satisfy this objective. Three of the *Lucy* Trojan targets, Orus, Eurybates, and Polymele had never previously been observed with HST and the high S/N images of Trojans from these deep searches were acquired explicitly to reveal previously unseen satellites. Patroclus and Leucus had been previously observed with HST, but not at the depth accomplished by this program. Here we report the discovery of a roughly 1km satellite in orbit about Eurybates.

**Observations:** The first pair of images of Eurybates were obtained on 12 and 14 September, 2018 (Table 1) using HST's Wide Field Camera 3 (WFC3). A possible satellite was identified in stacked images on both dates (Figure 1). In each case the four 350s images were registered and combined to remove cosmic ray artifacts and to increase S/N. The images show that the satellite moved by 2.24 pixels in the two days between these observations, consistent with a bound satellite. The satellite is detectable in individual frames as well as in the stacked image, although at lower S/N, ruling out artifacts from coincident cosmic rays.

Based on this initial detection, we sought and obtained three additional orbits to attempt a confirmation of the satellite detection. The satellite was detected again in images obtained on 03 January 2020, confirming the existence of this object. Observations are summarized in Table 1.

**Table 1. HST Observations of Eurybates**

| Date | Time (UT) | Filter | $n_{exp}$ | $t_{int}$ (sec) |
|---|---|---|---|---|
| 12 Sep 18 | 09:45 | 555W | 4 | 350 |
| 14 Sep 18 | 09:26 | 555W | 4 | 350 |
| 11 Dec 19 | 06:37 | 350LP | 6 | 330 |
| 21 Dec 19 | 22:35 | 350LP | 6 | 330 |
| 03 Jan 20 | 07:31 | 350LP | 6 | 330 |

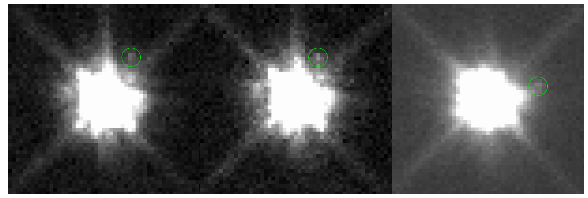

**Figure 1.** A 2x2 arcsec portion of combined HST WFC3 images of Eurybates from 12 and 14 Sep. 2018 (left, middle) and 03 Jan. 2020 (right) are shown. Images are unrotated and are shown in a linear stretch scaled to account for the different filter throughputs. The satellite is circled in each image. Other images features are due to the PSF of the overexposed Eurybates.

**Analysis:** Images taken on 12 and 14 September 2018 and 03 January 2020 show a satellite at separations of 0.589±0.020, 0.500±0.020, and 0.580±0.020 arcsec respectively. At the time of the observations, Eurybates was at a geocentric distance of 4.599, 4.619, and 5.452AU (Table 2). These angular separations correspond to projected distances of 1961±67, 1675±67, and 2292±79km. Positional uncertainty is conservatively estimated as 0.020 arcsec, one half of a WFC3 pixel. The position angle of the satellite, relative to Eurybates, is 259.9±0.3°, 263.3±0.3° and 224.4±0.3° East of North.

**Table 2. Observational Circumstances**

| Date | R (AU) | Δ (AU) | phase (°) |
|---|---|---|---|
| 12 Sep 18 | 5.371 | 4.599 | 7.43 |
| 14 Sep 18 | 5.370 | 4.619 | 7.70 |
| 11 Dec 19 | 5.074 | 5.122 | 11.07 |
| 21 Dec 19 | 5.067 | 5.280 | 10.65 |
| 03 Jan 20 | 5.059 | 5.452 | 9.84 |

The satellite's brightness was V=26.95±0.5 on 03 January; if the satellite has the same albedo as Eurybates, p=0.052 [2], it would have an effective diameter of 0.8±0.2 km. We assumed a phase law of 0.04 mag/deg when deriving the effective diameter. Photometric analysis yields similar brightness for the satellite on 12 and 14 Sep, but at lower S/N because of the 2.7× lower throughput of the F555W filter compared to the F350LP.

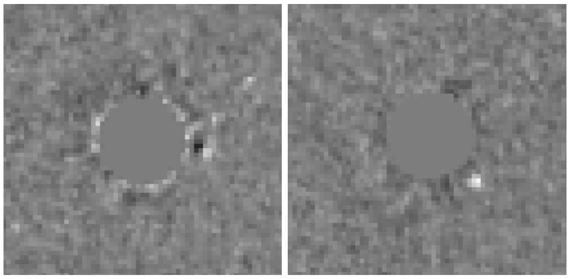

**Figure 2.** The difference between WFC3 images taken on 12 and 14 Sep. 2018 is shown (left). The satellite appears as a positive-negative pair with a separation of 2.2 pixels due to the motion of the satellite during the two days between observations. The image on the right is the difference between 03 Jan. 2020 and 21 Dec. 2019. In this case, only the positive image of the satellite from 03 Jan. appears. The satellite is not detected on 21 Dec., presumably because it is within 0.4 arcsec of Eurybates where the satellite is too faint to have been detected against the bright background from Eurybates (grayed out). Both frames have been rotated so that celestial North is up, and East is to the left.

**Discussion:** The existing positional constraints, including the non-detections, are compatible with many possible orbits that are physically reasonable. In particular, if we assume that we would not have seen the satellite when it was within 0.4 arcsec of Eurybates, we find orbits that are consistent with all our observations for assumed bulk densities ranging from 500 – 2500 kg $m^{-3}$. Note that the tidal timescales for the smallest possible orbit (a=2200 km) are still much longer than 4.5 Gyr, and so eccentricity of the mutual orbit is not constrained. Additional observations will be required to determine a unique orbit.

Eurybates is particularly interesting with respect to the presence of a satellite because it is the largest member of the only confirmed Trojan collisional family [3]. The family consists of ~100 members with $d \geq 10$ km and potentially many more smaller members. The collision that formed this family could also have resulted in the capture of one or more fragments as satellites [4]. Collisions likely are responsible for the formation of satellites in other small body populations and the opportunity to study a likely collisional satellite at close range will help constrain our understanding of this mechanism.

*Lucy* will fly by Eurybates in August 2027 at a distance of 1000 km, well within the Hill sphere, and closer than the projected distance of this satellite. The discovery of this satellite now will make it possible to increase the scientific yield by planning detailed and complementary observations of this satellite to be carried out during the flyby.

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**References:** [1] Margot J.-L. et al. (2015), in *Asteroids IV*, U AZ Press [2] Grav T. et al. (2012) *ApJ* 759, 49, [3] Brož M. & Rozehnal J. (2011) *MNRAS* 414, 565, [4] Durda D. D. et al. (2004) *Icarus* 167, 382.