Using Asteroids and their Moons for Closely Spaced Object Studies[1]

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ABSTRACT

After exploring binary stars as surrogates for closely space objects (CSO) in orbit around the Earth at geosynchronous altitudes (Geos), we have found a more appropriate proxy in moons around asteroids. The brightness ratio of binary stars tend to be less in the near infra-red than in visible wavelengths where most of the delta magnitudes have been accumulated. On the other hand, asteroids and their moons, being chips off the same block, preserve a delta mag over a wider range of wavelengths. Furthermore, the parent asteroids are generally at similar magnitudes to Geos and their moons cover a wide range of brightness differences from their larger companions, making asteroids with moons ideal targets for study with the Starfire Optical Range's 3.5 m telescope using adaptive optics with a laser or natural guide star.

1. Introduction

Between 2012 and 2014, while measuring binary stars (Drummond, 2014) with our 3.5 m telescope with adaptive optics (AO) in an attempt to determine capabilities and limitations in our study of closely spaced objects (CSO), we also attempted, unsuccessfully, to detect asteroid moons. Ultimately, in 2015, we observed and followed Romulus around asteroid (87) Sylvia (Drummond , Reynolds, and Buckman, 2015; 2016). Over the 2016-2017 winter observing season, we detected and followed two more asteroids and their moons, (22) Kalliope and its moon Linus, and (317) Roxane and its unnamed moon discovered in 2009, but unobserved since. In this paper we list the reasons for our newly found success, and show some preliminary results.

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2. Reasons for Success

Since the Starfire Optical Range (SOR) is a research and development facility, as opposed to a fielded or operational observatory, we have the luxury of tearing down and building up our equipment in accordance with our ongoing experience. After examining our successes and failures, we attribute our more recent successful asteroid/moon detections to the following: new lasers (Mark Eickhoff), new tracker (Odell Reynolds), Test Directors' experience (Odell Reynolds, Miles Buckman), and improving analysis (Jack Drummond, Lee Kann).

2.1. Lasers

We have now deployed two 20W Toptica cw lasers that produce 40W out the launch telescope, thus far without any apparent saturation. We combine the beams by creating different handed circular polarizations for each and separate them by ∼200 MHz symmetrically around the peak sodium D2a wavelength (Figure 1). This results in the two lasers interacting with different velocity classes, which avoids quenching the optical pumping process for a single velocity class. Each laser has a main frequency component and a sideband (10% of the launched power) 1.71 GHz away, around the D2b wavelength, corresponding to the sodium ground state hyperfine splitting. These sidebands at D2b pump atoms from F1 to F2, enhancing the number of atoms available for circular polarization optical pumping with the main lobe. If the two lasers are separated by 58.3 MHz, one velocity class of sodium atoms will interact with both lasers, so they must be separated by at least 102.7 MHz.

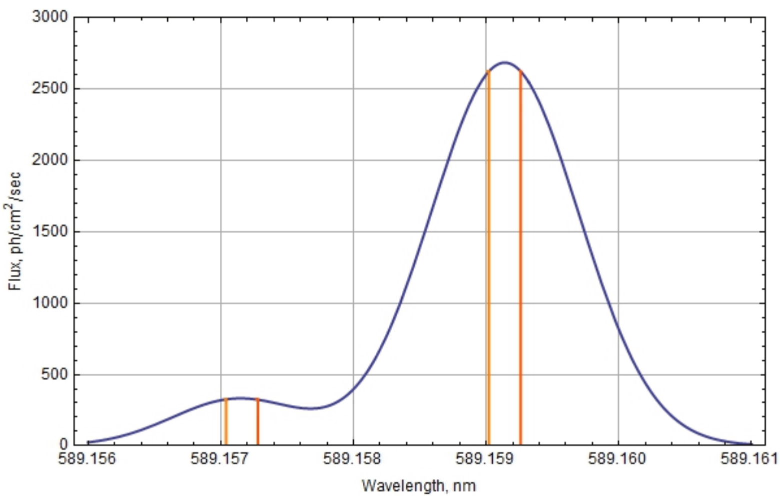

Fig. 1.— The two 20 W Toptica lasers are offset in wavelength in order to interact with different velocity classes. The side lobes around D2b continually pump atoms into the F2 state where they become available for optical pumping at the D2a wavelength.

2.2. Tracker

In order to employ AO on fainter objects, we redesigned the optical path to our tracker, a quad cell that keeps the object centered when the target, itself, is too faint to provide tip-tilt information through the wave front sensor in natural guide star mode (NGS), or when we operate in laser guide star (LGS) mode since the laser provides no tip-tilt. We now have the ability to steal light from our RI (0.8μm) imaging leg and send it to the tracker while we image in the J-band at 1.2μm. We previously sent about 35% of the light between 0.45 and 0.69μm to the tracker, but we can now send about 80% of the light between 0.49 and 1μm to the tracker, increasing its signal to noise while closing higher order loops with the wavefront sensor (WFS), and allowing us to work on fainter objects.

2.3. Experience

The Test Director (TD) for the night can choose frame rate/integration time for both the WFS and tracker to assess AO performance with visual real time diagnostic displays. It has not taken long before we were working comfortably on J=12-14 magnitude asteroids and man-made satellites by slowing the WFS and/or the tracker to 500Hz. It has been the TD's experience with balancing the two that has been responsible for our most recent successes.

2.4. Image Analysis

Our basic approach is to fit the primary object, whether man-made satellite or asteroid, as a Lorentzian since this is the shape of the AO PSF, and then remove this model to reveal a companion. If the separation between the two is great enough, and if the brightness ratio is small enough, the two components can be fit simultaneously to yield separations and delta mags. Determining the limits of these parameters is the goal of our CSO studies, but first the faint companion has to be detected. This involves science, math, art and magic. For example, dividing the image by the model and then displaying the log of this quotient often renders a companion more visible than subtraction. See Figure 2. Even in this case, however, a measured separation and delta mag has to be determined in the linear (not log) domain. Drummond et al. (2015;2016) list some of these methods.

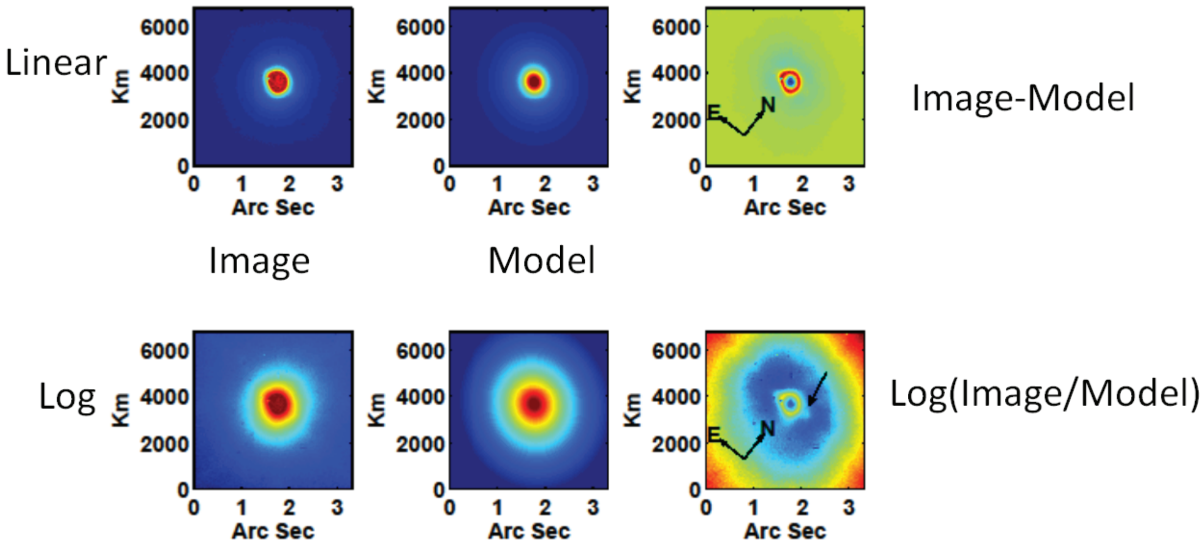

Fig. 2.— The image of the asteroid Sylvia subtracted by its Lorentzian fit model (top row) and the log of the quotient of the two (bottom row). The log of the quotient reveals the companion, Romulus, better than the subtraction.

3. Observations and Results

With the information (relative positions) from fitting the primary object and its companion simultaneously, we can find the apparent trajectory of two Geos or the true orbit of a moon around an asteroid. For example, in Figure 3 we plot the derived trajectory from a series of images of the ANGELS payload as it was maneuvered through the PSF of its spent rocket at geosynchronous altitude. The series of such close approaches has provided us with an opportunity to study our capability and limitations in the CSO problem.

Figure 4 shows the three asteroids with moons that we have observed from 2015 to 2017. The apparent moon for Eugenia is not real, but an artifact that appeared for several days. Even though Eugenia has two moons, this artifact did not have the expected Lorentzian shape and did not show any motion. This illustrates one half of the CSO problem, false positives. After subtracting or dividing out the Lorentzian PSF, there often remains non-constant abberations that look like real companions. Knowing or calculating the orbits of clearly detected moons aids in discriminating them from such abberations.

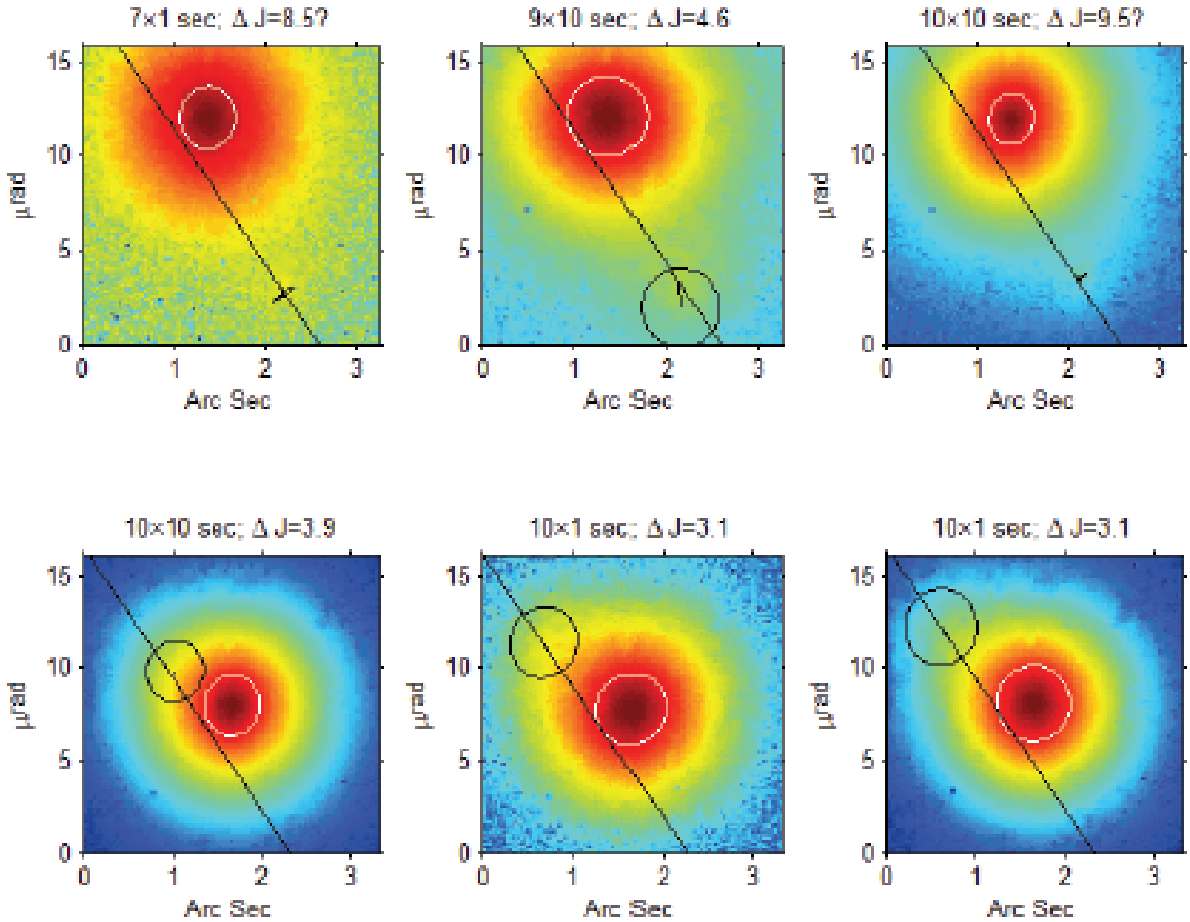

Fig. 3.— Last 3 positive detections of the ANGELS payload before and after closest approach on 2015 March 15. In these log displays, circles are FWHM of objects from Lorentzian fits, white for rocket, black for payload. The straight line is our trajectory. For the upper left and right panels, Lorenztian fits yield only X and Y positions; the FWHM is meaningless.

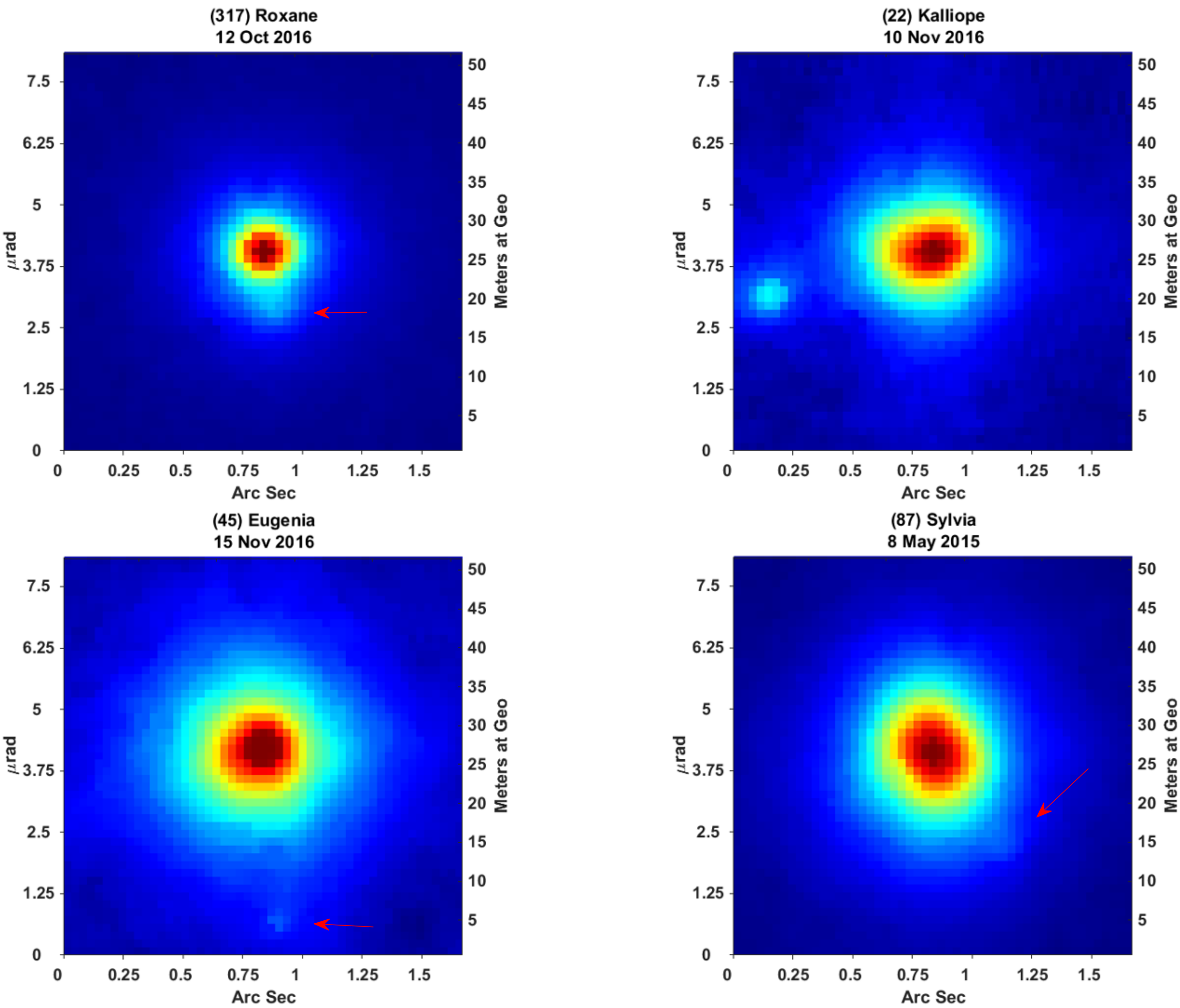

Fig. 4.— The moons of 3 asteroids from the SOR. The ΔJ for Roxane at upper left was 3.0, 3.1 for Kalliope at upper right, and 4.6 for Sylvia at lower right. The 'moon' for Eugenia at lower left is not real. It is an unexplained artifact that persisted over several nights.

Following the moons of Sylvia, Kalliope, and Roxane over 2-3 months allowed us to calculate an orbit for their moons. Sylvia and its moon, Romulus, and Kalliope and its moon, Linus (the brightest and most easily observed), both have well determined orbits from a decade of large 8-10m telescopes observations. The orbits we derive from just our own observations are comparable to these, and for Sylvia/Romulus, combining our observations with others lowers the uncertainty of the orbital elements (Drummond et al., 2016), especially the orbital period. The moon of Roxane was discovered in 2009 (Merline et al., 2009) and has not been observed until our observations in 2016-2017. Thus, our orbit is the first for this unnamed moon.

From the orbital period and the size of the semimajor axis, we can determine the sum of the two bodies' masses with Kepler's and Newton's laws, which we assume all lies in the primary since the moons are so much fainter and smaller. Then combining the size of the asteroid as determined mostly from AO on 8-10 m telescopes, we can find the density of the asteroid, a notoriously difficult but important parameter to obtain in their study. Table 1 gives our preliminary value of the mass and density for the three asteroids we have studied so far.

Table 1. Asteroid Masses and Densities from the SOR

	Sylvia	Kalliope	Roxane
Observations	Mar-May 2016	Nov 2016 - Feb 2017	Oct 2016 - Feb 2017
Semimajor Axis (km)	1355 ± 5	1099 ± 6	254 ± 6
Orbital Period (days)	3.641197±0.000066	3.595606±0.000375	11.5540±0.0158
Mass (gm)	$1.487 \pm 0.016 \times 10^{22}$	$8.13 \pm 0.14 \times 10^{21}$	$9.17 \pm 0.66 \times 10^{18}$
Density (gm/cm^3)	1.37 ± 0.04	3.38 ± 0.11	2.85 ± 0.42

4. Conclusions

The best opportunity to determine our capabilities and limitations for CSO studies is with asteroids and their moons. There are some two dozen well-studied examples, with other undiscovered pairs (inferred from lightcurves) within the reach of our 3.5 m telescope. Already we have made improvements to our optical setup in order to reach fainter and closer companions. Although observing actual close Geos would be more to the point, they require illumination permission, unlike asteroids. Thus, we will be concentrating on asteroids and moons, perhaps even discovering new moons along the way, as we define and sharpen our methods.

References

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