# ADAPTIVE OPTICS OBSERVATIONS OF THE BINARY SYSTEM (22) KALLIOPE: A THREE DIMENSIONAL ORBIT SOLUTION

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ABSTRACT

We carried out new observations of the binary asteroid (22) Kalliope (S/2001 (22)) with the Shane 3-m telescope of the Lick observatory in October and November 2001. With a FWHM (full width at half maximum) of $0''.2$, Kalliope (apparent size of about $0''.15$) was not resolved but it was possible to separate the secondary from its primary. As observations spanned a few days time, they are well distributed along the secondary's orbit allowing us to accurately estimate its orbit. The satellite orbits (22) Kalliope in a retrograde manner, on a highly inclined ($i = 160° \pm 2$) and eccentric orbit ($e = 0.28 \pm 0.06$) with an orbital period of $3.57 \pm 0.14$ days. The semi-major axis is $1024 \pm 40$ km. Using Kalliope's diameter as determined from IRAS data, the M-type asteroid's bulk density is about $2.19 \pm 0.20$ g/cm$^3$, suggestive of a highly porous body. The measured precession rate of the secondary's orbit is much higher than expected from Kalliope's oblateness, assuming a homogeneous body (constant density). This suggests that Kalliope may be more elongated than presently believed or/and that its internal structure is maybe highly inhomogeneous, perhaps caused by macroscopic porosity characteristics of a rubble-pile body.

Key words: Asteroids; Asteroids, composition; Infrared observations; Interiors; Orbits.

## 1. INTRODUCTION

Since the first asteroidal satellite discovery during the Galileo spacecraft's 1993 fly-by of Ida's moonlet, Dactyl (Chapman et al. 1995), over fifteen of moons have been found in orbits around asteroids. The asteroidal moon discovery rate has dramatically increased over the past years with the advent of Adaptive Optics (AO) on ground-based telescopes. This technique provides high contrast images with a resolution close to the diffraction limit of the telescope, which enables one to measure orbits of faint asteroidal satellites by collecting relative astrometric observations of the system. Large surveys with 3-10 m-class telescopes equipped with AO are performed.

Several theoretical studies and numerical calculations with regard to the dynamics of asteroidal satellites have been published over the past few decades (Chauvineau and Mignard 1990). We call an orbit *prograde* if the satellite's angular velocity around the asteroid is in the same sense as the asteroid's angular velocity around the Sun; for a *retrograde* orbit, the satellite's angular velocity is in the opposite sense. Observable parameters, such as the ratio in mass between the primary and secondary, their separation, etc ... should depend on the way binary asteroid systems were formed. Thus determining these parameters for a significant sample of binaries, should provide insights on the collisional history in the asteroid belt. Unfortunately among the asteroidal satellites discovered so far, there is no orbit that is precisely known.

The main goal of our study is to describe the orbit of the moonlet of (22) Kalliope. The binary character of this system was recently reported by W. J. Merline *et al.* on AO imaging obtained on September 2.6 UT, 2001 with the CFH telescope. A few days earlier, J.-L. Margot and M. E. Brown had also detected Kalliope's moonlet on AO H-band images obtained on August 29.6 and 31.6 UT, 2001 with the 10-m W. M. Keck II telescope on Mauna Kea (Merline et al. 2001). The observing strategy we adopted was to carry out observations over a few consecutive days at two distinct periods well separated in time in order to unambiguously determine all the orbital parameters and to detect the possible advance of the line of apsides due to the secular perturbation arisen from the non-spherical shape of Kalliope.

## 2. OBSERVATIONS

The asteroid Kalliope had an apparent visible magnitude of 11.0±0.3 in October and November 2001, so it was directly observable using AO systems. Since the sensitivity limit of existing AO systems is around 14th magnitude, an excellent wavefront correction was expected.

In October 2001, we used the Shane 3-m telescope of the Lick Observatory with its AO system and the IRCAL camera developed by UC-Berkeley (Lloyd et al. 2000; Gavel et al. 2000). The camera is equipped with a PICNIC HgCdTe 256×256 pixel detector, sensitive at 1-2.5 $\mu$m and with a pixel size of 0″.0765. Excellent observations were obtained on Oct. 3, 4, and 6 UT. The first night revealed the companion in H-band (1.656 $\mu$m), somewhat better in K-band (2.195 $\mu$m) and quite marginally in J-band (1.238 $\mu$m). We therefore focused our program on the K-band observations with an individual integration time of 4 seconds. Object and sky frames were obtained by moving the target to 5 different positions on the detector. The resulting image, with a total integration time of 1 minute, is composed of 15 shift-added frames. From images of a nearby star with a similar magnitude, we estimate the angular resolution (FWHM) at 0″.157 ± 0.004, and the Strehl Ratio (Ratio of observed to theoretical peak intensity) at 40-55%. This resolution does not allow to resolve the main asteroid whose predicted angular size was 0″.15, but the high signal-to-noise on the AO data enabled the detection of its companion at an angular distance of 0″.545 ± 0.077, 3.22 ± 0.20 magnitude fainter than the primary.

On 2 and 3 November 2001 (UT), observations were performed at the 3-m Shane telescope at Lick observatory, and also with the Palomar AO system (PALAO) at the Palomar 5-m telescope. Its camera, PHARO, built by the Cornell University Astronomy Department Infrared Group is a 1024×1024 Rockwell HAWAII HgCdTe array detector (Hayward et al. 2001), sensitive also between 1-2.5 $\mu$m and with a pixel size of 0″.025. J,H, and K band data were taken on November, 1st and 2nd, 2001 using the same technique as described for the Lick data. The total integration time was ~54.5 seconds and the data have an angular resolution of 0″.097, 0″.084 and 0″.094, respectively, at J, H, and K band (estimated on a Point Spread Function or PSF star). The moonlet companion was clearly detected and well separated from the primary, allowing to accurately estimate its position relative to the primary. Figure 1 shows two images taken at the Lick and Palomar Observatory in the Ks band.

## 3. ASTROMETRY

The CCD positions of Kalliope and its satellite are measured by centroiding with a two-dimensional Moffat-Gauss profile, especially suited to AO images (Descamps et al. 2002). The background is modeled by an inclined quadratic surface due to the strong luminosity gradient in the vicinity of Kalliope.

As there was no reference star in the small field of view, it is not possible to determine the astrometric parameters of the frames. Thus we use the theoretical ones to transform the CCD $(x, y)$ coordinates into celestial coordinates. In order to quantify the uncertainties introduced by this assumption, we carried out an astrometric calibration of the system using two images of the central part of the Trapezium cluster centered on $\theta^1$ Ori in the Orion nebula. These images contain about 10 known stars (McCaughrean and Stauffer 1994), which were used as reference stars to calculate the scale and orientation factors with a classical plate constants model.

## 4. THE APPARENT ORBIT

### 4.1. Method and uncertainties

The orbital elements that are determined are the semi-major axis $a$, eccentricity $e$, inclination $i$ and the argument of periastron $\omega$.

For each period of time, where observations were performed over a few consecutive days, we assumed the secondary to follow a purely keplerian orbit, and neglected perturbations due to Kalliope's oblateness and by other massive bodies - especially the giant planets and the Sun - whose effects are noticeable only after a couple of days. In other words, it is a snapshot of the motion and the orbit may be considered as the osculating orbit which is defined as the orbit that would be followed if the perturbing force were instantaneously turned off. With an adequate choice of angular variables, initial estimates of the orbital elements are easily found and convergence is achieved after a few iterations with a fitting algorithm based on the Levenberg-Marquardt technique. This method will be completely described in a forthcoming paper (Descamps in preparation). Briefly, the time of apsidal passage is not determined (second law of Kepler), and we look for a geometric solution to the apparent ellipse at a given epoch, taking into account Kepler's first law (the primary is at one of the ellipse focii). This always provides two solutions that are symmetric, since the inclination of the orbital plane (or the direction of the angular momentum vector) cannot be determined unambiguously from a single epoch observation.

The reduced $\chi^2$ of the fit of the binary model to the data is near 1 which means that uncertainties on the measures are correct. As far as the November 2001 data are concerned, only three observations were carried out. In this case, the fitting process converges only if at least two parameters of the orbit are fixed. This is why we did not re-fit the orbital shape parameters $a$ and $e$, but used those derived from the October observations. We can then determine the orbit's orientation in space.

### 4.2. Adjusted orbital parameters

Table 1 lists the orbital elements for the October and November data as derived from the diagonal elements of the covariance matrix, and uncertainties as given by their 68% confidence level (the so-called one-$\sigma$ uncertainty) on the $\chi^2$ surface. Inclination is calculated with respect to the equatorial plane of Kalliope.

As said before, there are two orbit solutions for each of the October and November run. Combined with the ambiguity in the pole determination of (22) Kalliope, for

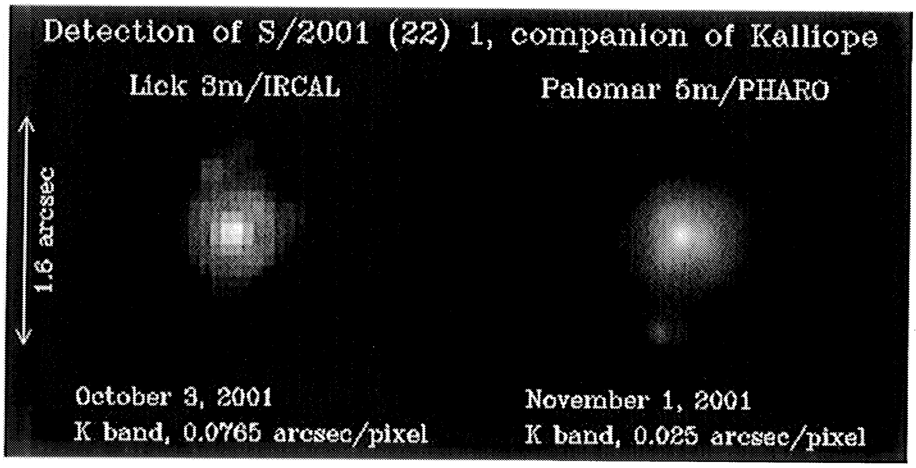


*Figure 1. Image of Kalliope with its moonlet, taken at Lick-Shane 3m telescope (October 04, 2001) and Palomar 5m telescope (November 03, 2001) in the Ks band with their Adaptive Optics system. The FWHM is* $0''.17$ *and* $0''.13$ *respectively. North is up and East is right.*

*Table 1. Orbital elements of the Kalliope's satellite*

| Element | October 2001 orbit | November 2001 orbit |
|---|---|---|
| Period (days) | $3.57 \pm 0.14$ | |
| Major semiaxis (arcsec) | $0.640 \pm 0.025$ | 0.763 |
| Major semiaxis (km) | $1024 \pm 40$ | 1024 |
| Argument of the pericenter (deg.) | $1.57 \pm 1.90$ | $23.10 \pm 0.70$ |
| Eccentricity | $0.282 \pm 0.060$ | 0.282 |
| Inclination (degrees) | $159.94 \pm 3.0$ | $151.35 \pm 3.0$ |
| $\chi_r^2$ | 1.02 | 1.66 |
| $\sigma_0$ (mas) | 8.5 | 11.0 |

which there are two pole solutions from the synthesis of Magnusson (Magnusson 1994), this provides two prograde and two retrograde orbits. However, in order to make coherent the general apparent motion of the orbital plane between the two periods, we got the only required solution for both the pole position and the orbit inclination, that is the retrograde solution named $P_1$ with the North pole ecliptic coordinates (B1950) $\lambda_0$ and $\beta_0$: $\lambda_0 = 21^\circ.0 \pm 3^\circ$ and $\beta_0 = -23^\circ.0 \pm 5^\circ$. The variation of inclination between October and November is not significant, since additionaly to the uncertainties introduced by the calculation method (3°), one must also consider the same order uncertainty coming from the pole solution. Like Dactyl, the satellite of (243) Ida (Belton et al 1996), or Petit-Prince, the satellite of (45) Eugenia (Merline et al. 1999), the satellite of Kalliope evolves on an orbit in a prograde direction with respect to the central body spin. We have to notice that in each of theses cases the primary has a retrograde rotation and consequently the motion of the satellite is retrograde with respect to asteroid's orbital motion. It is well known that each asteroid is surrounded by a zone of stable satellite motion which lies within the Hill's sphere. The Hill's sphere boundary is not less than 200 asteroid radii. In particular, retrograde orbits are more stable than prograde ones against the solar perturbations which can disrupt an orbit weakly gravitationally bound (Hamilton and Krivov 1997; Chauvineau and Mignard 1990). But this effect becomes larger at great separations where the gravitational interaction between the small bodies is negligible in regard to the tidal acceleration due to the local imbalance between the Sun's attraction and that needed to cause the asteroid's circular path. This means that at small separations neither solar, nor weaker Jovian perturbations can destabilize the asteroid's satellite orbit.

The motion of the satellite is in the same direction as Kalliope's retrograde spin, thus such binary system may be formed from an impact-generated orbital debris after a disruptive collision (Weidenschilling et al. 1989). This may explain as well the significant eccentricity and inclination to the central body equator.

## 5. PHYSICAL PARAMETERS OF (22) KALLIOPE AND ITS SATELLITE

We used the set of orbital parameters to derive the mass of Kalliope from Kepler's third law:

$$a^3 n^2 = G(M_K + M_S) \tag{1}$$

where $G = 6.67259 \times 10^{-11}$ m$^3$kg$^{-1}$s$^{-2}$ is the universal gravitational constant, $a$ the semimajor axis previously determined and $n = 100.9^\circ$/day the mean motion of the satellite. Based upon the observed ratio in brightness between the primary and secondary, the mass of the satellite $M_S$ may be neglected, *a priori*, compared to Kalliope's mass, $M_K$. We then find $M_K \simeq 6.68\,10^{18}$ kg. With its IRAS radius, $R_{IRAS} = 90.50 \pm 2.3$ km, we get a bulk density of $2.19 \pm 0.20$ g/cm$^3$ much lower than the densities of M-type meteorites.

From the flux ratios between Kalliope and its secondary estimated on our observation, we can derive an equivalent radius of the satellite. Assuming the flux ratio to be proportional to the surface ratio of the primary and the secondary, and taking into account the aspect of Kalliope at each time of observation (the apparent ellipse), we found a radius of $19 \pm 3$ km. The large scatter in this radius may suggest that the secondary is elongated rather than spheroidal, as expected from tidal distortions (Leone et al. 1984), but may come from the quality of the AO correction as well. If we assume that the satellite is part of Kalliope pulled apart by an impact, we can consider the same bulk density and derive an *a posteriori* mass $M_S \simeq 6.3\,10^{16}$kg and a mass ratio $q = M_S/M_K = 0.009$. With such a mass ratio and separation, we can infer from figure 1 of (Weidenschilling et al. 1989), an evolution time scale to the present state of $10^7$ years.

## 6. SECULAR PERTURBATIONS OF THE KALLIOPE'S SATELLITE ORBIT

We saw that owing to the small separation between Kalliope and its satellite, the orbital dynamics reduces to the classical two-body problem and is therefore dominated by the harmonics of the gravitational potential. The influence of Kalliope's shape may then be approximated by the $J_2 (= -C_{20})$. The secular variations expressed in terms of the orbital elements then write (for a non-rotating primary):

$$\frac{d\omega}{dt} = \frac{3}{4} \frac{n r_e^2}{a^2 (1 - e^2)^2} (1 - 5\cos^2 i)\, C_{20}$$

where $r_e$ is the normalization equatorial radius of Kalliope (IRAS radius). Taking the orbital elements derived here and the ellipsoidal figure given in the litterature, $a/b = 1.32$, $b/c = 1.2$, together with the IRAS radius (which gives the following semimajor axis: $a = 115.71$ km, $b = 87.67$ km, $c = 73.06$ km), one finds, assuming a constant density, $J_2 = 0.127$.

If we consider the advance of the pericenter observed of 21.5°, we get an observed $J_2$ of $0.304 \pm 0.020$ much higher than the theoretical value previously derived. In order to explain this important difference, we may first invoke a much higher equatorial radius. The required value of the radius is of about 140 km, thus 50% larger than the IRAS radius, which is not acceptable. Another possible explanation may lie in a non-constant density of Kalliope and/or a more elongated shape. These assumptions are detailed in Marchis et al., 2002.

## 7. CONCLUSION

Direct AO observation of a binary asteroid by means of high resolution imaging with large optical instruments allows us not only to determine the apparent orbit of the secondary but also to get some crucial information about the physical properties and internal structure of the asteroid.

The high apsidal rate measurement is not consistent with the usual assumption of a constant density, suggesting a rubble pile internal structure.. Such structure can explain the observed zonal harmonics $J_2$ in the gravity potential of Kalliope, responsible of the large secular advances of the pericenter of the orbit.

Further observations are needed in order to tightly constrain both the orbit of the secondary and the physical parameters of Kalliope. Of course, this work can be applied to other known binary asteroids.

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