Component-resolved Near-infrared Spectra of the (22) Kalliope System

Conor Laver\textsuperscript{1}, Imke de Pater\textsuperscript{1}, Franck Marchis\textsuperscript{1,2}, Máté Ádámkovics\textsuperscript{1}, and Michael H. Wong\textsuperscript{1}

\textsuperscript{1}Department of Astronomy, 601 Campbell Hall, University of California, Berkeley, CA 94720

\textsuperscript{2}SETI Institute, 515 Whisman Rd, Mountain View, CA 94043

Received \underline{______________}; accepted \underline{______________}

Pages: 20, Figures: 5, Tables: 1
Proposed running head:
Near IR spectra of the (22) Kalliope System

Please send editorial correspondance to:
Conor Laver
Department of Astronomy
University of California
Berkeley, CA 94708, USA

Email: conor@astro.berkeley.edu
Phone: +1 510 643 8591
Abstract: We observed (22) Kalliope and its companion Linus with the integral-field spectrograph OSIRIS, which is coupled to the adaptive optics system at the W.M. Keck 2 telescope on March 25 2008. We present, for the first time, component-resolved spectra acquired simultaneously in each of the $Z_{bb}$ (1-1.18$\mu$m), $J_{bb}$ (1.18-1.42$\mu$m), $H_{bb}$ (1.47-1.80$\mu$m), and $K_{bb}$ (1.97-2.38$\mu$m) bands. The spectra of the two bodies are remarkably similar and imply that both bodies were formed at the same time from the same material; such as via incomplete re-accretion after a major impact on the precursor body.

Keywords: Infrared Observations; IR Spectroscopy; Asteroids
1. Introduction

The large main-belt asteroid (22) Kalliope, discovered in 1852, is classified as a M-type asteroid (Tedesco et al. 1989). Almost 150 years after its discovery, it was found to have a small companion, Kalliope I Linus (Merline et al. 2001, Margot and Brown 2001), orbiting the primary in a near-circular orbit with a semimajor axis of 1095 ± 11 km in 3.596 ± 0.001 days (Marchis et al. 2008a). For simplicity, in this work we will refer to the primary of the (22) Kalliope system as “Kalliope” and its companion satellite as “Linus”.

Analysis of the orbit of Linus has been used to derive a mass of $8.1 \pm 0.2 \times 10^{18}$ kg for the primary (Marchis et al. 2008a). In addition to these direct observations of the binary system, Descamps et al. (2008) used mutual eclipses during an equinox in 2007 and a stellar occultation event observed in 2006 to constrain the sizes and shapes of the two bodies, and hence the density of the primary. Kalliope’s equivalent radius is $83.1 \pm 1.4$ km and its shape can be approximated by a triaxial ellipsoid with semimajor axes of $117.5 \times 82 \times 62$ km. With this size and mass, Kalliope’s bulk density is $3.35 \pm 0.33$ g/cm$^3$, significantly larger than estimates for C-type or S-type binary asteroids derived so far (Marchis et al. 2008a) and larger than previous estimates of Kalliope’s bulk density, which were based on a larger (IRAS-derived) size of the object (Margot and Brown 2003; Marchis et al. 2003, 2008a). Although Descamps et al. (2008) derived a radius of $14 \pm 1$ km for Linus, this measurement was based on one eclipse detection taken at a particular viewing geometry. Since the shape of Linus is unknown, we will adopt here the more conservative estimate of $13\pm5.5$ km based on multiple adaptive optics (AO) observations (Marchis et al. 2008a).

Since Kalliope is a M-type asteroid with almost featureless visible and near-infrared spectra and a high albedo (Marchis et al. 2008b), it is difficult to assess its meteorite analog and derive its macro-porosity. An upper limit of 50–60% for the porosity can be obtained by assuming a pure Ni-Fe asteroid (Britt et al. 2002). Based upon the theoretical work by Wilson et al. (1999) with regard to gravitational re-accretion of bodies after a complete disruption, Descamps et al. (2008) adopt a porosity of 20–40% for Kalliope, i.e., they assume the body is at least heavily fractured or perhaps a rubble-pile. Such a porosity implies a grain density between 4 and 6 g/cm$^3$,
suggestive of a mixture of Ni-Fe alloys and silicates, consistent with near- and mid-IR spectroscopy (Marchis et al. 2008b). Such a heavily fractured primary, combined with the retrograde nature of the secondary’s orbit suggest that the system may have formed from a large impact on a proto-Kalliope (Durda et al. 2004).

With the increasing number of known multiple systems in all populations of small solar system bodies, one can begin to statistically analyze the distribution of mass ratios and orbital characteristics, which provide constraints on the formation of such systems. This is an important step towards developing an accurate picture of the environment during the solar system’s formative period. It is particularly helpful to determine whether these asteroidal satellites formed simultaneously with the primary, through catastrophic impacts, or via capture. Component-resolved color ratio measurements are used to determine if an asteroid and its companion have the same surface composition. For example, Marchis et al. (2006) report identical color ratios for the double trojan asteroid (617) Patroclus-Menoetius, which suggests a similar surface composition. However, without detailed spectroscopic measurements, such inferences remain speculative. Moreover, it is difficult to make accurate flux measurements if the secondary is faint ($3 < \Delta m < 7$) and close (0.3-0.7") to the primary.

A spectroscopic comparison of a primary and its satellite in binary systems such as Kalliope-Linus, may help to distinguish between the various formation scenarios. Similar spectra would indicate that the formation of both bodies was likely in situ or through a catastrophic collision, whereas measurably different spectra would point towards a foreign body capture. In order to constrain the origin of the binary asteroid system (22) Kalliope, we use the field-integral spectrograph OSIRIS (OH-Suppressing Infra-Red Imaging Spectrograph), on the W.M. Keck II 10-m telescope, to combine the high angular resolution provided by the telescope’s adaptive optics system with spectroscopy. The observations and the data analysis are presented in Sections 2 and 3 respectively, with a discussion of the results in Section 4.
2. Observations

We observed (22) Kalliope and its satellite Linus on 25 March 2008 between 07:33 and 08:13 UT using OSIRIS at the W.M. Keck observatory in Hawaii. OSIRIS is equipped with a 2048 x 2048 pixel Rockwell Hawaii-2 detector (Krabbe et al. 2006) and covers a wavelength range from 0.9 µm to 2.4 µm. In each of four broadband filters (Zbb, Jbb, Hbb and Kbb), OSIRIS records data cubes with 2 spatial and 1 spectral dimensions. We present observations in each of these broadband filters using the 0.02" platescale, which provides a field-of-view of 0.32" × 1.28" (Table I). The spectral resolution was $R = \frac{\lambda}{\Delta \lambda} \approx 3800$. The angular resolution depends on the brightness of the target (V-mag for wavefront sensing) and the atmospheric conditions. We estimate a spatial resolution of 0.06" from observations of nearby PSF (point spread function) stars.

At the time of the observations, Kalliope was at a geocentric distance $\Delta = 2.083$ AU, heliocentric distance $r = 3.048$ AU, and was observed almost pole-on according to the pole-solution and shape model derived in Descamps et al. (2008). This 3D-shape model predicts a projected equivalent diameter of 194±2km throughout the 45 min of observations. A sample model image of Kalliope at 07:47UT is shown in Fig. 1. The angular resolution of 0.06" leads to a spatial resolution of $\sim$91 km at Kalliope’s distance. Consequently, Kalliope’s primary is resolved in our image data cubes, while Linus is a point source. The $\sim$1100 km semi-major axis of the satellite’s orbit corresponds to $\sim$0.72" for a perfectly pole-on orientation. The binary system is therefore well resolved in our data (see Fig. 2).

The data are reduced with the OSIRIS pipeline (Larkin et al. 2006). This pipeline corrects for instrumental effects before rectifying and calibrating the data cubes in preparation for analysis. Nodded positions of the target are subtracted for correction of the sky background contamination. Sample images are shown in Fig. 2 where the data cube is averaged over all wavelengths in the filter. Inverted images of the targets arise from the nodded sky subtraction. The extraction discussed below is performed for each target individually and the inverted spectra are averaged with the positive spectra to provide one final spectrum per target.
At each wavelength, aperture photometry was performed on both science targets and corrected for any residual background. This provides a raw spectrum of Kalliope and Linus. The proximity of the secondary object and the observing method of nodding the target up and down the slit for background subtraction, both possibly lead to some contamination of the secondary’s spectra. This is exacerbated in the Zbb filter where the primary halo is brightest because the AO performance (wavefront correction) is not as good as at the longer wavelengths; in addition, the primary is much brighter because the solar flux is higher. More accurate flux measurements can be obtained by nodding completely off the object for sky calibration (but this decreases the total on-source integration time).

We corrected both primary and secondary object spectra for telluric absorption in Earth’s atmosphere, and photometrically calibrated them in a manner similar to that described by Laver et al. (2007), using observed spectra of the stars HD77281 (type A2) and HD111133 (type A0), both 2MASS catalog stars (see Table 1). The telluric correction was determined by comparing the spectra of the stars to the calibrated spectra from stellar atmosphere models. These spectra were created using the Kurucz stellar models1, which were adjusted for reddening using a Fitzpatrick reddening curve (Fitzpatrick 1999). The model spectra were subsequently scaled to match the 2MASS J,H,K magnitudes for the target stars (Cutri et al. 2003). The wavelength-dependent factor needed to scale the observations of the stars to match the models is used to calibrate the target spectra. Although we use both stars to estimate the telluric correction, differences in time and airmass result in imperfect corrections near the edges of some of the filters where water and CO₂ bands dominate.

As Kalliope and Linus are seen in reflected solar light, we corrected the spectra for solar features by dividing them by a normalized solar spectrum, and a solar blackbody curve. We used the high resolution solar spectrum from the ISAAC website2, which was convolved to the spectral resolution of the OSIRIS instrument. Rather than calibrating the data by observing G-type stars,

1ref. http://kurucz.harvard.edu/stars

2ref. http://www.eso.org/sci/facilities/paranal/instruments/isaac/tools/
we use a combination of library solar spectra with A-type stars for two reasons: A-star spectra have fewer absorption lines than G stars, and because other G stars are not perfect solar analogs. In general these steps are sufficient to produce high-sensitivity spectra; however, slight imperfections in the data rectification matrices of the Jbb and Zbb filters occasionally result in corrupted data, manifested as single aberrant pixels in the cube. Where applicable these outliers have been cleaned up during the data processing.

The units on the spectra were converted to the dimensionless parameter $I/F$, where $I$ is the reflected intensity and $\pi F$ the solar flux density at Kalliope’s distance (Hammel et al. 1989):

$$\frac{I}{F} = \frac{r^2 F_p}{\Omega F_\odot},$$

(1)

with $r$ Kalliope’s heliocentric distance, $\pi F_\odot$ the Sun’s flux density at Earth’s orbit, $F_p$ the observed flux density from the object, and $\Omega$ is the solid angle (in steradians) subtended by the body ($\pi R^2/\Delta^2$). By this definition, $I/F = 1$ for uniformly diffuse scattering from a (Lambert) surface when viewed at normal incidence, and is equal to the geometric albedo if the object is observed at a solar phase angle of 0°. To determine $\Omega$, we used Kalliope’s effective size as derived from Descamps et al. (2008)’s models. The spin rate and shape of Linus are not well known and thus the $I/F$ of Linus inherits the large error bars of the estimated diameter ($26 \pm 11$km). We also note that the photometry of OSIRIS data at the 20 mas platescale is not perfect, due to a loss of flux into the PSF halo. Although to first approximation our calibration procedure has taken this into account, we adopt a 15% uncertainty in our absolute flux calibration, based on previous OSIRIS observations (Laver et al. 2007). Our results are shown in Figs. 3 and 4 for Kalliope and Linus, respectively.

3. Analysis

Both bodies are slightly reddish, with an $I/F$ of 0.05-0.15, which is typical for M-type asteroids (Gaffey et al. 1989). Kalliope’s size is based on the Descamps et al. (2008) model, which predicts a nearly pole-on configuration during our observations, with no discernible change in the
projected equivalent diameter, even though the observations span almost 1/4 of Kalliope’s spin period (which is 4.18 hrs). The shape and spin of the secondary are unknown, yet it is reasonable to assume that Linus is tidally locked (such that the spin period equals the orbital period of $\approx 3.6$ days), given its proximity to the primary ($a \sim 12 \times R_{\text{primary}}$) (Marchis et al. 2008a) and its low orbital inclination relative to Kalliope’s equatorial plane ($\sim 0^\circ$).

There are small differences in the absolute $I/F$ between filters, which may be larger than the red slope expected for a M-type asteroid. Such differences may stem from either errors in the above assumptions about Linus, the Kalliope model, or simply the photometric uncertainties in some of the filters. In addition, the calibration of the slopes in spectral datacubes from OSIRIS may be somewhat problematic. With a small field of view (0.32”x1.28”) it is easy to encounter difficulties with the wings of a PSF falling off the edges of the detector. While this makes photometric calibration more challenging, it can also affect the overall slope of the spectrum as PSFs broaden at longer wavelengths, and hence more light can be ‘lost’ at longer wavelengths, i.e., the spectra may in fact be slightly more red than shown. However, while it is difficult to quantify such effects, these have been largely corrected for in our calibration scheme as we used entire spectra for photometric calibration (and our science targets are only slightly resolved).

The ratio of the spectra is, however, much more stable as the slopes of the spectra of each target are affected in a similar way. The ratios of the spectra of Kalliope and Linus are plotted in Fig 5; these reveal a remarkably flat slope. The flux ratio is $\sim 30$ in all three J, H, and K bands, which equates to a difference in magnitude of $3.7 \pm 0.1$. The Zbb spectrum of Linus has a lower intensity (relative to longer wavelengths) and a much noisier spectrum. This is caused by the brighter halo of the primary at Zbb wavelengths due to the poor correction provided by the AO system at shorter wavelengths, which increases the background noise in the vicinity of the secondary. The flux ratios, as indicated in Table 1 for each filter, depend upon the relative sizes and albedos of the primary and secondary. Given the uncertainties in the size of Linus, however, it is difficult to extract information about the relative albedos of the bodies. Assuming similar albedos for the two bodies, as one might expect based on the similarity of their spectral shapes,
we derive an effective diameter of 35±2km for Linus on the night of the observations, which is consistent with the size estimate of 26±11km.

We see an apparent absorption line at 1.49 \( \mu \)m in Kalliope’s spectrum (Fig. 3). This line occurs at the same location as a moderately strong solar absorption line (Mg I line at 1.48817 microns) and the narrowness of the feature leads suggests that this line is not intrinsic to the asteroid but is an artifact of the reduction process. However, all other solar lines of similar strength are correctly removed, so the presence of this line remains unexplained. The remaining apparent features have all been attributed to incomplete telluric correction due to the variation in the atmosphere between the science target and calibration stars.

4. Discussion

The spectra in Fig. 3 confirm previous findings that Kalliope is a M type asteroid, devoid of silicate features. Potentially interesting hydrated features in the 3 \( \mu \)m wavelength range, which may be present on Kalliope (Rivkin et al. 2000), are outside the wavelength range of the OSIRIS instrument. Linus displays a very similar spectrum as shown in Figs. 4 and 5. This implies that the surface material on both bodies is similar in composition and may have undergone similar degrees of space weathering.

Using the orbital characteristics of Linus and Kalliope, Descamps et al. (2008) showed that (22) Kalliope may be one of the oldest binary asteroid systems, with an estimated age between 1 and 3 Gyrs. Hence a study of this system provides a window into the conditions in the early solar system. It is apparent from Fig. 5 that the spectra of Kalliope and Linus are essentially the same, implying that both bodies formed at the same time from the same material. One explanation is that the Kalliope-Linus system formed from the same parent body. A proto-Kalliope could have been disrupted in a catastrophic impact, and re-accretion of material led to the formation of Kalliope and its satellite (Margot and Brown 2003; Marchis et al. 2003, 2008a). Due to Kalliope’s weak self gravity, this re-accretion naturally leads to an irregular, heavily fractured or rubble-pile
body (Durda et al. 2004).

Descamps et al. (2008) argued that an oblique impact on an already fractured or porous proto-Kalliope could also lead to the formation of a binary system via fission. If this were the case, one might expect space weathering effects to be different on the primary and secondary surfaces, unlike the catastrophic impact theory. There is no clear measurement of the space weathering effect on M-type asteroids, mostly because we do not know their composition and we do not know any young collisional families from this taxonomic class. Vernazza et al. (2009) studied the reddening of the spectra for young S-type collisional families. They showed that after a fast reddening due to ion implantation (∼1 Myr), the spectra of asteroids continue to change (‘mature’) at a slower pace by micro-meteorite impacts (up to 2,500 Myr). The bulk density and mid-infrared emissivity spectrum of (22) Kalliope (Marchis et al. 2008b) suggest that the asteroid is composed of a mixture of enstatite, iron and also olivine which is ‘weathered’ in S-type asteroids. If this is true, we can conclude from the striking similarities between the near-infrared spectra of the two components of (22) Kalliope, that the satellite and the primary likely formed at approximately the same time from the same parent body, and that the ejecta scenario is highly unlikely.

5. Conclusion

This paper presents the first component-resolved spectra of (22) Kalliope and its satellite Linus, obtained with the field-integral spectrograph OSIRIS at the W.M. 10-m Keck telescope. The data reveal remarkably similar M-type spectra for the two objects in the Zbb, Jbb, Hbb and Kbb infrared filters. This similarity between the spectra implies a common origin for the two bodies, i.e., they must have formed at the same time from the same materials, most likely via a catastrophic disruption of a proto-Kalliope. The relative intensity of the two objects differs by a factor of ∼30, or 3.7 magnitudes which is consistent with the size estimates of the primary (D_{app}=194 km) at the time of the observation and the satellite (D=26±11 km). If similar albedos are assumed this relative intensity implies an effective diameter of 35±2 km for Linus.
Our study shows the value of using an integral field spectrometer combined with an adaptive optics system, to simultaneously record spectra of several objects in multiple asteroid systems. A spectral survey of multiple asteroid systems will reveal if the observed similarity of the spectra of Kalliope-Linus is typical for binary asteroids, or if there is a large variety amongst them. Such surveys are therefore important to constrain theories on the formation and evolution of multiple asteroid systems, and hence provide information on the environment of our early solar system.

6. Acknowledgments

This work was supported in part by the National Science Foundation Science and Technology Center for Adaptive Optics, managed by the University of California at Santa Cruz under cooperative agreement AST 98-76783. FM acknowledges additional support from NASA grant NNX07AP70G and NSF grant AAG-0807468. CL thanks the American Museum of Natural History for their support and the use of their facilities. The data were obtained with the W.M. Keck Observatory, which is operated by the California Institute of Technology, the University of California, Berkeley and the National Aeronautics and Space Administration. The observatory was made possible by the generous financial support of the W.M. Keck Foundation. The authors extend special thanks to those of Hawaiian ancestry on whose sacred mountain we are privileged to be guests. Without their generous hospitality, none of the observations presented would have been possible.
REFERENCES

Britt, D. T., Yeomans, D., Housen, K., and Consolmagno, G. (2002). Asteroid Density, Porosity, and Structure. *Asteroids III*, pages 485–500.

Cutri, R. M., Skrutskie, M. F., van Dyk, S., Beichman, C. A., Carpenter, J. M., Chester, T., Cambresy, L., Evans, T., Fowler, J., Gizis, J., Howard, E., Huchra, J., Jarrett, T., Kopan, E. L., Kirkpatrick, J. D., Light, R. M., Marsh, K. A., McCallon, H., Schneider, S., Stiening, R., Sykes, M., Weinberg, M., Wheaton, W. A., Wheelock, S., and Zacarias, N. (2003). *2MASS All Sky Catalog of point sources*. The IRSA 2MASS All-Sky Point Source Catalog, NASA/IPAC Infrared Science Archive. [http://irsa.ipac.caltech.edu/applications/Gator/](http://irsa.ipac.caltech.edu/applications/Gator/)

Descamps, P., Marchis, F., Pollock, J., Berthier, J., Vachier, F., Birlan, M., Kaasalainen, M., Harris, A. W., Wong, M. H., Romanishin, W. J., Cooper, E. M., Kettner, K. A., Wiggins, P., Kryszczynska, A., Polinska, M., Coliac, J.-F., Devyatkin, A., Verestchagina, I., and Gorshanov, D. (2008). New determination of the size and bulk density of the binary Asteroid 22 Kalliope from observations of mutual eclipses. *Icarus*, 196:578–600.

Durda, D. D., Botkje, W. F., Enke, B. L., Merline, W. J., Asphaug, E., Richardson, D. C., Leinhardt, Z. M. 2004. The formation of asteroid satellites in large impacts: results from numerical simulations. *Icarus*, 170:243-257.

Fitzpatrick, E. L. (1999). Correcting for the Effects of Interstellar Extinction. *PASP*, 111:63–75.

Gaffey, M. J., Bell, J. F., and Cruikshank, D. P. (1989). Reflectance spectroscopy and asteroid surface mineralogy. In Binzel, R. P., Gehrels, T., and Matthews, M. S., editors, *Asteroids II*, pages 98–127.

Hammel, H. B., Baines K. H., and Bergstrahl J. T. (1989). Vertical aerosol structure of Neptune: Constraints from center-to-limb profiles. *Icarus*, 80:416-438

Krabbe, A., Larkin, J. E., Iserlohe, C., Baraczys, M., Quirrenbach, A., McElwain, M., Weiss, J., and Wright, S. A. (2006). First results with OSIRIS: NIR-imaging spectroscopy at the
diffraction limit. In *Ground-based and Airborne Instrumentation for Astronomy*. Edited by McLean, Ian S.; Iye, Masanori. Proceedings of the SPIE, Volume 6269, pp. (2006).

Larkin, J., Barczys, M., Krabbe, A., Adkins, S., Aliado, T., Amico, P., Brims, G., Campbell, R., Canfield, J., Gasaway, T., Honey, A., Iserlohe, C., Johnson, C., Kress, E., Lafreniere, D., Magnone, K., Magnone, N., McElwain, M., Moon, J., Quirrenbach, A., Skulason, G., Song, I., Spencer, M., Weiss, J., and Wright, S. (2006). OSIRIS: A diffraction limited integral field spectrograph for Keck. *New Astronomy Review*, 50:362–364.

Laver, C., de Pater, I., and Marchis, F. (2007). Tvashtar awakening detected in April 2006 with OSIRIS at the W.M. Keck Observatory. *Icarus*, 191:749–754.

Marchis, F., Descamps, P., Baek, M., Harris, A. W., Kaasalainen, M., Berthier, J., Hestroffer, D., and Vachier, F. (2008a). Main belt binary asteroidal systems with circular mutual orbits. *Icarus*, 196:97–118.

Marchis, F., Descamps, P., Hestroffer, D., Berthier, J., Vachier, F., Boccaletti, A., de Pater, I., and Gavel, D. (2003). A three-dimensional solution for the orbit of the asteroidal satellite of 22 Kalliope. *Icarus*, 165:112–120.

Marchis, F., Hardersen, P. S., Emery, J. P., Descamps, P., Reddy, V., and Lim, L. F. (2008b). Composition of the Binary Main-Belt Asteroid (22) Kalliope. In *Lunar and Planetary Institute Conference Abstracts*, volume 39 of *Lunar and Planetary Institute Conference Abstracts*, page 2526.

Marchis, F., and 17 co-authors (2006). A low density of 0.8gc m$^{-3}$ for the Trojan binary asteroid 617 Patroclus. *Nature*, 439:565-567.

Margot, J.-L. and Brown, M. E. (2001). S/2001 (22) 1. *IAU Circ.*, 7703:3.

Margot, J. L. and Brown, M. E. (2003). A Low-Density M-type Asteroid in the Main Belt. *Science*, 300:1939–1942.
Merline, W. J., Menard, F., Close, L., Dumas, C., Chapman, C. R., and Slater, D. C. (2001). S/2001 (22) 1. *IAU Circ.*, 7703:2.

Rivkin, A. S., Howell, E. S., Lebofsky, L. A., Clark, B. E., and Britt, D. T. (2000). The nature of M-class asteroids from 3-micron observations. *Icarus*, 145:351–368.

Vernazza, P., Binzel, R. P., Rossi, A., Fulchignoni, M., and Birlan, M. (2009). Solar wind as the origin of rapid reddening of asteroid surfaces. *Nature*, 458:993-995.

Tedesco, E. F., Williams, J. G., Matson, D. L., Weeder, G. J., Gradie, J. C., and Lebofsky, L. A. (1989). A three-parameter asteroid taxonomy. *AJ*, 97:580–606.

Wilson, L., Keil, K., and Love, S. J. (1999). The internal structures and densities of asteroids. *Meteoritics and Planetary Science*, 34:479–483.

This manuscript was prepared with the AAS \LaTeX\ macros v5.2.
Table 1. Observations of the (22) Kalliope system on UT 25 March 2008. The flux ratios as observed for Kalliope/Linus are indicated\(^1\).

| Date (UT) | Start (UT) | Object | Filter/Scale | Int Time (coadds x s) | Airmass | Flux ratio Kalliope/Linus |
|-----------|------------|--------|--------------|-----------------------|---------|------------------------|
| Mar 25 2008 06:26 | HD77281 | Kbb/0.02” | 1 x 30 | 1.10 |
| Mar 25 2008 06:33 | HD77281 | Hbb/0.02” | 1 x 30 | 1.09 |
| Mar 25 2008 07:33 | Kalliope | Hbb/0.02” | 1 x 300 | 1.54 | 30±1 |
| Mar 25 2008 07:47 | Kalliope | Kbb/0.02” | 1 x 300 | 1.46 | 28±1 |
| Mar 25 2008 08:00 | Kalliope | Jbb/0.02” | 1 x 300 | 1.38 | 32±1 |
| Mar 25 2008 08:13 | Kalliope | Zbb/0.02” | 1 x 300 | 1.32 | 53±1 |
| Mar 25 2008 08:32 | HD111133 | Kbb/0.02” | 1 x 30 | 1.26 |
| Mar 25 2008 08:36 | HD111133 | Hbb/0.02” | 1 x 30 | 1.24 |
| Mar 25 2008 08:41 | HD111133 | Jbb/0.02” | 1 x 30 | 1.22 |
| Mar 25 2008 08:46 | HD111133 | Zbb/0.02” | 1 x 30 | 1.21 |
Fig. 1.— Generated image showing Kalliope’s primary appearance at 07:47UT on March 25 2008 according to the Descamps et al. (2008) 3D-shape model. The image has been rotated to match the observed position angle in Fig. 2 (Generated using AsteROT, P. Descamps IMCCE).
Fig. 2.— Wavelength averaged Hbb datacube subtraction showing Kalliope (bottom) and its companion (top), Linus, in two nod positions (positive and negative after subtraction). The figure has a normalized intensity on a linear scale.
Fig. 3.— Zbb, Jbb, Hbb and Kbb spectra of Kalliope shown in $I/F$, using the apparent diameter of 194km. Dashed lines show the effect of the photometric calibration uncertainty, which is wavelength independent.
Fig. 4.— Zbb, Jbb, Hbb and Kbb spectra of Linus shown in $I/F$, using a diameter of 26 ±11km. Dashed lines show the effect of the size uncertainty, combined with the photometric calibration errors, which is wavelength independent.
Fig. 5.— Zbb, Jbb, Hbb and Kbb band comparisons of the primary and secondary spectra. The data have been smoothed using a 10 pixel running boxcar. The grey areas indicate with strong telluric absorption which is difficult to fully correct. The dashed lines indicate the average flux ratio (with $1\sigma$ errors) in the regions of the spectra least affected by the telluric correction.