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Component-resolved near-infrared spectra of the (22) Kalliope system

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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 Zbb (1–1.18 μm), Jbb (1.18–1.42 μm), Hbb (1.47–1.80 μm), and Kbb (1.97–2.38 μm) 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.

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 ± 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 ± 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 ± 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 ± 5.5 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.

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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 $\times$ 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 two spatial and one 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″ $\times$ 1.28″ (Table 1). 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 Δ = 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 ± 2 km throughout the 45 min of observations. A sample model image of Kalliope at 07:47 UT 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 datacubes 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 datacube 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.

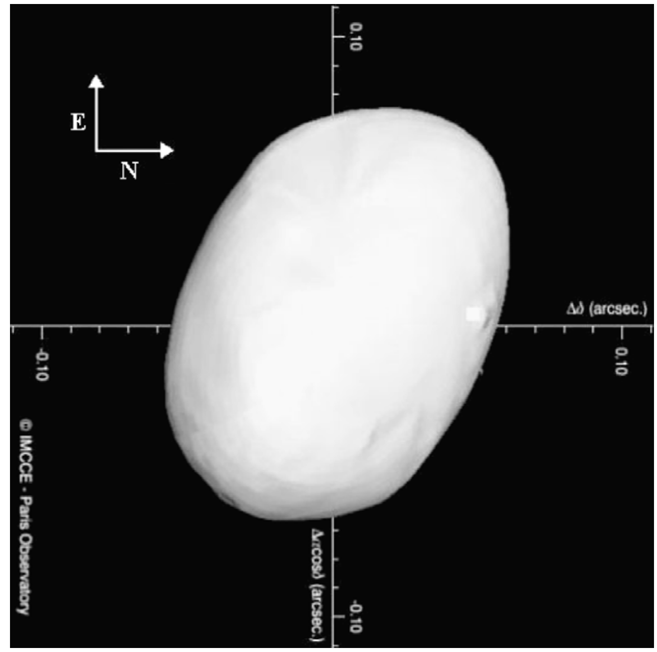

Fig. 1. Generated image showing Kalliope's primary appearance at 07:47 UT on March 25 2008 according to the Descamps et al. (2008) 3D-shape model. The image has been rotated to match the observed position angle in Fig. 2 (Generated using AsteROT, P. Descamps IMCCE).

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 mod-

Table 1
Observations of the (22) Kalliope system on UT 25 March, 2008. The flux ratios as observed for Kalliope/Linus are indicated.

Date (UT)	Start (UT)	Object	Filter/scale	Int time (coadds $\times$ s)	Airmass	Flux ratio Kalliope/Linus
March 25, 2008	06:26	HD77281	Kbb/0.02″	1 $\times$ 30	1.10	
March 25, 2008	06:33	HD77281	Hbb/0.02″	1 $\times$ 30	1.09	
March 25, 2008	07:33	Kalliope	Hbb/0.02″	1 $\times$ 300	1.54	30 ± 1
March 25, 2008	07:47	Kalliope	Kbb/0.02″	1 $\times$ 300	1.46	28 ± 1
March 25, 2008	08:00	Kalliope	Jbb/0.02″	1 $\times$ 300	1.38	32 ± 1
March 25, 2008	08:13	Kalliope	Zbb/0.02″	1 $\times$ 300	1.32	53 ± 1
March 25, 2008	08:32	HD111133	Kbb/0.02″	1 $\times$ 30	1.26	
March 25, 2008	08:36	HD111133	Hbb/0.02″	1 $\times$ 30	1.24	
March 25, 2008	08:41	HD111133	Jbb/0.02″	1 $\times$ 30	1.22	
March 25, 2008	08:46	HD111133	Zbb/0.02″	1 $\times$ 30	1.21	