Spectroscopy and surface properties of (809) Lundia

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ABSTRACT
Telescopic observation of binary system of (809) Lundia in the in the 0.8–2.5 μm spectral range is presented in order to determine its physical and mineralogical parameters. Observations covering several oppositions were performed using NASA telescope Infrared Telescope Facility and SpeX spectrograph. One of these spectra was observed during a mutual event (an occultation between components). A detailed analysis of spectra was performed using M4AST tools. (809) Lundia complex is a V-type object having similar mineralogy on both components of the system. By applying different mineralogical models a composition similar to the one of howardite–diogenite meteorites was found. The comparison of composite visible and near-infrared spectra with meteorites from Relab data base confirms this solution. From this comparison a surface covered by fine dusty regolith with grain size less than 100 μm was found. Orthopyroxene is the most abundant pyroxene of the regolith. Howarditic and diogenitic minerals seem to be the most abundant on the surface of (809) Lundia. The discrepancy between howardite–eucrite–diogenite meteorite bulk density and the one computed for the binary system suggests a rubble pile structure of both components.

Key words: methods: observational – techniques: spectroscopic – minor planets, asteroids: general.

1 INTRODUCTION
Several discoveries of complexes of bodies among asteroids have been announced during the last 10 yr. The binary or multiple structures of asteroids, hypothesized around 1980 (Zappala et al. 1980; Leone et al. 1984), were accessible for observing later by means of the large aperture telescopes and innovative techniques (adaptive optics, correlated observations photometry/radar).

When the components of a double object have comparable sizes, the generic term of binary object is commonly used. Particular geometries of the system will allow observations from the ground where the components will be mutually occulted or eclipsed. Recording these events by photometric techniques (obtaining the light curve) allows to model several physical and dynamical parameters such as dimensions, shape, bulk density and dynamical parameters of the binary system.

The occultation of a component by its pair in a binary asteroid allows to investigate its mineralogical structure and to discriminate between the homogeneity/heterogeneity of components, tracing a probable history of the system. Spectroscopy in the visible and near-infrared regions can be used for these investigations. The enlargement of the available observing time for spectroscopy of the Solar system has increased the sample of asteroids with well-defined spectral characteristics, also widening the asteroid period coverage having spectra taken at different rotation phases. If any difference is to be find, discriminating the real, intrinsic variation from more spurious instrumental-induced artefacts (Gaffey et al. 2002; Hardersen et al. 2006) is a necessary step before advancing a surface inhomogeneity explanation.

Laboratory studies are also used in order to compare both telescopic spectra and the one of irradiated minerals in order to simulate the space weathering. One important aspect of this promising work is the correlation of the surface astrophysical age with the amount of irradiation experienced by the surface.

The number of identified binary/multiple systems or asteroids with satellites is relatively low. Moreover, very few of them are...
characterized in terms of physical and mineralogical properties (Carry et al. 2011; DeMeo et al. 2011). Each new investigation of a binary system will improve our knowledge concerning the internal structure, mineralogical composition and dynamical evolution of minor bodies which in fine will bring clues for a better understanding of formation and evolution of our Solar system. Binary asteroids could be seen as first stages of asteroids-pair formation thus providing constrains of their fissional disruption (Moskovitz 2012).

(809) Lundia was reported as a V-type asteroid based on the spectroscopic observations in the visible region (Florczak, Lazzaro & Duffard 2002; Duffard et al. 2004; Lazzaro et al. 2004). As long as its orbital elements are far enough from Vesta family, the authors suggested that (809) Lundia is a V-type asteroid non-member of Vesta family. Carruba et al. (2005) investigated also the membership of (809) Lundia to Vesta family to whom the orbital elements drifted mainly by non-gravitational effects, thus being captured by the z2 resonance.

Photometric observations of (809) Lundia asteroid obtained over the period 2005 September–2007 January allow to conclude that the asteroid is a binary system spinning with a period of 15.418 ± 0.001 h (Kryszczyńska et al. 2009). The composite light curve of (809) Lundia shows a periodicity with large and non-equally variations in amplitude up to 1 mag for the period 2005 October–2006 January. These variations are associated with mutual occultations of components. These observations are followed by observational periods on which the composite light curve has small amplitude variation, associated with pole-on/pole-silhouette geometry of the system. Photometric data were modelled using Roche ellipsoids approach (Descamps et al. 2007) and the pole solution was obtained for the I2000 ecliptic coordinates $\lambda = 119^\circ \pm 2^\circ$, $\beta = 28^\circ \pm 4^\circ$. The kinematic model (Kryszczyńska et al. 2009) applied to the binary system of (809) Lundia computes a pole solution of $\lambda = 120^\circ \pm 5^\circ$, $\beta = 18^\circ \pm 12^\circ$, in agreement to the first one. The separation between components was computed to the value of 15.8 km. The components, assuming triaxial ellipsoid shapes and homogeneous composition, were estimated to be in a mass ratio of 0.7, and a bulk density $\rho = 1.64 \pm 0.05$ g cm$^{-3}$ (Kryszczyńska et al. 2009).

This paper is the completion of results already published by Kryszczyńska et al. (2009) and it is the result of an international campaign of observations for the global characterization of (809) Lundia in terms of internal structure, mineralogy and dynamics. The paper presents 0.8–2.5 μm near-infrared spectroscopic observations of (809) Lundia obtained over three oppositions in 2005, 2007 and 2010. One of our spectra in 2005 was obtained at the observation obtained at the maximum of the light curve and the other one corresponds to the sum of reflected light of both components (Fig. 1).

The observations of 2010 March 1 were performed in ideal weather conditions with low-speed wind (less than 1 mph) and very dry atmosphere (humidity less than 5 per cent). These conditions allow a signal-to-noise ratio (S/N) > 90–100 also in the spectral bands around 1.4 and 1.9 μm which usually are influenced by the telluric vapours.

Spectroscopic observations performed on 2007 March 12 were performed in poor atmospheric conditions, with humidity at 83 per cent and the seeing close to 1 arcsec. However, the apparent magnitude of the asteroid as well as the integration time allows a good S/N ratio for this object.

Data reduction was carried out by means of standard procedures for near-IR spectral range. The median flat-field for each night was constructed, then all images were corrected with this median flat-field referred as nodding procedure.

Table 1 summarizes the observational circumstances of our spectroscopic observations. SpeX was used in low-resolution Prism mode (Rayner et al. 2003), with a 0.8 × 15 arcsec$^2$ slit oriented north–south. Spectra of the asteroids and solar analogues were obtained alternatively on two distinct location on the slit (A and B beam) referred as nodding procedure.

The asteroid was observed as close as possible to the zenith and the solar analogues were chosen as close as possible to the asteroids.

In the case of observational runs in 2005 December, the observation time was limited for two time intervals of 1 h each, for two distinct configurations of the binary system. The constraints of observations were imposed by the light curves of the asteroid (809) Lundia, obtained just before these two runs. Photometry obtained by the 1-m telescope located at Pic du Midi, France, was used in order to increase the precision in time of mutual phenomena of the binary system.

The allowed observations were scheduled to obtain spectra corresponding to one of the minima of the light curve and the other one observation on the plateau. The observation obtained at the minimum of the light curve corresponds to a mutual phenomenon of the binary system, while the other one corresponds to the sum of reflected light of both components (Fig. 1).

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Data reduction was carried out by means of standard procedures for near-IR spectral range. The median flat-field for each night was constructed, then all images were corrected with this median flat-field. In order to eliminate the sky influence, the A–B pairs of images were subtracted. The result was the addition of these images. The final images were collapsed to a two-dimensional pixel–flux matrix. The result obtained was then calibrated in wavelength, using the

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### Table 1

<table>
<thead>
<tr>
<th>Date (UT)</th>
<th>$V$ (mag)</th>
<th>$\Phi$ (°)</th>
<th>$r$ (au)</th>
<th>Airmass</th>
<th>$T_{\text{exp}}$ (min)</th>
<th>Time (s)</th>
<th>Cycles</th>
<th>Seeing (arcsec)</th>
<th>Humidity (per cent)</th>
<th>Solar analogue</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005 December 21, 7 h 16 m</td>
<td>15.01</td>
<td>22.3</td>
<td>1.3041</td>
<td>1.04</td>
<td>16</td>
<td>120</td>
<td>4</td>
<td>0.7</td>
<td>18</td>
<td>HD 16018</td>
</tr>
<tr>
<td>2005 December 22, 9 h 26 m</td>
<td>15.04</td>
<td>22.5</td>
<td>1.3136</td>
<td>1.52</td>
<td>20</td>
<td>120</td>
<td>5</td>
<td>0.56</td>
<td>14</td>
<td>HD 16018</td>
</tr>
<tr>
<td>2007 March 12, 10 h 42 m</td>
<td>15.39</td>
<td>1.7</td>
<td>1.7308</td>
<td>1.03</td>
<td>32</td>
<td>120</td>
<td>8</td>
<td>0.8</td>
<td>83</td>
<td>HD 127913</td>
</tr>
<tr>
<td>2010 March 1, 9 h 10 m</td>
<td>15.94</td>
<td>14.8</td>
<td>1.7733</td>
<td>1.07</td>
<td>20</td>
<td>120</td>
<td>5</td>
<td>0.5</td>
<td>4</td>
<td>HD 60298</td>
</tr>
</tbody>
</table>
Spectroscopy and surface properties of Lundia

3 RESULTS AND MODELLING

The NIR spectral region of (809) Lundia was investigated and a detailed analysis using mineralogical models, spectral comparison with laboratory spectra and mineralogical charts are presented.

3.1 Results

Four spectra are presented in Fig. 2. The spectral trend suggests to a V-taxon type (DeMeo et al. 2009) of components, with large absorption bands around 0.93 and 1.92 \( \mu \)m. Our data are in agreement with the one of Florczak et al. (2002).

The spectra of 2005 December 21, 22 and 2007 March 12 exhibit spectral variations around 1.45 and 1.9 \( \mu \)m which are due to the influence of telluric water bands which were not completely removed during the data reduction procedure.

The spectra obtained on 2005 December 22, 2007 March 12 and 2010 March 1 are very similar over the whole spectral interval. The spectrum of 2005 December 21 is slightly different in the region 0.7–0.9 \( \mu \)m. All the spectra present a maximum of reflectance around 1.45 \( \mu \)m, and a shoulder around 1.15 \( \mu \)m. This region of spectrum between 1.15 and 1.4 \( \mu \)m is influenced either by the presence of plagioclase feldspar feature (Feierberg et al. 1980; Gaffey et al. 2002) or pyroxene (Cloutis & Gaffey 1991).

3.2 Modelling

The modelling of (809) Lundia is mainly based on the protocols implemented in the procedures of Modeling for Asteroids (M4AST) and largely presented in the paper of Popescu et al. (2012b).

The NIR spectra were combined with the visible spectrum of (809) Lundia published by Florczak et al. (2002). The visible and near-infrared (VNIR) spectrum was constructed by the minimization the spectral reflectance values of the common spectral interval of visible and NIR spectra, which is usually between 0.7 and 0.9 \( \mu \)m. The advantages of a composite spectrum are the possibility of analysis of whole 1 \( \mu \)m band profile, and to compute a mineralogical model based on the large wavelength interval of spectral reflectance data. The inconsistency of a composite spectrum could consists in merging two spectra which are not obtained in quasi-similar aspect angle (quasi-similar physical ephemerides). The composite spectrum VNIR of 2005 December 21 will be further denominate Sp1, and we will note Sp2 the result for the one of 2005 December 22, Sp3 the result for the one of 2007 March 12 and Sp4 the result obtained for the one of 2010 March 1.

The procedure of merging for Sp1 produces a spectrum much redder than the spectra Sp2–Sp4. While NIR part of Sp1 was obtained during the mutual event presented in Fig. 1, we consider the behaviour of Sp1 intimately linked to the structure of reflected light from the asteroid and less than an artefact obtained by the data reduction pipeline.

3.2.1 Taxonomy

The comparison with Bus–DeMeo taxonomy (DeMeo et al. 2009) reveals that all composite VNIR spectra of (809) Lundia are typically to V-taxon with a reliability factor (Popescu et al. 2012b) of 95.1 percent. This result complements the one produced by Florczak et al. (2002) for the visible region. V-taxon characteristics are the very strong 1 \( \mu \)m absorption band and as well as strong 2 \( \mu \)m absorption feature (DeMeo et al. 2009).

\(^1\) Sp1 and Sp2 were observed at the same phase angle and the solar analogue was the same.
3.2.2 Spectral band characteristics and mineralogy

Two prominent absorption features in the reflectance spectra occurs near 1 and 2 \( \mu \text{m} \). The band at 1 \( \mu \text{m} \) is characteristics of both olivine (Ol) and pyroxene (Px). Generally, mafic minerals (Ol, Px, certain Fe-phyllosilicates) are the most abundant phases in chondrite and in most achondrites (Gaffey et al. 2002). The olivine band is related to Fe\(^{2+}\) presence either in distorted octahedral M2 crystals and/or the weaker sidelobes of Fe\(^{2+}\) in M1 crystals (Burns 1970). In the case of orthopyroxene (OPx) the presence of Fe\(^{2+}\) in M2 octahedral crystallography produces symmetric 1 \( \mu \text{m} \) absorption band (Burns 1993). The 2 \( \mu \text{m} \) absorption band is produced by pyroxenes. This absorption feature is due to Fe\(^{2+}\) in a highly distorted M2 octahedral sites (Burns 1993). Both 1 and 2 \( \mu \text{m} \) bands could be shifted by the molar iron content as well as by the substitution of Fe\(^{2+}\) by other ions of metal, such as Mg\(^{2+}\) (Adams 1974).

Spectral region around 1.25 \( \mu \text{m} \) could be influenced either by the presence of plagioclase or pyroxene. Plagioclase feldspars exhibits weak absorption band centred near 1.25 \( \mu \text{m} \) due to Fe\(^{2+}\) occurrence on tetrahedral sites or Ca sites. In general, the presence of feldspars is inferred by the flattening or shift of interband peak, and the absorption band is clearly resolvable if the plagioclase abundances reaches 75 per cent. Laboratory studies conclude that quantitative determination of plagioclase abundances in mafic silicate bearing mixtures is very imprecise using 0.4–2.5 \( \mu \text{m} \) spectral region. The shoulder in spectra at 1.15 \( \mu \text{m} \) could be also due to the presence of Ca-rich pyroxenes. For example, type A clinopyroxene exhibits a large absorption band around 1.15 \( \mu \text{m} \) due to crystal field transitions in ferrous iron in the M1 crystallographic site (Cloutis & Gaffey 1991).

All spectra were investigated using the model of Cloutis et al. (1986), beforehand applying the temperature correction of band centres computed by Burbine et al. (2009). The results are summarized in Table 2.

The evolution of Band I (BI) minimum versus band area ratio (BAR) is a good indicator characterizing different mineralogies (Gaffey et al. 1993). Fig. 3 contains polygonal regions corresponding to meteoritic silicate assemblages (olivine, mafic silicates in ordinary chondrites and basaltic achondrite mineralogy). We placed our measurement into this diagram and the plot shows that all of our spectra are typically basaltic, being inside the rectangle which delimits basaltic mineralogy.

Another mineralogical indicator is the BI and Band II (BII) minimum in the context of pyroxene types of crystals, namely orthopyroxene (OPx) and clinopyroxene (CPx; Adams 1974). Our spectra parameters are placed mainly into the OPx predominant material region as shown in Fig. 4. This implies that on the surface of (809) Lundia, OPx is the predominant material which will impose its spectral signature to our spectra.\(^2\)

\(^2\) We cannot exclude the hypothesis of presence of minerals which are spectrally neutral for these wavelengths.

![Figure 3](image3.png)

Figure 3. The values obtained for Sp1–Sp4 are placed in the diagram of Gaffey et al. (1993). The computed values are inside the rectangle which delimits the basals.

![Figure 4](image4.png)

Figure 4. Band minima of four composite spectra in the diagram OPx+CPx computed by Adams (1974). The characteristic of band centres place the binary system of (809) Lundia into OPx-rich component of the diagram.

Spectral characteristics of (809) Lundia were also computed using the empiric model proposed by Gaffey et al. (2002). This iterative procedure allows the estimation of pyroxene composition in terms of molar Ca and Fe content. These computations converge towards a low Ca molar content, the solutions spanning the interval Wo\(_{86-87}\)Fs\(_{19-27}\) at \( \pm 4 \) molar per cent level of error. In the case of Sp3 there is an ambiguity into its final result while the molar content of Fs is 11 per cent which allows the bifurcation of mineralogical solution. Thus, two values of Fs were obtained for this spectrum with 37 and 19 per cent molar Fe. This bifurcation explains the wide interval of forsterite into our mineralogical formula. These values are also in agreement with the results presented in Fig. 5.

### Table 2. Mineralogical parameters obtained using Cloutis model and temperature correction (Burbine et al. 2009).

<table>
<thead>
<tr>
<th>Date</th>
<th>Band I (( \mu \text{m} ))</th>
<th>Band II (( \mu \text{m} ))</th>
<th>Band II–Band I (( \mu \text{m} ))</th>
<th>BAR</th>
<th>OPx/(OPx+Ol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005 December 21</td>
<td>0.9230 ± 0.0024</td>
<td>1.9385 ± 0.0025</td>
<td>1.0155</td>
<td>2.0024 ± 0.0018</td>
<td>0.891</td>
</tr>
<tr>
<td>2005 December 22</td>
<td>0.9308 ± 0.0027</td>
<td>1.8970 ± 0.0052</td>
<td>0.9662</td>
<td>2.1366 ± 0.0130</td>
<td>0.947</td>
</tr>
<tr>
<td>2007 March 12</td>
<td>0.9351 ± 0.0014</td>
<td>1.8792 ± 0.0321</td>
<td>0.9441</td>
<td>2.1938 ± 0.0077</td>
<td>0.971</td>
</tr>
<tr>
<td>2010 March 1</td>
<td>0.9318 ± 0.0008</td>
<td>1.9438 ± 0.0032</td>
<td>1.0120</td>
<td>2.0509 ± 0.0009</td>
<td>0.911</td>
</tr>
</tbody>
</table>
Spectroscopy and surface properties of Lundia

The difference between the two band minima, called band separation, can be used to estimate the iron content (de Sanctis et al. 2011). Laboratory calibration indicates that the band separation given as a function of BII minima shows a linear trend which can be correlated with the iron content (Cloutis et al. 1990). In Fig. 5 the data obtained for Lundia are plotted together with the linear fit obtained by Cloutis et al. (1990). Our measurements match well this linear trend, indicating an iron content between 20 and 40 per cent, according to the laboratory calibrations. These values agree with those obtained by applying the model of Gaffey et al. (2002). However, these calibrations are true for a number of low aluminium orthopyroxenes and are not valid for mixtures of olivine, metal, OPx and CPx (de Sanctis et al. 2011).

3.2.3 Mineralogical charts

Sp1–Sp4 were investigated with three component mixtures. These components were selected from Relab. The end members of Ol, OPx and CPx sets contain 44, 33 and 55 spectra, respectively. The olivine set includes synthetic spectra that span the Fa\textsubscript{0}–Fa\textsubscript{100} domain in 5–10 mol per cent increments (Dyar et al. 2009) while the members of orthopyroxene set sample the range En\textsubscript{0}–En\textsubscript{100} for CPx spectra represents minerals with different Wo, En, Fs content. This wide variety of minerals included in the three above sets make them suitable for generating synthetic mixtures spectra.

The computation of each mineralogical chart follows the procedure presented in Birlan et al. (2011). The mixture producing the best fit in χ\textsuperscript{2} sense is (Opx, Cpx, Ol) = (0.725, 0.275, 0). The Relab end-members of this mixture are c1dl03 (DL-CMP-003) for OPx and c1dl17a (DL-CMP-017-A) for CPx. The corresponding WoFs solution of the mixture is Wo\textsubscript{6}Fs\textsubscript{23}. These results, presented in Fig. 6, outline an OPx-dominated mineralogy in agreement with our previous spectral bands analysis.

The WoFs values obtained using two methods together with the average Fs and Wo contents of pyroxenes (Burbine et al. 2009) are presented in Table 3. If (809) Lundia is a member of Vesta family that has drifted under a non-gravitational mechanism it could represent a fragment of Vesta’s howarditic layer.

3.2.4 Space weathering

Space weathering effects have been analysed by laboratory measurements on irradiated eucritic and basaltic meteorites (Vernazza et al. 2006; Fulvio et al. 2012). These experiments conclude to a darkening of sample and the reddening of the spectra, together with the decreasing depth in absorption bands. Fulvio et al. (2012) conclude to a rapid reddening of spectra on a time-scale less than
### Table 4. Results obtained by matching spectra of (809) Lundia with laboratory spectra from Relab data base.

<table>
<thead>
<tr>
<th>Date</th>
<th>Meteorite</th>
<th>Sample ID</th>
<th>Type</th>
<th>Texture</th>
<th>Size (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005 December 21</td>
<td>ALH-78132, 61</td>
<td>MB-TXH-072-B</td>
<td>HED eucrite</td>
<td>Particulate</td>
<td>25–50</td>
</tr>
<tr>
<td></td>
<td>Y-790727, 144</td>
<td>MP-TXH-098-A</td>
<td>HED howardite</td>
<td>Particulate</td>
<td>0–25</td>
</tr>
<tr>
<td></td>
<td>ALHA76005, 85</td>
<td>MB-TXH-066-B</td>
<td>HED eucrite</td>
<td>Particulate</td>
<td>25–45</td>
</tr>
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<td>2005 December 22</td>
<td>Le Teilleul</td>
<td>MP-TXH-093-A</td>
<td>HED howardite</td>
<td>Particulate</td>
<td>0–25</td>
</tr>
<tr>
<td></td>
<td>Kapoeta P11410</td>
<td>SN-CMP-012</td>
<td>HED breccia</td>
<td>Thin section</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Pavlovka</td>
<td>MR-MJG-094</td>
<td>Howardite</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>2007 March 12</td>
<td>Nobleborough</td>
<td>MR-MJG-093</td>
<td>Eucrite</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Le Teilleul</td>
<td>MP-TXH-093-A</td>
<td>HED howardite</td>
<td>Particulate</td>
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<tr>
<td></td>
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<td>MP-TXH-099-A</td>
<td>HED howardite</td>
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<td>0–25</td>
</tr>
<tr>
<td>2010 March 1</td>
<td>EETA79005</td>
<td>TB-RPB-026</td>
<td>Euc polymict</td>
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<td>0–250</td>
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<td></td>
<td>Y-791573, 145</td>
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<td>HED howardite</td>
<td>Particulate</td>
<td>0–25</td>
</tr>
<tr>
<td></td>
<td>Haraya</td>
<td>TB-RPB-024</td>
<td>Achondrite eucrite</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Figure 7. Examples of spectral matching between Sp1 and the meteorite ALH-78132, 61 (left-hand side), Sp4 and the meteorite EETA79005 (right-hand side).

3 Myr, highly influenced by the cross-section efficiency of flux particle into the collision with the sample (in their case C$^+$ ions is the most efficient comparing to Ar$^+$). In the approach of laboratory space weathering experiments, the composite spectra of (809) Lundia appears unaltered.

#### 3.2.5 Comparison to Relab spectra

Comparative mineralogy was performed using laboratory spectra from Relab data base.\(^3\) This approach provide insights on the possible surface mineralogy of asteroids, based on a large specific data base of minerals studied in laboratory. The limitation of this method is synthesized by Gaffey et al. (2002) and Gaffey (2010). As a corollary, comparison between laboratory and telescopic spectra is useful in identifying the reason of differences between asteroid spectrum and the possible meteorite analogue spectrum. The degeneracy of mineralogical solution (several minerals and mixtures exhibit similar spectral behaviours) should be also taken into account during the interpretation of telescopic data.

The routine of spectral comparison implemented by M\textsuperscript{4}AST was used for our objective; the combined method of matching (Popescu et al. 2012b) was chosen in finding analogue minerals among meteoritic spectra. The choice of the method of matching was imposed by two major aspects: (i) this method keeps as close as possible the extrema position between the asteroid spectrum and the one of meteorite, and (ii) this method minimizes the $\chi^2$ between the asteroid spectrum and the meteorite one.

Spectral matching was performed for Sp1–Sp4 spectra. Overall, the first 50 spectral analogues found by the procedure are belonging to the basaltic meteorites (howardite, achondrite, eucrite). The large part of best matches are composed by small 0–100 µm grain size, which imply that the surface is covered by fine dusty regolith.

Table 4 synthesized the three best matches for our spectra, while Fig. 7 shows two examples of matching for Sp1 and Sp4.

### 4 DISCUSSION

Orbital elements of (809) Lundia show an object which is located into the inner part of main belt, in the vicinity of the space region of Vesta family. The revised Vesta family using hierarchical clustering method (Cellino & Dell’Oro 2010) count 4547 objects; the cluster was obtained for a cut-off value of the relative velocity of 57.5 m s\(^{-1}\) (Moth\’e-Diniz, Roig & Carvano 2005). Spectroscopic evidences of asteroid family of Vesta were published by Binzel & Xu (1993) on 20 small objects (diameter less than 10 km) which attest the presence of chips of Vesta over a large region in space. Binzel & Xu (1993) estimate a mean ejection velocity of 590 m s\(^{-1}\) of their fragments with diameters of 5–10 km for attending the vicinity of 3:1 resonance while for small fragments (0.1–1.0 km) the ejection

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\(^3\) http://www.planetary.brown.edu/relabdocs/relab.htm
velocity could attain 700 and 1000 m s\(^{-1}\) for falling into the same resonance.

Dynamically (809) Lundia is located into the \(z_2\) resonance, one of the strongest non-linear secular resonance into the inner belt (Carruba et al. 2005). Evolutions of orbits by clones and taking into consideration the Yarkovsky effect show that mechanisms of migration chips of Vesta into the \(z_2\) resonance could be imagined and in some cases these objects will be trapped into the resonance for long periods (Carruba et al. 2005).\(^4\)

We computed the \(\Delta v\) distance (Zappala et al. 1990) of (809) Lundia as a chip of (4) Vesta to 1469 m s\(^{-1}\). This value is much larger than the threshold of Vesta family delimited by Mothé-Diniz et al. (2005), thus a small probability of dynamical association between the two objects.

Our spectral data show that both components of binary system are mineralogically very close. This result is similar to the one obtained by DeMeo et al. (2011) on the asteroid (379) Huenna and its satellite.

Duffard et al. (2004) published a composite VNIR spectrum of (809) Lundia obtained using Telescopio Nazionale Galileo 3.5-m facilities, during the asteroid opposition in 2004. Mineralogical analysis performed by the authors on 15 V-type objects placed Lundia into an intermediate position between eucritic and diogenitic mineralogy (fig. 7 of their paper).

The statistical analysis and comparison between howardite–eucrite–diogenite (HED) meteorites and V-type asteroids performed by Moskovitz et al. (2010) contain one NIR spectrum of (809) Lundia obtained during its opposition of 2008.\(^5\) This spectrum is quite similar to our spectra, the BI and BII minima being in the same range to ours. However, BAR is relatively different by approximately 0.4 and this result is the consequence of difference of limit we used for the upper limit of BII. Placed into the context of HED diagram of Moskovitz et al. (2010), our results are an indication that the surface of (809) Lundia is mostly howarditic and diogenitic materials as presented in Fig. 8. The howarditic composition is also shown by the comparison with Relab spectra.

New spectroscopic results concerning the (4) Vesta observed visible and infrared (VIR) spectrometer on-board Dawn mission were published recently (de Sanctis et al. 2012). These in situ results, obtained on a spatially resolved asteroid, contain NIR spectra of Vesta which present characteristics of HED meteorites. de Sanctis et al. (2012) clearly distinguish differences in spectra correlated to specific locations on the asteroid surface (such is the big basin Rhea Silvia on the South Pole). These variations were also detected on ground-based spectral observations (Vernazza et al. 2005) thus confirming that telescopic observations could be very reliable in describing the possible spectral variation over the rotational period of asteroid.

As it can be noticed from Fig. 2 spectra published in this paper present some variations in their global trend, similar to the one of published by de Sanctis et al. (2012) for Vesta. In the assumption that these variations are not artefacts due to the atmosphere or bad manipulation during data reduction procedures, we can speculate concerning the origin of these variations. While the geometry of binary system is different in each date of observations these variations represent the addition of reflected VNIR electromagnetic waves on both components. The variation is either the competition between two bodies of different surfaces (HED like but different spectral properties) or the result of two bodies which presents geographic variations of their surface. While Sp1 was observed during the mutual event, and its slope is more important, the hypothesis of slightly dichotomous surface\(^6\) should be more favourable.

Another important aspect is related to the density of (809) Lundia. Kryszczyńska et al. (2009) modelling of photometric data of binary system computed the best solution for a bulk density of 1.6 \(\pm\) 0.1 g cm\(^{-3}\) in the case of Roche ellipsoid model and a bulk density of 1.7 \(\pm\) 0.1 g cm\(^{-3}\) for the best solution in the case of kinematic model. Our spectral observations reveal a V-type system which is similar to HED meteorite spectra. Laboratory measurements of the bulk density of HED meteorites span the range 2.7–3.4 g cm\(^{-3}\) depending on their eucritic, howarditic or diogenitic nature (Britt & Consolmagno 2003).\(^7\) These values could be reconciled only if (i) we consider a macroporosity rather large between 30 and 50 percent for the binary asteroid or (ii) the object is composed of vesicular volcanic material.\(^8\) While the mineralogical analysis is in favour of fragments with howarditic (with diogenites and less eucritic structure) we can conclude that the interior of components of (809) Lundia is more probable a rubble pile structure.

Spectral comparison to HED meteorite spectra from Relab shows very good matches between achondrite meteorites and (809) Lundia. The comparison favours the meteoritic samples with small grain size allowing to conclude that both components of binary system are covered by small size regoliths. This conclusion could be confirmed by future polarimetric measurements which will give more information concerning the surface roughness and physical properties (Belskaya et al. 2009).

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\(^4\) The authors also claims that several V-type asteroids genetically linked to Vesta must be present into the \(z_2\) resonance.

\(^5\) The paper of Moskovitz et al. (2010) presents new calibration for mineralogical parameters which are different of those computed by Cloutis et al. (1986).

\(^6\) General trend of both component is similar to HED meteorites.

\(^7\) If we consider a howarditic and diogenitic nature of (809) Lundia the bulk density range spans 3.0 – 3.4 g cm\(^{-3}\).

\(^8\) Very few meteorites such are Ibitira, Dhofar, Silistra present pumice or vesicular structure.
In the last years large number of V-type small asteroids were discovered. Some of them could not belong to Vesta family considering the dynamical criteria even if their surface composition is similar to the one of Vesta (Duffard & Roig 2009; de San
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ces et al. 2011; Popescu et al. 2012a). The hypothesis of several basaltic asteroids at the origin of discovered V-type objects in the main belt (Nesvorný et al. 2008; Roig et al. 2008) seems to be now sustained by good arguments.

How numerous V-type rubble piles asteroids are in the main belt? Is this a common internal structure for V-type objects? Laboratory experiments on mechanical properties (elastic and shear moduli, compressive and tensile strengths) of HED meteorites (Petrovic 2001) conclude that these are bigger than the one of ordinary chon-
drite meteorites (Slyuta 2010). This implies that complex, rubble pile structure could be more difficult to realize. If the situation occurs for V-type asteroids, then the energetic balance is more important that in the case of rubble pile structures for ordinary chondrites. Thus we expect that rubble pile V-type asteroids to be relatively less abundant, which is not really the case. Indeed, (809) Lundia complex is not unique among binary objects, while the asteroid (854) Frostia was already reported as binary object (Behrend et al. 2006) and its spectral properties are similar to the one of Vesta (Birlan et al. 2011). The density of (857) Frostia estimated by Behrend et al. (2006) requires a porosity of 40–60 percent of the components for fitting the HED range of densities, which imply a rubble pile structure.

Another aspect of rubble pile structures could be derived from asteroids pairs (Pravec & Vokrouhlický 2009; Pravec et al. 2010). The fission mechanisms proposed by Pravec et al. (2010) require a rubble pile structure of parent body. While mechanical properties of HED meteorites show cohesion properties (shear and elastic moduli, compressive and tensile strength) with bigger values than for other stony materials, we expect a less important fraction of V-type objects into the category of asteroid pairs. Spectroscopic observations reveals that at least two pairs contain objects with spectral properties similar to vestoids (Birlan et al. 2012; Polishook et al. 2012).

Even if (809) Lundia is not unique, this binary object allows us to address a battery of questions and aspects related to Vesta and Vesta-like objects.

5 CONCLUSIONS

NIR spectroscopy of asteroid (809) Lundia was obtained during three distinct oppositions. In 2005 a spectrum of binary system was obtained during a mutual event. The interpretation of spectroscopic data was done by using the information in the visible spectral range published by Florczak et al. (2002). Photometry (Apogee/TIM Pic du Midi, France) were used in order to refine physical ephemeris of (809) Lundia and to determine the optimum timing of spectro-
coscopic observations (SpeX/IRTF, Hawaii). The composite spectrum Sp1 was obtained during the mutual event between the components of the binary system. Our observations performed during three oppositions show that NIR spectral behaviours are those of a V-type asteroid. The spectrum obtained during the mutual event exhibits similar mineralogical parameters than other three spectra which imply that (809) Lundia is an object having similar mineralogy on both components of the system. The comparison of composite VNIR spectra to meteorites one from Relab data base shows that the best matches correspond to a surface covered by fine dusty regolith with grain size less than 100 µm. OPx is the most abundant pyroxene of the regolith. Diogenitic and howarditic minerals seem to be the most abundant on the surface of (809) Lundia. The discrepancy between HED meteorite bulk density and the one computed for the binary system suggests a rubble pile structure of both components.

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