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# Mineralogical characterization of A-type asteroid (1951) Lick*

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**Abstract.** We have obtained visible and near-infrared reflectance spectra of asteroid (1951) Lick. According to its spectral characteristics in the visible region, this object has been classified as an A-type asteroid by Bus & Binzel (2002b). Here we present a mineralogical analysis of the reflectance spectrum obtained for this object. We compute several parameters that are extracted from the spectrum of the asteroid and that give relevant information about its mineralogical composition, using the method defined by Gaffey et al. (1993). We also present results obtained through the fit to the absorption band associated to the pressence of olivine using the Modified Gaussian Model (MGM) method developed by Sunshine et al. (1990). Our results indicate that (1951) Lick is an almost pure olivine. The composition of olivine on the surface of Lick is estimated to be about $Fo_{90\pm10}$ (low-iron content).

**Key words.** minor planets, asteroids – solar system: general

## 1. Introduction

A new class of asteroids with unusual visible and near-infrared spectra was discovered in the early 80s. These asteroids, named A-type, are usually found in the main asteroid belt between Mars and Jupiter. Observations at longer wavelengths, to 2.5 $\mu$m, revealed that spectra of these asteroids are very similar to spectra of the silicate mineral olivine (Cruikshank & Hartmann 1984).

The existence of olivine-rich asteroids is of interest because olivine is an igneous silicate mineral that is found in pure or nearly pure assemblages only as a result of differentiation. In terrestrial volcanic settings it is the material that settles to the bottom of a magma chamber, and it is sometimes erupted onto the surface in a late stage of basaltic volcanism. In once-melted asteroids it could be a major constituent of the mantle or of certain mantle zones. Extraterrestrial sources of such material must exist because we have two meteorites that are nearly pure olivine. Their origin is of special interest because their existence indicates the occurrence of secondary events on asteroids, and their visibility requires the exposure of asteroid interiors.

Several works have been done related to this kind of objects, such as Gaussian analysis to determine composition of olivine, studies of the influence of temperature on the spectra of A-asteroids or the importance of space weathering in simulating compositional models for these objects (Sunshine et al. 1990; Lucey et al. 1998; Hiroi & Sasaki 2001). In his paper of 1993, Gaffey analyses the mineralogical composition of several S(I)-asteroids and at least one A-type asteroid, following Cloutis et al. (1986). S(I) asteroids occupy or are just below the nearly monomineralic olivine region. There is a limited number of asteroids classified as A-type and only few of them present a detailed compositional analysis, which is necessary to better understand their origin and formation.

Asteroid (1951) Lick has been classified as an A-type by Bus & Binzel (2002b). Although considered as an Amor object by several authors, according to its orbital parameters ($a$ = 1.390 AU, $e$ = 0.061, $i$ = 39.093°, $q$ = 1.304 AU) this object is just in the limit that separates Amors from Mars Crossers ($q$ = 1.3 AU).

We have observed this interesting object and characterized its mineralogical properties and the results are presented in this paper. In the next section we describe the observing and reduction procedures. The analysis of the data, extraction of the relevant parameters and their mineralogical interpretations are presented in Sect. 3, as well as a brief discussion of the

* Based on observations made with the Nordic Optical Telescope, operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway, and Sweden, and on observations made with the Italian Telescopio Nazionale Galileo (TNG) operated on the island of La Palma by the Centro Galileo Galilei of the INAF (Instituto Nazionale di Astrofisica), both telescopes located at the Spanish "Observatorio del Roque de los Muchachos" of the Instituto de Astrofísica de Canarias.

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obtained results. We conclude with a review of our main results in Sect. 4.

## 2. Observations and reduction

Low resolution spectra of (1951) Lick was obtained on June 22, 2003, with the 3.6 m Telescopio Nazionale Galileo (TNG) using NICS (Near Infrared Camera Spectrograph). NICS is a FOSC-Type cryogenic focal reducer, equipped with two interchangeable cameras feeding a Rockwell Hawaii 1024 × 1024 array. Among the many imaging and spectroscopic observing modes, NICS offers a unique, high-throughput, low resolution spectroscopic mode with an Amici prism disperser, which yields a complete 0.8−2.4 $\mu$m spectrum. A 1.5″ width slit corresponding to a spectral resolving power $R \approx 34$ quasi-constant along the spectrum has been used.

The identification of the asteroid was done by taking images through the $J_s$ ($\lambda_{\rm cent}$ = 1.25 $\mu$m) filter. It was identified as the moving object at the predicted position and with the predicted proper motion. The slit was oriented in the parallactic angle, and the tracking was at the object proper motion. The phase angle of the object was $\alpha = 50\overset{\circ}{.}7$.

The acquisition consisted of a series of 3 images of 90 s of exposure time in one position (position A) of the slit and then offsetting the telescope by 10″ in the direction of the slit (position B). One cycle of ABBA images was obtained, corresponding to a total on-object exposure time of 1080 s.

The reduction of the spectra followed the scheme described in Licandro et al. (2001). Wavelength calibration was performed using an argon lamp and the deep telluric absorption features. To correct for telluric absorption and to obtain the relative reflectance, four G-type stars (Landolt 107−998, Landolt 110−361, Landolt 112−1333 and Landolt 115−271) were observed during the night at different airmasses. By dividing the spectra of Landolt 107−998, Landolt 110−361, Landolt 112−1333 by the spectrum of Landolt 115−271, and then normalizing to unity around 1.6 $\mu$m, we obtained featurless spectra with slope 0, indicating that the atmosphere was very stable during the observations. The reflectance spectrum of the asteroid was obtained by applying the same procedure to its spectrum, dividing it by the spectra of the 4 solar analogues and then averaging the results. The final uncertainty in the slope is smaller than 0.3%/1000 Å.

Visible spectrum of the same object was obtained on the night of August 25, 2003, with the 2.5 m Nordic Optical Telescope (NOT) using ALFOSC (Andalucia Faint Object Spectrograph and Camera) instrument. We have used a grism disperser with a wavelength range of 0.32−0.91 $\mu$m ($\lambda_{\rm cent}$ = 0.58 $\mu$m) and a second order blocking filter (cut-off wavelength at 0.47 $\mu$m). A 1.3″ slit has been used. As in the infrared observations, the slit was oriented in the parallactic angle and the tracking was at the object proper motion. Phase angle of the object was $\alpha = 50\overset{\circ}{.}1$, almost the same as in the near-infrared observations. The spectral data reduction was done using the Image Reduction and Analysis Facility (IRAF) package, following standard procedures. Wavelength calibration was performed using a helium-neon lamp and two solar analog stars

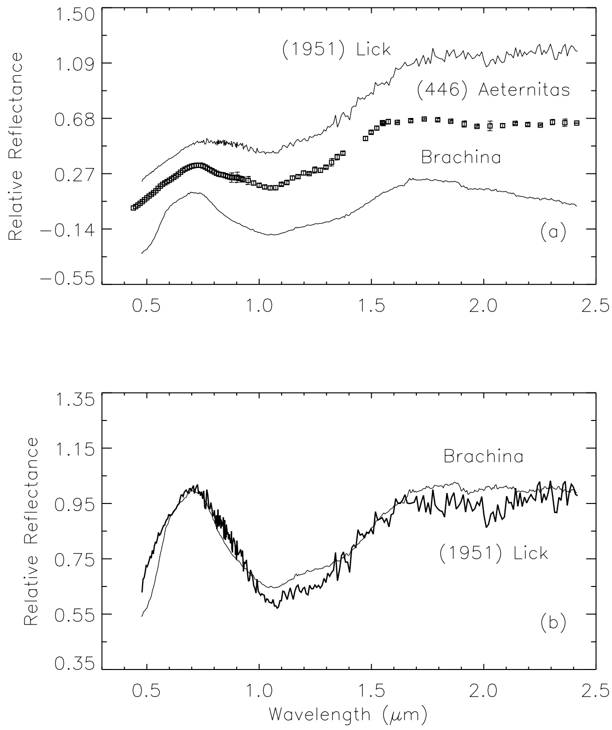


**Fig. 1. a)** Complete visible and near-infrared spectrum of asteroid (1951) Lick. In comparison, data from SMASSII and 52-colors surveys of asteroid (446) Aeternitas, and RELAB database spectrum of Brachina meteorite are also shown; **b)** spectra of (1951) Lick (thick line) and Brachina meteorite, both after removing of the continuum following Gaffey et al. (1993).

(Landolt 115−271 and Landolt 110−361) were observed to correct for telluric absorption and to obtain the reflectance spectrum of the asteroid, as it was done in the near-infrared.

## 3. Analysis of the data and discussion

The mineralogical composition of an asteroid can be obtained through the analysis of its spectrum in the visible and near-infrared region (VNIR). As described in the previous section our observations of (1951) Lick consisted of a visible and a near-infrared spectrum with useful ranges of 0.47−0.91 $\mu$m and of 0.78−2.40 $\mu$m, respectively. In order to analyze the complete VNIR spectrum we first overlap the visible and near-infrared spectra using the common interval between 0.78 and 0.90 $\mu$m by performing a least-square minimum procedure. The resulting spectrum is shown in Fig. 1a, along with that of the A-type asteroid (446) Aeternitas obtained from the SMASSII (Bus & Binzel 2002a) and 52-colors (Bell et al. 1988) surveys, and arbitrary shifted for comparison. In addition, spectrum of Brachina meteorite, from RELAB database and taken by using a rusted sample crushed to a grain size smaller than 75 $\mu$m, is also shown in the same figure.

The resulting spectrum of (1951) Lick shows a very reddish slope in the visible region, a deep assymetric absorption band near 1 $\mu$m and no absorption band around 2 $\mu$m within the signal-to-noise ratio.

**Table 1.** Spectral parameters of A-type asteroids (1951) Lick (this paper), (446) Aeternitas (Gaffey et al. 1993) and Brachina meteorite (this paper).

| | (1951) Lick | (446) Aeternitas | Brachina |
|---|---|---|---|
| Band I minimum [$\mu$m] | 1.032 ± 0.023 | – | 1.045 ± 0.005 |
| Band I center [$\mu$m] | 1.083 ± 0.022 | 1.070 ± 0.020 | 1.070 ± 0.005 |
| Slope I | 0.707 | 0.750 | 0.104 |
| Band area I | 0.252 | – | 0.218 |
| Band area II | 0.000 | – | 0.006 |
| BAR | 0.000 | 0.090 | 0.027 |

We have performed a first mineralogical analysis using the method outlined in Cloutis et al. (1986) and Gaffey et al. (2002), where they extract several useful parameters from the spectrum, such as the band minimum and center and band area. All these parameters have been computed for our spectrum of (1951) Lick and are given in Table 1 along with those obtained by Gaffey et al. (1993) for asteroid (446) Aeternitas. We have also computed the same parameters for the spectrum of Brachina meteorite. Notice the similarity between (1951) Lick and Brachina meteorite for all but *slope I* spectral parameter, which presents a higher value in the case of the asteroid due to the reddening of the slope of its spectrum after 1.5 $\mu$m. Figure 1b shows the spectra of asteroid (1951) Lick and Brachina meteorite, both after removing of the continuum following Gaffey et al. (1993). We can see the good equivalence between both spectra.

The parameter BAR, which is the ratio between the band areas II and I, gives information about the abundance of olivine, since for pure olivine this parameter is essentially zero for all the phases and increases for olivine-pyroxene mixtures due to the pressence of the second absorption band associated to pyroxene. A second absorption band around 2 $\mu$m, typical of pyroxene, is not definitively detected under the S/N of our data. Our BAR value, according to Gaffey et al. (1993), indicates almost pure olivine.

Burbine & Binzel (2002) calculated centers and depths of first absorption band of 10 A-type asteroids, subdividing them into two groups of asteroids based on “deep or weaker” features out to 1.6 $\mu$m. Binzel et al. (2004) have obtained the visible and near-infrared spectrum of A-type asteroid (4142) Dersu-Uzala, which is a Mars Crosser object and presents similar orbital parameters to those of (1951) Lick. They calculate a band I position of 0.97 ± 0.01 $\mu$m and a BAR of 0.75 ± 0.08. According to Burbine & Binzel (2002) (4142) Dersu-Uzala is in the “weaker” group. Both (1951) Lick and (4142) Dersu-Uzala present a very steep visible wavelength spectrum, although, contrary to (1951) Lick, (4142) Dersu-Uzala presents a clear second absorption band around 2 $\mu$m, typical of pyroxene.

Olivine posseses a strong absorption near 1 $\mu$m, which is composed of four overlapping absorption bands, centered at 0.85, 1.05, 1.25 $\mu$m in the case of the three major absorption features and 0.70 $\mu$m for the fourth and less important one.

In order to further constrain the olivine present in the spectrum of (1951) Lick, we have used the Modified Gaussian Model method, developed by Sunshine et al. (1990). This is an improved approach to spectral deconvolution that accurately represents absorption bands as discrete mathematical distributions and resolves composite absorption features into individual absorption bands superimposed onto a background continuum.

Sunshine & Pieters (1998) analyzed reflectance spectra of olivines spanning the forsterite **Fo** (magnesium rich) to fayalite **Fa** (iron rich) solid-solution series. Their conclusion was that the wavelength position of all three absorption bands shifts toward longer wavelengths with increasing iron content. They calculated a linear calibration between wavelength and Fo molar percentage, and obtained an average band width for the three major absorption bands of 0.245 $\mu$m, 0.178 $\mu$m and 0.466 $\mu$m respectively. Finally, they presented the relative strengths of the three primary 1.0 $\mu$m olivine individual absorption bands, normalized to the strength of the third band (centered in 1.25 $\mu$m). In order to monitor changes in composition the authors present relative, rather than absolute strengths to avoid dependence on viewing geometry and particle size.

We have applied the MGM fit to our spectrum using as initial estimates of band centers those corresponding to a composition of $Fo_{50}$, leaving all the parameters free. Each solution was compared with the calibrations until we found one that fitted simultaneously the constraints obtained for widths and relative strengths, that provided a coherent Fo number and that gave a reasonable residual. Our values for the centers, widths and strengths of these bands are in accordance with the calibrations and are shown in Table 2. The resulting model fit and the residual error (less than 3%) are shown in Fig. 2.

If we put our derived band centers of the three primary 1.0 $\mu$m olivine individual absorptions in the Fo molar percentage calibration line of Sunshine & Pieters (1998), we obtain a forsteritic solution of $Fo_{90\pm10}$, that is to say, an iron poor olivine. Several asteroids classified as A-type that have been analyzed show similar results. Sunshine & Pieters (1998) applied MGM method to (246) Asporina, obtaining a composition of $Fo_{80}$. A year before, Sunshine et al. (1997) obtained a composition of $Fo_{60}$ for (289) Nenetta using MGM fit, while Lucey et al. (1998) obtained a value of $Fo_{95\pm5}$ for the same asteroid and for (446) Aeternitas, (246) Asporina and (863) Benkoela comparing their spectra with spectra of laboratory olivines of different compositions.

**Table 2.** Centers, widths (*FWHM*) and strengths of the three major individual absorption bands obtained from MGM fit to the spectrum of (1951) Lick. The same parameters for (446) Aeternitas from Ueda et al. (2002).

| (1951) Lick | Center [$\mu$m] | *FWHM* [$\mu$m] | Strength [natural log] |
|---|---|---|---|
| Band 1 | 0.835 | 0.240 | −0.322 |
| Band 2 | 1.025 | 0.191 | −0.366 |
| Band 3 | 1.222 | 0.411 | −0.563 |
| (446) Aeternitas | | | |
| Band 1 | 0.834 | | |
| Band 2 | 1.033 | | |
| Band 3 | 1.264 | | |

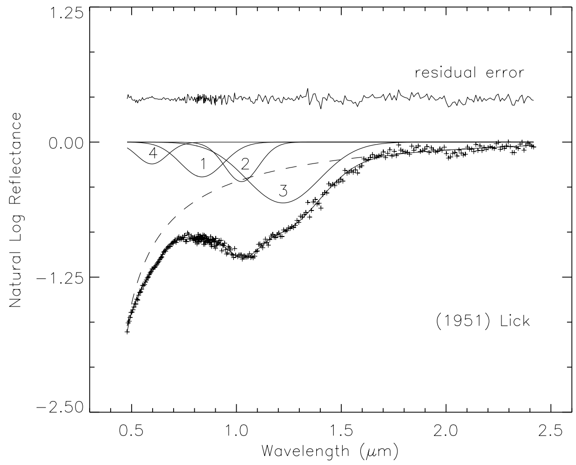


**Fig. 2.** (1951) Lick spectrum (crosses) fitted with four modified Gaussians (solid lines) corresponding to individual absorption bands associated to olivine, superimposed onto a background continuum (dashed line). Residual error spectrum corresponding to the fitted region is shown in the top part of the plot with an appropriate offset for clarity.

## 4. Conclusions

Mineralogical analysis of A-type asteroid (1951) Lick indicates that its surface is composed by almost pure olivine. The composition of olivine on the surface of (1951) Lick is estimated to be about $Fo_{90\pm10}$ (low-iron content). Several uncertainties remain due to diverse effects, such as temperature effects, observational errors (mainly in the atmospheric telluric bands) and reddening of the spectrum due to space weathering effects (Hiroi & Sasaki 2001), but their analysis would require more data.

We would need more observations of A-type asteroids and their mineralogical characterization in order to be able to compare this population with olivine-rich meteorites, in particular with meteorite Brachina, which has an olivine composition of approximately $Fo_{66}$ (Nehru et al. 1983). The few A-type asteroids that have been analyzed, including (1951) Lick, present iron-poor olivine compositions, in contrast to what is found for meteorite Brachina.

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