Icarus 228 (2014) 288–300

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Olivine-dominated asteroids: Mineralogy and origin

Juan A. Sanchez [a,*,1], Vishnu Reddy [b,1], Michael S. Kelley [c,1,2], Edward A. Cloutis [d], William F. Bottke [e], David Nesvorný [e], Michael P. Lucas [f], Paul S. Hardersen [g,1], Michael J. Gaffey [g,1], Paul A. Abell [h,1], Lucille Le Corre [b]

[a] Max Planck Institut für Sonnensystemforschung, Katlenburg-Lindau, Germany
[b] Planetary Science Institute, 1700 East Fort Lowell Road, Tucson, AZ 85719, USA
[c] Department of Geology and Geography, Georgia Southern University, Statesboro, Georgia 30460, USA
[d] Department of Geography, University of Winnipeg, Winnipeg, Manitoba, Canada
[e] Southwest Research Institute and NASA Lunar Science Institute, Boulder, Colorado 80302, USA
[f] Department of Earth and Planetary Sciences, University of Tennessee, Tennessee 37996, USA
[g] Department of Space Studies, University of North Dakota, Grand Forks, North Dakota 58202, USA
[h] NASA Johnson Space Center, Houston, Texas 77058, USA

ARTICLE INFO

Article history:
Received 19 July 2013
Revised 29 September 2013
Accepted 2 October 2013
Available online 18 October 2013

Keywords:
Asteroids
Spectroscopy
Infrared observations
Meteorites

ABSTRACT

Olivine-dominated asteroids are a rare type of objects formed either in nebular processes or through magmatic differentiation. The analysis of meteorite samples suggest that at least 100 parent bodies in the main belt experienced partial or complete melting and differentiation before being disrupted. However, only a few olivine-dominated asteroids, representative of the mantle of disrupted differentiated bodies, are known to exist. Due to the paucity of these objects in the main belt their origin and evolution have been a matter of great debate over the years. In this work we present a detailed mineralogical analysis of twelve olivine-dominated asteroids. We have obtained near-infrared (NIR) spectra (0.7–2.4 μm) of asteroids (246) Asporina, (289) Nenetta, (446) Aeternitas, (863) Benkoela, (4125) Lew Allen and (4490) Bamberry. Observations were conducted with the Infrared Telescope Facility (IRTF) on Mauna Kea, Hawai'i. This sample was complemented with spectra of six other olivine-dominated asteroids including (354) Eleonora, (984) Gretia, (1951) Lick, (2501) Lohja, (3819) Robinson and (5261) Eureka obtained by previous workers. Within our sample we distinguish two classes, one that we call monomineralic-olivine asteroids, which are those whose spectra only exhibit the 1 μm feature, and another referred to as olivine-rich asteroids, whose spectra exhibit the 1 μm feature and a weak (Band II depth ~4%) 2 μm feature. For the monomineralic-olivine asteroids the olivine chemistry was found to range from ~Fo_{49} to Fo_{70}, consistent with the values measured for brachinites and R chondrites. In the case of the olivine-rich asteroids we determined their olivine and low-Ca pyroxene abundance using a new set of spectral calibrations derived from the analysis of R chondrites spectra. We found that the olivine abundance for these asteroids varies from 0.68 to 0.93, while the fraction of low-Ca pyroxene to total pyroxene ranges from 0.6 to 0.9. A search for dynamical connections between the olivine-dominated asteroids and asteroid families found no genetic link (of the type core–mantel–crust) between these objects.

1. Introduction

A-type asteroids are a unique class of objects that were initially distinguished from the R-type asteroids (the group into which they'd previously been classified) based on broadband spectrophotometry by Veeder et al. (1983) and were later re-classified based on Eight Color Asteroid Survey (ECAS) data (0.3–1.1 μm) by Tholen (1984). Asteroids of this taxonomic class have moderately high albedos, extremely reddish slopes shortward of 0.7 μm, and a strong absorption feature centered at ~1.05 μm (Tholen and Barucci, 1989). Subsequent near-infrared (NIR) spectra have shown that in these original A-type asteroids a ~2 μm feature is absent or very weak, consistent with a silicate component of nearly monomineralic olivine on the surface of these bodies.

The discovery of olivine-dominated asteroids is of considerable interest regarding the accretion and geochemical evolution of

* Corresponding author. Address: Max Planck Institut für Sonnensystemforschung, Max Planck Str. 2, 37191 Katlenburg-Lindau, Germany.
E-mail address: sanchez@mps.mpg.de (J.A. Sanchez).
[1] Visiting Astronomer at the Infrared Telescope Facility, which is operated by the University of Hawaii under Cooperative Agreement No. NNX-08AE38A with the National Aeronautics and Space Administration, Science Mission Directorate, Planetary Astronomy Program.
[2] Planetary Science Division, Science Mission Directorate, NASA Headquarters, Washington, DC 20546, USA.

0019-1035/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.icarus.2013.10.006

primitive bodies. Olivine-dominated objects are expected to form either through magmatic differentiation, being the major constituent of the mantles of most differentiated bodies (Burbine et al., 1996), or through nebular processes which can produce olivine-dominated objects like the R-chondrite parent body (Schulze et al., 1994). The presence of olivine-dominated asteroids suggests that at least some objects in the asteroid belt underwent complete or near-complete melting that led to the differentiation of their interiors. Another interesting aspect is that in order for the mantle to be exposed, the parent body must be fragmented or its deep interior exposed by large impacts. Based on meteorites in terrestrial collections, it is estimated that at least ∼100 meteorite parent bodies should have existed in the asteroid belt that underwent partial or complete melting and differentiation before disruption and fragmentation (Keil, 2000). However, even assuming all A-type asteroids are olivine-dominated, only a handful of objects from the mantles of differentiated and disrupted parent bodies were discovered during the taxonomic surveys. This is described as the "missing mantle" problem because the corresponding mantle components of the iron cores (as represented by iron meteorites) are missing (Chapman, 1986; Bell et al., 1989; Burbine et al., 1996). More recent work on M-type asteroids by Hardersen et al. (2011) indicates that a subset of that population (766 Moguntia, 798 Ruth and 1210 Morosovia) shows a significant olivine component in the surface assemblage. It is unclear, at this point, if the olivine seen on these M-type asteroids are pieces of mantle remaining on an iron-rich core or formed via nebular processes.

More recent surveys like the Small Main-Belt Asteroid Spectroscopic Survey (SMASS) (Xu et al., 1995), and SMASS II (Bus and Binzel, 2002a,b) have expanded the number of members within each taxonomic class based on visible spectroscopy. Twelve new A-type asteroids were added to the original five from Tholen (1984). Burbine and Binzel (2002) observed 10 A-type asteroids at near-infrared wavelengths, four from Tholen (1984) and six from Bus and Binzel (2002a,b). They subsequently divided the A-type asteroids into two groups based on the strength of the 1 μm feature. Because the Burbine and Binzel (2002) data do not extend beyond 1.65 μm, the possibility of a 2 μm feature due to pyroxene cannot be ruled out. It is important to note that A-type asteroids under the Bus and Binzel (2002a,b) taxonomic system are not the same as those under the original Tholen system. Some A-types in the SMASS II taxonomic system contain up to ∼20% pyroxene, as indicated by the presence of a 2 μm feature in NIR data, e.g., (4142) Dersu-Uzala (Binzel et al., 2004), and are similar to S-I/S-II asteroids in the Gaffey S-asteroid subtypes (Gaffey et al., 1993).

A comprehensive summary of all previous work on A-type asteroids is published in Sunshine et al. (2007). This study was based on the work of Sunshine and Pieters (1998), and included VIS–NIR spectra of nine olivine-dominated asteroids. Of these nine objects, four were analyzed using the Modified Gaussian Model (MGM) (Sunshine et al., 1990) in order to derive their olivine compositions. Those four objects that included (1951) Lick, (289) Nenetta, (246) Asporina, and (354) Eleonora were characterized by the lack of a detectable 2 μm feature. The other five asteroids; (446) Aeternitas, (863) Benkoela, (984) Gretia, (2501) Lohja, and (3819) Robinson, whose spectra have a detectable 2 μm feature, were not analyzed due to the difficulties inherent to the modeling of olivine–pyroxene mixtures (Sunshine et al., 2007).

In the present work we analyze VIS–NIR spectra of twelve olivine-dominated asteroids, six observed by our group and six obtained from previous studies. Because taxonomic classification can be ambiguous depending on the system used we will refer to these objects as S(I)-types, which is the designation introduced by Gaffey et al. (1993) that includes objects where olivine is the major silicate phase present. We further distinguish two classes within our sample: one class that will be called *monomineralic-olivine* asteroids, which are those whose spectra exhibit the 1 μm feature and no detectable 2 μm feature, and another class that will be called *olivine-rich* asteroids, whose spectra exhibit the 1 μm feature and a weak 2 μm feature.

The approach used in the present study differs from previous work (e.g., Sunshine and Pieters, 1998; Sunshine et al., 2007) in that olivine compositions are determined from the measured Band I centers, along with a spectral calibration derived from laboratory measurements. Furthermore, in the case of the olivine-rich asteroids, the olivine–pyroxene abundance ratio (ol/(ol + px)) and the ratio of low-Ca pyroxene (LCP) to total pyroxene (LCP/(LCP + HCP)) are determined using a set of equations derived from the analysis of meteorite samples. Here we define low-Ca pyroxenes (LCP) as pyroxenes with <25% iron and include pigeonite and orthopyroxene, and high-Ca pyroxenes (HCP) as those with >25% iron, including augite-diopside-hedenbergite.

In addition to the mineralogical analysis we also search for dynamical connections between the studied objects and asteroid families. Using this information we finally discuss possible formation scenarios for the olivine-dominated asteroids.

2. Observations and data reduction

Observations were carried out with the NASA IRTF on Mauna Kea, Hawai'i. NIR spectra (∼0.7–2.5 μm) were obtained with the SpeX instrument (Rayner et al., 2003) in its low resolution ($R \sim 150$) prism mode with a 0.8" slit width. A typical observing sequence consists of spectra taken in pairs (A-beam and B-beam) by nodding the telescope. Nodding enables the subtraction of the sky background from the object during the data reduction process. Depending on the magnitude of the asteroid, 10–20 spectra are taken per asteroid with a maximum integration of 120 s due to saturation from the background sky. In order to correct for telluric water vapor features and to obtain relative reflectance values, local standard and solar analog stars were also observed. For each night, flat fields and arc line spectra were acquired. Data reduction was carried out with Spextool (Cushing et al., 2004). Detailed descriptions of observation and data reduction protocols are presented in Reddy (2009) and Reddy et al. (2011a, 2012a). NIR spectra are normalized to unity at 1.5 μm. Table 1 lists observational circumstances for the observed asteroids.

In order to extend our study we also analyzed data from Sunshine et al. (2007), de León et al. (2010), and the MIT-UH-IRTF Joint Campaign for NEO Spectral Reconnaissance (NEOSR). NIR spectra were combined with VIS spectra in order to increase the wavelength coverage. VIS spectra were obtained from the SMASS II (Bus and Binzel, 2002a,b), and the Small Solar System Objects Spectroscopic Survey (S^3OS^2) (Lazzaro et al., 2004). VIS–NIR spectra of the studied asteroids are shown in Figs. 1 and 2.

3. Results

3.1. Monomineralic-olivine asteroids

Asteroids in our sample that fall into the class of *monomineralic-olivines* are: (246) Asporina, (289) Nenetta, (354) Eleonora, (1951) Lick, (4125) Lew Allen, (4490) Bambery, and (5261) Eureka. The spectra of these asteroids lack detectable 2 μm feature (Band II depth <1%), and the combined VIS–NIR spectra typically overlap at ∼0.7 μm. For each spectrum the Band I center and Band I depth are calculated after dividing out the linear continuum (a straight line tangent to the reflectance maxima) and fitting a polynomial over the bottom third of the band. A detailed explanation about the procedure used to measure the band parameters and their uncertainties