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Note

Quantified mineralogical evidence for a common origin of 1929 Kollaa with 4 Vesta and the HED meteorites

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Abstract

In this paper, we present the first correlation of derived mineral abundances of V-class Asteroid 1929 Kollaa, 4 Vesta, and the HED meteorites. We demonstrate that 1929 Kollaa has a basaltic composition consistent with an origin within the crustal layer of 4 Vesta, and show a plausible genetic connection between Kollaa and the cumulate eucrite meteorites. These data support the proposed delivery mechanism of HED meteorites to the Earth from Vesta, and provide the first mineralogical constraint derived from the observation of a small V-class, Vesta family asteroid on the crustal thickness of 4 Vesta.

Keywords: Asteroids; Vesta; Surfaces, asteroids; Asteroids, composition; Spectroscopy

Since 1970, it has been recognized that asteroid 4 Vesta has spectral properties that closely resemble those of the basaltic achondrite (howardite, eucrite and diogenite, or "HED") meteorites (McCord et al., 1970). This led to the first suggestions that Vesta could be the parent body of this group of achondrites (Consolmagno and Drake, 1977; Feierberg and Drake, 1980; Gaffey, 1983). However, Vesta's orbit is unfavorably situated to deliver ejecta directly into Earth-crossing orbits (Wasson and Wetherill, 1979; Wetherill and Chapman, 1988). In 1993, new visible-region spectra of members of the Vesta dynamical family (Zappalà et al., 1990; Williams, 1992) with orbits bridging the gap between Vesta, the 3:1 resonance at 2.5 AU, and the ν_6 resonance, showed that these small asteroids also belonged to the taxonomic V class (Tholen, 1984; Binzel and Xu, 1993). If these small V-class objects were derived from 4 Vesta, the proximity of some of them to these resonances would allow relatively efficient delivery of Vesta fragments from the main asteroid belt to the inner solar system.

Hubble Space Telescope images obtained in 1996 revealed a giant impact basin 460 km in diameter and 13-km deep in the south polar region of Vesta (Thomas et al., 1997). Approximately 1% of Vesta's volume was excavated by this event—an amount sufficient to account for many more V-class asteroids than we now know reside between Vesta and the resonances. By the late 1990's, the existence of a mechanism for ejecting large fragments from Vesta was established and a pathway for getting them to a dynamical source region for meteorites had been found (Asphaug, 1997). What was still lacking was solid mineralogical evidence connecting any other V-class asteroid to either Vesta or the HED meteorites. This was due to the absence of spectra for small V-class asteroids with sufficient, appropriate wavelength coverage to quantify the mineralogy of the pyroxenes identified by the presence of the deep 1- and 2-μm mafic silicate absorption features in the visible/near IR spectra.

Mainbelt asteroid 1929 Kollaa is ∼ 14 km in diameter and has been listed as a member of the Vesta dynamical asteroid family. We observed Kollaa as part of the Family Asteroid Compositional Evaluation Survey (FACES); a project that seeks to identify genetic asteroid families within the variety

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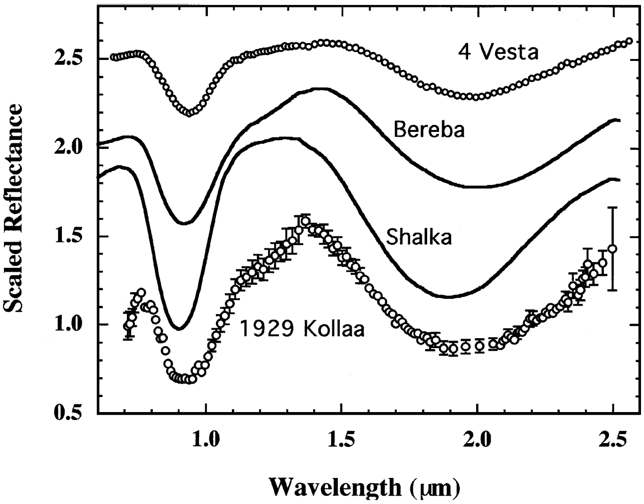

Fig. 1. The new spectrum of 1929 Kollaa compared with typical examples of a eucrite (Bereba), a diogenite (Shalka), and the average 4 Vesta surface (Gaffey, 1976, 1997) over the same wavelength region.

Table 1
Comparison of parameters derived from the analyses of visible to near-IR spectra for 1929 Kollaa and the average 4 Vesta surface

Spectral parameter	1929 Kollaa	4 Vesta[a]
Band I center wavelength (μm)	0.937 ± 0.002	0.936 ± 0.001
Band II center wavelength (μm)	1.914 ± 0.003	1.969 ± 0.005
Band II/Band I Area Ratio	2.29 ± 0.02	2.74 ± 0.09
Plag. Band II/Band I Area Ratio	0.086 ± 0.002	~ 0.10

[a] Results are taken from Gaffey (1997).

of previously published dynamical families. Near-infrared reflectance spectra of Kollaa were obtained on March 24, 2001, with the NASA Infrared Telescope at Mauna Kea Observatory, covering the spectral interval of 0.71 to 2.5 μm using the SpeX medium-resolution spectrograph. The asteroid was observed under sub-arcsecond seeing conditions at an airmass of 1.02–1.03, $V = 14.9$, and a phase angle of 6.9°. We used data reduction and analysis procedures described in detail by previous asteroid compositional studies (e.g., Gaffey, 1984, 1997; Gaffey et al., 1989, 1993; Cloutis et al., 1986) to produce relative reflectance spectra.

The new near-infrared reflectance spectrum of 1929 Kollaa is shown in Fig. 1. The spectrum exhibits broad absorption features near 1- and 2-μm (Band I and Band II, respectively) that are typical of rocks dominated by mafic silicates. Parameters derived from the analyses of these features allow us to unravel the compositional nature of Kollaa and compare it to previously analyzed spectra of HED meteorite samples and Vesta. The centers (continuum-removed wavelength positions) of the 1- and 2-μm absorption bands provide information about the Ca^{2+} (Wo) and Fe^{2+} (Fs) content, respectively, of the pyroxene (Cloutis and Gaffey, 1991). A continuum-removed Band II/Band I area ratio provides a measure of the olivine-to-pyroxene abundance ratio (Gaffey et al., 1993). The long-wavelength limb of Band I exhibits an inflection between 1.2 and 1.4 μm indicating the presence of plagioclase feldspar. A ratio of the area under this shallow plagioclase feature to that of Band I provides a measure of the plagioclase-to-pyroxene abundance ratio (Gaffey et al., 1989). Table 1 compares our new values derived for 1929 Kollaa with those previously determined for 4 Vesta (Gaffey, 1997).

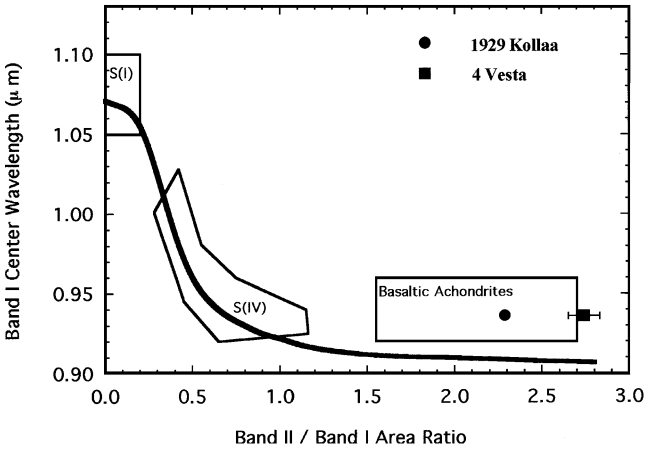

Fig. 2. In a plot of asteroid and meteorite compositional space (Gaffey et al., 1993), 1929 Kollaa is situated well within the basaltic achondrite (including HED meteorites) field. The value for the average surface composition of 4 Vesta (Gaffey, 1997) is shown for comparison. Standard error of the mean is plotted for both asteroids, but is generally smaller than the symbols used for the data points. It should be noted that the right (high BAR) boundary of the basaltic achondrite field was defined based on a limited dataset. More recent work indicates that the basaltic achondrite field should be extended further to the right.

The Small Mainbelt Asteroid Spectroscopic Survey (SMASS) data (Xu et al., 1995; Bus, 1999; Burbine, 2000) provided valuable taxonomic information on Vesta family members, and indicated which of them might provide likely spectral matches to Vesta and the HED meteorites. However, the visible/near-IR spectra (SMASS I and II) and the near-infrared array spectra (SMASSIR) do not have sufficient spectral coverage to allow quantitative determination of the Band II center and the Band II/Band I area ratio. Without quantified mineralogy for the objects in question, probable genetic relationships cannot be established. Both the SMASS I and II spectra have a broader peak near 0.75 μm than the new FACES spectrum. These two SMASS spectra of 1929 Kollaa differ from each other in the 0.4- to 1-μm region. Additionally, when combined with the SMASSIR data, there are differences in the Band I intensities, areas, and continuum slopes. A number of factors (such as phase angle, metal content, or surface compositional heterogeneities) can change the continuum slope and band intensity in this spectral region. For example, the difference in Band I depth between the January and February 1981 spectra of Vesta (Gaffey, 1997) is due to a 13° difference in Vesta's phase angle. Since the continuum-removed band center is critical in determining the Ca^{2+} content of the pyroxene, the continuum differences in this region can affect the derived Band I center and hence the calcium content determination.

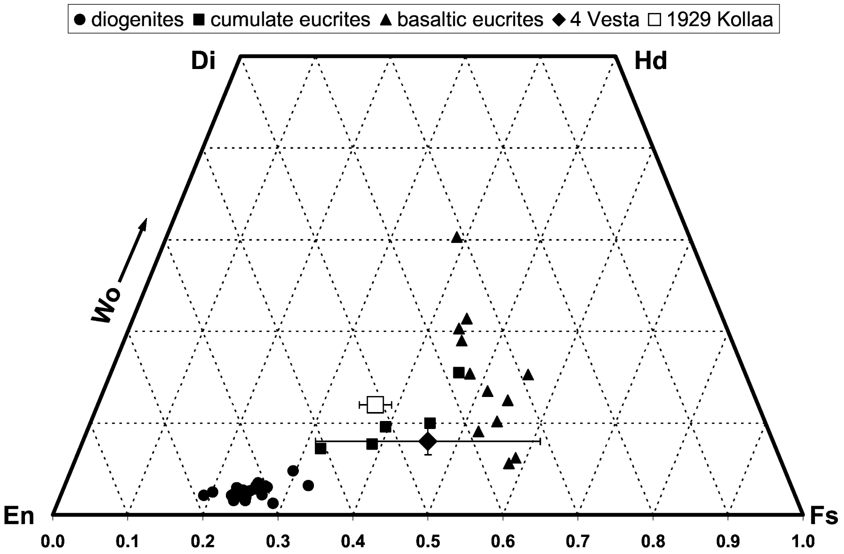

Fig. 3. Pyroxene quadrilateral for HED meteorite pyroxenes (Mittlefehldt et al., 1998). The pyroxene composition for 1929 Kollaa falls toward the diogenitic end of the cumulate eucrite range. The average pyroxene composition on the surface of 4 Vesta resembles more closely that of the basaltic eucrites. The error bars for 1929 Kollaa represent the ∼ 5% systematic uncertainty in the compositional determination, although the Wo-content error bar is smaller than the symbol used for the data point. In the case of 4 Vesta, the error bars represent the maximum compositional range for the asteroid.

A difference in Band I area could very well affect the determination of the olivine-to-pyroxene abundance ratio.

In terms of spectral appearance (absorption band shapes, wavelength positions, and widths), the new FACES data for 1929 Kollaa compare favorably to those of typical eucrites (Fig. 1). As is the case with 4 Vesta, the 1-μm band of 1929 Kollaa is quite symmetrical around the band center except on the long wavelength limb near 1.3 μm, where the spectrum falls below a rounded peak expected for a pure pyroxene assemblage. The overall symmetry and lack of a spectrally significant olivine signature indicate that olivine is at most only a minor component of the observed face of Kollaa. The pyroxene chemistry of Kollaa ($Fs_{37}Wo_{12}$—derived from the absorption band positions and the interpretive calibrations of Gaffey et al., 2002) is similar to that of average Vesta ($Fs_{46}Wo_8$) derived from previous studies (Gaffey et al., 1993; Gaffey, 1997), and falls well within the range of basaltic achondrite meteorites (Fig. 2). There is a systematic uncertainty of approximately ±5% in these compositional determinations due to the limitations in the calibrations between band positions and mineral chemistry. However, the uncertainty in the relative differences between the mineral compositions for the two objects is substantially smaller than the differences themselves. Within the HED meteorite population (Mittlefehldt et al., 1998), the best mineralogical match to 1929 Kollaa is found among the cumulate eucrites (Fig. 3).

We have demonstrated that the mineral abundances of 1929 Kollaa match those of 4 Vesta and the HED meteorites. Furthermore, we have shown that the pyroxene chemistry for Kollaa is consistent with its derivation deep in the eucritic layer of Vesta, which is where the cumulate eucrites would reside. Kollaa's ∼ 14-km diameter provides a useful constraint on the minimum thickness of the eucritic layer on Vesta. Compared with the present spectrum, the SMASS II spectrum (Burbine et al., 2001) for Kollaa shows a less pronounced feldspar feature between ∼ 1.1 and 1.3 μm, although observational limitations in those data preclude a robust conclusion regarding the implication of this difference.

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