**HOW MANY VESTA-LIKE BODIES EXISTED IN THE ASTEROID BELT?** T. H. Burbine[1,2], R. C. Greenwood[3], B. Zhang[4], and P. C. Buchanan[5], [1]Department of Astronomy, Mount Holyoke College, 50 College Street, South Hadley, MA 01075, USA (tburbine@mtholyoke.edu), [2]Planetary Science Institute, 1700 East Fort Lowell, Suite 106, Tucson, AZ 85719, USA, [3]The Open University, Walton Hall, Milton Keynes MK7 6AA, UK, [4] Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, Los Angeles, CA 90095-1567, USA, [5]Department of Geology, Kilgore College, Kilgore, TX 75662, USA.

**Introduction:** Asteroid (4) Vesta has long been known to have a distinctive reflectance spectrum that closely matches the spectra of the pyroxene-rich HED (howardite, eucrite, and diogenite) meteorites. Spectral and geochemical analyses by the Dawn spacecraft [1] were also consistent with an HED surface for Vesta. Many smaller bodies have also been found to have HED-like spectra, and as a consequence are known as V-types. Objects that can potentially be linked to Vesta are called Vestoids. V-types can be identified through visible and/or near-infrared spectral observations. V-types have very distinctive absorption features due to pyroxene, with strong absorption bands centered at ~0.9 and ~1.9 µm. However, near-infrared spectra are much more conclusive since both pyroxene bands can be characterized. Other types of meteoritical "crustal" material (e.g., angrites, aubrites) have very different spectral properties in the visible and near-infrared than HEDs.

Lazzaro et al. [2] identified a body, (1459) Magnya, with an HED-like spectrum in the near-infrared that is located far from Vesta in the outer part of the asteroid belt. Subsequently, a meteorite originally classified as a eucrite, Northwest Africa (NWA) 011, was found to have an oxygen isotopic composition that was very different to that of "typical" HEDs [3]. Both discoveries imply the existence of multiple Vesta-like bodies.

This work will discuss the current evidence for other Vesta-like bodies besides Vesta in the asteroid belt. We first discuss what we define as a Vesta-like body. We then look at the astronomical evidence for V-types not related to Vesta, isotopic studies of "anomalous" HEDs, and implications from iron meteorites. Our goal is to estimate how many distinct Vesta-like bodies existed in the asteroid belt.

**Vesta-Like Bodies:** We define a Vesta-like body as a differentiated asteroid-sized object with a crust composed predominantly of Ca-poor pyroxene and plagioclase. Eucrites are primarily composed of pyroxene and anorthite-rich plagioclase, while diogenites are primarily magnesian-rich, orthopyroxenites [4]. Howardites are polymict breccias that contain both eucritic and diogenitic fragments.

From a geochemical standpoint, eucrites can be subdivided into cumulate and non-cumulate groups. Non-cumulate eucrites are further subdivided into two types: (i) main-group Nuevo Laredo trend and (ii) Stannern trend [5]. Eucrites show varying degrees of brecciation, from unbrecciated to highly brecciated. Amongst those showing evidence of brecciation, variable amounts of intermixing of different lithologies has produced both monomict and polymict varieties of HEDs. Vesta appears to have had a complex geologic history as a result of both melting and impacts.

Jurewicz et al. [6,7] found that partial melts of carbonaceous chondritic material could resemble eucrites at low oxygen fugacities and angrites at high oxygen fugacities. Differentiation of these early Solar System bodies was most likely caused by the decay of $^{26}$Al, which would have produced a significant amount of heat and whose decay products have been identified by the isotopic analysis of plagioclase in some eucrites (e.g., Piplia Kalan) [8].

**Astronomical Evidence:** V-types are identified through spectral or color surveys in the visible. Near-infrared spectral surveys have been used to "confirm" the HED-like nature of these objects. **Figure 1** plots the distribution of V-types in the asteroid belt.

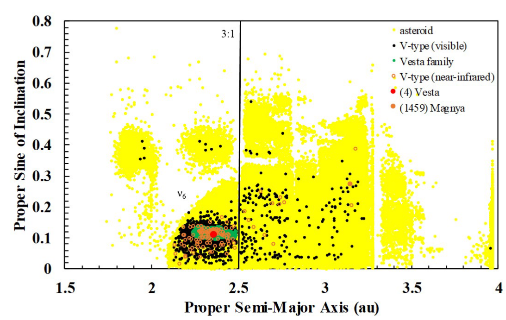


**Figure 1.** Proper sine of inclination versus proper semi-major axis (au) for bodies in the main belt. Asteroids are plotted with yellow dots. V-types that have been identified by visible surveys but not observed in the near-infrared are plotted with black dots. Vesta-family members are plotted with green dots. Vesta is plotted with a red circle. V-types that have near-infrared spectra consistent with an HED-like mineralogy are identified with orange open circles except for Magnya at 3.15 au, which is plotted with a filled orange circle. We do not plot bodies with visible or near-infrared spectra that are not consistent with "typical" V-types. The locations of the 3:1 and $\nu_6$ resonances are also shown.

As can be seen in **Figure 1**, the inner main belt is full of V-type bodies and the distribution is centered around Vesta. Fragments of Vesta also appear to be "spilling" across the 3:1 resonance. Most V-types identified in the middle and outer belt have not been confirmed by near-infrared observations. There appears to be evidence for at least one Vesta-like body in the middle and for one in the outer belt near Magnya. Including Vesta, our cautious estimate of the Vesta-like bodies from astronomical observations is 3. However, we can not rule out the existence of many more Vesta-like bodies in the asteroid belt.

**Isotopic Evidence:** Several pieces of evidence suggest that more than one early Solar System body experienced Vesta-like melting and differentiation. Specifically, oxygen isotopic analyses indicate that more than one other Vesta-like body existed. For example, Yamaguchi et al. [3] described NWA 011 as a eucrite-like meteorite in terms of texture and mineralogy. But NWA 011 has a distinctly different oxygen isotopic composition than typical HEDs and chromium (Cr) and titanium (Ti) isotopic compositions that are similar to the carbonaceous chondrites (CC) [9]. Consequently, NWA 011 is believed to have formed in the outer Solar System.

The HEDs are generally characterized by a relatively uniform O-isotope composition, consistent with being derived from a parent body that underwent extensive melting and consequent isotopic homogenization. Thus, samples that have O-isotope compositions that deviate significantly from the "normal" HED range may be derived from parent bodies other than Vesta [10,11]. It has been estimated that basaltic meteorites with a non-HED O-isotope composition may be derived from between 5 and 11 asteroid sources [12]. If we average this range, we get 8 non-HED parent bodies. Including Vesta, the number of Vesta-like bodies implied from the oxygen isotopic evidence is 9.

**Iron Meteorite Evidence:** Iron meteorites, primarily consisting of Fe-Ni phases, are the remnants of metallic solids formed in the early Solar System. Based on their crystallization processes, iron meteorites can be classified as magmatic and non-magmatic types. Magmatic irons originate from the metallic cores of differentiated asteroids. These asteroids experienced core-mantle differentiation, and trace siderophile elements in the iron meteorites from a single core show fractional crystallization trends. Non-magmatic irons may originate from metallic melt pools on asteroids, and these irons likely formed by crystal segregation.

Magmatic iron-meteorite parent bodies, although overlaid by a silicate lid, do not usually contain silicates. In most cases, the silicate portion of magmatic iron-meteorite parent bodies would have been differentiated and did not mix with the cores to any significant extent. If these iron-meteorite parent bodies had survived to this day, their silicate part might have a similar lithology to that of Vesta. In contrast, although non-magmatic irons can have abundant rock-forming silicates they would have formed rapidly in the metallic melt pools and so did not experience mantle-core differentiation.

Eleven magmatic groups plus a trio (so-called South Byron trio) have been found in our collections. Since two groups (IIAB and IIG) are believed to originate from different layers of a single core [13], the magmatic groups/trio evidence argues for 11 different Vesta-like parent bodies. There are also over 140 recorded ungrouped irons that cannot fit into the current groups [14]. Wasson [15] concluded that at least 16 parent bodies of the ungrouped irons could be magmatic. Including Vesta, the number of Vesta-like bodies implied from the iron meteorite evidence is 28. However, the identification of andesitic meteorites such as Erg Chech (EC) 002 [16] may imply that not all known magmatic irons had Vesta-like crusts.

**Conclusions:** If we average our three preliminary estimates, the number of Vesta-like bodies that existed in the main belt is 13. Our astronomical guess probably underestimates the number of Vesta-like bodies while the guess from studying iron meteorites probably overestimates the number. Further work needs to be done to better estimate the number of Vesta-like bodies.

**Acknowledgments:** This abstract is dedicated to the memory of Edward R. D. Scott (1947-2021) who was a pioneer in the study of iron meteorites. THB would like to thank the Remote, In Situ, and Synchrotron Studies for Science and Exploration 2 (RISE2) Solar System Exploration Research Virtual Institute (SSERVI) for support.

**References:** [1] McSween H.Y. et al. (2014) *MAPS*, 48, 2090-2104. [2] Lazzaro D. et al. (2000) *Science*, 288, 2033-2035. [3] Yamaguchi, A. et al. (2000) *Science*, 296, 334-336. [4] Mittlefehldt D. W. et al. (1998) In *Reviews in Mineralogy: Planetary Materials*, pp. 4-1–4-195. [5] Barrat J. A. et al. (2007) *GCA*, 71, 4108-4124. [6] Jurewicz A. J. G. et al. (1991) *Science*, 252, 695-698. [7] Jurewicz A. J. G. et al. (1993) *GCA,* 57, 2123-2139. [8] Srinivasan G. et al. (1999) *Science*, 284, 1348-1350. [9] Warren P. H. (2011) *EPSL*, 311, 93-100. [10] Scott E. R. D. et al. (2009) *GCA,* 73, 5835-5853. [11] Mittlefehldt D. W. et al. (2022) *MAPS,* 57, 484-526. [12] Greenwood R. C. et al. (2020) *GCA*, 277, 377-406. [13] Wasson J. T. and Choe W.-H. (2009) *GCA*, 73, 4879-4890. [14] Meteoritical Bulletin Database (2023) https://www.lpi.usra.edu/meteor/. [15] Wasson J. T. (2013) *EPSL*, 381, 138-146. [16] Nicklas R. W. et al. (2022) *Nature Geoscience*, 15, 696-699.