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► To cite this version:

P. Vernazza, R. Brunetto, R.P. Binzel, C. Perron, D. Fulvio, et al.. Plausible parent bodies for enstatite chondrites and mesosiderites: Implications for Lutetia's fly-by. *Icarus*, 2009, 202 (2), pp.477. 10.1016/j.icarus.2009.03.016 . hal-00554489

HAL Id: hal-00554489

<https://hal.science/hal-00554489>

Submitted on 11 Jan 2011

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Accepted Manuscript

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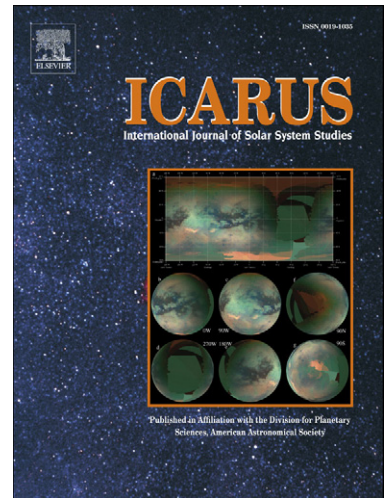
PII: S0019-1035(09)00125-0
DOI: [10.1016/j.icarus.2009.03.016](https://doi.org/10.1016/j.icarus.2009.03.016)
Reference: YICAR 8969

To appear in: *Icarus*

Received date: 6 November 2008
Revised date: 11 March 2009
Accepted date: 13 March 2009

Please cite this article as: P. Vernazza, R. Brunetto, R.P. Binzel, C. Perron, D. Fulvio, G. Strazzulla, M. Fulchignoni, Plausible parent bodies for enstatite chondrites and mesosiderites: Implications for Lutetia's fly-by, *Icarus* (2009), doi: 10.1016/j.icarus.2009.03.016

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Plausible parent bodies for enstatite chondrites and mesosiderites:**Implications for Lutetia's fly-by**

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Abstract

We present new irradiation experiments performed on the enstatite chondrite Eagle (EL6) and the mesosiderite Vaca Muerta. These experiments were performed with the aims of (a) quantifying the spectral effect of the solar wind on their parent asteroid surfaces and (b) identifying their parent bodies within the asteroid belt. For Vaca Muerta we observe a reddening and darkening of the reflectance spectrum with progressive irradiation, consistent with what is observed in the cases of silicates and silicate-rich meteorites such as OCs and HEDs. For Eagle we observe little spectral variation, and therefore we do not expect to observe a significant spectral difference between EC meteorites and their parent bodies. We evaluated possible parent bodies for both meteorites by comparing their VNIR spectra (before and after irradiation) with those of ~400 main-belt asteroids. We found that 21 Lutetia (Rosetta's forthcoming fly-by target) and 97 Klotho (both Xc types in the new Bus-DeMeo taxonomy) have physical properties compatible with those of enstatite chondrite meteorites while 201 Penelope, 250 Bettina and 337 Devosa (all three are Xk types in the Bus-DeMeo taxonomy) are compatible with the properties of mesosiderites.

Keywords: Asteroid Surfaces, Spectroscopy, Experimental Techniques, Radiation Chemistry, Meteorites

Introduction

Meteorites are time capsules from the beginning of the Solar System. The value of their record of the earliest epoch of planetary formation is, with a few exceptions (e.g., Bogard & Johnson 1983; McSween (1994), Consolmagno & Drake 1977), compromised by the lack of precision with which we can pinpoint the location of their parent bodies (Burbine 2002). Determining the linkages between meteorites and their parent bodies is therefore a critical goal of planetary studies. The identification of meteorite parent bodies is a subject strongly affected by processes generically called space weathering. These processes modify the remotely sensed properties of the surfaces of airless Solar System bodies and can impede our ability to remotely assess the mineralogy and other attributes of the surfaces of asteroids and other airless bodies. Such changes involve accretion or erosion of particular materials or modification of surface materials by energetic impacts with micrometeorites or irradiation by cosmic and solar wind ions (Chapman 2004). The spectral effects due to the continuous bombardment by solar wind ions and interplanetary dust have been studied via laboratory experiments in order to explain the observed spectral mismatch between (1) lunar soils and underlying rocks and (2) the most populous class of meteorites (ordinary chondrites, OCs) and the surface spectra of their presumed (S-type) asteroidal parent bodies (Cassidy and Hapke, 1975; Chapman 1996, Pieters et al., 2000; Hapke 2001, Sasaki et al. 2001, Strazzulla et al., 2005; Marchi et al., 2005, Brunetto et al. 2006a, Loeffler et al. 2008; see Clark et al. 2002 and Chapman 2004 for reviews on space weathering processes). These experiments demonstrate that space weathering processes can be the cause of the observed spectral mismatch. The importance of space weathering in affecting asteroid surfaces is now widely accepted and in-situ measurements from the NEAR and Hayabusa spacecrafts have provided clear evidence for its existence (Clark et al. 2001; Hiroi et al. 2006).

Because of the significance of the S-type/OC conundrum, most discussions of asteroid space weathering have been in that context. However, the processes of impact and irradiation that affect S-types are ubiquitous and necessarily occur on asteroids of all types (Chapman, 2004). Some space weathering experiments have been performed on carbonaceous materials (Moroz et al., 1996, Shingareva et al., 2003 and 2004, Lazzarin et al., 2006), and on eucrite meteorites (Vernazza et al., 2006) thought to originate from Vesta.

All in all, space weathering experiments remain rare. Therefore as a first approach, researchers usually compare unweathered meteoritic data with asteroidal data. In the case of a good match, a plausible link can be proposed between the given meteorite and the asteroid. A robust understanding of the full range of plausible weathering outcomes and meteorite associations requires that space weathering experiments should be performed on all kinds of meteorites.

Thus, in this paper we present new experiments on two other meteorite types: (1) an enstatite chondrite (Eagle-EL6) and (2) a mesosiderite (Vaca Muerta). The main goal of this study is to help illuminate the parent bodies of these two meteorite types. To do so, it is necessary to understand the spectral difference we might expect between the parent asteroids and their meteoritic analogues.

The irradiation experiment of the enstatite chondrite was performed with the specific purpose of a) testing whether a plausible analog could be found for Lutetia's surface composition and b) finding other plausible parent bodies for this meteorite class. Well before we decided to perform this irradiation experiment, we had found that enstatite chondrite meteorites provide a good match to Lutetia's physical properties (good match in terms of the VNIR spectrum and albedo), but the space weathering characteristics of enstatite chondrites were unknown. Nedelcu et al. (2007a) also considered an enstatite chondrite association as one of several possibilities for Lutetia. Further consideration of an enstatite chondrite association, however, requires an understanding of the effects of space weathering on this class of planetary material. Hence our motivation to test the solar wind effect on an enstatite

chondrite sample to further support or refute a possible analog for Lutetia. In contrast, the experiment on the mesosiderite meteorite was performed with the unique goal of learning more about the parent bodies of these meteorites.

We first describe the experimental setup, then devote a section to each meteorite where we first introduce the intrinsic properties of the given meteorite followed by results and discussion subsections.

Experimental setup and procedures

We report results of new ion irradiation experiments performed at INAF - Laboratory of Experimental Astrophysics (Catania, Italy), similar to those described in more detail by Brunetto & Strazzulla (2005). The experimental setup consisted of a stainless steel vacuum chamber ($P < 10^{-7}$ mbar) interfaced to an ion implanter (Danfysik 1080-200) from which ions with energy from 30 keV up to 200 keV (400 keV for double ionization) can be obtained; the ion beam produces a uniform spot (about 1.5 cm in diameter) on the target, and the irradiated area is larger than the spot of the UV-Vis-NIR beam. The ion current is continuously monitored and kept below $1 \mu\text{A}/\text{cm}^2$ to avoid macroscopic heating of the sample. At the center of the chamber, samples are mounted vertically, in contact with a cold finger. The experiments were performed at room temperature.

We collected directional-hemispherical reflectance spectra (spectral range 0.3-2.5 μm , resolution 2 nm) of unirradiated and irradiated samples at INAF - Laboratory of Experimental Astrophysics (Catania, Italy), outside the vacuum chamber, using an UV-Vis-NIR spectrometer (Perkin Elmer - Lambda 19), equipped with an integrating sphere in BaSO_4 . Meteorite spectra were ratioed to a blank spectrum of a standard BaSO_4 substrate. The error in the reflectance spectra was of about 5%. When comparing with RELAB spectra, one should consider that RELAB spectra are collected using a

bi-directional geometry. The resulting spectra may differ, but not dramatically. For instance, in the case of particulate media consisting of very irregular particles, Shkuratov and Grynko (2005) provided a way to estimate reflectance at 30° , $R(30^\circ)$, using the integral (hemispherical) albedo (A_{int}) and vice versa, through the equation: $\log R(30^\circ) = 1.088 \log A_{int}$. The proportion of this correction is much smaller than the spectral variations induced by space weathering (see e.g. discussion in Brunetto et al., 2007).

We performed the experiments on the enstatite chondrite Eagle (EL6) and on the mesosiderite Vaca Muerta. Eagle was provided by Museo Nazionale dell'Antartide (Siena, Italy); Vaca Muerta was provided by Muséum national d'Histoire naturelle (Paris, France), in the form of a slab. For Vaca Muerta, irradiation was performed on both sides of the sample: we irradiated one side as cut at the Muséum national d'Histoire naturelle, and the other side after scraping the surface with a diamond point. This was done to increase the surface roughness, and to check if spectral modifications upon irradiation depend on the roughness of the target. Eagle was available in the form of 10-200 μm grain-sized dust, simulating asteroidal regolith, and pellets were obtained by pressing the meteorite powder (~ 8 tons for 10 min) to put them vertically in the vacuum chamber.

Irradiations were performed using 200 keV Ar^+ ions, with a fluence up to 10^{17} ions/ cm^2 . There are a number of energetic ion populations bombarding the surfaces of asteroids: solar wind ions, ions from solar flares, galactic cosmic rays, and the so called "anomalous" cosmic ray component (the two last components are relevant only for Trans-Neptunian objects). The solar wind particles are by far the most abundant and they can heavily modify the optical properties of the surface, although they affect only a thin surface layer (< 200 nm) that can be easily destroyed by impact resurfacing (even collisions with mm-sized impactors can efficiently remove it or remix it with more pristine materials). Radiation-induced damage of deeper layers is induced by more energetic ions, such as the solar cosmic rays produced during solar flares.

Ar is a minor component of these ion populations, so one should scale the effects observed at the given Ar fluence to all the other ions (H, He, C, O, N, etc.), and similarly for the energy. Thus, our simulation should not be regarded as a direct reproduction of the large variety of ion masses and energies affecting asteroids (low energy solar wind ions, high energy particles from solar flares and co-rotating events, cosmic ions). However, in previous studies it has been shown (Brunetto & Strazzulla, 2005; Brunetto et al., 2006b) that such fluence range corresponds to realistic irradiation timescales in the near-Earth region and in the main belt. Comparing laboratory spectra of irradiated samples with observations of silicate-rich asteroids, and scaling the fluences and doses used in the laboratory to the fluxes of the solar wind ions, the timescales for the space weathering of S-type asteroids was estimated to be in the order of 10^4 - 10^6 years. Thus, energies and fluxes used here are similar to those used in previous works by the Catania laboratory, and these would most probably turn a lunar meteorite into a lunar soil.

Other laboratory experimentalists have simulated the SW ion-induced effects on asteroid material analogues: spectral darkening and reddening were observed after ion irradiation of silicate samples with H^+ and He^+ ions at keV energies (Hapke, 1973). A principal factor in producing these spectral changes is thought to be the sputtering of iron from iron-bearing silicates due to ion irradiation and the deposition of nanophase neutral Fe on adjacent grains (Hapke, 2001). On the contrary, high energy (MeV) proton implantation produced only small changes in the spectra (Yamada et al., 1999).

In our case, the use of Ar^+ ions at this specific energy induces different physical processes expected to take place on Small Solar System Bodies (SSSB): the penetration depth of the beam in the target is shorter than 200 nm (estimated running a SRIM simulation; <http://www.SRIM.org/>; Ziegler et al., 1985), and the ions remain implanted; the energy is lost in the target preferentially by ionization processes (about 60%), but elastic collisions play an important role, producing more than 2000

vacancies per impinging ion; the sputtering yield is also high, producing on average more than 5 sputtered atoms per impinging ion.

In the case of E chondrite Eagle, Raman spectra were obtained (before and after irradiation) using the system described by Brunetto et al. (2004). Raman spectroscopy is a technique complementary to VIS-IR spectroscopy. It gives valuable information on the structure of materials (amorphous vs. crystalline), especially carbons, and it can be used to detect minerals and partially estimate their elemental composition. The Raman spectrometer is equipped with a continuous Ar ion laser beam (514.5 nm) which acts as an exciting radiation. The laser is focused on a 50 μm wide spot, with laser power on the sample ranging from 5 to 15 mW ($\sim 5 \text{ W/mm}^2$) to avoid modification of the target due to laser-induced heating effects.

Results

1) Enstatite chondrite

The enstatite chondrites (E chondrites) are a unique class of meteorites ($\sim 2\%$ of the recovered falls) that consist of highly reduced phase assemblages. Similar to the ordinary chondrites, they have been further subdivided into 2 groups (EL and EH) based on their mineralogy and bulk chemistry; members of the EL group contain less iron than members of the EH group. Most of the E chondrite iron is in the form of metal or sulfide rather than taken up as oxides in silicates; this implies that E chondrites formed in a region of the solar nebula with a very low oxygen fugacity. The E chondrites generally have FeO-free enstatite (56-66%¹), plagioclase (albite-anorthite; 6-12%), forsterite (2-7%, only in type 3), Si-bearing metal (4-13%), and contain a variety of sulfides (7-16%), mostly troilite

¹ the mineral abundances are given in volume % and are from Weisberg et al. (1995); we indicate the compositional range rather than the average abundance for observed EH3 and EL3

(FeS), with smaller amounts of niningerite [(Mg,Fe)S, in EHs] or alabandite [(Mn,Fe)S, in ELs], oldhamite (CaS), daubréelite (FeCr₂S₄), and other minor minerals. As for the origin of EH and EL chondrites on one single or two separate parent bodies, arguments exist in favor of both hypotheses (Keil, 1989; Kong et al., 1997), and the question is not settled yet. It has even been proposed that E3 chondrites come from one parent body, and E4-6 from another one (Patzner and Schultz, 2002), and that, taking into account the enstatite achondrites (aubrites) and some unique meteorites, we possess samples from 5 enstatite meteorite parent bodies (Keil and Bischoff, 2008).

From the reduced mineralogy and chemistry of E chondrites, it is believed that they formed relatively close to the Sun. A study of the ⁵³Mn-⁵³Cr isotope systematics in meteorites revealed a radial gradient of the radiogenic ⁵³Cr relative abundance in the Solar System, and suggested that the E chondrites formed between at least 1 AU outward to 1.4 AU (Shukolyukov and Lugmair, 2004). This is further supported by oxygen isotope measurements: E chondrites, together with aubrites, are the only groups of meteorites that have the same oxygen isotopic composition as the Earth-Moon system (Clayton et al., 1984). This has been taken as a major argument in favor of the formation of the Earth from enstatite chondrite-type materials (Javoy, 1995), and thus for formation of E chondrites at about the same heliocentric distance as the Earth. If the region between 1.0 and 1.4 AU has indeed been the formation region of E chondrites, it is yet excluded that their parent bodies still reside in this region. A migration scenario as mentioned by Bottke et al. (2006) where their parent bodies would have been scattered outward into the main-belt would explain their 1-1.4 AU formation location while still surviving in the modern era to be available as meteorite falls. Bottke et al.'s simulation showed that planetesimals that formed between 1.0 and 1.5 AU could have been scattered into a main-belt zone between ~2.2 and ~3.0 AU. We might thus expect that the present location of E chondrite parent bodies could be sparse and/or broad rather than confined to a narrow zone (a,e,i space).

Up to now, no unambiguous link has been established between this meteorite class and an asteroid taxonomic group or even a single asteroid. The apparently featureless spectra of M-type asteroids led some authors to suggest that either enstatite chondrites or iron meteorites were their best meteoritic analog (Chapman and Salisbury 1973; Gaffey and McCord, 1979). These inferences were based on the general similarities between M-type asteroid spectra and the spectra of these meteorite types, although specific diagnostic features were lacking. However, the discovery of repeatable and consistent $\sim 0.9\mu\text{m}$ features on several M-type (X-type in the new Bus-DeMeo taxonomy) asteroids (Clark et al. 2004; Hardersen et al. 2005) makes the link between those asteroids and E chondrites less likely as the spectra of these meteorites do not display any similar absorption feature in the VNIR range, because their pyroxene are iron free (see Fig. 1). Another aspect is that the spectral properties of this meteorite class have been poorly investigated. Spectral libraries such the RELAB database (<http://www.planetary.brown.edu/relab/>) contain just a few spectra of enstatite chondrites (4 EH4, 2 EH5, 6 EL6) which is essentially due to the rarity of this meteorite type.

a) Experiments

The Eagle E chondrite spectra before and after irradiation are shown in Fig. 1. These spectra reveal a small variation of the spectral slope (slightly reddening) with progressive irradiation while the visual albedo gets darker by no more than 3% (from 0.258 at 0.55 micron to 0.242). Small changes of curvature around 500-600 nm are observed, where the disappearing of the 500 nm absorption band is due to removal of terrestrial weathering (Fe hydroxides) and the 600 nm curvature change is probably due to the formation of nanophase reduced Fe (enstatite in Eagle chondrite is Fe free, but the metallic Fe phase may provide some Fe atoms in sputtering processes). The visible curvature around 500-600 nm has been shown to be correlated with the degree of space weathering (Hiroi et al. (2006), Ishiguro et al. (2007)). The observed effect, however, is relatively minor ($<3\%$) with respect to

spectral variations observed in other space weathering simulation experiments. In particular, the present result differs from the ones obtained from irradiation experiments of ordinary chondrites and other silicate analogues (e.g. Strazzulla et al., 2005) where a strong reddening and darkening of the reflectance was observed with progressive irradiation. Here, the effects on the collected spectra due to the ion bombardment remain minor, although the irradiation fluence is relatively high. We thus expect a minimal spectral mismatch between enstatite chondrites and their parent bodies (the later ones being slightly redder and darker).

In Fig. 2 we present Raman spectra of Eagle before and after irradiation. Several bands are detected (peak positions are given in Fig. 2), attributed to the presence of iron-free enstatite (see e.g. Huang et al., 2000). Generally speaking, pyroxene Raman bands above 800 cm^{-1} are related to the Si–O stretching modes, bands between 500 and 760 cm^{-1} are attributed to the Si–O–Si and O–Si–O bending, whereas SiO_4 rotation and metal-oxygen translation are responsible for bands below 500 cm^{-1} . A fluorescence continuum is present that can be due to crystal defects, impurities or contaminants. If present, these contaminants would be easily destroyed by Ar^+ ions and the associated fluorescence would disappear. In addition, this destruction would produce a carbonaceous film characterized by Raman peaks at ~ 1350 and $\sim 1580\text{ cm}^{-1}$, which are not seen after irradiation. Figure 2 shows that after ion irradiation the fluorescence signal increases, thus an initial contamination from hydrocarbons should be absent or very minor. The increasing fluorescence after irradiation would instead suggest connection with crystal defects formed by the impinging ions.

b) Search for the parent bodies of enstatite chondrites

As outlined briefly in the introduction, we chose to irradiate an enstatite chondrite sample with the primary goal being to explore further (or refute entirely) that the asteroid 21 Lutetia may be a

plausible parent body for this meteorite class. [We focused on this object since it is the next fly-by target of the Rosetta mission]. The good match between the reflectance spectra of certain enstatite chondrite meteorites (from RELAB) and Lutetia's spectrum (see Figure 3) suggested such association. We will show here that a broad search with pre- and post-experiment spectra confirmed our previous results.

We compared the VNIR reflectance properties of various enstatite chondrites (spectra of Eagle before and after irradiation and spectra of enstatite chondrites available from RELAB) with those of ~400 asteroids, the aim being to find likely links between both groups. For comparison, we used the VNIR asteroid spectra published by Clark et al. (2004), DeMeo et al. (2008, submitted to *Icarus*) and the spectra we obtained over the last few years [Barucci et al. 2005, Birlan et al. 2007, Nedelcu et al. (2007a and 2007b)]. For the search of plausible parent bodies, we used 2 different methods: 1) the χ^2 method and 2) the new Bus-DeMeo taxonomy [DeMeo et al. (2008, submitted to *Icarus*)]. The albedo was not constrained during the search since it is not known for all asteroids. However, the albedo was used as an additional constraint when it was known for both meteorites and a given asteroid. For the first method, we excluded spectra having absorption bands deeper than 2-3%. We performed the search with and without removing the spectral continuum slope. For the second method, we classified the enstatite chondrite spectra with the Bus-DeMeo taxonomy and then compared their spectra to those asteroids belonging to the same class.

We found only 2 asteroids having spectral properties compatible with those of enstatite chondrites, namely 21 Lutetia ($a \approx 2.44$ AU, $e \approx 0.16$, $D \approx 96$ km) and 97 Klotho ($a \approx 2.67$ AU, $e \approx 0.26$, $D \approx 83$ km). Both objects are classified as Xc types in the new Bus-DeMeo taxonomy (DeMeo et al. 2008, submitted).

We present the spectral similarity of both asteroids in the upper part of Figure 4. Besides having very similar spectra, Lutetia and Klotho have a similar (a) geometric albedo (≈ 0.205 for Lutetia and

≈ 0.23 for Klotho; for Lutetia we calculate the mean value using the IRAS albedo [$A=0.22\pm 0.02$] & the albedos determined by Mueller et al. (2006) [$A=0.208\pm 0.025$] and Barucci et al (2008) [$A=0.19\pm 0.02$]; for Klotho we use the IRAS albedo only) and (b) radar albedo (0.215 ± 0.07 for Lutetia and 0.235 ± 0.05 for Klotho; the mentioned albedos are averages of both the Magri et al. 2007 and the Shepard et al. 2008 values) which reinforces the idea that both objects have a very similar surface composition. The geometric albedo of both asteroids is fully compatible with the one of ECs (0.16-0.26 range) while their relatively high radar albedo provides evidence of the presence of metallic iron on their surfaces which again fully agrees with the composition of ECs. [Note that Lutetia's geometric albedo is defined at the opposition (0 degree incidence and 0 degree emergence angles) which could give a much higher albedo value than laboratory reflectance values (RELAB takes spectra at 30 degree incidence and 0 degree emergence angles; see Hiroi et al. (2001)).]

To allow for the possibility that several different ECs can come from one parent body whose surface regolith reflects a mixture of several meteorite spectral characteristics, we modeled Lutetia's spectrum using 3 enstatite chondrite (all three are EL6 chondrites) spectra as end-members [Eagle before or after irradiation, Hvittis (MR-MJG-024) and Pillistfer (MR-MJG-038) from RELAB]. We performed a linear combination of the 3 input spectra and determined the abundance of each end-member via the χ^2 method. The best fit was obtained for a composition of 53% irradiated Eagle, 25% Hvittis, and 22% Pillistfer (Fig. 4 bottom, green color). The modeled spectrum matches closely Lutetia's spectrum while the albedo of the fit (equal to 0.193, the albedo is the reflectance at $0.55 \mu\text{m}$) is very close to Lutetia's albedo (≈ 0.205). As a test, we also used Eagle's spectrum before irradiation instead of the spectrum collected after irradiation (Fig. 4 bottom, red color). It basically did not change the quality of the fit; it just increased the abundance of Hvittis and Pillistfer. Due to the absence of strong diagnostic mineral absorption features, our curve matching should not be regarded as a definite compositional interpretation of the asteroid. The use of an areal mixture to describe Lutetia is due to a

lack of adequate optical constants that would allow a more precise description. Thus, the result shown in the lower panel of Fig. 4 should be simply interpreted as an indication of a general spectral agreement and certainly a non-unique agreement between ECs and the asteroid. In particular, the considered meteorites have very similar spectra and compositions, and since we have found that ion irradiation has very little effects on meteorite Eagle, it is reasonable to assume that this result can be extended to all ECs meteorites. Thus, taking into account the (minor) effects of space weathering, in this first step we can argue that ECs are compatible with Lutetia and Klotho's surface spectra and that among ~400 asteroids only those 2 have spectral properties similar to those of ECs.

In a second step, we looked at all other meteorite types to check whether some of them may also explain Lutetia and Klotho's composition. We found a single additional class of meteorites for which we obtained a good spectral match and that is aubrites (see Figure 3). This is not a surprise since these meteorites have similar compositions to those of ECs (see next subsection for more details). Indeed, the spectra of aubrites such as Peña Blanca Spring (TB-TJM-045), Mayo Belwa (TB-TJM-046) and Bishopville (TB-TJM-047) strongly resemble the spectrum of the enstatite chondrite Eagle. The fundamental problem with an aubrite – Lutetia & Klotho association is that these meteorites are much brighter (reflectance at 0.55 μm is around 0.5) than both asteroids (more than a factor of 2). It is therefore very unlikely that aubrites originate from these 2 asteroids. Briefly, the good matches between Lutetia and ECs in terms of (i) albedo (visible and radar) and (ii) spectral behavior over the VNIR range strongly suggest a genetical link between the two groups. Said differently, taking into account the contribution of space weathering, among all meteorites for which we have VNIR spectra ECs provide the best match to Lutetia's spectrum and therefore can help to retrieve information on its surface composition. This association appears to be the first between enstatite chondrite meteorites and given asteroids (namely 21 Lutetia and 97 Klotho).

c) Preparation for Rosetta

A possible Enstatite chondrite analog is particularly important in the frame of the forthcoming fly-by of Lutetia by the Rosetta spacecraft. Originally, Lutetia was selected as fly-by target with the view of being a 'primitive' asteroid and a possible parent body of carbonaceous chondrites (Barucci et al. 2005). Our interpretation provides a new explanation of Lutetia's surface composition. Note that Nedelcu et al. (2007a) already found good matches between Lutetia's spectra and enstatite chondrites; but they also found (in terms of χ^2) good matches with carbonaceous chondrite meteorites and suggested a mixture of both meteorites as the best explanation of Lutetia's composition. One fundamental problem with this latter association is the systematic presence of a 1 micron absorption band in the spectra of CC meteorites which is mainly due to the presence of olivine. Since Lutetia's spectrum is free of any similar absorption band in the VNIR range, it is very unlikely that its surface composition is similar to the composition of CCs. An additional argument is that Lutetia's albedo is too high when compared to the albedo of CCs (CCs albedo are in the 0.03-0.15 range). The same conclusion on the incompatibility between Lutetia and CCs was reached by Mueller et al. (2006) based on Lutetia's high geometric albedo and by Shepard et al. (2008) based on Lutetia's high radar albedo.

2) Mesosiderites

Mesosiderites are a rare type of meteorite representing just 0.7% of the recovered falls. They are a puzzling class of brecciated stony-iron meteorites consisting of about equal parts of (1) metallic Fe-Ni, chemically related to the IIIAB group of iron meteorites, and (2) silicates making up evolved igneous rocks, mainly basalts, gabbros and orthopyroxenites, i.e. rocks from the crust of a differentiated asteroid. The most abundant minerals are orthopyroxene and Ca-rich plagioclase, with

minor amounts of olivine, clinopyroxene, silica, and a few other minerals. This silicate assemblage is very similar to that of the basaltic achondrites, howardites-eucrites-diogenites (HEDs). Moreover it has long been known that mesosiderites, HEDs and main group pallasites have the same oxygen isotopic composition. Intuitively it would seem that the mesosiderites might represent mixtures of core, mantle and crust of a single body that was, or is, the parent of IIIAB irons, HEDs and main group pallasites (Hutchison 2004). However, recent high precision oxygen isotope measurements have resolved a clear difference between the O isotopic compositions of mesosiderites and pallasites (Greenwood et al., 2006), excluding that these come from the same body. In contrast, they confirmed that the O isotopic compositions of mesosiderites and HEDs are identical, which has been taken by Greenwood et al. (2006) as a proof that they share the same parent body. In the case of the HEDs, the parent body is believed to be 4 Vesta.

A number of contrasting scenarios explaining the formation of the mesosiderites have been published (Mittlefehldt et al., 1998, and references therein; Scott et al., 2001). They all start with the differentiation of a large asteroid (several hundred km in diameter), 4.56 Gyr ago. Mixture of crustal material with liquid metal occurs, following an impact, around 4.4 Gyr. Depending on the model, the metal is from the core of the asteroid in question or from the projectile, in both cases still molten at the time of impact. The asteroid undergoes disruption and gravitational reassembly in the same or a later impact, so that the mesosiderites-to-be get deeply buried and so cool extremely slowly at low temperature, as observed. Alternatively, the catastrophic break up is replaced by the rapid growth of a thick, insulating regolith (several hundred meters thick) by accumulation of impact debris. No really convincing explanation has been provided for the absence or paucity of mantle material (olivine) in the mesosiderites, nor do we know what has finally become of the large asteroid. On the basis of these models, identifying the mesosiderite parent bodies from the optical properties of their surface appears particularly challenging.

Importantly, no potential parent body has yet been identified and therefore the provenance of mesosiderites remains highly uncertain. The identification of one or several mesosiderite-like asteroids could help to shed light on the formation history of these meteorites and may allow us to accept or reject a primordial link between these meteorites and HEDs.

a) Experiments

Figure 1 (bottom) shows Vaca Muerta's spectrum before and after irradiation. We see that ion irradiation has some influence on the albedo (darkening) and produces a redder spectral slope. The reddening is stronger than in the case of irradiated Eagle, and it is more pronounced for the scraped side of Vaca Muerta (lower spectra) than the smooth side (upper spectra). The observed effects may be due to the presence of silicates, in a space weathering scheme similar to that of OCs (e.g. Strazzulla et al. 2005). As a result, we expect to observe a certain spectral mismatch between mesosiderites and their parent asteroids due to space weathering. The presence of 2 clear but not deep absorption bands around 0.9 and 2 micron which are mainly due to the presence of pyroxene should simplify the search of potential parent bodies. To highlight the spectral difference between this mesosiderite and other silicate-rich meteorites (OCs, ureilites and HEDs; these meteorite types contain silicates such as olivine and/or pyroxene), we display their average spectrum in Figure 5 (average takes all the available spectra as input; spectra are from the RELAB database). It appears that the absorption bands in the mesosiderite spectrum are much weaker (in terms of band depth) than those in the OC and HED spectra. This can be explained by the abundance of metal in mesosiderites; such a neutral component (i.e. iron) tends to weaken the absorption bands when mixed with silicates such olivine and pyroxene (e.g. Cloutis & Gaffey 1991). The comparison of the spectral properties of this meteorite (that is the mesosiderite Vaca Muerta) with those of ordinary chondrites and HEDs shows that a link between this

meteorite class and S- or V-types seems excluded. The parent bodies of mesosiderites must be hidden among asteroids having weak 0.9 and 2 micron absorption bands in their VNIR spectra.

b) Comparison with asteroids

We searched for plausible parent bodies for the Vaca Muerta meteorite and therefore mesosiderites. As for the search of the ECs parent bodies, we compared the VNIR reflectance properties of the mesosiderite Vaca Muerta (before and after irradiation) with those of ~400 asteroids (same technique as mentioned earlier in the text). We found three asteroids having spectral properties compatible with those of Vaca Muerta, namely 201 Penelope ($a \approx 2.68\text{AU}$, $e \approx 0.18$, $D \approx 68\text{km}$, IRAS albedo ≈ 0.16), 250 Bettina ($a \approx 3.15\text{AU}$, $e \approx 0.13$, $D \approx 80\text{km}$, IRAS albedo ≈ 0.26) and 337 Devosa ($a \approx 2.38\text{AU}$, $e \approx 0.14$, $D \approx 60\text{km}$, IRAS albedo ≈ 0.16). The three objects are classified as Xk types in the new Bus-DeMeo taxonomy (DeMeo et al. 2008, submitted). We present their spectrum as well as the Vaca Muerta spectrum (smooth surface) obtained after irradiation in Fig 6 (top).

As one can see, there is a slope difference between the various spectra, the asteroidal spectra being redder. As shown in Fig 1, the space weathering effect tends to redden the spectrum of Vaca Muerta. Assuming these asteroids are related to mesosiderites, the fact that the three asteroids are redder than the irradiated meteorite could be because the doses used in our experiments did not simulate the accumulated damage present at asteroidal surfaces. In addition, the preparation of the sample (cut slab) introduces albedo and slope effects. It is known that powdered surfaces and regolith (rough and porous samples) produce redder spectra than smooth and compact surfaces (Brunetto et al., 2007). This is confirmed by the fact that the Vaca Muerta smooth side spectrum before irradiation appears bluish, which would be otherwise difficult to reconcile with the composition of the meteorite. This gives additional explanation to the fact that the irradiated meteorite is less red than the possible asteroid analogues. In any case the main criterion used to select these asteroids was the presence of

weak bands around 0.9 and 2 micron as well as the global shape of the asteroid spectra. To highlight the spectral resemblance among the various spectra, we compare the same spectra after slope removal at the bottom of Figure 6. Besides a general spectral agreement (ignoring the slope difference), the geometric albedo of Penelope and Devosa (0.16 for both) is fully compatible with the ones of Vaca Muerta (0.14-0.2 range) while Bettina's albedo appears to be slightly higher and outside that range (0.26). However, considering the influence of the preparation of the sample on the collected albedo (e.g. Fig. 1), we do not exclude Bettina as being a potential parent body of mesosiderites. No radar albedo value has been yet reported for Penelope, Bettina and Devosa. If those three asteroids have a surface composition akin to mesosiderites, we can predict their radar albedo to be somewhere in between the radar albedo of S-types (mostly in the 0.1-0.2 range, see Magri et al. (2007) and Shepard et al. (2008)) and metal-rich asteroids (i.e. M-types, mostly in the 0.17-0.6 range).

There were additional asteroids with faint 0.9 and 2.0 micron bands that we did not select as mesosiderite analogs. These asteroids (e.g. 16 Psyche, 69 Hesperia, 110 Lydia, 125 Liberatrix and 216 Kleopatra) have been presented by Hardersen et al. (2005). The reason of their non-selection is that the depth of their absorption band is at least a factor of 2 shorter than Vaca Muerta's band depth. Note however, that all these asteroids have geometric albedos fully compatible with Vaca Muerta's albedo and that the radar albedo of these bodies, when available, indicates a high fraction of metal on their surfaces which is fully consistent with the composition of mesosiderites (radar albedo exists for Psyche and Kleopatra – see Shepard et al. (2008)). We therefore do not exclude a link between these objects and mesosiderites considering that we do not have enough spectral measurements for these meteorites.

One of the key questions while searching for the parent bodies of mesosiderites is: “are these bodies somehow connected to 4 Vesta, i.e. are they close (in the a,e space) to this asteroid?” This question is naturally raised by the identical O isotopic compositions of mesosiderites and HEDs (Greenwood et al. 2006). The identical O isotopic composition tends to imply that Vesta and the

mesosiderite parent body had a nearly identical formation location, that is Vesta's present location or a different location as envisioned by Bottke et al. (2006) who assume that Vesta is a main-belt interloper. The discovery of the mesosiderite parent asteroid(s) may allow bringing precious constraints to the Bottke et al. scenario. Here, we find that the three mesosiderite-like objects seem poorly linked to Vesta. While 337 Devosa lies relatively close (in the a, e space) to Vesta, 201 Penelope and 250 Bettina are located very far from Vesta. Assuming all three objects are connected to mesosiderites (which implies a close connection to HEDs and therefore Vesta), their present location can not be the same as their initial formation location. Similarly to Vesta, these asteroids must be main-belt interlopers; this gives precious support to Bottke et al.'s idea.

Conclusion

The plausible genetic links found here will hopefully motivate researchers from different fields to continue collecting data on unusual meteorites and asteroids. The spectral properties of rare types of meteorites should be investigated in greater detail and the spectral effects of ion irradiation should be quantified. We have shown here that in the case of asteroids having featureless spectra throughout the NIR range, the knowledge of both their visual and radar albedos provides crucial constraints for linking these bodies to their meteoritic analogs. We are confident that additional (i) spectral measurements in the NIR (completing SMASS; Bus & Binzel 2002) and (ii) visual and radar albedo measurements will significantly improve the number of established links between asteroid and meteorite groups. This in turn will help to constrain dynamical models which tend to explain the anomalous location for given asteroids, i.e. given compositions (following Bottke et al. 2006, metallic asteroids and Vesta appear to be main-belt interlopers but so do the parent bodies of ECs and most likely mesosiderites).

Acknowledgements

We warmly thank L. Folco for providing the Eagle meteorite samples and B. Zanda for Vaca Muerta. We are grateful to F. Spinella and G.A. Baratta for precious help in the laboratory. We thank Beth Clark for kindly sending us her X-type data (from Clark et al. 2004). We thank Beth Clark and an anonymous referee for their excellent review on this manuscript.

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Figure captions

Figure 1: Vis–NIR (0.4–2.5 μm) reflectance spectra of the enstatite chondrite meteorite Eagle (upper panel) and the mesosiderite meteorite Vaca Muerta (lower panel) before (black line) and after (red line) irradiation (200 keV Ar^+ ions, fluence of 10^{17} ions/ cm^2). For both experiments, spectra have been collected ex situ (at atmospheric pressure). We label the spectra collected on the smooth side with an (a) and the spectra collected on the rough side with a (b).

Figure 2: Raman spectra (laser 514.5 nm, spectral resolution 2 cm^{-1}) of the Eagle (EL6) meteorite before and after irradiation. All marked peaks are attributed to FeO-free enstatite (Huang et al., 2000).

Figure 3: Comparison of Lutetia’s VNIR spectrum (black) with the reflectance spectra of the enstatite chondrite meteorites Hvittis and Pillistfer (EL6) and the aubrites Mayo Belwa and Bishopville. Spectra have been normalized to 1 at 0.55 μm . Here, we show that both aubrites and enstatite chondrite meteorites can explain Lutetia’s surface composition without invoking “space weathering”. Both classes are the only one sharing a similar spectrum to Lutetia’s one. However, the aubrite-Lutetia association appears to be ruled out due to a significant albedo difference (~ 0.5 for aubrites versus ~ 0.2 for Lutetia).

Figure 4: (a) Comparison of 21 Lutetia (black) and 97 Klotho’s (blue) reflectance spectra in the 0.4–2.5 μm range. Both spectra are normalized to 1 at 0.55 μm . The visible part of Lutetia’s spectrum was published by Barucci et al. (2005). For the NIR part, we show an average spectrum with a 1-sigma standard deviation of the eight Lutetia spectra published by Nedelcu et al. (2007a). The Klotho spectrum is issued from the DeMeo et al. paper (submitted to Icarus). (b) Lutetia’s VNIR spectrum and

the reflectance spectra of the enstatite chondrite meteorite Eagle before (blue line) and after (red line) irradiation (200 keV Ar⁺ ions, fluence of 10¹⁷ ions/cm²). (c) Comparison of Lutetia's VNIR spectrum (black) with our best fits (red and green) as presented in the text.

Figure 5: Comparison of the mesosiderite (Vaca Muerta) spectrum (black) with the mean spectra of pyroxene-rich meteorites (H chondrite in blue, Diogenite in red and ureilite in green). All spectra are normalized to 1 at 0.55 μm.

Figure 6: (upper part) The reflectance spectrum of Vaca Muerta after irradiation and the spectra of four main-belt asteroids are shown normalized to 1 at 0.55 μm. The four asteroid spectra are presented in the DeMeo et al. paper (submitted to Icarus). 337 Devosa's NIR spectrum was kindly provided by Beth Clark (Clark et al. 2004). (lower part) The same spectra are shown after slope removal (normalized to 1 at 0.55 μm and shifted vertically for clarity).

Figure 1

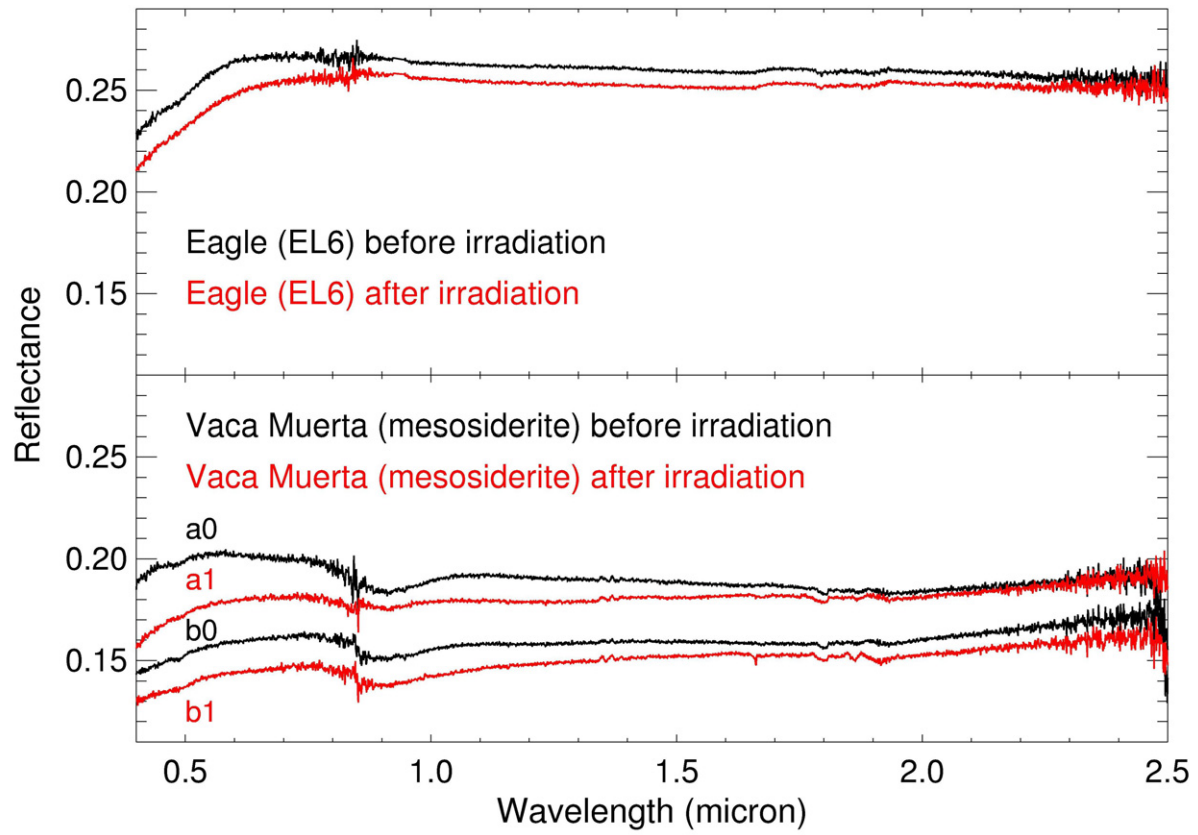


Figure 2

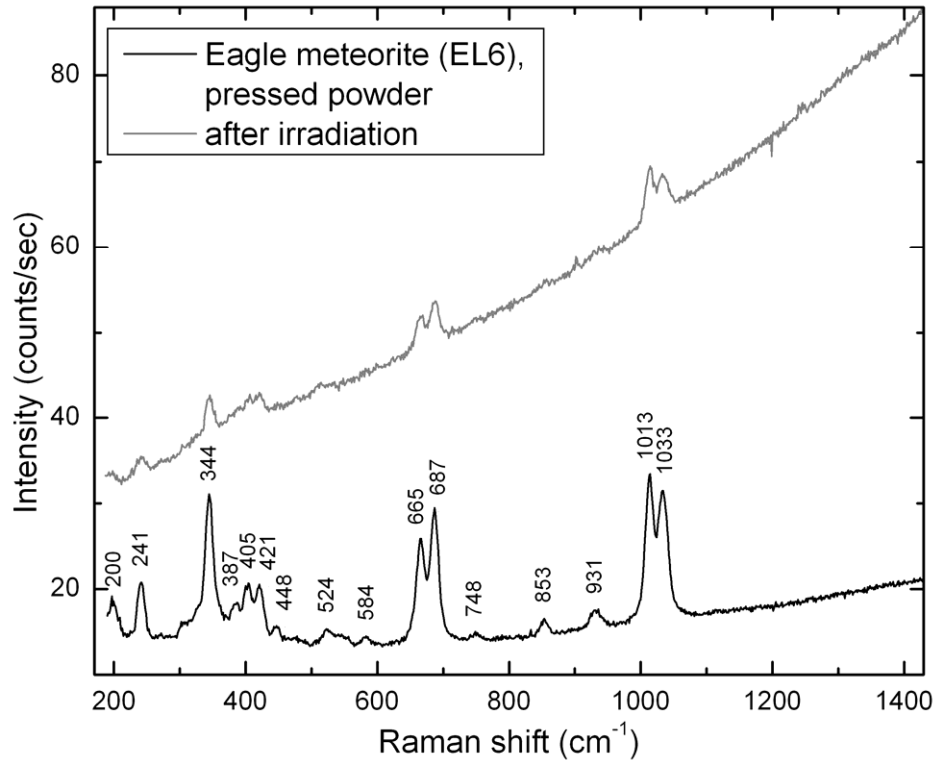


Figure 3

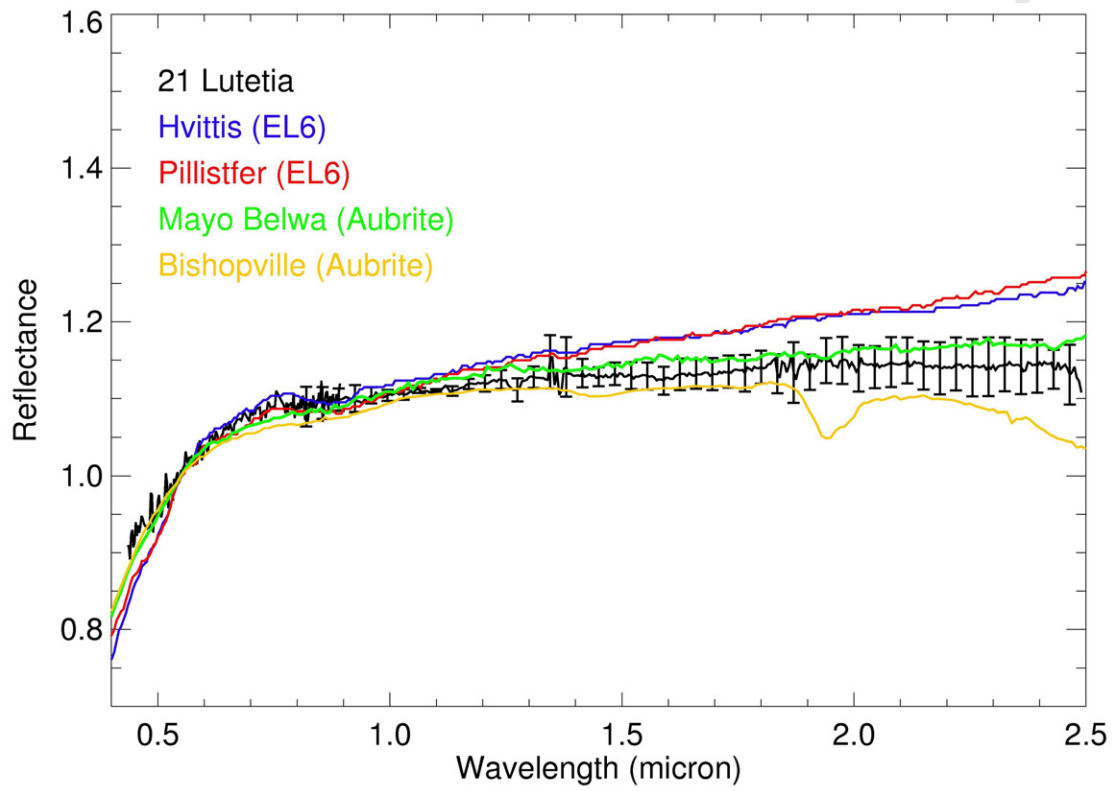


Figure 4

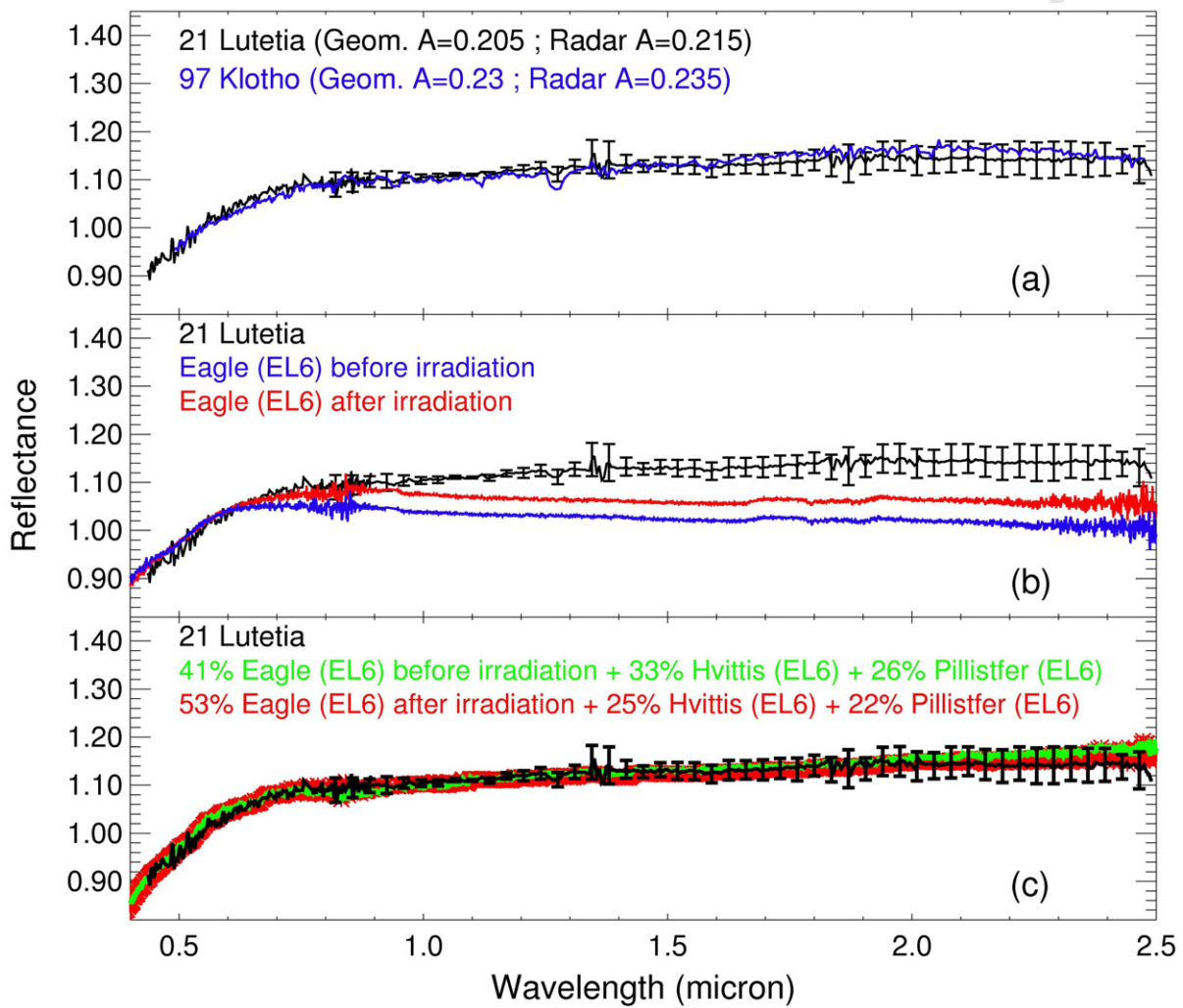


Figure 5

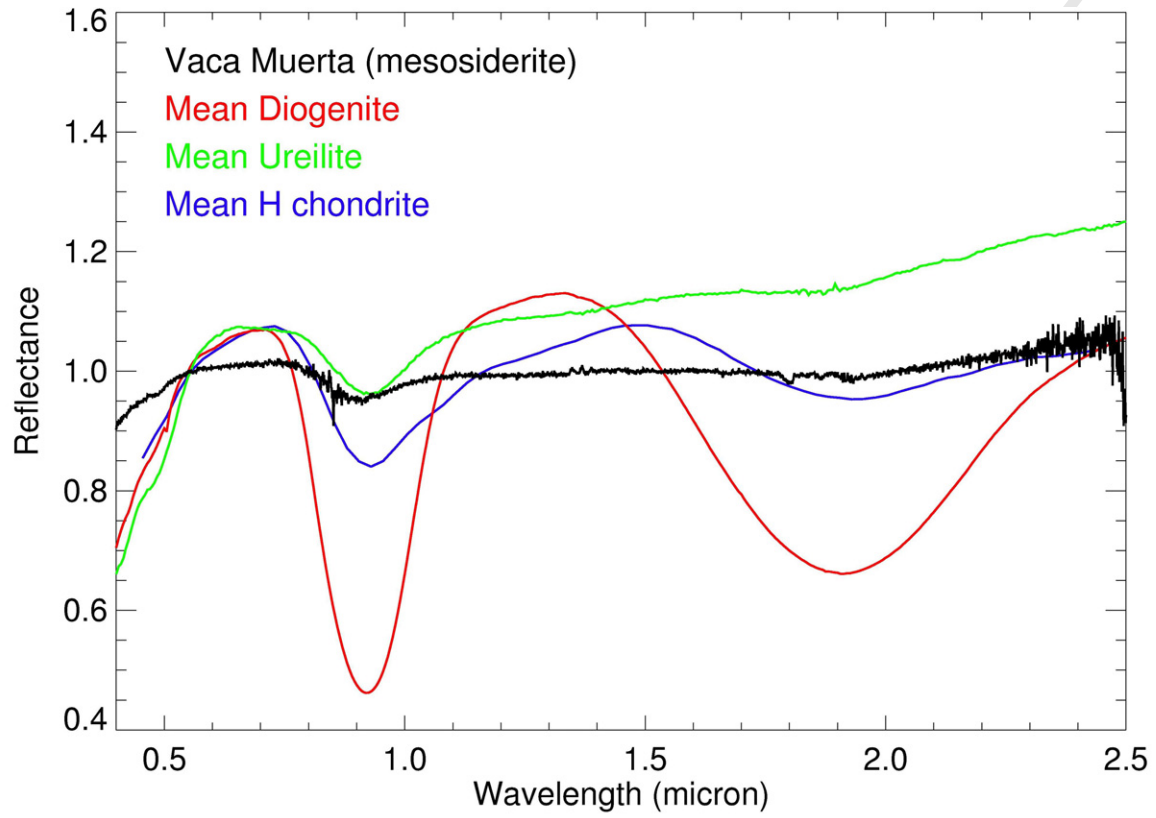


Figure 6

