SURFACE COMPOSITION OF ASTEROID (21) LUTETIA: LESSON LEARNED FROM THE ROSETTA FLYBY.
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Introduction: During the close encounter of the Rosetta spacecraft with (21) Lutetia on July 10, 2010, the instruments OSIRIS, VIRTIS, ALICE, and MIRO were turned on to characterize the surface properties of the asteroid. Even with the obtained results, the ambiguity in understanding Lutetia's surface composition still exists. We have assembled and analysed the information available from space missions (Rosetta, Herschel and Spitzer) and ground observations collected over 30+ years to interpret the Lutetia's surface composition.

Rosetta results: During the flyby, Lutetia was seen at pole-on aspect and consequently only the northern hemisphere was observed. The images taken by OSIRIS cameras [1] reveal a complex geology. Lutetia appears to be a very old object with an irregular shape resulting from its collisional history. Some smooth, younger areas have also been observed. Continuous bombardment over Lutetia's lifetime has created several large and numerous small craters. About 350 craters have been counted with diameters between 600 m and 55 km. The North Pole, in the Baetica region, is covered by a thick layer of regolith, which flows in major landslides, most likely generated by impact-induced seismic activity. The sparse presence of dark boulders inside some big craters, indicates a complex impact mechanism. Variations on Lutetia surface have been highlighted and are clearly connected to different composition and morphology. The images display albedo variations and a great richness of different structures: pits, craters chains, ridges, scarps. Lutetia is likely a remnant of the primordial planetesimal population.

The analysis of the spectral data obtained by VIRTIS [2] revealed featureless spectra between 0.5 and 5.0 μm. Beyond 3.5 μm the radiance spectra are characterized by the presence of thermal emission from the surface superimposed on the solar reflected radiance. No olivine or pyroxene signatures of the 1 and 2 μm bands are evident in the spectra, nor were mineral aqueous alteration bands detected at 1.9, 2.7 or 3 μm. Moreover, no organic material was identified at 3.3-3.6 μm.

The UV ALICE imaging spectrometer results report no gas emissions around Lutetia. A precipitous drop between 180 and 160 nm has been measured which represents the strongest spectral feature detected by Rosetta instruments. No similar feature has been observed in the UV reflectance of any asteroid and it is particularly difficult to interpret [3] due to the lack of laboratory data at these wavelengths.

A temperature map has been derived that shows good agreement between the values measured by MIRO and VIRTIS [2,4]. The thermal inertia has been found to be between 20 and 30 $Jm^{-2}K^{-1}s^{-0.5}$ implying a surface which, on a gross scale, is uniformly covered by a fine regolith. This low thermal inertia value has also been confirmed by observations of (21) Lutetia performed by the instruments onboard the Herschel spacecraft at longer wavelengths, complementary to those covered by VIRTIS and MIRO [5].

Combining the volume determined by OSIRIS imaging [1] and the mass determined by the RSI experiment [6], Lutetia's bulk density of 3400±300 kg m^{-3} has been determined. This is one of the highest known densities of any asteroid and it is similar to that of the differentiated asteroid (4) Vesta.

Ground observations results: Ground-based observations of Lutetia using many different techniques have been performed over the last 30 years. In particular, spectral measurements have been obtained at multiple aspects covering most of Lutetia's surface. Barucci et al [7] reanalyzed all the available measurements in different spectral ranges. Systematic differences were found in the visible and near-infrared spectra of the northern and southern hemisphere. In terms of taxonomy, spectral properties of the southern surface are more C-like while the spectra of the northern surface are more X-like. This confirms previous findings by Nedelcu et al. [8] and Lazzarin et al. [9]. Moreover Rivkin et al. [10] showed that the 3-μm band depths were deeper for the southern hemisphere.

To fit the spectral behavior, the closest analogues among the available meteorites are some types of carbonaceous chondrites and in a few cases enstatite chondrites. Nedelcu et al. [8] showed that some of Lutetia's spectra were fitted better with carbonaceous chondrites while others were fitted better with enstatite chondrites. They also mentioned as a possible analogue the meteorite Kaidun.

Mid-infrared data obtained with the Spitzer space telescope are also available on Lutetia [11]. The most diagnostic features in the analysis of mid-infared spectra are the Christiansen peak, the Restrstrahlen, and the Transparency features. The Christiansen peak is the most important as it is connected to mineralogy and grain size. From the analysis of the Spitzer data, Lutetia spectra, taken a nearly equatorial view, are similar to CO and CV carbonaceous chondrite meteorites, particularly at small grain sizes. The Spitzer spectra show a clear Christiansen peak at 9.3 micron which is typical of carbonaceous chondrites and rules out the links with available spectra of enstatite chondrite meteorites for which the principal Christensen feature measured is at 8.3 μm.

Lutetia also exhibits particular polarization properties. The polarization phase function of Lutetia differs from that of any other asteroids measured so far [12]. Among studied meteorites, similar polarization properties were found for pulverized samples of CV3 and CO3 carbonaceous chondrites.

Radar data are consistent with composition similar to either enstatite chondrites or particular types of metal-rich carbonaceous chondrites [13] .

Discussion: All available data show that Lutetia's surface composition is particular with respect to other studied asteroids. None of the known meteorites exactly matches all measured Lutetia's properties.

A search for the best meteorite analogue by matching featureless asteroid and meteorite spectra should be taken with caution. It was shown that the particle size distribution of laboratory samples greatly affects spectral parameters such as the slopes and the depths of absorption bands. Fine-grained mixtures of components with different optical properties (irons, silicates, carbon) can drastically alter the spectral reflectivity and suppress silicate bands. Another problem in comparing meteorite and asteroid spectra is connected to space weathering of asteroid surfaces due to micrometeorite impacts, solar wind, etc. while meteorites could have suffered terrestrial weathering. Interpretation of spectra with no signatures are in general inconclusive. Arguments given by Vernazza et al. [14] in support of enstatite chondrite composition of Lutetia look one-sided. Their analysis involved only one near-infrared spectrum and an ad hoc comparison of Lutetia's mid-infrared data with the KBr-diluted spectra of enstatite chondrites. Vernazza et al. [14] postulated that Lutetia's surface scattering is dominated by the fine-grained components but ignored particle-size effect when compared with carbonaceos chondrites.

The moderate geometric albedo of Lutetia is often invoked to argue against carbonaceous-chondrite surface compositions. However, direct comparison of asteroid geometric albedos and reflectances of meteorites should be approached with caution. We have to consider that the reflectance of laboratory samples is usually measured at phase angles 15°-30° and is not corrected to zero phase angle. Moreover, laboratory samples cannot reproduce macroscopic surface roughness and their phase curves are much more flat than those of asteroids. To be comparable with meteorite reflectance, the asteroid albedo should be calculated not taking into account the opposition surge. This value for Lutetia (0.13±0.01) is consistent with both carbonaceous chondrites of higher petrological types and enstatite chondrites [6].

The surface of Lutetia is most probably composed of a variety of materials similar to chondrites. The composition of some regions (predominantly in the southern hemisphere) seems more similar to carbonaceous chondrites (like CV, CO, CK) while that of the northern hemisphere could be more similar to a mixture of enstatite and carbonaceous chondrites.

An aggregate of different materials could be possible as was found in some particles of the comet 81/P Wild 2, and in the Kaidun and Almahata Sitta meteorites. In fact, the laboratory analysis of small grains returned to Earth by the Stardust mission revealed an unexpected mixture of materials formed in different regions of the planetary disk. The extremely heterogeneous meteorite Kaidun shows assemblages of material ranging from CM to enstatite chondrite clasts which have been interpreted as the result of collisional formation of its parent body from asteroids having different composition (E, D, C). The mechanism for transport of these diverse materials within Kaidun all in one parent body must have involved numerous impacts. In the same way, the complicated surface composition of Lutetia could be explained by an unknown peculiar material resulting from collisions of objects with different composition [7].

Conclusions: After the Rosetta flyby, Lutetia's composition remains a puzzle. Lutetia is clearly an old object (about 3.5 Ga), possibly partially differentiated [15], with a highly complex surface and a particular surface composition probably due to a mixture of "incompatible" types of materials, like carbonaceous and enstatite chondrites, which may have aggregated due to impacts.

Only in-situ examination or sample return could allow us to solve the puzzle of the surface composition of this intriguing object.

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