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# Near-ultraviolet to near-infrared spectral properties of hollows on Mercury: Implications for origin and formation process

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1 **Near-ultraviolet to near-infrared spectral properties of**  
2 **hollows on Mercury: Implications for origin and**  
3 **formation process**

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10 **Key Points:**

- 11 • Hollows have unique spectral properties in the near-ultraviolet.  
12 • The reflectance spectra of hollows have a pronounced curvature between 300 and  
13 600 nm.  
14 • Eminescu impact crater hollows are seen to grow via scarp retreat.

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**Abstract**

[Among the geological features revealed by the MESSENGER (MErcury Surface, Space ENvironment, GEOchemistry and Ranging) mission on the surface of Mercury, hollows are the most surprising and least understood. Possibly related to volatile components, hollows are small depressions, surrounded by bright halos and are not observed on any other surfaces in our Solar System. Previous analysis of multi-spectral data obtained by Mercury Dual Imaging System (MDIS) has shown that some hollows have weak spectral absorption features centered at around 600 nm. In this work, we analyzed four hollows with observations acquired by the Mercury Atmospheric and Surface Composition Spectrometer (MASCS) on board MESSENGER with more than 230 spectral channels from the near-ultraviolet to the near-infrared. Unlike previous MDIS multispectral data, the MASCS reflectance spectra exhibit no absorption features in the MDIS wavelength range. However, we found that hollows have unique spectral properties in the near-ultraviolet, with a spectral curvature between 300 and 600 nm that is distinctly different from other geological units. Moreover, we used MASCS observations with the best available spatial resolution (less than 0.5 km/pixel) to analyze both parts of a hollow: the flat floor and the surrounding halo. Our results support the hypothesis that hollows form by a sublimation process and scarp retreat.]

**Plain Language Summary**

[The MESSENGER (MErcury Surface, Space ENvironment, GEOchemistry and Ranging) mission highlighted several geological terrains on Mercury's surface. Among the unexpected discoveries are small bright depressions, named hollows. Often found within impact craters, hollows have irregular shapes, flat floors and are surrounded by bright halos. Hollows are still poorly understood and their formation remains a mystery for the scientific community. Using observations made by the spectrometer on board the MESSENGER probe, we show for the first time that the spectra of hollows exhibit unique reflectance properties at near-ultraviolet to visible wavelengths, which spectrally distinguishes them from other geological terrains. Moreover, the most detailed observations show that their flat floors have different spectral characteristics from the bright halos. Our results provide new knowledge about their formation, nature and differences from other geological terrains and is consistent with them forming from sublimation processes.]

## 1 Introduction

The MESSENGER (MErcury Surface, Space ENvironment, GEOchemistry and Ranging; Solomon et al., 2007) missions highlighted the complex geological history of Mercury’s crust (Denevi et al., 2009). Multi-spectral images returned by the Mercury Dual Imaging System (MDIS, Hawkins et al., 2007) and spectral observations obtained with the Mercury Atmospheric and Surface Composition Spectrometer (MASCS, McClintock & Lankton, 2007) show that Mercury’s surface has steeper spectral slopes and lower reflectance than the Moon (Robinson et al., 2008; McClintock et al., 2008; Denevi et al., 2009). Mercury’s reflectance spectra exhibit a red spectral slope (i.e the reflectance increases with increasing wavelength) without silicates absorption features (Robinson et al., 2008; Izenberg et al., 2014). Although the spectral signatures are few, the surface of Mercury is spectrally and morphologically diverse. Based on spectral variation and morphology, two main terrain types and several smaller units have been identified at the surface of Mercury (Robinson et al., 2008; Denevi et al., 2009; Izenberg et al., 2014).

Low Reflectance Materials (LRM) covers approximately 15 % of the planet’s surface. They are among the darkest features on Mercury with an absolute reflectance 30 % below the average surface (Robinson et al., 2008). LRM have a shallower spectral slope than Mercury’s mean spectrum. They have diffuse margins and are generally associated with impact structures, suggesting that this material has been excavated by impact cratering. The smooth plains represent 27 % of Mercury’s surface (Denevi et al., 2013). They exhibit a large range of spectral properties: from high-reflectance red plains to low-reflectance “blue” plains (blue corresponding to a less steep spectral slope than the average surface, but still with an increasing reflectance with increasing wavelength) (Denevi et al., 2009, 2013). Smooth plains on Mercury could result from effusive volcanism, impact melting or basin ejecta (Denevi et al., 2009, 2013). The majority of them share the spectral properties of the Northern Smooth Plains (NSP), the more largest (occupying 7% of the Mercury’s surface) and continuous area of smooth plains on Mercury (Denevi et al., 2013; Byrne et al., 2018).

Besides LRM and smooth plains, which are considered as large units, there are also small units that can be darkest features or high reflectance material. Dark spots are sub-categories of LRM (Xiao et al., 2013), with diffuse edges but covering smaller areas (less than  $100 \text{ km}^2$  by dark spot) than LRM (often larger than  $10^6 \text{ km}^2$ ). They have spectral slopes similar to the LRM but a lower reflectance (Xiao et al., 2013). Another spectral units are faculae which appear brighter and redder than the Mercury’s average surface. Most of faculae are accepted to be pyroclastic deposits emplaced by explosive eruption. Brighter than faculae, small depressions named hollows have a reflectance approximately twice the average reflectance of Mercury (Blewett et al., 2013). Hollows-like formations have never been observed on other airless silicate bodies, which makes them an interesting case study.

Hollows are irregularly shaped, shallow, with flat floors. Their edges are usually diffused and brighter. They most often form near or directly within impact craters (Blewett et al., 2011, 2013). Some appear on crater rims, others around central peaks/rings and sometimes even in ejecta (Blewett et al., 2011, 2013). They have been often associated with LRM, Low-reflectance Blue Plains (LBP) or dark spots (Blewett et al., 2013; Xiao et al., 2013; Thomas et al., 2014a). The formation mechanism of hollows is widely discussed in literature (Blewett et al., 2013, 2018), and the loss of a volatile component is the most commonly proposed process. The arguments favoring volatile loss are i) the important abundance of volatile species in Mercury’s crust as measured by X-Ray spectroscopy (Nittler et al., 2011), and ii) the preferable distribution of hollows on Sun-facing-slopes (Blewett et al., 2011, 2013; Thomas et al., 2014a). Blewett et al. (2013) proposed a formation scenario based on a vertical growth by loss of a volatile compound to a certain depth, and then an extension of the hollows by scarp-retreat.

98 Due to the high abundance of sulfur in the sub-surface of Mercury (Nittler et al.,  
 99 2011), CaS and MgS are commonly proposed as the volatile species (Blewett et al., 2011,  
 100 2013; Vilas et al., 2016; Lucchetti et al., 2018). This hypothesis is supported by the high  
 101 concentration of exospheric calcium (Bennett et al., 2016) above the Tyagaraja impact  
 102 crater in which there is a large field of hollows (Blewett et al., 2011). Vilas et al. (2016)  
 103 studied in detail the Dominici and Hopper crater hollows and showed a possible absorp-  
 104 tion band centered around 630 nm in MDIS multispectral observations. This feature was  
 105 also found in hollows from Canova and Velazquez impact craters (Lucchetti et al., 2018)  
 106 and Raditladi Basin (Thomas et al., 2016). The absorption feature is often attributed  
 107 to sulfides-like CaS and/or MgS (Vilas et al., 2016) or a mixture of sulfides and pyrox-  
 108 enes (Lucchetti et al., 2018). Thomas et al. (2016) compared hollows spectral proper-  
 109 ties with material in which they form, using MDIS multi-spectral images and the vis-  
 110 ible spectra of the Mercury Atmospheric and Surface Composition Spectrometer (MASCS).  
 111 Hollows parent material seems to have lost a component that is inherently has, or a pro-  
 112 cess that produced, a red spectral slope in the visible. This result is consistent with the  
 113 presence of sulfides like CaS or MgS as a volatile component (Helbert et al., 2013).

114 Because of their possible association with volatile species, hollows allow a better  
 115 understanding of the planet’s geochemical evolution. The most often used instrument  
 116 for spectral analysis of hollows is MDIS, due to its higher spatial resolution than that  
 117 of the MASCS spectrometer. MASCS footprint sizes are often larger than the dimen-  
 118 sions of hollows. However, MASCS has a better spectral resolution and wider spectral  
 119 range than MDIS. MDIS-Wide Angle Camera (WAC) is a multispectral camera with 11  
 120 usable filters centered between 395 and 1040 nm and with an average spectral resolu-  
 121 tion around 60 nm (Hawkins et al., 2007), while MASCS spectrometer operates between  
 122 300 and 1450 nm with a spectral resolution around 5 nm (McClintock & Lankton, 2007).  
 123 The 5 hollow groups studied with more than 8 MDIS channels are those located in the  
 124 Hopper, Dominici (Vilas et al., 2016; Lucchetti et al., 2018), Canova, Velazquez (Lucchetti  
 125 et al., 2018) and Raditladi (Thomas et al., 2016) impact craters. Thomas et al. (2016)  
 126 studied 9 additional groups using only 2 MDIS channels at about 433 and 749 nm. Some  
 127 studies (Thomas et al., 2016; Izenberg et al., 2015) used the visible part of the MASCS  
 128 spectra in the hollows of the Eminescu, Raditladi, Bacho and Tyagaraja impact craters,  
 129 but the spatial resolution of the observations used was not always sufficient to resolve  
 130 the hollows. The comparison between the hollows and the surrounding terrain, mainly  
 131 LRM (Thomas et al., 2016) and Facula (Izenberg et al., 2015), were made using reflectance  
 132 ratios of 2 channels of MASCS or MDIS.

133 In this work, we used MASCS spectra at the best spatial resolution available (less  
 134 than 0.5 km/footprint) to improve the spectral resolution and the wavelength range com-  
 135 pared to previous studies of hollows (Vilas et al., 2016; Thomas et al., 2016; Lucchetti  
 136 et al., 2018). We found 4 large fields of hollows spatially resolved with MASCS obser-  
 137 vations located in the Tyagaraja, Hopper, Warhol and Eminescu impact craters. The  
 138 main objective of this study is to improve our understanding of the spectral character-  
 139 istics of hollows. In particular, we will characterize the hollows in the near-ultraviolet  
 140 through near-infrared, using parameters derived from full spectral coverage. In addition,  
 141 we will examine the MASCS spectra for absorptions such as those observed in MDIS fil-  
 142 ters (Vilas et al., 2016; Lucchetti et al., 2018), directly comparing the MASCS and MDIS  
 143 observations in the Hopper crater.

## 144 2 Datasets and Method

145 The data used in this work are obtained from the final delivery of products at the  
 146 Planetary Data System (PDS) and have the best calibration (photometric and radiomet-  
 147 ric) performed by the MESSENGER team (Izenberg & Holsclaw, 2017).

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## 2.1 Selection and correction of the spectra

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MASCS Visible and InfraRed Spectrometer (VIRS) is composed of two detectors: a visible (VIS) detector operating between 300 and 1050 nm and a near-infrared (NIR) detector sensitive to wavelengths between 900 and 1450 nm. The NIR detector is more dependent on the orbital, seasonal and instrumental temperature variations (Izenberg et al., 2014). Consequently, the signal-to-noise ratio varies substantially between VIS and NIR detector, which complicates analysis (Izenberg et al., 2014).

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Therefore, we selected the spectra measured in the two lowest temperature regimes of the instrument ( $\leq 25^\circ\text{C}$ ), except for 2 orbits located in Tyagaraja (see section 2.3) where low temperature data are not available. We selected these ranges of temperature because the reference spectrum (Izenberg et al., 2014) used in this analysis (see section 2.2) is based on spectra obtained at temperatures lower than  $30^\circ\text{C}$ . Also, we selected a grating temperature under  $40^\circ\text{C}$ , because if we selected less than  $25^\circ\text{C}$ , 78 % of data corresponding to the hollows would be removed.

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Additional processing is applied to the data using the method developed by Besse et al. (2015). This approach, based on 3 main steps (as described below) allows the merger of the VIS and NIR data in a combined spectrum. The first step consists to remove the outliers deviating by more than 2 sigma from the mean. Only the most distant outliers are removed using this method, which represents less than 1% of the measurements by the VIS detector and less than 4% in the NIR. In a second step, a moving average window of three points is applied to the entire VIS and NIR to smooth the data. Smoothing implies a loss of information on the signal without consequences on the analysis performed in this study. Finally, an offset is applied to the NIR to combine the two parts of the spectrum (Besse et al., 2015). The approach tested on lunar spectra by Besse et al. (2015), has been validated for observations of Mercury's surface. Moreover, this method allows the scatter of the channel-to-channel reflectance to be reduced, especially in the NIR domain. Besse et al. (2015) and Besse et al. (2020) demonstrated that the NIR channel could be analyzed with reasonable confidence in the study of pyroclastic deposits.

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## 2.2 Spectral analysis

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Our analysis is focused on spectral parameters encompassing the entire spectral range of MASCS from the near-ultraviolet to the near-infrared.

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- In the near-ultraviolet (UV), the UV-downturn described by Goudge et al. (2014), which characterizes the drop of the reflectance shortward of 350 nm, is calculated. This parameter gives the offset between measured reflectance and the expected reflectance at 3 wavelengths (300, 325 and 350 nm) if the reflectance had the same slope in the UV and in the visible. The mathematical definition of the UV-Downturn is (Goudge et al., 2014):

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$$UV - downturn = Depth_{300} + Depth_{325} + Depth_{350}$$

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where,

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$$Depth_{300} = (R_{(401)} - (401 - 303)S_{VIS})/R_{(303)}$$

$$Depth_{325} = (R_{(401)} - (401 - 324)S_{VIS})/R_{(324)}$$

$$Depth_{350} = (R_{(401)} - (401 - 350)S_{VIS})/R_{(350)}$$

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and,

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$$S_{VIS} = \frac{R_{(750)} - R_{(445)}}{750 - 445}$$

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where  $R_{(\lambda)}$  is the reflectance at the wavelength  $\lambda$  given in nanometers.

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- In the visible, the absolute reflectance at 750 nm ( $R_{750}$ ), which is an average value of three points due to the smoothing of the data (see section 2.1), is used.

- 195 • For the characterization of the spectral slope, we calculate the visible (VIS) slope  
 196 as defined in Besse et al. (2015) between 445 and 750 nm. We extended the range  
 197 of wavelength to the NIR domain (1400 nm) to define the visible to near infrared  
 198 (VISNIR) slope. The slopes are determined by a linear fit:

$$199 \quad \text{Reflectance} = a\lambda + b \quad (\text{a=slope})$$

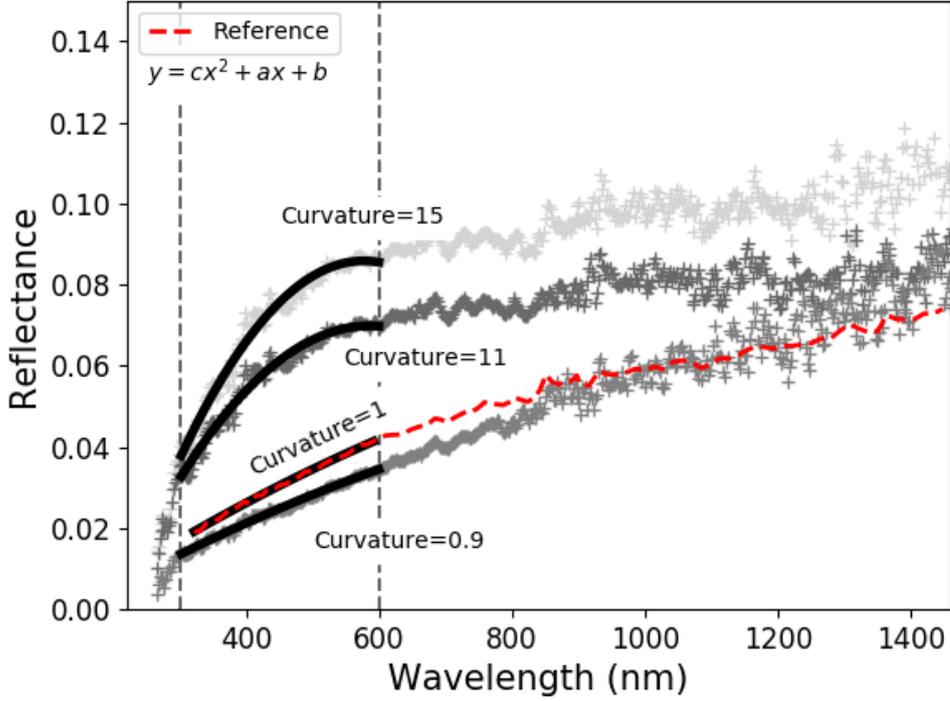
200 where  $445 \text{ nm} \leq \lambda \leq 750 \text{ nm}$  for the VIS-slope and  $445 \text{ nm} \leq \lambda \leq 1400 \text{ nm}$  for  
 201 the VISNIR-slope.

- 202 • After a visual inspection of the spectra, a parameter named Curvature was defined.  
 203 The Curvature is calculated before 600 nm, that is the point at which the spec-  
 204 trum changes from UV curvature to near-infrared slope (arbitrarily by visible in-  
 205 spection). This parameter is represented by the coefficient of the squared power  
 206 of the polynomial fit (degree 2) of the spectrum between 300 and 600 nm:

$$207 \quad \text{Reflectance} = c\lambda^2 + a\lambda + b \quad (\text{c=curvature})$$

208 Random examples are shown in Figure 1.

209 The slopes and the Curvature parameter are normalized to the reference spectrum  
 210 provided by Izenberg et al. (2014) who computed it from the average of 850,000 spec-  
 211 tra of Mercury's surface. By definition, slopes and Curvature are equal to 1 for the av-  
 212 erage surface of Mercury. The UV-downturn parameter previously estimated to 3.0 for  
 213 Mercury's background, using Izenberg et al. (2014) reference spectra, was re-evaluated  
 214 as 3.1 by Besse et al. (2020).



**Figure 1.** Example of calculated Curvature on MASCS spectra, and on Mercury’s reference spectrum (Izenberg et al., 2014). The black curve represents the polynomial fit (degree 2) of the spectrum between 300 and 600 nm. The Curvature parameter corresponds to the variable  $c$  in the equation of the polynomial curve. Furthermore, the Curvature coefficient is normalized to the reference spectra (red, Izenberg et al., 2014) such that the Curvature of the reference spectrum is equal to 1. The spectra with the highest reflectance were randomly selected in Eminescu’s hollows (ob4\_14327\_010045 and ob4\_14326\_164731, see section 2.3). The spectrum with the lowest reflectance was randomly selected in the Northern smooth plains (ob2\_12187\_063041, see section 2.4).

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### 2.3 Hollows observations with MASCS

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MDIS instrument acquired a global and uniform coverage in 8 of its 11 colour filters of more than 90% of the planetary surface during the orbital phase (Domingue et al., 2017). On the other hand, the MASCS instrument is a point spectrometer and thus only observed discrete areas. Dimensions of MASCS footprints vary between 0.1x3km to over 6x7km (Izenberg et al., 2014). Hollows are small depressions, which range in size between several tens of meters to several kilometers (Blewett et al., 2018), hence, they are less likely to be observed with MASCS.

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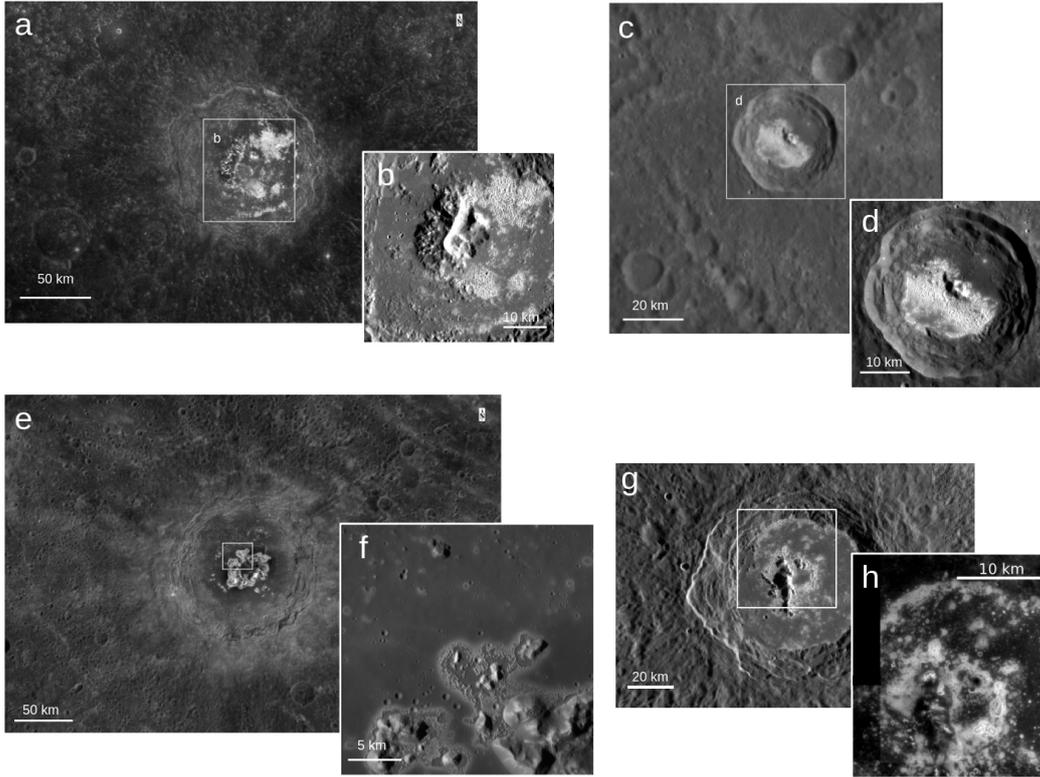
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Using the list defined by Thomas et al. (2014a), we found four hollows observed with sufficient spatial resolution by MASCS. They span a large range of longitudes, but a restricted range of latitudes (15°N to 15°S). Observable hollows are located in the Tyagaraja, Hopper, Eminescu, and Warhol impact crater floors, as shown in Figure 2.

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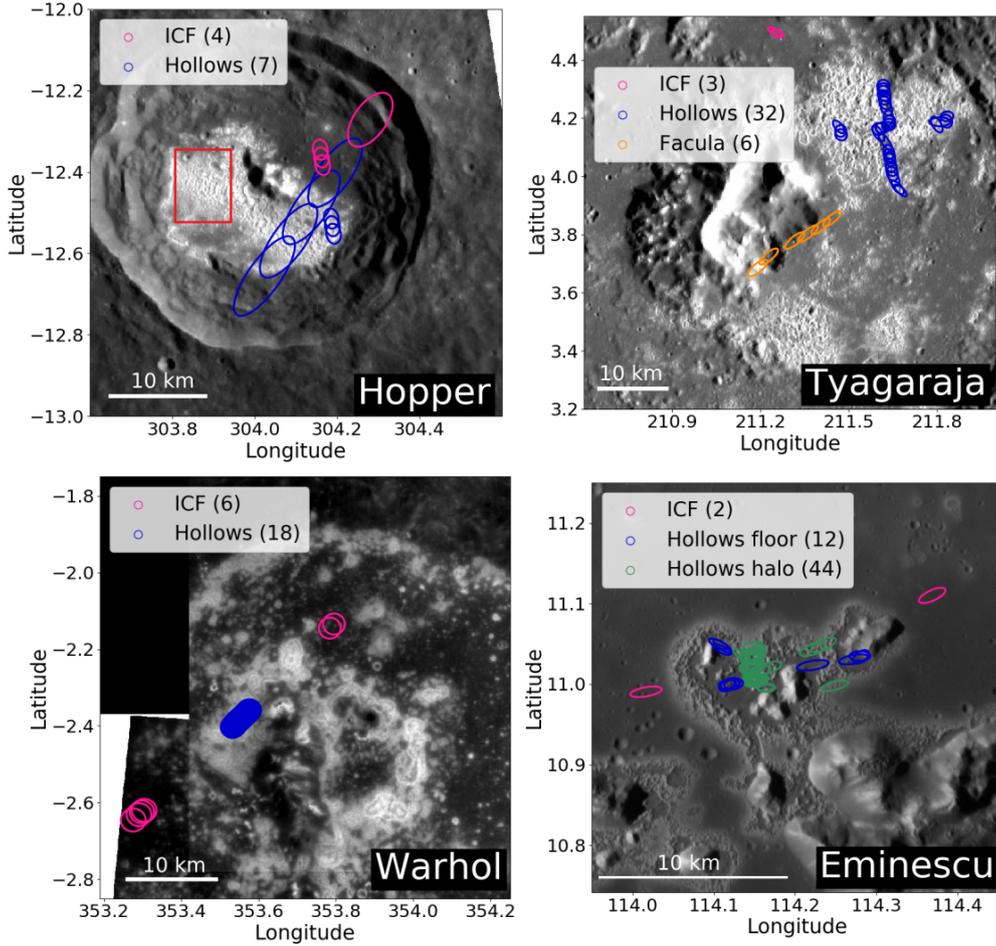
High-resolution images produced by the Narrow Angle Camera (NAC) of the MDIS instrument are used for selecting MASCS footprints. Footprints are represented by an



**Figure 2.** Hollows analyzed in this work. a) Tyagaraja impact crater ( $3.89^{\circ}\text{N}$ ,  $211.10^{\circ}\text{W}$ ; from Wide Angle Camera (WAC)-MDIS image EW1009232948G, 383 m/pixel). b) Zoom on the north-east hollows in Tyagaraja crater (from Narrow Angle Camera (NAC)-MDIS image EN0242713071M, 130 m/pixel). c) Hopper impact crater ( $12.44^{\circ}\text{S}$ ,  $304.40^{\circ}\text{W}$ ; EN1048482439M, 110 m/pixel). d) Zoom on hollows in Hopper crater (EN0223616383M, 49 m/pixel). e) Eminescu impact crater ( $10.66^{\circ}\text{N}$ ,  $245.79^{\circ}\text{W}$ ; EW0234069376G, 476 m/pixel). f) North-north-east part of the central peak in Eminescu impact crater (EN0251632156M, 35 m/pixel). g) Warhol impact crater ( $2.55^{\circ}\text{S}$ ,  $6.27^{\circ}\text{W}$ ; MDIS\_RTM\_N01\_009974\_5942839\_1, 92 m/pixel). h) North part of Warhol impact crater (EN1034982894M and EN1035068908M, 56 m/pixel).

229 ellipse on the NAC images and are selected manually. Figure 3 shows footprints used in  
 230 this study. For each site, at least one footprint located in the host impact crater floor  
 231 is selected. The spatial resolution of MASCS in the Tyagaraja, Hopper and Warhol im-  
 232 pact craters allows the analysis of the properties of the hollows group (Figure 3). In the  
 233 case of Eminescu, a particular hollow can be analyzed. Moreover, the footprint size in  
 234 Eminescu is sufficient to distinguish the hollow floor from the surrounding halo.

235 As for the Hopper impact crater, data of two orbits are used. For the largest foot-  
 236 prints, the spatial resolution of MASCS is too large (around 10 km/footprint) to include  
 237 only material from the hollows (Figure 3). Consequently, the spectra obtained from these  
 238 footprints are thought to be representative of a mixing between hollows and crater floor  
 239 material. By superimposing each footprint on the NAC image, we are able to estimate  
 240 the proportion of hollows field contained in the ellipse with uncertainty of  $\pm 5\%$ .



**Figure 3.** Representation of MASCS footprints used in this study. a) Hopper impact crater floor (ICF) hollows and footprints from 2 orbits (ob2\_12268\_133540, ob3\_13276\_093728) with a spatial resolution between 0.6 to 10 km/footprint. The red rectangle shows the area sampled by Vilas et al. (2016). b) Tyagaraja hollow’s field, the first orbit (ob4\_14128\_101058, 0.7 to 2 km/footprint) is used for hollows and impact crater floor (ICF) and the second one (orange: orb\_11346\_182504, 2.5 to 3.6 km/footprint) is used for Tyagaraja facula. c) Warhol impact crater, the orbit used is ob4\_15064\_011135 (around 2.5 km/footprint). d) Eminescu impact crater central peak (north-west part), the two orbits used are very similar (ob4\_14327\_010045, ob4\_14326\_164731) and are obtained one day apart. The spatial resolution varies between 0.3 to 1.7 km/footprint. The NAC images used are the same as in the previous figure. The number in the legends give the number of MASCS observations for each hollows, Impact crater floor (ICF) and facula in Tyagaraja.

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#### 2.4 Observations of other geological units

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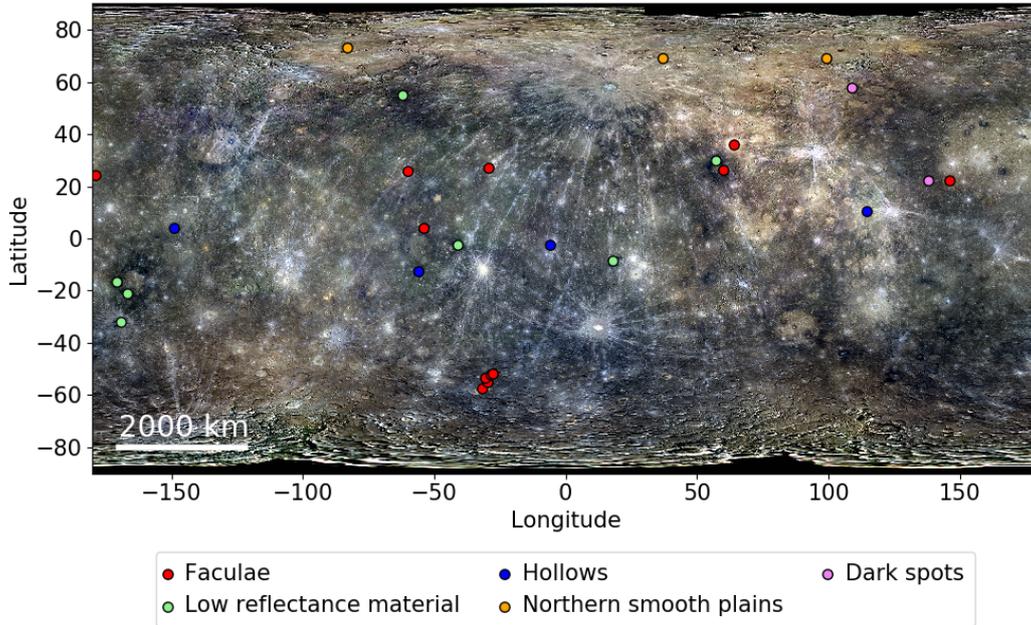
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Hollows are among the brightest features at the surface of Mercury. In order to understand their spectral characteristics in the near-ultraviolet to near-infrared wavelength, we compare them with MASCS observations of other geological units. Several terrains around the Mercury’s surface are used: Dark spots (DS), Low reflectance material (LRM), faculae and Northern Smooth Plains (NSP).

247 DS and LRM materials are thought to be potential parent material to hollows (Xiao  
 248 et al., 2013; Thomas et al., 2016). Due to the elliptical orbit of MESSENGER and their  
 249 small size, the DS which are resolvable with MASCS are located only in the northern  
 250 hemisphere at latitudes higher than 20°N (Figure 4 and Table S1 in the Supporting in-  
 251 formation) (Xiao et al., 2013). LRM are more extended units, several observed by MASCS  
 252 were found at latitudes similar to hollows analyzed in this study (Figure 4 and Table S2).



**Figure 4.** Global distribution of hollows (blue dots) analyzed in this work, relative to other geological units. Low reflectance material, northern smooth plains and faculae areas selected are similar to the size of the dots. The background is a MDIS color global mosaic (3-filters) red: 1000 nm, green: 750 nm, and blue: 430 nm (665 m/pixel; Denevi et al., 2018).

253 Hollows are often found nearby faculae, as in the Tyagaraja impact crater (Blewett  
 254 et al., 2011). The volatile species causing volcanic eruptions could be a source of volatile  
 255 material for the formation of hollows as well (Blewett et al., 2011, 2013; Thomas et al.,  
 256 2014a). To investigate their possible relationship, we compare the spectral properties of  
 257 hollows and faculae. We selected MASCS observations in the facula of the Tyagaraja im-  
 258 pact crater (Figure 3). Moreover, spectral properties of faculae were studied by Goudge  
 259 et al. (2014) and Besse et al. (2015) using the MASCS spectrometer. Besse et al. (2020)  
 260 determined the diameter of 14 faculae, and 12 of them (Figure 4 and Table S3) have in-  
 261 strumental conditions (i.e. temperatures, see section 2.1) similar to those determined suit-  
 262 able in this analysis, and are thus used for comparison to hollows.

263 Northern smooth plains (NSP) occupy more than 7% of Mercury's surface (Byrne  
 264 et al., 2018) and are, similarly to faculae, a consequence of volcanic activity. We have  
 265 selected 3 regions with a large number of MASCS footprints passing through NSP re-  
 266 gions (Figure 4 and Table S4).

267 Table 1 lists the number of observations used in each unit and illustrates the diffi-  
 268 culty in finding MASCS footprints in smaller units like hollows and DS. Although we  
 269 selected regions in LRM and NSP with the least surface feature heterogeneity (impact

270 craters, ejecta, rays, possible hollows and dark spots that can modify spectral proper-  
 271 ties), we eliminated spectra which deviate more than 3 sigma from the median.

**Table 1.** Number of MASCS observations selected per geological unit.

<b>Geological unit</b>	<b>Description</b>	<b>Number of observations</b>
<b>Low Reflectance Material</b>	Dark material excavated by impact cratering and potentially parent material of hollows (Thomas et al., 2016).	1115
<b>Northern Smooth Plains</b>	Largest continuous plains resulting of effusive volcanism (Denevi et al., 2013; Byrne et al., 2018).	1352
<b>Faculae</b>	Pyroclastic deposits formed through explosive volcanic processes. (Kerber et al., 2009, 2011)	1377
<b>Dark spots</b>	Sub-category of LRM at smaller scale. Hollows commonly occupy the centers of the observed dark spots (Xiao et al., 2013).	6
<b>Hollows (4)</b>	Irregularly shaped depressions, shallow, with flat floor and surrounded by bright halo (Blewett et al., 2018).	113

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### 3 Spectral properties of hollows from near-ultraviolet to near-infrared

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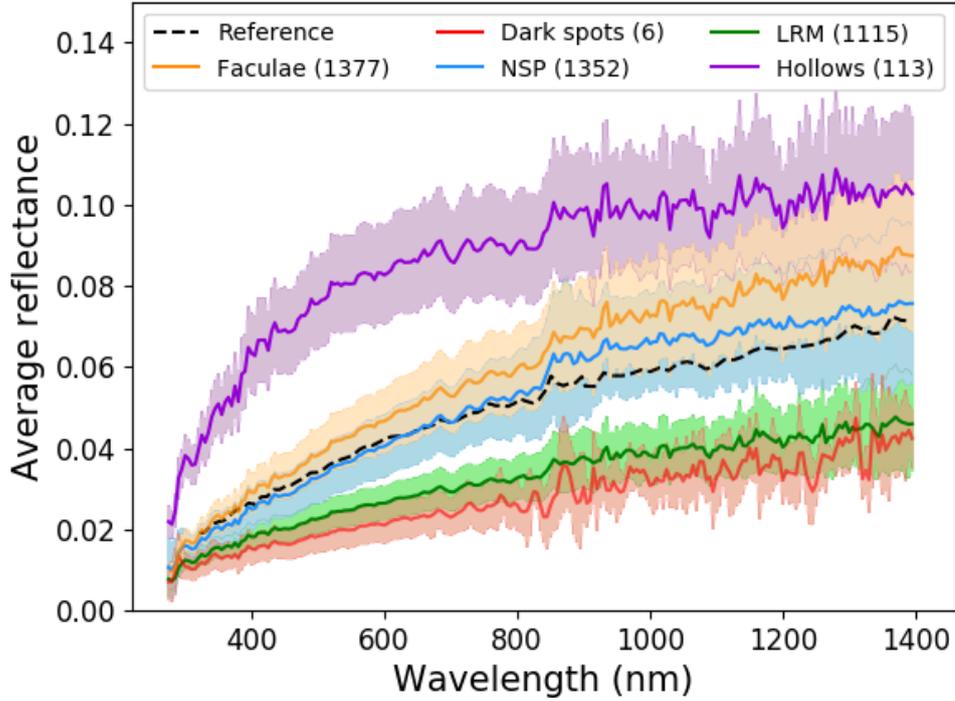
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Before starting the analysis with the spectral parameters, the average spectrum of each geological unit is derived from the corrected spectra (see section 2.1). The mean spectrum of hollows differs from others by its unique shape in the near-ultraviolet and a higher reflectance while the others average spectra overlap across the entire spectral range of MASCS (Figure 5).



**Figure 5.** Average reflectance spectrum of each geological unit described in section 2.3 and 2.4. LRM: Low Reflectance Material, NSP: Northern Smooth Plains. The shaded regions are error bars, which correspond to the standard deviation of the spectra around the mean. Reference is the average spectrum of Mercury’s surface (Izenberg et al., 2014).

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### 3.1 Visible to near-infrared properties

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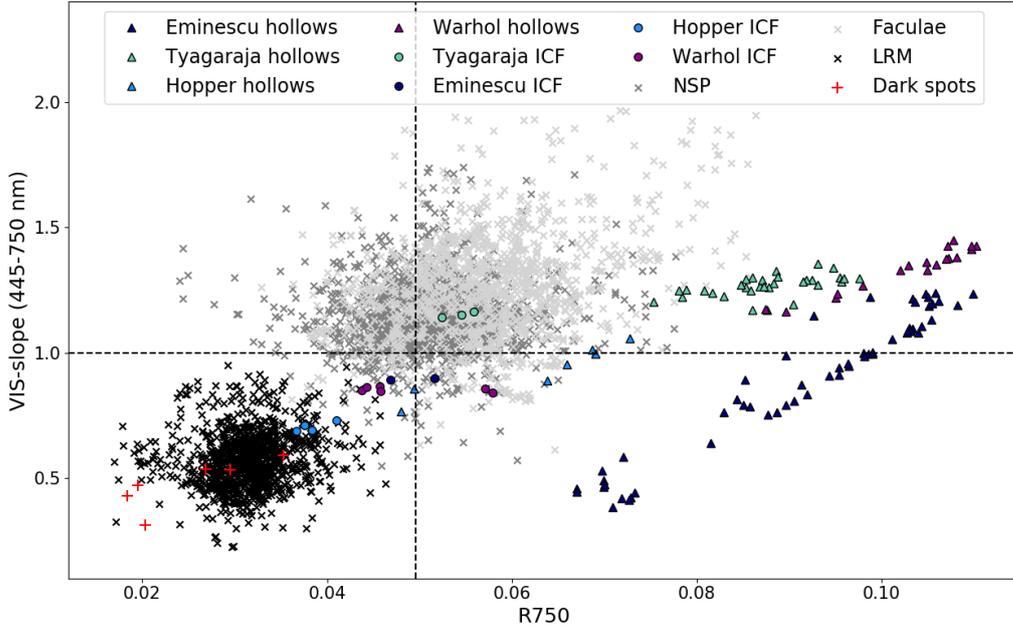
The MASCs reflectance at 750 nm is approximately twice as high for the hollows than Mercury's mean spectrum (Figure 5 and 6). While the faculae are also bright features on the surface of Mercury (Kerber et al., 2009), they have a significant lower reflectance than the hollows at all wavelengths (Figure 5). These results are consistent with those obtained from MDIS observations, which show that the hollows are among the brightest geological units on the surface of Mercury (Blewett et al., 2011, 2013).

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All geological features observed with MASCs in this study have positive spectral slopes (reflectance increases toward longer wavelengths). VIS-slope of hollows ranges from 0.38 to 1.45 (Figure 6).



**Figure 6.** VIS-slope parameter versus R750 parameter in hollows and in various geological units: Low Reflectance Material (LRM), faculae, Northern Smooth Plains (NSP), dark spots and Impact Crater Floor (ICF). Black dashed lines show reflectance at 750 nm and value of the VIS-slope parameter for the average surface of Mercury. In general, the hollows are brighter than other units on Mercury.

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MDIS spectral analysis showed that the hollows are less red than the Mercury's mean surface (Blewett et al., 2013; Thomas et al., 2016), i.e. a VIS-slope parameter lower than 1. However, those results were obtained using only two spectral channels (433 and 749 nm). Thomas et al. (2016) estimated the visible slope by dividing images at 430 nm by images at 750 nm for MDIS and/or calculating the ratio of reflectance at 445nm/750nm in MASCs data. In our study, the parameter VIS-slope is derived from the best fit line between 445 and 750 nm, that is from around 60 data points. Therefore this parameter is more sensitive to the overall shape of the spectra compared to a ratio using 2 bands. The curvature of the hollows' mean spectrum at the shortest wavelengths (Figure 5) could explain why the VIS-slope is higher than 1 for many of the hollows.

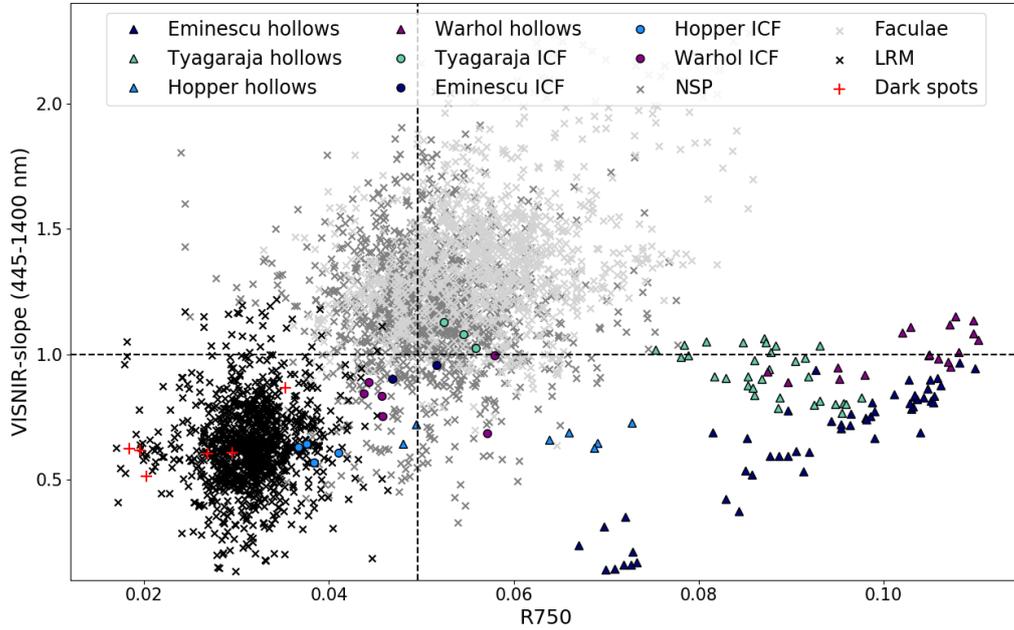
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At longer wavelengths, the hollows mean spectrum is flatter than that of the mean spectra of other geological units (Figure 5). The VISNIR-slope parameter allows the study of the effect of the near-infrared wavelengths. The hollows spectra have a VISNIR-slope

301 lower than their VIS-slope (Figure 7). In fact, 76% of the normalized spectral slopes in  
 302 the VIS to NIR are lower than 1, while only 30% are in the visible. For the other geo-  
 303 logical units, the difference between VIS-slope and VISNIR-slope is not as significant (Fig-  
 304 ure 6 and 7), suggesting that the hollows spectra are flatter in the NIR than the spec-  
 305 tra of the other units.



**Figure 7.** VISNIR-slope parameter versus R750 parameter in hollows and various geological units: Low Reflectance Material (LRM), faculae, Northern Smooth Plains (NSP), dark spots and Impact Crater Floor (ICF). Black dashed lines show reflectance at 750 nm and value of the VISNIR-slope parameter for the average surface of Mercury. In general, hollows have a visible to near-infrared slope less steep than the Mercury’s mean spectrum (Izenberg et al., 2014).

306 Space weathering affects the reflectance spectra by increasing the spectral slope in  
 307 the visible-near-infrared due to the presence of submicroscopic iron (smFe) (McCord &  
 308 Adams, 1972a; McCord & Adams, 1972b; Fischer & Pieters, 1994; Domingue et al., 2014).  
 309 Hollows are thought to be among the most recent geological units on the surface of Mer-  
 310 cury (Blewett et al., 2018). Their reduced spectral slope in the VISNIR could be a con-  
 311 sequence of their relatively young age.

312 Although the spectral parameters in the visible (VIS-slope, VISNIR-slope and R750)  
 313 allow assumptions to be made about the hollows, they overlap with those of other geo-  
 314 logical units. Thus at visible wavelengths, no spectral parameters used in this paper  
 315 allow the hollows to be uniquely characterised.

### 3.2 Near-ultraviolet properties and spectral curvature as diagnostic of hollows

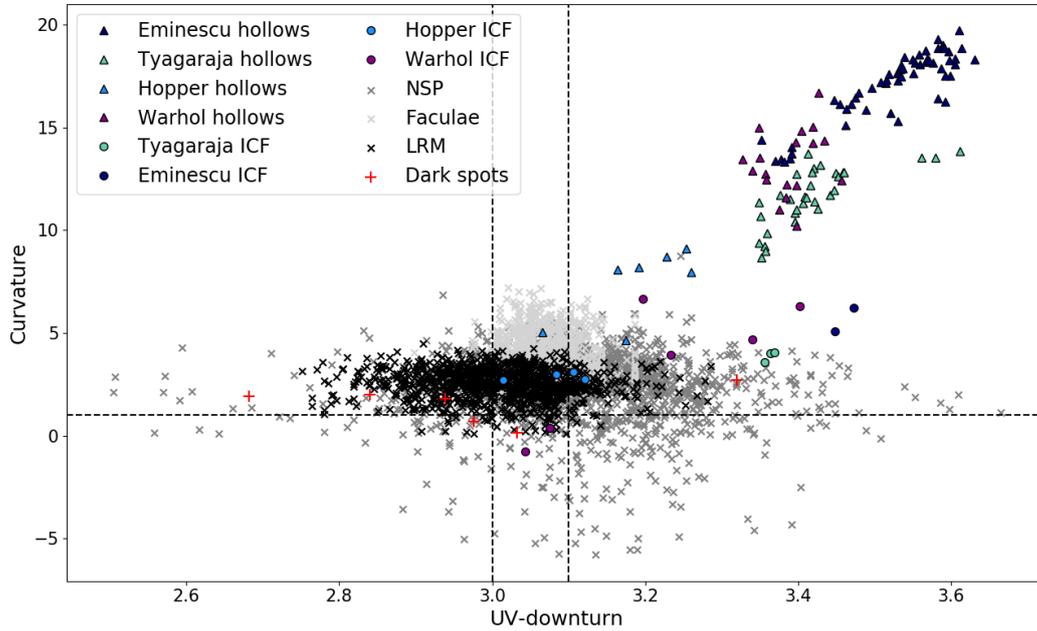
The MASCS reflectance spectra of hollows reveal the highest UV downturn and curvature at wavelengths shortward of 600 nm. The strength of the downturn and the curvature differs among the hollows and are linearly correlated (Pearson coefficient correlation of 0.88 with a significance level of 99.9%). For the other geological units, no correlation was found between the two parameters. This result implies a process or material influencing the two spectral parameters in the hollows that would not be found in other geological units. Several factors could potentially influence the downturn of the reflectance in the ultraviolet, we mention three hypotheses here: 1) the space weathering, 2) the grain size of the material forming the hollows and 3) the presence of sulfides.

As mention on the previous section, space weathering increases the spectral slope in the VISNIR, resulting in a reddening of the spectrum. (Domingue et al., 2014). In the near-ultraviolet, it will start to decrease the slope (bluing), especially between 300 and 400 nm (Hendrix & Vilas, 2006; Vilas & Hendrix, 2015). This change of the slope in the near-ultraviolet has been interpreted by Hendrix and Vilas (2006) as the result of the formation of nanophase iron coatings on mineral grains. The hypothesis of space weathering could explain the slopes of the hollows spectra in the near-ultraviolet and visible-near-infrared. Research on the effects (Hendrix & Vilas, 2006; Vilas & Hendrix, 2015) of space weathering on reflectance spectra does not indicate a curvature of the spectrum between 300 and 600 nm, making the idea of space weathering, in the absence of other possible factors, less likely.

Another possible contributor to the high UV-downturn in the hollows is a difference in grain size between hollows and other geological units. Laboratory studies have shown that as the grain-size decreases, the UV-downturn increases for common planetary minerals (Cloutis et al., 2008). If the particle size is the only one contributing factor to the high downturn of the hollows, then the hollows have finer grain size than the other geological units studied here. Phase ratio analysis suggests that hollows around the central peak of Eminescu crater have finer particle sizes than the surrounding crater floor (Blewett et al., 2014). A second phase ratio analysis confirms on a sample of eight sites that hollows have finer grain size than their adjacent terrains (Thomas et al., 2016). However, hollows often have UV-downturn close to that of their host crater floor, which is particularly the case for Eminescu (Figure 8). Consequently, grain size does not appear to be the only one factor influencing this spectral parameter. In addition, no studies have shown that particle size has an impact on the curvature of the spectrum between 300 and 600 nm, making this idea unlikely.

An alternative possibility to the specific properties of hollows in the UV is a specific composition. Sulfides are the most commonly cited candidates for the volatile species at the origin of the hollows (Blewett et al., 2011, 2013; Vilas et al., 2016; Lucchetti et al., 2018; Helbert et al., 2013). Laboratory measurements carried out under the conditions of MASCS observations show that the spectra of fresh CaS, NaS and MgS (2 samples) have a strong absorption band between 280 and 350 nm, centered at 300 nm (Varatharajan et al., 2019). The Mercury daytime temperatures have different implications on the spectral features of these samples (Varatharajan et al., 2019). For one of the MgS sample, the absorption features disappear after the thermal processing at Mercury's surface temperatures. The spectral contrast of the absorption features around 300 nm is slightly subdued for the heated CaS and the second heated MgS sample while the heated NaS shows stronger UV spectral features (Varatharajan et al., 2019). In consequence, the spectral features of CaS, MgS and NaS, even under the temperature conditions of Mercury, may involve the high UV downturn of the hollows. The curvature of laboratory spectra of Mercury analogs has not been studied, however it would be interesting to compare the Curvature of spectra measured in the laboratory on materials possibly representative of hollows with our values in order to determine if this curvature can be related to the pres-

369 ence of sulfides or any other minerals. For example, we calculated the reflectance cur-  
 370 vature for one of the MgS sample presented by Varatharajan et al. (2019) and obtained  
 371 a value of 22, slightly higher than our hollow values.



**Figure 8.** Curvature versus UV-downturn for hollows and the various geological units: Low Reflectance Material (LRM), faculae, Northern Smooth Plains (NSP), dark spots and Impact Crater Floor (ICF). Black dashed lines show the values of these parameters for the mean spectrum of Mercury. The UV-downturn estimated at 3.0 for the average surface was re-evaluated at 3.1 (Besse et al., 2020). The hollows stand out slightly by UV-downturn parameter and largely by Curvature parameter.

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### 3.3 Influence of abundance: The Case of Hopper Crater

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The spatial resolution of the largest MASCS footprints inside Hopper is insufficient to discriminate the hollows from the crater floors (Figure 3). However, these observations can be used to investigate the evolution of the spectral parameters with the percentage of hollows material in the MASCS footprint (Table 3). We found a linear increase in the absolute reflectance at 750 nm with increasing the percentage of hollows in the footprint area. The same result is observed with the visible slope (Table 3). The orbit with the highest spatial resolution confirms this observation: the footprints covering 100% of the hollows field show higher values of VIS-slope and R750 than the footprints which did not contain the hollows field (Table 4). The evolution of these parameters is independent of the observation conditions (viewing geometry, in particular emission angle, and temperature).

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The increasing VIS-slope with the increasing percentage of hollows in the footprint is a surprising result. In fact, the hollows are described in literature as having a less steep slope than the surrounding material (Blewett et al., 2013; Thomas et al., 2016). However, in our study, the calculation of the slope in the visible seems impacted by the shape of the spectrum in the UV (see section 3.1). Although the Curvature is not linearly correlated with the percentage of hollows in the footprint, footprints containing 0% hollows still have lowest Curvature values. Furthermore, footprints with 100% hollows have the highest Curvature values (Table 3).

**Table 2.** Spectral parameters derived from the observations of the orbit with the largest footprints (ob2\_12268\_133540) in Hopper impact crater (Figure 3).

Area of hollows in footprint (%)	R750*	VIS-slope**	UV-downturn	VISNIR-slope	Curvature
<b>0</b>	0.038	0.70	3.08	0.64	3.00
<b>25</b>	0.048	0.77	3.06	0.64	5.04
<b>45</b>	0.049	0.86	3.17	0.72	4.64
<b>80</b>	0.064	0.89	3.19	0.66	8.20
<b>95</b>	0.066	0.95	3.26	0.70	7.97

\*Pearson correlation coefficient between percentage of hollows in the footprint and R750: 0.99 (significance level: 99%) \*\*Pearson correlation coefficient between percentage of hollows in the footprint and VIS-slope: 0.98 (significance level: 97%)

**Table 3.** Spectral parameters obtained from the observations of the orbit with the smallest footprints (ob3\_13276\_093728) in Hopper impact crater (Figure 3).

<b>Area of hollows in footprint (%)</b>	<b>R750*</b>	<b>VIS-slope**</b>	<b>UV-downturn</b>	<b>VISNIR-slope</b>	<b>Curvature</b>
<b>0</b>	0.038	0.72	3.01	0.72	2.72
<b>0</b>	0.037	0.70	3.11	0.65	3.09
<b>0</b>	0.037	0.68	3.12	0.59	2.75
<b>100</b>	0.069	0.99	3.16	0.64	8.07
<b>100</b>	0.069	1.01	3.23	0.63	8.72
<b>100</b>	0.073	1.06	3.25	0.73	9.09

\*Pearson correlation coefficient between percentage of hollows in the footprint and R750: 0.99 (significance level: 99%) \*\*Pearson correlation coefficient between percentage of hollows in the footprint and VIS-slope: 0.98 (significance level: 97%)

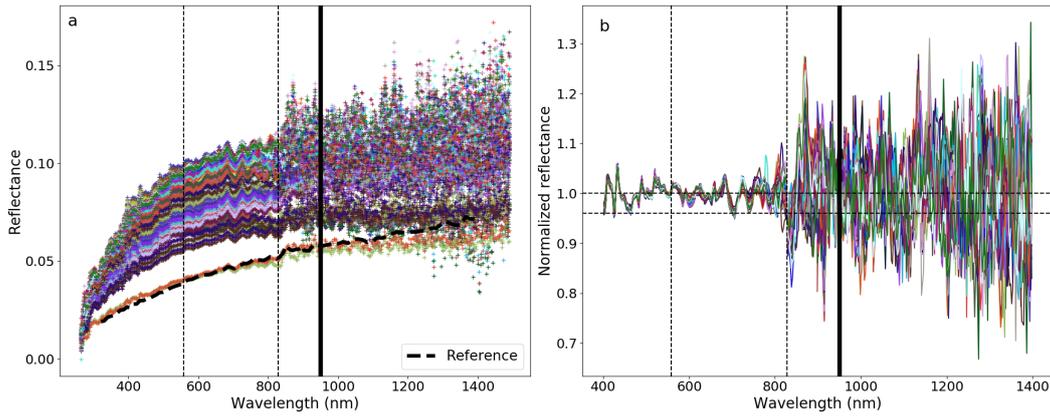
#### 392 4 Investigation of absorption bands in hollows

393 Previous analysis of MASCS spectra did not identify any absorption features, sug-  
 394 gesting that Mercury’s surface is dominated by silicates with low ferrous iron content  
 395 (Izenberg et al., 2014). Thomas et al. (2016) did not find any absorptions in the MASCS  
 396 spectra obtained in the hollows of Eminescu and Raditladi. However, they found a weak  
 397 absorption band in the MDIS data for Raditladi centered around 600 nm, as observed  
 398 in the Dominici, Hopper, Canova and Velazquez impact craters by Vilas et al. (2016) and  
 399 Lucchetti et al. (2018). In this study, we performed a detailed analysis in order to in-  
 400 vestigate absorption features specific to hollows in the four studied samples.

#### 401 4.1 Searching absorption bands with MASCS

402 A continuum removal has been applied to the MASCS spectra of hollows to high-  
 403 light the absorption bands observed with MDIS between 528 and 828 nm with a max-  
 404 imum depth of 4% (Vilas et al., 2016; Lucchetti et al., 2018) and towards 1000 nm (Lucchetti  
 405 et al., 2018). The shape of the MASCS spectra of hollows in the visible is not linear (Fig-  
 406 ure 5), thus the continuum is approximated by a polynomial fit of degree 2 between 400  
 407 and 828 nm, and a straight line between 828 and 1400 nm. Continuum removed spec-  
 408 tra are flat and lack absorption bands (Figure 9). The noise of the MASCS VIS detec-  
 409 tor is stable between 400 and 700 nm and seems to be related to the instrument. At longer  
 410 wavelengths, the noise increases and differs between observations. A strong signal vari-  
 411 ation occurs between 800 and 900 nm, and is not related to the junction of the spectra  
 412 obtained by the 2 detectors (Besse et al., 2015). This small jump in reflectance is reported  
 413 in spectra obtained in various units and is also observable on the Mercury’s reference spec-  
 414 tra obtained using more than 850 000 spectra (Izenberg et al., 2014). We interpreted this  
 415 variation in reflectance as a residual error in the calibration related to a change in the  
 416 response of the instrument in this wavelength range. As expected, in the NIR the signal-  
 417 to-noise ratio decreases and no conclusion can be made about the existence of a weak  
 418 absorption band towards 1000 nm.

419 The large phase angles of the MASCS data could be the source of the lack of ab-  
 420 sorption bands in the MASCS spectra. However, Varatharajan et al. (2019) has shown



**Figure 9.** a) MASCs spectra obtained in hollows (113). The two spectra close to the reference spectrum are measured in Hopper impact crater and contain 25% and 45 % of hollows (cf. Table 2). b) Continuum removed hollows spectra. The thick vertical black line shows the junction of the two detectors of MASCs VIRS spectrometer. The two vertical dashed lines are the wavelengths used by Vilas et al. (2016) and Lucchetti et al. (2018) to define the absorption bands in MDIS filters. The horizontal dashed lines highlight a band depth of 4% as reported in Lucchetti et al. (2018). No absorptions above the noise are seen in these MASCs spectra.

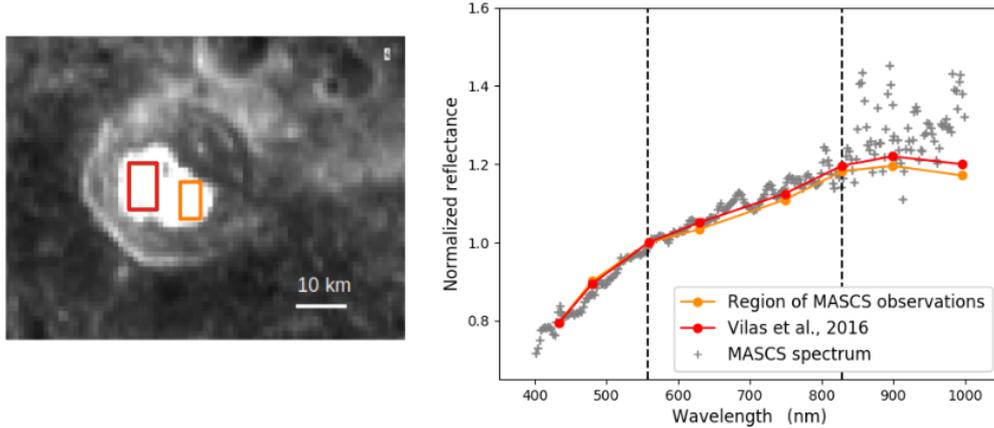
421 that the phase angle has only minor effects on sulfides spectral features in the UV and  
 422 VIS. Residual calibration error is a possible factor explaining the differences between the  
 423 two instruments. For example, a calibration error could create an absorption band in MDIS  
 424 or remove one in the MASCs data. Another hypothesis to explain the lack of absorp-  
 425 tion features is a low content of pure sulfides in the MASCs footprints. In fact, Izenberg  
 426 et al. (2014) showed that at least 75% of pure sulfides are needed in the MASCs field-  
 427 of-view to be detectable in the spectra. The absorption band around 600 nm observed  
 428 in several hollows has a maximum depth of 4% (Vilas et al., 2016; Lucchetti et al., 2018),  
 429 if the concentration of pure sulfides is too low the band is within the noise of MASCs  
 430 spectra.

431 However, the absence of a band at 600 nm does not exclude the presence of sul-  
 432 fides. Helbert et al. (2013) showed that the thermal processing at Mercury daytime tem-  
 433 perature reduces the spectral contrast of the diagnostic features of sulfides around 600  
 434 nm. In addition, recent laboratory measurements under MASCs observing conditions  
 435 show that the sulfides (fresh or heated) proposed in section 3.2 (CaS, NaS and one MgS  
 436 sample) to explain the high values of UV-downturn in hollows spectra, do not exhibit  
 437 absorption bands in the visible range (Varatharajan et al., 2019).

#### 438 4.2 MDIS and MASCs comparison of Hopper’s hollows

439 Intrinsic change in the composition of the hollows could explain why we do not ob-  
 440 serve an absorption band in the spectra obtained by MASCs. Vilas et al. (2016) stud-  
 441 ied the western part of the group of hollows in Hopper impact crater while MASCs looked  
 442 at the eastern one. In order to investigate possible spectral changes within Hopper, we  
 443 compared MDIS observations in the two parts of the hollows. Moreover, we compared  
 444 MDIS measurements with MASCs spectra directly. We used the Experiment data record  
 445 (EDR) of MDIS-WAC (Hawkins et al., 2007), and applied a radiometric and photomet-  
 446 ric calibration (Hapke, 1981; Domingue et al., 2015; Bott et al., 2019). Average reflectance  
 447 obtained in both areas (the original area studied by Vilas et al. (2016), and the area ob-

448 served with MASCS) of the hollows is represented in Figure 10. The absorption feature  
 449 seems to be homogeneous in the hollows field from the MDIS observations, which excludes  
 450 the hypothesis of an intrinsic spectral variation. The lack of spectral features in the MASCS  
 451 spectra is then mostly likely linked to residual calibration errors in one of the two instru-  
 452 ments or a pure sulfides concentration too low to be detected with the MASCS instru-  
 453 ment (see section 4.1). Moreover, the absorption band observed by Vilas et al. (2016)  
 454 in Hopper is the weakest of the hollows they studied. MASCS observations in the Do-  
 455 minici crater, where the band is deeper, do not have sufficient spatial resolution.



**Figure 10.** a) WAC-MDIS image (EW0211022288D) of Hopper crater with the red rectangle marking the area sampled by Vilas et al. (2016) and orange rectangle marking region observed with MASCS (Figure 3). b) Normalised reflectance of the two areas as observed by MDIS, and one example of normalized MASCS spectra in the same region. The two black dashed lines bound the upper and lower wavelength limits of the absorption band identified by Lucchetti et al. (2018) and Vilas et al. (2016). The aspect ratio is different from Vilas et al. (2016) however the depth of the absorption band is similar.

## 456 5 Discussion

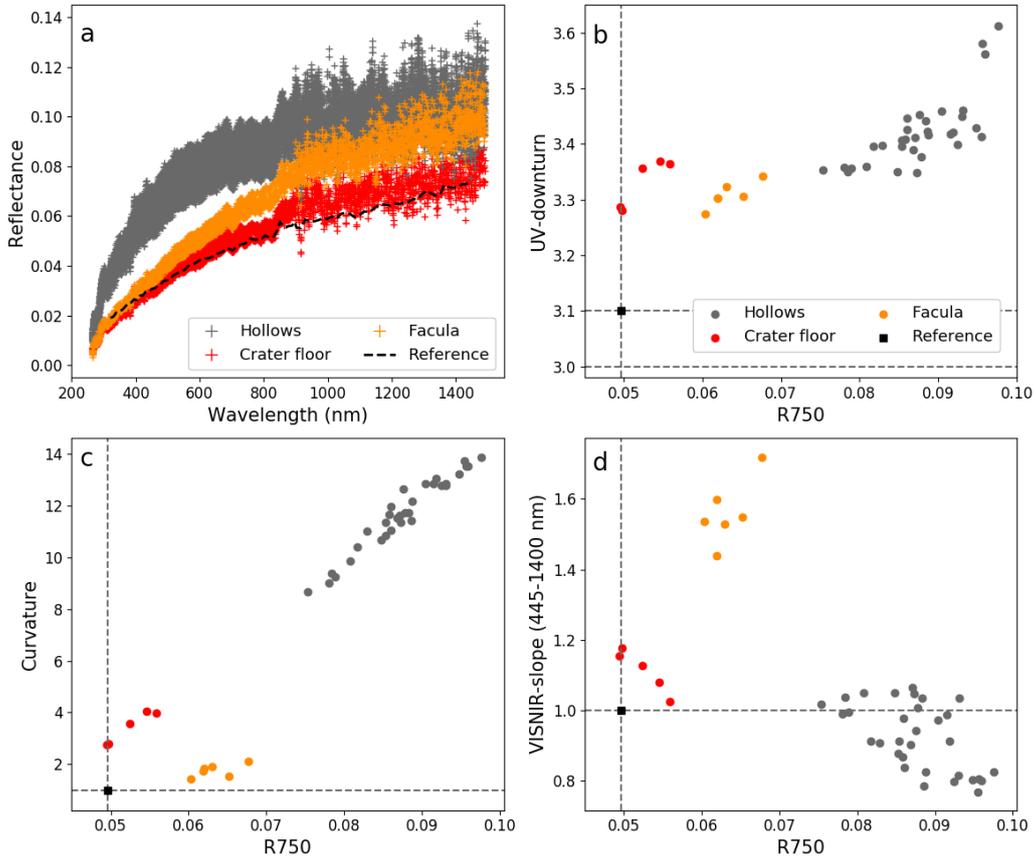
### 457 5.1 Origin of hollows volatile components

#### 458 5.1.1 Are volatile components of hollows linked to pyroclastic deposits?

459 The geological history of the Tyagaraja crater seems to be complex given that the  
 460 crater floor is covered both by hollows and facula (Blewett et al., 2011). Unfortunately,  
 461 the spatial resolution of images is insufficient to distinguish if the surface of the bright  
 462 patches is fully covered by hollows material (Figure 3). Consequently, the spectral vari-  
 463 ability of Tyagaraja hollows could be due to different proportions of materials within the  
 464 instrument footprint area (e.g. hollows, crater floor, facula). Tyagaraja’s facula and crater  
 465 floor have similar values of UV-downturn (Figure 11b). The hollows tend toward high  
 466 UV downturns (Figure 11b). However, these units are clearly distinct in the Curvature  
 467 and the VISNIR-slope (Figure 11c and d). As expected, the spectral slope of facula is  
 468 redder than Mercury’s average, while the spectral slope of hollows is generally less red.  
 469 The Curvature parameter of hollows is much higher than the Curvature of the facula.

470 In section 3.1 and 3.2, we proposed several factors that can influence the spectral  
 471 properties. These contributors can also influence the spectral properties of the pyroclas-  
 472 tic deposits. If we considered the space weathering, resulting in a reddening of the spec-

473 tral slope in the visible-near-infrared, as the only contributing factor for the VISNIR slope,  
 474 the chronological sequence of events would therefore be: 1) formation of the facula, 2)  
 475 crater formation and finally 3) the formation of the hollows. However, it is impossible  
 476 for the facula to be older than the crater in which it formed. A physical difference (e.g.  
 477 grain size) between each geological unit could play a role in the near-ultraviolet (Cloutis  
 478 et al., 2008). However, space weathering or grain size is not known to create a curvature  
 479 of the spectrum between 300 and 600 nm (see section 3.2). Compositional differences be-  
 480 tween each geological unit seem necessary to explain the different effects on the spectra.



**Figure 11.** a) MASCS spectra obtained in the Tyagaraja impact crater for three geological units: facula, hollows and impact crater floor. Each spectra correspond to a footprint shown in Figure 2. b, c and d) Spectral parameters versus R750 for the spectra shown in (a). Hollows and facula in the Tyagaraja impact crater have distinct spectral properties.

481 Blewett et al. (2011, 2013) proposed that volatile species could be trapped under  
 482 the pyroclastic deposits during the lava emplacement and after be at the origin of the  
 483 hollows formation. Hollows formed under these conditions could have different proper-  
 484 ties than hollows formed on LRM or impact melt, for example, because the origin and/or  
 485 nature of the volatile component could be different. However, in our study, the Tyagaraja  
 486 hollows do not have spectral properties that are different from other hollows. In partic-  
 487 ular, they have spectral properties close to those of Warhol hollows (Figures 6, 7 and 8),  
 488 yet no faculae are identified in Warhol impact crater. Thus, the volatile compound re-  
 489 sponsible for the formation of Tyagaraja’s hollows is probably similar to the others. This  
 490 result suggests two hypotheses:

- 491 1. The material forming hollows has a close composition to volatile material that can  
 492 be condensed or trapped after/during an explosive eruption on Mercury. Nittler  
 493 et al. (2014) showed that the largest pyroclastic deposit on Mercury is depleted  
 494 in S and C compared to their surroundings. These elements could be the volatile  
 495 species driving the explosive eruptions on Mercury (Blewett et al., 2018) and also  
 496 responsible for the formation of hollows.
- 497 2. The parent material of the hollows would be the crater floor, even if it is covered  
 498 by faculae. In this case, the heat of the pyroclastic deposit on the impact crater  
 499 floor could be responsible for the formation of the hollows, which could explain  
 500 why hollows are often found near faculae. This hypothesis is supported by the dif-  
 501 ferences in curvature and VISNIR-slope between faculae and hollows that suggest  
 502 differences between material forming these units. Some faculae would have to be  
 503 relatively young, as hollows are identified among the youngest formations on the  
 504 surface of Mercury. Thomas et al. (2014a) showed that faculae occurred until less  
 505 than 1 Ga, and Blewett et al. (2018) dated hollows as up to 1 Ga. Therefore, on  
 506 a geological time scale, the formation of hollows and faculae could be close, sup-  
 507 porting our hypothesis.

### 508 **5.1.2 Are volatile components of hollows linked to the host-crater?**

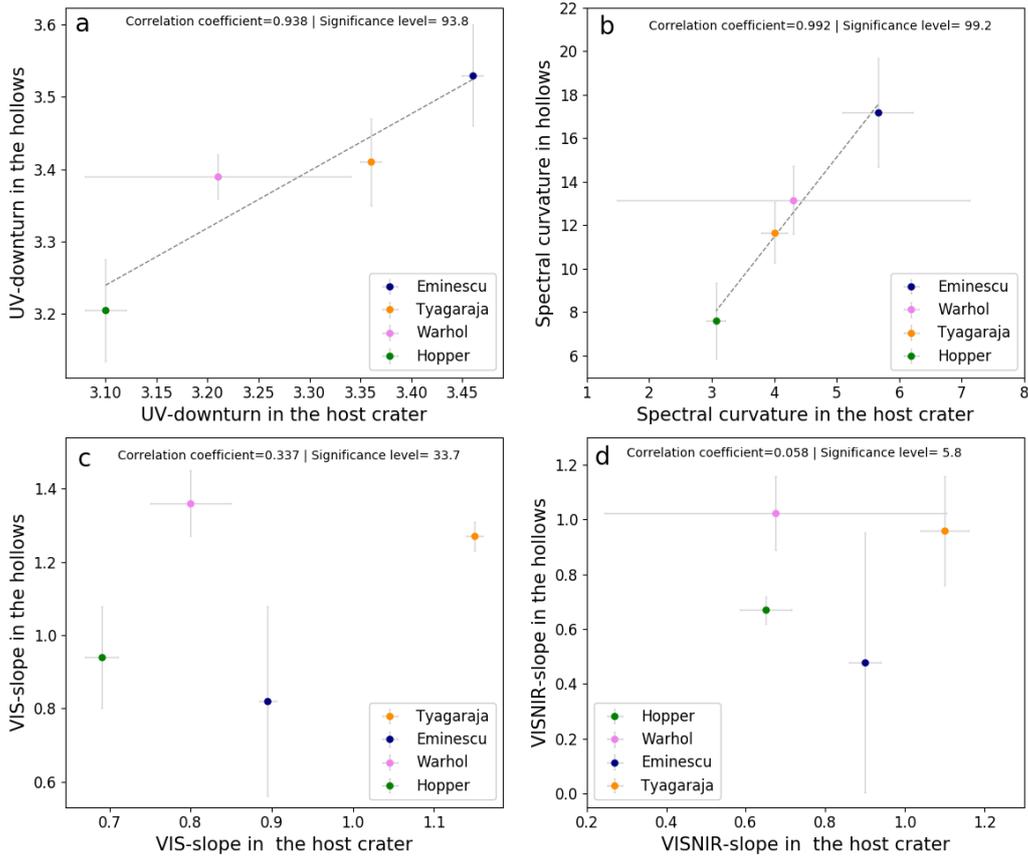
509 MASCS observations allow the comparison of the spectral properties between the  
 510 hollows and their parent material: crater floor. We found a strong linear correlation be-  
 511 tween UV-downturn in the host-craters and their associated hollows (Figure 12). The  
 512 same correlation is observed for the Curvature. This result is consistent with the cor-  
 513 relation found before between UV-downturn and Curvature (see section 3.2). The spec-  
 514 tral slopes are uncorrelated between hollows and the host crater floor.

515 This correlation could be explained by two hypotheses:

- 516 1. A mixing between hollows and local crater floor material in the MASCS footprints.  
 517 We have shown in section 3.3 that a mixing can have an effect on spectral prop-  
 518 erties.
- 519 2. The physical and/or chemical properties of the hollows material are dependent on  
 520 the parent material. If the volatile rich layer is created during the differentiation  
 521 of the impact melt, as proposed by Vaughan et al. (2012), there is no reason for  
 522 the composition of this layer to be the same for all the impact craters. In fact, the  
 523 composition of the volatile-rich layer can vary for example with the depth of ex-  
 524 cavation, the material excavated and also with the temperature of the impact melt.  
 525 The differentiation of a possible sulfide layer will therefore be different in terms  
 526 of composition for each impact melt and crater, especially if heterogeneity is present  
 527 in the crust even before the impact. Our analysis is in agreement with a differ-  
 528 ent volatile layer depending on each impact crater. These interpretations exclude  
 529 the presence of a global volatile rich layer with unique composition.

### 530 **5.2 Formation and evolution of hollows**

531 The high spatial resolution of MASCS observations and NAC-MDIS images around  
 532 the central peak of Eminescu impact crater offers the opportunity to investigate the spec-  
 533 tral properties across the different parts of this particular hollow (Figure 3). Some foot-  
 534 prints are located in the interior of the hollows and others on the surrounding bright part.  
 535 We found that all the parameters have higher values in the halo than in the hollows floor.  
 536 In the VIS to NIR, the two parts of the hollows have less steep slopes than the impact  
 537 crater floor (Figure 13). The UV-downturn in the hollows floor is close to the UV-downturn  
 538 of the impact crater floor (Figure 13). The UV-downturn in the halo is greater than the  
 539 UV-downturn in the host-crater. In the halo, all the parameters (VIS-slope, VISNIR-  
 540 slope, UV-downturn and curvature) are correlated with the R750, and we can observe

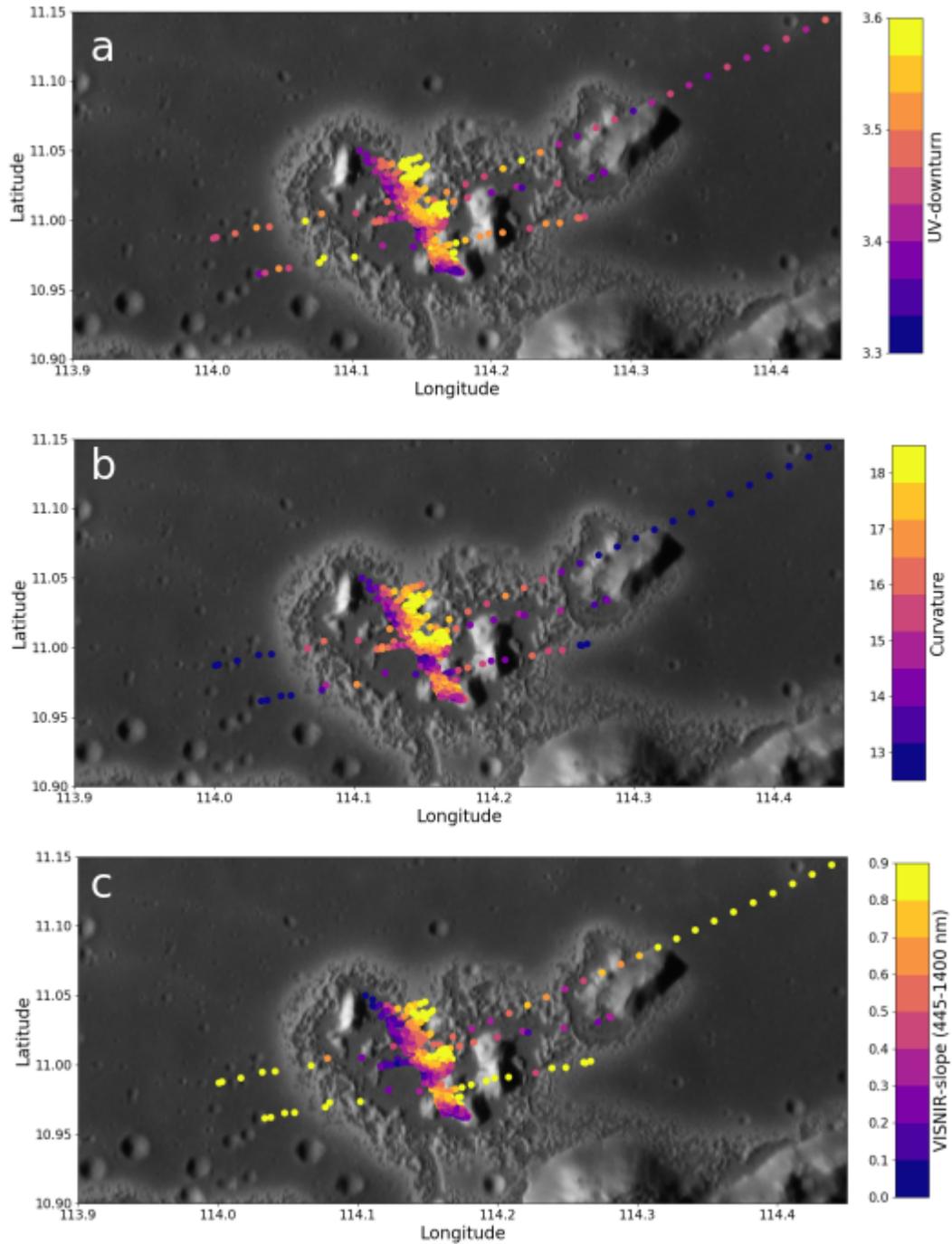


**Figure 12.** Linear correlation between parameters in the host crater and parameters of its associated hollows field. Dots represent the median value of all spectra used and the error bars correspond to the standard-deviation. Near-ultraviolet properties of hollows are dependent on the host crater.

541 a linear change between the hollows interior and the bright halo (Figure 13). Spectral  
 542 parameters are not correlated to the observation conditions (incidence, emission, phase  
 543 angles), so this evolution is not an artifact of varying viewing geometry.

544 Several hypotheses can explain this gradual change in spectral parameters between  
 545 the two parts of the hollows: 1) The bright halo and the hollows interior have very dif-  
 546 ferent spectral properties, which at the spatial resolution of MASCS footprints results  
 547 in spectra that are geographical mixtures between hollow floors material and halo ma-  
 548 terial that create intermediate values of spectral parameters, 2) The bright halo tends  
 549 gradually to have the same spectral properties of the hollows interior. The physical and  
 550 chemical properties of the material can change along the halo from the inner part of it  
 551 to the edges.

552 Blewett et al. (2013) proposed several explanations on the presence of the bright  
 553 halo around hollows. Among these hypotheses are the destruction of nanophase sulfides  
 554 and physical properties modified during the formation of the hollows. In this analysis,  
 555 we showed that halo has also steeper slopes and higher curvature. The destruction of  
 556 nanophase sulfides increases the reflectance and decreases the spectral slope and that could  
 557 explain why hollows interior have higher reflectance and less steep VIS to NIR slope than  
 558 parent material (crater floor). In addition, as mentioned in section 3.2, the particular



**Figure 13.** MASCS footprints in the Eminescu hollows (ob4\_14327\_010045, ob4\_14326\_164731). The spatial resolution is from 0.3 to 1.7 km/footprint, so the length of the footprint is approximately four times larger than the dot. The color code shows increasing values of UV-downturn (a), curvature (b) and VISNIR-slope (c) from blue to yellow. The three parameters gradually increase between hollow floor and bright halo.

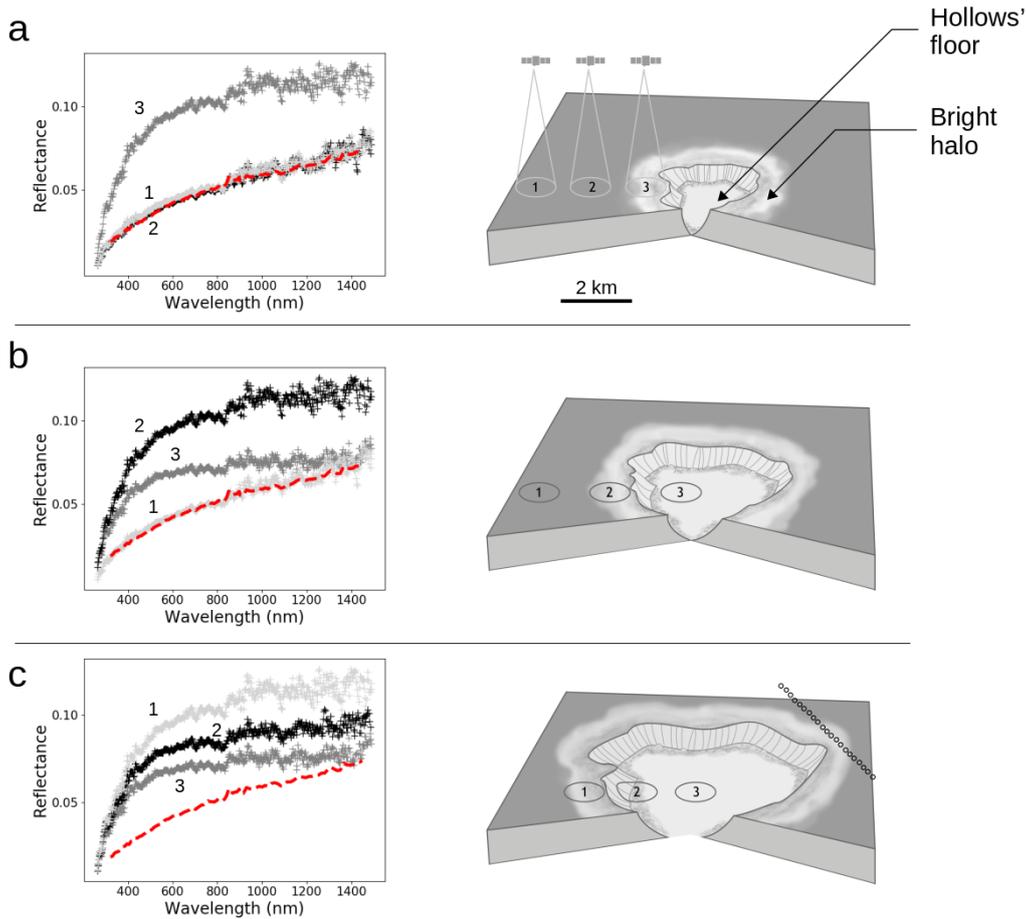
559 spectral properties of hollows may be related to the presence of an absorption band cen-

560 tred around 300 nm associated with the sulfides CaS, NaS and MgS (Varatharajan et  
561 al., 2019). The results shown in Figure 13 are consistent with the loss of sulfides pro-  
562 gressively decreasing the depth of the absorption band, and thus decreasing the UV-downturn  
563 and curvature during the hollows formation.

564 Moreover, the loss of a volatile component could result in a change in grain size.  
565 Thomas et al. (2016) showed differences in grain-size in Eminescu’s hollows: grains seem  
566 to be finer in the halo than in the hollow floors. The reflectance increases when the grain  
567 size decreases (Crown & Pieters, 1987). This result could explain the very high reflectance  
568 in the halo.

569 These observations support the scenario of a formation by scarp retreat proposed  
570 by Blewett et al. (2013). In fact, some favorable physical conditions could lead the for-  
571 mation process of hollows in a given spot. After the destruction of the volatile compo-  
572 nent, new material is exposed on the surface. The evolution of the reflectance spectra  
573 according to the growth of the hollow is represented in Figure 14. In the place where the  
574 hollows begins to grow, the reflectance, UV-downturn, and Curvature increases and the  
575 VISNIR-slope starts to slightly decrease (spectrum 3 compared to spectra 1, 2 in Fig-  
576 ure 14a). This variation seems to be related to the beginning of the loss of the volatile  
577 element. At this point, unaltered material present under the regolith and rich in volatile  
578 elements seems to be exposed at the surface. Then, as the volatile element is destroyed  
579 in the unaltered material exposed, the reflectance, UV-downturn and Curvature begin  
580 to decrease (Spectrum 2 in figure 14c). The slope of the spectrum continues to decrease.  
581 The destruction of volatile-rich material changes the physical structure of the material  
582 exposed on the surface and makes it unstable. Some parts begin to destabilize and then  
583 collapse along the hollow escarpment exposing unaltered material on the surface. When  
584 the volatile phase is lost, the vertical progression of the hollows stops.

585 Determination of the nature and rate of hollows formation process is one of the ob-  
586 jectives of the BepiColombo mission to Mercury (Rothery et al., 2020). In particular,  
587 VIHI (Visual and Infrared Hyperspectral Imager) on the instrumental suite SIMBIO-  
588 SYS (Spectrometer and Imaging for MPO BepiColombo Integrated Observatory SYS-  
589 tem, Flamini et al., 2010; Cremonese et al., 2020) should be able to confirm the valid-  
590 ity of the scenario proposed in figure 14. The spatial resolution of this instrument (up  
591 to 100m/pixel) is represented on the figure 14 panel c. Observations of hollows with VIHI  
592 will certainly make it possible to define the spectral characteristics of each hollows fa-  
593 cies (floor, bright halo and background terrain) more distinctly than the MASCS instru-  
594 ment and increase the number of hollows observed with sufficient spatial resolution to  
595 resolve each facies.



**Figure 14.** A schematic illustration of possible hollows growth and the evolution of reflectance spectra. Diagrams a, b and c are in chronological order. The red spectrum is the Mercury's reference (Izenberg et al., 2014). The small circles on panel c represent the spatial resolution of future hyper-spectral observations with BepiColombo.

## 6 Conclusion

Images from MESSENGER revealed the presence of hollows on the surface of Mercury; however their origin and nature remained unconstrained. Multispectral data showed that hollows are among the brightest features on the surface of Mercury and exhibit possible absorption features associated with sulfides. From the highest spatial resolution observations with the Mercury Atmospheric and Surface Composition spectrometer (MASCS) examined here, several important conclusions about the hollows can be made.

1. Hollows have unique spectral properties in the near-ultraviolet. Their reflectance spectra are quite distinct from other geological units. Hollows have a steeper downturn in reflectance between 300 and 350 nm and are characterized by a distinct spectral curvature between 300 and 600 nm. These properties may be related to the absorption feature of certain sulfides such as CaS, NaS and MgS, centered around 300 nm (Varatharajan et al., 2019).
2. Hollows reflectance spectra exhibit no clear evidence of absorption features in the visible in MASCS data as was observed in the MDIS multi-color data. The lack of consistent absorption bands seems to be related to calibration errors in one or

- 612 both instruments, or could be attributed a lack of sufficient concentration of sul-  
 613 fides in the MASCS field-of-view.
- 614 3. The evolution of spectral properties throughout the Eminescu hollows are consis-  
 615 tent with a formation by destruction of nanophase sulfides. In addition, the spec-  
 616 tral properties are correlated with the morphology of the hollows supporting the  
 617 suggestion that hollows grow by scarp retreat.
  - 618 4. Faculae and hollows have distinct spectral properties. This suggests that the volatile  
 619 species driving explosive eruption and formation of hollows on Mercury have dif-  
 620 ferent nature and origin. On the other hand, near-ultraviolet and Curvature prop-  
 621 erties of hollows are correlated with properties of host crater floor implying that  
 622 the composition and/or physical properties of the hollows material depend on those  
 623 of the host crater. This supports the hypothesis of the differentiation of a volatile  
 624 rich layer in the impact melt.

625 The Bepicolombo mission is equipped with an instrumental suite (Flamini et al.,  
 626 2010; Cremonese et al., 2020) including a hyperspectral imager: VIHI (Visual and In-  
 627 frared Hyperspectral Imager). This instrument has higher spatial resolution (up to 100  
 628 m/pixel), a higher signal-to-noise ratio and a wider range of wavelength (0.4 to 2  $\mu\text{m}$ )  
 629 than MASCS. The future VIHI global coverage (at 480m/pixel) and high resolution im-  
 630 ages (which will cover 20% of the surface) will extend the MASCS results obtained in  
 631 hollows (Cremonese et al., 2020). These observations of different hollows will provide ad-  
 632 ditional insight into the nature and processes of hollow formation. In addition, these data  
 633 will be essential in differentiating the effects of composition, grain size and space-weathering  
 634 on hollow spectra. Together with observations from the spectrometer MERTIS (Mercury  
 635 Radiometer and Thermal Infrared Spectrometer, Hiesinger et al., 2010), BepiColombo  
 636 may lead to the discovery of new spectral characteristics of hollows at infrared wavelengths  
 637 (7 to 14  $\mu\text{m}$ ) not observed by MASCS.

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