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1 **Mercury's surface and composition to be studied by BepiColombo**

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39 **Abstract**

40 We describe the contributions that we expect the BepiColombo mission to make
41 towards increased knowledge and understanding of Mercury's surface and
42 composition. BepiColombo will have a larger and more capable suite of instruments
43 relevant for determination of the topographic, physical, chemical and mineralogical
44 properties of the surface than carried by NASA's MESSENGER mission. We
45 anticipate that the insights gained into the planet's geological history and its current
46 space-weathering environment will enable us to understand the relationships between
47 surface composition and the composition of different types of crust. This will enable
48 estimation of the composition of the mantle from which the crust was derived, and

49 lead to better constraints on models for Mercury's origin and the nature of the
50 material from which it formed.

51 **1 Introduction**

52 The two spacecraft of the BepiColombo mission are scheduled to arrive in orbit about
53 Mercury in 2020 (Fujimoto et al., this issue; Hajakawa et al., this issue). By then the
54 fly-by and orbital phases of NASA's MESSENGER mission (Solomon et al., 2001,
55 2007) should have advanced our knowledge considerably, but many issues will
56 inevitably remain unresolved. Here we outline measurements to be made by
57 BepiColombo that are intended to enhance our understanding of Mercury's surface
58 and composition, and then discuss the 'Big Questions' that these measurements
59 should help us to answer.

60 BepiColombo's instruments and their capabilities are described in detail in individual
61 papers (most of them elsewhere in this issue) so we do not assess them individually
62 here. However, for convenience those on the BepiColombo Mercury Planetary Orbiter
63 (MPO), which is the craft most relevant to study of Mercury's surface and
64 composition, are listed in Table 1.

65 Our recent understanding of Mercury has been well reviewed by Strom (1997),
66 Solomon (2003), Strom and Sprague (2003), Clark (2007) and Head et al. (2007).
67 Additional insights from the first MESSENGER flyby are summarized by Solomon et
68 al. (2008).

69 Mercury's high uncompressed density indicates a metallic mass-fraction at least twice
70 that of the other terrestrial planets (e.g. Solomon, 2003). A large iron-rich core is
71 postulated, occupying about 42% of the planet's volume and 75% of its radius.
72 Studies of Mercury's libration in longitude have revealed this to be at least partly

73 molten (requiring a light alloying element to lower the melting temperature), and this
74 strengthens the hypothesis that the planet's magnetic field is generated by a core
75 dynamo (Margot et al., 2007). Despite the enormous quantity of iron inferred in its
76 core, optical spectra suggest that Mercury's crust has low (<3 wt%) iron oxide
77 abundance, supplemented by nanophase metallic iron (both meteoritic and resulting
78 from space weathering) amounting no more than about 0.5 wt% (Hapke, 2001; Warell
79 and Blewett, 2004; McClintock et al., 2008). Low iron oxide abundance is also
80 indicated by the regolith's remarkable transparency to microwaves (Mitchell and de
81 Peter, 1994; Jeanloz et al., 1995). Fractionation of iron during partial melting or
82 modest fractional crystallization is slight (Robinson and Taylor, 2001), with the
83 consequence that Mercury's low crustal abundance of iron implies a similar but
84 probably somewhat lower iron abundance in its mantle. For example, Taylor and
85 Scott (2004) note that the abundance of FeO in terrestrial mid-ocean ridge basalts
86 exceeds its abundance in primitive mantle by a factor of 1.3. This low iron abundance
87 in Mercury's bulk silicate fraction could be a consequence of a radial oxidation
88 gradient in the solar nebula, and hence in the local planetesimals that contributed the
89 bulk of Mercury's matter (Robinson and Taylor, 2001), or result from one or more
90 giant impacts that removed Fe-rich crust and upper mantle during the series of
91 collisions by which Mercury was assembled.

92 Several models have been proposed to explain the large size of Mercury's core
93 relative to the bulk silicate fraction, now represented by its mantle + crust (e.g.,
94 Taylor and Scott, 2004). These models fall in to three basic categories:

- 95 • selective accretion
- 96 • post accretion vaporisation
- 97 • crust/mantle loss resulting from a giant impact.

98 In the first of these models the oxidation gradient during solar nebula condensation,
99 aided by gravitational and drag forces, resulted in an enrichment of metallic iron
100 compared to other terrestrial planets (Weidenschilling, 1978). In the second, intense
101 radiation from the young Sun led to vaporisation and loss of silicates from Mercury's
102 exterior after the planet had formed (Cameron, 1985), or possibly from the
103 differentiated exteriors of planetary embryos before they collided to form Mercury. In
104 the third model, a giant impact stripped Mercury of much of its rocky exterior (Benz
105 et al., 1988, 2007). Some different predicted compositions for Mercury's averaged
106 mantle + crust, resulting from the proposed models, are given in Table 2. If
107 BepiColombo measurements of Mercury's surface can be used to deduce the average
108 composition of Mercury's bulk silicate fraction, this will provide a major test to
109 discriminate between these competing models.

110 However, it would be unreasonable to expect the abundances of the elements on
111 Mercury's surface to be representative of the planet's bulk silicate fraction, and they
112 certainly cannot correspond to the planet's overall composition. Such may be the case
113 (after due allowance for space weathering) for undifferentiated bodies like most
114 asteroids, but Mercury clearly has a differentiated structure, besides which its surface
115 is heterogeneous in age, morphology and spectral properties (Robinson and Lucey,
116 1997; Strom, 1997; Sprague et al., 2002, 2007; Warell et al., 2006, Robinson et al.,
117 2008). Determination of Mercury's bulk silicate composition on the basis of what we
118 can measure at the surface can be achieved only after identification and understanding
119 of the nature and history of crust formation and of subsequent surface processes.

120 Almost irrespective of the mechanism by which Mercury grew, accretional/collisional
121 heating makes it highly likely that the body we now know as Mercury was covered by
122 a magma ocean before any of its present surface was formed. Using concepts fully

123 applicable to Mercury, Taylor (1982, 1989) defined two distinct ways in which
124 planetary crust may form during and after freezing of a magma ocean. Primary crust
125 (for example, the feldspathic lunar highlands) is built by floatation of agglomerations
126 of low-density crystals that grew by fractional crystallization within the cooling
127 magma ocean. Secondary crust (for example, the lunar maria) arrives later in the form
128 of magma produced by subsequent partial melting of the mantle, and is emplaced
129 volcanically upon, or intrusively within, older crust. The mantle from which
130 secondary crust is extracted is likely to be broadly similar in composition to the
131 former magma ocean, but will be deficient in those elements preferentially
132 fractionated into primary crust. This may be a small effect for major elements (e.g., Al,
133 Ca), because the volume of primary crust extracted from the mantle is small in
134 proportion to the total silicate fraction of the planet. However, the effect may be
135 significant for chemically incompatible elements preferentially concentrated below
136 the crust in the last volume of the magma ocean to crystallize, in a manner analogous
137 to the formation of a KREEP-rich mantle layer below the lunar crust (e.g., Shearer et
138 al, 2006).

139 We note that in the case of differentiated planetary bodies stripped (perhaps more than
140 once) of their crust and uppermost mantle by giant impacts, the process of primary
141 crust formation can begin again in the new magma ocean, and in due course new
142 secondary crust could follow. The volumes and compositions of both types of crust
143 would be different in each generation, and so the compositions that we measure must
144 contain clues to the history of giant impacts and magma oceans. For example, if
145 Mercury's relatively thin mantle is indeed a consequence of an early giant impact
146 event, we might expect KREEP-rich materials to be absent. Moreover, to the extent
147 that Fe and Ti are also preferentially concentrated into later stages of magma ocean

148 crystallization, and thus towards upper mantle layers (see Fig. 4.10 of Shearer et al.,
149 2006), removal of the uppermost mantle by giant impact(s) prior to density-driven
150 mantle overturn (as hypothesised for the Moon by Hess and Parmentier, 1995) might
151 explain the apparently Fe-poor nature of Mercury's mantle.

152 However, irrespective of previous history, the contrasting modes of origin of primary
153 and secondary crust mean that their composition, and the relationship between their
154 composition and the bulk silicate composition of the planet, will be different. Thus, if
155 we wish to measure crustal composition and use this to deduce the composition of the
156 underlying mantle (or of the bulk silicate fraction of the planet), it is vital to
157 understand what type of crust we are observing, and to distinguish between
158 measurements of primary crust and secondary crust rather than aggregating them
159 together.

160 If large exposed tracts of primary crust composition have survived on Mercury, they
161 are likely to be in the heavily cratered terrain, and also in intercrater plains if any parts
162 of those are ejecta deposits of redistributed primary crust (Wilhelms, 1976; Strom,
163 1997). The smooth plains, which have a younger crater age, are long-established
164 candidates for volcanically-emplaced secondary crust (Strom et al., 1975), although it
165 seems likely that their iron content is too low for them to be a familiar sort of basalt.

166 Data from the first MESSENGER fly-by strengthen the view that there are multiple
167 generations of volcanic activity preserved on Mercury (Head et al., 2008; Murchie et
168 al., 2008; Robinson et al., 2008; Strom et al., 2008), including at least some parts of
169 the intercrater plains.

170 It may turn out that secondary crust emplacement by volcanism has been so
171 widespread that primary crust is no longer exposed in situ except in uplifted crater
172 peaks, inner walls of craters, and tectonic scarps. However, the 'low-reflectance

173 material' identified by Robinson et al. (2008) in ejecta blankets, including that of the
174 Tolstoj basin, may have been excavated from the buried primary crust. Multiple
175 episodes of volcanism in some parts of Mercury (Head et al., 2008; Murchie et al.,
176 2008) offer an opportunity to study Mercury's history of magmagenesis and magma
177 fractionation. It is unlikely that Mercury has any extensive tertiary crust resulting
178 from melting and differentiation of older crust (Taylor, 1989), but if this does occur it
179 will be important to recognise it and interpret its composition separately. The picture
180 may be further complicated if Mercury has impact-melt sheets in which former
181 primary and secondary crust have been intermingled, each in significant proportions.
182 In addition, studies of Mercury's surface and its composition will allow us to
183 document and understand the processes of space weathering and volatile release
184 and/or migration (which will affect the observed surface composition) and the tectonic
185 and impact processes that have shaped the planet.

186 **2 Measurements**

187 We review here various attributes of Mercury's surface that can be measured or
188 determined from BepiColombo data: these are topography/morphology, geological
189 units, regolith physical properties, crater statistics, mineralogical composition of
190 surface materials, elemental abundances in surface materials, space weathering, and
191 polar volatiles.

192 ***2.1 Topography and morphology of the crust***

193 Mercury's crust has only a modest range of elevations, generally less than 2 km and
194 rarely exceeding 3 km (e.g. Harmon and Campbell, 1988; Cook and Robinson, 2000).
195 The most significant elevation changes are related to impact craters and basins whose
196 rims can reach elevations of 2 km (e.g. Strom and Sprague, 2003), compressional

197 lobate scarps ranging in height from few hundred meters to 3 km (e.g. Strom et al.,
198 1975; Watters et al., 1998; Cook and Robinson, 2000) and the rugged hilly and
199 lineated terrain at the antipode to the Caloris basin (e.g. Schultz and Gault, 1975;
200 Melosh and McKinnon, 1988; Neukum et al., 2001). Minor morphological features
201 include wrinkle ridges and grabens inside the Caloris basin (e.g. Watters et al., 2005).
202 Volcanic vent structures were reported by Head et al. (2008), and although sinuous
203 rilles have not yet been detected they cannot be ruled out.

204 BELA will determine the topography of Mercury's crust on global to local scales
205 (Thomas et al., 2007). The initial density of spatial measurements is defined by the
206 along-track shot-to-shot distance of about 260 m and the cross-track distance of about
207 25 km at the equator. Density will increase considerably as more orbits are completed,
208 which will be particularly beneficial for filling the gaps between the more widely-
209 spaced ground tracks in equatorial regions. The vertical precision of the
210 measurements will be in the order of one meter or even better. These measurements
211 will complement and improve the laser altimetry provided by the MESSENGER
212 Laser Altimeter, MLA (Solomon et al., 2001; Krebs et al., 2005).

213 On local scales (a few kilometres), consecutive measurements at a spacing of ~260 m
214 along single BELA tracks will constitute a powerful tool for the investigation of
215 specific landforms. Impact craters are particularly well suited for analysis by such
216 profiles, since they usually have axisymmetric topography. Because impact cratering
217 is probably the dominant geological surface process through time on Mercury, the
218 morphology of impact craters can reveal important properties of the target material
219 and/or the effects of velocity on the crater size-frequency distribution. BELA profiles
220 crossing crater centres will be sufficient to characterize key morphometric parameters

221 of crater populations, like the depth-to-diameter relationship or the rim height (e.g.,
222 Pike, 1988; Melosh, 1989; André and Watters, 2006).

223 Laser profiles, in particular in combination with imaging data, can also yield insights
224 into the rheology and emplacement mechanism of lava flows, based on measurements
225 of slope and flow thickness (e.g., Glaze et al., 2003; Hiesinger et al., 2007). Slope will
226 be easy to determine, but ability to determine flow thickness may be compromised by
227 degradation of flow margins.

228 The stereoscopic channel (STC) of SIMBIO-SYS will provide a 3D global colour
229 coverage of the surface with a spatial resolution of 50 m/pixel at the equator and 110
230 m/pixel at the poles. The estimated STC precision in elevation is calculated to
231 deteriorate from about 80 m at the equator in the periherm arc, to about 150 m at the
232 pole and to 215 m at the equator in the apoherm arc (see Cremonese et al., 2008;
233 Flamini et al., this issue), as a result of the ellipticity of the orbit and taking into
234 account off-nadir looking sensors. In addition a series of simulations has been
235 performed using Earth analogues (a crater, a lava cone and an endogenous dome
236 complex) of structures expected on Mercury's surface, small enough to be near the
237 detection limit of the STC (Massironi et al., 2008). The results indicate that for data
238 acquisition from periherm, shapes and dimensions are well reconstructed, although
239 minor details such as variations in surface roughness and joints cannot be rendered
240 (BELA is more suited for roughness estimates). As regards crater science, this means
241 that studies of the degree of maturity, depth analyses, slope stability, resurfacing and
242 deformation processes will be very reliable even for small craters (at least down to 2.5
243 km in diameter) having low depth/diameter ratios (1/15, 1/20). In addition, reliable
244 size measurement and basic classification of volcanic features as small as 1.5 km in
245 diameter and 120 m in elevation could be achieved. At the poles, the accuracy will be

246 sufficient to reconstruct convex landforms and simple crater shapes in 3D, although
247 quantitative morphological analyses based on polar DTMs (digital terrain models)
248 produced by single stereo-pairs should be treated with caution. Fortunately,
249 BepiColombo's polar orbit will result in multiple stereo images of regions near the
250 poles, enabling construction of DTMs with an accuracy comparable to that achieved
251 at periherm. The integration of BELA and STC data will provide even better-
252 constrained DTMs, including by eliminating any steep-slope occlusion phenomena
253 affecting STC acquisitions.

254 MIXS will make use of morphological information provided by BELA and SIMBIO-
255 SYS to correct the raw measurements for regolith properties and the effects of
256 incidence angle and shadowing.

257 **2.2 Discrimination of geological units and stratigraphy**

258 It is very likely that the MESSENGER and BepiColombo missions will lead to
259 refinement and subdivision of the basic stratigraphic/tectonic units identified on
260 Mariner-10 images (e.g. Spudis and Guest, 1988), by means of clearer and more
261 complete documentation of morphology, context, texture and spectral signature.
262 Analysis and mapping of stratigraphic and tectonic contacts between geological units
263 is the basis for establishing the sequence of events responsible for the current
264 appearance of Mercury's surface. The hyperspectral potential of SIMBIO-SYS VIHI
265 (Flamini et al., this issue) together with the SIMBIO-SYS STC and BELA three-
266 dimensional rendering capabilities will allow the discrimination of different
267 geological units and constrain their mutual stratigraphic relationships across extended
268 regions; consequently a satisfactory knowledge of global stratigraphy will be
269 achieved. The powerful high resolution potential of SIMBIO-SYS HRIC (up to 5
270 m/pixel; Flamini et al., this issue) will provide additional insights into the

271 characterization of geological units and essential information on the relationships of
272 embayment (onlap) and mutual intersection between different deposits and structural
273 features. In addition, stratigraphic analysis could be performed even for subsurface
274 layers using three-dimensional morphology of craters coupled with spectral
275 information derived by SIMBIO-SYS channels.

276 The spectrometer channel of MERTIS covers the spectral range from 7-14 μm with a
277 spectral resolution better than 200nm, while the radiometer channel covers the
278 spectral range up to 40 μm (Hiesinger et al., this issue), and will provide
279 complementary spectral discrimination to SIMBIO-SYS (see section 2.5). MERTIS
280 will map the planet globally with a spatial resolution of 500 m and a signal-to-noise
281 ratio of at least 100, and will map 5-10% of the surface with a spatial resolution
282 smaller than 500 m. For a typical dayside observation the signal-to-noise ratio will
283 exceed 200 even for a fine-grained and partly glassy regolith. The flexibility of the
284 instrumental setup will allow adjustment of the spatial and spectral resolutions to
285 optimize the S/N ratio under varying observing conditions. In addition, by use of its
286 radiometer channel, MERTIS will be able to measure thermo-physical properties of
287 the surface such as thermal inertia and internal heat flux, and derive from this further
288 information on surface texture and structure.

289 MIXS will provide the main source of information on element abundances within the
290 units mapped by the higher resolution imaging systems, and should be able to confirm
291 whether or not the elemental composition of units is consistent with interpretations
292 based on morphologic and spectroscopic information. There are a number of simple
293 tests that can be made using major element abundances to confirm the identification
294 of primary and secondary crust (Fraser et al., this issue). For example, both Fe and Mg
295 should be less abundant in primary crust than secondary crust, but Ca and Al should

296 be more abundant in primary crust. The expected differences are about a factor of two
297 in each case; compare the lunar situation, where Apollo 16 highland soils are
298 characterised by FeO, MgO, CaO and Al₂O₃ concentrations of about 5, 6, 15 and 27
299 wt%, respectively, whereas the corresponding values for mare basalts are about 16, 10,
300 10 and 10 wt% (Haskin and Warren, 1991).

301 MIXS data will also be used to seek geochemical sub-units within major terrain units
302 that lack any more obvious distinguishing features; a lunar analogy would be the
303 Procellarum KREEP terrain whose extent is defined primarily by anomalous Th
304 concentrations (Jolliff et al., 2000). MIXS-T will be able to probe the stratigraphy of
305 the mercurian crust to depths of up to several tens of km by determining the
306 major element geochemistry of the central peaks and/or ejecta blankets of impact
307 craters in the diameter range ~50 to 300 km. Such craters will have excavated crustal
308 materials from depths of 5 to 30 km respectively (e.g. Melosh, 1989), and materials
309 from just below these depths will be exposed in rebounded central peaks. By analogy
310 with the Moon (e.g., Jolliff, 2006), variations of the Fe/Mg ratio with depth can be
311 used to discriminate between different models of crustal evolution. These studies will
312 benefit from very high spatial resolution of MIXS-T (~20 km under normal solar
313 conditions, and up to a factor of ten better during solar flares; Fraser et al., this
314 volume).

315 The roughness of a planetary surface is a function of its geological history. Surface
316 roughness is, therefore, a parameter that can be used to distinguish geological or
317 geomorphological units (e.g., Bondarenko et al., 2003; Cord et al., 2007). BELA will
318 provide roughness information at different scales: on large scales, the roughness is
319 determined by the elevation differences between the individual laser measurements.
320 Roughness can be calculated over specific “baselengths” (i.e. over a specified number

321 of shots along the groundtrack). Kreslavsky and Head (2000) used this technique to
322 show that surface roughness on Mars is correlated with geology, and they found that
323 different geologic units display distinctive roughness characteristics at kilometre-
324 scales. Smaller scale roughness is discussed in the next section.

325 **2.3 Physical properties of the regolith**

326 **2.3.1 Optical photometry**

327 The reflectance spectrum of a particulate medium depends not only on its composition,
328 but also on its physical properties and especially particle size. This controls the
329 strength and presence of spectral absorption features, and how band contrast and
330 spectral slope vary with viewing geometry. In practice, these dependences make it
331 difficult to compare spectra acquired under different geometries, because of
332 uncertainty over whether variations are a response to differences in composition, in
333 particle size, or in surface roughness. Photometric measurements therefore have two
334 purposes: first to provide information on the local characteristics of the surface
335 regardless of variations due to observing conditions, and second to characterize these
336 variations so that measurements can be corrected to a common geometry. A third
337 possible application is related to the thermal balance at the local scale, since the
338 incoming solar flux is weighted by the phase function of the medium.

339 Reflectance spectra from the UV (ultraviolet) to the NIR (near-infrared) can be
340 described by specific radiative transfer models in the geometrical optics
341 approximation, which assumes that the particles are much larger than the wavelength.
342 Two such models are commonly used in planetary science, with numerous variations
343 (Hapke, 1981, 1993; Shkuratov et al., 1999). Both provide an expression of the
344 reflectance at a given wavelength in terms of observing conditions (incidence,

345 emergence, and phase angles) and physical properties. In Hapke's model, the
346 parameters are the single scattering albedo, the asymmetry parameter of the phase
347 function, and surface roughness. In Shkuratov's model they are the optical constants,
348 grain size and porosity. Inversion of these models on the data provides these
349 quantities locally, provided that sufficient measurements at different phase angles are
350 available (ranging from 15° to at least 60°). Study of the opposition effect (for phase
351 angles < 15°) allows derivation of the mean particle size and/or constraints on the size
352 distribution. Furthermore, numerical methods for coherent backscattering and
353 shadowing by particulate media can be applied to constrain the physical properties of
354 Mercury' regolith (e.g., Muinonen et al., 2002; Muinonen, 2004; Parviainen and
355 Muinonen, 2007).

356 Since these effects are expected to affect mainly the spectral slope in the NIR, such
357 observations are chiefly relevant for the VIHI channel of SIMBIO-SYS. For
358 BepiColombo study of Mercury, low resolution observations will be sufficient to
359 derive the physical properties of the regolith associated with major geological units,
360 although high resolution may be interesting in specific areas such as ejecta blankets or
361 patterned areas of high-albedo known as swirls (Dzurizin, 1977; Starukhina and
362 Shkuratov, 2003). Lunar swirls have very specific photometric behaviour, which gives
363 insights into their origin, and display rapid spatial variations (Kreslavsky and
364 Shkuratov 2003) that may also be evident on Mercury. Spectral coverage is also
365 interesting, most notably to derive the single scattering albedo and roughness
366 estimates at various scales. In more uniform areas the spectrometers will provide
367 photometric information relevant for study of possible regional variations in space
368 weathering effects (Sprague et al 2007).

369 **2.3.2 Laser altimetry**

370 The returned BELA laser signal can be used to measure the local surface roughness
371 and the albedo, including within permanently shadowed polar craters. The shape of
372 the returned laser pulse yields information on the roughness within the spot size of the
373 laser beam on the ground. Such an analysis was performed for MOLA data by
374 Neumann et al. (2003), who showed that the lowlands of Mars are smooth at all scales,
375 while other locations are smooth at long wavelengths but rough at the MOLA
376 footprint scale.

377 **2.3.3 X-ray fluorescence**

378 MIXS will measure the fluorescent intensity of elemental lines emergent from the
379 surface as a function of the viewing geometry. These measurements can be
380 synthesized into a phase curve that can subsequently be compared against semi-
381 empirical models to obtain additional information on the surface roughness of
382 different terrain types. Even though this method will be limited to quite large spatial
383 units, it may help to constrain the most likely parameters for physical properties of the
384 regolith obtained through other investigations. Parviainen and Muinonen (2007) have
385 assessed shadowing effects due to the rough interface between free space and the
386 regolith, and Näränen et al. (in press) have carried out laboratory studies of the
387 regolith effects on X-ray fluorescence.

388 **2.4 *Relative and absolute dating***

389 The cratering record is the primary tool for dating planetary surfaces, and also
390 provides important information on the origin of impacting objects whose size-
391 frequency distribution and impact rates could both have varied during the planet's
392 history. The possible sources of impactors onto Mercury's surface include the Main

393 asteroid belt, Near-Earth asteroids, comets, and hypothetical asteroids with orbits
394 closer to the Sun than Mercury known as vulcanoids (Strom et al. 2005; Bottke et al.
395 2005; Cremonese et al. 2008). Large ejecta from any of these can also produce
396 secondary craters.

397 The size-frequency distributions of craters on the Moon and their calibration against
398 absolute ages derived from Apollo samples allowed cratering chronology models to
399 be determined, and adapted for use on Mercury (e.g. Strom and Neukum, 1988;
400 Neukum et al., 2001a,b). According to these models and Mercury's cratering record
401 based on Mariner 10 data, internal activity of Mercury seemed to have been initiated
402 earlier than that on the Moon, but also to have ended sooner.

403 However, models of the planetary interior and thermal evolution are not yet in full
404 accord with the conclusion of crater counting studies on Mariner data since the
405 conditions allowing both limited internal activity and radial contraction after 4 Ga,
406 and the persistence of a hydromagnetic dynamo remain unclear (e.g. Hauck et al.,
407 2004). In addition, crater counts based on imaging from the first MESSENGER flyby
408 (Strom et al., 2008) showed that smooth plains exterior to the Caloris basin have a
409 significantly lower crater density than the interior of the basin (demonstrating that
410 they must be younger; presumably volcanic rather than ejecta from the basin-forming
411 event) and that there is at least one smooth plains area (the interior of the peak-ring
412 basin Raditladi) whose crater density is an order of magnitude lower still, suggesting
413 an age of less than 1 billion years.

414 The crater chronology on the Moon is well established (e.g. Neukum et al. 1975;
415 Hartmann et al. 1981), but has limitations due the possible biases introduced by crater
416 counting, uncertainty in the attribution of some radiometric ages to specific surface
417 units, and the substantial age gap of the lunar samples between 1 and 3 Ga. Other

418 sources of error can reside in the scaling laws necessary to convert the observed crater
419 distribution into an impact flux for the Moon and hence to Mercury itself. In view of
420 these uncertainties, we should not yet expect total agreement may between the dates
421 of internal activity of the planet inferred from crater counting and the duration of such
422 activity called for by thermal modelling. In order to limit some of these problems (at
423 least the crater counting biases and the adaptation of lunar age calibration to Mercury)
424 a novel crater chronology is under evaluation (Marchi et al., 2008, submitted). This
425 approach depends on a model for the formation and evolution of asteroids in the inner
426 Solar System (Bottke et al., 2005) to derive the impact flux through time on the Moon
427 which is, in turn, converted into crater distribution and calibrated for chronology
428 using the lunar radiometric ages. This approach should provide detailed information
429 on the size and the impact velocity distributions impinging on any body in the inner
430 Solar System, allowing the lunar calibration to be exported with greater precision to
431 Mercury.

432 The impact crater population on Mercury ranges in size up to at least 1550 km, and
433 there is a wide range in their state of preservation (e.g. Pike, 1988). The highly
434 cratered terrains are characterized by fewer craters with diameter smaller than 50 km
435 than their lunar highlands counterpart (Strom and Neukum, 1988; Neukum et al. 2001,
436 Strom et al. 2005). This is generally attributed to the widespread presence of the
437 intercrater plains, but needs to be better constrained.

438 Important uncertainties in the definition of the chronostratigraphic evolution of
439 Mercury remain due to the lack of knowledge about the largest part of the planetary
440 surface and the low Mariner 10 spatial resolution. The SIMBIO-SYS STC global
441 coverage will provide the opportunity to date the whole surface of Mercury. In
442 particular, unlike MESSENGER that will not provide high resolution images over the

443 whole planetary surface, the SIMBIO-SYS STC spatial resolution (up to 50 m/pixel)
444 will allow identification of craters with diameter larger than about 0.2 km across the
445 entire globe. This will provide accurate estimates of model ages through crater
446 counting of the different terrains, even for very recent units. Locally, age
447 determination could be achieved or refined also using SIMBIO-SYS HRIC images, on
448 small areas with sufficient crater density provided that secondary craters can be
449 recognised and excluded from the count. All these data will also be useful to better
450 constrain impact flux in the inner Solar System through time.

451 **2.5 Mineralogical composition of different units**

452 Due to the difficulties of observing Mercury from ground, relatively little is known
453 about its surface composition, and Mercury spectra are vulnerable to incomplete
454 removal of telluric absorptions. Some early visible to near-infrared (Vis-NIR) spectra
455 of Mercury displayed an absorption near 1 μ m (McCord and Clark, 1979) that was
456 attributed to the presence of ferrous iron, which is responsible for prominent 1 μ m
457 absorption bands in spectra of the lunar maria and some basaltic asteroids, like Vesta.
458 More recent Vis-NIR spectra of Mercury lack evidence for this band (Warell, 2003;
459 Warell and Blewett, 2004; McClintock et al., 2008), while some other spectra, taken
460 of different parts of the planet, exhibit very weak absorptions near 1 μ m (Warell et al.,
461 2006), providing the first evidence that Mercury's surface is compositionally
462 heterogeneous in the near infrared spectral range. Overall, the spectra are indicative of
463 an iron-poor mineralogy, so the 1 μ m absorption has been attributed to Ca-rich
464 clinopyroxene.

465 Based on early Earth-based telescopic observations and, especially, on the first images
466 of Mercury acquired by Mariner 10 in 1974, similarities between the Moon and
467 Mercury's surface compositions were suggested (Murray et al, 1974). Several studies

468 subsequently used the Moon as an analogue for Mercury (e.g., Blewett et al., 2002
469 and references therein), despite differences in their geophysical characteristics, and
470 the fact that many aspects of the origin and evolution of the two bodies are still
471 unresolved (e.g., Lucey et al., 1995; Ruzicka et al., 2001; Solomon, 2003). Lunar
472 anorthosites have been suggested as Mercury analogues from their spectral properties
473 (Blewett et al., 1997, 2002). Lunar pure anorthosite is a highland rock type consisting
474 of more than 90% plagioclase feldspar and containing less than 2–3 wt.% FeO.
475 Comparison between the spectral slopes of lunar pure anorthosites with Mercury
476 spectral slopes indicates mercurian spectra to be steeper (redder) (Blewett et al.,
477 1997). The spectral properties of small farside regions of the Moon that are highly
478 mature and very low in FeO (about 3 wt.%) have similarities with Mercury. However
479 Mercury appears lower in FeO than even these very low-iron lunar areas (Blewett et
480 al., 2002). Warell and Blewett (2004) performed Hapke modelling of telescopic
481 spectra of Mercury. Their favoured model was a 3:1 mixture of feldspar and enstatite,
482 with a bulk FeO content of 1.2 wt.%.

483 Mariner 10 made no direct measurements of Mercury's surface composition.
484 However, Blewett et al. (2007) used recalibrated Mariner 10 color image data (UV
485 and orange) to examine spectral trends associated with crater features on the inbound
486 hemisphere of Mercury. These recalibrated Mariner 10 mosaics were used to create
487 two spectral parameter images similar to those of Robinson and Lucey (1997): one
488 able to indicate variations in the abundance of spectrally neutral opaque phases, and
489 one controlled by differences in degree of maturity and/or FeO content. They found
490 that Mercury's surface features exhibit a variety of colour relationships, discriminable
491 by orange reflectance and the UV/orange ratio. These color-reflectance properties can
492 indicate variations in composition (specifically, the abundance of spectrally neutral

493 opaque phases) and the state of maturity of the regolith. Using this method, they
494 concluded that some craters, such as Kuiper and its rays, are bright not only because
495 they are fresh (immature) but also because Kuiper has excavated material with a lower
496 opaque content than the surroundings. Some other craters, like Lermontov and nearby
497 smaller craters, are probably mature, but remain bright because the material exposed
498 on their floors is poor in opaques, suggesting a 3-4 km surface layer with moderate-
499 opaque abundance overlying deeper opaque-poor material. Disk-resolved visible to
500 near infrared telescope images plus colour imaging and spectroscopic data from the
501 first MESSENGER flyby suggest a similar range of heterogeneity elsewhere on
502 Mercury (Warell and Valegård, 2006; McClintock et al, 2008; Robinson et al., 2008).
503 Combined with laboratory studies of terrestrial, lunar and meteoritic materials
504 (Burbine et al., 2002; Cooper et al., 2001; Hinrichs and Lucey, 2002; Salisbury et al.,
505 1997, Sprague et al., 2002), Mercury's spectra further suggest that its surface is
506 dominated by feldspars and low-iron pyroxene. There is little evidence for iron-rich
507 mafic rocks such as basalt, and lower abundances of dark opaque minerals (such as
508 ilmenite and rutile Ti-oxides, and spinels) than the Moon. In particular, calcium-rich
509 feldspars (labradorite, bytownite and anorthite) and pyroxenes (augite, hypersthene,
510 diopside, and enstatite) have been suggested in a number of spectra from different
511 locations on the planet (Sprague and Roush, 1998; Cooper et al., 2001; Sprague et al.,
512 2002).

513 However, metallic iron may be an important component of Mercury's regolith. Warell
514 (2003) found that the shape of Mercury's spectrum at wavelengths below 550 nm may
515 be critically important in the determination of the abundance of metallic iron, because
516 its high absorbance at these wavelengths (e.g., Hapke, 2001) causes a change in the

517 spectral slope. However, the spectra acquired by Warell and Blewett (2004) indicated
518 a continuous spectral slope extending to 400 nm.

519 The determination of surface mineralogy and the origin of geologically significant
520 morphologic features are among the primary objectives of SIMBIO-SYS. The
521 combination of the SIMBIO-SYS STereoCamera (STC) with its broad spectral bands
522 in the 400-900 nm range and medium spatial resolution (up to 50 m), and the Visible-
523 near Infrared Hyperspectral Imager (VIHI) with its 256-channel hyperspectral (about
524 6 nm) resolution in the 400-2000 nm range and spatial resolution up to 100 m
525 (Flamini et al., this issue), will be powerful tools for discriminating, identifying and
526 mapping variations in the surface reflectance spectrum. They will provide higher
527 spatial resolution and broader spectral coverage than MESSENGER, which will
528 collect no imaging or spectroscopic data at wavelengths longer than 1450 nm
529 (Boynton et al., 2007; Solomon et al, 2007).

530 The VIHI spectral range includes mostly electronic transitions related to Fe in silicate
531 lattices. It is particularly useful for identifying and characterizing pyroxenes from
532 their 1 and 2 μm crystal field transitions, the details of which depend on the Fe/Mg
533 ratio. On the Moon, feldspars are clearly detected in pyroxene-free areas, but less
534 easily when they are mixed, and Fe-bearing olivine is also readily identified (e.g., in
535 central peaks of craters). Furthermore, many salts have specific vibration signatures in
536 this range, and sulfides should also be detected from absorptions in the visible part of
537 the spectrum. The geomorphological information provided by STC will allow the
538 discrimination of different units within the larger footprint of VIHI, helping the
539 interpretation of the hyperspectral spectrum of VIHI mixed pixels.

540 The 7-14 μm spectral coverage of MERTIS offers unique diagnostic capabilities for
541 the surface composition of Mercury, in a spectral region not covered by

542 MESSENGER (Helbert et al., 2007). In particular, feldspars can be readily spectrally
543 identified and characterized, by means of several diagnostic spectral features in the 7-
544 14 μm range: the Christiansen frequency, Reststrahlen bands, and the transparency
545 feature. In the thermal infrared range at wavelengths longer than 7 μm , spectral
546 signatures in silicates result from characteristic fundamental Si-O vibrations.
547 Therefore FeO- and TiO₂-free silicates (e.g., feldspars, Fe-free pyroxenes and Fe-free
548 olivines), which are almost undetectable in the visible-NIR region, can be identified.
549 MERTIS will not merely be capable of detecting feldspars, its spectral resolution will
550 allow identification of the member within the series. For example, in the plagioclase
551 series ranging from the sodium-rich end-member albite (NaAlSi₃O₈) to the calcium-
552 rich end-member anorthite (CaAl₂Si₂O₈), as the paired substitution of Ca²⁺ and Al³⁺
553 for Na⁺ and Si⁴⁺ progresses, structural changes occur that affect the frequencies of Si-
554 O vibrations, as well as the related Christiansen frequencies. The spectral changes
555 include a progressive shift of the Christiansen maximum and Reststrahlen bands to
556 shorter wavenumbers (longer wavelengths), which will be measurable by MERTIS.
557 By determining abundances of all elements likely to be present in excess of about
558 0.1% (Fraser et al., this issue), MIXS will act as a test of the credibility of the
559 mineralogy suggested by SIMBIO-SYS and MERTIS, and will enable calculation of
560 the normative mineralogy of different units (of particular relevance to igneous
561 assemblages at equilibrium). MIXS will measure the abundance of the main anion
562 species (O and S), and so provide a test of whether the surface materials are fully
563 oxidised. Furthermore, if MIXS shows Fe to be more abundant than seems consistent
564 with the SIMBIO-SYS and MERTIS mineralogy, this would provide a measure of the
565 amount of nanophase metallic iron at the surface.

566 **2.6 Elemental abundances**

567 Mapping the abundances of the rock-forming elements on Mercury's surface is the
568 main science goal of MIXS (Fraser et al., this issue), which will detect many more
569 elements and operate at higher spatial resolution than MESSENGER's X-ray
570 Spectrometer (Boynton et al., 2007). The achievable spatial resolution depends on the
571 abundance of each element, the strength and distinctiveness of its fluorescent lines,
572 and the solar state (flares increase the stimulus for fluorescence by orders of
573 magnitude). Averaged globally, the abundances of O, Na, Mg, Al, Si, P, K, Ca, Ti, Fe
574 and Ni will be measured to high statistical precision even during solar quiet. With the
575 aid of maps based on SIMBIO-SYS and MERTIS data, it should be possible to
576 subdivide the global dataset of X-ray data into primary crust and secondary crust, with
577 little loss in precision (except for primary crust if exposures are small and rare).
578 Therefore MIXS will be used to determine average abundances of all those elements
579 in each of the two main crustal types. Sprague et al. (1995) argue that sulfur might be
580 widespread in Mercury's regolith in the form of sulphide minerals, and if S is more
581 abundant than about 0.1% MIXS should be capable of revealing it during solar flares.
582 Solar flares may also enable detection of Cr, whose abundance in lavas may exceed
583 1% or be an order of magnitude less according to different models for mantle
584 composition (Taylor and Scott, 2004).
585 Higher resolution mapping of elemental abundance should be achieved for the more
586 common elements at all times, and for others during solar flares. For example, under
587 typical solar conditions O, Na, Mg, Al, Si and Fe will be mapped with spatial
588 resolution of tens of km with MIXS-T and 100s of km with MIXS-C. Measurements
589 at the highest spatial resolution, of the order of a few km, will be achieved by MIXS-
590 T during solar flares of M class or stronger for O, Na, Mg, Si, P, K, Ca, Ti and Fe.

591 These events, expected less than 0.6% of the time (Fraser et al., this issue), will yield
592 serendipitous high resolution data takes lasting about 30 minutes (about a quarter of
593 an orbit), and are expected to be especially useful where they cross the uplifted central
594 peaks of large craters and other units of limited spatial extent such as fresh ejecta
595 blankets, crater walls or fault scarps that may expose variations in crustal composition
596 with depth. Any igneous material with enhanced abundances of Si and alkalis (Na, K)
597 would suggest fractionation during storage in magma chambers, whereas abundant Ti
598 would indicate the minerals ilmenite or ulvöspinel that on the Moon occur only in
599 basalts.

600 MERTIS would be capable of detecting elemental sulfur, thanks to distinctive spectral
601 features near 12 μm , but this will not work inside the polar cold traps (section 2.8),
602 which are too cold.

603 The gamma-ray spectrometer of MGNS (Mitrofanov et al., this issue) will detect
604 gamma rays from natural radioactivity (U, Th, K) and stimulated by solar gamma rays
605 (C, Na, Fe, Al, Si) with a surface resolution of about 400 km below the pericentre of
606 the MPO orbit. U, Th and K are chemically incompatible elements, which would have
607 become concentrated near the top of a primordial magma ocean (along with the
608 KREEP elements). As noted above, a deficiency of these elements on Mercury would
609 be consistent with the early removal of the uppermost mantle by a giant impact event.

610 In situ measurements of the exospheric composition by SERENA will offer an
611 independent check on the element abundances measured by remote sensing
612 techniques, since matter in the exosphere is directly released from the surface (Wurz
613 and Lammer, 2003; Milillo et al., 2005). There are four release processes capable of
614 delivering surface material to the exosphere, which have been discussed at length in
615 the literature (e.g. Wurz and Lammer, 2003; Killen et al., 2007). These processes are

616 thermal desorption, photon-stimulated desorption, sputtering by energetic ion impact,
617 and meteoritic impact vaporisation. The latter two are stoichiometric processes, such
618 that the release of elements into the exosphere (including refractory elements) is
619 proportional to their abundance at the surface.

620 The release process by sputtering into the lunar exosphere has been studied in detail
621 for typical lunar mineralogical compositions (Wurz et al., 2007). Sputtering releases
622 particles from the topmost atomic layers of the surface. This is where space
623 weathering will be effective, and so must be taken into account when interpreting the
624 data. Unfortunately, exospheric measurements in orbit cannot be closely related to a
625 location on the surface, the likely origin being within a circle of a size equivalent to
626 the spacecraft altitude (Wurz and Lammer, 2003). However, Mercury has a magnetic
627 field that is responsible for a small magnetosphere around the planet. The solar wind
628 can penetrate the magnetosphere and impinge only upon limited areas of the surface
629 (e.g. Massetti et al., 2003). The ELENA sensor of SERENA will detect the sputtered
630 particles with angular resolution of 2° at best, allowing mapping of their origin.

631 Plasma measurements will be performed with the MIPA and PICAM sensors of
632 SERENA, and the places where ion precipitation onto the surface occurs can be
633 inferred from these measurements, in conjunction with the magnetic field
634 measurements by MAG. Moreover, knowing the precipitating ion flux, the sputtered
635 particle release flux plus its source region, and the composition of the exosphere
636 above that region, we will be able to infer the expected exospheric density for a given
637 surface concentration and impacting plasma. Thus, it will be possible to deduce the
638 surface concentration of refractories such as Si, Mg, Ca that are released mainly by
639 ion sputtering from SERENA measurements.

640 It is also likely that the SERENA-STROFIO instrument will be able to detect
641 concentrations of refractory elements Mg, Al and Si and possibly also Ca and S and
642 molecules released by meteoritic impact vaporisation. Mangano et al. (2007) point out
643 that on average two 1 m impactors may be expected to strike Mercury per year, with a
644 detection probability of >50%, whereas 10 cm impactors strike so often that the
645 likelihood of detecting an event is almost 100% after only one month.

646 The in situ measurements by SERENA will be even more valuable if the origin of
647 detected material can be identified. For sputtering, the flux of precipitating ions will
648 be measured by SERENA-MIPA, and from that the location of sputtering on the
649 surface could be deduced. For a meteoritic impact the impact location might be
650 observed optically, or can be inferred from the plume when flying through it. A
651 comparison with MIXS composition maps will be fruitful to validate the observations
652 and to estimate the impact location.

653 During the Mercury flyby of MESSENGER on 14 January 2008 the plasma ion
654 spectrometer, FIPS, detected pickup ions (Zurbuchen et al., 2008). Although the mass
655 resolution of FIPS allows only for the identification of mass groups (Na^+/Mg^+ , S^+/O_2^+ ,
656 K^+/Ca^+ , and others) the origin of these ions in the refractory material of the surface is
657 clear. SERENA-PICAM has sufficient mass resolution to resolve all these ions, and
658 thus will contribute to the compositional analysis of the surface. These pickup ions
659 originate mostly from neutral atoms in the exosphere, which were ionised by the solar
660 UV radiation. Since the ionisation process has a low yield, one can infer that the
661 neutral atom densities are orders of magnitude larger and thus direct detection by
662 SERENA-STROFIO will be possible.

663 **2.7 Soil maturity and alteration (the extent, rate and nature**
664 **of ‘space weathering’)**

665 “Space weathering” is a term used for a number of processes that act on any airless
666 body exposed to the harsh environment of space (Hapke 2001, Sprague et al., 2007,
667 Langevin and Arnold 1977; Langevin 1997; Cintala 1992; Noble and Pieters 2003,
668 Noble et al., 2007), and must strongly affect the chemistry and observed properties of
669 the mercurian surface. Thus, no interpretation of the composition of Mercury’s crust
670 can be made without thoroughly accounting for space weathering, including
671 maturation and exogenic deposition on its surface. On the Moon (Lucey et al., 2006),
672 the products of these weathering processes include complex agglutinates as well as
673 surface-correlated products on individual soil grains (implanted rare gases, solar flare
674 tracks, and a variety of accreted components).

675 The visible to NIR spectral properties of the regolith of an atmosphereless body like
676 Mercury are governed by three major components (Hapke et al., 1975; Rava and
677 Hapke, 1987; Hapke, 2001): ferrous iron as FeO in mafic minerals and glasses,
678 nanophase metallic iron (npFe⁰) particles formed by vapour deposition reduction, and
679 spectrally neutral Ti-rich opaque phases in minerals and glasses. Increases in
680 abundance of these components have different effects on the spectra: ferrous iron
681 increases the depth of the near-infrared Fe²⁺ crystal field absorption band near 1µm,
682 npFe⁰ particles decrease the reflectance and increase the spectral slope (“reddening”),
683 and opaque phases have the effect of decreasing both the reflectance and the spectral
684 slope. Images from the first MESSENGER fly-by show well-defined ray craters
685 corresponding to the latest impacts on the surface of Mercury being distinctly “bluer”
686 and brighter than older surfaces, supporting the influence of maturity in the optical
687 properties of Mercury’s surface.

688 Very small abundances of metallic iron as npFe^0 have drastic effects on visible to NIR
689 spectral shape and so must be understood and calibrated out of observed spectra in
690 order to derive the composition of the unweathered material. The size distribution of
691 metallic Fe particles in a soil strongly controls the effects on the visible to NIR
692 spectrum: the larger npFe^0 particles (greater than approximately 10 nm) darken the
693 soil (Keller and McKay, 1993; Britt and Pieters, 1994), whereas smaller particles
694 (below 5 nm) are responsible for more complex continuum-altering effects including a
695 general reddening (Noble and Pieters, 2003). Soil maturation through sputtering to
696 produce npFe^0 particles is expected to proceed on Mercury faster than the lunar rate
697 because of the 5.5 times greater flux and higher mean velocity of impactors at
698 Mercury (Cintala, 1992). On the other hand, the ability of solar-wind protons to
699 reduce FeO in impact melts will be less on Mercury owing to its magnetic field. The
700 rate and style of space weathering on Mercury is expected to be further influenced by
701 ‘Ostwald ripening’, whereby high daytime temperatures will permit diffusion within
702 glass to allow the average size of npFe^0 particles to coarsen. This effect ought to be
703 greater towards the equator, so equatorial regions are predicted to be darker but less
704 red than polar regions of similar age (Noble and Pieters, 2003).

705 It should be possible to observe the effects of space weathering in visible to NIR
706 spectra of the type expected to be returned by VIHI, the Visible Infrared
707 Hyperspectral Imager of SIMBIO-SYS. Understanding these weathering processes
708 and their consequences is essential for evaluating the spectral data returned from VIHI
709 in order to determine the abundance of iron and the mineralogy of Mercury’s surface.
710 The optical scattering parameters derived locally by SIMBIO-SYS will allow retrieval
711 of global albedo maps at various wavelengths. Spectral mixture modelling will
712 provide an estimate of the fraction of dark, glassy particles at the surface. Knowledge

713 of grain size and glass fraction will allow quantification of maturation effects.
714 Inversion of spectral models should allow simultaneous retrieval of a maturation
715 parameter and the FeO content of surface material (Le Mouélic et al., 2002; Lucey,
716 2006).

717 If MIXS were to show Fe to be more abundant than seemed consistent with the
718 mineralogy inferred from SIMBIO-SYS and MERTIS investigations, the difference
719 would provide a measure of the amount of nanophase metallic iron at the surface.

720 Spatially resolved element abundance maps from MIXS will be useful to compare
721 older surfaces from which Na has been lost by sputtering processes with fresh ejecta
722 blankets, where we might expect to find ‘excess’ Na. Note that the SERENA-
723 STROFIO measurements in the exosphere (via sputtering and meteorite impact
724 vaporisation) will be almost independent of the grain size and vitrification of the
725 particles, but merely reflect the atomic composition of the grains undergoing
726 sputtering.

727 BepiColombo will offer for the first time the opportunity to evaluate the regolith
728 efficiency to eject material when impacted by ions from space, thus providing crucial
729 information about the effects of space weathering and about surface evolution. This
730 will be achieved thanks to specific joint measurements that will permit correlation of
731 the neutral particles observed at thermal energy by the mass spectrometer SERENA-
732 STROFIO and the generation region on the surface mapped through higher energy
733 neutral detection by SERENA-ELENA, together with simultaneous observations of
734 plasma precipitation by ion sensors SERENA-MIPA and -PICAM and to the
735 magnetic field measurements by MERMAG. The surface composition mapped by
736 MIXS, the surface mineralogy mapped by MERTIS and the surface cratering mapped

737 by SIMBIO-SYS will allow the released exospheric atoms to be related to the surface
738 properties.

739 **2.8 Characterising polar volatiles**

740 Permanently-shadowed regions of Mercury's polar craters are anomalous radar
741 reflectors, consistent with either ice or elemental sulfur (Harmon et al., 1994; Sprague
742 et al., 1995), held as a cold-trapped volatile within the shallow regolith. The neutron
743 spectrometer of MGNS (Mitrofanov et al., this issue) will place constraints on the
744 amount of hydrogen and, by inference, water-ice in polar regions (with an accuracy of
745 0.1 g cm^{-2} and a surface resolution of about 400 km) by characterizing the epithermal
746 neutron flux, as achieved on the Moon by Lunar Prospector (Feldman et al., 1998). If
747 sulfur is present, it may prove detectable by MIXS thanks to X-ray fluorescence
748 induced by electrons reaching the surface along magnetic field lines. It may also
749 prove possible to image any polar deposits optically by light reflected from the
750 opposite walls and central peaks.

751 The topography of landforms in an ice-rich substrate material can become subdued
752 due to relaxation by ice-enhanced creep of the regolith ("terrain softening"; e.g.,
753 Squyres and Carr, 1986). Possible (subsurface) ice deposits at Mercury's poles might
754 produce a similar effect (e.g., Barlow et al., 1999), which could be identified by
755 precise topographic measurements by BELA of, for example, the depth-to-diameter
756 relationships of permanently shadowed craters. Furthermore, BELA will also be able
757 to detect the relatively high albedo of any ice-rich surfaces within shadowed polar
758 craters.

759 **3 Data products**

760 **3.1 Photomosaic maps**

761 The US Geological Survey published 1: 5 million scale shaded-relief maps and
762 photomosaics based on Mariner-10 images (Davies et al., 1978), dividing Mercury
763 into fifteen quadrangles recognised by the International Astronomical Union
764 (although less than half the planet was imaged). This product type is important for
765 regional studies particularly for the reconstruction the tectonic settings and
766 geological/compositional context. An important outcome of the BepiColombo
767 mission will be the production of photomosaics of each quadrangle based on
768 SIMBIO-SYS STC images (up to 50 m/pixel in the original data), providing details of
769 the surface at higher resolution than MESSENGER images (which will range in
770 resolution from ~100 to 500 m/pixel for most of the planet's surface). Larger scale
771 photomosaic maps (1:1 million or better) will be produced for limited areas
772 containing interesting morphological and geological features to be selected during the
773 mission activities.

774 **3.2 Topographic maps and digital terrain models**

775 The combination of altimetric and topographic information provided by BELA and
776 SIMBIO-SYS STC will be used to derive global topographic maps and a DTM for the
777 whole planet and for each individual quadrangle. Three-dimensional reconstruction of
778 local topography overlain by images or compositional maps will be used for
779 geological interpretation and public outreach.

780 **3.3 Compositional maps and a Mercury geographic**
781 **information system**

782 BepiColombo will achieve a wide variety of mineralogical and elemental abundance
783 measurements. Mineralogy will be revealed chiefly by UV-IR reflectance
784 spectroscopy (SYMBIO-SYS) and thermal infrared emission spectroscopy (MERTIS)
785 whereas elemental abundances at spatial resolution adequate for mapping will be
786 revealed chiefly by X-ray fluorescence spectroscopy (MIXS). The resulting dataset
787 will be complex because of its many derivation routes and because its spatial
788 resolution and quality will vary with location and with the time of acquisition.
789 However, with the use of a common spatial reference system and suitable data fusion
790 techniques, it will be possible to set up a geographic information system (GIS) that
791 could be interrogated by the user to find information such as absolute element
792 abundances, element abundance ratios, and mineral abundances for any location on
793 Mercury's surface, together with estimates of the error (uncertainty) in each value. In
794 addition, the Mercury GIS will allow such data to be overlaid on other digital maps
795 or a digital photomosaic base, and could also include crater statistics and surface
796 physical properties such as slope, surface roughness and regolith grain-size. This will
797 be a powerful tool for many studies, such as geological mapping and investigation of
798 soil maturity across the globe.

799 **3.4 Geological maps**

800 Geological maps will provide a visual synthesis of knowledge of Mercury's geology
801 as revealed by the BepiColombo mission. A geological map is a derived product,
802 relying on assimilation and interpretation of multiple datasets. Because it portrays
803 terrain units in a stratigraphic framework, a geological map enables the three-

804 dimensional spatial relationships and the local and regional sequence of events to be
805 made clear (Wilhelms, 1990).

806 Mariner-10 imagery enabled the production of geological maps of all or parts of nine
807 quadrangles (out of 15) at a scale of 1:5 million, recently converted by USGS into a
808 digital format (http://webgis.wr.usgs.gov/pigwad/down/mercury_geology.htm). The
809 comprehensive coverage by BepiColombo will be sufficient not only to complete this
810 global mapping, with reinterpretation as necessary, but also to produce worthwhile
811 geological maps at 1:1 million scale globally, and at larger scales in regions of special
812 interest. The exact placement of geological boundaries will, in most cases, be done on
813 the basis of the highest resolution SIMBIO-SYS images (stereo images from STC at
814 50 to 110 m/pixel for the whole globe, and 5 m/pixel images of 20% of the globe from
815 HRIC), but data from several other experiments will feed in to the identification and
816 definition of the extent of each unit.

817 Regional coverage provided by photomosaics of STC images will show configuration
818 of bedrock, the extent of geological structures, and broad stratigraphic correlations
819 and age assessment from cratering records. The high resolution images from HRIC
820 will show most clearly the details of regolith surface, stratigraphic contacts and
821 onlapping/embayment relationships between bedrock units, and cross-cutting
822 relationships among structures. The third dimension provided by digital elevation
823 models and topographic maps from BELA and SIMBIO-SYS STC data will be
824 fundamental for evaluating thickness of geological units, to relate them to their
825 morphological characteristics and to infer the propagation of geological contacts and
826 tectonic features below the surface (i.e., geological sections and true volumetric three
827 dimensional rendering). The compositional information described in the previous
828 section will help to define geological units on the basis of their lithological

829 characteristics. This last requirement, fundamental for geological unit definition on
830 the Earth, has rarely been applied in the geological cartography of planetary surfaces,
831 which is usually limited to surface morphology, texture, albedo, stratigraphic
832 relationships and indirect age determinations.

833 **4 Big questions**

834 We conclude by considering some of the ‘big questions’ that BepiColombo’s
835 documenttion of Mercury’s surface and its composition may be particularly useful in
836 answering.

837 **4.1 What is the tectonic history of Mercury’s lithosphere?**

838 Given the small size of Mercury compared to the other terrestrial planets of the Solar
839 System, a prolonged tectonic history is not expected. However, for the same reason,
840 Mercury’s surface, like the lunar one, preserves traces of early tectonic processes.
841 These include: tidal despinning and consequent bulge relaxation manifested by the
842 global grid network affecting the ancient cratered regions (Burns, 1976; Melosh, 1977;
843 Melosh and Dzurisin 1978; Melosh and McKinnon, 1988); global contraction due to
844 planetary cooling manifested by widespread compressional lobate scarps (Murray et
845 al. 1974; Strom et al. 1975; Dzurisin, 1978; Watters et al., 1998; Solomon et al, 2008);
846 dynamic loading by giant impacts during heavy bombardment epoch well testified by
847 the basin structures and the hilly and lineated terrains at Caloris antipodes (Schultz
848 and Gault, 1975; McKinnon, 1981; Melosh and McKinnon, 1988, Murchie et al.
849 2008). The evolution of these phenomena, their mutual relationships and their
850 relations with respect to the progressively thickening of the crust and lithosphere
851 await elaboration based on orbital survey of the kind anticipated from BepiColombo.

852 The global lineament pattern on Mercury does not fit the predicted models for tidal
853 despinning (Thomas et al., 1988, Thomas 1997). This may be partly accounted for by
854 the incomplete Mariner-10 coverage of Mercury's surface obtained under a single set
855 of illumination conditions, varying across the globe. The three dimensional surface
856 mapping obtained by SIMBIO-SYS STC and BELA images should lead to more
857 reliable global lineament mapping, almost free of directional bias. In addition, thanks
858 to their resolution, SIMBIO-SYS HRIC images should provide important insights into
859 kinematics related to structural features. Therefore, despinning models will be better
860 constrained and other mechanisms that changed the planet's shape during the early
861 history of its surface may be recognized.

862 Interpretation of lobate scarps (e.g., Thomas et al., 1988; Thomas, 1997; Watters et al.,
863 2004) is presently hampered by incomplete coverage and paucity of stereo imaging
864 (Cook and Robinson, 2000). DTMs derived from SIMBIO-SYS and BELA will fill
865 this gap and will consistently improve upon present estimates of crustal shortening
866 and decrease of planetary radius (Strom et al., 1975; Watters et al., 1998). In addition
867 cross-sections through lobate scarps derived from DTMs will be used as input to
868 faulting models, resulting in better estimates of fault displacement, paleoseismicity,
869 and the thickness of the elastic lithosphere at the time of faulting (e.g. Watters et al.
870 2000, 2002; Nimmo and Watters, 2004; Grott et al., 2007). Accurate assessment of
871 the strain across contractional features will offer an important constraint on the
872 amount of global cooling, inner core solidification and hence on the models of the
873 planetary interior and its thermal evolution (Hauck et al., 2004; Solomon et al. 2008).

874 Long-wavelength lithospheric flexure is another process that can accommodate strain
875 induced by planetary contraction, and therefore it will be investigated using the
876 gravity data resulting from the radio tracking of BepiColombo's Mercury Planetary

877 Orbiter on the one hand, and the DTM from the BELA and SIMBIO-SYS STC on the
878 other. Furthermore, the same data can give important clues to assess whether there is
879 any correlation between topography and gravity anomalies, and at which wavelengths,
880 or to what extent the topography is supported by the mechanical strength of the
881 lithosphere or, finally, if a mechanism of isostatic compensation needs to be invoked
882 for the larger topographic features.

883 Recent analysis of the Moon has demonstrated that the detection, geomorphological
884 characterization and depth estimates of multi-ring basins can give important
885 information on the rheology of the ancient lithosphere and mantle (e.g. Mohit and
886 Phillips, 2006). Two multi-ring basins, Caloris and Tolstoj, were particularly apparent
887 on Mariner-10 images. The most interesting characteristics of the Caloris basin are the
888 lack of a well developed ring outside the main crater rim and the presence of
889 extensional grabens superimposed on compressional ridges deforming the post-impact
890 lava plains inside the basin. The lack of a well developed external ring could be due to
891 a thick (>100 km) lithosphere preventing penetration (Melosh and McKinnon, 1988),
892 but additional explanations include later viscous relaxation of topography or smooth
893 plains emplacement over subsiding ring-bounded blocks of the lithosphere
894 (McKinnon, 1981).

895 The extensional troughs cutting convex shaped ridges inside the basin have been
896 explained through different models (Murchie et al., 2008). The main ones are:
897 subsidence-related compression during smooth plains extrusion outside Caloris
898 followed by isostatic uplift and pellicular extension of the as yet incompletely
899 compensated basin (Dzurisin, 1978; Melosh and Dzurisin, 1978); compression related
900 to subsidence for interior plains load, followed by outer smooth plains emplacement
901 and consequent basin centre uplift and extension as result of the annular load

902 (McKinnon, 1981); uplift and extension due to lateral flow of the lower part of
903 relatively thick lithosphere toward the basin centre (Fleitout and Thomas, 1982;
904 Thomas et al. 1988 Watters et al., 2005).
905 A detailed structural analysis, aided by perspective views (BELA and SIMBIO-SYS
906 STC), high resolution (SIMBIO-SYS HRIC) and/or large area coverage (BELA and
907 SIMBIO-SYS STC), will bring important insights on large basin evolution, the
908 focusing of seismic waves after huge impacts, post-impact plains emplacement, and
909 deformation structures inside basins and in the surrounding areas.

910 **4.2 What is the composition of Mercury's crust and how did** 911 **it evolve?**

912 The surface compositions determined by BepiColombo will be measured across a
913 depth sampling range varying from tens of μm in the case of MIXS to 0.5 m for
914 MGNS. The optical and infrared spectrometers will gather data over a depth range of
915 the order of 1 mm. Almost the entire visible surface will be agglutinate-rich regolith
916 rather than bedrock (Cintala, 1992; Harmon, 1997), which may be vertically
917 homogenised across the depth range of the measurements by impact gardening except
918 in the cases of the most volatile elements and extremely fresh ejecta. In the case of the
919 Moon, homogenisation by impact gardening is effective on vertical scale of 1 m and a
920 horizontal scale of about a kilometre (Mustard, 1997). The rate of gardening on
921 Mercury should be higher because of higher meteorite flux, but lateral transport is
922 expected to be less because of Mercury's higher gravity (Langevin, 1997). Apart from
923 its meteoritic content, which may be as much as 5-20% (Noble and Pieters, 2003),
924 regolith on Mercury is therefore expected to be representative of the underlying
925 bedrock. By making allowance for space weathering (which in any case is unlikely to

926 affect significantly the abundances of elements such as Al, Si and Mg), the
927 composition of the upper crust can be determined in terms of both elemental
928 abundances (primarily MIXS and MGNS) and mineralogy (primarily SIMBIO-SYS
929 and MERTIS). However, it is possible that, as noted by Noble and Pieters (2003),
930 mature soils will be so dominated by glassy agglutinates with so little surviving
931 crystalline material that original crustal mineralogy will be revealed only in freshly-
932 exposed material.

933 Compositional variability of the shallowest layers of the crust may be revealed by
934 study of large crater walls. Opportunities to study deeper layers may be provided by
935 central peaks of craters (which are uplifted; Tompkins and Pieters, 1999) and floors of
936 any major basins analogous to the Moon's South Pole-Aitken basin that have avoided
937 later infill. Robinson et al. (2008) argue that 'low-reflectance material' identified in
938 MESSENGER images of some proximal ejecta reveals an opaque-enriched crustal
939 layer, which clearly warrants further scrutiny. Finally if lobate scarps are faults that
940 actually cut the surface they may reveal material exhumed from depths of around 1
941 km (Watters et al., 2000). This may prove to be mineralogically distinct and
942 resolvable by SIMBIO-SYS VIHI, but good exposures are likely to be rare and the
943 width of outcrop will be too narrow to be resolved by the element abundance
944 experiments MIXS and MGNS.

945 In combination with photogeologic interpretation and crater counting on high
946 resolution images (SIMBIO-SYS) and digital elevation models (SIMBIO-SYS and
947 BELA) we expect to be able to use this information to identify, distinguish and
948 interpret the nature of each major terrain unit within Mercury's crust. Apart from
949 answering the fundamental question of the presence and relative abundances of
950 primary crust and secondary crust, we will have a stratigraphic framework derived

951 from cross-cutting and superposition relationships and crater counting to enable crust-
952 forming events to be placed into context.

953 We note that if any of the hitherto elusive but statistically possible meteorites from
954 Mercury come to light (Love and Keil, 1995), then a crucial test of their provenance
955 will be compatibility with the mineralogy and element abundances deduced for units
956 in Mercury's crust on the basis of BepiColombo data (Nittler et al., 2004). Any strong
957 meteorite candidate for a sample of Mercury's crust thus revealed would open the way
958 for fuller understanding of Mercury based on its petrography, trace elements and
959 isotopes.

960 **4.3 What is the composition of Mercury's mantle?**

961 Determination of the composition of Mercury's mantle, and hence the composition of
962 its bulk silicate fraction, is an important goal that can be achieved indirectly via an
963 understanding of the nature and composition of the planet's crust. Although we will
964 lack seismic, petrological, trace element and isotopic data such as are available for the
965 Moon (Mueller et al., 1988; Warren, 2004) the BepiColombo measurements described
966 above will place our understanding of Mercury's mantle on a considerably firmer
967 foundation than previously, especially when coupled with BepiColombo's
968 geophysical study of the planetary interior (Spohn et al., this issue). For example, the
969 limited fractionation of Fe during partial melting of mantle material, means that the Fe
970 abundance in secondary crust can be used to define a conservative upper limit to the
971 mantle Fe abundance (Robinson and Taylor, 2001). Using the measured crustal
972 composition as a basis for modelling back to the mantle composition will be more
973 complex than this for most elements. However, provided primary and secondary crust
974 can be correctly identified and distinguished, their contrasting modes of origin may
975 provide a way to avoid at least some of the ambiguities.

976 **4.4 Origin and evolution of Mercury**

977 Taylor and Scott (2004) proposed various ways that knowledge of Mercury's crustal
978 composition could be used to distinguish between the competing models for
979 Mercury's origin. Among these are: low Si but high Mg would support Cameron's
980 (1985) evaporative silicate loss model; lavas with Ca <9% and Fe <0.3% would fit
981 with the enstatite chondrite model for Mercury (Wasson, 1988); Mg of about 10% and
982 Cr 1% in lava would be consistent with Goettel's (1988) refractory-volatile mixture
983 model, whereas other models would predict higher Mg, but Cr of only 0.1%. We also
984 note that P and Ti have similar partitioning behaviour during partial melting, and so
985 Ti/P in lavas should be similar to the mantle Ti/P ratio. This would be about 1 if the
986 mantle retains a chondritic Ti/P ratio, but if (as is likely, but unproven) core formation
987 preceded volcanism, prior scavenging of P into the core would boost the Ti/P ratio to
988 about 10 in secondary crust. Finally if Mercury lost its original crust in a giant impact
989 event, then, as pointed out by Benz et al. (2007), its present crust should be depleted
990 in large ion lithophile elements, and so be relatively poor in K and Ca. As previously
991 noted, the remaining mantle is likely to be depleted in chemically incompatible
992 elements (KREEP), and be relatively iron-poor (as seems to be the case). These
993 effects would be more extreme if the Mercury predecessor body/bodies experienced
994 more than one such episode, and observations by BepiColombo will help to better
995 constrain such giant impact models.

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1001 **6 References**

- 1002 André, S. L. and Watters, T. R., 2006. Depth to diameter measurements of Mercurian
1003 mature complex craters. Lunar Planet. Sci. Conf. XXXVII, abstract 2054.
- 1004 Barlow, N. G., Allen, R. A., Vilas, F., 1999. Mercurian Impact Craters: Implications
1005 for Polar Ground Ice. *Icarus* 141, 194-204.
- 1006 Basaltic Volcanism Study Project, 1981, Basaltic volcanism on the terrestrial planets,
1007 sponsored by the Lunar and Planetary Institute, Pergamon Press, New York, 1286
1008 pp.
- 1009 Benz, W, Slattery, W.L., Cameron, A.G.W., 1988, Collisional stripping of Mercury's
1010 mantle, *Icarus*, 74, 516-528.
- 1011 Benz, W., Anic, A., Horner, J., Whitby, J.A., 2007, The origin of Mercury, *Space*
1012 *Science Reviews*, DOI 10.1007/s11214-007-9284-1
- 1013 Blewett, D. T., Lucey, P. G., Hawke, B. R., Ling, G. G., Robinson, M. S., 1997, A
1014 comparison of Mercurian reflectance and spectral quantities with those of the
1015 Moon, *Icarus*, 191, 217-231.
- 1016 Blewett, D. T.; Hawke, B. R.; Lucey, P. G.(2002) Lunar pure anorthosite as a spectral
1017 analog for Mercury, *Meteoritics & Planetary Science*, 37, 9, pp. 1245-1254.
- 1018 Blewett, D. T., Hawke, B. R., Lucey, P. G., Robinson, M. S., 2007, A Mariner 10
1019 colour study of Mercurian craters, *J. Geophys. Res.* 112, E02005,
1020 doi:10.1029/2006JE002713.

1021 Bondarenko, N. V., Kreslavsky, M. A., and Head, J. W., 2006. North-south roughness
1022 anisotropy on Venus from the Magellan Radar Altimeter: Correlation with
1023 geology. . J. Geophys. Res. 111, E06S12, doi: [10.1029/2005JE002599](https://doi.org/10.1029/2005JE002599).

1024 Bottke, W. F. Jr, Durda, D. D., Nesvorny, D., Jedicke, R., Morbidelli, A.,
1025 Vokrouhlicky, D., Levison, H. S., 2005, Linking the collisional history of the main
1026 asteroid belt to its dynamical excitation and depletion, Icarus, 179, 63-94.

1027 Boynton, W. V., Sprague, A. L., Solomon, S. C., Starr, R. D., Evans, L. G., Feldman,
1028 W. C., Trombka, J. I., Rhodes, E. A., 2007, MESSENGER and the chemistry of
1029 Mercury's surface, Space Science Reviews, 131, 85-104.

1030 Britt, D. T., Pieters, C. M., 1994, Darkening in black and gas-rich ordinary chondrites:
1031 the spectral effects of opaque mineralogy and distribution, Geochimica et
1032 Cosmochimica Acta, 58, 3905-3919.

1033 Burbine T. H., McCoy T. J., Nittler L. R., Benedix G. K., Cloutis E. A. and Dickinson
1034 T. L. (2002). Spectra of extremely reduced assemblages: Implications for Mercury.
1035 Meteorit. Planet. Sci., 37, 1233-1244.

1036 Burns J. A., 1976, Consequences of the tidal slowing of Mercury, Icarus, 28, 453-458.

1037 Cameron, A.G.W., 1985, The partial volatilization of Mercury, Icarus, 71, 337-349.

1038 Cintala, M.J., 1992, Impact-induced thermal effects in the lunar and mercurian
1039 regoliths, J. Geophys. Res., 97, 947

1040 Clark, P. E., 2007, Dynamic Planet: Mercury in the Context of its Environment,
1041 Springer, New York, 219pp.

1042 Cook, A.C., Robinson, M.S., 2000, Mariner 10 stereo image coverage of Mercury, J.
1043 Geophys. Res., 105, 0429-9444.

1044 Cooper, B., Potter, A. E., Killen, R. M., Morgan T. H., 2001, Mid-infrared spectra of
1045 Mercury, J. Geophys. Res., 106, 32803-32814.

1046 Cord, A., Baratoux, D., Mangold, N., Martin, P., Pinet, P., Greeley, R., Costard, F.,
1047 Masson, P., Foing, B., Neukum, G., 2007. Surface roughness and geological
1048 mapping at subhectometer scale from the High Resolution Stereo Camera onboard
1049 Mars Express. *Icarus* 191, 38-51.

1050 Cremonese G., Sprague A., Warell J., Thomas N., Ksamfomality L., 2007. The
1051 Surface of Mercury as seen by Mariner 10. *Space Sci. Rev.* 132, 291-306.

1052 Cremonese G., Fantinel D., Giro E., Capria M. T., Da Deppo V., Naletto G., Forlani
1053 G., Massironi M., Giacomini L., Sgavetti M., Simioni E., Debei S., Marinangeli L.,
1054 Flamini E., 2008. The Stereo Camera on the Bepicolombo ESA/JAXA mission, A
1055 novel approach. *Advances In Geosciences (Accepted Pending Revision)*

1056 Davies, M. E., Dwornik, S. E., Gault, D. E., Strom, R. G., 1978. *Atlas of Mercury*,
1057 NASA SP-423, 128 pp.

1058 Dzurisin, D., 1977, Mercurian bright patches: evidence for physico-chemical
1059 alteration of surface material? *Geophysical Research Letters*, 4, 383-386.

1060 Dzurisin, D., 1978. The tectonic and volcanic history of Mercury as inferred from
1061 studies of scarps, ridges, troughs, and other lineaments. *J. Geophys. Res.* 83, 4883-
1062 4906.

1063 Fegley, B., Cameron, A.G.W., 1987, A vaporization model for iron/silicate
1064 fractionation in the Mercury protoplanet, *Earth and Planetary Science Letters*, 82
1065 (3-4), 207-222.

1066 Feldman, W.C., Maurice, S., Binder, A.B., Barraclough, B.L., Elphic, R.C., Lawrence,
1067 D.J., 1998, Fluxes of fast and epithermal neutrons from Lunar Prospector: evidence
1068 for water ice at the lunar poles, *Science*, 281, 1496-1500.

1069 Flamini, E. et al. this issue

- 1070 Fleitout, L., Thomas, P.G., 1982, Far-field tectonics associated with a large impact
1071 basin: applications to Caloris on Mercury and Imbrium on the Moon. *Earth. Planet.*
1072 *Sci. Let.*, 58, 104-115.
- 1073 Fraser, G. et al. this issue
- 1074 Fujimoto, Laakso, H., Benkhoff, J. this issue
- 1075 Glaze, L. S., Baloga, S. M., and Stofan, E. R., 2003. A methodology for constraining
1076 lava flow rheologies with MOLA. *Icarus* 165, 26-33.
- 1077 Goettel, K.A., 1988, Present bounds on the bulk composition of Mercury -
1078 Implications for planetary formation processes. In: Matthews, M.S., Chapman, C.,
1079 Vilas, F. (Eds), *Mercury*, University of Arizona Press, Tucson, AZ, pp. 613-621,
1080 1988.
- 1081 Grott, M., Hauber, E., Werner, S. C., Kronberg, P., Neukum, G., 2007. Mechanical
1082 modeling of thrust faults in the Thaumasia region, Mars, and implications for the
1083 Noachian heat flux. *Icarus* 186, 517-526.
- 1084 Hajakawa, van Casteren, Ferri, this issue
- 1085 Hapke, B., 1981, Bidirectional reflectance spectroscopy I. Theory. *J. Geophys. Res.*
1086 86, 3039-3054.
- 1087 Hapke, B. 1993. *Theory of reflectance and emittance spectroscopy*. Cambridge
1088 University Press, New-York, 455 pp.
- 1089 Hapke, B., 2001. Space weathering from Mercury to the asteroid belt. *J. Geophys. Res.*
1090 106, 10039-10074.
- 1091 Hapke, B., Danielson, G. E. Jr, Klaasen, K., Wilson, L., 1975, Photometric
1092 observations of Mercury from Mariner 10, *J. Geophys. Res.* 80, 2431-2443.
- 1093 Hapke, B., Wells, E., Wagner, J., Partlow, W., 1981. Far-UV, visible, and near
1094 infrared reflectance spectra of frost of H₂O, CO₂, NH₃, and SO₂. *Icarus* 47, 361.

1095 Harmon, J.K., 1997, Mercury radar studies and lunar comparisons, *Advances in*
1096 *Space Research*, 19, 1487-1496.

1097 Harmon, J.K., Campbell, D.B., 1988, Radar observations of Mercury. In: Matthews,
1098 M.S., Chapman, C., Vilas, F. (Eds), *Mercury*, University of Arizona Press, Tucson,
1099 AZ, pp. 101-117, 1988.

1100 Harmon, J.K., Slade, M.A., Velez, R.A., Crespo, A., Dryer, M.J., Jonson, J.M., 1994,
1101 Radar mapping of Mercury's polar anomalies, *Nature*, 369, 213-215.

1102 Hartmann, W. K., Neukum, G., 2001, Cratering chronology and the evolution of Mars,
1103 *Space Science Reviews*, 96, 165-194.

1104 Hartmann, W.K., Strom, R., Weidenschilling, S., Blasius, K., Woronow, A., Dence,
1105 M., Grieve, R., Diaz, J., Chapman, C., Shoemaker, E., Jones K., 1981. Chronology
1106 of planetary volcanism by comparative studies of planetary cratering. In: *Basaltic*
1107 *Volcanism on the Terrestrial Planets*, 1050-1129.

1108 Hauck, S.A., Dombard, A.J., Phillips R.J., Solomon S.C., 2004. Internal and tectonic
1109 evolution of Mercury. *Earth and Planetary Science Letters*, 222, 713-728.

1110 Haskin, L. and Warren, P., 1991, *Lunar Chemistry*. In: Heiken, G.H., Vaniman, D.
1111 and French, B.M. (Eds.), *The Lunar sourcebook: A user's guide to the Moon*,
1112 Cambridge University Press.

1113 Head, J.W., Chapman, C.R., Domingue, D.L., Hawkins, S.E., McClintock, W.E.,
1114 Murchie, S. L., Prockter, L.M., Robinson, M.S., Strom, R.G., Watters, T.R., 2007,
1115 *The geology of Mercury: the view prior to the MESSENGER mission*, *Space*
1116 *Science Review*, 131, 41-84.

1117 Head, J.W., Murchie, S.L., Prockter, L.M., Robinson, M.S., Solomon, S.C., Strom,
1118 R.S., Chapman, C.R., Watters, T.R., McClintock, W.E., Blewett, D.T., Gillis-Davis,

1119 J.J., 2008, Volcanism on Mercury: evidence from the first MESSENGER flyby,
1120 Science, 321, 69-72.

1121 Helbert, J., Moroz, L. V., Maturilli, A., Bischoff, A., Warell, J., 2007, A set of
1122 laboratory analogue materials for the MERTIS instrument on the ESA
1123 BepiColombo mission to Mercury, Advances in Space Research, 40, 272-279.

1124 Hess, P.C., Parmentier, E.M., 1995. A model for the thermal and chemical evolution
1125 of the Moon's interior: implications for the onset of mare volcanism. Earth Plat. Sci.
1126 Lett., 134, 501-514.

1127 Hiesinger, H., Head, J. W., Neukum, G., 2007. Young lava flows on the eastern flank
1128 of Ascræus Mons: Rheological properties derived from High Resolution Stereo
1129 Camera (HRSC) images and Mars Orbiter Laser Altimeter (MOLA) data. . J.
1130 Geophys. Res. 112, doi: 10.1029/2006JE002717.

1131 Hinrichs, J. L.; Lucey, P.G., 2002. Temperature-Dependent Near-Infrared Spectral
1132 Properties of Minerals, Meteorites, and Lunar Soil, Icarus, 155, 169-180.

1133 Ivanov B.A., 2001, Mars/Moon cratering rate ratio estimates. Space Sci. Rev., 96, 87-
1134 104.

1135 Jeanloz, R.; Mitchell, D. L.; Sprague, A. L.; de Pater, I., 1995. Evidence for a Basalt-
1136 Free Surface on Mercury and Implications for Internal Heat. Science, 268, 1455-
1137 1457.

1138 Jolliff, B.L., 2006. What is the composition of the Moon's lower crust? Lunar Planet.
1139 Sci. Conf., 37, 2346.

1140 Jolliff, B.L., Gillis, J.J., Haskin, L., Korotev, R.L., Wieczorek, M.A., 2000, Major
1141 lunar crustal terranes: Surface expressions and crust-mantle origins, J. Geophys.
1142 Res., 105, 4197-4216.

1143 Keller, L. P., McKay, D. S., 1993, Discovery of vapor deposits in the lunar regolith,
1144 Science, 261, 1305-1307.

1145 Killen, R., Cremonese, G., Lammer, H., Orsini, S., Potter, A.E., Sprague, A.L., Wurz,
1146 P., Khodachenko, M.,Lichtenegger, H.I.M., Milillo, A, Mura, A., 2007, Processes
1147 that promote and deplete the exosphere of Mercury, Space Science Rev., 132, 433-
1148 509.

1149 Krebs, D. J., Novo-Gradac, A.-M., Li, S. X., Lindauer, S. J., Afzal, R. S., Yu, A. W.,
1150 2005. Compact, passively Q-switched Nd:YAG laser for the MESSENGER
1151 mission to Mercury. Appl. Opt. 44 (9), 1715-1718.

1152 Kreslavsky, M. A., Head, J. W., 2000. Kilometer-scale roughness of Mars: Results
1153 from MOLA data analysis. J. Geophys. Res. 105, 26,695-26,712.

1154 Kreslavsky, M.A. and Y.G. Shkuratov 2003. Photometric anomalies of the lunar
1155 surface: Results from Clementine data, Journal of Geophysical Research (Planets)
1156 108c, 1-1

1157 Langevin, Y., 1997, The regolith of Mercury: present knowledge and implications for
1158 the Mercury Orbiter mission, Planetary and Space Science, 45, 31-38.

1159 Langevin, Y., Arnold, J. R., 1977, The evolution of the lunar regolith. Ann. Rev.
1160 Earth Planet. Sci., 5, 449-489.

1161 Le Mouélic, S., Lucey, P.G., Langevin, Y., Hawke,B.R. 2002. Calculating iron
1162 contents of lunar highland materials surrounding Tycho crater from integrated
1163 Clementine UV-visible and near-infrared data, Journal of Geophysical Research
1164 (Planets) 107, 4-1.

1165 Love, S., Keil, K., 1995. Recognizing mercurian meteorites. Meteoritics, 30, 269 -278

1166 Lucey, P.G. 2006. Radiative transfer modeling of the effect of mineralogy on some
1167 empirical methods for estimating iron concentration from multispectral imaging of
1168 the Moon, *Journal of Geophysical Research (Planets)* 111, 08003

1169 Lucey, P. G., Taylor, G. J., Malaret, E., 1995, Abundance and distribution of iron on
1170 the Moon, *Science*, 268, 1150-1153.

1171 Lucey, P., R.L., Gillis J.J., Taylor L.A., Lawrence D., Campbell B.A., Elphic R., Feldmann B.,
1172 Hood L.L., Hunten D., Mendillo M., Noble S., Papike J.J., Reedy R.C., Lawson S.,
1173 Prettyman T., Gasault O., Maurice S., 2006, Understanding the Lunar Surface and Space-
1174 Moon Interactions in New Views of the Moon, *Rev. Mineral. Geochem.* 60. 83 - 219.

1175 Mangano, V., Milillo, A., Mura, A., Orsini, S. De Angelis, E., Di Lellis, A.M., Wurz,
1176 P., 2007, The contribution of impulsive meteoritic impact vaporization to the
1177 Hermean exosphere, *Planetary and Space Science*, 55, 1541-1556.

1178 Margot, J.L., Peale, S.J., Jurgens, R.F., Slade, M.A., Holin, I.V., 2007, Large
1179 longitude libration of Mercury reveals a molten core, *Science*, 316, 710-714.

1180 Marchi, S., Mottola, F., Cremonese, G., Massironi, M., Martellato, E., 2008. A new
1181 model for age determination of lunar region. The 10th Asteroids, Comets, Meteors
1182 meeting, Baltimore, Maryland, USA

1183 Marchi, S., Mottola, F., Cremonese, G., Massironi, M., Martellat,o E., submitted. A
1184 new chronology for the Moon and Mercury. Submitted to *Astronomical Journal*.

1185 Massironi M., Forlani G., Cremonese G., Capria M. T ., Da Deppo V., Giacomini L.,
1186 Naletto G., Pasquaré G., Roncella R., Flamini E., 2008. Simulations using
1187 terrestrial geological analogues to assess interpretability of potential geological
1188 features of the Hermean surface restituted by the STereo imaging Camera of the
1189 SIMBIO-SYS package (BepiColombo mission). *Planetary and Space Science*
1190 (accepted pending revision).

- 1191 McClintock, W.E., Izenberg, N.R., Holsclaw, G.M., Blewett, D.T., Domingue, D.L.,
1192 Head, J.W., Helbert, J., McCoy, T.J., Murchie, S.L., Robinson, M.S., Solomon,
1193 S.L., Sprague, A.L., Vilas, F., 2008, Spectroscopic observations of Mercury's
1194 surface reflectance during MESSENGER's first Mercury flyby, *Science*, 321, 62-
1195 65.
- 1196 McCord, T.B., Clark, R.N., 1979, The Mercury soil: presence of Fe²⁺, *Journal of*
1197 *Geophysical Research*, 178, 745-747.
- 1198 McKinnon W.B., 1981. Application of ring tectonic theory to Mercury and other solar
1199 system bodies. In *Multi-ring Basins*, Proc. Lunar Planet. Sci., eds P.H: Shultz and
1200 R.B: Merril, 12, 259-273.
- 1201 Melosh H. J., 1977, Global tectonics of a despun planet. *Icarus*, 31, 221-243.
- 1202 Melosh, H. J., 1989. *Impact Cratering*. Oxford University Press.
- 1203 Melosh, H. J, Dzurisin, D., 1978, The mechanics of ringed basin formation, *Geophys.*
1204 *Res. Lett.*, 5, 985-988.
- 1205 Melosh, H. J, McKinnon, B, 1988, The tectonics of Mercury, In: Matthews, M.S.,
1206 Chapman, C., Vilas, F. (Eds), *Mercury*, University of Arizona Press, Tucson, AZ,
1207 pp. 401-28, 1988
- 1208 Milillo, A., P. Wurz, S. Orsini, D. Delcourt, E. Kallio, R.M. Killen, H. Lammer, S.
1209 Massetti, A. Mura, S. Barabash, G. Cremonese, I.A. Daglis, E. DeAngelis, A.M. Di
1210 Lellis, S. Livi, V. Mangano, and K. Torkar, "Surface-exosphere-magnetosphere
1211 system of Mercury," *Space Science Review*, 117 (2005) 397-443.
- 1212 Mitchell, D. L.; de Pater, I., 1994. Microwave Imaging of Mercury's Thermal
1213 Emission at Wavelengths from 0.3 to 20.5 cm, *Icarus*, 110, 2-32
- 1214 Mitrofanov et al., this issue

- 1215 Mohit, P. S., Phillips, R. J., 2006, Viscoelastic relaxation of lunar multiring basins, J.
1216 Geophys. Res., 111, doi:10.1029/2005JE002654
- 1217 Morgan, J.W., Anders, E., 1980, Chemical composition of earth, Venus, and Mercury,
1218 Proc. Natl. Acad. Sci. USA, Vol. 77, pp. 6973-6977.
- 1219 Muinonen, K., 2004, Coherent backscattering of light by complex random media of
1220 spherical scatterers: Numerical solution, Waves in Random Media 14(3), 365-388.
- 1221 Muinonen, K., Piironen, J., Shkuratov, Yu. G., Ovcharenko, A., and Clark, B. E.,
1222 2002, Asteroid photometric and polarimetric phase effects, In: Bottke, W., Binzel,
1223 R. P., Cellino, A., Paolicchi, P. (Eds), Asteroids III, University of Arizona Press,
1224 Tucson, AZ, U.S.A., pp. 123-138.
- 1225 Murchie, S.L., Watters, T.R., Robinson, M.S., Head, J.W., Strom, R.S., Chapman,
1226 C.R., Solomon, S.C., McClintock, W. E., Prockter, L.M., Domingue, D.L., Blewett,
1227 D.T., 2008, Geology of the Caloris Basin, Mercury: a view from MESSENGER,
1228 Science, 321, 73-76.
- 1229 Murray B.C., Belton M.J.S., Danielson G.E., Davies M.E., Gault D., Hapke B.,
1230 O'Leary B., Strom R.G., Suomi V. , Trask N., 1974. Mercury's surface:
1231 preliminary descriptions and interpretations from Mariner 10 pictures. Science, 185,
1232 169-179.
- 1233 Mustard, J.F., 1997, Constraints on the magnitude of vertical and lateral mass
1234 transport on the Moon, Technical Report NASA/CR-1998-208203
- 1235 Näränen, J., Parviainen, H., Muinonen, K., Nygård, K., Peura, M., Carpenter, J, in
1236 press, Laboratory studies into the effect of regolith on planetary X-ray fluorescence
1237 spectroscopy, Icarus, in press.
- 1238 Neumann, G. A., Abshire, J. B., Aharonson, O., Garvin, J. B., Sun, X., and Zuber,
1239 M. T., 2003. Mars Orbiter Laser Altimeter pulse width measurements and

1240 footprint-scale roughness. *Geophys. Res. Lett.* 30, 15-1, doi:
1241 10.1029/2003GL017048.

1242 Neukum, G., Köning, B., Arkani-Hamed, J., 1975. A study of lunar impact crater size
1243 distributions. *The Moon* 12, 201–229.

1244 Neukum, G., Ivanov B.A., Hartmann W.K., 2001a - Cratering records in the Inner
1245 Solar System in relation to the lunar reference system. *Space Science Reviews* 96,
1246 55-86.

1247 Neukum, G., Oberst, J., Hoffmann, H., Wagner, R., Ivaov, B. A., 2001a, Geologic
1248 evolution and cratering history of Mercury, *Planet. Space Sci.*, 49, 1507-1521.

1249 Nimmo, F., Watters, T.R., 2004. Depth of faulting on Mercury: Implications for heat
1250 flux and crustal and effective elastic thickness. *Geophysical Research Letters*, vol.
1251 31, L02701, doi:10.1029/2003GL018847.

1252 Nittler, L.R., McCoy, T.J., Clark, P.E., Murphy, M.E., Trombka, J.I., Jarosewich, E.,
1253 2004, Bulk element compositions of meteorites: a guide for interpreting remote-
1254 sensing geochemical measurements of planet and asteroids, *Antaract. Meteorite Res.*,
1255 17, 233-253.

1256 Noble, S. K., Pieters, C.M., 2003, Space weathering on Mercury: implications for
1257 remote sensing, *Solar System Res.* 37, 34–39

1258 Noble, S.K., Pieters, C.M., Keller, L.P., 2007, An experimental approach to
1259 understanding the optical effects of space weathering, *Icarus*, 192, 629-642.

1260 Parviainen, H., Muinonen, K., 2007, Rough-surface shadowing for self-affine random
1261 rough surfaces, *J. Quantitat. Spectrosc. Radiat. Transfer* 106, 398-416.

1262 Pieters, C.M., Taylor, L. A., Noble, S. K., Keller, L.P., Hapke, B., Morris, R. V.,
1263 Allen, C. C., McKay, D. S., Wentworth, S. 2000. Space weathering on airless

- 1264 bodies: Resolving a mystery with lunar samples. *Meteoritics Planet. Sci.* 35, 1101-
1265 1107.
- 1266 Pike, R. J., 1988. Geomorphology of impact craters on Mercury. In: Vilas, F.,
1267 Chapman, C.R., Matthews, M.S. (Eds.), *Mercury*, pp. 165-273, University of
1268 Arizona Press, Tucson, AZ.
- 1269 Rava, B, Hapke, B., 1987, An analysis of the Mariner 10 color ratio map of Mercury,
1270 *Icarus*, 71, 397–429
- 1271 Robinson, M. S., Taylor, G. J., 2001. Ferrous oxide in Mercury’s crust and mantle,
1272 *Meteoritics and Planetary Science* 36, 841-847.
- 1273 Robinson, M. S., Lucey, P. G., 1997, Recalibrated Mariner 10 color mosaics:
1274 implications for Mercurian Volcanism, *Science*, 275, 197-200.
- 1275 Robinson, M.S., Murchie, S.L., Blewett, D.T., Domingue, D.L., Hawkins, S.E., Head,
1276 J.W., Holsclaw, G.M., McClintock, W.E., McCoy, T.J., McNutt, R.L., Prockter,
1277 L.M., Solomon, S.C., Watters, T.R., Reflectance and color variations on Mercury:
1278 regolith processes and compositional heterogeneity, *Science*, 321, 66-69/
- 1279 Ruzicka, A., Snyder, G. A., Taylor, L. A., 2001, Comparative geochemistry of basalts
1280 from the Moon, Earth, HED asteroid, and Mars. Implications for the origin of the
1281 Moon, *Geochim. Cosmochim. Acta*, 65, 979–997
- 1282 Salisbury, J. W., Basu, A., Fischer, E. M., 1997, Thermal infrared spectra of lunar
1283 soils. *Icarus*, 130, 125–139
- 1284 Schultz P. H., Gault, D. E., 1975. Seismic effects from major basin formation on the
1285 Moon and Mercury. *The Moon*, 12, 159-177.
- 1286 Schultz, R. A., Okubo, C. H., Goudy, C. L., Wilkins, S. J., 2004. Igneous dikes on
1287 Mars revealed by Mars Orbiter Laser Altimeter topography. *Geology* 32, 889-892.

1288 Shearer, C.K., Hess, P.C., Wieczorek, M.A., Pritchard, M.E., Parmentier, E.M., Borg,
1289 L., Longhi, J., Elkins-Tanton, L.T., Neal, C.R., Antonenko, I., Canup, R.M.,
1290 Halliday, A.N., Grove, T.L., Hager, B.H., Less, D.-C., and Wiechert, U., 2006.
1291 Thermal and magmatic evolution of the Moon. In: Jolliff, B.L., et al. (Eds.), New
1292 Views of the Moon, *Rev. Min. Geochem.*, 60, 365-518.

1293 Shkuratov, Y., Starukhina, L., Hoffmann, H., Arnold, G. 1999. A Model of Spectral
1294 Albedo of Particulate Surfaces: Implications for Optical Properties of the Moon.
1295 *Icarus* 137, 235-246
1296 Solomon, S.C., 2003. Mercury: the enigmatic planet. *Earth
1297 Planet. Sci.Lett.* 216, 441–455.

1297 Solomon S., 2003, Mercury: the enigmatic innermost planet, *Earth and Planetary
1298 Science Letters*, 216, 441-455.

1299 Solomon, S.C., McNutt, Jr., R.L., Gold, R.E., Acuña, M.H., Baker, D.N., Boynton,
1300 W.V., Chapman, C.R., Cheng, A.F., Gloeckler, G., Head, III, J.W., Krimigis, S.M.,
1301 McClintock, W.E., Murchie, S.L., Peale, S.J., Phillips, R.J., Robinson, M.S., Slavin,
1302 J.A., Smith, D.E., Strom, R.G., Trombka, J.I., Zuber, M.T., 2001. The
1303 MESSENGER mission to Mercury: scientific objectives and implementation.
1304 *Planet. Space Sci.*, 49, 1445-1465

1305 Solomon, S.C., McNutt, R.L., Gold, R.E., Domingue, D.L, 2007, MESSENGER
1306 mission overview, *Space Science Reviews*, 131, 3-39.

1307 Solomon, S.C., McNutt, R.L., Watters, T.R., Lawrence, D.J., Feldman, W.C., Head,
1308 J.W., Krimigis, S.M., Murchie, S.L., Phillips, R.J., Slavin, J.A., Zuber. M.T., 2008,
1309 Return to Mercury: A global perspective on MESSENGER’s first Mercury flyby,
1310 *Science*, 321, 59-62

1311 Spohn, T., Iess, L., et al. This issue (interior working group paper)

1312 Sprague, A. L., Roush, T. L., 1988, Comparison of laboratory emission spectra with
1313 Mercury telescopic data, *Icarus*, 133, 174-183.

1314 Sprague, A.L., Hunten, D.M., Lodders, K., 1995, Sulfur at Mercury, elemental at the
1315 polar and sulfides in the regolith, *Icarus*, 118, 211-215.

1316 Sprague, A.L., Emery, J.P., Donaldson, K.L., Russell, R. W., Lynch, D.K., Mazuk,
1317 A.L., 2002, Mercury: Mid-infrared (3-13.5 μm) observations show heterogeneous
1318 composition, presence of intermediate and basic soil types, and pyroxene.
1319 *Meteoritics and Planetary Science*, 37, 1255-1268.

1320 Sprague, A.L., Warell, J., Cremonese, G., Langevin, Y., Helbert, J., Wurz, P.,
1321 Veselovsky, I., Orsini, S., Milillo, A. 2007, Mercury's surface composition and
1322 character as measured by ground-based observations, *Space Science Reviews*, DOI
1323 10.1007/s11214-007-9221-3.

1324 Spudis, P. D., Guest, J. E., 1988, Stratigraphy and geologic history of Mercury. In:
1325 Matthews, M.S., Chapman, C., Vilas, F. (Eds), *Mercury*, University of Arizona
1326 Press, Tucson, AZ, pp. 118-164, 1988.

1327 Squyres, S. W., Carr, M. H., 1986. Geomorphic evidence for the distribution of ground
1328 ice on Mars. *Science* 231, 249-252.

1329 Starukhina, L. V., Shkuratov, Y. G., 2004, Swirls on the Moon and Mercury:
1330 meteoroid swarm encounters as a formation mechanism. *Icarus* 167, 136-147.

1331 Strom, R.G., 1997. Mercury: an overview. *Adv. Space Res.* 19, 1471–1485.

1332 Strom R.G., Neukum, G., 1988, The cratering record on Mercury and the origin of
1333 impact objects, *Mercury*. In: Matthews, M.S., Chapman, C., Vilas, F. (Eds),
1334 *Mercury*, University of Arizona Press, Tucson, AZ, pp. 336-373.

1335 Strom R. G., Sprague, A. L., 2003, *Exploring Mercury: the Iron Planet*, Springer-
1336 Praxis, Chichester UK, 216pp.

- 1337 Strom, R.G., Trask, N.J., Guest, J.E., 1975, Tectonism and volcanism on Mercury, J.
1338 Geophys. Res., 80, 2478-2507.
- 1339 Strom R.G., Malhotra, R., Ito, T., Yoshida, F., Kring, D.A., 2005, The origin of
1340 planetary impactors in the inner Solar System, Science, 309, 1847-1850.
- 1341 Strom, R.G., Chapman, C.R., Merline, W.J., Solomon, S.C., Head, J.W., 2008,
1342 Mercury cratering record viewed from MESSENGER's first flyby, Science, 321,
1343 79-81.
- 1344 Taylor, S.R., 1982, Lunar and terrestrial crusts: a contrast in origin and evolution,
1345 Physics of the Earth and Planetary Interiors, 29, 233-241.
- 1346 Taylor, S.R., 1989, Growth of planetary crusts, Tectonophysics, 161, 147-156.
- 1347 Taylor, G.J., Scott, E.R.D., 2004, Mercury. In: Davis, A.M. (Ed.) Treatise on
1348 Geochemistry, volume 1, Meteorites, Comets, and Planets, Elsevier, Oxford and
1349 San Diego, pp. 477-485.
- 1350 Thomas, P. G., 1997, Are there other tectonics than tidal despinning, global
1351 contraction and Caloris related events on Mercury? A review of questions and
1352 problems, Planet. Space. Sci., 45, 3-13.
- 1353 Thomas, P.G., Masson, P., In: Matthews, M.S., Chapman, C., Vilas, F. (Eds),
1354 Mercury, University of Arizona Press, Tucson, AZ, pp. 401-428, 1988
- 1355 Thomas, N. and 26 co-authors, 2007. The BepiColombo Laser Altimeter (BELA):
1356 Concept and baseline design. Planetary and Space Science 55, 1398-1413.
- 1357 Tompkins, S.; Pieters, C. M., 1999, Mineralogy of the lunar crust: Results from
1358 Clementine, Meteorit. Planet. Sci., 34, 25-41.
- 1359 Vilas, F., 1988, Surface composition of Mercury from reflectance spectrophotometry.
1360 In: Matthews, M.S., Chapman, C., Vilas, F. (Eds), Mercury, University of Arizona
1361 Press, Tucson, AZ, pp. 59-76, 1988.

- 1362 Warell, J., 2002, Properties of the Hermean regolith: II. Disk-resolved multicolour
1363 photometry and color variations of the “unknown” hemisphere, *Icarus*, 156, 303-
1364 317.
- 1365 Warell, J., 2003, Properties of the Hermean regolith: III. Disk-resolved VIS-NIR
1366 reflectance spectra and implications for the abundance of iron, *Icarus*, 161, 199-
1367 222.
- 1368 Warell, J., Blewett, D. T., 2004, Properties of the Hermean regolith: V. New optical
1369 reflectance spectra, comparisons with lunar anorthosites and mineralogical
1370 modelling, *Icarus*, 168, 257-276.
- 1371 Warell, J., Valegård, P.-G., 2007, Albedo-colour distribution on Mercury:
1372 photometric study of the poorly known hemisphere, *Astronomy and Astrophysics*,
1373 460, 625-633.
- 1374 Warell, J. A., Sprague, A., Emry, J., Kozłowski, R. W., Long, A., 2006, The 0.7-5.3
1375 micrometer IR spectra of Mercury and the Moon: Evidence for high-Ca
1376 clinopyroxene on Mercury, *Icarus*, 180, 281-291.
- 1377 Warren, P.H., 2004, The Moon. In: Davis, A.M. (Ed.) *Treatise on Geochemistry*,
1378 volume 1, Meteorites, Comets, and Planets, Elsevier, Oxford and San Diego, pp.
1379 559-599.
- 1380 Wasson, J.T., 1988, The building stones of the planets. In: Vils F., Chapman, C.R.,
1381 Matthews, M.S. (Eds) *Mercury*, University of Arizona Press, Tucson, pp.622-
1382 650. Watters, T., R., Robinson, M. S., Cook, A. C., 1998, Topography of lobate
1383 scarps on Mercury: new constraints on the planet’s contraction, *Geology*, 26, 991-
1384 994.

- 1385 Watters, T.R., Schultz, R.A., Robinson, M.S., 2000, Displacement-length relations of
1386 thrust faults associated with lobate scarps on Mercury and Mars: comparisons with
1387 terrestrial faults, , *Geophys. Res. Lett.*, 22, 3659-3662.
- 1388 Watters, T.,R., Shultz, R.A., Robinson, M. S., Cook, A.C., 2002. The mechanical and
1389 thermal structure of Mercury's early lithosphere, *Geophys. Res. Lett.*, 29,
1390 1029/2001GL014308.
- 1391 Watters, T.R., Robinson, M.S., Bina, C.R., and Spudis, P. D., 2004. Thrust faults and
1392 the global contraction of Mercury, *Geophys. Res. Lett.*, 31, doi:
1393 10.1029/2003GL019171.
- 1394 Watters, T. R., Nimmo, F., and Robinson, M. S., 2005. Extensional troughs in the
1395 Caloris Basin of Mercury: Evidence of lateral crustal flow. *Geology* 33, 669-672.
- 1396 Weidenschilling, S.J., 1978, Iron/silicate fractionation ad the origin of Mercury,
1397 *Icarus*, 35, 99-111.
- 1398 Wilhelms, D.E., 1976, Mercurian volcanism questioned, *Icarus*, 28, 551-558.
- 1399 Wilhelms, D.E., 1990, Geologic mapping. In: Greeley, R., Batson, R.M. (Eds)
1400 *Planetary Mapping*, Cambridge University Press, Cambridge, pp. 208-260.
- 1401 Wurz, P., Lammer, H.,2003, Monte-Carlo Simulation of Mercury's Exosphere, *Icarus*,
1402 164(1), (1-13).
- 1403 Wurz, P., Rohner, U., Whitby, J. A., Kolb, C., Lammer, H., Dobnikar, P., Martín-
1404 Fernández, J. A., 2007, The Lunar Exosphere: The Sputtering Contribution, *Icarus*
1405 191, 486-496.
- 1406 Zurbuchen, T. H., J.M. Raines, G. Gloeckler, S.M. Krimigis, J.A. Slavin, P.L. Koehn,
1407 R. M. Killen, A. L. Sprague, R. L. McNutt Jr., S. C. Solomon, 2008,
1408 MESSENGER Observations of the Composition of Mercury's Ionized Exosphere
1409 and Plasma Environment, *Science*, 321, 90-92.

