In search of Bennu analogs: Hapke modeling of meteorite mixtures

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ABSTRACT

Context. The OSIRIS-REx Visible and InfraRed Spectrometer onboard the Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer spacecraft obtained many spectra from the surface of the near-Earth asteroid (101955) Bennu, enabling the characterization of this primitive small body. Bennu is spectrally similar to the hydrated carbonaceous chondrites (CCs), but questions remain as to which CCs, or combinations thereof, offer the best analogy to its surface.

Aims. We aim to understand in more detail the composition and particle size of Bennu’s surface by refining the relationship between this asteroid and various CC meteorites.

Methods. We used published absorbance and reflectance data to identify new optical constants for various CC meteorites measured in the laboratory at different temperatures. We then used the Hapke model to randomly generate 1000 synthetic spectra in order to find the combinations of these potential meteoritic analogs that best reproduce the spectral features of the asteroid.

Results. Our investigations suggest that the surface of Bennu, though visibly dominated by boulders and coarse rubble, is covered by small particles (tens to a few hundreds of \(\mu\)m) and that possibly dust or powder covers the larger rocks. We further find that the surface is best modeled using a mixture of heated CM, C2-ungrouped, and, to some extent, CI materials.

Conclusions. Bennu is best approximated spectrally by a combination of CC materials and may not fall into an existing CC group.

Key words. techniques: spectroscopic – minor planets, asteroids: individual: (101955) Bennu – methods: observational – methods: data analysis

1. Introduction

In early December 2018, NASA’s Origins, Spectral Interpretation, Resource Identification and Security-Regolith Explorer (OSIRIS-REx) spacecraft arrived at the near-Earth asteroid (101955) Bennu, with the objective to study the surface of this small primitive object and return a sample of pristine carbonaceous regolith to Earth (Lauretta et al. 2017, 2021). Bennu is spectrally classified as a B-type asteroid, part of the larger C-complex of asteroids, with visible to near-infrared spectral properties resembling those of carbonaceous chondrite meteorites, particularly the CMs and CIs (Clark et al. 2011; Hamilton et al. 2019; Simon et al. 2020). These meteorites are water- and organic-bearing and may have delivered such materials to Earth early in Solar System history.

Bennu is among the darkest objects of the Solar System, with a global mean normal albedo of about 4.4\% (Lauretta et al. 2019). However, in contrast to the asteroid Ryugu, which exhibits a homogeneously dark surface (Kitazato et al. 2019), images acquired by the OSIRIS-REx Camera Suite (OCAMS) reveal an unexpected degree of albedo heterogeneity on Bennu, with a ratio of reflected to incident flux ranging roughly from 3 to 15\% (Lauretta et al. 2019) and normal albedo mainly ranging from 1.5 to 17\% (Golish et al. 2021). The differences in albedo generally correspond to two primary boulder populations that dominate Bennu’s rubble-covered surface (DellaGiustina et al. 2019, 2020). Rocks on Bennu are broken down by processes such as thermal fatigue (Molaro et al. 2020) and meteoroid bombardment (Bottke et al. 2020; Ballouz et al. 2020).

Spectral investigation performed using the OSIRIS-REx Visible and InfraRed Spectrometer (OVIRS, Reuter et al. 2018) and Thermal Emission Spectrometer (OTES, Christensen et al. 2018) has revealed evidence of abundant hydrated phyllosilicates that are widespread on Bennu’s surface (Hamilton et al. 2019). Bennu’s spectrum in the [0.4–2.4]\,\mu m range appears featureless with a negative slope, confirming previous ground-based observations (Clark et al. 2011; Binzel et al. 2015). All OVIRS spectra exhibit a near-infrared absorption feature near 2.7\,\mu m, and together with thermal infrared spectral features observed at longer wavelengths, the data confirm the spectral resemblance of Bennu to the aqueously altered CM-type carbonaceous chondrites (Hamilton et al. 2019). In a multivariate statistical analysis of OVIRS spectral data, Barucci et al. (2020) find a spectrally homogeneous surface, as seen in the near-infrared range. No significant multimodality or grouping has been found to depend on the band area or band depth, although small variations in
band area or depth at 2.74 μm have been observed (Simon et al. 2020).

In more recent works, Simon et al. (2020) focused their analyses on the spectral features in the 3.4 μm region. This feature is ubiquitous on the surface of Bennu at different spatial scales, with the deepest 3.4 μm absorptions occurring on individual boulders. This feature is distinct from that seen on other C-complex asteroids for which the attribution was for primarily aliphatic organic molecules or carbonates (for Themis-like asteroids or Ceres-like asteroids, respectively). In individual spot spectra of Bennu, the shape and depth of this absorption feature vary and are similar to those of Themis and Ceres, along with other main-belt asteroids, indicating potential compositional variation in the carbon-bearing materials.

Kaplan et al. (2020) investigate this 3.4 μm absorption feature more thoroughly using OVIRS spectra acquired from different locations surrounding Nightingale, the site from which the OSIRIS-REx spacecraft collected a sample in October 2020. They found good fits with laboratory spectra of calcite, dolomite, magnesite, and meteorite insoluble organic matter (IOM). They conclude that bright veins observed in boulders are probably filled by carbonate. Regions of the surface that are relatively rich in IOM probably have experienced little thermal alteration. Elevated temperatures and space weathering should quickly alter these absorption features, so the strongest organic spectral features are likely connected with the most recently exposed surfaces.

To further refine the understanding of the compositional and physical surface properties of Bennu, as observed by the OVIRS instrument, here, we present a new approach in which we applied the Hapke model to interpret Bennu spectra using carbonaceous chondrites as input. This model is able to generate synthetic spectra of various mixtures of materials, with the possibility to change the particle size of each constituent. Such spectral modeling could efficiently constrain the abundance and particle size of the constituents of any atmosphereless body and has been widely used (see Reddy et al. 2015, for a short review). Models of radiative transfer involve computing reflectivity based on optical constants and particles’ sizes of specific mineral species. However, this model ultimately requires optical constants of the constituent materials, and the number of available optical constants is very limited. This lack usually restricts models to simple areal mixtures of different materials, consisting of a linear mixture of reflectance spectra, for which reflectance spectra have been obtained in the laboratory, or to simple spectral comparisons as done in previous works (see Kaplan et al. 2020, for instance). To solve this problem, in this work we used laboratory data to generate optical constants of carbonaceous chondrites that were not previously available. We then used the Hapke model to synthesize spectra of various mixtures of the meteorites and amorphous carbon and assessed which are the best matches to the global spectrum of Bennu.

2. OVIRS data acquired at Bennu

The OVIRS hyperspectral point spectrometer operates in the spectral range of 0.4–4.3 μm. It has a circular aperture with a field of view of 4 mrad (Reuter et al. 2018). The data were calibrated according to the procedure detailed in Simon et al. (2018). The calibrated data were converted to the reflectance factor (REFF) and photometrically corrected to the standard geometry of $i = 30^\circ$, $e = 0^\circ$, and $\alpha = 30^\circ$ (Zou et al. 2020).

We derived an average global spectrum from different spectra (Reuter et al. 2019) acquired during the 2019 May 9 Equatorial Station 3 observation of the Detailed Survey mission phase (Lauretta et al. 2017, 2021), which covered ±50° latitude with a spatial resolution of 19 m. These data were obtained at similar phase angles (7.8° < $\alpha$ < 10.4°), which provide high signal-to-noise ratios (S/Ns) and minimize the uncorrected effects of the phase slope and phase reddening (Fornasier et al. 2020). Each of the 778 spectra, which follow our criteria (i.e., acquired in the ±50° latitude range), was normalized at 2.2 μm to the mean reflectance value of the whole set of selected spectra. Variability at each wavelength was computed as the quadratic error composed of the standard deviation of the 778 normalized spectra and the mean individual error divided by $\sqrt{778}$.

3. Laboratory data and spectral modeling

To compare the spectra of Bennu with synthetic spectra generated using the Hapke model, we needed to retrieve several input parameters. Among these inputs, the optical constants are the most important to generate reflectance spectra of different mixtures of meteorites that may represent the properties of the surface of Bennu.

3.1. Generation of optical constants from absorbance measurements

To generate optical constants for possible meteorite analogs of Bennu, we used absorbance parameters of materials determined in the laboratory from which we could extract accurate optical constants using scripts based on the Kramers-Kroning method (Rocha & Pilling 2014). We used absorbance data available from the SHHADE database, published in Beck et al. (2014) and reported in Table 1. Although Bennu most closely resembles CMs and to some extent CIIs (Clark et al. 2011; Hamilton et al. 2019), we tested all carbonaceous chondrite materials for which the absorbance data are available – including some CV, CK, CR, and ungrouped meteorites – for a comprehensive analysis.

All materials listed in Table 1 have been analyzed at three different temperatures (ambient or 22°C, mildly heated at 150°C, and more severely heated at 300°C). Unfortunately, the data are limited to the [2–4] μm range (versus the OVIRS spectral range of 0.4–4.3 μm), but this spectral range allowed us to analyze the near-infrared continuum from 2 to 2.6 μm and the complete structure of the absorption bands located in the [2.6–3.4] μm range.

We used a script to generate the optical constants from these data, detailed in Rocha & Pilling (2014). In this method, we initialized the value of $n_0$ (initial value of the real part of the refractive index) to a reasonable 1.7, because this value is commonly seen for a range of materials (see Roush 2003, for estimated optical constants of the Tagish Lake meteorite). We note that $n_0$ was only initialized; the values of $n$ over the entire wavelength range were then adjusted by the method (as well as the values of $k$, the imaginary part of the refractive index). We also made an assumption about the particle size of the material from which the absorbance values were computed. The meteorite powders, which were crushed and sieved in the [5–15] μm range, were embedded in a 8-mm-thick KBr matrix, so we can infer a particle size on the order of a few microns given that the mass ratio of the material in the matrix is ~1:300. For the purpose of our analysis, we adopted a slightly high estimated particle size of the 10 μm version, corresponding to the initial mean particle size of the meteorite powder. The sizes retrieved by our models therefore could be slightly overestimated.

1. https://www.sshade.eu/search/spectrum
3.2. Spectral modeling

We used the spectral model developed by Hapke (1981, 1993) to generate synthetic spectra. This model allowed us to determine the reflectance spectra or the albedo of a medium from individual physical properties of the different components (with optical constants). We first briefly present the basis of the Hapke model to investigate the surface properties of Bennu. All the developments of the model are presented in Hapke (1981, 1993). In our case, we neglected light interferences and approximated the reflectance spectra or the albedo of a medium from individual particles of the medium have a similar phase function and, for simplification, the resulting photometric parameter corresponding to \( (1 + B(\alpha))P(\alpha) - 1 \) is represented by one global free parameter only (i.e., only one photometric parameter was adjusted for a given synthetic spectrum). This is mainly motivated by the fact that most of the parameters cannot be disentangled (Takir et al. 2015). Hapke developed refinements of his model to correct for macroscopic surface roughness (Hapke 1984) and porosity (Hapke 2008). They are not taken into account due to the large number of parameters already included in the models and since we consider a normalized model in this work, in which \( w \) and \( H \) contain most of the spectral information.

3.3. Generation of optical constants from reflectance data

To increase the number of optical constants of possible analogs, we also used the Hapke model to extract optical constants from reflectance data. Indeed, the general formalism of Eq. (1) allowed us to link the bidirectional reflectance to the average single-scattering albedo \( (w) \) of a sample, which is itself linked to the optical constants (see Hapke 1981). From this formalism, it is possible to derive \( k \) from the bidirectional reflectance if \( n \) and the size of the materials are well constrained. For this purpose, we used the laboratory data reported by Takir et al. (2019) from which the size of the samples was constrained to [50–100] \( \mu \)m. We used the reflectance data acquired in asteroid-like conditions (vacuum and thermally desiccated), and we selected the best eight analogs (Table 1, bottom row) by direct comparison of the reflectance spectra in the near-infrared range. The \( n \) value is more difficult to establish in this case (i.e., without the Kramers-Kroning method), but the value of \( n \) does not vary more than the percent level from the visible to the near-infrared range for a wide variety of materials. So, we inferred a quasi-constant \( n \) particles of the medium have a similar phase function and, for simplification, the resulting photometric parameter corresponding to \( (1 + B(\alpha))P(\alpha) - 1 \) is represented by one global free parameter only (i.e., only one photometric parameter was adjusted for a given synthetic spectrum). This is mainly motivated by the fact that most of the parameters cannot be disentangled (Takir et al. 2015). Hapke developed refinements of his model to correct for macroscopic surface roughness (Hapke 1984) and porosity (Hapke 2008). They are not taken into account due to the large number of parameters already included in the models and since we consider a normalized model in this work, in which \( w \) and \( H \) contain most of the spectral information.

### Table 1. Material used to generate new optical constants.

<table>
<thead>
<tr>
<th>From absorbance data</th>
<th>From reflectance data</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI chondrite</td>
<td>CM chondrite</td>
</tr>
<tr>
<td>Ivuna CI1</td>
<td>ALH 83100 CM1/2</td>
</tr>
<tr>
<td></td>
<td>LEW 85311 CM2-an</td>
</tr>
<tr>
<td></td>
<td>Murchison CM2</td>
</tr>
<tr>
<td></td>
<td>CV chondrite</td>
</tr>
<tr>
<td></td>
<td>Grosnaja CV3</td>
</tr>
<tr>
<td></td>
<td>C2-ungrouped chondrite</td>
</tr>
<tr>
<td></td>
<td>Bells</td>
</tr>
<tr>
<td></td>
<td>CK chondrite</td>
</tr>
<tr>
<td></td>
<td>ALH 85002 CK4</td>
</tr>
<tr>
<td></td>
<td>Murchison CK4</td>
</tr>
<tr>
<td></td>
<td>Alais CI1</td>
</tr>
<tr>
<td></td>
<td>Crescent CM2</td>
</tr>
<tr>
<td></td>
<td>EET 83226 C2-ung</td>
</tr>
<tr>
<td></td>
<td>Essebi</td>
</tr>
<tr>
<td></td>
<td>Mokoia C2-ung</td>
</tr>
<tr>
<td></td>
<td>Tagish Lake C2-ung</td>
</tr>
<tr>
<td></td>
<td>Mokoia CV3</td>
</tr>
</tbody>
</table>


\[
\text{REFF}(\mu_0, \mu, \alpha) = \frac{w}{4\pi} \frac{\mu_0}{\mu_0 + \mu} \frac{1 - B(\alpha)}{1 + B(\alpha)} P(\alpha) + \frac{H(\mu_0)H(\mu)}{H(\mu_0) - 1} - 1, \tag{1}
\]

where \( \text{REFF}(\mu_0, \mu, \alpha) \) is the reflectance computed for a given set of an incidence angle \( (\mu_0 = \cos(\iota)) \), emittance angle \( (\mu = \cos(\epsilon)) \), and phase angle \( \alpha \). Note that \( w \) is the single-scattering albedo and depends on the optical constants of the particles and is described in Hapke (1981); \( B(\alpha) \) is the ratio of the near-surface contribution to the total particle scattering (Hapke 1986); and \( P(\alpha) \) is the phase function, which depends on the phase angle. The phase function describes the angular distribution of light reflected from a body. Furthermore, \( H(\mu_0) \) and \( H(\mu) \) take into account the multiple scattering of light by surface particles and were computed as follows (with \( j = \mu \) or \( \mu_0 \)):

\[
H(j) = \frac{1 + 2j}{1 + 2j \sqrt{1 - w}} \tag{2}
\]

We followed the formalism of Emery & Brown (2004) to compute \( w \) from different compounds, assuming a "salt and pepper" or "intimate" mixture. In this work, we assume that all the
value (i.e., we expect a variation of 1% compared to the average value) in the wavelengths covered by the OVIRS instrument and set this value at 1.7 for the [2–3.8] μm range. Once $n$ was fixed, we iterated the $k$ value for each wavelength to compute $w$ and numerically adjusted the synthetic reflectance value (REFF) to the measured one. The accuracy of the iteration step for $k$ is always better than 0.1%.

The optical constants generated with this method should be used with a bit more caution. In addition to the problem explained with the choice of $n$, the use of reflectance spectra as inputs to extract $n$ and $k$ values is subject to $B$ and $P$ functions, which are both unknown. The Hapke model is assumed to take into account these parameters; however, without knowing complete phase functions of the samples, we expect some discrepancies using different values of incidence, emission, and phase angles. These discrepancies should be limited because the Bennu data have been corrected and scaled for the same observational geometry as those of the laboratory measurements (i.e., $i = 30°$, $e = 0°$, $α = 30°$). The second limitation of the extraction of such optical constants is the fact that the size parameter is not accurate; samples have been ground into fine powders (50–100 micrometers), but the size distribution was not well characterized. Thus, the significance of the extracted size parameters is limited.

### 3.4. Limits of the models

To search for the best free parameters that fit the surface spectra of Bennu, we derived abundances and a particle size by means of Marquardt-Levenberg minimization (Marquardt 1963; Levenberg 1944). This algorithm allowed us to obtain a minimization of the reduced $χ^2$ between synthetic spectra and the reflectance spectra of Bennu. However, the results are not unique because similar reduced $χ^2$ values can exist with different parameter combinations. The use of more or less dark material can reduce or increase the albedo of the synthetic spectrum and compensate for the use of larger or smaller amounts of bright compounds. At the same time, different combinations could produce similar absorption features. For example, the same depths and widths of absorption bands could be obtained from a combination of small numbers of large particles or large numbers of small particles. However, we used different initial conditions to take the best result into account in terms of reduced $χ^2$. On the other hand, the reduced $χ^2$ is a mathematical result that can favor large-scale features (spectrum continuum for instance) rather than the small ones (absorption bands). Moreover, the S/N of our spectra reaches its peak in the [2–3] μm range, and the results are mainly constrained in this range because the standard deviation of the data is used in the algorithm to determine the best reduced $χ^2$. The calibration is least well-constrained in the [2.6–3] μm range, and the thermal tail removal procedure could also affect the fits roughly longward ~3.4 μm (Simon et al. 2020).

To understand how the initial choice of the $n_0$ parameter affects our method, we extracted the optical constants for the CM chondrite ALH 83100 at 150°C (we chose ALH 83100 for this test because it is one of the best candidates to fit the Bennu spectrum) considering various $n_0$ parameters (i.e., 1.3, 1.7, and 2.1). Once the optical constants were extracted for each $n_0$, we generated two synthetic reflectance spectra from the pure ALH 83100 sample, considering the higher case of $n_0$ at 2.1 and two different particle sizes (10 and 100 μm). We then used the Hapke model to fit these two initial synthetic spectra considering an intimate mixture of an ALH 83100 sample with amorphous carbon (Zubko et al. 1996), used as a dark and featureless constituent in the subsequent mixtures. The presence of amorphous carbon could physically and numerically accommodate small spectral differences. The new synthetic spectra were then generated considering optical constants generated at lower $n_0$ values (at 1.7 and 1.3). For this particular test, the free parameters in the models are the amount and size of each constituent in the mixture. In order to mimic the expected effects on the whole spectral range of the Bennu spectrum, we adjusted the synthetic spectra and computed the $χ^2$ using the errors estimated from the average spectrum of Bennu. The results are plotted in Fig. 1. The fits are very satisfactory with the particle size initialized at 10 μm. Indeed, the differences between the synthetic spectra are very small (i.e., it is possible to reproduce the entire shape of the initial spectrum) and the physical and chemical properties of the initial sample are well represented (i.e., the particle size is similar and the need for an additional featureless constituent is limited to a few percent). Problems arise at 100 μm, especially when the $n_0$ value is too far from the initial one (1.3 instead of 2.1), but the fits stay acceptable when the $n_0$ value differs by no more than 20% (1.7 instead of 2.1). In this last case, the particle size increases from 100 to 122 μm and the need for an additional featureless constituent reaches no more than 10%. Our conclusion at this step is that we should be careful in interpreting the model results in terms of the accuracy of the retrieved particle sizes and abundances. However, these optical constants are accurate enough to produce realistic synthetic spectra and provide a valuable tool to constrain the chemical and physical properties of the surface of Bennu.

### 4. Results

The first step of our analysis is to rank the different meteorite analogs (Table 1) using a direct comparison with the average reflectance spectrum of Bennu. For this purpose, we generated a simple intimate mixture of amorphous carbon with only one meteorite sample and for all available temperatures. Amorphous carbon is present in a wide range of meteorites (Murase et al. 1993), and it has been chosen as a dark and featureless end member. Table 2 reports the best 20 analogs in terms of reduced $χ^2$. The synthetic spectra of three of the best fits are presented in Fig. 2.
None of the materials considered in this work exhibit precisely the same spectral properties as those reported for Bennu in the [2–3.8] μm range. In general, the slope in the [2–2.65] μm range could be fitted with only one analog intimately mixed with amorphous carbon, but the broad 2.7 μm absorption band and the wavelengths longward of 3.3 μm are more difficult to reproduce using a simple model. The best results, in terms of the lowest reduced χ², are achieved mostly using CM chondrites (usually heated in laboratory), such as ALH 83100, Boriskono, DOM 08003, or ALH 84044. There are a few other chondrites having low reduced χ² values, such as Essebi (C2-ung), Orgueil (CI), or GRO 95577 (CR1) chondrites. Heating processes mainly affect the amount of adsorbed water of the samples and usually change the intensity and shape of the 3 μm band. At this step, we confirm that Bennu isspectrally most similar to CM meteorites and this strengthens previous speculations that Bennu may not fall into an existing carbonaceous chondrite group (see Hamilton et al. 2019; Kaplan et al. 2020, for instance). We then pursued the idea that a combination of several materials could fit the spectral properties of Bennu and give new insights as to the composition and physical properties of the surface of Bennu.

The number of different materials used in this work is large, so we did not attempt to produce all possible combinations. To obtain results that take into account a substantial but reasonable number of possible choices, we ran 1000 different spectral models. Each synthetic spectrum was computed assuming an intimate mixture of amorphous carbon, with four of the potential meteorite analogs listed in Table 1 chosen randomly. We limited the total number of different materials in a mixture to five because it appears that fits are usually achieved with rarely more than three or four different materials. Again, this choice helped to minimize the computation time. The free parameters are the particle sizes, the ratio of the different materials in the intimate mixtures, and the global photometric parameter (PHO), which accounts for \((1 + B(g))P(g) - 1\), as presented previously. We focused our analyses more particularly on the retrieved abundances and particle sizes, as constrained by the different models.

The results from these 1000 simulations show an improvement of the fits compared to those obtained considering only one CC mixed with amorphous carbon; the reduced χ² is divided by a factor of 2 at least, but it is always limited to ~2.8 at best (Fig. 3). We checked that all the individual samples presented in Table 1 have been used at least several times. This cannot fully ensure that we obtained the best achievable combination from our data set, but it allowed us to provide the main trends. In order to better rank the different materials, we computed what we call the fitting score (FS) of each constituent in each model. For each model, we computed FS for each constituent as the reduced χ² of the fit divided by the proportion of the constituent considered in the mixture. The advantage of FS is to consider the contribution (small or large) of each component, avoiding using the same value for all the components of a given mixture, as done in the previous analysis. Figure 3 presents this value for a restricted sample of constituents (each mixture gives a particular reduced χ²). By extension, for a given material, we could also search for the minimal value (mFS) from all computed FS.

Good combinations for approximating the surface of Bennu appear in the left part of Fig. 3; the best analogs are concentrated in the upper left part of this figure, because a large amount of the materials is also required. These tend to be materials with low FS, such as Tagish Lake, LEW 87022, ALH 83100, and MCY 05230. These new models mainly confirm trends obtained in the previous section when considering a simple mixture of amorphous carbon with one other constituent, preferentially classified in the CM group. However, the results obtained with the association of several materials seem to indicate that C2-ungrouped meteorites, such as the sample of Tagish Lake published in Takir et al. (2019), could also be good analogs. Among the best analogs, as classified using mFS < 7.0 (a part of the list appears in the lower part of Fig. 3), we find thirteen chondrites from the CM group, three from the C2-ung group (Tagish Lake, Essebi, Bells), two from the CI group (Alais, Orgueil), one from the CR group (GRO 95577), and one from the CV3 group (Vigarano). These findings are compatible with those of Hamilton et al. (2020) and Kaplan et al. (2020) to some extent.

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**Table 2.** Best 20 results, ranked by reduced χ² value, considering an intimate mixture of amorphous carbon with only one other analog from Table 1.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Analog</th>
<th>Temperature</th>
<th>red.χ²</th>
<th>Per.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ALH 83100 CM1/2</td>
<td>150°C</td>
<td>5.95</td>
<td>80%</td>
</tr>
<tr>
<td>2</td>
<td>Essebi C2-ung</td>
<td>22°C</td>
<td>6.79</td>
<td>93%</td>
</tr>
<tr>
<td>3</td>
<td>Boriskino CM2</td>
<td>22°C</td>
<td>7.86</td>
<td>95%</td>
</tr>
<tr>
<td>4</td>
<td>Orgueil CI1</td>
<td>102°C</td>
<td>8.11</td>
<td>92%</td>
</tr>
<tr>
<td>5</td>
<td>DOM 08003 CM2</td>
<td>150°C</td>
<td>9.38</td>
<td>46%</td>
</tr>
<tr>
<td>6</td>
<td>GRO 95577 CR1</td>
<td>150°C</td>
<td>9.43</td>
<td>32%</td>
</tr>
<tr>
<td>7</td>
<td>ALH 84044 CM2</td>
<td>150°C</td>
<td>10.24</td>
<td>32%</td>
</tr>
<tr>
<td>8</td>
<td>ALH 84044 CM2</td>
<td>22°C</td>
<td>11.62</td>
<td>8%</td>
</tr>
<tr>
<td>9</td>
<td>LON 94101 CM2</td>
<td>150°C</td>
<td>12.32</td>
<td>29%</td>
</tr>
<tr>
<td>10</td>
<td>DOM 08003 CM2</td>
<td>22°C</td>
<td>12.84</td>
<td>18%</td>
</tr>
<tr>
<td>11</td>
<td>LEW 85311 CM2-un</td>
<td>150°C</td>
<td>12.39</td>
<td>59%</td>
</tr>
<tr>
<td>12</td>
<td>Mokoia CV3</td>
<td>102°C</td>
<td>12.97</td>
<td>99%</td>
</tr>
<tr>
<td>13</td>
<td>QUE 99355 CM2</td>
<td>22°C</td>
<td>13.78</td>
<td>7%</td>
</tr>
<tr>
<td>14</td>
<td>Nogoya CM2</td>
<td>22°C</td>
<td>13.81</td>
<td>13%</td>
</tr>
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<td>15</td>
<td>LEW 87022 CM2</td>
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<td>14.49</td>
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</tr>
<tr>
<td>16</td>
<td>Niger CM2</td>
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<td>15.47</td>
<td>19%</td>
</tr>
<tr>
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<td>LON 94101 CM2</td>
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<td>10%</td>
</tr>
<tr>
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</tr>
<tr>
<td>20</td>
<td>Vigarano 99790 CM2</td>
<td>22°C</td>
<td>16.14</td>
<td>34%</td>
</tr>
</tbody>
</table>

**Notes.** The percentage (Per.) of the mixture accounted for by the other analog in each case is reported in the rightmost column. °Sample temperature reached ~102°C, but spectrum was taken after the sample had cooled.

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**Fig. 2.** Synthetic spectra obtained using an intimate mixture of amorphous carbon with ALH 83100, DOM 08003 (both heated at 150°C) or Essebi (obtained at 22°C), and the average spectrum of Bennu obtained during Equatorial Station 3 (~50°/lattitudinal range).
Fig. 3. Results showing only a part, for clarity, of the best fits obtained from our simulations (reduced $\chi^2 < 5.6$). For each reduced $\chi^2$, the amount of each material, with low mFS in the models, is indicated. For example, there is a model (presented in Fig. 4) with a reduced $\chi^2$ of $\sim 2.83$ (represented by the vertical dashed line) composed of $\sim 53\%$ of Tagish Lake (desiccated at 102°C), and $\sim 27\%$ of DOM 08003 (measured at 300°C). The remaining $\sim 20\%$ is Mokoia (measured at 300°C and not represented for clarity and due to its higher mFS). All constituents located in the upper left part represent the best analogs tested in this work for Bennu's surface. The legend below the plot reports the lowest 20 minimum FS (mFS) values obtained from our simulations.

The former find, from a more restricted set of analogs, that the CMs AhS91A_1 and ALH 83100, as well as the CI1 Orgueil, are the best analogs to reproduce the [7–30]$\mu$m range of Bennu spectra. They conclude that the bulk mineralogy of the sample returned to Earth from Bennu likely will be dominated by Mg-phyllosilicates, with some magnetite and a volume less than $\sim 10\%$ anhydrous silicates. The latter find minerals that are in the highly aqueously altered CM- and CI-group carbonaceous chondrites.

The presence of the CR chondrite GRO 95577 could appear incompatible, at first sight, with the main picture provided by this work, assuming that the surface of Bennu is mainly covered by materials having experienced similar histories of aqueous alteration and a thermal event. However, Beck et al. (2014) summarize that GRO 95577 was initially classified as a C2 chondrite and it was classified as a CR from its petrology and oxygen isotopic composition. From its IR spectrum alone, it is not possible to distinguish GRO 95577 from a heavily altered CM or CI. From its IR spectrum alone, it is not possible to distinguish GRO 95577 from a heavily altered CM or CI. In addition to that, GRO 95577 phyllosilicates, as observed in the infrared, resemble saponite, possibly because of their poor crystallinity, as also observed for CMs.

We present two of the best models obtained from our simulation in Fig. 4. The first one was generated from a mixture of Tagish Lake, Mokoia, and DOM 08003, while the second model was generated from a mixture of Tagish Lake, Niger, and

![Graph showing results of simulations](image_url)
Orgueil. These models suggest the presence of small particles on Bennu, roughly in the [10–300] µm range. In order to check these values, we computed the average particle size from all our models. The average particle size for a given mixture was computed at 250 ± 215 µm (the error represents one standard deviation). The average particle size seems to be slightly dependent on the quality of the fit, defined by the χ² value (see panel A from Fig. 5). From the linear regression, we could assume an average particle size to be a bit larger considering the better fits (i.e., up to 300 µm). Furthermore, a correlation exists between the average particle size and PHO (see panel B from Fig. 5), with larger particle sizes retrieved for higher PHO. The reduced χ² distribution versus PHO (see panel C from Fig. 5) indicates that the [−1:1+4] range is favored and could produce models with similar reduced χ² (there is no apparent trend from the linear regression). From our simulations, we computed an average PHO value of 1.5 ± 1.6 (the error represents one standard deviation). Beyond this range, although the PHO value is not limited in our models, the number of cases drops. This could tentatively rule out lower and higher values, but our investigation is limited in constraining this parameter. Indeed, similar results could be achieved at some points, tuning all the parameters of the model (i.e., size, abundance, and PHO). The highest PHO values retrieved from our models are compatible with values we can extract from photometric investigation in the literature (from Takir et al. 2015, for instance). Even if small particles, on the order of tens of microns, are still needed in our models, the literature gives a stronger case for the restricted set of temperatures investigated in laboratory for each sample. However, the abundances and particle sizes of the materials are more susceptible to change when changing the initial (1 + B(g))P(g) − 1 value. In our models, initialized values of ~1 reduce the amount and particle size of Tagish Lake and amorphous carbon constituents and increase the amount of finer Mokoia and DOM 08003 particles. When this parameter is set at approximately −1, the amount and particle size of Tagish Lake material increase.

These results confirm that the modeled values provided from the abundances and particle size should be used with caution, given that the initial parameters are not yet well constrained. In addition, the five models considered in this subsection yield similar reduced χ² (within 7% and we cannot discard any of the solutions within this criterion. However, we can confidently report from the different optical constants used in these five models that the abundance of Tagish Lake-like material in the best mixture is close to 50%, and particles are mainly on the order of tens of microns.

5. Discussion

The results obtained in this work are based on spectral modeling, restricted by a large but ultimately limited number of samples. Beyond the fact that we probably do not have the ultimate candidate to reproduce the entire spectrum of Bennu exactly, and that the optical constants extracted in this work could be improved, we could also infer limits of our models due to the restricted set of temperatures investigated in laboratory for each sample. As presented in Beck et al. (2014) or Takir et al. (2019), temperatures reached for each sample greatly modify the bulk composition, and then modify the spectral behavior. The main spectral changes occur when removing variable amounts of adsorbed water when the temperature reaches but does not strongly exceed ~100°C in a laboratory environment. At warmer temperatures, structural water bound into the mineral

Fig. 5: A: mean particle size retrieved for each model as a function of the reduced χ². B: reduced χ² of each model as a function of the retrieved global photometric parameter (PHO). C: mean particle size retrieved for each model as a function of the retrieved PHO. The average particle size and the mean PHO, as well as their standard deviation, have been computed from all the models.
structure could also be modified, with various effects in the reflectance spectrum in the [2.7–3.3] µm range. The content of carbonates and organic matter are also dependent on the heating level; this could affect the reflectance spectrum in the [3.3–3.6] µm range.

Our findings indicate that a mixture of C2-ung, CM, and possibly CI materials is the best analog for Bennu’s surface. Global analyses do not support either strong longitudinal or latitudinal spectral variations and, as such, we can cautiously expect that this finding applies across the whole surface of Bennu, except in peculiar areas observed at a higher spatial resolution (Barucci et al. 2020). Beck et al. (2014) show a correlation between the classification of carbonaceous chondrites based on spectral parameters such as the 3 µm band intensity and the 11.2 µm band intensity in their absorbance data. These two criteria are very peculiar areas observed at a higher spatial resolution (Barucci et al. 2020). From simulations based on laboratory measurements of meteorites and 1000 synthetic spectra generated using the Hapke model, covering the [2.0–3.8] µm range, we find that the mean reflectance spectrum of Bennu is best fitted by an intimate mixture of several possible carbonaceous chondrite analogs, specifically the following.

1. A few members of the C2-ung, CM, and, to some extent, CI groups are the best possible analogs to reproduce the spectral behaviors of Bennu’s surface, when mixed together. Even if there is not a unique solution, Tagish Lake seems to be one of the samples best able to reproduce the behavior of the reflectance spectrum of Bennu in the [2–3.8] µm range, when intimately mixed with CM components, such as DOM 08003 (heated at 300°C) or Niger (measured at 22°C).

2. The models suggest the presence of particles on the order of tens to a few hundreds of microns on the surface of Bennu. As Bennu’s surface is visually covered by boulders, this result suggests the presence of fine particulates on top of the surface elements of Bennu, consistent with previous findings.

We can consider these properties to be applicable to the whole surface of Bennu, given that a global spectral analysis, performed at the identical spatial resolution, by multivariate statistics indicates a relative homogeneous surface, except for a few peculiar areas observed at a higher spatial resolution (Barucci et al. 2020). From our investigation, Bennu does not seem to be similar to any known meteorite, but more similar to a mixture of various materials. This conclusion is consistent with those of other kinds of investigation (Hamilton et al. 2020; Kaplan et al. 2020). The sample that OSIRIS-REx will return in 2023 will reveal the composition of the Bennu’s surface and the limitations of the method we used. The conclusions of this paper should be confirmed by additional models accounting for the

<table>
<thead>
<tr>
<th>Pho, (a)</th>
<th>n (a)</th>
<th>Red. χ²</th>
<th>Pho, (b)</th>
<th>Tagish Lake (%-µm)</th>
<th>Mokoia (%-µm)</th>
<th>DOM 08003 (%-µm)</th>
<th>Amor.Ca (%-µm)</th>
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<tbody>
<tr>
<td>−0.9</td>
<td>1.5</td>
<td>−0.771</td>
<td>69</td>
<td>57</td>
<td>15</td>
<td>10</td>
<td>37</td>
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<td>42</td>
<td>44</td>
<td>31</td>
<td>5</td>
<td>27</td>
</tr>
</tbody>
</table>

Notes. For a given set of parameters set to generate the Tagish Lake optical constants, this table indicates the following: the reduced χ² of the fit, the (1 + B(g))P(g) − 1 value of the entire mixture as provided by the fit, and the amount and size of the materials considered for each case.

(a)Initialized (1 + B(g))P(g) − 1 and n values to compute k of Tagish Lake. (b)(1 + B(g))P(g) − 1 provided by the fit.
whole wavelength range covered by OVIRS, but new laboratory data are required for this purpose.

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