
Introduction: A major space weathering conundrum is why some carbonaceous asteroids become spectrally redder (the continuum becomes more positively sloped) and others become bluer (the continuum becomes more negatively sloped) after their surfaces experience space weathering [1,2]. On the Moon, changes in spectral slopes are associated with the production of nanophase (<40 nm) and microphase (>40 nm) iron particles during the space weathering process [e.g., 3, 4]. However, these spectral changes uniformly result in a reflectance spectrum becoming redder, whereas the cause of the spectral bluing on some carbonaceous asteroids is unknown.

Several studies have turned to space weathering experiments on carbonaceous meteorites to explore this conundrum [e.g., 5–7]. Laboratory experiments (i.e., ion and laser irradiation) on carbonaceous meteorites (e.g., CM, CV, Tagish Lake) demonstrated that the reflectance of these meteorites also became either redder or bluer with exposure to simulated space weathering, yielding divergent trends similar to asteroids [5–7]. Because of the diverse mineralogy of carbonaceous meteorites relative to the Moon, space weathering experiments on carbonaceous meteorites can produce nanophase and microphase particles consisting of mineral phases other than iron, such as sulfides (e.g., troilite and pentlandite) and magnetite [6,7]. By using the radiative transfer model with these different mineral phases, we found that the presence of nanophase and microphase magnetite as well as microphase troilite could result in these asteroids and meteorites becoming spectrally bluer [8]. In addition, laboratory experiments also showed carbonization, where hydrocarbons experience hydrogen loss and the enlargement of aromatic carbon structures could also be the cause of the spectral bluing on these asteroids [5,9]. In this study, we modeled visible to near-infrared reflectance spectra returned from the OSIRIS-REx mission to test whether nanophase and microphase iron, magnetite, and troilite particles can account for the bluing on the asteroid (101955) Bennu.

Methods: We applied a Hapke radiative transfer model, which can also model the spectral effects of nanophase and microphase particles [3,4], to reproduce visible to near-infrared spectra, captured by the OVIRS instrument onboard the OSIRIS-REx spacecraft, by only using space weathering particles. To use this model, we assumed that Bennu’s surface consists of 45-µm sized particles—which host the nanophase and microphase particles—with a constant visible to near-infrared reflectance of ~3%. We use this set of parameters to keep the nanophase and microphase abundances to values similar to the Moon [10]. Based upon the particles found in space weathering experiments of carbonaceous meteorites [6,7], we include nanophase and microphase metallic iron, troilite, and magnetite in our model. Next, we applied the model to the photometrically-corrected OVIRS data collected during the 12:30pm Equatorial Station of the Detailed Survey to obtain the relative abundances of the six particles.

Results: We find that our radiative transfer model can consistently model the visible to near-infrared reflectance (0.4–1.1 µm) including the blue continuum slope, an important characteristic of Bennu. We also created six space weathering maps (Fig. 1), one for each particle type. From these maps, we observe that the surface contains negligible abundances of nanophase iron and microphase magnetite, moderate abundances of nanophase troilite (0.1±0.0 wt.%), microphase iron (0.2±0.1 wt.%), and nanophase magnetite (0.2±0.0 wt.%), and relatively high abundances of microphase troilite with 1.0±0.1 wt.%. Although Bennu consists of boulders, the particle size is likely capturing the surface roughness of these boulders. We find that changing the particle size (or surface roughness) to 40 or 50 µm in the model does not change the magnetite abundances, but changes the iron and troilite abundances by about ~0.3 wt.% microphase troilite and magnetite. However, the proportions between iron and troilite remain same.

Discussion: The space weathering maps show negligible abundances of nanophase iron, but moderate abundances of microphase iron. Space weathering experiments on carbonaceous meteorites show that producing nanophase iron is possible, but have not resulted in observations of an appreciable abundance of mi-
microphase iron [6,7]. The difference in relative submicronic iron abundances between the laboratory and our model abundances on Bennu could be due to our assumption that the host particle has a constant reflectance of 3%. In areas that contain low albedo boulders, more microphase iron particles are required to match these low reflectance blocks. This is further supported by the fact that the microphase iron abundance increases with 750-nm reflectance.

Our modeled relative nanophase and microphase magnetite abundances appear consistent with the laboratory results. In a laser irradiation experiment of a CM meteorite, they found the presence of only nanophase magnetite embedded in vapor deposits [7]. However, there were no observations of magnetite in the melt deposits. Our model concurs with this result where we observe the presence of nanophase magnetite, but negligible amounts of microphase magnetite.

Space weathering experiments produced both nanophase and microphase troilite in carbonaceous meteorites [6,7]. Our space weathering maps of Bennu agrees with these experiments as our model shows moderate and high abundances of nanophase and microphase troilite, respectively.

Assuming space weathering on Bennu’s surface can only produce iron, troilite, and magnetite particles, the potential particles that could cause bluing on carbonaceous asteroids are nanophase and microphase magnetite and microphase troilite. From these particles, we find that the spectral bluing is consistent with nanophase magnetite as microphase magnetite is not present in the experiments or our models of Bennu and microphase troilite is still present in space weathering experiments that resulted in reddening. However, carbonization may also contribute in the bluing of asteroids, but how much it contributes is unknown [5].

From the experiments and the radiative transfer model, the spectral bluing on asteroid is likely due to micrometeoroid impacts on Fe-bearing hydrated minerals resulting in nanophase magnetite [7], which is present in moderate abundances on Bennu, and solar wind, which causes carbonization [5]. Our interpretation may be supported from spectral observations of Ryugu, which is spectrally red with a weak 3-µm hydration band [11], and Bennu, which is spectrally blue with a strong 3-µm hydration band [12]. However, further study is required to understand the Mg to Fe ratio needed in phyllosilicates to produce a sufficient amount of nanophase magnetite to cause the bluing, as well as which minerals on Bennu contains Fe [13].

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Fig. 1. The six space weathering maps representing the relative abundances of nanophase and microphase iron, troilite, and magnetite.