# FLAT SPECTRAL CURVES OF LOW-ALBEDO ASTEROIDS: THERMAL METAMORPHISM OR SPACE WEATHERING?

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**Introduction:** Primitive carbonaceous chondrites (CI/CMs) containing hydrated minerals are believed to originate from low-albedo asteroids belonging to C complex. The C-complex [1] is composed of relatively featureless asteroids with near-infrared (NIR) spectral slopes ranging from slightly red to slightly blue, and mostly corresponds to types C, B, F, and G in Tholen's taxonomy. Many of these asteroids have spectral features consistent with the presence of hydrated minerals on their surfaces. These spectral features include: UV falloff [2], 3-µm absorption due to water of hydration [3], and weak 0.7-µm absorption band due to $Fe^{2+} \rightarrow Fe^{3+}$ transitions in hydrated silicates [4]. The latter feature is common in the spectra of low-albedo asteroids between 2.6 and 3.5 AU [5]. Not all primitive carbonaceous chondrites (CCs) show this absorption band in their reflectance spectra, but only some members of CM2 group [6]. This suggests that CM2-like chondritic material is rather common within the C asteroid complex.

**Metamorphism:** Hiroi et al. [7] showed that spectral curves of C, B, F, and G-type asteroids in general have flatter NIR spectral slopes than powedered CM2 chondrites characterized by red-sloped reflectance spectra. These authors found that Antarctic metamorphosed chondrites and CM2 chondrite Murchison heated to 600°C provide better spectral matches to C, B, F, and G-type asteroids in terms of spectral slopes and depths of the UV-feature. Hiroi et al. [7] suggest that these asteroids represent material that had undergone extensive thermal metamorphism.

Three unusual CCs from Antarctica - Belgica-7904, Yamato-82162, and Yamato-86720 - have properties indicating that these meteorites have been thermally metamorphosed in their parent bodies, but their mineralogical and chemical characteristics are typical of CI or CM meteorites before metamorphism. Recently, another two metamorphosed CM chondrites – Dho 225 and Dho735 – were found in Oman [8].

Similar to the Antarctic metamorphosed CCs and the heated Murchison, these new meteorites show flatter spectral curves than normal CM2 chondrites [9] (Fig.1) and lack the 0.7-µm absorption feature. Hiroi et al. [10] stated that overall red spectral profile of CM chondrites is due to submicron phyllosilicates, and dehydration of phyllosilicates is responsible for the flat slopes of heated/metamorphosed CCs. This explanation appears to be unlikely. In normal CM2 chondrites matrix phyllosilicates are intergrown with OH-bearing sulfide tochilinite and organic material. Moroz and Pieters [11] demonstrated that matrix separates of CM2 chondrite Mighei are spectrally flat (Fig. 2) and show no grain size dependence. Although it is widely believed that low albedos and featureless spectra of primitive CCs are due to organic phases, the main darkening agents in such meteorites are more abundant fine sulfides, in particular, tochilinite. Organic phases do not significantly contribute to the spectral properties of matrix material. Bulk CM2 material, however, contains abundant coarse-grained olivine. Fine dust on the surface of olivine grains contains organic phases.. These organics with relatively high H/C ratio show wavelength-dependent transparency, being more transparent with increasing wavelength. This enhances spectral contribution of transparent olivine towards infrared. Therefore spectral curves of bulk CM2 chondrites are characterized by reddish spectral slopes.

Antarctic metamorphosed CCs mentioned above are extremely depleted in insoluble and soluble organic matter despite their relatively high C contents (up to 2.5wt.%) [12]. H/C ratios in their carbonaceous components is <0.5 [12, 13], indicating significant carbonization of organics due to thermal metamorphism. This effect is the most likely reason for the flat NIR spectral curves of the Antarctic metamorphosed CCs and new metamorphosed CCs from Oman. Carbonization should increase absorption coefficients of carbo-

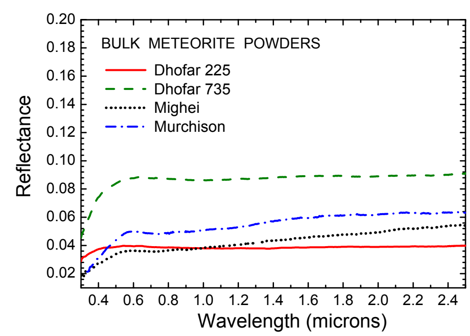


Fig. 1. Bidirectional Vis-NIR spectra of metamorphosed (Dho 225, Dho 735) and non-metamorphosed (Mighei, Murchison) CM chondrites. Particle sizes are: <125 µm (Dho 225), <150 µm (Dho 735), <200 (Mighei and Murchison). The spectra were measured at the NASA-supported RELAB multiuser facility.

naceous components in the Vis-IR region [14], hence suppressing the spectral contribution of olivine.

If C, B, F, and G-type asteroids are so heavily affected by thermal metamorphism as suggested by Hiroi et al. [7], then they should be significantly depleted in soluble organics and insoluble macromolecular organics found in normal primitive CI/CM chondrites [12].

However, the scenario involving widespread thermal metamorphism on low-albedo asteroids have some difficulties discussed by Vilas [5], Vilas and Sykes [15], and Carvano et al. [16].

**Space weathering:** Alternatively, space weathering effects could be responsible for the observed spectral differences between primitive CCs and C, B, F, and G-type asteroids. Space weathering includes micrometeoritic bombardment and irradiation with charged particles and affects only surface layers of asteroids. Effects of space weathering on optical properties of parent bodies of primitive CCs remain an open question [17].

However, recent experimental results may provide some hints indicating that space weathering may be a reason for the flat and bluish spectral curves of C, B, F, and G-type asteroids. Irradiation of complex hydrocarbon materials with charged particles leads to carbonization of their surface layers [14]. This causes reduction of their Vis-NIR spectral slopes [14].

Ion irradiation experiments on CM2 chodrites are needed to test whether irradiation-induced carbonization of their organic phases may suppress their spectral slopes.

Micrometeoritic bombardment is another effect which can modify optical properties of asteroid surfaces. This process can be simulated by irradiation of meteorite samples with pulsed lasers [18]. Shingareva et al. [19] used a microsecond pulsed laser to irradiate a powdered sample of CM2 chondrite Mighei. The irradiated samples did not show significant change in spectral slope compared to the non-irradiated Mighei sample [20]. However, the microsecond laser experiments simulate bombardment of planetary surfaces with relatively large/fast particles causing complete melting and subsequent crystallization of irradiated material. Irradiation with a nanosecond pulsed laser [21] would be a better simulation of micrometeoritic bombardment, producing milder effects. Such an experiment has been performed on the uniquie primitive carbonaceous chondrite Tagish Lake [22]. Initially reddish Vis-NIR spectral slope became flatter after irradiation [22], most probably due to carbonization of the meteorite's organic components, as discussed above.

Similar experiments on CM2 chondrites are needed to understand how micrometeoritic bombardment affects optical properties of C, B, F, and G-type asteroids.

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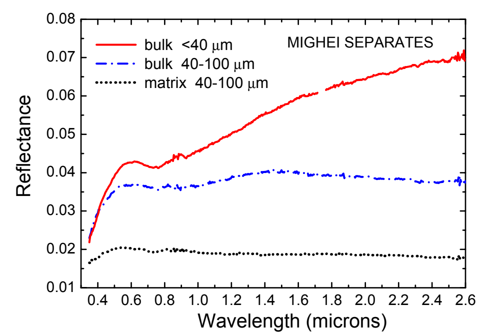


Fig. 2. Bidirectional Vis-NIR spectra of Mighei (CM2) separates (From [11]). Particle sizes are indicated on the plot. The spectra were measured at the NASA-supported RELAB multiuser facility.