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Continuum definition for ~3.1, ~3.4 and ~4.0 μm absorption bands in Ceres spectra and evaluation of effects of smoothing procedure in the retrieved spectral parameters

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Abstract

NASA's Dawn spacecraft acquired images and hyperspectral data of Ceres by means of FC and VIR instruments, and identified some widespread bright areas or bright spots (BS). The most peculiar BS is inside Occator crater and it is characterized by spectral properties very dissimilar from the rest of Ceres' surface. To perform a mineralogical analysis, absorption bands in reflectance spectra must be properly isolated by removal of continuum, and related descriptors (such as band centers and band depths) can be computed. The method for continuum removal must be applicable to all Ceres spectra, relative to different areas, so that a comparison among spectral parameters can be made and mineralogical interpretation can be achieved. This work focuses on the definition of the most appropriate continuum to isolate absorption bands located at ~3.1, ~3.4 and ~4.0 μm. The ~3.1 μm feature is related to ammoniated phyllosilicates, while the ~3.4 and ~4.0 μm absorption bands are indicative of carbonates. Thermal emission affects the continuum for these bands in the VIR spectral range, which extends up to 5.1 μm, moreover all thermal-removed reliable data stop at 4.2 μm. This implies that the shoulder of bands at longer wavelength cannot be identified. We therefore defined alternative continua, i.e., a linear and two polynomial ones, able to describe spectra of any area (i.e. bright or dark) and regardless of spatial resolution. We found that the linear definition satisfies these requirements best. For the first time, we performed an error evaluation on band depths and band centers introduced by the applied method, which is relevant for comparison of spectral parameters of Ceres regions and to better interpret mineralogy and photometric effects.

Keywords: Dwarf planet Ceres; Removal continuum method; Linear continuum; Polynomial continuum; Mineralogy

1. Introduction

NASA's Dawn spacecraft is orbiting around dwarf planet Ceres since March 2015, acquiring images and hyperspectral data by means of the Framing Camera (FC) and Visible and Infrared Mapping Spectrometer (VIR-MS), respectively. Ceres is a dark object with some localized bright areas, termed as "bright spots" (BS; Palomba et al.,

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2017). The two brightest ones are located inside the Occator crater (20°N 240°E), i.e. *Cerealia Facula* and *Vinalia Faculae* (De Sanctis et al., 2016). By applying the photometric correction method already validated for Vesta (Longobardo et al., 2014), the Ceres average equigonal albedo (R30m), estimated at 1.2 μm under a phase angle of 30°, is around 0.035 (Longobardo et al., 2017b). The largest number of BS has an albedo value of about 0.05, while Cerealia Facula can reach an albedo of 0.079 (Palomba et al., 2017).

Spectral analyses from ground-based observations (Rivkin et al., 2006) and by VIR data (De Sanctis et al. 2015, 2016; Ammannito et al., 2016) identified, on Ceres spectra, absorption bands at ~2.7, ~3.1, ~3.4 and ~4.0 μm. Hapke modeling of these observations suggests a mixture of Mg-phyllosilicates (antigorite), ammoniated phyllosilicates (NH_4-annite or NH_4-montmotillonite), Ca-Mg carbonates (such as dolomite, magnesite or calcite) and dark material as components of the mean surface of the dwarf planet (De Sanctis et al., 2015). In particular, the ~2.7 μm feature is due to the metal hydroxide present in Mg-phyllosilicates (De Sanctis et al., 2015) and the ~3.1 μm band is related to NH_4 bearing clays (De Sanctis et al., 2016). The ~3.4 μm band is due to the double contribution of asymmetric stretching ($2\nu_3$) of CO_3^{2-} and the ~4.0 μm is the result of a combination of symmetric and asymmetric stretching ($\nu_1 + \nu_3$) of CO_3^{2-} (Nuevo et al., 2014), indicative of carbonates. Spectra of Occator BS show substantial differences with respect to the Ceres mean spectra, such as the shift of 2.7 μm band center toward longer wavelengths (the band center is at 2.72 μm for Ceres mean spectra and at 2.76 μm for Occator BS), the disappearance of the ~3.1 μm band and the increase of carbonates band depths (~3.4 and ~4.0 μm bands), in addition to the presence of new spectral features at 2.21 and 2.86 μm. The composition of Occator Faculae is probably a mixture of Al-phyllosilicates (illite or montmorillonite), Na-carbonate (natrite), ammoniated minerals and dark material (De Sanctis et al., 2016). Furthermore, since the 3.4 μm band in Occator BS is characterized by secondary absorptions at about 3.2 and 3.3 μm, other species are probably present (De Sanctis et al., 2016).

Spectral descriptors of absorption bands (such as band centers, band depths, etc.), especially if they are combined in a scatterplot or a statistical analysis, are important to evaluate the abundance of mineral end-members or their grain size (Palomba et al., 2014, 2015; Longobardo et al., 2017b). In order to compare band descriptors of spectra acquired in several phases of the mission (described in Section 2) and from areas with different equigonal albedo, the same continuum removal method must be applied on all VIR dataset. The problem of defining a continuum is in the VIR spectral range, which ends at 5.0 μm. The thermal contribute cannot be negligible at wavelengths longer than 4.2 μm, making difficult to identify the shoulder of bands beyond this spectral range. We therefore defined alternative continua, i.e. a linear and two polynomial ones, in order to identify which best isolates the three considered absorption bands. Furthermore, for the first time, we estimated the errors on band depths and band centers introduced by the application of our method. This information is essential in the comparison among spectral descriptors of different Ceres regions and in understanding their mineralogy.

In Section 2 VIR data used for this work are described. In Section 3 the method adopted to search the best fit for spectral continuum is given. In Section 4, we estimated the error on spectral parameters, i.e., band centers and band depths, derived from the removal of the most suitable spectral continuum from smoothed spectra. Finally, in Section 5, conclusions are given.

2. VIR data

The Visible and InfraRed (VIR) mapping spectrometer covers the wavelength range between 0.25 and 5.1 μm, by using two spectral channels, operating in the spectral range 0.25–1.05 μm (VIS channel) and 1.05–5.1 μm (IR channel), with a spectral sampling of 1.8 nm and 9.8 nm, respectively (De Sanctis et al., 2011). After the approach to Ceres, Dawn performed several mapping orbits and the spatial resolution of the observations depended on the spacecraft altitude on the surface. The first phase, the Rotation Characterization 3 (RC3) occurred between April 23 and May 9, 2015, when the spacecraft was at an altitude of 13600 km, acquiring hyperspectral data with a spatial resolution of about 3.4 km/pixel. From June 6 to June 30 Dawn orbited at a distance from Ceres surface of 4400 km, in the Survey phase, obtaining a global spectral map with a spatial resolution of 1.1 km/pixel. On August 17, Dawn entered the HAMO (High-Altitude Mapping Orbit) phase orbit, descending to an altitude of 1470 km. Consequently, spectra with a spatial sampling of 360–400 m/pixel were acquired until October 23. The highest spatial resolution of 90–110 m/pixel was reached during the LAMO (Low-Altitude Mapping Orbit) phase, when Dawn orbited at an altitude of 385 km, starting on December 16, 2015 and ending on September 2, 2016.

3. Method

3.1. Scientific and spectral motivations

Although Ceres surface is quite homogeneous in reflectance (e.g. Ciarniello et al., 2017), we can identify areas with equigonal albedo significantly different from the average value. Cerealia Facula and Vinalia Faculae BS, located on the dome and on the floor of Occator crater, respectively, are the brightest spots. The differences in equigonal albedo may be related to mineralogical composition. A mineralogical analysis of Ceres surface can be performed by studying distribution of spectral parameters. Band centers provide information about the identity of minerals,

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