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Spectroscopic investigations of meteorites

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ABSTRACT

We have measured reflectance spectra (450–2250 nm) of centimeter-size pieces of 18 different meteorites. The measurements were carried out with the Finnish Geodetic Institute Field Goniospectrometer. Principal Component Analysis performed on the spectra tends to separate the undifferentiated ordinary chondrites and differentiated achondrites. Furthermore, we determined single-scattering albedos for meteoritic single particles with a phenomenological radiative-transfer model using realistic scattering phase functions. Single-scattering albedos for the analyzed ordinary chondrites range from 0.65 to 0.9.

1. Introduction

Numerous breathtakingly fundamental questions are yet unanswered about the origin, evolution, and current state of the solar system. The fact that asteroids have remained in many ways the same for the past 4.5 billion years ensures us test samples of the early solar system. Knowledge of their composition constrains our models of solar system evolution. The interpretation of asteroid composition is closely tied to surface structure. Asteroid surfaces are usually assumed to be covered with a regolith, which is a mixture of mineral grains ranging in size from micron to centimeter scales. The comprehensive range directly affects the scattering of light, and thus observations. The inverse problem of deducing the characteristics of the grains from the scattering of light is extremely difficult. We will focus on meteorites and how spectral information from them facilitates the study of asteroid composition.

According to the meteorite classification scheme by Weisberg et al. [1], meteorites are divided into chondrites, primitive achondrites, and achondrites. Chondrites are undifferentiated meteorites, which is to say, they have protoplanetary disk consistencies and are not derived from parent bodies with a core, mantle, and crust. Achondrites are at least partially melted and originate from differentiated parents. Primitive achondrites are in between: they are chemically closer to chondrites, but show some melting. Table 1 depicts a simplification of the meteorite classification system. For our purposes, the achondrites are shortlisted into Howardites–Eucrites–Diogenites (HED) meteorites, which according to spectroscopic observations most likely have originated from asteroid (4) Vesta, the only asteroid currently known to be differentiated [2]. Though not shown in the table, achondrites also contain the stony-iron, Martian, and lunar meteorites.

Meteorites are further graded according to their petrologic properties and how much shock pressure and terrestrial weathering they have experienced [1,3,4]. The petrological grade of a meteorite describes the extent of thermal metamorphism it has undergone and the distribution and mixing of its minerals. Achondrites are not petrologically graded, but instead, they are divided into subgroups with similar compositions, degrees of melting, and suspected common parent bodies [5]. Shock grades describe the shock pressures meteorites experience during an impact

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Table 1
Simplified meteorite classification system.

Differentiation	Class	Group
Undifferentiated chondrites	Carbonaceous chondrites	CI
		CM
		CO
		CV
		CK
		CR
		CH
		CB
	Ordinary chondrites	H
		L
		LL
	Enstatite chondrites	EH
		EL
Differentiated achondrites	No class designation	Howardites
		Eucrites
		Diogenites

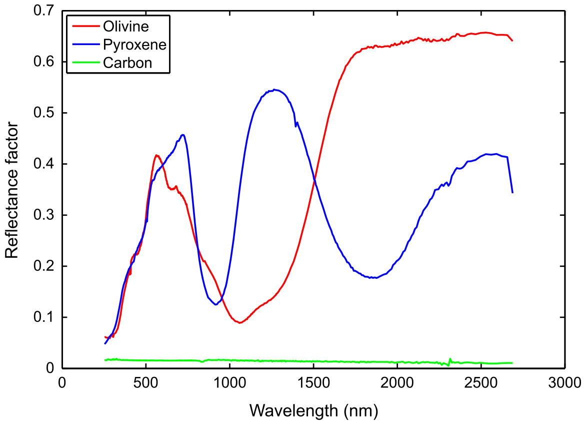

Fig. 1. Spectra of common minerals in meteorites. Measurements are taken from the United States Geological Survey (USGS) Digital Spectral Library [10]. The pyroxene spectrum is from the bronzite mineral, and the carbon spectrum is from synthetic black carbon.

event. Lightly shocked meteorites have dark shock veins, while highly shocked rocks exhibit melted and deformed matrices (exposed interior surfaces) [3].

Meteorites are affected by the Earth's environment as soon as they enter the Earth's atmosphere. On the ground, meteorites experience chemical weathering by water, oxygen, and chlorine, and physical weathering in cold, wet environments. The degree of terrestrial weathering of a meteorite speaks of its terrestrial age, but the environment dictates the specific relationship between the two. Meteorite finds from Antarctica are more long-lived than finds from other environments [6]. Observing a meteorite's descent onto Earth and then subsequently finding it makes the found meteorite a “fall”, not a “find”. Falls do not have time to be significantly altered by terrestrial weathering and they are not hugely contaminated by dust and other terrestrial particles.

When considering objects made up of minerals, troughs in their spectra usually represent absorption of light in transition -metal (Ti, V, Cr, Mn, Fe, Co, Ni, Cu) silicates and are called absorption bands [7]. These bands are explained by crystal field theory, which was developed in the late 1960s [8], and the bands were confirmed by laboratory measurements of silicate spectra around the same time [9]. Some minerals in meteorites and asteroids have absorption features, which are dominant enough to enable their identification in the visible and near-infrared spectral regions. Mafic minerals olivine and orthopyroxene have such diagnostic absorption bands at around 1 μm, and 0.9 and 1.8 μm, respectively (Fig. 1).

Additionally, olivine and orthopyroxene are the most abundant of minerals in meteorites [11]. Different mineral combinations change the position and strength of the minima of the absorption bands. Meteorites high in amorphous carbon have spectra that are darkened throughout the visible and near-infrared regions, because the opaque carbon uniformly reduces the reflectance of light [12]. If iron is present, the charge-transfer processes between iron and oxygen ions result in multiple absorption bands in the near-ultraviolet [13]. Some spectral features important for asteroid classification are only present in the near infrared [14], which is also true for meteorites.

The aim of our research was to investigate how the structure of meteorites, and especially, the scatterers within them, affect their reflectance. Spectra of 18 meteorite samples were measured with a remote-sensing spectrometer. The reliability of the spectral measurements was examined by comparing them to the spectra of well-characterized meteorites in two other data sets. The principal components of the measurement data were also resolved to determine whether or not the Principal Component Analysis (PCA) could be used to discern spectra of structurally and compositionally different meteorites from each other. PCA and the spectral measurement method are presented in Sections 3 and 2.

A radiative-transfer model for chondritic olivine-rich meteorites was created with the contentious assumption that the scatterers forming a plane-parallel medium were mostly forward scattering, but with noticeable backscattering behavior. The scattering phase functions used in the model were not randomly chosen: they were derived from fitting triple Henyey–Greenstein functions to the measured scattering phase functions of real olivine particles found in the Amsterdam–Granada light scattering database [15,16]. In order to determine if the assumptions were realistic, the single-scattering albedos of the modeled scatterers were extracted by matching the simulated reflectances for the particulate media to the measured meteorite spectra across the wavelength range. A detailed description of the model can be found in Section 4.2 and the modeling results are presented in Section 5.3.

2. Spectrometric measurements

2.1. Experimental setup

The reflectance spectra of 18 meteorite samples were measured with the Finnish Geodetic Institute Field Goniospectrometer (FIGIFIGO) at the Finnish Geodetic Institute in Masala, Finland. FIGIFIGO operates by measuring the Bidirectional Reflectance Factor (BRF) in different illumination and observational geometries inside a laboratory or outdoors [17]. The spectral range is from 350 to 2500 nm with sampling at