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A PCA study to determine how features in meteorite reflectance spectra vary with the samples' physical properties

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ABSTRACT

Meteorites have advanced our knowledge of processes in the Solar System with the application of high precision instruments here on Earth. The study of asteroids, the source of most meteorites, has in turn given us knowledge regarding the large scale evolution of the Solar System. Using the complementary information that asteroids and meteorites give us the story of our cosmic backyard can be more easily read. One efficient way to link meteorites to asteroids is by matching their respective reflectance spectra. There have been few convincing matches because of observational and scale differences as well as an incomplete knowledge of the light scattering physics involved. To better interpret the reflectance data we need to know the dependencies of the reflectance on physical properties and develop techniques for better comparisons of data sets. For these purposes we utilise our own measurements of 26 different meteorites together with spectra available on the NASA PDS.

We find that normalisation of reflectance at a wavelength between 1.1 and 1.3 μm gives the closest match of spectra from meteorites common to both data sets. The depth of the spectra bands deepens by similar amounts for different types of surface texture alterations i.e. rock to sawn surface, rock to polished surface and rock to powdered surface. Principal Component Analysis (PCA) is able to easily place carbonaceous chondrites, ordinary chondrites and achondrites into distinct groups using their reflectance spectra. We track the variation of spectral features in principal component space by using a set of meteorite spectra synthesised from mineral and elemental spectra. A spectral agent that reduces the reflectance at all wavelengths is required, in addition to olivine, pyroxene and carbon, to generate a set of synthesised spectra to match the distribution of measured spectra, in principal component space.

1. Introduction

Meteorites contain a diverse range of over 300 minerals with about 40 not found in terrestrial rocks [1]. Common mineral groups found in meteorites are silicates, oxides, carbonates, phosphides, phosphates and sulphides. Nickel–iron metal and carbon in the form of graphite or diamond are also relatively common in meteorites. Pyroxene, plagioclase and olivine are the most common and can be found in achondrites and chondrites. Table 1 shows the mineral and elemental (carbon) contents of meteorites. These reflect their formation processes e.g. see Ref. [2] or Ref. [3] for further details. It is generally accepted that

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Table 1
Average percent weight of minerals in meteorite groups. The table is split into non-differentiated (top) and differentiated meteorites (below). A range of weights is shown for achondrites to highlight their variability. Values for H, L and LL chondrites are an average of values measured in Ref. [4]. Carbon references were found in Ref. [5].

Meteorite group	Olivine	Pyroxene	Plagioclase	Carbon	Metal
Carbon. chondrites	~7.5[f] (81.6)[g]	0[f]	(0.9)[g]	0.10–5.00[a,b]	(0.01)[g]
H chondrites	32.9	32.4	9.0	0.03–0.60	18.3
L chondrites	42.0	31.4	9.4	0.03–0.60	8.4
LL chondrites	51.1	26.3	9.9	0.03–0.60	2.6
Howardites	–	15–60[e]	–	0.001–0.003[c]	< 0.1
Eucrites	–	45–70[e]	–	0.001–0.003[c]	< 0.1
Diogenites	–	~26[e]	–	0.001–0.003[c]	< 0.1

[a]Ref. [6], [b]Ref. [7], c. Ref. [8], e. Ref. [9], f. average of a CM2, C2, CI2 in Ref. [10] g. Allende CV3 Ref. [10].

Table 2
Classification of chondrites. The numbers that are italicized indicate how many meteorites have been classified with the associated petrographical grade. The numbers in the cell are the number of each meteorite in our collections [11]. Absent, sparse and distinct refer to chondrules in the meteorite. The petrographical types 1, 2 and 3 apply to carbonaceous chondrites and are in order of decreasing aqueous alteration. The petrographical types 3, 4, 5 and 6 apply to ordinary chondrites and are in order of increasing thermal metamorphism.

Clan	Group	Petrographical type						
		1	2	3	4	5	6	
		Absent	Sparse	Abundant, distinct		Increasingly indistinct		
Carbonaceous Chondrites	CI	*5*						
	CM	*3*	*150*					
	CR		*78*					
	CO			*91*				
	CV		*1*	*54*				
	CK			*6*	*23*	*51*	*1*	
R Chondrites	R			*5*	*4, 1*[a]	*1, 2*[b]	*5*[c]	
K Chondrites	K			*2*				
Ordinary Chondrites	LL			*33*	*72*	*952*	*471*	*LL7 10*
	L			*148* (3%)	*464* (7%)	*1368* (22%)	*4443* (68%)	*L7 15*
	H			*138* (3%)	*1448* (23%)	*3563* (40%)	*2032* (34%)	
	EL			*10*	*1*	*2*	*23*	
	EH			*98*	*11*	*5*	*6*	

a. R3–4, b. R3–5, c. R3–6.

chondrites are primitive while achondrites have experienced some differentiation.

Meteorites are graded in three main ways to describe petrology, shock and terrestrial weathering. Petrographical grades of chondrites, shown in Table 2, attempt to describe the thermochemical equilibration with 1 being the least affected by thermal metamorphism and 6 being the most effected by thermal metamorphism. A grade 6 chondrite has experienced a similar degree of melting as an achondrite but will not have experienced differentiation. The grades also describe the distribution and mixing of minerals like olivine and pyroxene in the meteorite. A meteorite with a lower grade will be more heterogeneous and a meteorite with a higher grade will be more homogeneous.

A similar petrographical grade is not available for achondrites as these are from differentiated bodies and have been at least partially melted, moving them beyond the petrographical grade 6 used for chondrites. Achondrites are instead organised into subgroups with similar compositions and degrees of melting. They are sometimes organised into groups when it is suspected they share a common parent body. For example the subgroups Howardite, Eucrite and Diogenite meteorites (see Table 1) are thought to originate from asteroid Vesta and are known collectively as the Howardite–Eucrite–Diogenite (HED) group.

A grading system is employed to describe the degree of shock received by the meteorite during an impact event. The grade increases with increasing shock pressures. Lightly shocked meteorites may display dark shock veins while highly shocked impact melts will display a melted and deformed matrix. A grading system is also used to describe the amount of degradational terrestrial weathering affecting the meteorite sample. Terrestrial weathering first affects the metal grains, then the troilite and finally the silicates. The shock [12] and weathering grading systems are shown in Table 3 together with more details regarding the petrographical grading system introduced in Table 2.

Fortunately, pyroxene, plagioclase and olivine have diagnostic absorption bands centred at wavelengths of ~1 and ~2 μm in the reflectance spectra. These are within the range of spectrometer instruments currently used for asteroid observations. The bands due to pyroxene