VISIBLE AND INFRARED SPECTRAL ANALYSIS OF THE WINCHCOMBE METEORITE FOR COMPARISON TO PLANETARY SURFACES.

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Introduction: On the 28th of February 2021 a meteorite fall was observed in Winchcombe, UK. Numerous eye-witness accounts and video recordings of the fireball reported to the UK Meteor Observation Network allowed quick retrieval of the main mass (within 12 hours post fall) and ~600 g of meteoritic material was recovered over the following month [1]. Winchcombe is classified as a CM2 chondrite, though several lithologies are represented in the recovered material showing variations in petrologic type and degree of aqueous alteration [1]. Analyses of the material were organized on a national level, representing a collaboration across the UK to gain a comprehensive understanding of its bulk material properties and connection to its origin in the Solar System [e.g. 1, 2].

Here we discuss one facet of that collaboration: the spectral analyses conducted at the Planetary Spectroscopy Facility at the University of Oxford. These measurements include visible to near-infrared (VNIR; 0.7-5 um) and mid-infrared (MIR; 5-25 um) reflectance measurements of Winchcombe to look for variation within the recovered material. Additionally, multi-angle VNIR Bidirectional Reflectance Distribution Function (BRDF) measurements were made using the Visible Oxford Space Environment Goniometer (VOSEG) [3]. The BRDF was measured for a powdered sample characterized in terms of porosity and surface roughness, and this dataset was used to determine the broadband albedo (0.35-1.25 um) of Winchcombe in [1].

IR Spectroscopy: Reflectance spectra of two samples (BM.2022,M1-91; BM.2022,M2-41) were measured with a Bruker VERTEX 70v Fourier Transform Infrared spectrometer, using a diffuse reflectance accessory under vacuum (~2 hPa) at 4 cm^{-1} resolution and an average of 150 scans calibrated to a diffuse gold target. The shortest wavelength range (0.8-2 µm) was acquired using an InGaAs detector coupled with a VIS/Quartz beamsplitter, while a RT-DLaTGS detector and a wide range beamsplitter were used for the near- and mid-infrared (2-25 µm). We correlate the spectra with modal mineralogy as determined using position-sensitive-detector X-ray diffraction (PSD-XRD) [1] and water abundance using thermogravimetric analysis (TGA) [2] for the same samples.

The slope of the spectra in Fig. 1a is likely attributed to compositional differences between the two samples which show a phyllosilicate content of 88 & 93 vol%.

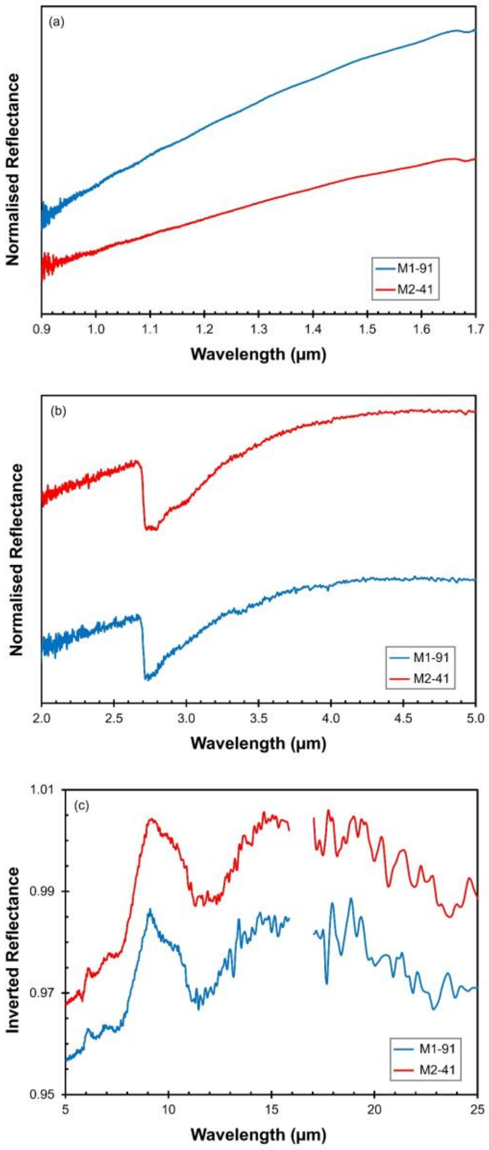

Figure 1. The spectra of the two samples normalized and split into different wavelength regions for clarity.

The feature near 2.75 µm (Fig. 1b) is attributed to OH^- stretching and indicates aqueously altered mineralogy. Several studies [4,5,6] have used reflectance near this feature to estimate water content of asteroids and meteorites. We calculated an estimated water content for M1-91 and M2-41 of 6.0 and 5.61 wt% using the methods of [4] and 10.5 and 9.5 wt% using the methods of [5]. These are both lower estimates than the values of 12.4 and 13.3 wt% measured through thermogravimetric analysis [2], but this may be due to other mineralogy (eg. Sulfides) contributing to the mass loss in TGA [7].

The Christiansen feature (CF; reflectance minimum) is located near 9 µm and indicates poor silicate polymerization (Fig. 1c). The slight variation (~0.1 µm) in the CF position is likely due to a higher olivine content in M1-91 [1]. The positions in the Winchcombe spectra are consistent with spectra of other CM chondrites [e.g. 8]. The transparency feature (reflectance maximum) near 11.5 um is another compositional indicator and has been shown to correlate to aqueous alteration in CM chondrites [8]. Shifts in this feature indicate BM.2022,M2-41 is more aqueously altered than BM.2022,M1-91. This is consistent with the determined mineralogy [1].

Bidirectional Reflectance Distribution Function (BRDF): The BRDF was measured for a powdered sample of the Winchcombe meteorite (BM.2022,M1-22; Fig. 2a) across 0 – 70° reflectance angles, in steps of 5°; at 15°, 30°, 45° and 60° incidence angles; and at 0°, 90° and 180° azimuthal angles within VOSEG (Fig. 2c&d). The dataset was then fit using the Hapke BRDF model to constrain the bulk scattering properties of the meteorite sample [9].

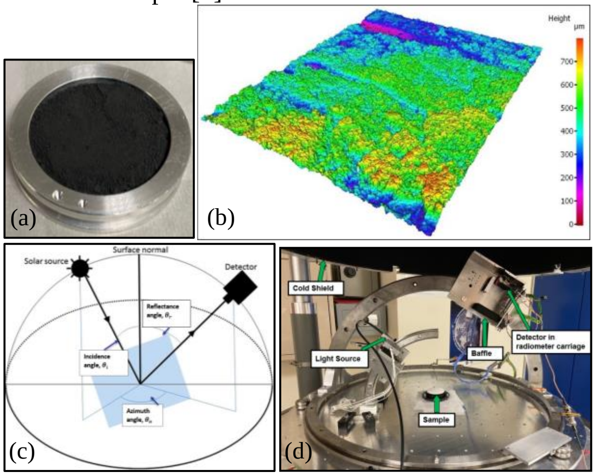

Figure 2. (a) Image of BM.2022,M1-22 particulate sample; (b) surface profile of the sample taken using the Alicona 3D instrument; (c) diagram of angle definitions within (d) the VOSEG set-up.

The surface profile of the sample was characterized at several scales/resolutions using an Alicona 3D® instrument (Fig. 2b). Therefore, two of the free parameters within the model – the filling factor, φ; and the RMS slope angle, θ – could be determined independently, as $\varphi = 0.65 \pm 0.02$ and $\theta = 16.11°$ (at 500 µm size-scale). Thus there were only three open parameters within the Hapke BRDF model Least-Squares Levenberg-Marquardt fitting function: w (volume average single scattering albedo), b (Henyey-Greenstein forward scattering parameter) and h_S (width of the opposition effect). The best fit parameters were determined to be $w = 0.152 \pm 0.030$, $b = 0.633 \pm 0.064$ and $h_S = 0.016 \pm 0.008$.

Once all of these values were determined, we calculated the broadband albedo (0.35-1.25 µm) value to be $A = 4.09 \pm 0.18$ %, which can be converted to hemispheric albedo by multiplying by π [9]. The parameter values are similar to reported values for other carbonaceous chondrites (Table 1) [3,10].

Summary: IR spectroscopy is a useful technique for investigating the composition and physical properties of rocks and minerals of planetary bodies. It is particularly powerful when we can compare remote sensing data to laboratory studies of extraterrestrial material in the form of meteorites and sample return. Here we cataloged several important spectral features and derived properties of Winchcombe material for comparison to other meteorites and asteroids. Overall, the spectra show Winchcombe to be consistent with other highly aqueously altered CM chondrites, and further analyses highlight the subtle composition and alteration variability within the meteorite also seen in the modal mineralogy of each sample [1,2].

The laboratory measured Winchcombe BRDF provides a reference photometric dataset for use in remote sensing studies of asteroids. The opportunity to measure these spectral features of the pristine Winchcombe material along with the thorough analysis with other techniques by scientists across the UK, allows us to better understand and interpret data from Solar System objects and, in turn, learn more about their origins and evolution.

Name	**Class**	$\boldsymbol{\omega}$	$\boldsymbol{b}$	$\boldsymbol{\phi}$	$\boldsymbol{\bar{\theta}}$
Orgueil	CI	0.461	0.671	0.169	22.6
Allende	CV	0.399	0.366	0.048	12.8
Tagish Lake	C2-ung	0.157	0.431	0.056	14.1
Winchcombe	CM	0.152	0.633	0.649	16.1

Table 1. Hapke parameters ω , b, ϕ and θ determined for the Winchcombe meteorite sample and for the Orgueil, Allende and Tagish Lake carbonaceous chondrite meteorite samples [10].

References: [1] King A. J. et al. 2022. *Sci. Ad*.8:46 [2] Bates H.C. et al. 2022. *MAPS*. [3] Curtis R. et al. 2021. *RSI* 92.3:034504 [4] Rivkin A. S. et al. 2003. *MAPS*. 38:1383-1398. [5] Sato K. et al. 1997. *MAPS*. 32:503-507. [6] Beck P. et al. 2021. *Icarus*. 357: 114125 [7] Garenne et al., 2014. *GCA*, 137. [8] Bates H. C. et al. 2020. *MAPS*. 55:77-101. [9] Hapke B. 2012. *Icarus*. 221:1079-1083. [10] Beck et al., 2012 *Icarus*, 218(1), 364-377.