Spectral Properties of Primitive Achondrite Meteorites: Establishing S-type Asteroid-Meteorite Connections

Michael P. Lucas[1], Joshua P. Emery[1], Takahiro Hiroi[2], and Ralph E. Milliken[2], [1]Department of Earth & Planetary Sciences, University of Tennessee, 1412 Circle Drive, Knoxville, TN 37996, (mlucas9@vols.utk.edu), [2]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912

Introduction: Meteorites arrive to Earth as essentially "free" samples of asteroids. Unfortunately, these samples usually arrive without context of their source region [1]. However, by comparing spectral and geochemical data of meteorites obtained in the laboratory with asteroid spectral data acquired at the telescope, robust asteroid-meteorite connections can be established. Accordingly, ground-based telescopic spectral observations can economically provide fundamental knowledge of certain asteroid surface compositions. This is practicable because S-complex and several end-member asteroid types [2] reflect near-infrared photons that carry strong 1 µm and/or 2 µm absorption bands caused by the presence of Fe^{2+} in olivine and pyroxene, revealing surface mineralogic signatures. Initial work in developing mineralogic calibrations useful for correlating asteroid compositions were developed by obtaining laboratory spectra of natural terrestrial olivine and pyroxene mixtures [3,4,5]. More recent studies have utilized the geochemical and spectral analyses of stony-meteorite samples to develop mineralogic calibrations for HEDs [6], ordinary chondrites (H,L,LL) [7], and olivine-rich (R-chondrites, brachinites, pallasites) meteorites [8]. These calibrations are useful for estimating the chemistry and abundance of mafic silicates on asteroid surfaces through analysis of their VISNIR spectra. Despite these advances, no calibrations exist to provide direct comparison of primitive achondrite mineralogy to asteroid spectra.

Primitive Achondrite Heating: Primitive achondrites are the solid residues left from low-degrees (~1-20%) of partial melting of chondritic material [9,10]. Acapulcoites are essentially chondritic in composition, but have been heated to ~950-1050˚C, warm enough to induce Fe,Ni-FeS cotectic melting [10]. Lodranites show higher-degrees of partial melting than acapulcoites, as they have been heated to ~1050-1200˚C, hot enough to produce basaltic partial melts [9,11]. Acapulcoites and lodranites are thought to originate from a single, partially-differentiated parent-body [11,9]. Another uncommon (~25 examples) group of primitive achondrites are the winonaites, which also have chondritic mineralogies and bulk compositions [12].

Primitive Achondrite Sample Suite: In this study, we present new laboratory spectra for 12 primitive achondrite meteorites. Five samples (Figure 1) were provided by the NASA Antarctic Meteorite Working Group (AMWG). Seven Northwest Africa (NWA) samples were acquired commercially (Figure 2). Primitive achondrite meteorites demonstrate the existence of partially melted material among the asteroids and provide a basis for spectral comparison to S-type asteroids. Forthcoming mineral chemistry and modal abundance analyses of these samples, combined with the spectral band parameter measurements presented herein, will enable the development of new calibrations to provide insight on meteorite-asteroid connections for partially differentiated objects.

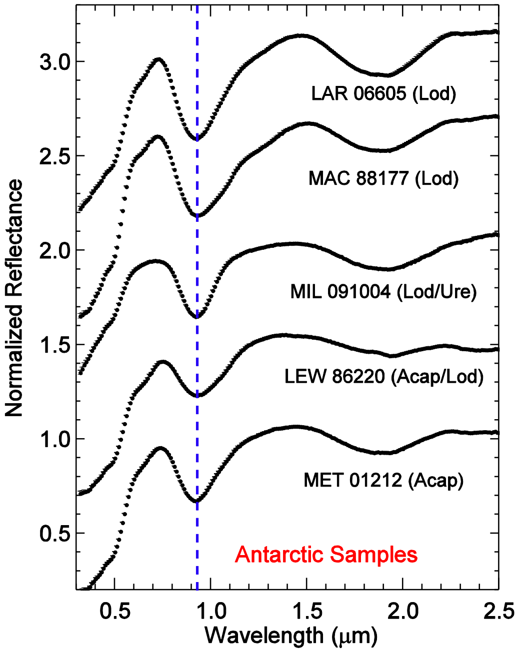

Figure 1. *– Five Antarctic primitive achondrite spectra. For band parameter values see Table 1. Blue line indicates the average Band I center of 0.927 µm.*

RELAB VISNIR Spectra: VISNIR spectra were acquired (Figures 1 and 2) using the bi-directional reflectance spectrometer (0.3-2.6 µm) at the Keck/NASA Reflectance Experiment Laboratory (RELAB) [13]. Sample preparation techniques were kept consistent and care was taken to prevent cross-contamination. The meteorites were coarsely crushed (~250-500 µm) and placed in a Pyrex culture dish. The metal fraction of each meteorite was serially removed with a magnet, leaving behind the silicate fraction and weathered material. To compare meteorite spectra to asteroid surfaces that are blanketed in regolith, the remaining silicate fractions were powdered in an agate mortar and pestle and sieved to <125 µm. Our new spectral data were supplemented with existing spectra of six primitive achondrites (see Table 1) from the RELAB database.

Spectral Band Parameter Measurements: Band parameter values (Band I & II centers, band depths, Band Area Ratio-BAR) were measured for 15 primitive achondrites (Table 1) using SARA, a freely-available IDL-based code. For details regarding SARA see [14].

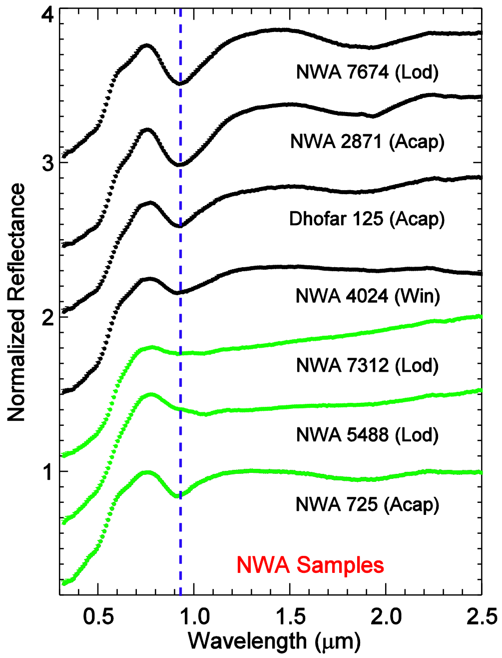

Figure 2. *– Seven NWA primitive achondrite meteorite spectra, lower three (green) spectra not analyzed for band parameter., See Table 1 for values for upper four spectra (black). Blue-dashed line same as Figure 1.*

Results: The variety of primitive achondrite meteorite types used in this study produce distinguishing features controlled mainly by the Fe^{2+} content of their silicates, and by the modal abundances of olivine and pyroxene. Interestingly, Band I centers show a narrow range of values (Figures 1 and 2; Table 1) despite the fact that olivine and pyroxene mineral chemistry span ranges of Fa_{4-13} and Fs_{3-14}, respectively. The presence of iron hyroxides (Band I centers ~0.90 µm) due to terrestrial weathering may partially effect the band results.

Asteroid-Meteorite Connections: : Figure 3 shows Band I center vs. BAR for 14 primitive achondrite meteorites from Table 1 (NWA 4024 not shown). Band Area Ratios display a wide range of values, only five samples plot within the spectral region analogous with primitive achondrites. Nine samples have lower BARs and trend toward the spectral region analogous to partially-melted ureilite meteorites [15,16]. Nevertheless, most samples plot near or outside of the ordinary chondrite "boot", in spectral regions consistent with their partially-melted nature.

Table 1. *– Analyzed primitive achondrite spectra.*

Meteorite	Group	RELAB ID	Band I (µm)	BAR
Existing RELAB Spectra				
ALH 81261	Acap	TB-TJM-039	0.930	0.647
ALH 81187	Acap	TB-TJM-040	0.930	0.182
Lodran	Lod	TB-TJM-041	0.920	0.868
EET 84302	Acap/Lod	TB-TJM-042	0.920	1.06
Acapulco	Acap	TB-TJM-043	0.923	0.854
GRA 95209	Lod	TB-TJM-044	0.920	0.770
New RELAB Spectra				
LAR 06605	Lod	MT-JPE-300-A	0.923	0.623
MET 01212	Acap	MT-JPE-301-A	0.923	0.617
MAC 88177	Lod	MT-JPE-302-A	0.940	0.432
MIL 091004	Lod/Ure	MT-JPE-303-A	0.923	1.02
Dhofar 125	Acap	MT-JPE-304-A	0.920	0.552
NWA 2871	Acap	MT-JPE-306-A	0.930	0.316
NWA 4024	Win	MT-JPE-307-A	0.930	-0.190
NWA 7674	Lod	MT-JPE-310-A	0.930	0.569
LEW 86220	Acap/Lod	MT-JPE-314-A	0.940	0.280

Acap=acapulcoite; Lod=lodranite; Ure=ureilite; Win=winonaite

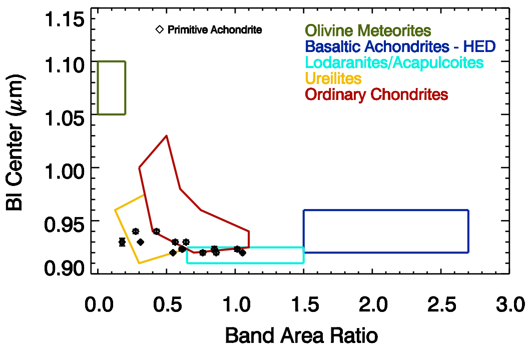

Figure 3. *– Fourteen primitive achondrites plotted on the S-subtype plot of [15] adapted in [17] to illustrate spectral regions analogous to varous meteorite groups*

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References: [1] Cloutis, E.A. et al. (2014) *Elements* 10, 25-30. [2] DeMeo, F.E. et al. (2009) *Icarus* 202, 160-180. [3] Adams, J.B. (1974) *JGR* 79, 4829-4836. [4] Cloutis, E.A. et al. (1986) *JGR* 91, 11641-11653. [5] King, T.V. and Ridley, W.I. (1987) *JGR* 92, 11457-11469. [6] Burbine, T.H. et al. (2009) *MPS* 44, 1331-1341. [7] Dunn, T.L. et al. (2010) *Icarus* 208, 789-797. [8] Sanchez, et al. (2014) *Icarus* 228, 288-300. [9] McCoy, T.J. et al. (2000) *Icarus* 148, 29–36. [10] McCoy, T.J. et al. (1997) *GCA* 61, 639-650. [11] McCoy, T.J. et al. (1997) *GCA* 61, 623-637. [12] Floss, C. et al. (2008) *MPS* 43, 657-674. [13] Pieters, C.M. and Hiroi, T. (2004) *LPSC* abs#1720. [14] Lindsay, S.S. et al. (2015), *Icarus* 247, 53-70. [15] Gaffey, M. J. et al. (1993) *Icarus* 106, 573-602. [16] Cloutis et al. (2010) *MPS* 45, 1668-1694. [17] Dunn, T. L. et al. (2013) *Icarus* 222, 273-282.