Spectral Feature Analysis of Minerals and Planetary Surfaces in an Introductory Planetary Science Course

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ABSTRACT

Using an ALTA II reflectance spectrometer, the USGS digital spectral library, graphs of planetary spectra, and a few mineral hand samples, one can teach how light can be used to study planets and moons. The author created the hands-on, inquiry-based activity for an undergraduate planetary science course consisting of freshman to senior level science majors and nonmajors. The activity follows a guided-inquiry approach that unites lab-based investigation of minerals with online datasets, and enables students to import, configure, graph, analyze, and compare data using spreadsheet software. The activity includes two parts: (1) analysis of mineral hand samples and spectra, and (2) exploration of planetary reflectance spectra. The activity culminates with students using techniques analogous to those employed by planetary scientists to establish rationales for determining compositional information about, and categorizing and identifying, several planetary bodies in the solar system based solely on reflectance spectra. © *2013 National Association of Geoscience Teachers*. [DOI: 10.5408/12-293.1]

Key words: geoscience education, online data, planetary science, reflectance spectra, spectrometers

INTRODUCTION

Studies of light, both emission and reflection, are critical to learning about the composition of planetary objects, and are routinely conducted with the data collected by orbiters, probes, and landers. Studies of light are also essential for studying exoplanets, which cannot be visited with current technology because of their extreme distances from Earth. In an attempt to foster better student understanding and appreciation of the value of studying light within planetary science, an activity was created wherein students use mineral hand samples, a hand-held spectrometer, and two online sources of mineral and planetary surface reflectance data to practice skills and techniques rudimentarily analogous to those utilized by scientists for studies of the surface composition of terrestrial bodies in our solar system. The activity helps students better understand the critical role light plays in studying planetary objects by showcasing the union of scientific processes, technology, and problem-solving skills. The description that follows outlines the specific aspects of the activity as it was used in an undergraduate college geoscience course.

BACKGROUND

Reflected light from planetary surfaces is useful for identifying the minerals present. Examination of this reflected light for patterns may be referred to as spectral feature analysis (Clark, 1999). When light encounters matter, a mineral on the surface of a rock may undergo several possible interactions: light may be absorbed, transmitted, or reflected. The percentage of light reflected from the surface of a mineral is called the reflectance of the mineral (Nesse, 2000). Although the details of this process are complex, the outcome is quite elegant and useful. The reflectance spectra of minerals exhibit absorption bands at specific wavelengths corresponding to the energy required for electrons in certain atoms of a mineral to move from lower to higher orbitals or energy states. The resulting peaks and valleys in the reflectance spectra of each mineral create diagnostically significant signatures (Clark, 1999). Individual mineral signatures may be similar to other minerals, similar within specific mineral groups (e.g., pyroxenes), and similar across general groups (e.g., silicates). A few very important signatures are prominent in the reflectance spectra of terrestrial planetary bodies: metals, silicates, and ices. Iron-nickel metals produce relatively linear spectral signatures, whereas pyroxene and olivine produce curved signatures with somewhat pronounced absorption bands (McSween, 1999). The downward trending signature of water ice is also readily identifiable in the icy surfaces of many of the moons of the outer gas giants. A number of factors may cause a shift in the location and amplitude of the peaks and troughs of a typical mineral's spectral signature, such as space weathering (McSween, 1999) or combination with other minerals in a rock (e.g., Goettsch et al., 1998), but the presence of absorption bands is still in many cases a way for definitive mineral identification. By using reflectance spectra of minerals and planetary surfaces, scientists are able to learn detailed information about the composition of distant objects remotely.

Similarly, light is used to study exoplanets, or planets outside of our solar system, and some information about the materials that comprise distant objects can be determined via the transit method as light from a star passes through the atmosphere of an exoplanet. The transit method of exoplanet discovery works for extrasolar planetary systems that are viewed edge-on from the Earth; in these systems, an exoplanet passes in front of the star it orbits, which not only blocks some of the light from the star enabling its presence to be detected, but also affords an opportunity for compositional study as the background light from the star passes through the atmosphere of the exoplanet. Scientists

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TABLE I: Learning objectives and materials needed for the activity.

Learning Objectives	Activity Materials
1. Hone skills related to using the reflectance spectrometers 2. Foster an understanding of how light is used to learn about distant objects in our solar system 3. Analyze mineralogy of a planetary surface and/or atmospheric composition of objects in our solar system using reflectance spectra 4. Determine probable terrestrial surface and/or atmospheric composition of unidentified solar system objects using reflectance spectra 5. (optional) Apply spreadsheet software to the exploration of data	• ALTA II Reflectance Spectrometer • Mineral hand samples • Graph paper (and/or access to spreadsheet software) • Hand-outs of reflectance graphs for: hematite, olivine, pyroxene, dolomite, enstatite, serpentine, microcline, muscovite, biotite, hornblende, water-ice, and (optional) spectral catalog data identifying peak absorption wavelengths for several gases including oxygen, carbon dioxide, methane, and water vapor • Link to the USGS Planetary Surface Data • (optional) Link to the USGS Digital Spectral Library for Minerals

determine the presence of specific elements and molecules in an exoplanet's atmosphere based on the wavelengths of light that are missing when the spectrum is compared to the unimpeded spectrum of light the star emits.

Inquiry approaches are known to benefit students because of the emphasis on problem-solving, practice of real-world skills, and practice developing scientific explanations (National Research Council, 2000a, 2000b). Scientists routinely use technology to complete investigations and modeling these authentic practices are beneficial within the college science curriculum. Inquiry-based activities involving the use of computers, software, and instruments are ways to provide opportunities for students to ask and answer questions in science, and may be used to enhance learning (Royuk and Brooks, 2003).

DESCRIPTION

Overview

This activity was created for an introductory planetary science course consisting of freshmen to senior level students at the undergraduate college level. The activity was administered once as described here; however, parts of it have been shared and used in other settings. During the semester this activity was implemented in its entirety, nearly half of the students were sophomores: freshman (20%), sophomores (45%), juniors (15%), and seniors (20%). Student majors varied, but the largest numbers consisted of education majors (elementary and secondary) at 10 and those with "undecided" majors at seven; other majors with fewer numbers included environmental studies, geography, history, computer science, sport management, psychology, and business administration.

The activity makes use of the ALTA II Reflectance Spectrometer (distributed by Vernier for about $175 each), the USGS Digital Spectral Library (Clark et al., 2007), graphs of planetary spectra (USGS, 1998), and several mineral hand samples (e.g., hematite, serpentine, muscovite, and microcline). The activity consists of two parts. In the first part, students collect and graph reflectance data at specific wavelengths of light for several mineral hand-samples using the spectrometers, then compare their instrument-derived graphs to representative USGS spectral graphs for the same minerals and look for similarities or patterns in the data. In the second part, students examine surface reflectance graphs for several solar system objects in order to determine compositional information by identifying signatures from the graphs of specific minerals. The activity allows students to use techniques similar to those employed by planetary scientists to study the materials present on the surfaces of planetary bodies in the solar system. Specific learning objectives for the entire laboratory investigation and materials are identified in Table I.

Part I - Analysis of Mineral Hand Samples and Spectra

The lab activity took place in one 2-hour lab session. In a previous lab session, students were introduced to a practice activity where they learned to use the ALTA-II spectrometers (described in the "Teaching Notes"). The students worked in small groups to complete all parts of the lab investigation, the procedure for which was distributed in the form of a worksheet. The instructor explained what the students would be doing for the first part of the investigation: using the ALTA-II spectrometers to collect reflectance data and plot the values on a graph (by hand or using spreadsheet software). Calibrations of instruments had been completed in the previous class period's activity, so students could apply the corrections to their data. The worksheet directed students to place wavelength (in micrometers) on the x-axis and reflectance (decimal percentage values) on the y-axis, as they had done in the previous practice activity. A stapled packet, or handout, of several identified and labeled USGS mineral spectra was distributed to each group. The handout consisted of reflectance spectra for minerals used in both parts of the activity. See Table I for more information.

Students used ALTA II reflectance spectrometers to collect spectral data at wavelengths of 0.470 μm, 0.525 μm, 0.560 μm, 0.585 μm, 0.600 μm, 0.645 μm, 0.560 μm, 0.700 μm, 0.735 μm, 0.810 μm, 0.880 μm, 0.940 μm for a mineral specimen and then graphed the data using spreadsheet software or graph paper. First, students used spectrometers to analyze a hand sample of serpentine, which yielded a close approximation to the reflectance spectrum for the mineral provided by the USGS (Clark et al., 2007). After measuring the intensity of reflectance at specified wavelengths, students plotted the values on a graph. Students were then instructed to respond to the following: "Compare your graph to the spectral graph for your sample from the USGS database (handout). Describe the similarities and differences between the two graphs." Students were charged with noting the position of peaks and troughs in the respective reflectance graphs, and writing explanations specifically describing the wavelengths at which the peaks occurred and how closely their reflectance data matched the accepted standards from the spectral library. Students were encouraged to speculate potential reasons for any differenc-

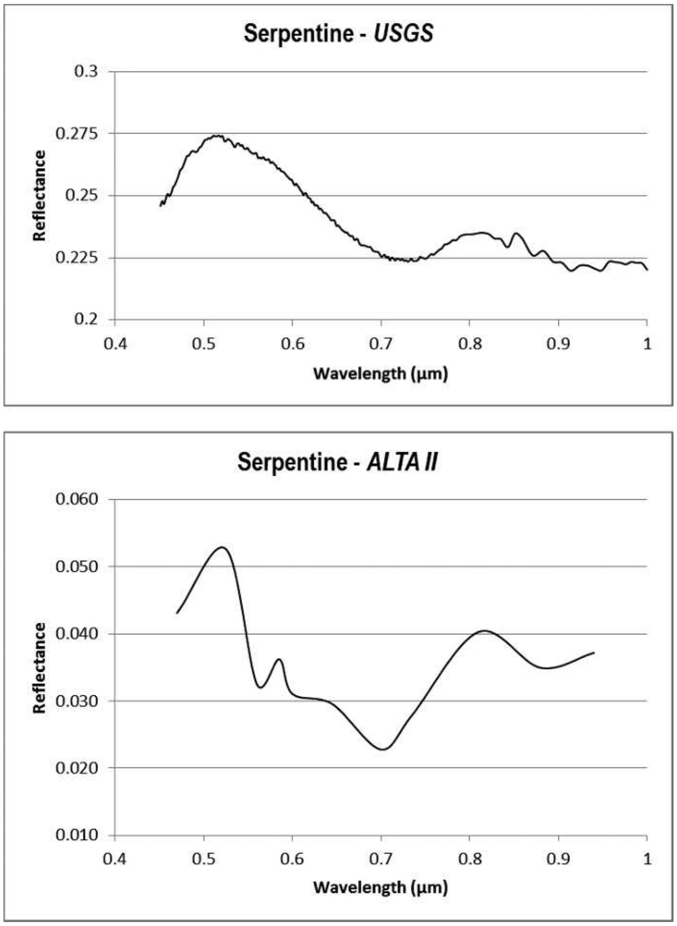

FIGURE 1: ALTA II spectrometer-generated spectrum for the mineral serpentine, compared to a spectrum for the same wavelengths produced from the USGS Digital Spectral Library (Clark et al., 2007).

es. Differences are typically seen in the exact wavelengths and amplitudes of absorption troughs and reflectance peaks.

Next, students were given an "unknown" mineral sample (hematite, microcline, or muscovite), asked to identify the sample, and provide a justification for why they selected the specific identity of the mineral. In retrospect, it would have been a good idea to ask students to examine one more known sample before looking at an unknown. Although students received no formal instruction on doing this, most figured out that they needed to graph reflectance data as they had done previously and attempt to match their graph to an equivalent reflectance graph from a handout of USGS mineral spectra. See Fig. 1 for an example. While students were working on this, the instructor walked around the lab posing questions to and guiding students. Some groups of students incorrectly identified minerals, for various reasons. One group of students was looking more at the shape of the reflectance curves rather than the wavelengths of peaks or troughs; the instructor pointed out these discrepancies, engaged students in a dialogue, and ultimately helped them to reevaluate their findings. The focus was not completely on obtaining the "correct" answer, but on the process of evaluating the data and justifying the selection. The technique can be used more realistically to narrow the identity of the sample to a list of possible minerals.

Part II - Exploration of Planetary Reflectance Spectra

For the second part of the activity, students were either provided graphs of planetary spectra or used computers to access online, download, and graph reflectance data for wavelengths 0.3 to 4.0 µm for several of the available and identified planetary objects: Earth's moon, Mars, Saturn's rings, and Jupiter's moon Europa (data from USGS, 1998). It should be noted here that the website from which the data comes discusses some of the answers to the questions and so students may need to be directed to close their browsers once they have generated their graphs. Students familiarized themselves with the reflectance characteristics of the planetary surfaces, atmospheres, and ring systems. For students who chose to download and plot the planetary data, the instructor explained the procedure for copying and pasting the data into the spreadsheet software, and then illustrated the steps necessary to generate the desired graphs. After plotting the reflectance graphs for each planetary object, either by hand or using spreadsheet software, the worksheet directions instructed students to compare their planetary reflectance graphs to the USGS mineral graphs in an attempt to identify and match specific mineral signatures in the planetary reflectance spectra. In some cases students were able to recognize certain mineral names and examine them for possible connections to planetary reflectance graphs. See Fig. 2 for an example. In addition, the worksheet provided specific directions related to each of the graphed objects: (1) Determine what mineral most likely accounts for the notable dips in the spectrum of the Moon at about 1.0 and 2.0 µm. Select the single most-likely mineral. Provide and support a rationale for why you think so by comparing and contrasting the two graphs. (2) Determine what most likely accounts for the notable dip in the spectrum of Mars at about 2.0 µm. Select the single most-likely mineral or gas. Provide and support a rationale for why you think so. (3) Determine the most likely composition of Saturn's rings. Provide and support a rationale for why you think so by comparing and contrasting the two graphs. (4) Determine the most likely surface composition of Europa. Provide and support a rationale for why you think so by comparing and contrasting the two graphs. The instructor again walked around the lab interacting with the students and observing their progress. When students were not sure where to begin or what mineral spectra might be likely candidates, the instructor asked questions and made suggestions, usually in the form of directing students to note the peak absorption wavelengths or general trends in the planetary graphs and to seek similar patterns in the provided mineral graphs. For example, a reflectance spectrum might trend upward from left to right, indicating greater reflectance at longer wavelengths and suggesting a rocky-metallic terrestrial surface. If students had incorrectly identified minerals, the instructor recommended they reexamine their data or asked them to explain why they selected a certain mineral. The instructor pointed out weaknesses in their justifications as necessary.

The final portion of Part II involved identifying several unlabeled planetary spectra. Graphs of planetary spectra were already plotted (from USGS, 1998) on the worksheet

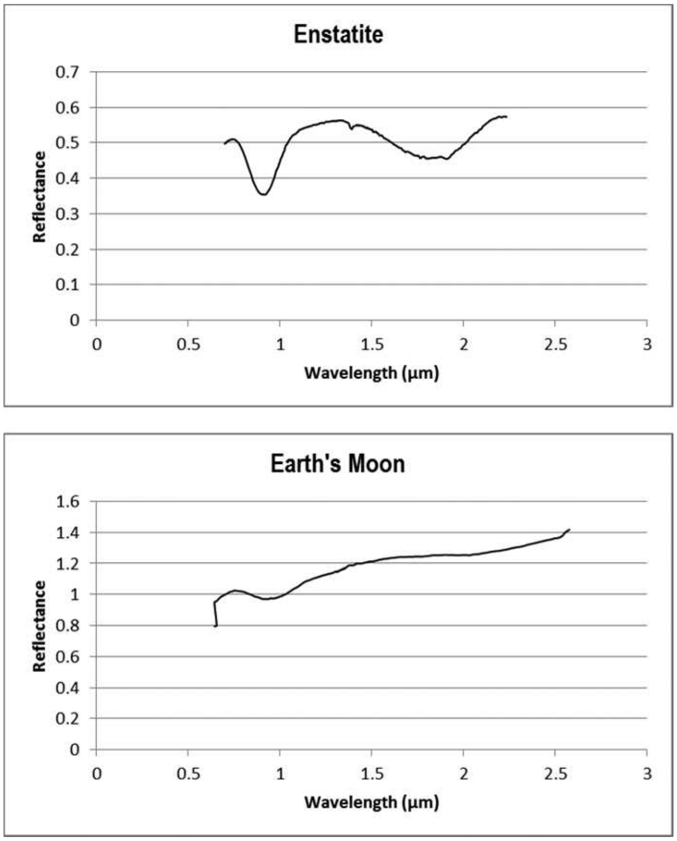

FIGURE 2: The moon's reflectance spectrum (bottom) exhibiting similar absorption bands to the pyroxene end-member enstatite (top) at approximately 0.90 and 1.90 (presence of olivine on the moon causes absorption bands to shift right according to Goettsch et al., 1998). Data for enstatite spectrum from Clark et al., 2007; data for spectrum of Earth's moon from USGS, 1998.

and students needed to select which graph matched the appropriate planetary object: Callisto (one of Jupiter's moons), Jupiter, and Mercury. Again students tried to identify mineral signatures within the planetary reflectance graphs. Students were asked to justify their reasoning (see Fig. 3). Some students struggled with this part. To assist them, the instructor would refer their attention back to previous parts of the activity and the reflectance graphs described therein, specifically asking students if the graphs of the unknown planetary bodies resembled others they had examined. This typically enabled students to correctly identify the terrestrial planet and the ice-covered world; through a process of elimination, they could then identify the third (Jovian planet). The instructor also asked these struggling students why there might be so many absorption bands in the spectrum for the Jovian planet, in an attempt to lead them to consider the extensive atmospheres of these types of worlds. The intended outcome of this part was for students to begin to see distinct differences among the reflectance spectra of rocky terrestrial bodies (e.g., Mercury), ice-covered terrestrial bodies (e.g., Jupiter's moon Callisto), and Jovian planets (e.g., Jupiter).

Interpreting the Data

Figure 1 illustrates a crude similarity between the USGS data for the mineral serpentine and the data collected from the ALTA II spectrometer. The USGS serpentine graph has been exaggerated in the vertical direction (y-axis) to more clearly accentuate the similarity between the two curves. In Fig. 2, a similarity is seen in the basic structure of the moon's reflectance curve to the orthopyroxene end-member enstatite. This should not surprise students, since such a large portion of the moon's surface is composed of pyroxene-rich rocks. Figure 3 illustrates the signature of water ice in the rings of Saturn and also on the surface of Jupiter's moon Europa. The presence of water ice explains the highly reflective nature of Saturn's rings, and helps students understand why Saturn's icy rings are visible from Earth-based telescopes whereas Jupiter's more "rocky" rings are not.

Atmospheric composition may be examined too. Although not discussed in detail here, the atmospheric composition of a terrestrial planet may also be considered by examining reflectance spectra. For example, the reflectance spectrum of Mars shows a strong absorption band corresponding to carbon dioxide (USGS, 1998). Because Mars has a more substantial atmosphere than some planetary bodies, such as Earth's moon or Mercury, additional absorption bands occur in the reflectance spectrum as reflected light from the planet's surface passes through the atmosphere on its way out. Exoplanets may be studied in planetary science courses as well, and a beneficial time might be after completing this activity, when students understand that atmospheric gases absorb certain wavelengths of light.

Assessment of Learning

The activity had only been completely administered once at the time of initial writing. During the revision process, parts of the activity were administered again, in order to refine the explanations used in the activity descriptions. No formal data were collected about the effectiveness of the activity on learning, but three multiple choice exam questions were directly or indirectly related to the reflectance lab investigations. The first asked about the wavelength(s) of light the ALTA spectrometers use to collect data (i.e., visible and infrared). Seventy percent of the test-takers answered correctly. The second question asked about the composition of the rings of Saturn (i.e., water ice), and 86% of test-takers answered correctly; however, this information had been covered in lecture notes as well as in the reflectance lab activity. The third question asked students how diagnostic absorption features in the spectra of asteroids can be used and for what purpose (i.e., identifies asteroid type, identifies minerals). Sixty-four percent of test-takers answered correctly.

The instructor made a number of informal observations while the students completed the activity. The students appeared engaged and on task throughout. Student remarks related to the activity being: (1) fun, (2) interesting, and (3) educational. In the instructor's view, students appeared motivated to learn by using the spectrometers and appeared to enjoy the hands-on nature of the activity. Many of the other lab-like activities in the class involved looking at maps and physical features on planetary bodies, and so were more paper-based. The spectrometer activity was the most hands-

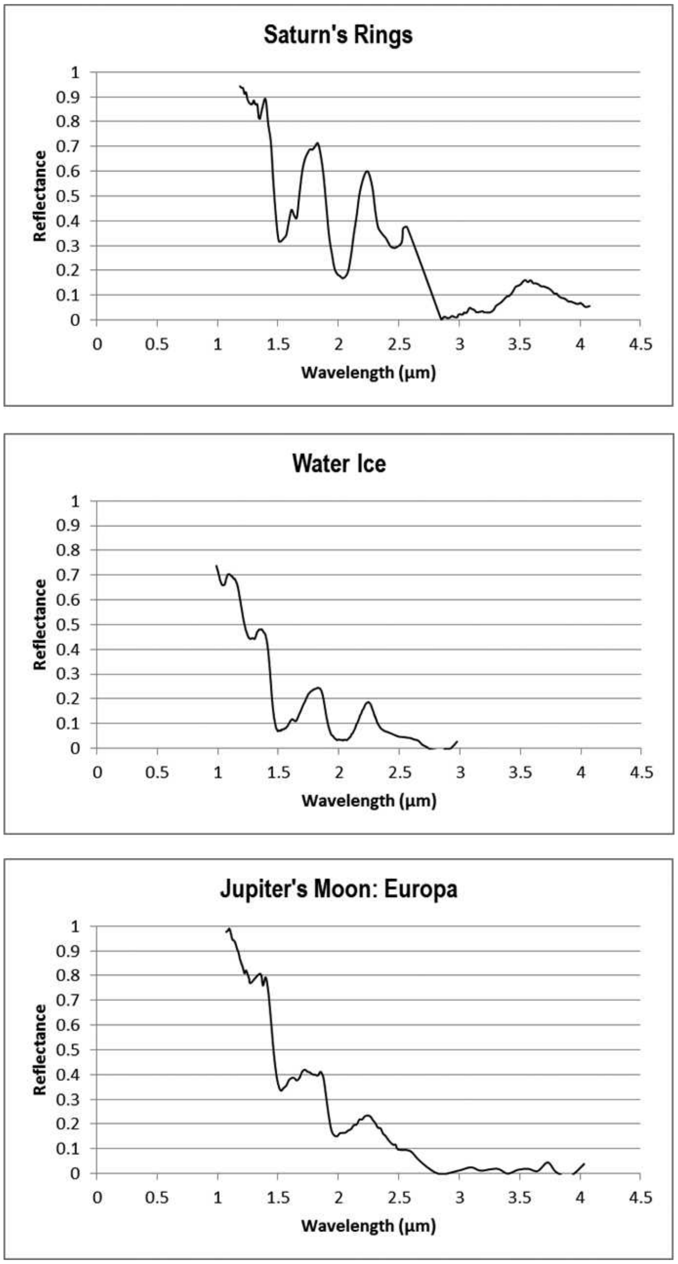

FIGURE 3: The signature (at approximately 1.5 µm, 2 µm, 2.8 µm) of water ice (data from Clark et al., 2007) is clearly evident in both the spectra for Saturn's rings and Europa (data from USGS, 1998).

on and technology-rich activity completed in the course, which likely contributed to both the motivation and enjoyment of the investigation. Several students had taken geology courses before and appeared to find the activity an interesting extension of ideas related to mineralogy. Discussions with students as they completed the activity revealed that some clearly understood the concepts, primarily the science and science education majors and minors. Others struggled, particularly with identifying and explaining the differences in the reflectance graphs when asked to make comparisons between terrestrial, Jovian, and ice-covered planets. Future implementations of the lab investigation will include at least one more reinforcing or extension lab activity on another day to provide students additional opportunities for applying what they have learned and practicing their emerging graphing and spectral analysis skills. During the next complete implementation, formal data will be collected to assess the degree of learning occurring about the concepts of spectroscopy.

Teaching Notes

Prior to completing this activity, students should be introduced to the ALTA II spectrometers. The author used Treiman's (2000) Lesson 3 from the activity book that accompanied the ALTA II spectrometer to familiarize students with the tool and principles of reflectance. Mineral sample sizes of greater than 2.5 cm x 2.5 cm are needed to cover the sensor on the ALTA-II spectrometers. It is possible to fasten pads around the sensor edges to more easily allow irregularly shaped hand samples to fit up close to the sensor and block out unwanted ambient light.

The USGS Spectral Library provides more than one reflectance spectrum for many of the minerals. In order to ensure student success, the author used a spectrometer to test available mineral hand samples prior to implementing the activity to identify specimens closely matching the USGS reflectance graphs. While not critical for advanced students, finding mineral samples that suitably match USGS graphs is important to avoid frustrating novice learners as they work through this type of activity. An examination of any discrepancies between the ALTA spectrometer graphs and the USGS reflectance graphs could be useful for advanced students.

Instructors should be mindful of the potential for this activity to mislead students into thinking there is only one likely mineral accounting for a reflectance spectrum. For novices, the emphasis in this activity should be on the process and students should be informed of the complexity of this in scientific practice. The activity could be modified to show a range of possible answers leading students to the understanding that additional information is needed to decide among possibilities. In advanced classes, emphasizing how certain mineral assemblages may affect the location of peak absorption wavelengths would be appropriate.

Students were organized into small groups of three or four for this activity. In Part I, the instructor provided handouts of USGS mineral reflectance graphs to the students. However, the activity could be modified for advanced users by referring them directly to the USGS Spectral Library. This would not only enhance their familiarity with the spectral library, but would also facilitate additional skill in using spreadsheet software. Part II of the activity required students to identify patterns in the reflectance spectra of planetary bodies and to match those patterns to specific minerals. Instructors may wish to narrow the number of mineral options students may select from in order to promote success in the activity. The choices of mineral possibilities could be expanded for advanced classes. The reasoning behind students' interpretations should be clearly articulated and errors should be addressed either as an instructor is walking around interacting with students during completion of the activity or in the form of written feedback on returned activity sheets. This activity could be completed in one to two hours of laboratory time. Preparation for this activity was time-consuming for the instructor, but the activity itself was well-received by students and it is the author's opinion that the activity helped students better understand the critical role of light in studying planetary objects. The activity was embedded within the curriculum about four weeks into the course during a unit on asteroids. Since asteroids are classified by their reflectance spectra, it seemed an excellent place to bring in the activity.

The data used in the activity were imported in ASCII form into Microsoft Excel. This process can be a bit cumbersome for novice users, but with a little practice, is fairly straightforward. Students may need guidance using spreadsheet software. For a thorough discussion of spectroscopy in remote sensing see Clark (1999). For reflectance data from planetary surfaces see USGS (1998).

SUMMARY AND USES

This activity combines mineral hand specimen examination, mineral reflectance, use of reflectance spectra for identifying minerals, and the determination of mineral characteristics of planetary objects. Without needing to understand a great deal about the complexities of spectroscopy, or the nuances related to mineral identification, students gain an appreciation for the role of light in planetary science. Students use tools, access and manipulate authentic data, and refer to online resources. Although student conclusions are not based on a comprehensive review of all available data, the activity showcases the union of scientific processes, technology, and problem-solving skills to illustrate how scientists rely on light to learn about planetary objects. The activity was created for a planetary science course, but could easily be modified for courses in geology, mineralogy, and astronomy.

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