

NOTE

Response to Comment on “Comparison of Laboratory Emission Spectra with Mercury Telescopic Data” by Melissa Lane

A. L. Sprague

*Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721*E-mail: sprague@lpl.arizona.edu

T. L. Roush

NASA Ames Research Center, Planetary System Branch, MS 245-3, Moffett Field, California 94035-1000

R. T. Downs

Department of Geology, University of Arizona, Tucson, Arizona 85721

and

K. Righter

Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721

Received April 9, 1999; revised September 20, 1999

The laboratory spectrum published in Fig. 3 of A. L. Sprague and T. L. Roush (1998, *Icarus* 133, 174–183) is a mixture of magnetite and hematite (~34–45% magnetite, ~55–66% hematite) rather than magnetite or hematite (M. D. Lane 2000, *Icarus* 143, 000–000) alone. Because of the unusual nature of this sample (it is uniformly magnetic) we present results of X-ray diffraction, petrographic microscopy, and additional microprobe analyses. We compare this spectrum with laboratory spectra of hematite and magnetite. We can draw no conclusions regarding the presence or absence of magnetite on Mercury based solely on data in the spectral region 7.5–12 μm . © 2000 Academic Press

In the Comment by Lane (2000) it is claimed that the laboratory spectrum published in Fig. 3 of Sprague and Roush (1998) (hereafter SR98) was actually hematite, not magnetite and that our conclusions regarding magnetite on Mercury were scientifically unsound. In order to address these questions we have: (1) more accurately characterized the sample; (2) compared the spectrum of SR98 to laboratory spectra of magnetite and hematite; and (3) addressed the implications regarding our interpretation of the Mercury data.

The sample, uniformly magnetic and black, was prepared from a Ward's sample labeled magnetite. The initial microprobe analysis (2nd column, Table I, SR98) was consistent with the stated magnetite composition. Because Lane (2000) correctly pointed out the spectral signature of hematite between 13 and 25 μm , we have reexamined our sample in three ways to more accurately determine its chemical and structural makeup and found it to be a mixture of magnetite and hematite.

X-ray diffraction analysis. A powder diffraction profile ($5^\circ < 2\theta < 70^\circ$) was collected on a Siemens D500 diffractometer at $1^\circ/\text{min}$ with Cu radiation. Three

phases were detected, hematite Fe_2O_3 , magnetite Fe_3O_4 , and minor chlorite. The chlorite species could not be determined because of the low intensities and overlap with the diffraction peaks of the other phases. However, the sample is reported to have originated in chlorite schist (Schwarz 1936), so the minor chlorite observed in the pattern probably represents a residue from the matrix. Relative volume concentrations of magnetite and hematite (1 : 1.9, respectively) were refined using a modified version of the software XPOWLOT (Downs *et al.* 1993), with standard fitting techniques as described in Mazin *et al.* (1998). The third phase identified as some type of chlorite contributes less than 1% by volume of the sample. Because of the highly magnetic nature of the sample it is important to report that the XRD analysis showed no peaks unique to maghemite.

Petrographic analysis. Approximately 100 mg of the sample grains were mounted in epoxy and polished for analysis by reflected light microscopy. Because magnetite appears darker brown against hematite in reflected light, it is straightforward to identify these minerals using this technique. Based on counting nearly 500 grains, 45 vol.% of the sample is magnetite, and 55 vol.% hematite (1.0 : 1.2, respectively), with a small amount ($\ll 1$ vol.%) of another phase (identified by XRD as chlorite).

Microprobe analysis. Standards used for this microprobe analysis included fayalite (for Fe), potassium feldspar (for Al), rutile (for Ti), chromite (for Mg and Cr), and rhodonite (for Mn). Operating conditions were a 15-kV accelerating voltage, 20-nA sample current, and 10-s counting times on K_α lines for all elements. Although many of the grains analyzed were the same composition reported in Table I of SR98, there are also compositionally distinct hematites (see current Table I). Note the small amount of TiO_2 and Al_2O_3 present in the hematite, but not in the magnetite. The analytical totals of both phases are lower than 100%, because electron microprobe analysis cannot distinguish between different valence states of iron— FeO and Fe_2O_3 —only the total amount of Fe present. As a result these two must be calculated based on charge balance and stoichiometry (after the procedure outlined by Carmichael 1967).

When such calculations are done, the recalculated totals are more reasonable (Table I).

Comparison to laboratory data. We obtained reflectance data from the literature (Salisbury *et al.* 1991, hereafter SEA, $2.1 < \lambda < 25 \mu\text{m}$, $< 74 \mu\text{m}$ grain size) and emissivity data from Christoph Wagner at the Planetary Science Institute in Berlin, Germany ($5 < \lambda < 17 \mu\text{m}$, $< 45 \mu\text{m}$ grain size). The spectrum from SR98 (solid line) is compared to the measured emissivities in Fig. 1A. It is clear the hematite spectrum (dotted line) provides a clear match in the region $14\text{--}17 \mu\text{m}$ but a poor match in the region $7\text{--}10 \mu\text{m}$. The magnetite spectrum (dashed line) provides a better match in the region $7\text{--}10 \mu\text{m}$, although its measured emissivity is somewhat too high compared to the SR98 sample. No single linear mixture of these individual mineral spectra can provide an adequate fit to the SR98 sample spectrum over the entire wavelength region $7\text{--}17 \mu\text{m}$. This may arise from the slight difference in grain sizes between the samples of Wagner and SR98. In Fig. 1B the spectrum from SR98 (solid line) is compared to calculated emissivity (via Kirchoff's Law) of the SEA data (note the change in scale for emissivity). The SEA hematite spectrum (dotted line) exhibits minima near 18 and $22 \mu\text{m}$, but these are significantly weaker and broader than similar bands in the SR98 spectrum, and a relatively poor match in the region $7\text{--}10 \mu\text{m}$. The SEA magnetite spectrum (dashed line) exhibits a single minimum near $18 \mu\text{m}$, which likely contributes to the overall depth seen in the SR98 spectrum, and is relatively featureless in the region $7\text{--}10 \mu\text{m}$. Although the particle size of the SEA samples is more comparable to the SR98 sample, once again no single linear combination of these individual mineral spectra can provide an adequate fit to the SR98 sample spectrum over the entire wavelength region $7\text{--}25 \mu\text{m}$.

Conclusions. 1. The spectrum labeled magnetite in Fig. 3 of SR98 should be labeled as a mixture of magnetite, hematite, and $\sim 1\%$ unidentified chlorite. This is despite the fact that the sample (with the exception of the $\sim 1\%$ unidentified chlorite) is strongly magnetic and there was no peak in the X-ray diffraction for maghemite.

2. The two minima centered at 18 and $22 \mu\text{m}$ are signatures of hematite, although magnetite may contribute to the minimum near $18 \mu\text{m}$.

3. For the particle size of the SR98 sample, the high spectral emissivity between 7 and $10 \mu\text{m}$ seen in Fig. 3 of SR98 is more characteristic of magnetite than hematite.

4. Linear mixing with "endmember components" using available laboratory data cannot simultaneously fit the SR98 spectrum over the entire spectral range.

TABLE I

Electron Microprobe Analyses of Magnetite and Hematite

	Magnetite	Hematite
Number of points sampled	20	20
SiO ₂	0.02	0.01
TiO ₂	0.01	1.01
Al ₂ O ₃	0.03	0.40
Cr ₂ O ₃	0.01	0.01
FeO ^a	92.77	88.40
MnO	0.02	0.01
MgO	n.d.	n.d.
Total	92.88	89.86
Fe ₂ O ₃	68.66	97.23
FeO	30.98	0.91
Recalculated totals	99.73	99.58

Note. n.d. = analyzed but not detected above background levels.

^a Fe₂O₃ and FeO calculated by charge balance and stoichiometry according to Carmichael (1967).

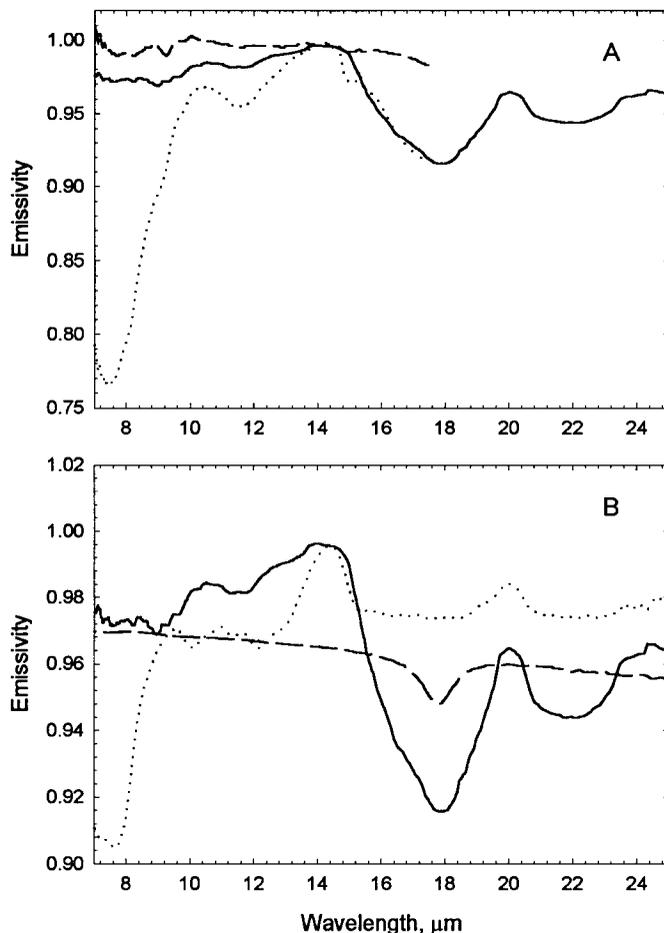


FIG. 1. (A) Spectral emissivity of magnetite (dashed line) and hematite (dotted line) and the laboratory emission spectrum from SR98 (solid line) are plotted. Magnetite and hematite spectra are from Wagner and of $< 45 \mu\text{m}$ grain size. (B) Emissivity, calculated via Kirchoff's Law, of magnetite (dashed line) and hematite (dotted line) and the laboratory emission spectrum from SR98 (solid line) are plotted. Magnetite and hematite spectra are from Salisbury *et al.* (1991) and of $< 74 \mu\text{m}$ grain size.

This result is inconsistent with the known composition and serves as a caution when attempting to identify surface materials through "endmember component" modeling.

5. Mercury's spectrum shows spectral activity between $7\text{--}10 \mu\text{m}$ that cannot be attributed to magnetite. However, because magnetite is relatively featureless in this region, we cannot rule it out as a potential component.

6. The spectral region $15\text{--}25 \mu\text{m}$ provides an excellent means for identifying hematite on Mercury. In the absence of hematite, it is also a good spectral region for identifying magnetite.

REFERENCES

- Carmichael, I. S. E. 1967. The iron-titanium oxides of salic volcanic rocks and their associated ferromagnesian silicates. *Contrib. Miner. Petrol.* **14**, 36–64.
- Downs, R. T., K. L. Bartelmehs, G. V. Gibbs, and M. B. Boisen, Jr. 1993. Interactive software for calculating and displaying X-ray or neutron

- powder diffractometer patterns of crystalline materials. *Am. Mineral.* **78**, 1104–1107.
- Lane, M. D. 2000. Comment on “Comparison of laboratory emission spectra with Mercury telescopic data” by A. L. Sprague and T. L. Roush. *Icarus* **143**, 407–408.
- Mazin, I., Y. Fei, R. T. Downs, and R. Cohen 1998. Possible polytypism in FeO at high pressure. *Am. Mineral.* **83**, 451–457.
- Salisbury, J. W., L. S. Walter, N. Vergo, and D. M. D’Aria 1991. *Infrared (2.1–25 μm) Spectra of Minerals*. Johns Hopkins Univ. Press, Baltimore.
- Schwarz, G. M. 1936. Magnetite metacrysts. *Am. Mineral.* **21**, 635–641.
- Sprague, A. L., and T. L. Roush 1998. Comparison of laboratory emission spectra with Mercury telescopic data. *Icarus* **133**, 174–183.