

Reflectance Spectral Characteristics of Lunar Surface Materials *

Yong-Liao Zou¹, Jian-Zhong Liu¹, Jian-Jun Liu¹ and Tao Xu²

¹ National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012;
ylzou@bao.ac.cn

² Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550002

Received 2003 July 8; accepted 2003 October 10

Abstract Based on a comprehensive analysis of the mineral composition of major lunar rocks (highland anorthosite, lunar mare basalt and KREEP rock), we investigate the reflectance spectral characteristics of the lunar rock-forming minerals, including feldspar, pyroxene and olivine. The affecting factors, the variation of the intensity of solar radiation with wavelength and the reflectance spectra of the lunar rocks are studied. We also calculate the reflectivity of lunar mare basalt and highland anorthosite at 300 nm, 415 nm, 750 nm, 900 nm, 950 nm and 1000 nm. It is considered that the difference in composition between lunar mare basalt and highland anorthosite is so large that separate analyses are needed in the study of the reflectivity of lunar surface materials in the two regions covered by mare basalt and highland anorthosite, and especially in the region with high Th contents, which may be the KREEP-distributed region.

Key words: Moon — mineral — lunar rock

1 INTRODUCTION

Solar radiation is by far the principal radiation source for the Moon, which includes electromagnetic waves, particle streams (solar wind and high-energy particle streams) and neutrinos, as well as gravity waves, sound waves and magnetic currents. The intensity of the energy flux of electromagnetic waves is far greater than that of any other forms, which can therefore be neglected, and solar radiation is usually regarded simply as solar electromagnetic wave radiation. The wavelengths of detectable solar electromagnetic wave radiation range from γ -rays, X-rays, ultraviolet rays, visible rays, infrared rays to the meter-band of electromagnetic wave. The intensities of the solar radiation at 300–1000 nm are highly variable (Piter & Englertm 1993; Zombeck 1990). As lunar surface materials are highly variable in composition (Heiken et al. 1991), their reflectance spectral characteristics caused by solar radiation are quite different.

* Supported by the National Natural Science Foundation of China (No. 40373037).

Thus, special attention should be paid to this wave range in the study of the reflectance spectral characteristics of lunar surface materials.

The reflectance spectral characteristics of lunar surface materials are of particular importance not only in understanding the environmental features of the lunar surface, but also in the processing, analysis and interpretation of the original spectrum data. Therefore, the reflectance spectra of lunar surface materials are the very important bases for the determination of the performance indices of scientific instruments and for the selection of the wave bands for high-sensitivity and spectral imaging instruments on lunar prospectors. (Piter & Englertm 1993; Cloutis & Gaffey 1991). Based on the lunar surveying data and previous analytical results, this paper analyzes in depth the mineralogical and reflectance spectral characteristics of two major types of lunar rocks—highland anorthosite and lunar mare basalt, calculates and comments on the reflectivity of the two types of lunar rocks in exposed regions.

2 MINERALOGICAL CHARACTERISTICS OF THE LUNAR ROCKS

Lunar surface materials are generally composed of two major types of materials, i.e., lunar highland materials and lunar mare materials (Ouyang 1989).

Lunar highland materials are composed essentially of anorthosite. The highland anorthosite is composed mainly of anorthosite, Mg-rich rocks and KREEP rocks. The anorthosite is composed of 95% plagioclase (Ca-rich plagioclase) and minor amounts of low-Ca pyroxene, olivine and clinopyroxene and Mg-rich rocks, which generally consist of norite, troctonite, dunite, spinel troctonite and gabbro anorthosite (Feldman et al. 1998).

KREEP rocks are extremely widespread on the lunar surface. The rocks are so named because they are highly enriched in K, P and REE (Heiken et al. 1991). KREEP rock was first detected in the light-colored fine powder prepared from an Apollo-12 lunar soil sample (sample No.112013). As viewed from the angle of its formation and evolution, KREEP was a kind of volatile element-rich rock that had resulted from magmatic differentiation or residual magma crystallization and its source region should be located in the transitional zone between the lunar crust and the lunar mantle (Heiken et al. 1991). There was a long-term controversy on the distribution region and the process of formation of KREEP rocks on the lunar surface. Recent results of analysis of the data returned by the “Lunar Prospector” mission showed that in the vast area on the near side of the Moon (i.e., near Oceanus Procellarum) the contents of Th in most cases are greater than 3.5×10^{-6} g/g, with the maximum value up to 13×10^{-6} g/g (Haskin et al. 2000; Jolliff et al. 2000). As viewed from the results of analysis of REE, Th and U in KREEP in lunar samples (Heiken et al. 1991; Ouyang 1989), there is an excellent correlation between Th and REE. So this region is likely to be a KREEP-exposed region, but since the provenance of KREEP is located in the transitional zone between the crust and mantle, and Oceanus Procellarum is a lunar mare basalt-distributed region, its exposure on, or near, the lunar surface may be attributed to an eruption (or intrusion) of KREEP on the lunar surface caused by a huge impact. For this reason, the lunar surface materials (lunar regolith) in this region are most likely to be of a mixing type, resulting from the mixing of lunar mare basalt, highland anorthosite and KREEP. At present time, three hypotheses have been proposed concerning the mechanism of the exposure of KREEP rocks on or near the surface (Jolliff et al. 2000; Wiezorek & Phillip 2000): (1) excavation of the lunar crust/mantle KREEP-enriched zone by a huge impact; (2) intrusion and exposure of KREEP-enriched lavas on the lunar surface; and (3) some KREEP rocks brought out by lunar mare basalt volcanism.

The results of analysis of the lunar samples returned from the lunar surface indicated that the major mineral components of KREEP are pyroxene and plagioclase, with no or only a trace amount of olivine. The pyroxenes, ranging from the early low-Ca enstatite to the late low-Ca and low-Mg pigeonite and then to the Ca-high pyroxene (Heiken et al. 1991; Ouyang 1989; Haskin et al. 2000; Wiezorek & Phillip 2000), display a wide range of variations with respect to their composition.

On the lunar surface there are 22 lunar mares, of which 19 are distributed on the near side of the Moon, approximately accounting for almost half the near side of the Moon; the three on the other side are Mare Orientale, Mare Moscoviense and Mare Ingenii. Analytical results of the lunar rock samples collected by the six Apollo missions, as well as by the “Luna” Series missions indicated that lunar mare materials are composed predominantly of basalts, in which TiO_2 accounts for 0.5%–13%. In addition, the basalts can be divided into three types: high-Ti basalt; low-Ti basalt and high-Al, low-Ti basalt (Cloutis & Gaffey 1991).

Table 1 (Ouyang 1989; Institute of Geochemistry, Chinese Academy of Sciences 1979) gives the mineral compositions of the various types of lunar mare basalts. It can be seen from this table that the major minerals contained in the lunar mare basalts are pyroxene, Mg-rich olivine, Ca-rich feldspar and ilmenite.

Table 1 Mineral Compositions of the Various Types of Lunar Mare Basalts (wt. %)

Sample No.	Rock type	Pyroxene	Feldspar	Olivine	Ilmenite
Luna-24	Extremely Low-Ti basalt	60	34	4	2
Apollo-17	Extremely Low-Ti basalt	62	32	5	1
Apollo-12	Olivine Low-Ti basalt	54	19	20	7
Apollo-15	Olivine Low-Ti basalt	63	24	7	6
Apollo-12	Augite Low-Ti basalt	69	21	1	9
Apollo-15	Augite Low-Ti basalt	62	34	–	4
Apollo-12	Ilmenite Low-Ti basalt	61	26	4	9
Apollo-11	High-Ti basalt	51	32	2	15
Apollo-17	High-Ti basalt	52	33	–	15
Apollo-17	Extremely High-Ti basalt	48	23	5	24
Luna-24	High-Al basalt	52	41	–	7
Apollo-14	High-Al basalt	54	43	–	3

3 REFLECTANCE SPECTRAL CHARACTERISTICS OF SOME LUNAR SURFACE MATERIALS

As mentioned above, the most common rock-forming minerals on the Moon are feldspar, pyroxene, olivine, and ilmenite. These minerals are free from water and formed in strong reduced condition, and are relatively poor in alkali metals. The laboratory measured reflectivity characteristics of some rock-forming minerals separated from the returned lunar rock samples are shown in Fig. 1 (Adams 1974).

From Fig. 1, we obtain the following information on the reflectivity of lunar surface materials:

(1) Most lunar materials are distinguished only on the basis of the types and contents of magnesiferous minerals, and these minerals display obvious absorption characteristics at

0.3 – 2.5 μm , with the center lying between 750 nm and 950 nm. However, the near-infrared bands have great importance for the analysis of lunar rock-forming minerals.

(2) The remarkable near-infrared spectral characteristics are attributed to the electron transition of ferrous ions in the specific lattice of the minerals mentioned above (Adams 1974), which is similar to those of the corresponding terrestrial minerals, though the spectroscopic features of lunar minerals are relatively simple as they contain no Fe^{3+} and are free from water.

(3) Ferrous ions in lunar minerals display two overlapping absorption peaks in the ultraviolet, visible and near-infrared wavelength ranges, i.e., there is a strong spin permitted absorption peak in the ultraviolet wavelength range and also a weak spin forbidden absorption peak at about 1 micrometer in the near-infrared bands. According to experimental analysis, starting from a ferrous ion-free silicate (its reflectivity is high and its spectrum is neutral), there will appear an absorption peak near 1 micrometer with increasing Fe^{2+} . In addition, there will be a marginal absorption peak toward the ultraviolet wavelength range. The overlapping of ultraviolet and visible absorption peaks made the whole mineral turn darker (Cloutis & Gaffey 1991; Adams 1974; Singer 1981).

(4) The existence of some elements can change the spectroscopic characteristics of the host materials. For example, in the process of maturation of Ti-containing lunar soil production of glass in response to impact of micrometeorites will inject titanium into the glass. The existence of titanium in the Fe^{2+} -containing glass will lead to intensive charge transfer, i.e., $\text{Fe}^{2+} \rightarrow \text{Ti}^{4+}$, and at the same time it will lead to the variation of the spectrum characteristics at 0.3–0.6 μm absorption wavelength range. In this wavelength range the ultraviolet-visible spectra will become dark and “red”, depending on the concentrations of Fe and Ti (Adams 1974; Singer 1981).

(5) Submicroscopic metallic Fe particulates can also exert a great influence on the spectroscopic characteristics of lunar materials, which were produced due to “space weathering”, i.e., vacuum reduction of Fe^{2+} in the lunar minerals caused by micrometeorite impact, in the process of maturation of lunar soil. The presence of these tiny (about several hundred Å) particulates will darken the lunar soil and weaken the spectral contrast of the spectra and introduce an intense, positive spectrum slope throughout the ultraviolet, visible and near-infrared wavelength ranges.

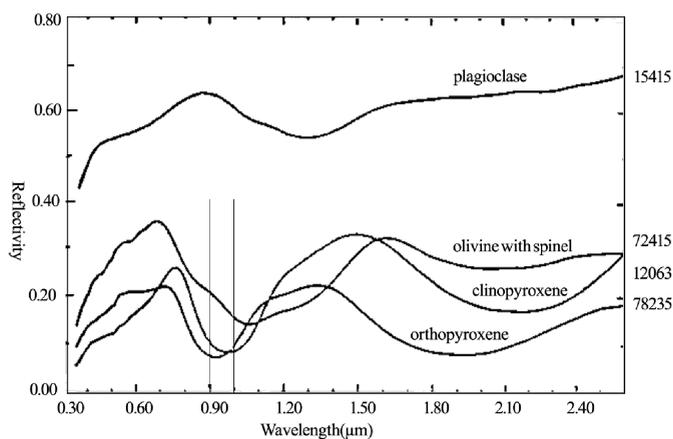


Fig. 1 Reflectivity characteristics of some lunar rock-forming minerals (Adams 1974).

As viewed from the above analyses of the rock-forming minerals and elements, the magnesiferous minerals can be used as the main indices for discriminating spectrally the various types of rocks.

Lunar mare basalt Lunar mare basalt contains abundant high-Ca pyroxene ($> 50\%$), so there should be an obvious absorption band at $0.98 - 1.00 \mu\text{m}$. If the content of olivine is considerably high ($10\% - 20\%$), the absorption band of pyroxene will become wider and the central position will shift slightly toward the long wavelength range (McCord et al. 1981; King and Ridley 1987). As the content of olivine in the lunar mare basalt is highly variable, ranging from 0 to 20% (Table 1), its spectrum also varies considerably.

Highland anorthosite Different types of lunar highland rocks have different proportions of feldspar minerals (mainly anorthite) and different kinds of magnesiferous minerals. If highland anorthosite contains no remarkable amount of magnesiferous minerals, the anorthite displays no main absorption band near the infrared range. As norite contains plagioclase and low-Ca pyroxene, there exists an absorption band characteristic of magnesiferous minerals at $0.9 - 0.93 \mu\text{m}$, whose intensity varies with the abundance of pyroxene. The rocks whose absorption bands appear at $0.93 - 0.95 \mu\text{m}$ are composed mainly of norite, but the content of calcium in the pyroxene is relatively high. This may be explained by the incorporation of minor high-Ca components into the rocks. Gabbro containing feldspar and high-Ca pyroxene is with an absorption band center at $0.97 - 1.0 \mu\text{m}$. Dunite is almost completely composed of olivine; troctonite is made up of feldspar and olivine. Both the rocks display wide multi-absorption bands near $1.1 \mu\text{m}$.

KREEP rocks The main mineralogical compositions of KREEP are identical to those of highland anorthosite (only some difference in content), therefore, its reflectance spectral characteristics should be close to those of anorthosite. However, in regions where KREEP is present, for instance in Oceanus Procellarum, lunar mare basalt, highland anorthosite and KREEP are mixed together. Then, the reflectance spectral characteristics are those of mixtures.

4 REFLECTIVITY OF THE MOON

The reflectivity of the lunar surface can be theoretically calculated according to the main reflectance spectral characteristics of the major lunar rock-forming minerals as mentioned above, and the mineral compositions of highland anorthosite and lunar mare basalt. Because the intensity of solar radiation is relatively weak at $> 1000 \text{ nm}$ and there are little data available at present on the reflectivity of lunar rocks, Table 2 only presents the reflectivity data of lunar rock samples at some key wave bands, between 300 nm and 1000 nm . In the table the calculation results of lunar mare basalts and highland anorthosites are based on both the results of Adams (1974) and on the mineral components with their reflectance spectral characteristics of lunar mare basalt and highland anorthosite (Ouyang 1989; Institute of Geochemistry, Chinese Academy of Sciences 1979). The average reflectivity of lunar mare basalt and highland anorthosite was acquired by weighting the reflectivity data at the main spectrum bands while the reflectivity of the whole Moon was calculated from the surface distribution of different lunar surface materials (about 25% mare, 75% highland, as Fig. 2 shows), weighted by the reflectivity of the materials (Institute of Geochemistry, Chinese Academy of Sciences 1979; Adams 1974).

As can be seen from Table 2, the calculated result differs greatly from the actual reflectivity of the lunar surface (the average reflectivity of the lunar surface at 300 nm is 0.09) (Preter 1999). The main reason is that the present calculation model was completely based on the

data from lunar mare basalt and highland anorthosite. However, the lunar surface is covered by a layer of lunar regolith which is somewhat different in composition from the underlying lunar rocks. Studies have demonstrated that approximately 5% of the rock detritus come from ejecta 100 km away, only 0.5% from ejecta 1000 km away, while more than 50% are from within 3 km (Ouyang 1989). Moreover, when glasses were produced as a result of micrometeorite impact in the process of maturation of the lunar soil, titanium would be incorporated into them. The existence of titanium in the Fe^{2+} -bearing glasses would lead to strong $\text{Fe}^{2+} \rightarrow \text{Ti}^{4+}$ charge transition and their spectrum characteristics of the corresponding absorption bands at 0.3–0.6 mm would also vary to some extent. In addition, when the solar wind particles found their way directly into the lunar soil, the latter's composition would be changed to some extent. All these factors can influence the reflectivity of the lunar surface. So, taking 0.09 as the basic reference of the average reflectivity of the moon at 300 nm, a correction factor should be considered, i.e., 0.09 divided by 0.129 (the model calculation result at 300 nm) equals 0.698. Thus, our model calculation data listed in Table 2 multiplied by this correction coefficient, will give the reflectivities, respectively, of the mare basalt regions, the highland anorthosite regions, and the whole moon, as shown in Table 3.

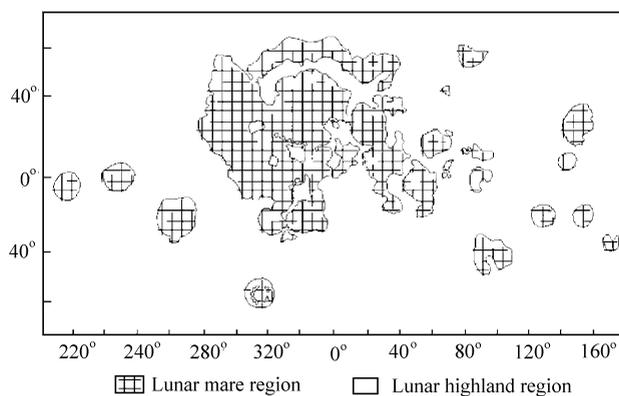


Fig. 2 Distribution of Mares and highlands on the lunar surface (Institute of Geochemistry, Chinese Academy of Sciences 1979).

Table 2 Reflectivity of Lunar Mare Basalt, Anorthosite and the Whole Moon at Some Key Wave Bands

Reflectivity wavelength	Lunar mare basalt		Lunar anorthosite		Whole Moon (average)	
	Variation range	Average	Variation range	Average	Variation range	Average
300	0.038 ~ 0.082	0.059	0.067 ~ 0.288	0.153	0.038 ~ 0.288	0.129
415	0.045 ~ 0.113	0.070	0.121 ~ 0.412	0.215	0.045 ~ 0.412	0.162
500	0.055 ~ 0.135	0.083	0.130 ~ 0.425	0.235	0.055 ~ 0.425	0.196
600	0.060 ~ 0.167	0.091	0.172 ~ 0.457	0.285	0.060 ~ 0.457	0.235
700	0.060 ~ 0.198	0.110	0.210 ~ 0.495	0.295	0.060 ~ 0.495	0.244
750	0.060 ~ 0.200	0.110	0.215 ~ 0.525	0.325	0.060 ~ 0.525	0.271
800	0.083 ~ 0.225	0.110	0.210 ~ 0.500	0.315	0.083 ~ 0.500	0.259
900	0.085 ~ 0.215	0.120	0.105 ~ 0.435	0.290	0.085 ~ 0.435	0.247
950	0.090 ~ 0.220	0.120	0.100 ~ 0.430	0.285	0.900 ~ 0.430	0.243
1000	0.095 ~ 0.225	0.113	0.100 ~ 0.425	0.280	0.950 ~ 0.425	0.237

Table 3 Reflectivity of the Lunar Surface Materials at Some Key Wave Bands

Reflectivity wavelength	Mare basalt regions		Highland anorthosite regions		Whole Moon	
	Variation range	Average	Variation range	Average	Variation range	Average
300	0.027 ~ 0.057	0.041	0.048 ~ 0.201	0.107	0.027 ~ 0.201	0.090
415	0.031 ~ 0.079	0.049	0.084 ~ 0.288	0.150	0.031 ~ 0.288	0.113
500	0.038 ~ 0.094	0.057	0.090 ~ 0.297	0.164	0.038 ~ 0.297	0.137
600	0.042 ~ 0.117	0.064	0.120 ~ 0.319	0.199	0.042 ~ 0.319	0.164
700	0.042 ~ 0.138	0.077	0.147 ~ 0.346	0.206	0.042 ~ 0.346	0.170
750	0.042 ~ 0.140	0.077	0.150 ~ 0.366	0.227	0.042 ~ 0.366	0.189
800	0.057 ~ 0.157	0.077	0.147 ~ 0.349	0.220	0.057 ~ 0.349	0.181
900	0.059 ~ 0.151	0.084	0.073 ~ 0.304	0.202	0.059 ~ 0.304	0.172
950	0.062 ~ 0.153	0.084	0.070 ~ 0.300	0.199	0.062 ~ 0.300	0.170
1000	0.066 ~ 0.157	0.079	0.070 ~ 0.297	0.195	0.066 ~ 0.297	0.165

As can be seen from Tables 2 and 3, lunar mare basalt and highland anorthosite are significantly different in composition, and hence there is also a significant difference in their reflectivity. Because the lunar surface is mainly covered by lunar mare basalts and highland anorthosites as shown in Fig. 2, the mare and highland regions should be taken into consideration separately when studying the lunar surface reflectivity. This is especially important when designing and developing sensitive instruments in the lunar prospector, such as the ultraviolet sensing instrument, also when analysing and interpreting the surveying data.

5 CONCLUSIONS

The following four points have been obtained on the reflectance spectral characteristics of lunar materials:

(1) The most common lunar rock-forming minerals are feldspar, pyroxene, olivine and ilmenite. These minerals contain no water and are of strong reduction. Their spectrum characteristics are simple compared to those of terrestrial minerals. Absorption spectra of these major lunar rock-forming minerals appear at some key wave bands and special attention should be paid to the spectra at 300, 415, 750, 900, 950 and 1000 nm.

(2) Lunar mare basalt and highland anorthosite are significantly different in composition. The reflectivity of regions with different surface materials should be carefully examined (Zou et al. 2002). Because the lunar surface is made up mainly of the two types of lunar rocks—mare basalt and highland anorthosite, lunar surface materials (lunar soil) can, to some extent, reflect the characteristics of these two types of lunar rocks. Although it is very simple as compared with terrestrial rocks, some special factors should be taken of account, for instance the variation of spectrum characteristics of lunar surface materials caused by micrometeorite impact and the incorporation of solar wind particles.

(3) When analysing lunar surface reflectivity and when designing and developing the payload of lunar prospectors, (the spectrum imaging and high-sensitivity instruments, the selection of wave bands), we should seriously consider and comprehensively analyze the spectrum characteristics of lunar surface materials at 300–1000 nm, while taking into account the variation of solar radiation intensity.

(4) Although KREEP rock has been regarded as highland anorthosite in the long past because its source region is located in the transition zone between the lunar crust and the lunar

mantle, the real surveying data have shown that KREEP is widespread on the lunar surface and is significantly different in composition from the highland anorthosite. At present time the spectral data of KREEP are less available and, therefore, further detailed studies are needed on the mechanism of on- and near- the-surface exposure and the spectrum characteristics of KREEP rocks.

References

- Adams J., 1974, *Journal of Geophysical Research*, 79, 4829
- Cloutis E. A., Gaffey M. J., 1991, *Journal of Geophysical Research*, 96, 22809
- Feldman W., Barraclough B., Maurice S. et al., 1998, *Science*, 281, 1489
- Haskin L. A., Gillis J. L., Korotev R. L. et al., 2000, *Journal of Geophysical Research*, 105, No. E8, 20403
- Heiken G., Vaniman D., French B. M., 1991, *Lunar Source Book –A User's Guide to the Moon*, Cambridge: Cambridge University Press, 121
- Institute of Geochemistry, Chinese Academy of Sciences, 1979, *Advances in Lunar Geology*, Beijing: Science Press, 48 (in Chinese)
- Jolliff B. L., Gillis J., Haskin L. A. et al., 2000, *Journal of Geophysical research*, 105, No. E2, 4197
- King T., Ridley W., 1987, *Journal of Geophysical Research*, 92, 11457
- McCord T. B., Clark R. N., Hawke B. R. et al., 1981, *Journal of Geophysical Research*, 86, 10883
- Ouyang Z. Y., 1989, *Cosmochemistry*, Beijing: Science Press, 93 (in Chinese)
- Preter E., 1999, *The Lunar Base Handbook*, McGraw-Hill Higher Education, 140
- Piters M., Englertm A. J., 1993, *Remote Geochemistry Analysis: Elemental and Mineralogical Composition*, Cambridge: Cambridge University Press, 309
- Singer R., 1981, *Journal of Geophysical Research*, 86, 7967
- Wiezorek M. A., Phillip R. J., 2000, *Journal of Geophysical Research*, 105, No.E8, 20417
- Zombeck M. V., 1990, *Handbook of Astronomy and Astrophysics, Second Edition* Cambridge, Cambridge: Cambridge University Press, 67
- Zou Y. L., Ouyang Z. Y., Xu L. et al., 2002, *Quaternary Research*, 22, 533 (in Chinese)