

SECTION 8: REMOTE SENSING OF PLANETARY SURFACES

8.1 Spectral Properties of Rocks and Reflectance Spectroscopy

How is it possible to determine the composition of rocks or the abundance of particular elements when you have access to them only through telescopes or orbiting spacecraft? Studying a body photographically can give you great insights into its history. However, it is not possible to derive accurate compositional or abundance values from photographs alone. Obtaining samples from sites of interest is obviously an excellent way to go about things, and from studies of those rocks you will know the abundance of all measurable elements in that rock and perhaps the prevailing conditions at the time of formation. However, there are obvious limitations at the current time with using samples to infer things about the whole body - we have them from only a handful of objects and surely cannot be representative of the entire Solar System. In addition, a rock with anomalously high or low abundances could lead you to believe that the whole area is of a similar composition and hence lead you to false conclusions about its origin and evolution. Unless we have sampling stations on every solid body, and on every single unit on those bodies, rock samples will never be able to give us the complete picture we require.

The spectral character of radiation reflected from a body is largely controlled by the composition of the surface. The reflected solar radiation in the visible and near-infrared exhibit absorption lines specific to the surface mineralogy. Lunar reflectance spectra have been measured from Earth-based telescopes for many years and whilst the resolution of these measurements was quite low, they gave us a clear indication that the surface composition of the Moon was not homogeneous. More recent observations have sufficient spectral resolution to identify specific minerals, thanks to our understanding of their spectral properties.

8.1.1 Reflectance spectroscopy of the Moon

The wavelength regions in the ultraviolet (UV, 0.2-0.4 μ m), visible (V, 0.4-0.7 μ m) and the near-infrared (NIR, 0.7-5.0 μ m) are the best places to look for features relating to specific mineral compounds. Lunar rocks tend to be less complicated spectroscopically than terrestrial ones, since they lack volatiles and have no features due to Fe³⁺, which would complicate things. Figure 8.1 shows the reflectance spectra of minerals found in lunar rocks and soils.

FIGURE 8.1 (Fig 14.1 Pieters)

Note that many have absorptions in the 1 μ m region. These are due to the presence of Fe²⁺. The pyroxenes exhibit two absorption features, one at ~1 μ m, the other at ~2 μ m. The deepest trough (band centre) of each of these varies with the composition of the pyroxene. Remember, pyroxene can have various forms and we find that the band centres move to longer wavelengths as Ca and Fe replace Mg in the mineral structure. Low-Ca pyroxenes will have a band centre between 0.9 and 0.94 μ m and high-Ca pyroxenes will have its centre at 0.98 μ m or longer. Crystalline plagioclase feldspar has a weak feature at ~1.25 μ m, but only if its FeO content is >0.1%. Below this the feature is not seen. In addition, shock pressures may disrupt the field around the Fe which can also wipe out the feature even if the FeO content is above 0.1%. Olivines show a triple absorption at >1.05 μ m which once again varies as the Fe replaces the Mg in the mineral. Olivine itself shows no features beyond ~1.6 μ m - in this sample, the 2 μ m feature is due to spinel. Using these as markers, the various rock types on the Moon can be distinguished using various criteria.

Maria: Since basalt contains lots of high-Ca pyroxene, mare rocks show a strong absorption at ~1 μ m. If there is a significant amount of olivine present (~10-20%), then it will broaden the pyroxene band and move the centre longward.

Highlands: The types that can be distinguished by their spectral properties generally contain various amounts of feldspar and mafic minerals.

1. Anorthosite - since it is almost totally plagioclase feldspar, it will show no absorption features in the UVNIR spectrum. In this case, pyroxene would make up <5% as this is its detectability limit in spectra of this kind.
2. Norite - these are made of plagioclase feldspar and low-Ca pyroxene and will show a band at ~0.9 μ m. A noritic rock may also have a band centre at ~0.95 μ m, but this may imply that it has a slightly higher Ca content, or contain a high-Ca pyroxene as well.
3. Gabbro - these are mainly feldspar and high-Ca pyroxene and so will have a band at ~1 μ m. Because of this, their spectra look very much like that of mare basalts, but as gabbros are usually found in the highland regions will have less pyroxene and hence a weaker absorption band.
4. Dunite - these are almost totally olivine and will therefore have an absorption band at ~1.1 μ m

Soil spectra are darker, show subdued absorption bands and have a more steeply sloped continuum than the parent rocks they were made from. These variations are due to the accumulation of agglutinates in the lunar soil caused by "space weathering", and so represent in some way the maturity of the soil sample. The more pronounced these variations, the longer the soil has been exposed to space, the older it is. The composition of these soils can be recovered by the removal of the continuum, or the background slope.

Whilst these particular trends are seen in spectra of samples, the same trend is also seen in remote observations through telescopes (Figure 8.2).

FIGURE 8.2 (Fig 14.4 Pieters)

Here, “crater” is deemed to represent fresh, unaltered lunar material, since it has just been excavated from beneath the surface. The difference between the two are clear - the unaltered material has stronger absorption bands and a shallow continuum. Note that to aid comparison, the spectra have been normalised, i.e. scaled, to a particular value. This enables differences to be seen more clearly.

So, in summary, reflectance spectroscopy is the measurement of reflected light from a surface. The surface material absorbs at specific wavelengths depending on its composition. By modelling the absorption and its characteristics, we can determine the composition of the rocks from remote spacecraft or telescopes.

8.1.2 Clementine

Launched in Jan 1994, Clementine was the first lunar mission for 20 years. It was funded by the American Department of Defence, and NASA “hitched a ride” and placed scientific instruments on board. Clementine was due to complete a 2 month mapping period of the Moon, then fly off to the asteroid Geographos. Unfortunately, after the lunar part of the mission, an error caused Clementine to fire all of its thrusters, burning its fuel and sending it into an uncontrollable spin. That ended the mission, but the lunar scientists were not concerned, as Clementine had done its job for the Moon.

The main objective of the lunar science to be carried out was undertaking reflectance spectroscopy of the entire lunar surface - this was the first time that a truly global survey of the Moon was carried out. Clementine carried four cameras and a laser altimeter. The cameras were each fitted with filters centred at specific wavelength bands, chosen to maximise the compositional information we could gain from them.

FIGURE 8.3 (Clementine filters)

Figure 8.3 shows each filter superimposed on the laboratory spectra of lunar materials. From this figure alone, it is clear why each filter was chosen - either to gain an idea of the continuum slope, or to characterise the absorption bands of different minerals. The most important filters to Clementine scientists so far are those of the UVVIS camera, which had filters centred at 0.415, 0.750, 0.900, 0.950 and 1.000 μm (labelled A, B, C, D, E). These are the most important because these are the ones that have been calibrated to the greatest

accuracy. The calibrations are not perfect by any means, but the information we get from them is likely to be no more than a percent or two away from the true value. The other filters however, are still being worked on, even after all this time. So, at the current time, the best we work with are the spectra from the UVVIS camera. [show spectrum] The spectra from Clementine look completely different to that in Fig 8.3. Why? Because we don't have the spectral resolution in Clementine data. In Fig 8.3, each dot is the equivalent of a different filter on the Clementine spacecraft. There are dozens. Using ground based instruments, we can afford to have that kind of spectral coverage, but it just wasn't available on this mission. However, the advantage of the Clementine mission was its spatial resolution - 250m/pixel as opposed to the several km spatial resolution of the ground-based observations. This means that we can now look in detail at very small craters, of the order of a few kilometres, instead of the several tens of kilometres we had to look at before. We can still gain lots of useful information from the Clementine spectra. If we look at the spacing of the longest three filters in the UVVIS camera, they are at the expected band centres for the pyroxenes, so an estimate of the composition can be made.

A more pleasing way to display Clementine data is in map form. Scientists have managed to put together maps of FeO and TiO₂ content for the whole Moon - nearside and farside. The data show high concentrations of both elements in the mare regions, consistent with returned samples. Although we knew this for the nearside through telescopic observations, we had no idea whether this extended to all of the mare regions on the farside. Being able to determine the iron content of lunar rocks is important in interpreting what we see both with photographic and Clementine data. Because of this, algorithms have been developed to derive iron and titanium abundances from Clementine pixel values by calibrating them with returned values from samples at all of the Apollo sites and the Luna sites. This method can be used not only on the global data, but on small areas too.

Remember, the redness and blueness of the surface can indicate the titanium content. The same is true for the Clementine data if you display it in the correct way. When you see Clementine data, you will often see it presented in false colour - a multispectral image of red green, blue. Here, the three colours are each represented by a different filter, or rather a ratio of filters. Standard Clementine multispectral images will have the red channel controlled by the 750/415nm ratio, the green by the 750/950nm ratio and the blue by the 415/750nm ratio. Ratios are used because they highlight the property you wish to see. Here, the red and blue channel give an indication of a) titanium content if you are in the mare regions (red = less, blue = more) or b) maturity if you are in a highland region, since there is no titanium there (red = more mature, blue = less mature). The green channel gives you an indication of the mafic content of the material - the greener (or yellower) it is, the more mafic the material. For the green channel to be dominant, there will be a

significant amount of mafic minerals present, and will usually be associated with fresh mare regions.

8.1.3 Other investigative techniques

Although reflectance spectroscopy is a powerful tool in the remote sensing of the Moon, it is not the only one that can give us information on abundances and minerals in rocks. The Apollo 15 and 16 missions were the first to use non-photographic remote sensing techniques on a significant portion of the Moon. Even so, they only covered a maximum of 14% of the Moon, and the situation remained that way until Clementine came along.

X-Ray Fluorescence

X-ray fluorescence spectroscopy has long been used in the laboratory to determine elemental abundances in samples. This method was scaled up and used in the Apollo 15 and 16 missions. Put simply, an x-ray source ejects electrons from the surface atoms giving rise to the emission of monoenergetic x-rays with energies characteristic to the elements in the area being studied. The energies involved range between 0.1 and 100keV, probing only the upper tens of microns of the surface in question.

In the case of the Apollo missions, the only x-ray source available to cause fluorescence was the Sun, and so this experiment could only be carried out on the sunlit side of the Moon. Because of the short duration of these missions only 10% of the surface was analysed using this technique. This technique was capable of measuring Mg, Al and Si, but because there was no calibration source on the Apollo missions, no absolute measurements could be taken. Surface maps of Al/Si and Mg/Si were produced instead. Because it is the Sun that causes the fluorescent x-rays to be produced, the calibration for this mission would have required measurements of the Sun to be taken at the same time as the measurements of the Moon. The Sun's x-ray output is not constant and its spectral distribution is also variable, and so later x-ray measurements of the Sun could not be used. Despite this problem, the results showed clear trends in both the Al and Mg data. Going eastwards from the nearside to farside, the Al/Si ratio increased whilst the Mg/Si ratio decreased. There were also systematic differences between mare and highland regions. Another important correlation from the Apollo experiments is that between the Al/Si ratio and the albedo. These data suggested strongly that the higher the Al₂O₃ content, the higher the albedo, and important discovery since it showed that albedo differences can also indicate compositional changes.

X-ray spectroscopy will be an excellent choice for an instrument on board a mission to Mercury. Being so close to the Sun, Mercury gets 4-6 times more incident flux than the

Moon, and so elements would be far easier to detect in shorter times. An x-ray spectrometer is to fly on ESA's SMART-1 mission to the Moon in late 2002. This is a British instrument and will, for the first time, map the Moon globally in x-rays. Named DCIXS, it will hopefully map Mg, Si, Al and Fe, with other elements possibly detected during solar flares.

Gamma-Ray Spectrometry

Again it was the Apollo 15 and 16 missions that carried the instruments to perform γ -ray spectrometry. Two types of line were detected by the experiments. The first are caused by natural radioactive decay of ⁴⁰K, ²³⁸U and ²³²Th. The second type is caused by galactic cosmic-ray particles exciting the nucleus of certain elements. The energies involved here are usually between 0.2 and 10MeV, but this time the gamma rays penetrate to the upper 10's of centimetres of the surface of the body in question.

This type of γ -ray production provides possible detection of Fe, Ti, Al and Si. For the Apollo mission data, surface abundances of Th, Fe and Ti were produced although there were large uncertainties associated with the Fe and Ti values (up to 50% for absolute values of Ti). As for the x-ray data, only a small portion of the Moon was covered, but in both cases farside regions were mapped. Nevertheless, the maps showed that the mare regions had higher concentrations of both Fe and Ti than the highland regions and that Ti had a greater range of abundances than Fe. This correlated well with analyses of returned samples. Since Th is found in KREEP basalts, its distribution could also give indications of the most abundant KREEP basalt regions. In addition, since the Th signature is produced from radioactive decay, it also indicates the areas of highest radioactivity on the Moon too.

These experiments both clearly showed the large variation of elemental abundance across the surface of the Moon covered by the Apollo 15 and 16 missions. The variation seen proves that data from a handful of sample returns cannot necessarily be extrapolated to other faraway regions of the Moon. Therefore the value of global datasets became obvious. Unfortunately after the Apollo missions ended, we still did not have that global abundance dataset.

8.1.4 Lunar Prospector

Lunar Prospector (LP), changed that. It was a NASA mission dedicated to mapping the Moon using a variety of techniques, including the γ -ray techniques used in the Apollo missions. LP was launched in January 1998, carrying a γ -ray spectrometer, neutron spectrometer, magnetometer, alpha-particle spectrometer and a gravity experiment. It remained in a 100km altitude lunar orbit for a period of one year, before being lowered to 25km until its fuel reserves were exhausted. At the end of the mission it underwent a controlled crash into a polar crater in an attempt to release water into space to be detected by ground based instruments. The main objective of LP was to map the surface abundances of a series of elements and to search for the presence of water ice at the lunar poles.

So far only the primary mission results have been released. The γ -ray experiment has shown that the KREEP-rich material is concentrated in the rim areas of Mare Imbrium, and the area around the South-pole-Aitken basin on the farside of the Moon. The data supports the idea that KREEP-rich material was distributed around the Moon by the Imbrium impact event. The γ -ray data also confirm that Fe is concentrated in the maria.

The gravity field of the Moon is still being mapped, but already LP has discovered 3 new mascons. Mascon is short for "mass concentration" and relates to an area of higher or lower gravity across the Moon. Most of the mascons already known about are over mare filled basins, and so are the ones discovered by the greater sensitivity of LP. It's important to map these features carefully as they can have a dramatic effect on the orbit of spacecraft. Gravity mapping is a slightly different form of remote sensing in that the entire spacecraft is used as the instrument. Tracking stations on the Earth continually monitor the position of the spacecraft, which is affected by the differing gravity. By measuring when it speeds up or slows down, the scientists on the ground can work out where those areas of higher or lower gravity exist.

The gravity data, coupled with the data from the magnetometer experiment can be used to infer the size of the lunar core. It has previously been surmised that the core of the Moon is very small and made of iron. Its size is very important as it may be able to distinguish between the theories of lunar origin. LP has determined that if the core is made of pure Fe, it will be ~320km in diameter, contributing only 1.4% of the mass of the Moon. LP has also determined that the maximum diameter the core can have is 450km - if it really is at this diameter, it will still be Fe or Fe-rich, but may also be composed of FeS to some degree. Scientists are still trying to work out what this is telling them in terms of origin models. The magnetometer has discovered that the strongest magnetic points on the Moon are antipodal to the large Imbrium basin and Serenitatis basin, which infers that some shock magnetisation of the lunar rocks took place at the time of impact. The magnetic

field antipodal to the Imbrium basin is actually strong enough to deflect the solar wind, and so constitutes the smallest magnetosphere and bow shock system in the solar system.

The most eagerly awaited result from LP was to come from the neutron spectrometer. This particular experiment detects neutrons of differing energies. Energetic neutrons occur when cosmic rays smash into atoms. These neutrons gradually slow down as they hit other atoms. Neutrons are slowed down most effectively by hydrogen atoms, and it is when the neutron spectrometer detects an increase in low energy neutrons, or a decrease in energetic neutrons that the scientists know something interesting is present. Note, that the experiment detects only hydrogen, not water, and it is an excess of hydrogen that LP has detected at the poles of the Moon. The scientists say that the most likely form that the hydrogen will take there is that of water ice. According to the data there is up to 3 billion metric tons in the top half a metre of regolith spread over the poles. The ice most likely is mixed up with the soil in permanently shadowed regions of the poles. However, the only way to be absolutely sure that water is present is to go there and look for it.

Reference List

"The Lunar Sourcebook", Heiken G.H., Vaniman D.T., French B.M., 1995, Cambridge University Press

"Remote Geochemical Analysis: Elemental and Mineralogical Composition", Pieters C.M., Englert P.A., 1993, Cambridge University Press

Clementine Reports, 1994, Science, 266, 1835-1862

Lunar Prospector Reports, 1998, Science, 281, 1475-1500