Observing the Moon in polarised light

A science project by
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Summary

Sunlight reflected from the Moon (moonlight) is partially polarised

The degree of polarisation depends on several factors, most importantly:

the phase of the Moon and

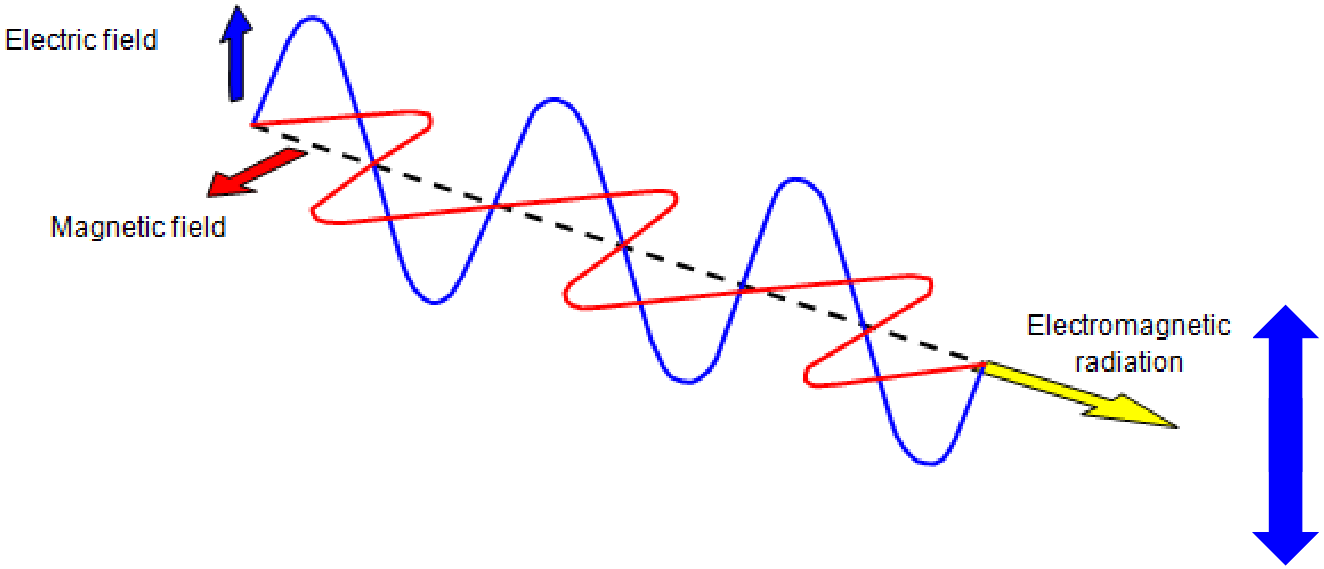
the refractive index and absorption of the scattering material

The fact that polarisation depends on refractive index is a new discovery made during this project

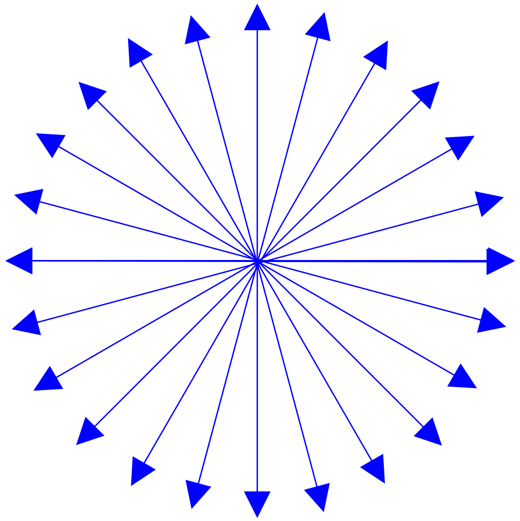
Analysing webcam images taken in different polarisations allows us

to determine the refractive index of the regolith particles

Light is a transverse electromagnetic wave

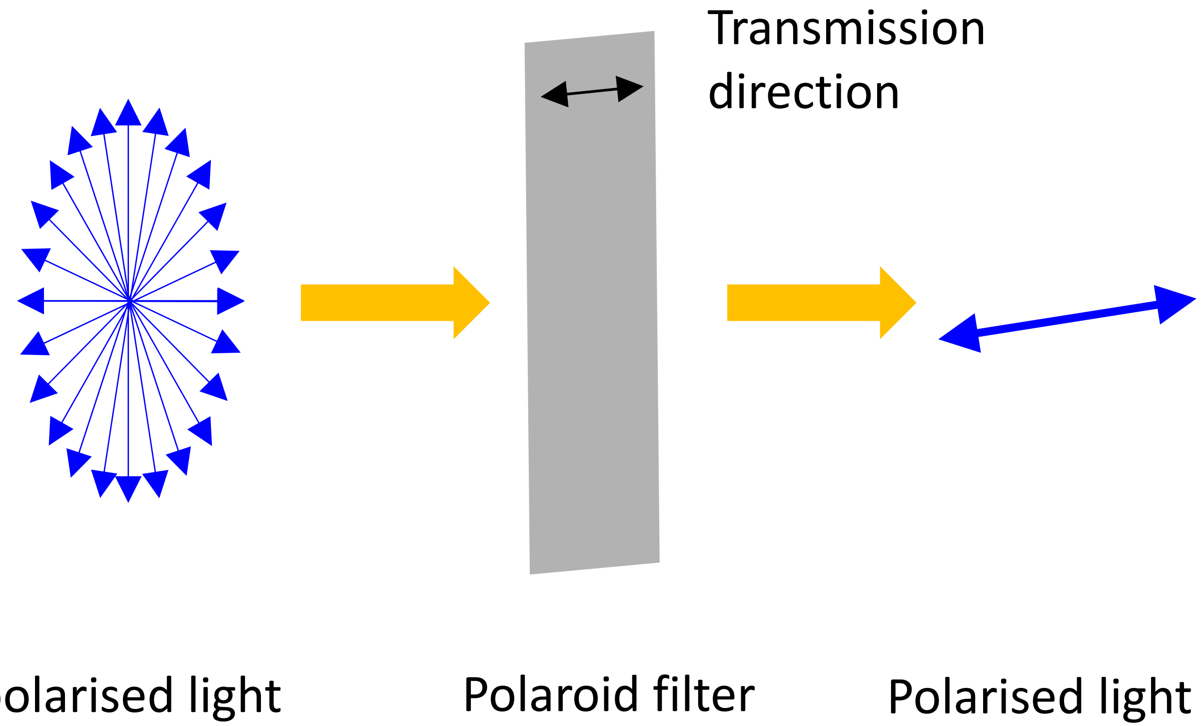


The electric field is the reference direction for describing polarisation



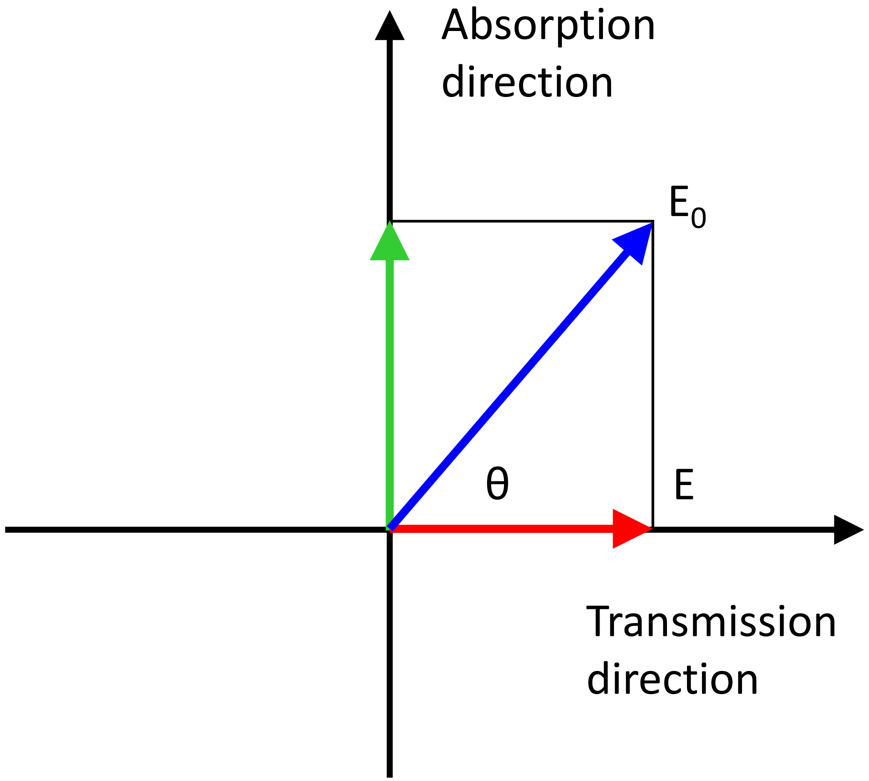
In unpolarised light, all possible orientations of the electric field are present in equal amounts

Light can be polarised by transmission



Dichroic polarising filters such as Polaroid absorb one component of polarisation and transmit the other

Light can be polarised by transmission

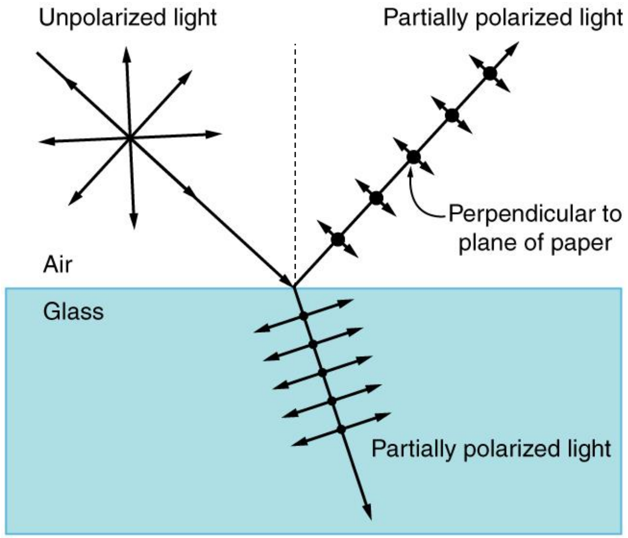


The transmitted component of the electric field is $E = E_0 \cos\theta$

The intensity of the transmitted light is proportional to E^2, so

$$I = I_0 \cos^2\theta \qquad \text{(Malus' Law)}$$

Light can be polarised by reflection from surfaces



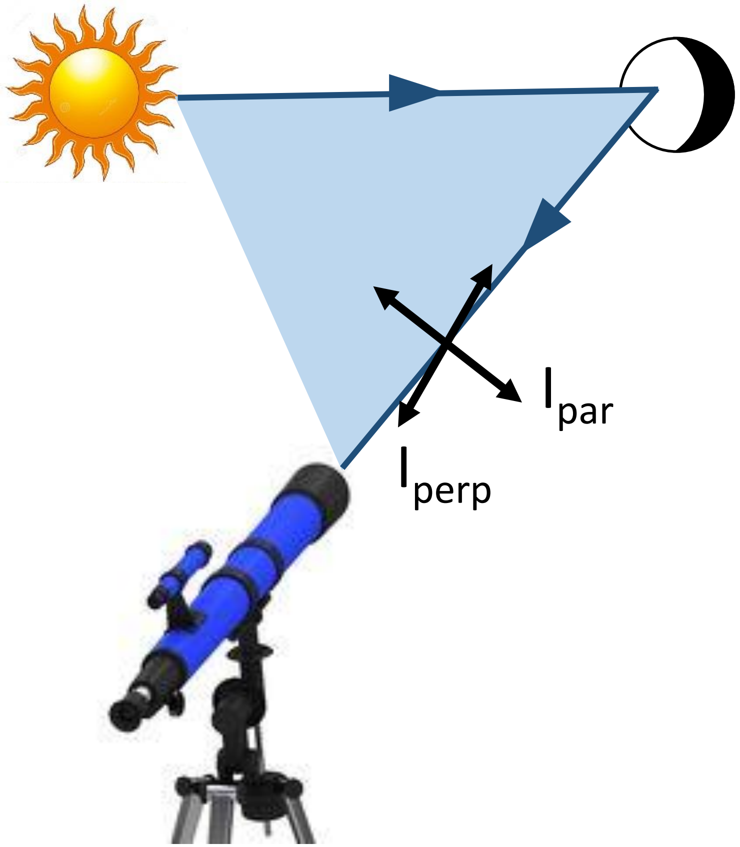
Light polarized parallel to the reflecting surface is more strongly reflected

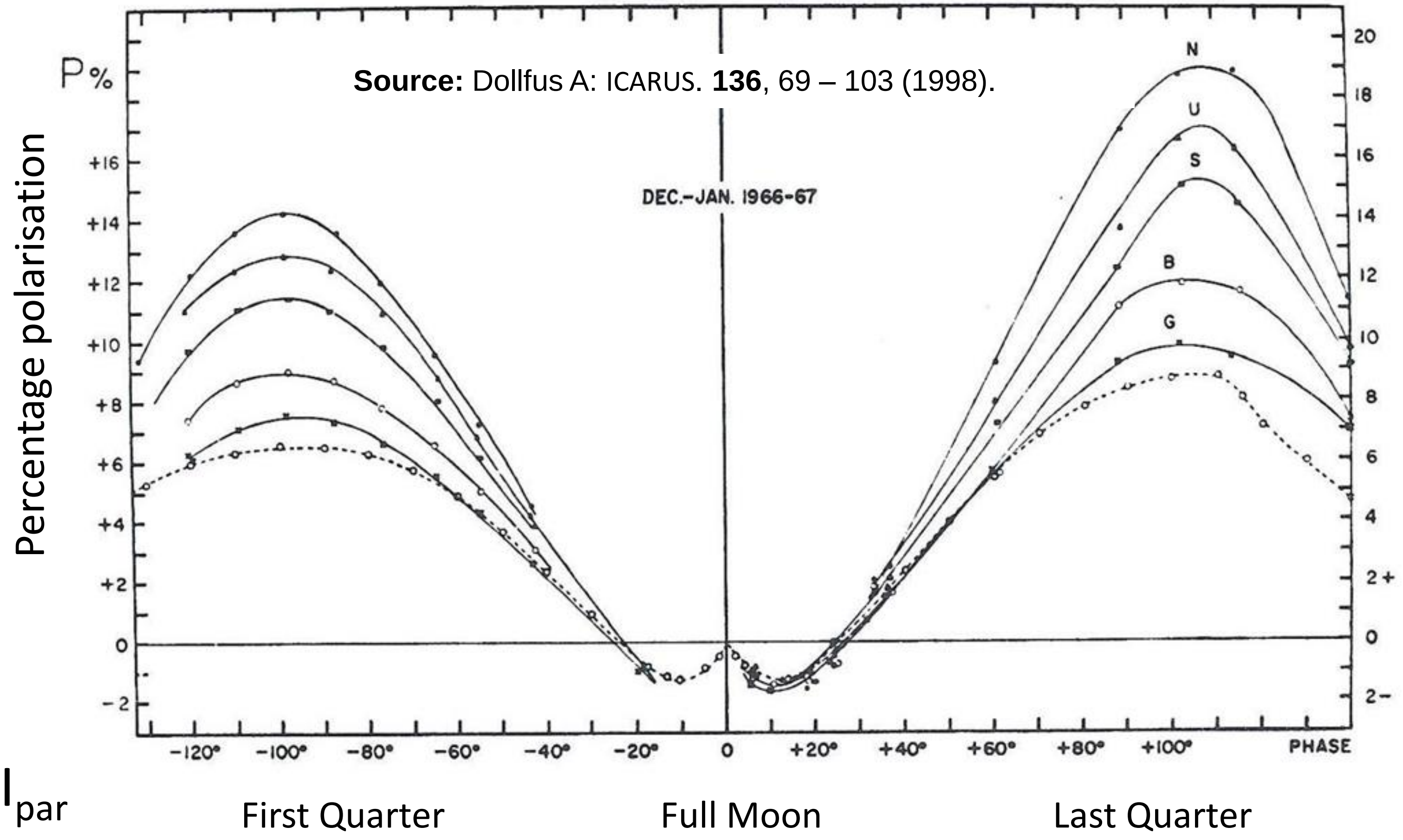
The amount of light reflected depends on the refractive index of the reflecting material

Left: naked eye view

Right: with polarizing filter

The polarisation of moonlight varies with the Moon’s phase





Degree of polarisation $P = \dfrac{I_{perp} - I_{par}}{I_{perp} + I_{par}}$

Measuring the polarisation of moonlight

We use conventional webcam imaging techniques, with a few extra precautions

A set of images is recorded through a polarising filter

The filter must be oriented differently for each image

A custom-made polariser mount allows the filter

to be rotated quickly and accurately between images

Measuring the polarisation of moonlight

Rotating polariser mount attached to 20 cm Meade LX-10 SCT

The polariser has marks every 10 degrees

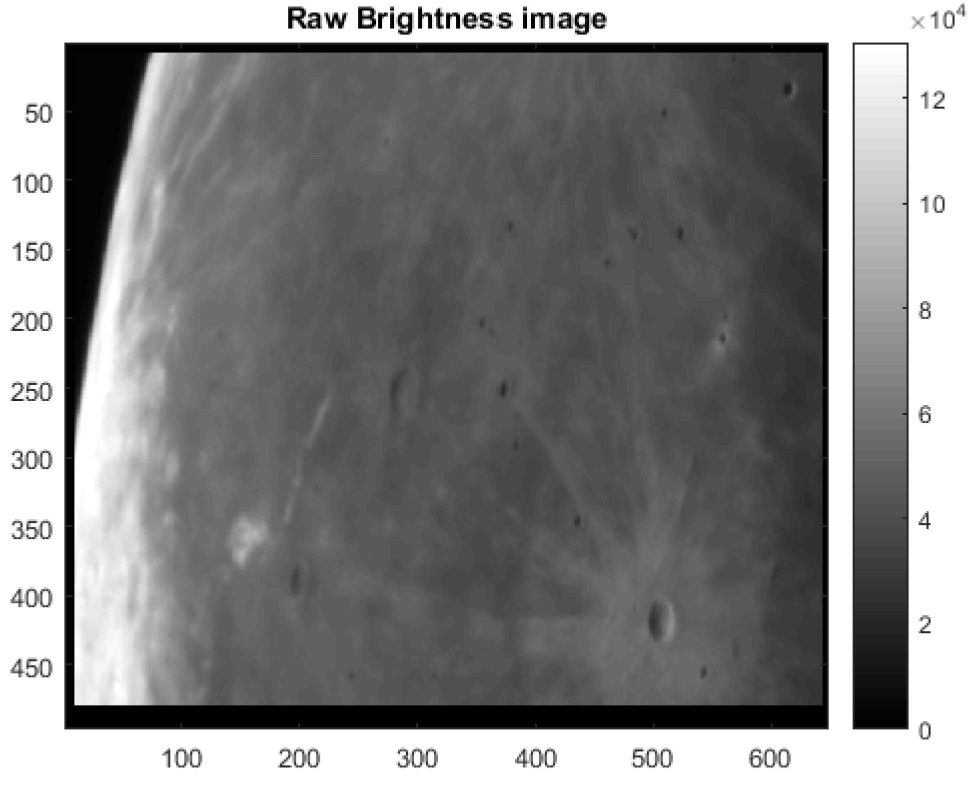
Measuring the polarisation of moonlight

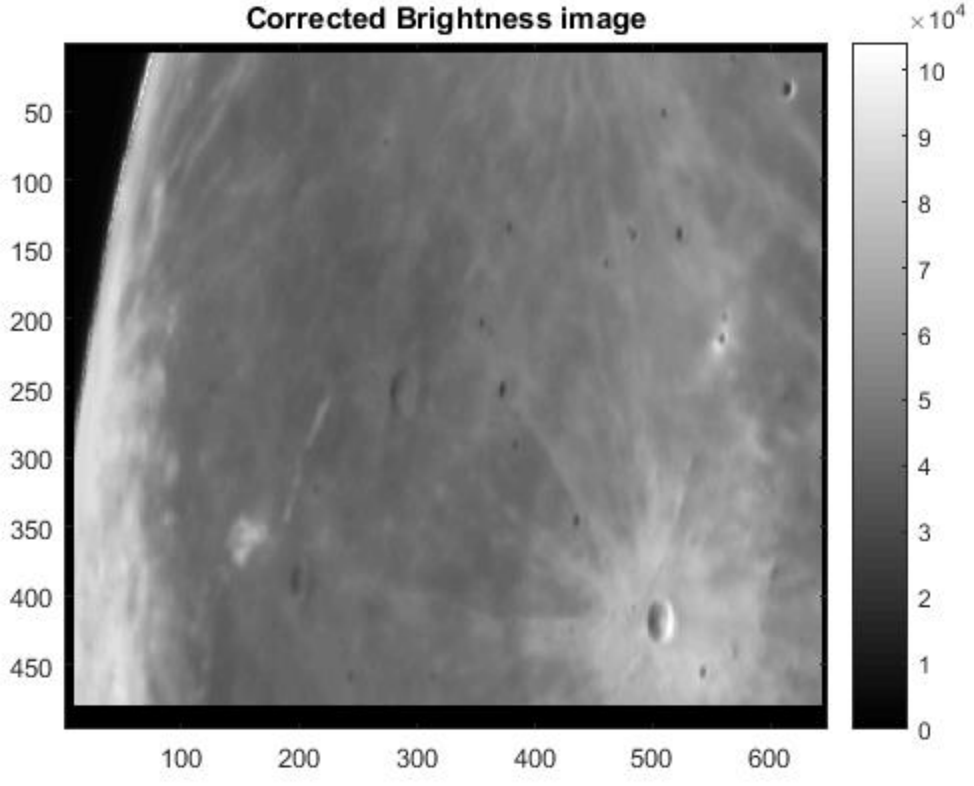
The procedure is very similar to standard imaging of the Moon:

1. Select the region to be imaged and frame it
2. Rotate the polariser to the start position
3. Capture an AVI of a few hundred frames
4. Change the polarization angle 10° and repeat
5. Record data over at least 180° rotation of the polariser
6. Stack the frames **but don’t sharpen the images**
7. Register the images and crop to a common outline

The images must be calibrated

The right side of the raw brightness image looks darker than the left
This is not due to a genuine variation in the brightness of the rock but due to the variation in the illumination angle from the Sun
In the corrected image we have compensated for this leaving only genuine brightness variations





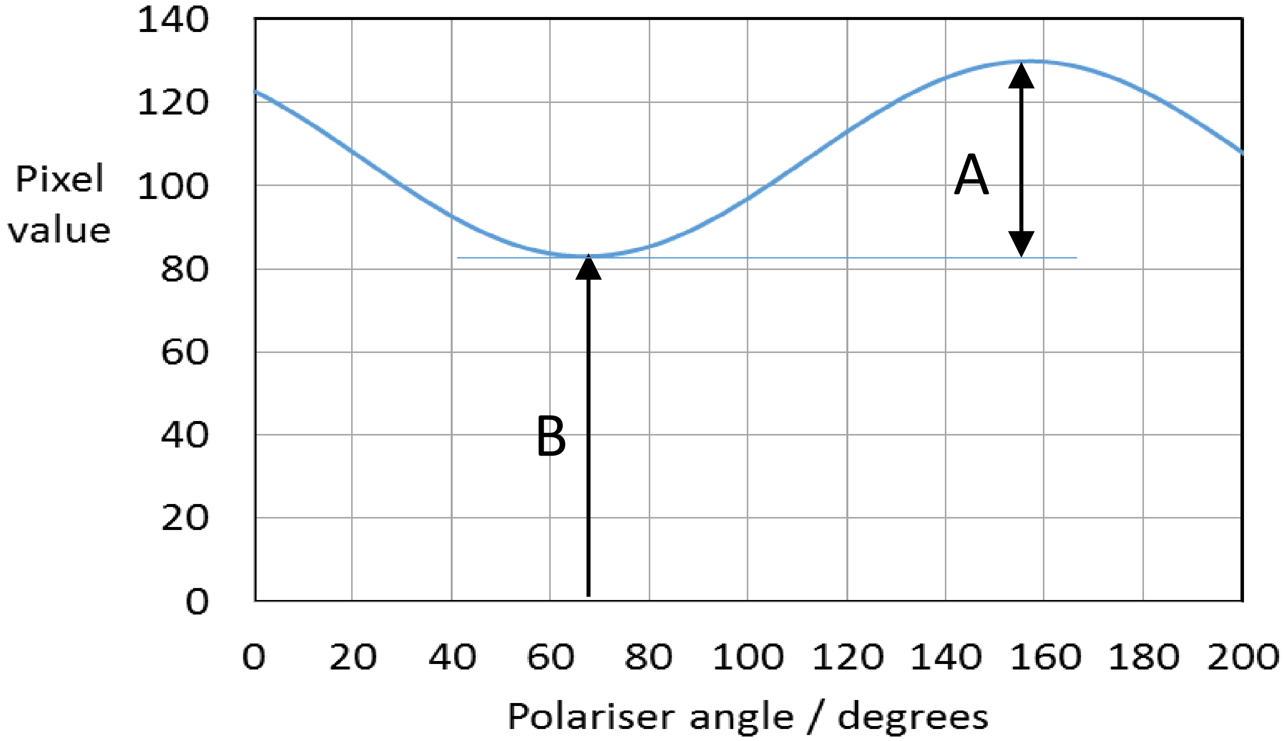
Variation in brightness with polariser angle

These two images have been corrected for the altitude of the Sun
The variation in brightness due to the polariser angle is subtle

Polariser at 0 degrees

Polariser at 90 degrees

Plotting brightness against polarization angle gives a $\cos^2$ curve



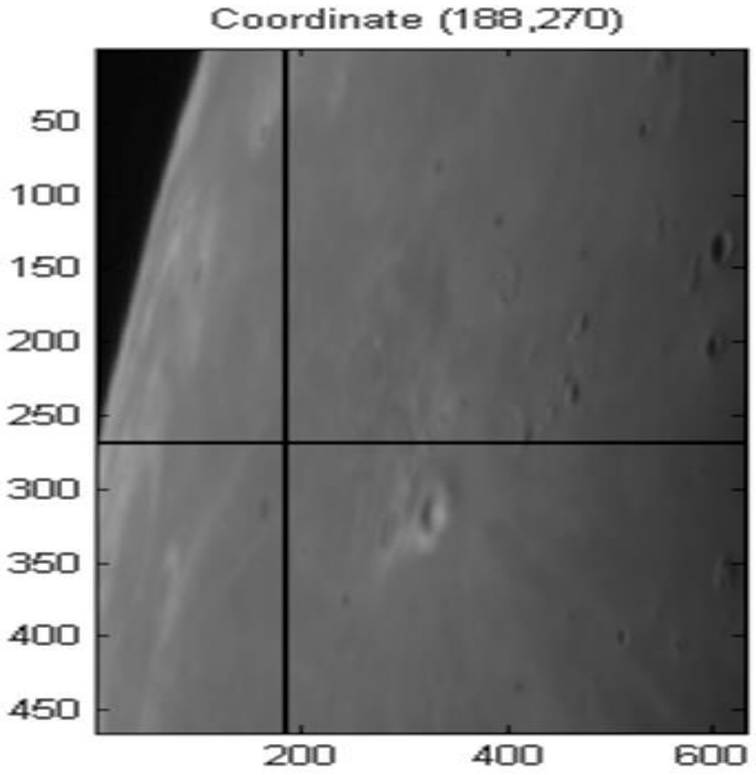
$$P = \frac{I_{perp} - I_{par}}{I_{perp} + I_{par}}$$

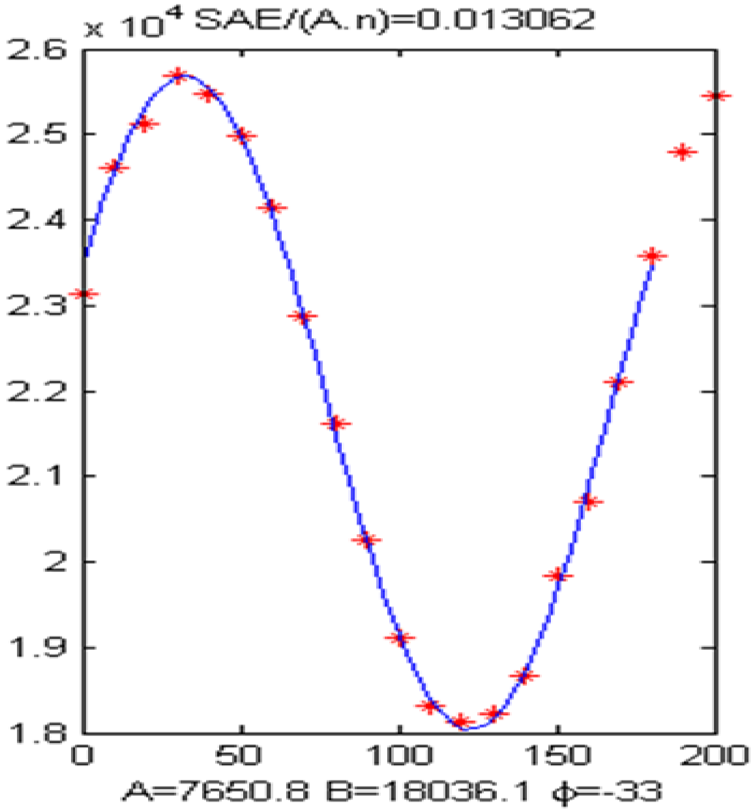
$$P = \frac{(A + B) - B}{(A + B) + B}$$

$$P = \frac{A}{(A + 2B)}$$

The curve is $y = A \times \cos^2(\theta + \varphi) + B$, where θ is the polarizer angle

Plotting brightness against polarization angle gives a $\cos^2$ curve





A = 7650.8

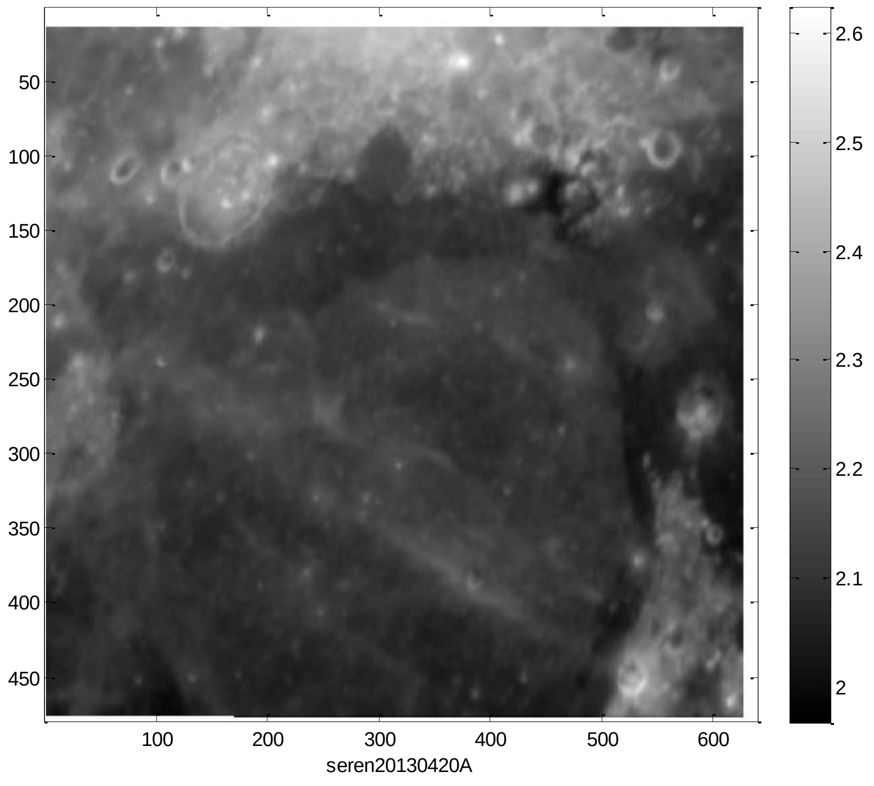
B = 18036.1

P = 0.175

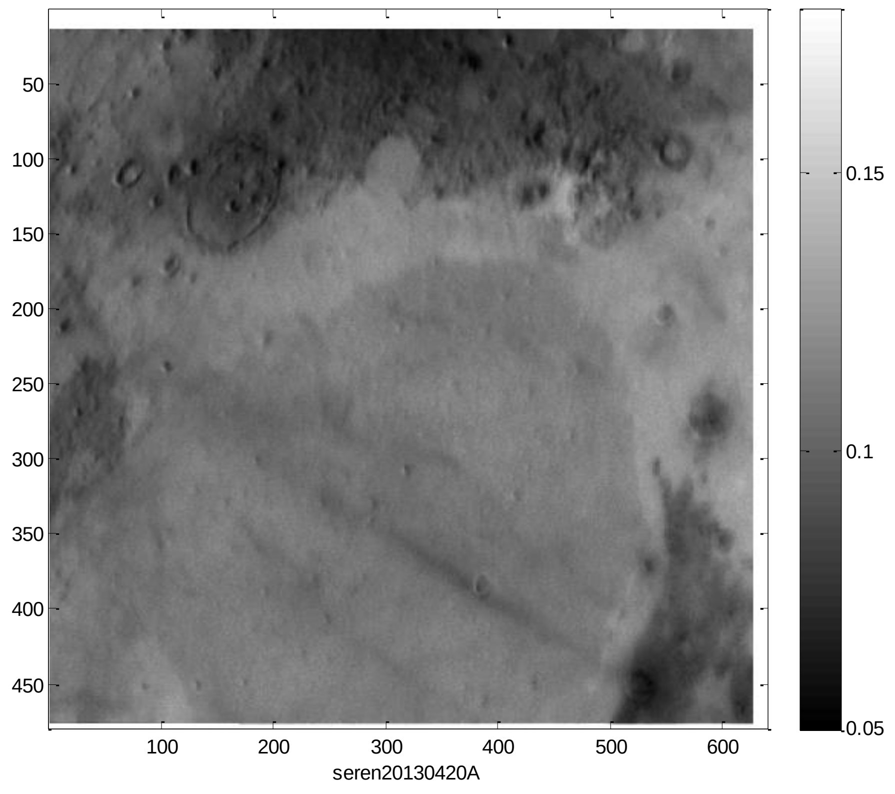
Example of $\cos^2$ curve from real data (Aristarchus and surroundings)

There is an inverse correlation between polarisation and albedo

Albedo image

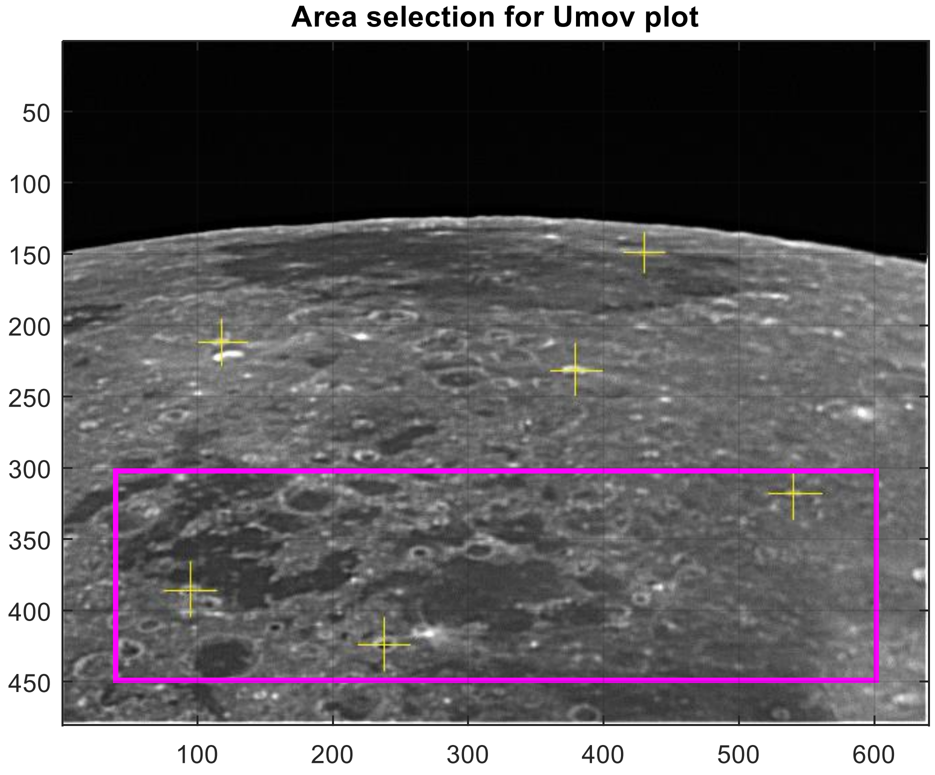


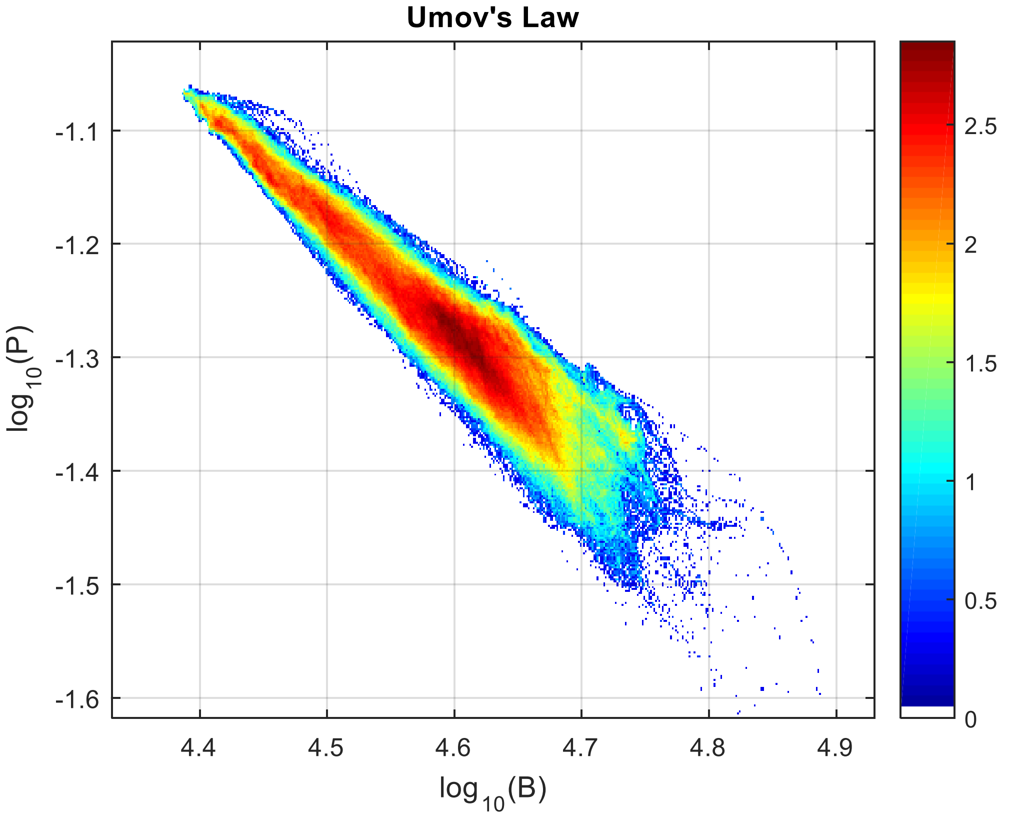
Polarisation image



This relationship is known as Umov’s Law

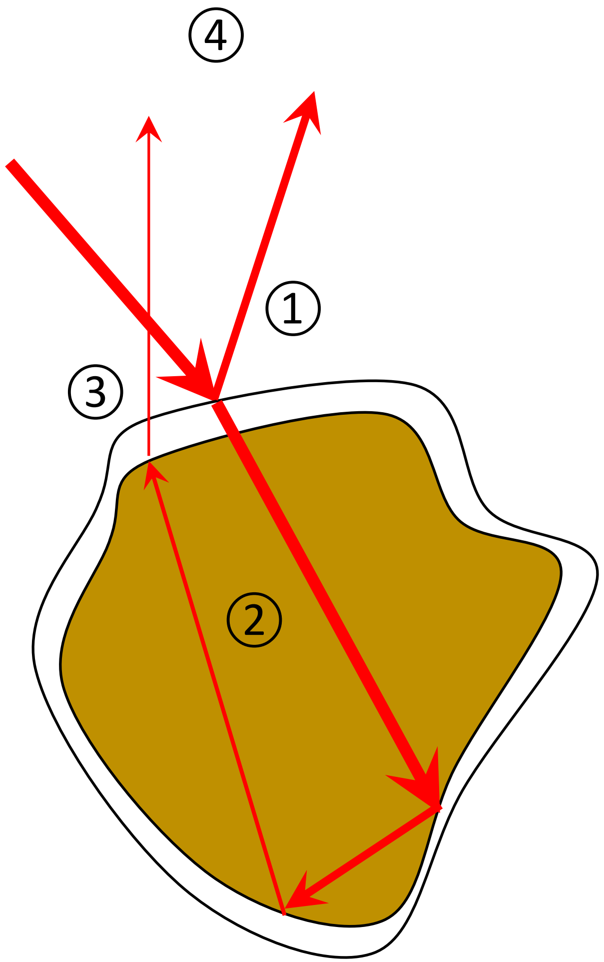
Umov’s Law plot from an observation





If we plot log polarisation against log brightness for every point in the box we get a rough straight line. This illustrates Umov’s Law

Why is Umov's Law true?



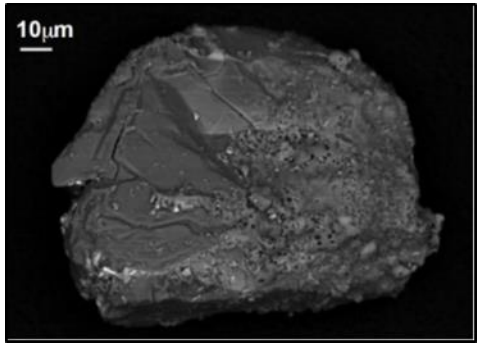
1. Reflected light from the first surface is partially polarised, approximately the same for all grains
2. After a few internal reflections the polarisation of the light inside the grain is re-oriented randomly
3. If the grain is strongly absorbing, the emerging light will be much weaker
4. The observed light is a mixture of the light initially reflected and the light that emerges from the grain
5. When more light is absorbed in the grain, the observed degree of polarisation will be greater

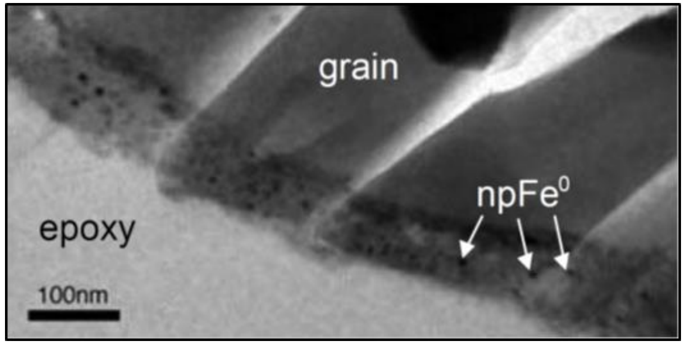
Mathematical modelling of dust grains

We have a mathematical model which can calculate the polarisation and brightness of a surface composed of small particles

The model has an inner core and an outer thin shell. We can vary the diameter and refractive index of the core as well as the thickness and iron content of the shell

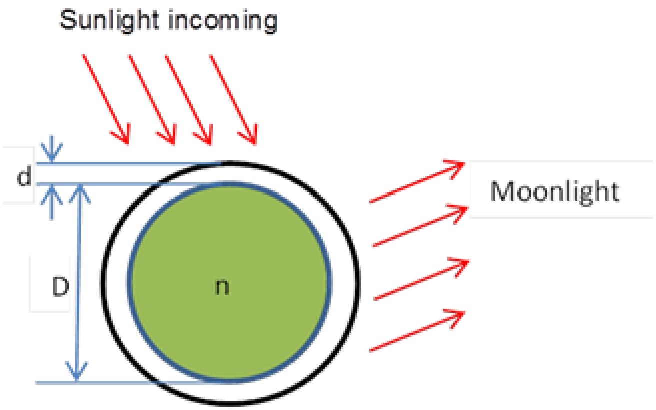
If we calculate brightness and albedo for 100,000+ grains with values chosen at random within ranges shown we get an Umov law plot (see next slide)





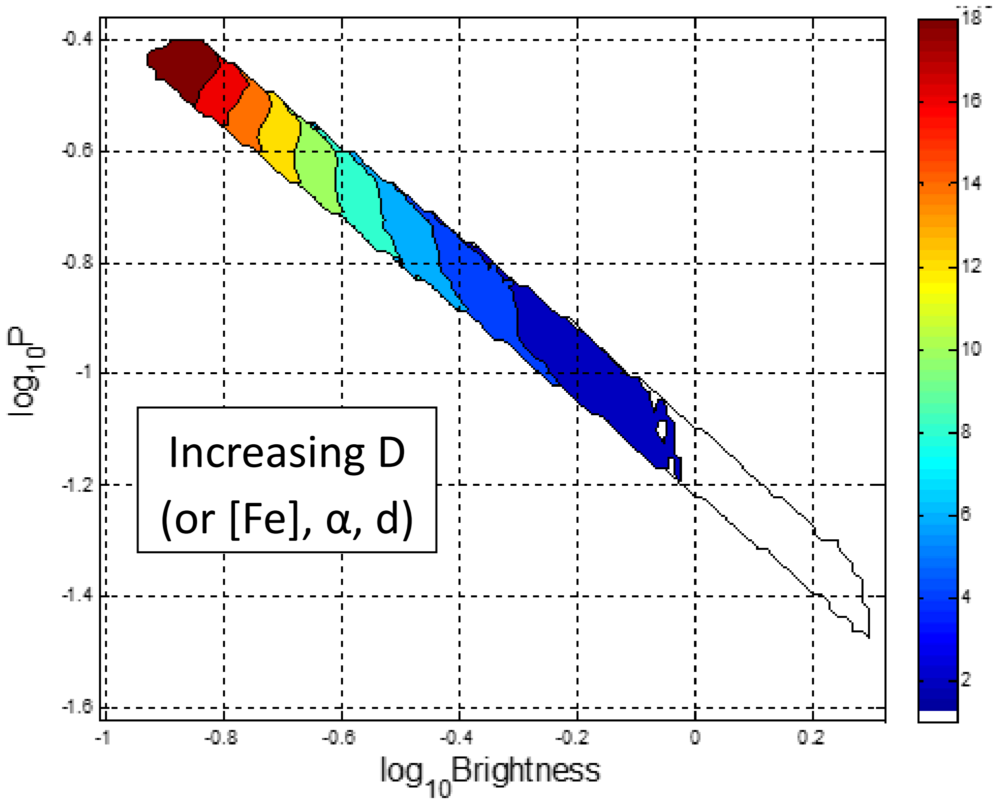
Parameter ranges for a grain

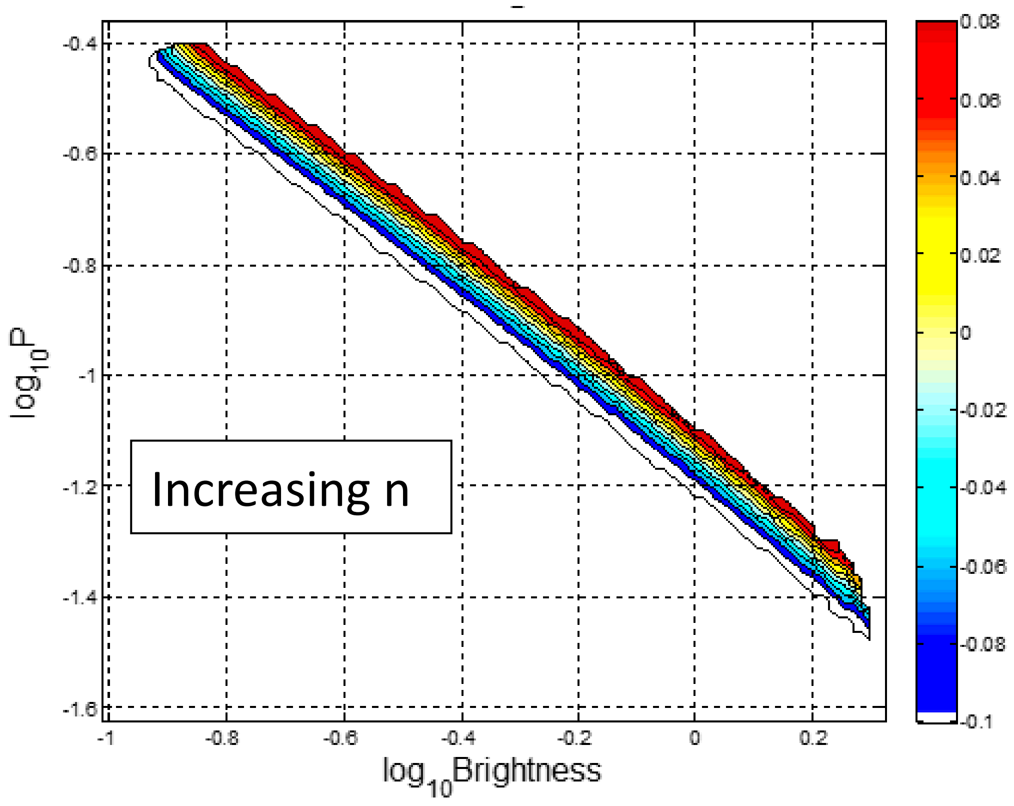
D: few to 50 microns
d: few to 100 nanometres
[Fe]: 0.1% to 3%
n: n_0, $n_0 \pm 10\%$
α: 0.004 to 0.005



Results from the model

Variation of overall diameter or iron content and thickness of the outer layer moves the point for the grain along the line
Refractive index moves the point perpendicular to the line this is the key discovery

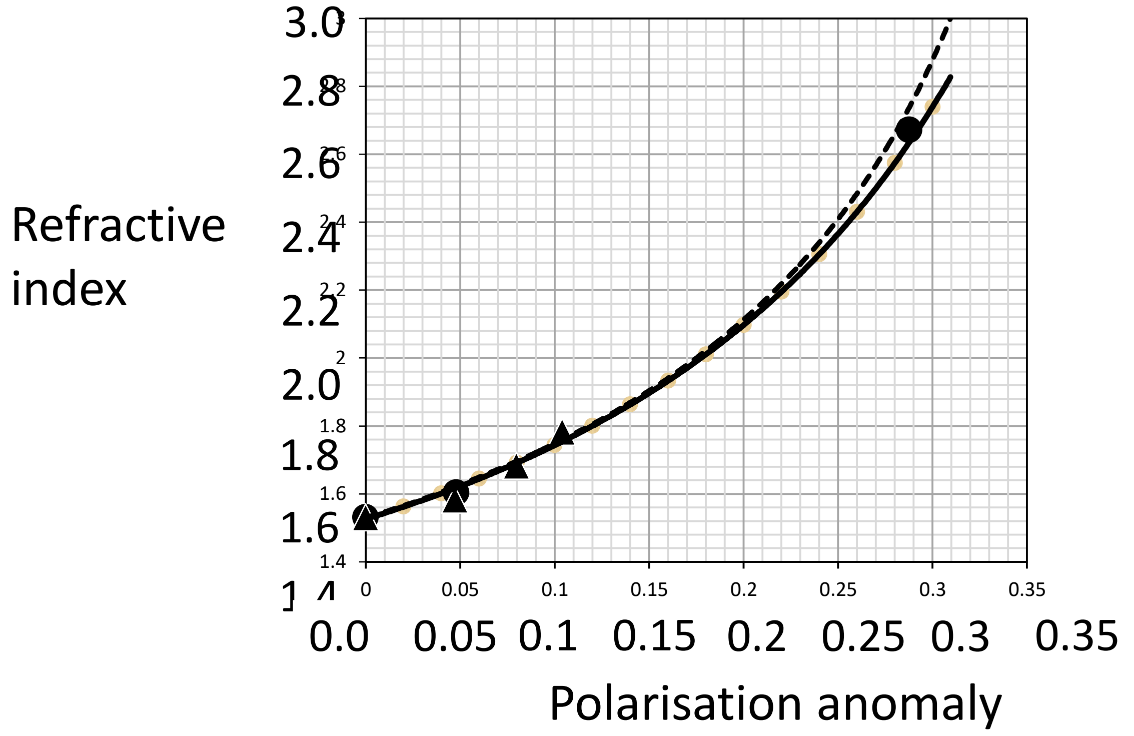




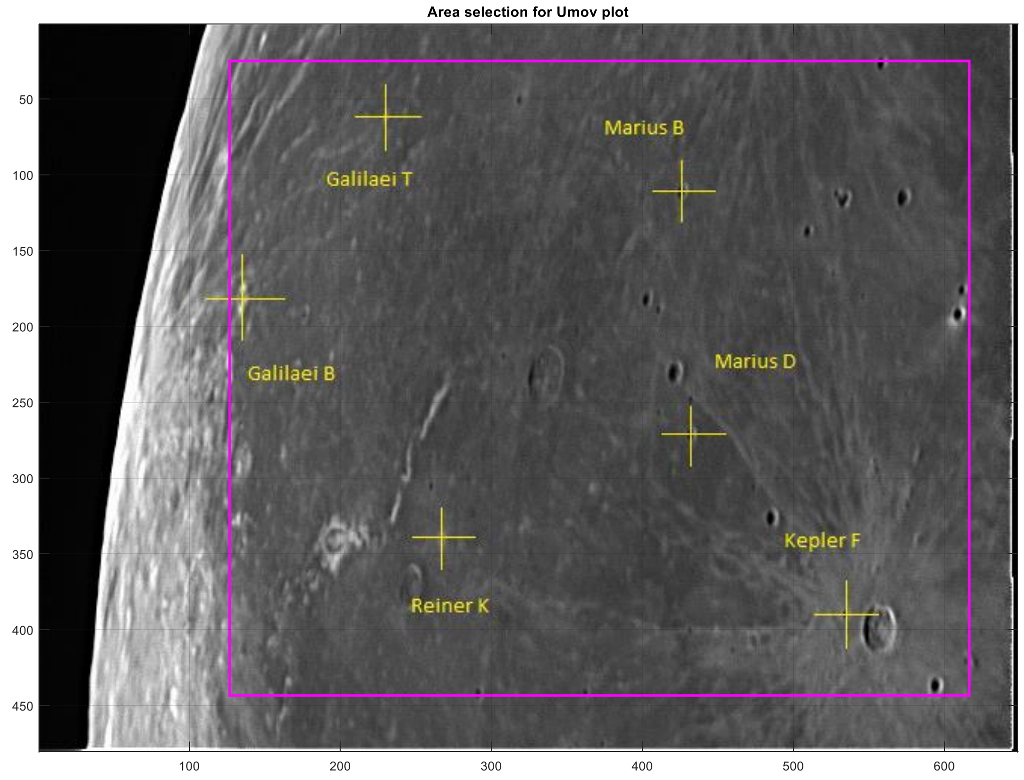
Polarisation anomaly calibration curve

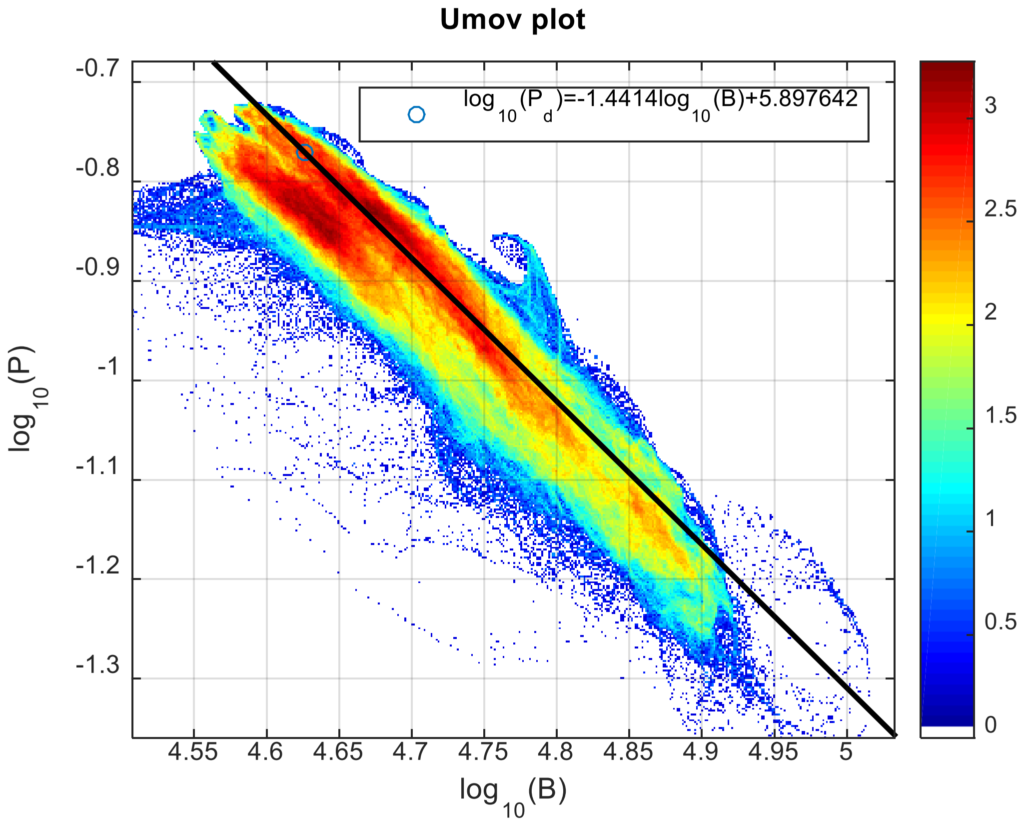
The polarisation anomaly is the perpendicular distance of a point from the main trend line

Once the polarisation anomaly is known it can be related to the refractive index using this curve



Actual observations show parallel trend lines indicating areas of differing refractive index

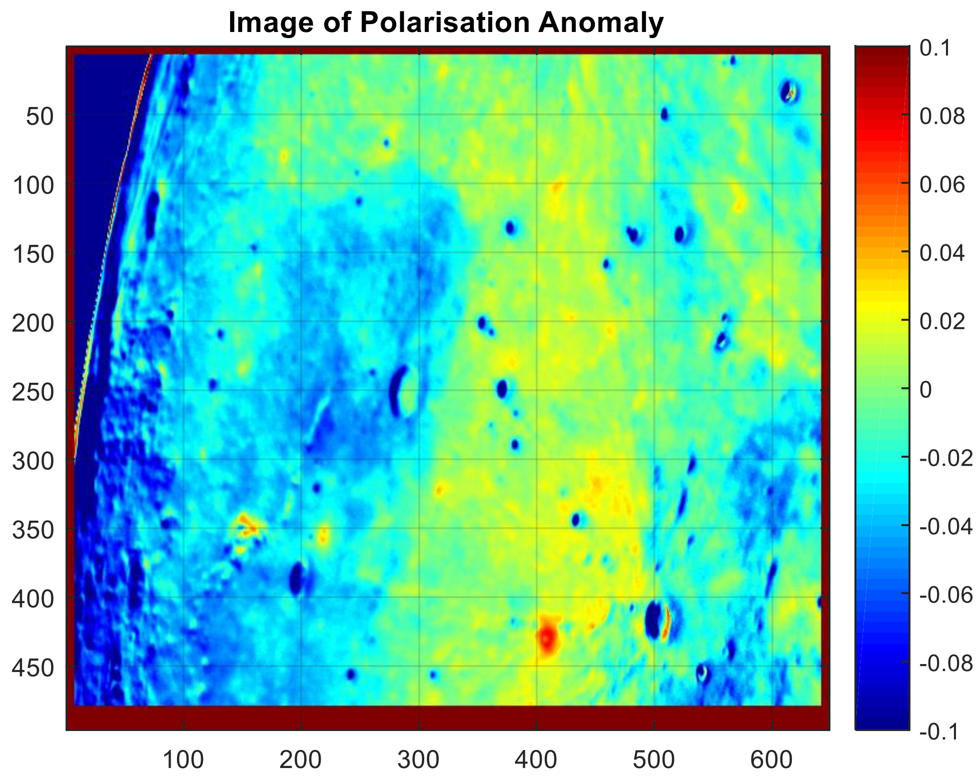




Reiner Gamma, Marius and Kepler: 07/09/2014

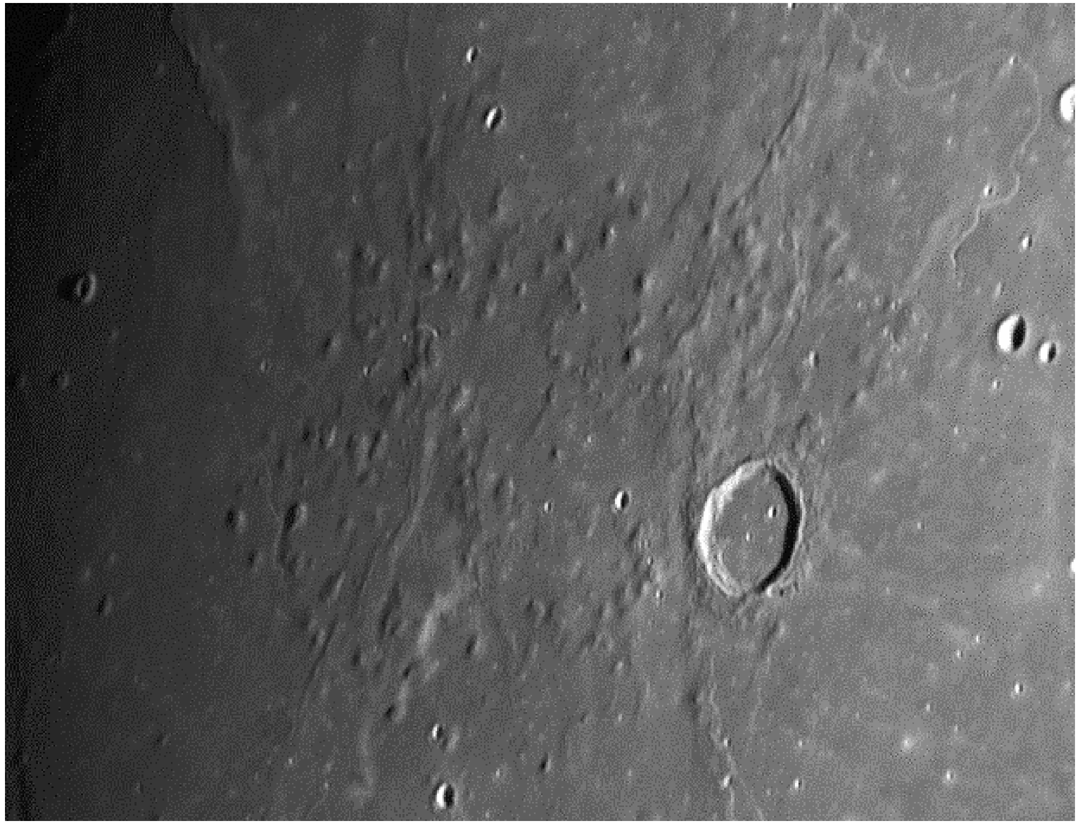
Polarisation anomaly image

We call the distance of each point from the line on the Umov plot the polarisation anomaly
Here we form an image of that distance
Points above the line are positive and appear progressively more red as they move away from the line.
Negative values are below the line and appear progressively more blue



Example observation Marius Hills

The Marius hills show signs of past volcanic activity
What is the resulting variation in refractive index across the surface



Refractive index of Marius Hills

Here we have calculated the refractive index of the Marius Hills area and projected it onto NASA elevation data

Professional studies of this area have suggested that rocks in the middle of this area are made of anorthosite type minerals and these would be expected to have a lower refractive index than the surrounding basalt.

This observation is clearly consistent with those results