Polarimetry: From the Sun to Stars and Stellar Environments
Proceedings IAU Symposium No. 305, 2014
K. N. Nagendra, S. Bagnulo, R. Centeno &
M. J. Martínez González, eds.

doi:10.1017/S1743921315004986

Linear spectropolarimetry: a new tool for the physical characterization of asteroids

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Abstract. The surfaces of the atmosphere-less objects of our solar system are traditionally probed via reflectance measurements and/or broadband linear polarimetry. Little attention has been paid so far to the wavelength dependence of the linear polarization of the scattered light. We decided to explore the potential of spectropolarimetry as a remote sensing tool for asteroids in addition to the more traditional reflectance measurements, and we carried out a spectropolarimetric survey of asteroids – to our best knolwedge, the first of its kind. We observed a sample of asteroids of different albedo and taxonomic classes, as well as a few regions at the limb of the Moon. We show that objects exhibiting similar reflectance spectra may display totally different polarization spectra, and we suggest that both intensity and polarization spectra should be used for asteroid classification. We also found that in some cases the Umov law is violated, that is, in contrast to what is expected from simple physical considerations, the fraction of linear polarization and the reflectance spectra may be correlated positively. We conclude that future modelling attempts of the surface structure of asteroids should be aimed at explaining both reflectance and polarization spectra.

Keywords. Polarization, minor planets, asteroids

1. Introduction

Polarization by reflection maybe understood in a schematic way by thinking of an electron in a planar reflecting surface as if it was "shaken" by the incoming radiation. The electron is less free to penetrate into the surface than to move in the direction perpendicular to the scattering plane (the plane that contains the incident and the reflected radiation). Therefore the reflected light has an excess of polarization perpendicular to the scattering plane. The amount of the reflected intensity and its fraction of linear polarization depend on the scattering angle, on the composition and on the structure of the scattering surface. This concept is applied in solar system science in the hope that the analysis of the Stokes parameters of the reflected light, measured at different scattering angles, may reveal some information about the structure and composition of the atmosphere-less bodies. Of course, in the case of ground based observations, one cannot arbitrarily modify the angle of incidence of the incoming radiation, but the targets can be observed at different geometrical configurations relative to the Earth as they orbit around the Sun.

2. Broadband linear polarization of asteroids

In these proceedings, Cellino & Bagnulo (2015) have shown some examples of polarimetric curves (the broadband linear polarization as a function of the phase-angle, which

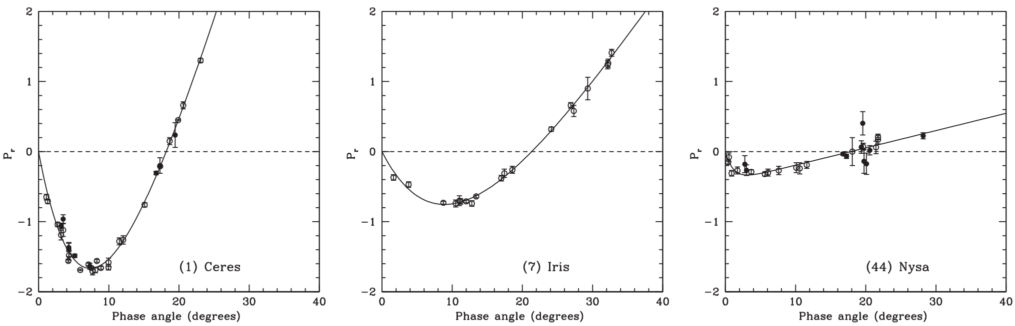

Figure 1. Broadband polarisation curves of asteroids (1) Ceres (C-type in the SMASS II taxonomic class), (7) Iris (S-type) and (44) Nysa (Xc-type).

is the angle between the Sun, the target, and the observer). An example of this kind of data is shown again in the left panels of Fig. 1, where the polarization P_r is the reduced Stokes Q parameter (the reference direction being the perpendicular to the scattering plane):

$$P_{\rm r} = \frac{I_\perp - I_\parallel}{I_\perp + I_\parallel} \quad .$$

Perhaps the most striking phenomenon revealed by these observations is that, at small phase-angles, $P_{\rm r}$ assumes negative values, i.e., the polarization of the reflected light is *parallel* to the scattering plane. This is in stark contrast with what is expected according to the simple model sketched in the previous section. Most asteroids exhibit a polarimetric curve that is negative at small phase-angles, and that reverses its sign around phase-angle $18^\circ - 22^\circ$ (there are notable exceptions to this rule, e.g., Barbarian asteroids exhibit a polarimetric curve with cross-over angles in the range $\sim 27^\circ - 30^\circ$, see Cellino et al. 2014). The two phase-angle intervals where the polarization is negative or positive are referred to as the negative branch and the positive branch, respectively. The shape of the polarimetric curves may be quite different from asteroid to asteroid, and some of their morphological features may be used to estimate the asteroid albedo (see Cellino & Bagnulo 2015 and references therein).

3. The spectral classification of asteroids

In the same way that stars are classified in various spectral types based on the apparence of their spectra, asteroids can be grouped in different taxonomic classes based on their reflectance spectra. There are two major differences, though. Stars are classified mainly based on the spectral lines that are formed in their atmospheres. Stellar spectra can be often straightforwardly interpreted in terms of stellar chemical composition, temperature and gravity. Compared to most of stellar spectra, asteroids reflectance spectra do not have narrow-band features; their main distinctive characteristics are their slope and maybe the presence of some broadband features. Taxonomic classification of asteroids has been refined over the years, and has culminated into two popular classifications: the classification by Tholen (1984), based on multicolour broadband measurements, and that by Bus & Binzel (2002), later extended to the infrared domain by De Meo et al. (2009). Figure 2 shows the 24 taxonomic classes in the 450-2450 nm domain taken from DeMeo et al. (2009). Taxonomic studies reveal features closely related to the surface structure and composition, and to the body's age.

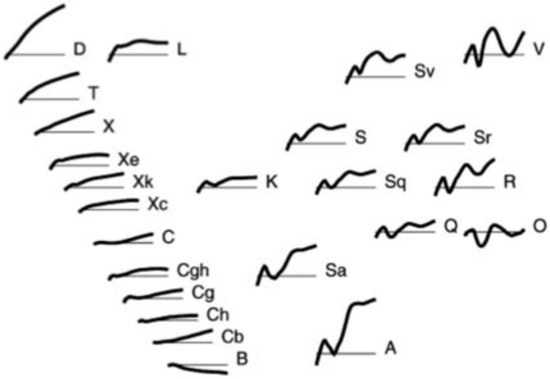

Figure 2. Taxonomic classes of asteroids based on optical and near-IR reflectance spectra (courtesy of Francesca DeMeo). One of the goals of our project is to check if it is possible to produce a similar or complementary classification based on polarization spectra.

While most of the stars exhibit a spectrum that is intrinsically unpolarised in the continuum (if a star is linearly polarised, this is often the effect of circumstellar or interstellar dust), the light reflected by asteroids is polarized, but little attention has been paid so far to how this polarization depends on wavelength. Here we suggest that polarization spectra may add information to the reflectance spectra, perhaps revealing a wealth of different characteristics ultimately allowing us a more refined classification. For instance, if we were to discover objects with similar reflectance but different polarization spectra, we could at the very least infer that the two objects are actually different in composition and/or surface structure, in spite of what is suggested from reflectance spectra alone. It would be especially important to discover a correlation between the shape of the polarization spectra and the object's albedo. This would allow us to measure the albedo with just one spectropolarimetric measurement. To explore these possibilities, we have requested and obtained observing time with the FORS instrument of the ESO VLT and with the ISIS instrument of the William Herschel Telescope in La Palma.

4. Spectropolarimetry of asteroids

It is not totally obvious how to compare the various polarization spectra among themselves, because they refer to objects of different taxonomic classes and were obtained at different phase-angles. In other words, a polarization spectrum depends not only on the properties intrinsic to the object itself, but also on the observing geometry. From broadband linear polarization measurements we already know that the fraction of linear polarization depends strongly on the phase-angle, but what about the shape of the polarization spectrum?

To answer this question, Bagnulo, Cellino & Sterzik (2015) introduced the polarization spectrum normalized to the polarization value at a certain arbitrary wavelength (in this case, 550 nm):

$$p_q(\lambda,\alpha) = \frac{P_Q(\lambda,\alpha)}{P_Q(\lambda = 550\,\mathrm{nm},\alpha)}\ .$$

If the polarization spectra (which depend on the wavelength, λ, and on the phase-angle, α) could be expressed as the product of two functions, one depending on λ and one on

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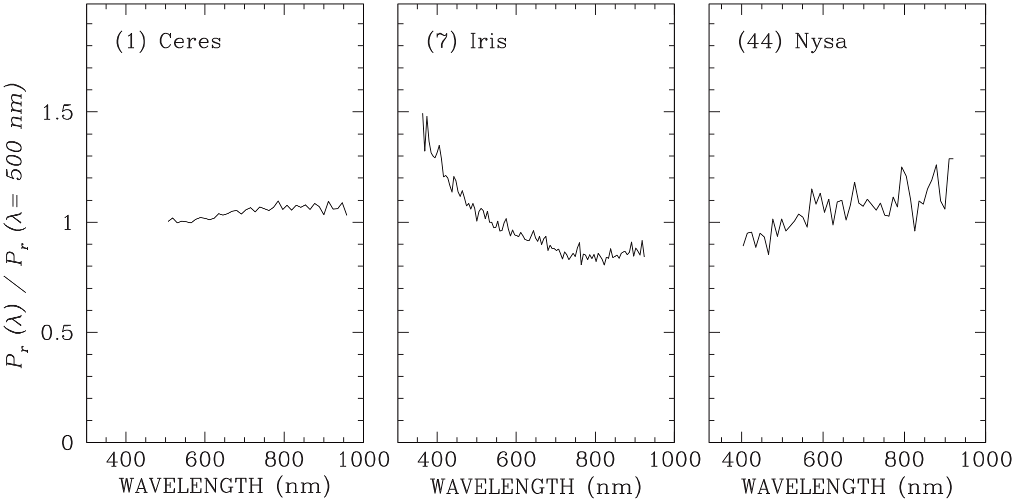

Figure 3. Normalised polarization spectra of asteroids (1) Ceres, (7) Iris and (44) Nysa.

α, then the normalised polarization spectra would depend only on wavelength:

$$p_q(\lambda) = \frac{P'_Q(\lambda)\; P''_Q(\alpha)}{P'_Q(\lambda = 550\,\mathrm{nm})\; P''_Q(\alpha)} = \frac{P'_Q(\lambda)}{P'_Q(\lambda = 550\,\mathrm{nm})} \; .$$

We note that, following their definition, the normalised polarization spectra p_q are positive both in the negative and in the positive branch, and that the wavelength gradient in the negative branch of p_q has the opposite sign to that of the wavelength gradient of P_Q. Figure 3 shows the normalised polarization spectra of the same objects of Fig. 1.

Results from a pilot study presented by Bagnulo, Cellino, & Sterzik (2015) show that P_Q spectra of low albedo asteroids always have a positive gradient, and P_Q spectra of intermediate albedo asteroids always have a negative gradient: this would be a confirmation of the preliminary results obtained in the works by Lupisko & Kieslev (1995) and Belskaya et al. (2009), based on multi-colour BBLP data. However, more observations are needed to check if this result can be generalized to a wide class of asteroids.

5. Comparing reflectance with polarization spectra

We naturally expect the light reflected by darker objects to be more polarized than the light reflected by objects with a higher albedo. This is because a darker surface absorbs more photons than a surface with a higher albedo. Therefore, if the reflectance increases with wavelength, then we would expect the absolute value of the polarization to decrease with wavelength, and viceversa. This behaviour is seen in many cases (e.g., in S-type asteroids, see Fig. 4), and is known as the *Umov effect* (Umov 1905). However, the Umov effect does not appear ubiquitously in asteroid polarization spectra. For instance, Fig. 5 shows the reflectance and polarization spectra of asteroids (236) Honoria and (208) Luisa, that were observed in the negative branch. The reflectance spectra of these two asteroids appear to be very similar, but the wavelength gradients of their polarization spectra have opposite signs, and in particular, data of (236) Honoria violate the Umov law. Since the Umov law is rooted on the basic mechanism described by the Fresnel laws, perhaps it is not surprising that it is violated in conditions in which the Fresnel laws cannot even

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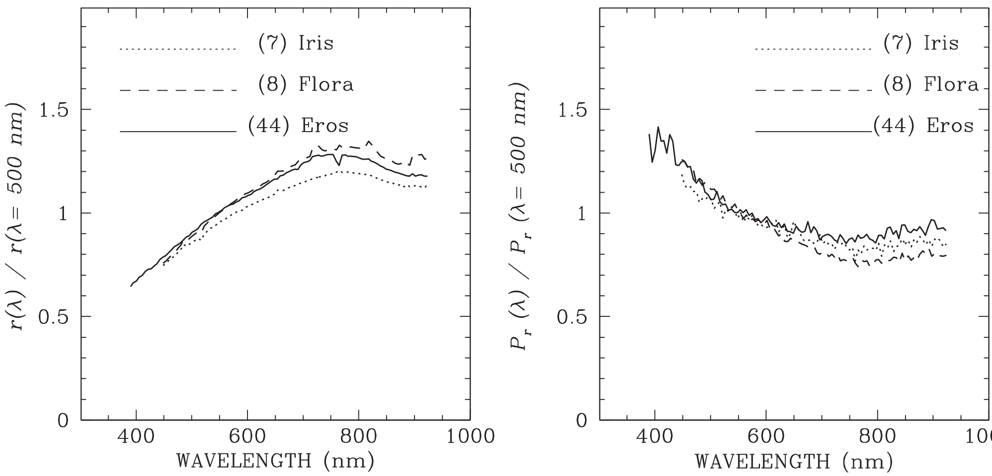

Figure 4. Left panel: the reflectance spectra of S-type asteroids (7) Iris (dotted line) (8) Flora (dashed line) and (44) Eros (solid line). Right panel: the normalised polarization spectra of these objects (all observed in the positive branch). Note that $P_{\rm r}(\lambda) \propto 1/r(\lambda)$ (where $r(\lambda)$ is the reflectance), as expected from the Umov law.

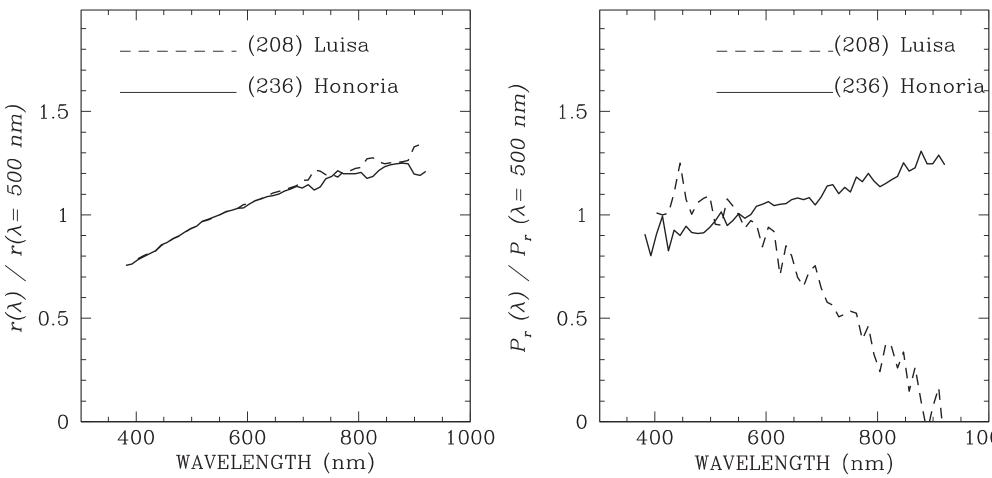

Figure 5. Left panel: the reflectance spectra of asteroids (236) Honoria (dashed line) and (208) Luisa (solid line) have both a positive gradient, i.e., the intensity increases towards the red. Right panel: the normalised polarization spectra (obtained in the negative branch) of the same objects have an opposite trend. The fraction of linear polarization of asteroid (208) Luisa (dashed line) decreases toward the red (consistent with the increase of its reflectance), whilst the linear polarization of (236) Honoria (solid line) is higher in the red than in the blue.

explain the orientation of the polarization. Certainly this phenomenon deserves further observational and theoretical investigation.

We finally comment that in asteroid spectroscopy, the choice of the solar analogue used for the normalisation of the intensity spectra and the quality of the calibration of the atmospheric extinction play a crucial role on the accuracy of the measurement of the reflectance spectra, and, ultimately, on the taxonomic classification of asteroids. By contrast, spectropolarimetric measurements are independent of atmospheric conditions, and do not require any calibration with a solar analogue star. If the instrumental polarization is low and under control, the measurements may be perfectly reproducible by

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different instruments. However, spectropolarimetric techniques still allow us to obtain the reflectance spectra simultaneously, provided that the usual calibrations are performed, therefore they can nicely complement traditional spectrophotometric techniques.

6. Conclusions

It has been shown (Penttila *et al.* 2005 and references therein) that even in the small phase angle regime at which asteroids are usually observed, broadband linear polarimetry can produce taxonomic classes close to the spectroscopic taxonomy. Here we have suggested that spectropolarimetry offers a new degree of constraint for the characterization of the atmosphere-less bodies of our solar system, which complements spectro-photometry and should be taken into account for asteroid classification. Future attempts to model the surface structure of asteroids should take into account both reflectance and polarization spectra.

Acknowledgements

SB and AC gratefully acknowledge support from COST Action MP1104 "Polarimetry as a tool to study the solar system and beyond" through funding generously granted for Short Term Scientific Missions. The authors wish to thank Francesca DeMeo for Fig. 2.

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