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Review

Polarimetry of small bodies of the solar system with large telescopes

S. Bagnulo [a,*], I. Belskaya [b,c], H. Boehnhardt [d], L. Kolokolova [e], K. Muinonen [f,g], M. Sterzik [h], G.-P. Tozzi [i]

[a] Armagh Observatory, College Hill, Armagh BT61 9DG, UK
[b] Institute of Astronomy, Kharkiv National University, 35 Sumska Str., 61022 Kharkiv, Ukraine
[c] LESIA, Observatoire de Paris, 5, pl.Jules Janssen, 92195 Meudon cedex, France
[d] Max-Planck-Institut für Sonnensystemforschung, Max-Planck-Strasse 2, D-37191 Katlenburg-Lindau, Germany
[e] University of Maryland, College Park, MD, USA
[f] Department of Physics, University of Helsinki, P.O. Box 64, Gustaf Hällströmin katu 2a, FI-00014, Finland
[g] Finnish Geodetic Institute, P.O. Box 15, Geodeetinrinne 2, FI-02431 Masala, Finland
[h] European Southern Observatory, Alonso de Cordova 3107, Santiago, Chile
[i] INAF – Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125 Firenze, Italy

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ABSTRACT

During the last 10 years, the FORS instrument of the ESO very large telescope was regularly used to obtain broadband linear polarization measurements of small bodies of the solar system. In particular, FORS was the first (and so far unique) instrument that allowed us to explore polarimetrically objects of the solar system other than planets, moons, asteroids, and active comets. From 2002 to 2010, more than 150 h of telescope time were allocated for the observations of Centaurs, trans-Neptunian objects, and cometary nuclei. With a *R* magnitude between 16 and 21, these targets are probably the faintest objects of the solar system ever observed in polarimetric mode. In addition to these objects, polarimetric measurements were obtained for asteroids, active comets, Mars, the Saturn moon Iapetus, and the Moon earthshine. Here we present a review of these measurements, from the strategies adopted for the observations to the observational results.

Contents

1. Introduction

Polarimetric techniques have been routinely exploited to investigate the physical properties of the various bodies of the solar system. All planets of our solar system

* Corresponding author.
E-mail address: sba@arm.ac.uk (S. Bagnulo).

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have been subject of numerous polarimetric investigations (see, for instance [1] for an interpretation of the observed polarization of the light reflected by the Venus atmosphere, and [2,3] for a recent analysis of imaging and spectropolarimetric data of Uranus and Neptune). A very important aspect of the polarimetric studies of the planets is that they represent a benchmark for future polarimetric investigations of the surface structure and/or of the atmospheres of the extrasolar planets (e.g., [4] and references therein). For the minor bodies of the solar system, which, with the exception of a handful number of objects, are not visited in situ by space missions, polarimetry represents a unique and powerful remote sensing tool both for the determination of their albedo, and for the detailed understanding of their micro-structure.

Until about 10 years ago, all polarimetric studies of our solar system were limited to the Sun, the planets and some of their moons, asteroids, and comets when approaching the Sun. The advent of large telescopes has opened the possibility to extend these studies to smaller and fainter objects such as trans-Neptunian objects (TNOs), Centaurs, and cometary nuclei. Future instruments of the large telescopes, like, e.g., the SPHERE-ZIMPOL [5] for the ESO very large telescope (VLT) will provide great support for the search and analysis of reflected light from extrasolar planets.

The term "large telescope" is traditionally used for a telescope with mirror size ≥ 6 m. Up to now, the only few instruments equipped with optical polarimetric capabilities attached at a large telescope are FORS of the ESO VLT, FOCAS of the Japanese Subaru, and LRIS of the Keck telescopes. All these instruments work both as imagers and low resolution spectrographs, and are all attached at the Cassegrain focus, which greatly helps to minimize instrumental polarization. This review paper is entirely focused on the observations obtained with the FORS instrument of the ESO VLT, which, to our best knowledge, represent the large majority of polarimetric data of small bodies of the solar system obtained with a large telescope. Although not immune from some spurious signals, FORS instrumental polarization is generally $\leq 10^{-3}$. Therefore it appears suitable for high-precision imaging and spectropolarimetric observations. We also note that the large collecting area ($\sim 50\,\mathrm{m}^2$) is not the only important feature of the VLT units. Many polarimetric studies of the solar system bodies require target *monitoring*, that is, to perform a short observation (lasting typically between 0.5 and 2 h), and repeat it a few times on the same object over a period of several months. This observing strategy, which would be extremely unpractical in visitor mode, becomes feasible thanks to the option of performing an observing run in "service mode".

This paper is concentrated on the observing and data reduction techniques, and on the description of the main observational results. For a broader review on a similar subject see, e.g., the book by Mishchenko et al. [6] and references therein.

2. Instrument, observing strategies, and data reduction

The FORS instrument [7] is a multipurpose instrument of the ESO VLT capable of doing imaging and low resolutions spectroscopy (R=150–2000) in the optical range.

It is equipped with $\lambda/4$ and $\lambda/2$ retarder waveplates and a Wollaston prism, which splits the incoming light into two beams of opposite linear polarization (named "parallel beam" and "perpendicular beam", respectively). A Wollaston mask with nine 22 arcsec strips is used in polarimetric mode to avoid the superposition of the beams split by the Wollaston, following the scheme of Scarrott et al. [8]. Linear polarization measurements are obtained using the $\lambda/2$ retarder waveplate, and circular polarization measurements are obtained using the $\lambda/4$ retarder waveplate. Following the so-called "difference method", the reduced Stokes parameters $P_X = X/I$ (where X stands for Q and U), defined according to Shurcliff [9], are obtained by combining a series of exposures taken at different position angles of the retarder waveplate, using the following expression:

$$P_X = \frac{1}{2N}\sum_{j=1}^{N}\left[\left(\frac{f^{\parallel}-f^{\perp}}{f^{\parallel}+f^{\perp}}\right)_{\alpha_j} - \left(\frac{f^{\parallel}-f^{\perp}}{f^{\parallel}+f^{\perp}}\right)_{\alpha_j+45^\circ}\right] \quad (1)$$

where $f^{\parallel}$ and $f^{\perp}$ are the fluxes measured in the beams split by the Wollaston prism, N is the number of *pairs* of exposures and α_j denotes the position angle of the retarder waveplate: for X=Q, α_j belongs to the set {0°, 90°, 180°, 270°}; for X=U, α_j belongs to the set {22.5°, 112.5°, 202.5°, 292.5°}. Circular polarization measurements are obtained with a similar technique, but using the $\lambda/4$ retarder waveplate changing its position angle at 90° steps, starting from $\alpha = -45^\circ$.

Fig. 1 shows part of a field image obtained in linear polarimetric mode with FORS, with the $\lambda/2$ retarder waveplate position angle set at 0°. The field of view of each open slit of the Wollaston mask is projected onto the CCD in two parallel strips: the flux measured in the top strip of each pair is proportional to $I+Q$, and the flux

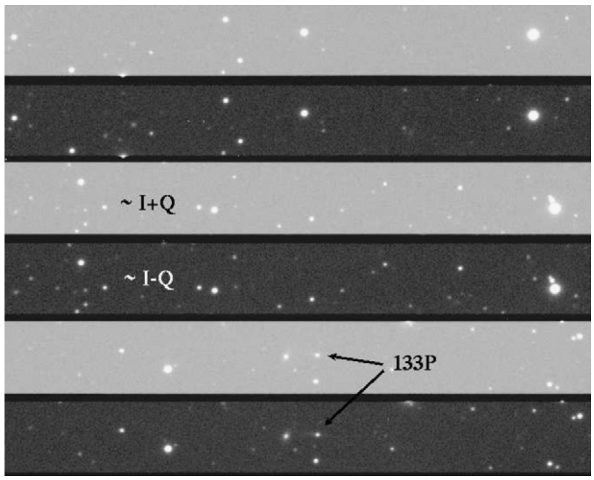

Fig. 1. A section of a field image obtained with FORS in polarimetric mode. The main target (its images in the parallel and in the perpendicular beams are pointed by the arrows) is the main-belt object 133P/Elst-Pizarro. Due to a nonnegligible lunar illumination, the sky is strongly polarized, and is responsible for the different background measured in the parallel and in the perpendicular beams.