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Discovery of two distinct polarimetric behaviours of trans-Neptunian objects ⋆

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ABSTRACT

Context. Trans-Neptunian objects (TNOs) contain the most primitive and thermally least-processed materials from the early accretional phase of the solar system. They allow us to study interrelations between various classes of small bodies, their origin and evolution.

Aims. We exploit the use of polarimetric techniques as a remote-sensing tool to characterize the surface of TNOs.

Methods. Using FORS1 of the ESO VLT, we have obtained linear-polarization measurements in the Bessell R filter for five TNOs at different values of their phase angle (i.e., the angle between the Sun, the object, and the Earth). Due to the large distance of the targets ($\gtrsim$ 30 AU), the observed range of phase angles is limited to about $0^\circ - 2^\circ$.

Results. We have analyzed our new observations of five TNOs, and those of another four TNOs obtained in previous works, and discovered that there exist two classes of objects that exhibit different polarimetric behaviour. Objects with a diameter > 1000 km, such as, e.g., Pluto and Eris, show a small polarization in the scattering plane (~ 0.5 %) which slowly changes in the observed phase angle range. In smaller objects such as, e.g., Ixion and Varuna, linear polarization changes rapidly with the phase angle, and reaches ~ 1 % (in the scattering plane) at phase angle 1°. The larger objects have a higher albedo than the smaller ones, and have the capability of retaining volatiles such as CO, N_2 and CH_4. Both of these facts can be linked to their different polarimetric behaviour compared to smaller objects.

Conclusions. In spite of the very limited range of observable phase angles, ground-based polarimetric observations are a powerful tool to identify different properties of the surfaces of TNOs. We suggest that a single polarimetric observation at phase angle $\sim 1^\circ$ allows one to determine whether the target albedo is low or high.

Key words. Kuiper Belt – dwarf planets – Polarization – Scattering

1. Introduction

For a long time, measurements of linear polarization have been exploited for the study and classification of the surfaces of small solar-system bodies e.g., particle size, complex refractive index, porosity, and heterogeneity are linked to the mechanism of light scattering.

A particularly interesting phenomenon is observed at small phase angles (the phase angle is the angle between the Sun, the object, and the Earth), where solar-system objects like comets, asteroids, satellites of major planets, and trans-Neptunian objects (TNOs) exhibit *negative polarization*. This is a peculiar case of partially linearly polarized scattered light where the electric field vector component parallel to the scattering plane predominates over the perpendicular component, in contrast to what is expected from the simple single Rayleigh-scattering or Fresnel-reflection model. Negative linear polarization was first discovered by Lyot (1929) in lunar observations, and later found to be a ubiquitous phenomenon for planetary surfaces at small phase angles. There are several physical mechanisms that explain the existence of negative polarization from scattering of light by particulate media, among which coherent backscattering (e.g. Muinonen 2004) is the most relevant one for the interpretation of TNO observations.

For many solar-system objects, it is possible to measure the behaviour of the polarization for an extended range of phase angles, and identify at least three important characteristics, i.e.: *i)* the slope of the polarimetric curve; *ii)* the minimum polarization; *iii)* the inversion angle at which the polarization changes from being parallel to the scattering plane and becomes, at larger phase angle values, perpendicular to the scattering plane. In contrast, ground-based polarimetric observations of TNOs can cover only a very limited phase-angle range (due to the large distance of these objects). The observed polarized light is always parallel to the scattering plane, and it is not possible, in general, to estimate the polarization minimum.

The first polarimetric observations of a TNO (except Pluto) were carried out by Boehnhardt et al. (2004) for 28978 Ixion. Within the very narrow range of the observed phase angles (0.2° – 1.3°), they revealed a pronounced negative polariza-

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Table 1. Polarimetry of five trans-Neptunian objects in Bessell R band. P_Q and P_U are the Stokes parameters transformed such that P_Q is the flux perpendicular to the plane Sun-Object-Earth (the scattering plane) minus the flux parallel to that plane, divided by the sum of the two fluxes.

Date (yyyy mm dd)	Time (UT) (hh:mm)	Exp (sec)	Object	Phase angle (DEG)	P_Q (%)	P_U (%)
2008 01 09	06:07	6000	26375 (1999 DE$_9$)	1.412	−1.39 ± 0.12	0.00 ± 0.12
2008 03 09	06:07	6000		0.110	−0.20 ± 0.11	0.08 ± 0.11
2008 03 29	03:19	6400		0.519	−0.66 ± 0.11	−0.16 ± 0.11
2008 07 08	09:20	2880	136199 Eris	0.600	−0.11 ± 0.05	0.04 ± 0.05
2008 09 07	03:40	2880		0.379	0.03 ± 0.05	0.12 ± 0.05
2007 05 10	01:54	3760	38628 Huya	0.614	−0.73 ± 0.07	−0.04 ± 0.07
2007 05 18	04:19	3760		0.831	−0.58 ± 0.07	0.08 ± 0.07
2007 07 17	01:44	3760		1.984	−1.61 ± 0.07	0.00 ± 0.07
2008 03 05	07:40	6000		1.624	−1.27 ± 0.06	0.05 ± 0.06
2008 05 30	04:54	5120		1.115	−1.10 ± 0.06	0.04 ± 0.06
2006 11 26	07:05	5800	20000 Varuna	0.91	−1.04 ± 0.12	0.08 ± 0.11
2006 12 14	06:03	5800		0.572	−0.45 ± 0.15	−0.11 ± 0.14
2007 01 13	02:55	5800		0.135	−0.22 ± 0.10	0.04 ± 0.10
2008 03 29	01:10	7200		1.301	−1.18 ± 0.13	0.06 ± 0.13
2008 08 09	23:59	960	136108 Haumea	0.987	−0.68 ± 0.06	−0.02 ± 0.06

tion changing rapidly as a function of the phase angle. Since then, three other TNOs have been the subject of a detailed study: 29981 (1999 TD$_{10}$) (Rousselot et al. 2005), 50000 Quaoar (Bagnulo et al. 2006), and 136199 Eris (Belskaya et al. 2008). Belskaya et al. (2008) noted that the available polarimetric data for TNOs show negative polarization with two different trends at small phase angles. Only a small fraction of linear polarization is measured in the largest objects Pluto, 136199 Eris, and 50000 Quaoar, with only subtle changes as a function of phase angle. This is in contrast with the steep gradient of about −1 % per degree that was measured for 28978 Ixion.

In this paper we present 13 observations of another four TNOs, and two new observations of 136199 Eris. These new data allow us to generalize the finding by Belskaya et al. (2008).

2. Observations

Fifteen new broadband linear polarization measurements of five TNOs were obtained from November 2006 to September 2008 at the ESO Very Large Telescope (VLT) with FORS1 (Appenzeller et al. 1998). Using the R Bessell filter, we obtained two new measurements of Eris, that was already observed by Belskaya et al. (2008), and thirteen measurements of 26375 (1999 DE$_9$), 38628 Huya, 136108 Haumea (2003 EL$_{61}$), and 20000 Varuna, that were never before observed in polarimetric mode.

The heliocentric distance of the observed TNOs is $\gtrsim 30$ AU. As a consequence, the observable phase-angle range is very limited, compared to what can be achieved for most asteroids and comets. The phase angle range that was sampled is $\lesssim 2°$ for all newly observed TNOs.

We aimed at obtaining polarization measurements with error bars between 0.05 % and 0.1 %, which requires a signal-to-noise ratio between 1000 and 2000 (cumulated on both beams and all positions of the retarder waveplate). Since our targets are faint ($R \sim 18-20$), these observations were possible only by using an 8-m telescope. In order to optimize the phase-angle sampling, our observations were scheduled in service mode. Observing blocks were planned so as to avoid too bright a background due to lunar illumination, and to avoid epochs when targets were too close to bright stars.

Polarimetric observations were generally performed with the retarder waveplate at all positions between 0° and 157.5°, at 22.5° steps. For each observation, the exposure time cumulated over all exposures varied from 24 minutes (for 136199 Eris) to 2 h (for 20000 Varuna). Raw data were then treated as explained in Bagnulo et al. (2006), and our measurements are reported adopting as a reference direction the perpendicular to the great circle passing through the object and the Sun. This way, P_Q represents the flux perpendicular to the plane Sun-Object-Earth (the scattering plane) minus the flux parallel to that plane, divided by the sum of these fluxes. For symmetry reasons, P_U values are always expected to be zero, and inspection of their values allows us to perform an indirect quality check of the P_Q values.

Our new polarimetric measurements are given in Table 1. These data have enlarged the number of TNOs for which polarimetric observations are available by a factor of two. Previously published data, that will be also considered in our analysis, include seven measurements of Pluto (Breger & Cochran 1982), nine measurements of 28978 Ixion (Boehnhardt et al. 2004), five measurements of 29981 (1999 TD$_{10}$) (Rousselot et al. 2005), five measurements of 50000 Quaoar (Bagnulo et al. 2006), and four measurements of 136199 Eris (Belskaya et al. 2008). For the sake of consistency, data of 29981 (1999 TD$_{10}$) were re-reduced adopting exactly the same reduction procedure as for the remaining observations obtained with FORS1, leading to values only slightly different from the previously published ones.

All data considered here, except for Pluto, were obtained with the FORS1 instrument with the Bessell R filter. Pluto's polarimetry refers to a filter similar to Bessell V. We note that Bagnulo et al. (2006) obtained polarimetric measurements of the Centaur Chiron in the Bessell B, V, and R bands at six different phase angles. At each phase angle, the polarimetric measurements obtained in the three different bands appear relatively consistent among themselves. A similar behaviour was found for 29981 (1999 TD$_{10}$) that was observed both in the Bessell R and V filters by Rousselot et al. (2005). Additional measurements of Pluto obtained by Kelsey & Fix (1973) and Avramchuk et al.

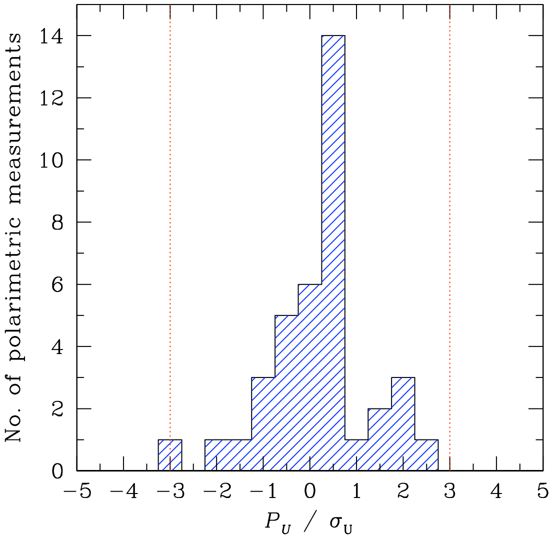

Fig. 1. Distribution of the P_U values normalized to their error bars. The null detection of P_U values serves as a quality check for the P_Q measurements of Fig. 2.

(1992) with no filter are also consistent with those by Breger & Cochran (1982). This suggests that even though Pluto polarimetry was obtained in a different band than the other TNOs, its comparison with new data obtained in the *R* band is still meaningful.

It should also be recalled that Pluto is in fact a double system. Yet, in the observed phase-angle interval, Pluto's intrinsic polarization is confined within the range −0.35 % and −0.1 %, for the following reason. We denote with Q the Stokes parameter not normalised to the intensity I, and with $P_Q^{(\mathrm{P})} = Q^{(\mathrm{P})}/I^{(\mathrm{P})}$ and $P_Q^{(\mathrm{C})} = Q^{(\mathrm{C})}/I^{(\mathrm{C})}$ Pluto's and Charon's intrinsic polarization, respectively. We can assume that, at each phase angle, Pluto, Charon, the Sun, and the Earth define an identical scattering plane, so that $P_Q^{(\mathrm{P})}$ and $P_Q^{(\mathrm{C})}$ are expressed in the same reference system. This allows us to write, for the observed polarization of the double system, $P_Q^{(\mathrm{P+C})} = (Q^{(\mathrm{P})} + Q^{(\mathrm{C})})/(I^{(\mathrm{P})} + I^{(\mathrm{C})})$. Taking into account that the ratio between the reflected light of the two objects is ∼ 0.17, we deduce that

$$P_Q^{(\mathrm{P})} = P_Q^{(\mathrm{P+C})} + 0.17\,(P_Q^{(\mathrm{P+C})} - P_Q^{(\mathrm{C})})\,. \tag{1}$$

Assuming that Charon has $-1.5\,\% \lesssim P_Q^{(\mathrm{C})} \lesssim 0\,\%$, and considering for the total polarization its mean value of −0.3 %, Eq. (1) tells us that $P_Q^{(\mathrm{P})}$ ranges between −0.35 % (in the case of $P_Q^{(\mathrm{C})} = 0$) and ≃ −0.1 % (in the case of $P_Q^{(\mathrm{C})} = -1.5\,\%$).

Some polarimetric measurements are close to the limit of instrumental polarization, which in FORS1 is $\lesssim 0.04\,\%$ (Fossati et al. 2007). Instrumental polarization is difficult to subtract from science data, since it depends on the instrument setting and telescope orientation but, for the same reason, we can assume that instrumental polarization does not introduce any *systematic* offset. An indirect confirmation that instrumental polarization does not introduce systematic offsets comes from inspection of the measured P_U values. Figure 1 shows the distributions of the P_U values for all objects observed with FORS1 expressed in error bar units (for most of new data between 0.05 % and 0.12 %). Due to the relatively limited number of measurements (38) we cannot expect to reproduce a Gaussian distribution. Yet, the fact that the P_U distribution is roughly centered at zero, and all points are within $-3 \le P_U/\sigma_U \le 3$, fully supports the reliability of the polarimetric measurements.

Figure 2 shows the P_Q values as a function of the phase angle measured for all data reported in Table 1, and those previously published listed above. The left panel of Fig. 2 refers to the larger TNOs 136199 Eris, Pluto, 50000 Quaoar, and 136108 Haumea. The right panel shows the polarization phase angle dependence for the remaining objects: 28978 Ixion, 38628 Huya, 26375 (1999 DE$_9$), 29981 (1999 TD$_{10}$), and 20000 Varuna.

3. Results and discussion

Figure 2 shows that larger TNOs exhibit a small fraction of negative linear polarization roughly constant in the observed phase angle range. As far as 136108 Haumea is concerned, the only conclusion that can be drawn from its single measurement is that the polarization is very similar to that measured for Quaoar and higher (in absolute value) than that of Pluto and 136199 Eris. Whether its phase angle dependence resembles that of other large objects will have to be checked with new observations. Our new polarimetric measurements of Eris, which were obtained with a higher accuracy than before, confirmed our previous findings about its small negative polarization (Belskaya et al. 2008) and expanded the observed phase angle range to the maximum range presently reachable for this distant object. In particular, a previous observation obtained at the phase angle of 0.35° showed the strongest negative polarization for this object (∼ −0.3 %, see Belskaya et al. 2008), whereas our new measurement obtained at a similar phase angle is practically consistent with zero. Therefore we cannot confirm the presence of a negative polarization surge around that phase angle.

The new observations of the classical TNOs 20000 Varuna, 38628 Huya and the scattered-disk object 26375 (1999 DE$_9$) reveal a pronounced negative polarization changing rapidly with phase angle and reaching about −1 % at the phase angle of 1°. Similar polarization behaviour was previously found for the resonant object 28978 Ixion by Boehnhardt et al. (2004), who pointed out that this object exhibits the most pronounced negative polarization measured for a solar-system body so far, and raised the question of whether this was a unique case or typical for TNOs. Our new observations have proved that the high negative polarization at small phase angles is quite typical for TNOs, as three newly observed objects have shown a polarimetric behaviour similar to that of Ixion. In fact, all four "small" TNOs together show a strikingly similar polarimetric behaviour that is practically indistinguishable within the error bars.

Data for 29981 (1999 TD$_{10}$) (Rousselot et al. 2005) extend up to phase angle ∼ 3°. In the phase-angle range 0° − 2°, the observed polarization behaviour is consistent with those of the other small objects, but this should be confirmed by a more refined sampling of this range. At phase angles 2° and 3° the observed polarization is about −1 %, which suggests a polarization minimum in that range. Observations of Centaurs Chiron obtained at larger phase angles compared to TNOs reveal a polarization minimum in the range ∼ 1.5° − 2° (Bagnulo et al. 2006), and new unpublished observations suggest a similar behaviour for Centaur Pholus (Belskaya et al., in preparation). All this leads us to speculate that the minimum of polarization of TNO phase curves are at phase angles slightly larger than 1.5°, perhaps between 1.5° and 3°, which would be noticeably different from that of asteroids and comets, that show a minimum between 7° and 10° (see, e.g., Penttilä et al. 2005).

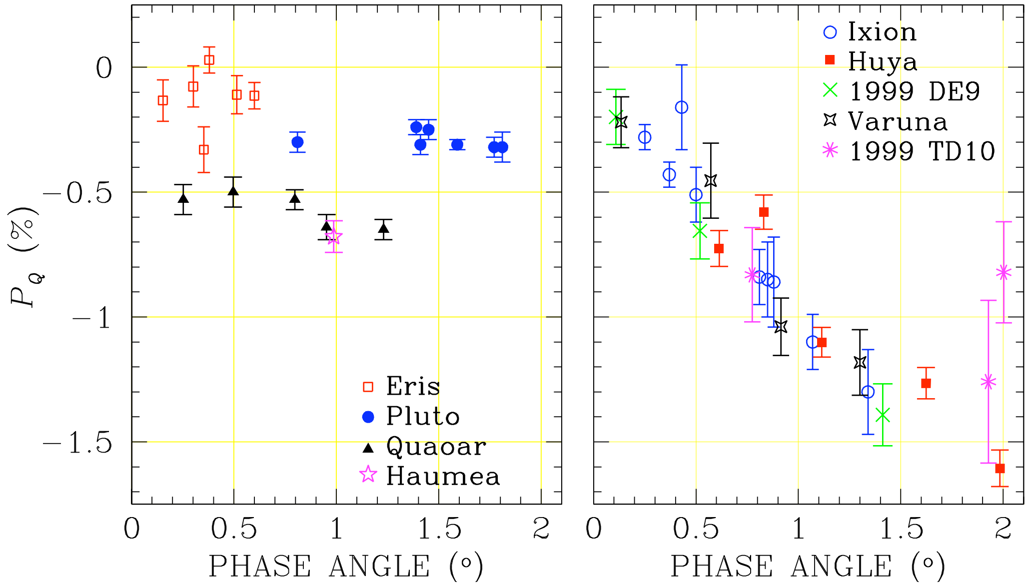

Fig. 2. Linear-polarization measurements of nine TNOs as a function of the phase angle.

In spite of the very limited observed phase angle range, polarimetric observations of TNOs reveal two different behaviours. TNOs with a diameter smaller than 1000 km exhibit a negative polarization that rapidly increases (in absolute value) with the phase angle, reaching about 1 % at the phase angle of 1°. Larger TNOs exhibit a small fraction of negative linear polarization ($\lesssim 0.7$ %) which does not noticeably change in the observed phase angle range.

It is quite natural to associate the two different behaviours of polarization phase dependencies with a different composition and/or structure of the surfaces of the objects. The two groups of objects with different polarimetric properties differ not only in size but also in surface albedo, which is higher in the larger objects than in the smaller ones. Although uncertainties in TNO albedo determination are quite large, it is evident that darker surfaces exhibit higher negative polarization than brighter surfaces. This trend resembles the dependence of the polarization minimum on the albedo found for asteroids, but the lack of accurate albedo data prevents us from attempting to obtain firm relationships between albedo and polarization such as those obtained for asteroids (e.g., Lupishko & Mohamed 1996). Yet, even a single measurement of linear polarization of a TNO at phase angle ~ 1° can provide at least a distinction between high- and low-albedo surfaces.

At first glance, our results seem contradictory to the predictions of the coherent-backscattering mechanism considered to be the most probable cause of negative polarization at small phase angles. The coherent-backscattering mechanism results in a sharp surge of negative polarization accompanied by narrow brightness opposition peaks that should be more prominent for the brighter surfaces. Such surges were found for bright satellites and asteroids with a peak polarization of about −0.4 % centered at the phase angle of 0.2° − 1° (for a review, see Mishchenko et al. 2006). The observations of Eris and Pluto do not show opposition surges in polarization or brightness in the phase-angle ranges covered (down to 0.15° and 0.80°, respectively). The observations can, however, be well explained by a narrower width of the coherent-backscattering opposition surges for large TNOs as compared to those observed for satellites and asteroids (see discussion in Belskaya et al. 2008). Note that, according to laboratory measurements, some bright powdered samples also do not show a negative-polarization surge in the phase-angle range of 0.2-4 deg (see Shkuratov et al. 2002).

Perhaps the most important difference between the surface characteristics of the objects that exhibit a different polarimetric behaviour is that the TNOs with small and constant negative polarization are supposed to have the capability of retaining volatiles such as CO, N_2 and CH_4 (Schaller & Brown 2008). 136199 Eris and Pluto have methane rich surfaces. The other two objects 136108 Haumea and 50000 Quaoar, with slightly higher polarization (in absolute value), exhibit dominantly water ice spectra, and are believed to be in a transition phase where not all volatiles are lost yet (Brown 2008). This evolutionary phase may explain their different albedo, as well as their different polarimetric behaviour compared to smaller objects, which have certainly lost the volatile components.

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