Polarimetry of Centaurs (2060) Chiron, (5145) Pholus and (10199) Chariklo

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Abstract

Results of the first polarimetric observations of Centaurs (5145) Pholus and (10199) Chariklo, and new observations of (2060) Chiron are presented together with the estimates of their absolute magnitudes. Observations were carried out at the 8 m ESO Very Large Telescope in 2007-2008. They revealed noticeable negative polarization in the phase angle range 0.5-4.4 deg with a minimum varying from -1% to -2.1% in the R band. All three objects show diverse polarization phase angle behaviour, each distinctly different from that of transneptunian objects. We found evidence of surface heterogeneity for Chariklo while Chiron and Pholus appear to have rather homogeneous surfaces. Polarization phase behaviours of Chiron and Pholus are significantly different from any other Solar system bodies studied so far. A shift of negative polarization minima toward small phase angles seems to be a characteristic feature of polarization properties of Centaurs. Presence of a small amount of water frost on a dark surface is considered as one of the possible ways to explain these properties.

Key Words: Centaurs, transneptunian objects, polarimetry, photometry, surface properties.

1. Introduction

Polarimetry is a powerful tool for investigating the physical properties of Solar system bodies. The intricate inverse problem to constrain surface properties from phase-angle-resolved polarimetry and photometry is almost the only way to assess the microscopic properties of the surface from remote observations. The study of polarimetric properties of transneptunian objects (TNOs) and Centaurs is in its early stages. The first polarimetric observations for a transneptunian object (except Pluto) were carried out in 2002 with the FORS1 instrument at the 8 m Very Large Telescope (VLT) by Boehnhardt et al. (2004). These observations have demonstrated both the capability of the instrument to provide good-quality observations of faint objects (~20^m), and the capability of the polarimetric technique to study distant objects even if they are observable only at very small phase angles. Successive polarimetric observations were carried out for Centaur (2060) Chiron and a classical TNO (50000) Quaoar by Bagnulo et al. (2006) and for a scattered disk object 29981 (1999 TD_{10}) by Rousselot et al. (2005). The obtained data have shown a noticeable diversity in the behavior of their polarization phase dependences.

New polarimetric observations were made within the context of the ESO VLT Large Programme 178.C-0036 in 2006-2008 with the aim to probe surface properties of objects from different dynamical groups and to make conclusions on their similarities and differences. The obtained results on two dwarf planets and three TNOs were published by Belskaya et al. (2008a) and Bagnulo et al. (2008). The analysis of these data together with the data on four other TNOs obtained in the previous works led to the conclusion on two different types of polarization phase behaviors for TNOs (Bagnulo et al. 2008). It was found that objects with diameters D>1000 km show modest negative polarization slowly changing in the phase-angle range observed. Smaller objects display mutually similar phase dependencies with rapid changes in linear polarization reaching -1% at phase angle of 1 deg. The different types of polarimetric behavior have been suggested to be related to different albedos and different capability of retaining volatiles for large and small TNOs (Bagnulo et al. 2008).

In this paper, we present and analyze polarimetric observations of three Centaurs and will show their diverse polarization phase-angle behaviour different from that of TNOs.

2. Observations and results

Polarimetric observations of selected Centaurs were made during an observing period from March 2007 to October 2008 within the ESO-VLT Large Program. Measurements of the linear polarization were carried out with the FORS1 instrument in the Bessell R filter. Taking advantage of the flexibility offered by the VLT service observing mode, we distributed the observations along the observing period to cover the maximum possible range of phase angles and to obtain a good phase angle sampling. Polarimetric observations and their reduction were performed in the same way as in our previous observations published by Bagnulo et al. (2006, 2008) and Belskaya et al. (2008a). To derive the values of the Stokes Q and U parameters we used observations obtained with a half-wave retarder plate at all positions between 0 and 157.5° at 22.5° steps. The possible sources of instrumental errors were thoroughly investigated. The detailed description of reduction procedure can be found in Bagnulo et al. (2006).

Results of our polarimetric observations are given in Table 1, which contains the epoch of the observations (date and UT), the exposure time, the phase angle, the measured Stokes parameters P'_Q and P'_U, transformed relative to the scattering plane, and their uncertainties. The transformation was made in such a way that P'_Q is equal to the flux perpendicular to the scattering plane minus the flux parallel to that plane, divided by the sum of the two fluxes, to represent the value of the polarization degree in the coordinate system referring to the scattering plane. The parameter P'_U characterizes a declination of the polarization plane position from a normal plane to the scattering plane. It equals zero when the position angle of the polarization equals to 90°. One can see from Table 1 that the P'_U values are always close to zero within uncertainties of the measurements which can be also considered as an indicator that the obtained data is of good quality.

Acquisition images were also used to measure the objects' magnitudes. To calculate calibrated magnitudes we used zeropoints obtained during the night when our observations were executed and the extinction coefficient K_R and the colour term k_{VR} available at **http://archive.eso.org/** for the various observing periods. We associated a minimal error of 0.05 mag to the photometry, which is consistent with the zero points of the calibration plan, while the errors of photon noise and background being negligible in comparison with those of the zero points. Measured magnitudes and their errors are given in Table 2 which also includes the date and UT at the start of observations, the helio- and geocentric distances, the phase angle, and the magnitudes R(1,1,α) reduced to the unit distances to the Sun and the Earth.

All images obtained have been checked for a possible coma presence. At first look, no coma is detectable in the images. A thorough analysis of the images for setting upper limits on the possible coma for all three objects is given by Tozzi et al. (2010).

Below, we describe the results of our observations for each object.

2.1. (2060) Chiron

Chiron is the first Centaur which was observed using the polarimetric technique (Bagnulo et al. 2006). Observations were performed in 2004 with FORS1 at the VLT and covered the phase angle range of 1.4-4.2°. They showed a pronounced branch of negative polarization with a minimum of about -1.4% occurred at phase angles less than 2°. New observations were planned in order to determine more precisely the position of polarization minimum α_{min} and to check whether polarization characteristics of Chiron's surface are invariable.

Our observations were carried out in the phase angle range of 0.5-2.9° in 2007 and 2008 with a high accuracy (see Table 1). The composite polarization-phase dependence of Chiron which includes observations in all three apparitions is shown in Fig.1. New observations reveal a good agreement with the previous ones within the observational errors. We have not found any noticeable variations in the polarization degree of Chiron's surface with heliocentric distance which changed from 12.8 AU in 2004 to 15.5 AU in 2008. To estimate polarization parameters we fitted the data by a so-called trigonometric fit proposed by Lumme and Muinonen (1993):

$$P(\alpha) = b \sin^{c_1} \alpha \cos^{c_2} \frac{1}{2} \alpha \sin(\alpha - \alpha_0),$$

where b and inversion angle α_0 are considered as free parameters while parameters c_1 and c_2 can be fixed for various classes of Solar system objects. The main advantage of the function is that it gives physically reasonable behaviour of the polarization phase dependence in a wide range of phase angles and thus can be used for its prediction (e.g. Pentillä et al. 2005). According to Lumme and Muinonen (1993) the parameter c_2=0.35 for all considered objects (asteroids, comets, satellites) while c_1 =0.7 for asteroids and c_1 =0.5 for other objects. The best fit of Chiron's data shown in Fig.1 by a dashed line was obtained for c_1 =0.3 and c_2=0.35. It gives P_{min} =-1.37% at α_{min}=1.5° and predicts the inversion angle α_{inv}=6.7°. Another estimation of the inversion angle can be achieved by using a linear fit to the data obtained at the ascending branch of polarization phase dependence. The use of a linear fit is reasonable because of typically small curvature of the ascending branch of polarization phase curves (e.g. Zellner and Gradie 1976). The linear fit to the data obtained at phase angles larger than 2° is shown in Fig.1 by the dotted line. It predicts the inversion angle of 8.5°.

Note that the above-mentioned estimates of the inversion angle of Chiron are valid in the assumption of a regular shape of its polarization phase dependence as observed for a majority of Solar system bodies. Only few high-albedo objects were found to show irregular shape of the polarization curve with a secondary minimum at small phase angles believed to be caused by the coherent backscattering enhancement (Mishchenko et al. 2006). According to the numerical modeling (Belskaya et al. 2008b) if such a peak exists for Chiron it should appear at phase angles less than 0.5º. We have not reached such small phase angles in our observations and can neither confirm nor decline predictions of the modeling.

Previous photometric observations of Chiron have shown considerable variations of its brightness with heliocentric distance caused by a cometary-like outburst activity (see Bus et al. 2001, Duffard et al. 2002 and references therein). Variations of Chiron's absolute magnitude in the V band versus time and heliocentric distance are shown in Fig. 2. They include the published data up to 2001 (Bus et al. 2001, Duffard et al. 2002) which have been extended to 2008 using the magnitude estimates from our observations. To calculate absolute magnitudes, we used V-R=0.36 for the observations in the R band (for references, see Barucci et al. 2005) and the phase coefficient of 0.06 mag/deg.

Peaks of Chiron's brightening were observed in 1975 near aphelion at 18.4 AU, in 1989 at about 12.5 AU, and in 2001 at about 10.6 AU. One can see that our observations are near the maximum of Chiron's brightness and demonstrate almost the same absolute magnitude H_v=5.82**±0.07** as at the previous peak in 1989 when H_v was equal to 5.7-5.9 mag (Meech and Belton 1990, Hartmann et al. 1990). However, unlike the previous brightening the absolute magnitude remains practically unchanged in 2004-2008 while the heliocentric distance changed from 12.8 AU to 15.5 AU. It means that the new and previous outbursts seem to have different nature.

Since variations of Chiron's magnitude due to rotation were found to be small, not exceeding 0.09 mag (see Groussin et al. 2004 and Table 2) we can use the obtained data to estimate the slope of the magnitude-phase dependence. A linear fit to the 2004-2008 data gives the phase coefficient of 0.06±0.01 mag/deg. This value is consistent with the previous one based only on 2004 data (Bagnulo et al. 2006).

2.2. (5145) Pholus

Polarimetric observations of Pholus were carried out in 2007-2008 at four phase angles in the range of 0.9-2.6°. Its apparent magnitude was 19.7 in the R-band which required about two hours of exposure time to measure the polarization degree with an accuracy better than 0.1%. However, the real uncertainties of our polarimetric measurements varied from 0.13% to 0.2% (see Table 1), because of considerable changes in Pholus' brightness due to its rotation. The lightcurve amplitude of Pholus was found to vary from 0.15 mag (Buie and Bus 1992) to 0.6 mag (Tegler et al. 2005). Using the pole coordinates given by Farnham (2001) we have found that our observations were close to the equatorial aspect where the lightcurve amplitude reached its maximum.

The measured linear polarization degree versus phase angle is shown in Fig.3. For comparison we also show the best fit to Chiron's phase curve. One can see that Pholus' surface is characterized by a deeper and apparently wider negative branch of polarization compared to that of Chiron. The polarization minimum occurs at phase angles of about 2.5º deg or larger. The values of linear polarization obtained in 2007 and 2008 at phase angles of 2.6º and 2.3º, respectively, are well consistent. During our observing campaign we reached the maximum phase angle at which Pholus can be observed from the Earth. At present Pholus is on its path to the aphelion and the range of observable phase angles will be smaller for the next few decades. In spite of a limited phase angle range our observations have clearly demonstrated a deep branch of negative polarization inherent for Pholus and its distinct difference from that of Chiron.

Our magnitude estimates in the R band (see Table 2) can not be used to determine the phase slope since they were contaminated by large short-term brightness variations due to rotation. However the mean absolute magnitude H=7.83±0.12 is consistent with that determined in 2000 by Farnham (2001) and excludes large variation of absolute magnitude with time as found for Chiron and Chariklo. To calculate the absolute magnitude of Pholus, we used V-R=0.77 mag (for references, see Barucci et al. 2005) and a phase coefficient of 0.083 mag/deg. The phase coefficient was determined by the linear fit to the data of Buie et al. (1992) in the phase angle range of 0.7-3.9°.

2.3. (10199) Chariklo

Polarimetric observations of Chariklo were carried out in 2007-2008 in the phase angle range of 2.7-4.4°. They revealed noticeable negative polarization that varied slightly with the phase angle. The measured linear polarization degree versus phase angle for Chariklo together with Chiron's phase curve is shown in Fig.4. Chariklo's polarization is smaller in absolute terms and has a smaller gradient compared to that observed for Chiron within the same phase angle range. Slow changes of Chariklo's polarization with the phase angle allow us to assume that the observations may be related to the vicinity of polarization minimum. We can give its tentative estimate as P_{min} ~ −1%. Note that the overall scatter of the data seen in Fig.4 is higher than the estimated errors of individual nights and can indicate possible changes of polarization degree over the surface. At present the rotational period of Chariklo remains undetermined. Noticeable short-term brightness variations in magnitude were not detected while Peixinho et al. (2001) reported considerable differences in Chariklo's magnitude between two observing runs. Dotto et al. (2003) found slight spectral variations between two observing runs and assumed possible surface heterogeneity of Chariklo. Further spectral observations in the range of 1.5-2.4 μm revealed strong compositional heterogeneity over Chariklo's surface (Guilbert et al. 2009).

We compiled the available measurements of Chariklo's magnitudes in the V and R bands and calculated absolute magnitudes in the V band assuming V-R=0.48 mag (for references, see Barucci et al. 2005) and the phase coefficient of 0.06±0.01 mag/deg. The phase coefficient was calculated using observations in 2000-2001 by Bauer et al. (2003), which were almost unaffected by either short-term or long-term brightness variations. A linear fit to the data in the range of 1.2-4.1° gave a phase coefficient of 0.06±0.01 mag/deg, which coincides with that for Chiron.

The absolute magnitude of Chariklo versus time is shown in Fig. 5 which includes also references to the original data. One can see that the data from different sources are in good agreement within the error bars. They show a gradual decrease of Chariklo's brightness of about 0.6 mag over the ten years. There are two possible explanation of such brightness behaviour. First, there could be cometary processes similar to those observed for Chiron although they would be weaker because the change in the heliocentric distance is small (13.1-13.8 AU). Second, the observations in 1999 were made at pole-on geometry while in 2008 they were close to the equatorial view. This assumption explains an absence of noticeable short-term brightness variations in 1999-2000 when Chariklo was extensively observed to search for its rotation period (McBride et al. 1999, Peihinxo et al. 2001) and the detection of surface heterogeneity in 2007-2008 (Guilbert et al. 2009). The assumption of pole-on aspect in 1999 gives the pole coordinates of Chariklo λ~140° and β~−10° and the aspect angle of about 70-75° in 2007-2008. The large aspect changes can be responsible for the observed differences in Chariklo's magnitude and spectra, particularly various depths of the water ice absorption band at 2 μm. Spectral measurements in 2007-2008 did not show the water ice absorption band detected in Chariklo's spectra in 1997-2001 (see Guilbert et al. 2009 for details). Within our assumption of pole-on aspect in 1999, the measured spectral differences can be explained as the polar surface having larger amounts of water ice compared to the equatorial surface.

3. Discussion

Our observations of selected Centaurs have clearly demonstrated a great diversity in their polarization properties. To understand what properties may be responsible for such diversity we have summarized the orbital and physical parameters of these objects in Table 3. It contains values of different parameters compiled from the literature with corresponding references and values of polarization parameters found in the present work.

All three objects have been thoroughly studied by different techniques and are representative of the Centaur population. Chiron and Pholus represent extreme cases of reflectance spectra as the "blue-est" and "reddest" objects among Centaurs. Chariklo has a reflectance spectrum with an intermediate slope closer to that of Chiron. Chiron is known to show a sporadic cometary activity while for the two other Centaurs no dust comae in optical images was found (see Jewitt 2009). The water ice absorption bands were detected in spectra of all three objects although the quality of spectra does not allow a distinction between amorphous and crystalline water ices (for review see Barucci et al. 2008). According to Cruikshank et al. (1998) Pholus can have frozen methanol on its surface which is indicative of its chemically primitive composition.

Although physical properties of these objects are rather diverse, the observed difference in their polarimetric characteristics is enormous compared to other classes of Solar system bodies. To demonstrate this, we plotted the depth of negative polarization versus the phase angle of polarization minimum for a variety of Solar system bodies (Fig.6) and polarization phase curves measured for Solar system bodies with surface albedos similar to that of the Centaurs (Fig.7). We took into consideration all available polarimetric data for various classes of Solar system bodies which include asteroids (Cellino et al. 2005, Fornasier et al. 2006, Lupishko and Vasilyev 2008), comets (Kiselev et al. 2010, Boehnhardt et al. 2008), including the main belt comet Elst-Pizarro (Bagnulo et al. 2010), transneptunian objects (Bagnulo et al. 2008), the Moon (Dollfus and Bowell 1971), Mars' satellite Deimos (Noland et al. 1973), Jupiter's satellites Europa, Callisto (Rosenbush and Kiselev 2005) and J7 Himalea (Degewij et al. 1980), and Saturnian satellite Iapetus (Zaitsev and Kiselev 2009). These data were obtained in the V and/or R photometric bands. As was shown by numerous observations, the wavelength dependence of the negative polarization in the wavelength range covered by these two bands does not typically exceed observational errors (e.g. Jockers and Kiselev, 2002; Bagnulo et al, 2006; Belskaya et al. 2009). The parameters P_{min} and α_{min} were calculated from the original observational data fitted by Lumme and Muinonen function (Lumme and Muinonen 1993). Most of the objects observed so far exhibit polarization minima at the phase angles 7-11º. A shift of minima toward small phase angles for high-albedo E-type asteroids and high albedo satellites is usually explained as a manifestation of the coherent backscattering mechanism (e.g., Mishchenko et al. 2006).
Among low and moderate albedo objects only Centaurs and the dark side of Saturnian satellite Iapetus are characterized by smaller values of α_{min}. Note that in the observations of the nucleus of comet Encke the position of polarization minimum is not well-constrained (Boehnhardt et al. 2008). But it certainly occurs at a smaller phase angle than the one observed for comets with a significant coma as in the case of comet Halley. It is probable that polarization phase curves of TNOs also have minima at small phase angles. We have no possibility to verify this by direct measurements due to the limited geometry of Earth-based observations. However, the existence of different trends for darker and brighter surfaces (Bagnulo et al. 2008) may indicate that the minimum of the negative polarization of TNOs lies at small phase angles (see discussion below). All four relatively dark TNOs exhibit similar phase-angle dependences of polarization (Bagnulo et al. 2008) unlike those measured for three Centaurs, each of which has their unique phase dependences. Differences in the polarization phase behaviours between different objects are clearly seen in Fig.7.

On the basis of the comparison of the polarimetric data of Centaurs and other classes of Solar system bodies the following conclusions can be made:

1) the diversity of the negative polarization values measured for three Centaurs is as large as the diversity in P_{min} among a variety of low and moderate albedo asteroids;

2) all three Centaurs show polarization properties different from those measured for transneptunian objects;

3) Chiron is characterized by the smallest phase angle at which the minimum of negative polarization occurs as compared to any other Solar system object observed thus far;

4) Pholus shows the deepest negative polarization branch at small phase angles measured so far for a Solar system object;

5) Chariklo's polarization properties do not differ much from those of asteroids and comets measured at the same phase angles and can be similar to the polarization characteristics of the dark side of Saturn's satellite Iapetus and the nucleus of comet Encke.

All these conclusions give evidence of diversity and particularity of polarization properties of Centaurs. What surface properties may be responsible for these polarimetric peculiarities? A behavior of linear polarization degree versus phase angle strongly depends on properties of the top surface layer such as the complex refractive index, particle size, packing density, microscopic optical heterogeneity etc. The physical parameters define observable parameter such as the geometric albedo of the surface. Typically the depth of the negative polarization branch $P_{\min}$ strongly depends on the surface albedo, increasing for low albedo surfaces. The relationship $P_{\min}$ and albedo p_V found for both telescopic observations and laboratory measurements is widely used to estimate asteroid surface albedo (e.g. Zellner et al. 1977). It was also shown that for very dark surfaces ($p_V \leq 0.06$) the depth of negative polarization begins to "saturate", i.e., it remains approximately constant or decreases when albedo decreases (Zellner et al. 1977, Belskaya et al. 2005).

The relationship between $P_{\min}$ and albedo for Centaurs and TNOs is shown in Fig.8. The depth of the negative polarization branch tends to increase when albedo decreases. This trend resembles that found for asteroids. Two objects, Chariklo and Haumea, are outside of the general trend. It is possible that the relatively small negative polarization branch of Chariklo which is the darkest object in the sample can be explained by the same reason as for very dark asteroids (see Belskaya et al. 2005). As for Haumea, the object could have a lower albedo of a part of its surface (Lacerda 2009).

Note that values of $P_{\min}$ are not well-defined for TNOs and Centaurs because of limited phase angle coverage. We used as $P_{\min}$ the minimal value of the polarization degree measured in the observed range of phase angles (up to 2 deg for TNOs and 4.4 deg for Centaurs). An existence of the trend between $P_{\min}$ and albedo may indicate that the real minimum of the negative polarization lies at small phase angles. It is confirmed by observations of Chiron for which the angle of polarization minimum $\alpha_{min}=1.5°$ was well-measured.

Numerical modeling has shown that a possible way to explain the observed polarization properties of TNOs and Centaur is to assume two-component surface media consisting of dark and bright scatterers (Bagnulo et al. 2006, Belskaya et al. 2008b). According to the laboratory measurements a small amount of water-ice frost formed at low temperatures (<100 K) on the top of a dark surface gave a deep negative polarization at small phase angles (Dougherty and Geake 1994). Varying the amount of frost resulted in large variations in the depth of negative polarization. The deepest negative polarization branch was measured for a very thin frost layer of subwavelength ice crystals which appeared grey on a black background. The laboratory phase dependences are very similar to that measured for Pholus. It is possible that various amount of water frost on the surfaces of Centaurs could explain the observed diversity in their polarization properties.

4. Conclusions

Polarimetric observations of Chiron, Chariklo and Pholus and their analysis allow us to make the first conclusions on polarization properties of Centaurs which can be summarized as follows:

1. Observed Centaurs revealed noticeable negative polarization of their surfaces with a minimum varying from -1% to -2.1%. All three objects show diverse polarization phase angle behaviour, each distinctly different from that of transneptunian objects. This implies noticeable differences in physical properties of the topmost surface layers of these objects.

2. A shift of negative polarization minima toward small phase angles seems to be a characteristic feature of the polarization properties of Centaurs. For (2060) Chiron the minimum polarization occurs at the phase angle of 1.5º which is the smallest angle as compared to any other Solar system body observed so far. The presence of a small amount of water frost on a dark surface is considered a possible explanation of these properties.

3. We found evidence of surface heterogeneity for Chariklo while Chiron and Pholus appear to have rather homogeneous surfaces. Polarization phase behaviours of Chiron and Pholus are significantly different from those for any other Solar system body studied so far by means of polarimetry. Chariklo's polarization characteristics are less distinct from dark asteroids and comets than those for two other Centaurs.

4. The relationship between the depth of negative polarization $P_{\min}$ and albedo for Centaurs and TNOs is similar to that found for asteroids, characterized by an increase of $P_{\min}$ (in absolute term) when albedo decreases. Data for Chariklo are outside of the general trend which is probably due to the same reason as for very dark asteroids, i.e. due to the domination of the single scattering and, thus, negligible amount of the multiple scattered unpolarizaed light that determines the albedo of brighter objects.

As a by-product of our polarimetric observations we have made estimates of the absolute magnitude of the observed Centaurs and have found that

(a) the absolute magnitude of Chiron remains practically unchanged in 2004-2008 unlike it was at the previous brightening in 1989 and suggests different characteristics of the new and previous outbursts;

(b) the absolute magnitude of Chariklo decreases by about 0.6 mag over ten years which is probably related to aspect changes from the pole-on aspect in 1999 to the near equatorial aspect in 2008.

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Table 1
Results of polarimetric observations

Object	Year	Month	Day, UT	Expo-sure, s	Phase angle, deg	P_Q, %	σ_{PQ}	P_U, %	σ_{PU}
2060 Chiron	2007	07	13.3521	1440	1.65	-1.26	0.04	-0.05	0.04
2060 Chiron	2007	07	22.1486	1440	1.12	-1.35	0.04	0.06	0.04
2060 Chiron	2007	08	04.0833	1440	0.51	-1.10	0.04	-0.05	0.04
2060 Chiron	2007	08	19.0958	1440	1.02	-1.35	0.04	-0.02	0.04
2060 Chiron	2008	08	03.3521	3280	0.68	-1.23	0.03	0.01	0.03
2060 Chiron	2008	09	21.1347	3280	2.50	-1.27	0.03	0.05	0.03
2060 Chiron	2008	10	01.0785	3280	2.92	-1.19	0.05	-0.03	0.03
5145 Pholus	2007	03	17.3569	7520	2.58	-2.09	0.18	-0.07	0.19
5145 Pholus	2008	04	02.3118	6800	2.26	-2.04	0.18	0.10	0.18
5145 Pholus	2008	05	30.2833	6800	0.93	-1.40	0.20	-0.12	0.19
5145 Pholus	2008	07	05.0986	6800	1.74	-1.96	0.13	-0.05	0.13
10199 Chariklo	2007	05	18.1451	800	2.66	-0.86	0.07	-0.01	0.07
10199 Chariklo	2007	07	17.1062	800	4.37	-0.74	0.10	0.00	0.10
10199 Chariklo	2008	03	03.3139	1600	3.71	-0.97	0.06	-0.05	0.06
10199 Chariklo	2008	06	01.9889	1280	2.90	-0.82	0.07	-0.13	0.07

Table 2
Results of photometry

Object	Year	Month	Day, UT	Δ	R	Phase angle, deg	R_{obs}	σ_R	R(1,1,α)
2060 Chiron	2007	07	13.3521	13.878	14.808	1.65	17.04	0.06	5.48
2060 Chiron	2007	07	22.1486	13.844	14.822	1.12	17.10	0.08	5.54
2060 Chiron	2007	08	04.0833	13.836	14.842	0.51	17.00	0.06	5.44
2060 Chiron	2007	08	19.0958	13.887	14.866	1.02	17.19	0.05	5.62
2060 Chiron	2008	08	03.3521	14.406	15.405	0.68	17.36	0.05	5.63
2060 Chiron	2008	09	21.1347	14.720	15.477	2.50	17.32	0.05	5.53
2060 Chiron	2008	10	01.0785	14.857	15.492	2.92	17.34	0.05	5.53
5145 Pholus	2007	03	17.3569	20.733	21.057	2.58	-	-	-
5145 Pholus	2008	04	02.3118	21.319	21.844	2.26	20.58	0.07	7.24
5145 Pholus	2008	05	30.2833	21.009	21.961	0.93	20.58	0.08	7.26
5145 Pholus	2008	07	05.0986	21.257	22.032	1.74	20.43	0.08	7.08
10199 Chariklo	2007	05	18.1451	12.480	13.296	2.66	18.18	0.05	7.08
10199 Chariklo	2007	07	17.1062	13.236	13.317	4.37	18.27	0.05	7.04
10199 Chariklo	2008	03	03.3139	12.896	13.407	3.71	18.32	0.05	7.13
10199 Chariklo	2008	06	01.9889	12.677	13.445	2.90	18.21	0.06	7.05

Table 3
Orbital and physical parameters of observed Centaurs

Parameters	(2060) Chiron	(5145) Pholus	(10199) Chariklo
Semimajor axis	13.709	20.337	15.795
Eccentricity	0.379	0.571	0.172
Inclination	6.9	24.7	23.4
Perihelion distance	8.511	8.720	13.083
Aphelion distance	18.906	31.955	18.507
Diameter[1] (km)	233 ± 15	140 ± 40	259 ± 10
Albedo	0.16 ± 0.02 (H=5.82)	$0.07^{+0.07}_{-0.03}$ (H=7.83)	0.04 ± 0.02 (H=7.05)
Composition (ices) [2,3]	H_2O (0.5%)	H_2O (2.9%), CH_3OH	H_2O (6.9%)
Cometary activity[4]	Yes	No	No
Classification[5]	BB	RR	BR
Rotation period (h) [6]	5.9178	9.98	Long?
Lightcurve amplitude[6]	0.04-0.09	0.15-0.6	?
Phase coefficient (^{m}/deg) (range of phase angles)	0.06 ± 0.01 (0.5-4.2°)	0.083 ± 0.005 (0.7-3.9°)	0.06 ± 0.01 (1.2-4.1°)
Linear polarization:			
P_{min} (%)	-1.37 ± 0.05	-2.09 ± 0.18	-0.97 ± 0.06
α_{min}(°)	1.5 ± 0.5	$2.6^{+3}_{-0.5}$	$3.7 \pm^{+3}_{-1}$
α_{inv}(°)	6.7 - 8.5	≥5.6	≥7.5

Albedos were calculated using the given diameter and our estimates of absolute magnitude H given in parentheses. Polarization parameters were estimated in an assumption of the standard phase curve fitted by Lumme and Muinonen function with the fixed parameter c_2=0.35 while c_1 varied from 0.3 to 0.7 (see section 2.1).
[1]Stansberry et al. (2008), [2]Barucci et al. (2008), [3]Brown (2000), [4]Jewitt (2009), [5]Barucci et al. (2005), [6]Sheppard et al. (2008).

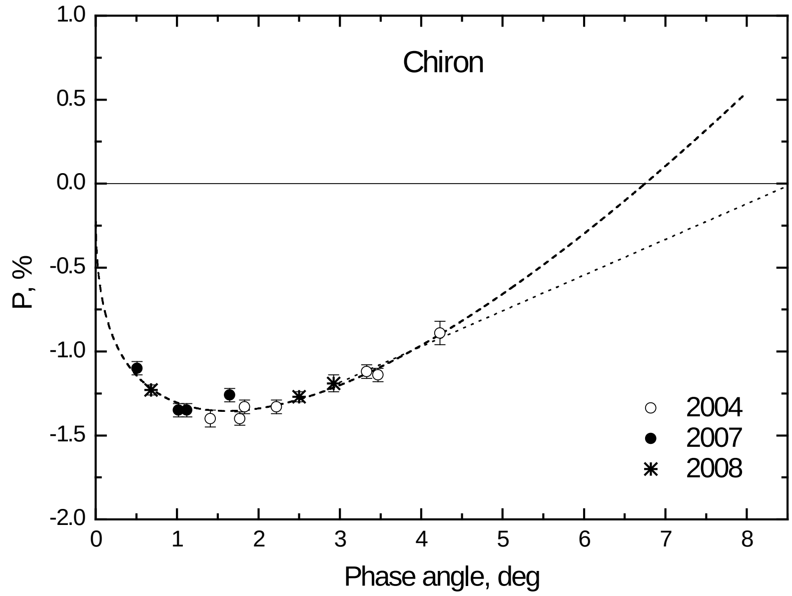

Figure 1. Polarization-phase dependence of (2060) Chiron. The observations in 2004 taken from Bagnulo et al. (2006) are shown by open circles. The fit by a Lumme and Muinonen function is shown by the dashed line. The dotted line shows a linear fit to the data at phase angles >2°.

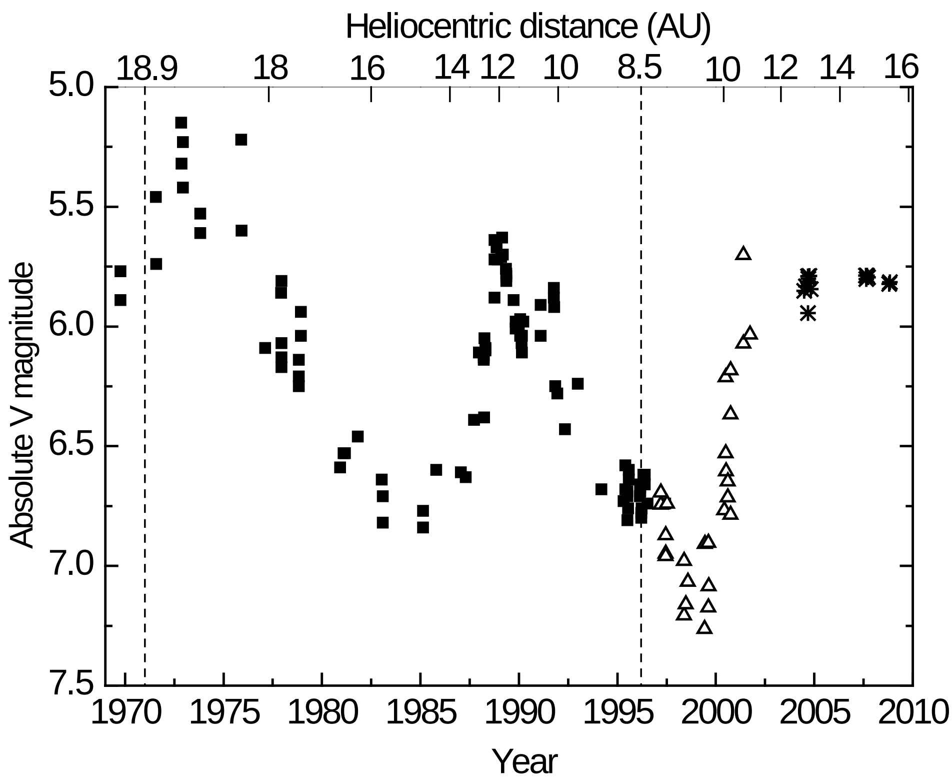

Figure 2. Absolute magnitude of Chiron versus time and heliocentric distance. Dashed lines show aphelion and perihelion. Data of 1969-1997 (squares) are plotted according to Bus et al. (2001). Data of 1997-2001 (triangles) were taken from Duffard et al. (2002). Stars correspond to the magnitude estimates from polarimetric measurements (Bagnulo et al. 2006 and present work).

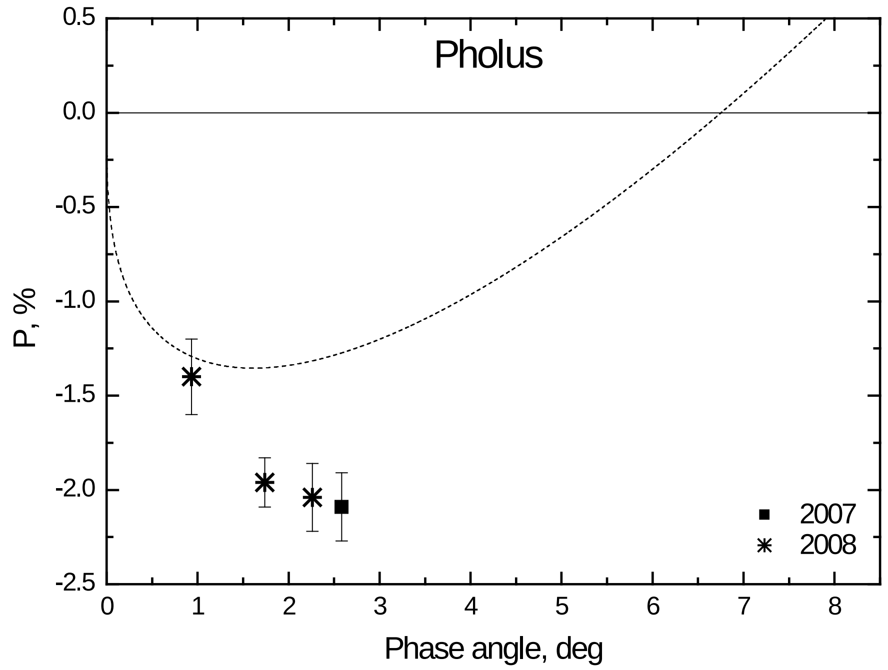

Figure 3. Polarization-phase dependence of (5145) Pholus. For comparison Chiron's polarization curve is shown by the dashed line.

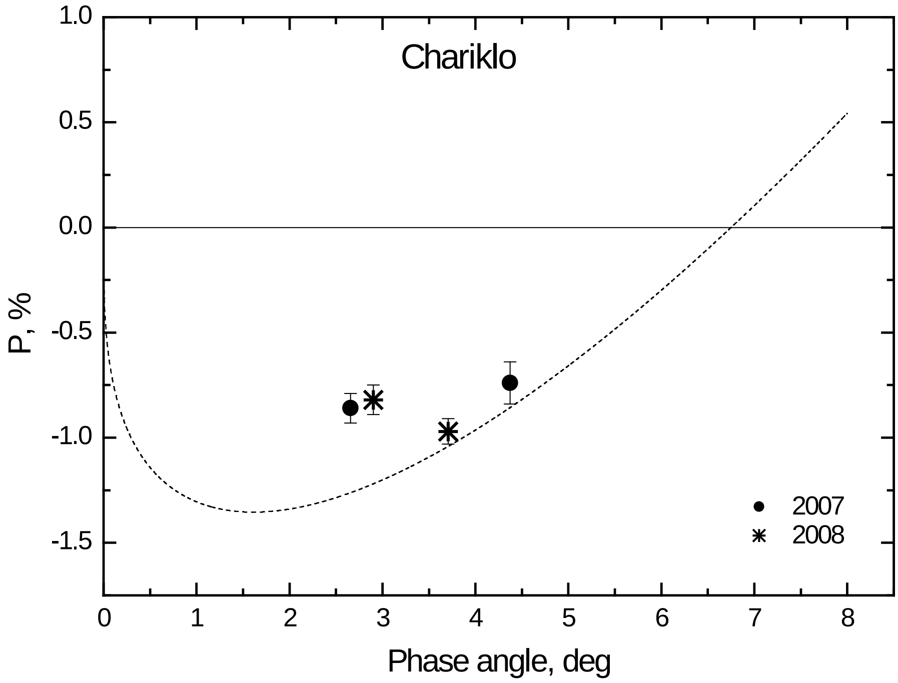

Figure 4. Polarization-phase dependence of (10199) Chariklo. For comparison Chiron's polarization curve is shown by the dashed line.

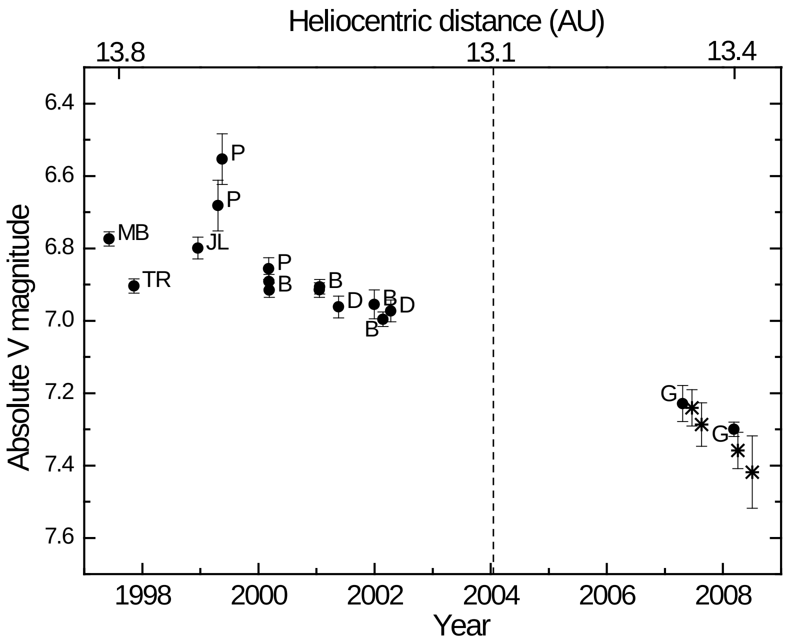

Figure 5. Absolute magnitude of Chariklo versus time and heliocentric distance. Perihelion is shown by the dashed line. The magnitudes are taken from the following papers: MB – McBride et al. (1999), JL – Jewitt and Luu (2001), TR – Tegler and Romanishin (1998), P – Peixinho et al. (2001), B – Bauer et al. (2003), D – Dotto et al. (2003), G – Guibert et al. (2009). Stars correspond to the magnitude estimates from our polarimetric measurements.

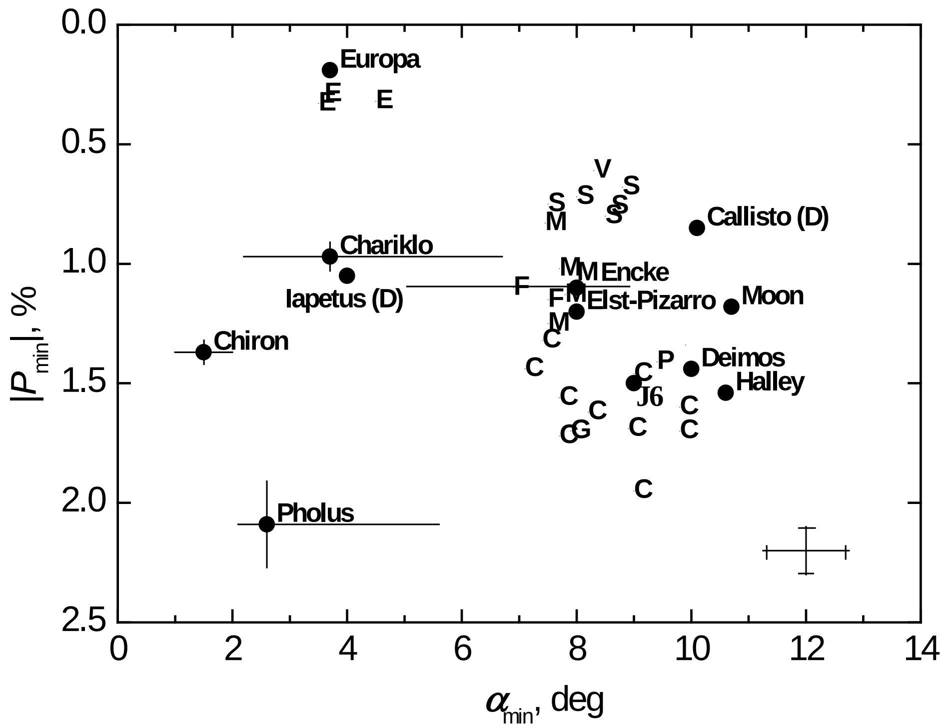

Figure 6. The depth of negative polarization $P_{\min}$ versus the phase angle of polarization minimum α_{min} for a variety of Solar system bodies (see text for references). Asteroids are designated by letters of their taxonomic classes according to the classification scheme by Tholen (1989). Typical uncertainties of the plotted parameters are shown in the lower-right corner. Note that the measurements of comet Encke are related to its nucleus while the data for comet Halley are contaminated by the coma.

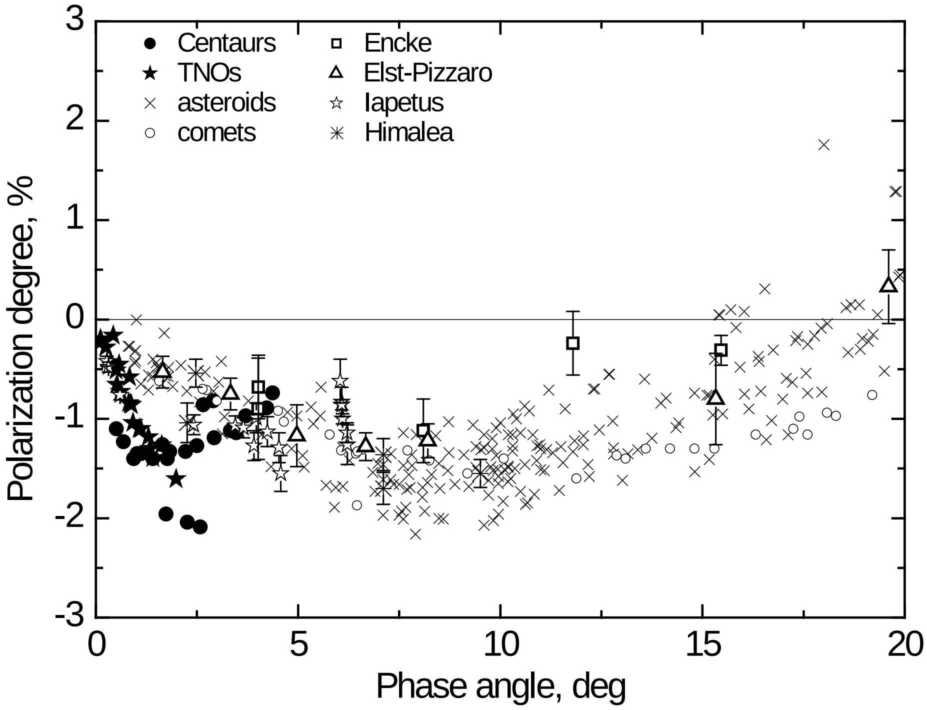

Figure 7. Comparison of polarization phase curves of Centaurs and various Solar system bodies. See text for references.

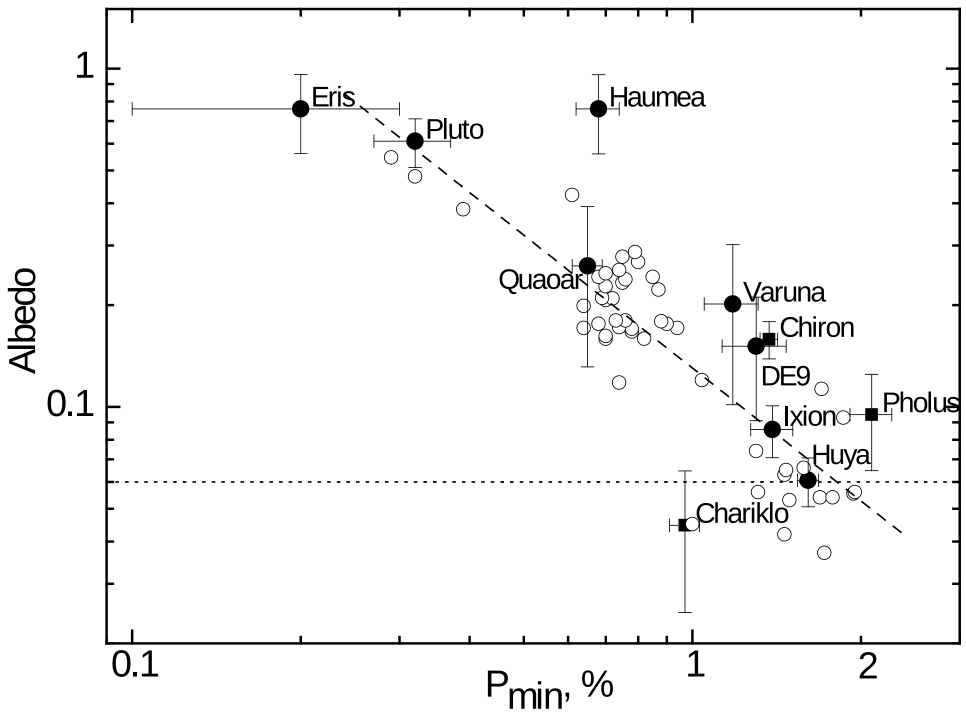

Figure 8. The relationship P_{min} and albedo for Centaurs and TNOs. The data for TNOs were taken from Bagnulo et al. (2006, 2008), Belskaya et al. (2008a), and Boehnhardt et al. (2004). The albedos were plotted according to Stansberry et al. (2008). The dashed line shows linear fit to the data. The dotted line corresponds to the albedo of 0.06. For comparison, the data for asteroids are shown using open circles (see Lupishko and Vasilyev 2008 for references).