POLARIMETRY OF TRANSNEPTUNIAN OBJECTS AND CENTAURS

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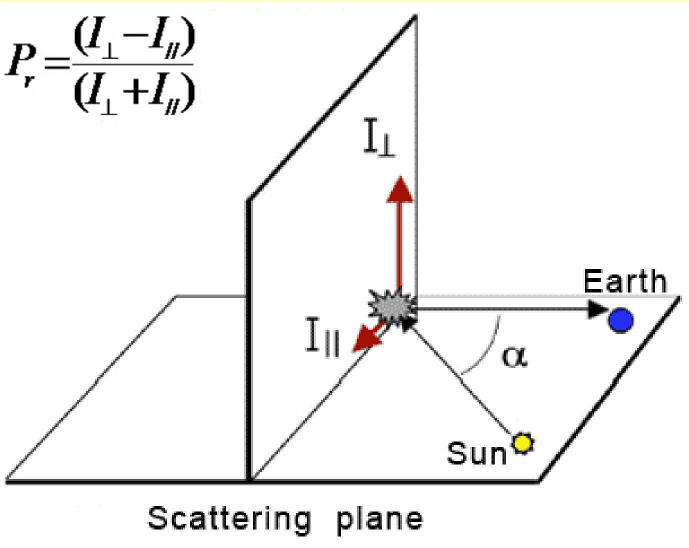
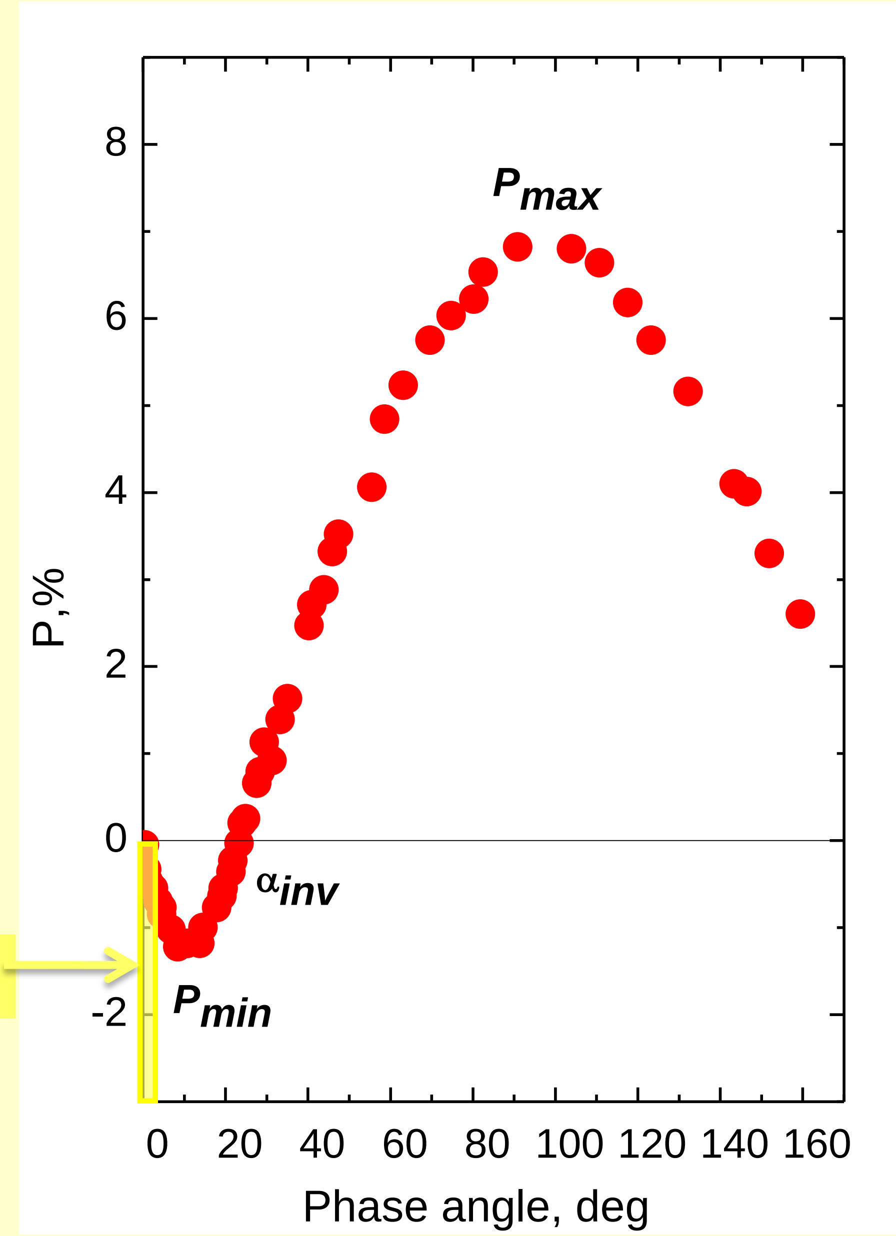
PHASE ANGLE DEPENDENCE OF POLARIZATION DEGREE



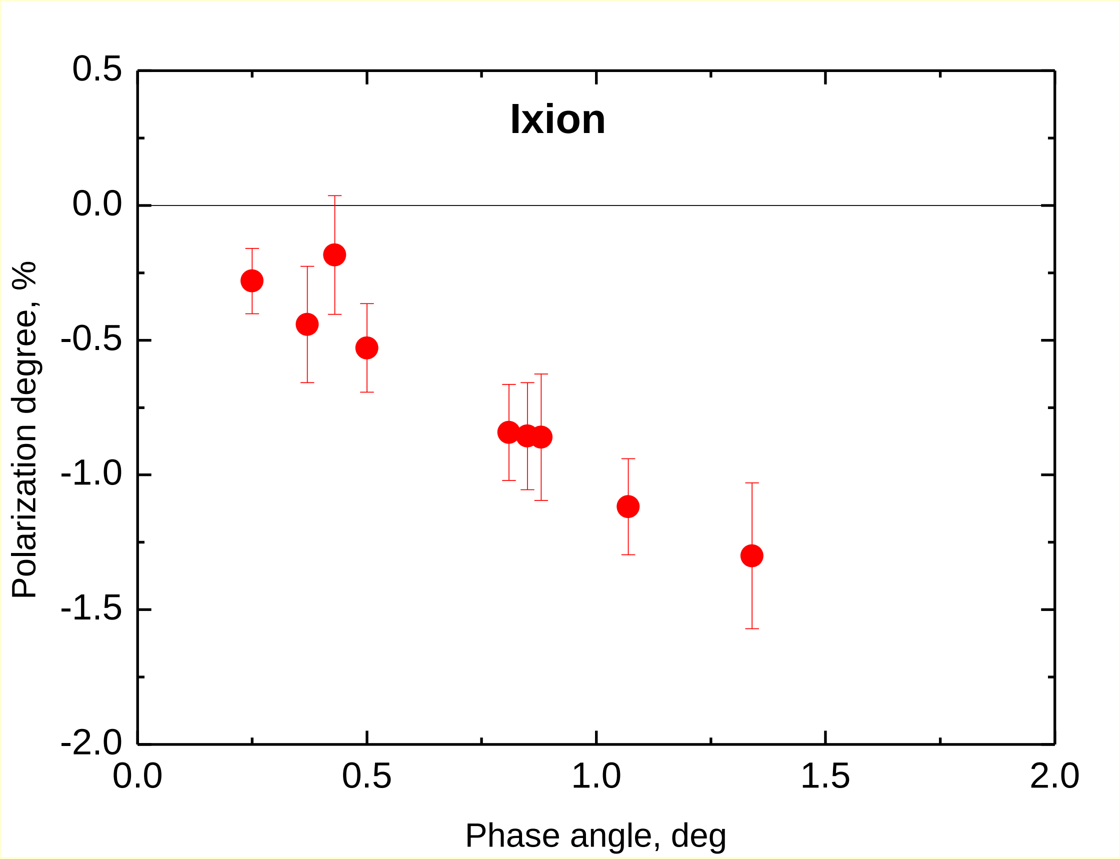
***P*(α, λ)** is determined by the physical properties of the topmost surface layer.



Phase angle range for TNOs

FIRST POLARIMETRIC OBSERVATIONS of a TNO WITH FORS1 AT THE ESO-VLT

Plutino (28978) Ixion (*D*=600 km, p_R=0.15)



R~ 19.7 mag

$P_{\min} \geq 1.3\%$

$\sigma_P \sim 0.1\%$

Boehnhardt et al. (2004)

- unusually high negative polarization at small phase angles
- rapid changes with the phase angle

FIRST PROGRAM OF POLARIMETRY OF TNO AND CENTAURS

The polarimetric observations of Ixion demonstrated

(a) the capability of the instrument (FORS1 VLT) to provide good-quality observations of faint objects (~20 mag);

(b) the capability of the polarimetric technique to study distant objects even if they are observable only at very small phase angles.

The aim of polarimetric observations was to probe surface properties of objects from different dynamical groups .

The following criteria were used to select objects :

- V≤ 21 mag. It lets to measure a polarization degree with accuracy better than 0.1% in less than two hours telescope time at 8 m telescope;
- the possibility to cover the largest phase angle range reachable from ground-based observations;
- availability of complementary information on object's physical properties.
- belonging to different dynamical group and spectral classes.

POLARIMETRIC OBSERVATIONS OF TNOs AT THE VLT

- ~100 h of total observing time at VLT in 2004-2011 (service mode);

- observations with FORS using a remotely controlled rotatable half-wave retarder plate in front of the Wollaston prism;

- measurements of the linear polarization mainly in the Bessell *R* filter;

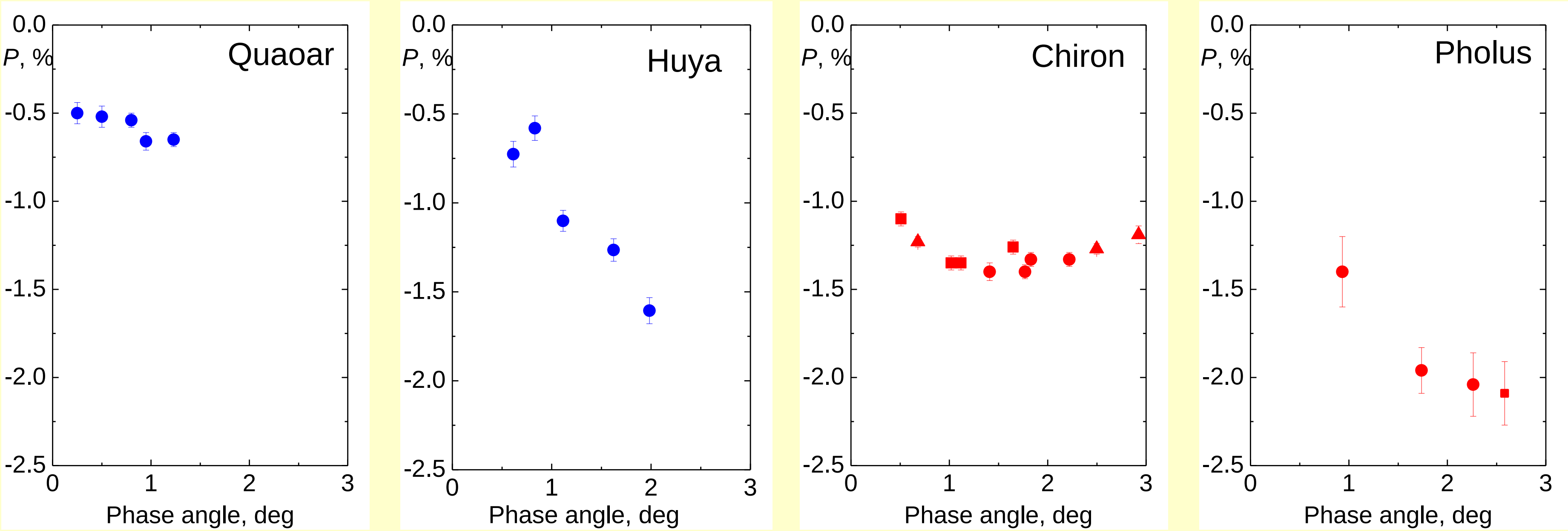
- well-controlled instrumental polarization (an accuracy of 0.03% in *P* and 0.2° in the position angle *θ*).

LIST OF TNOs AND CENTAURS OBSERVED BY POLARIMETRIC TECHNIQUE

Object	Type	Tax	D (km)	α (deg)	Reference
(2060) Chiron	Centaur	BB	218	0.5–4.2	Bagnulo et al. (2006)
(5145) Pholus	Centaur	RR	140	0.9- 2.6	Belskaya et al. (2010)
(10199) Chariklo	Centaur	BR	248	2.7–4.4	Belskaya et al. (2010)
(20000) Varuna	Classical	IR	668	0.1–1.3	Bagnulo et al. (2008)
(26375) 1999 DE_9	Scattered	IR	311	0.1–1.4	Bagnulo et al. (2008)
(28978) Ixion	Resonant	IR	617	0.2–1.3	Boehnhardt et al. (2004)
(29981) 1999 TD_{10}	Scattered	BR	104	0.8–3.1	Rousselot et al. (2005)
(38628) Huya	Resonant	IR	458	0.6–2.0	Bagnulo et al. (2008)
(50000) Quaoar	Classical	RR	1074	0.2–1.2	Bagnulo et al. (2006)
(90482) Orcus	Resonant	BB	958	1.1	Belskaya et al. (2012)
(134340) Pluto	Resonant	BR	2350	0.7–1.8	Breger&Cochran (1982)
(136108) Haumea	Classical	BB	1240	1.0	Bagnulo et al. (2008)
(136199) Eris	Detached	BB	2400	0.1–0.6	Belskaya et al. (2008)
(136472) Makemake	Classical	BR	1420	0.6-1.1	Belskaya et al. (2012)

14 objects (4 dwarf planets): 3 Centaurs, 4 classical, 4 resonant, 3 SDOs

DIVERSITY OF POLARIZATION PHASE BEHAVIOR



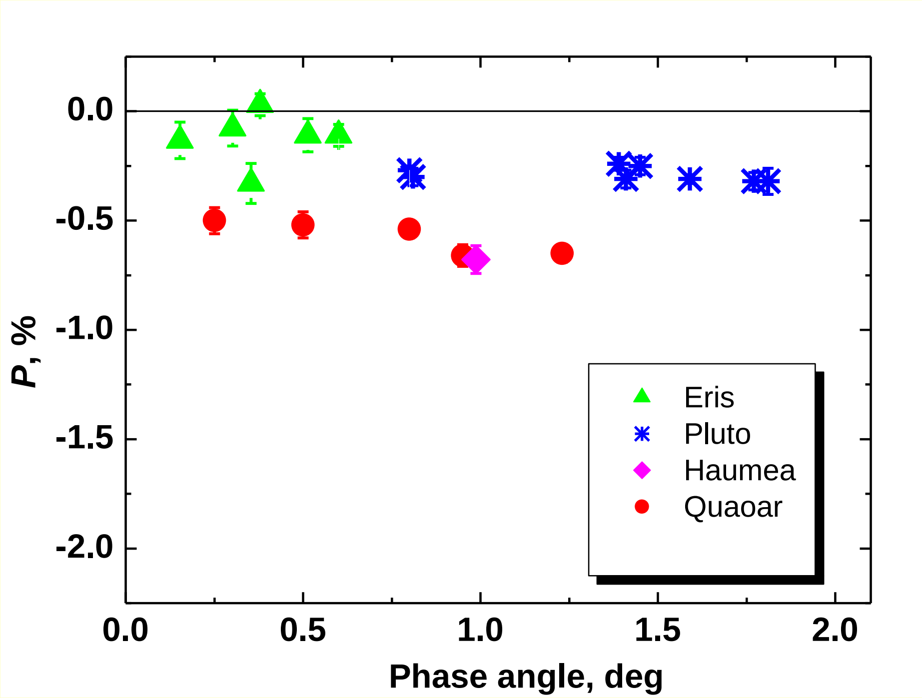
- **presence of the negative polarization, varying from -0.2% to -2.3%**
- **diverse phase angle behavior of polarization degree**

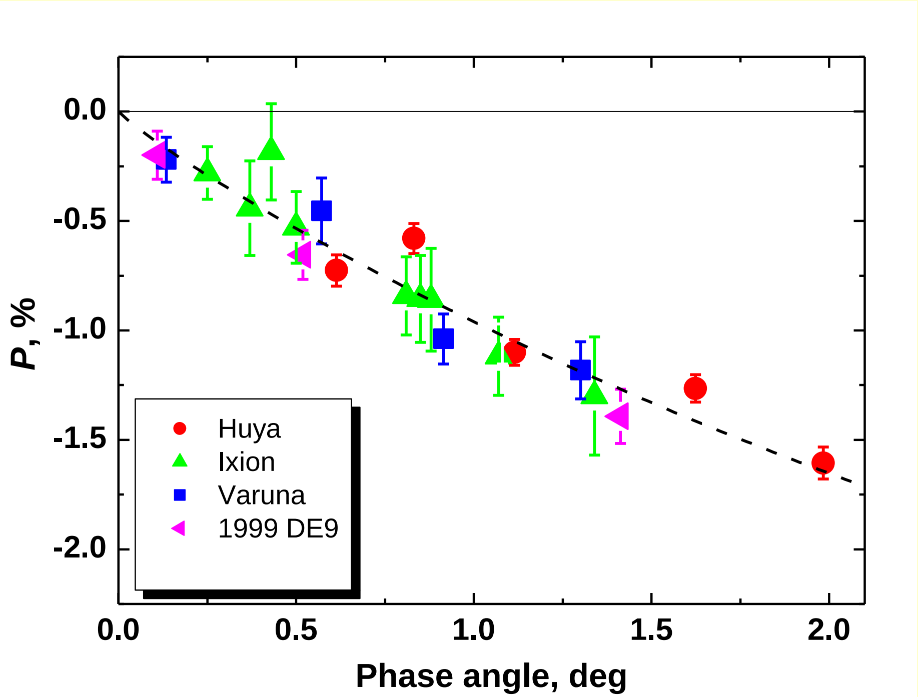
TWO DISTINCT BEHAVIOURS OF POLARIZATION-PHASE DEPENDENCES FOR LARGE AND SMALL TNOs

• the largest objects show a shallow branch of the polarization-phase curve with slow changes of polarization with the phase angle;

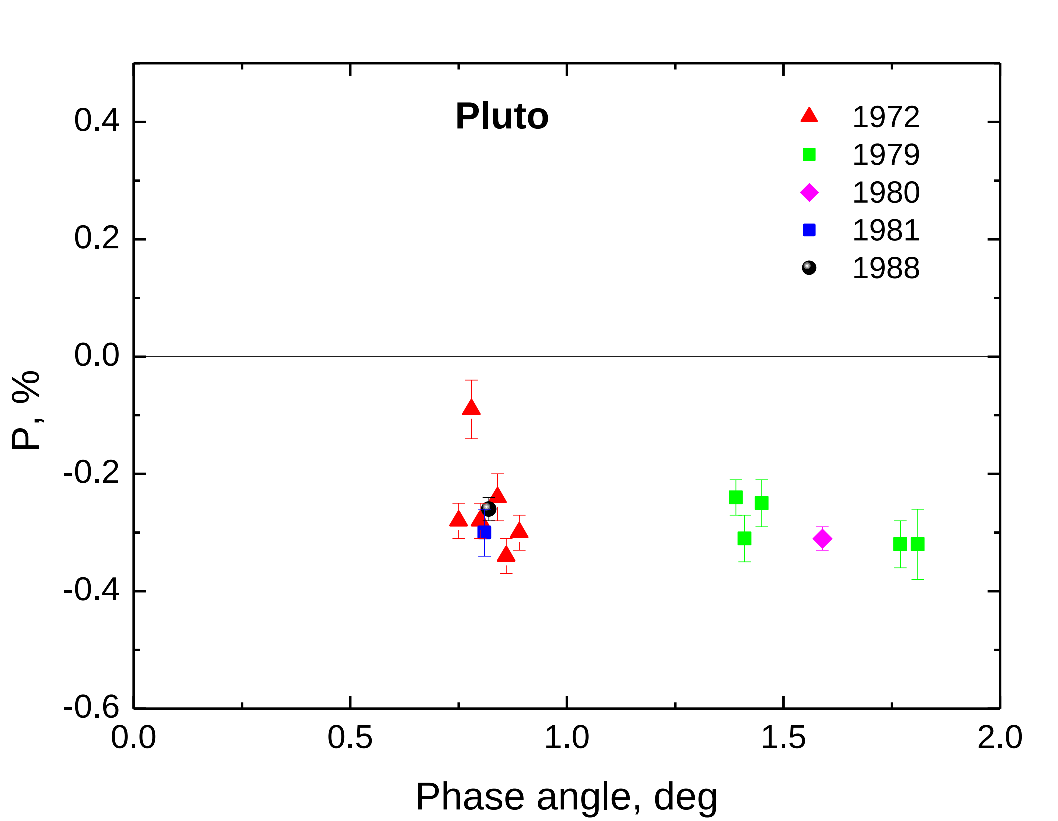
• the smaller size objects show a rapid enhancement in the negative polarization reaching about -1% at the phase angle of 1 deg.

(Bagnulo et al. A&A 491, L33-36, 2008)





POLARIMETRY OF PLUTO

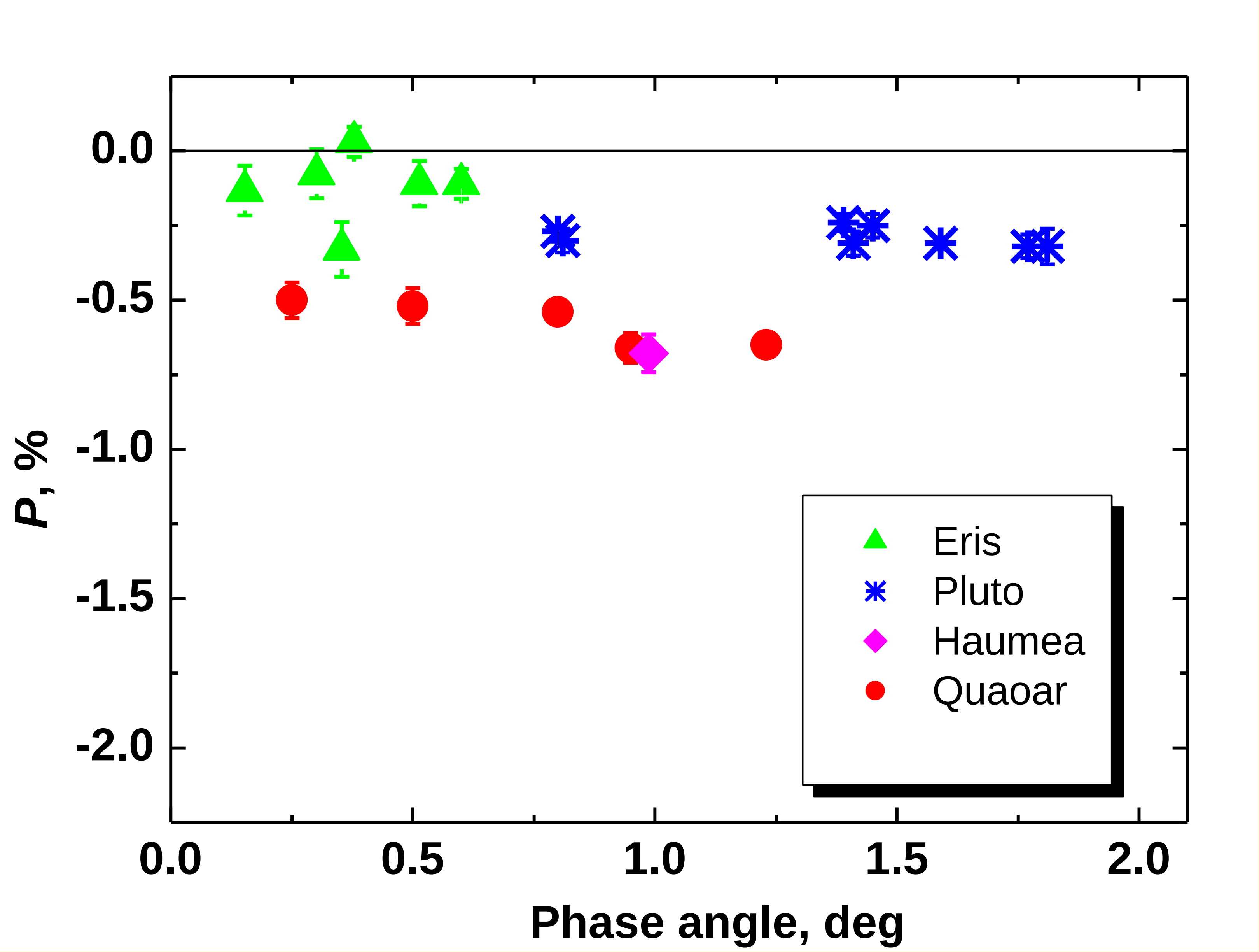


Kelsey & Fix 1973
Breger & Cochran 1982
Avramchuk et al. 1992

V~ 15 mag
Telescopes: 1 m, 1.3 m, 2 m
σ_P~0.03-0.05%
V (1979-1981) or without filters

- negative polarization
- no evidence of polarization variations with rotation
-no noticeable phase angle dependence
-- measurements refer to the Pluto-Charon system
-0.35% ≤ P(Pluto) ≤ -0.1% if -1.5% ≤ P(Charon) ≤ 0%

POLARIZATION-PHASE ANGLE DEPENDENCE OF THE LARGEST TNOs



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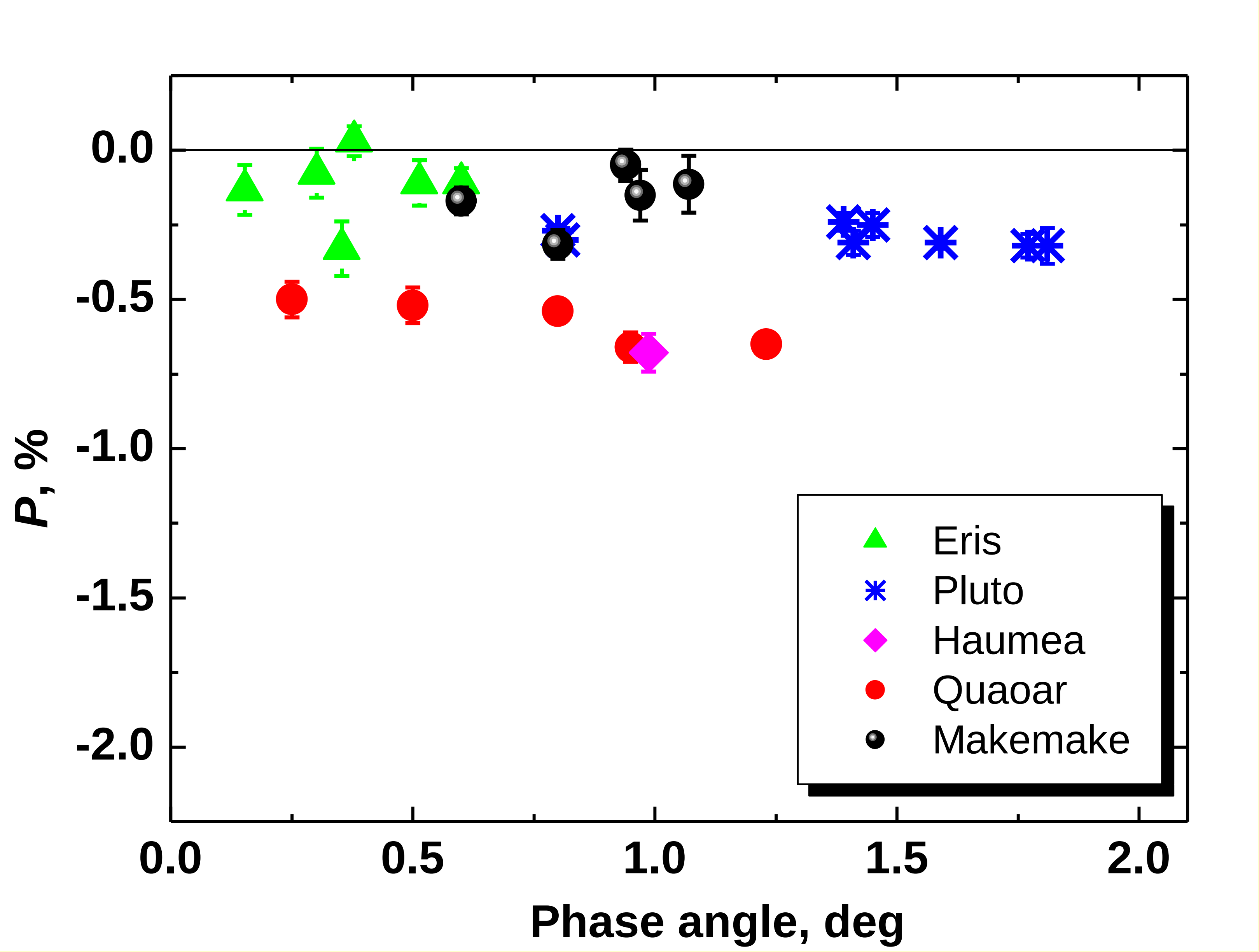

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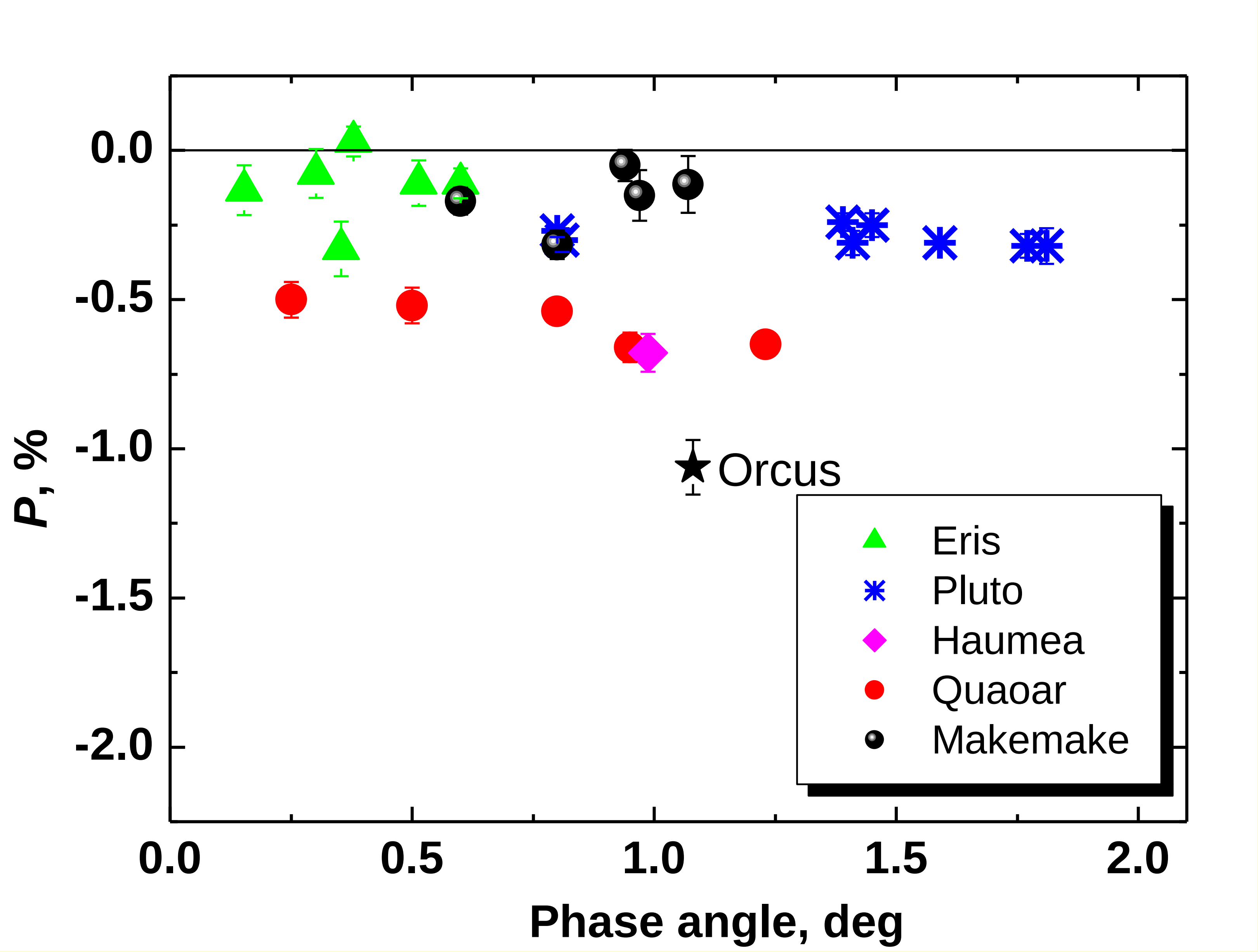
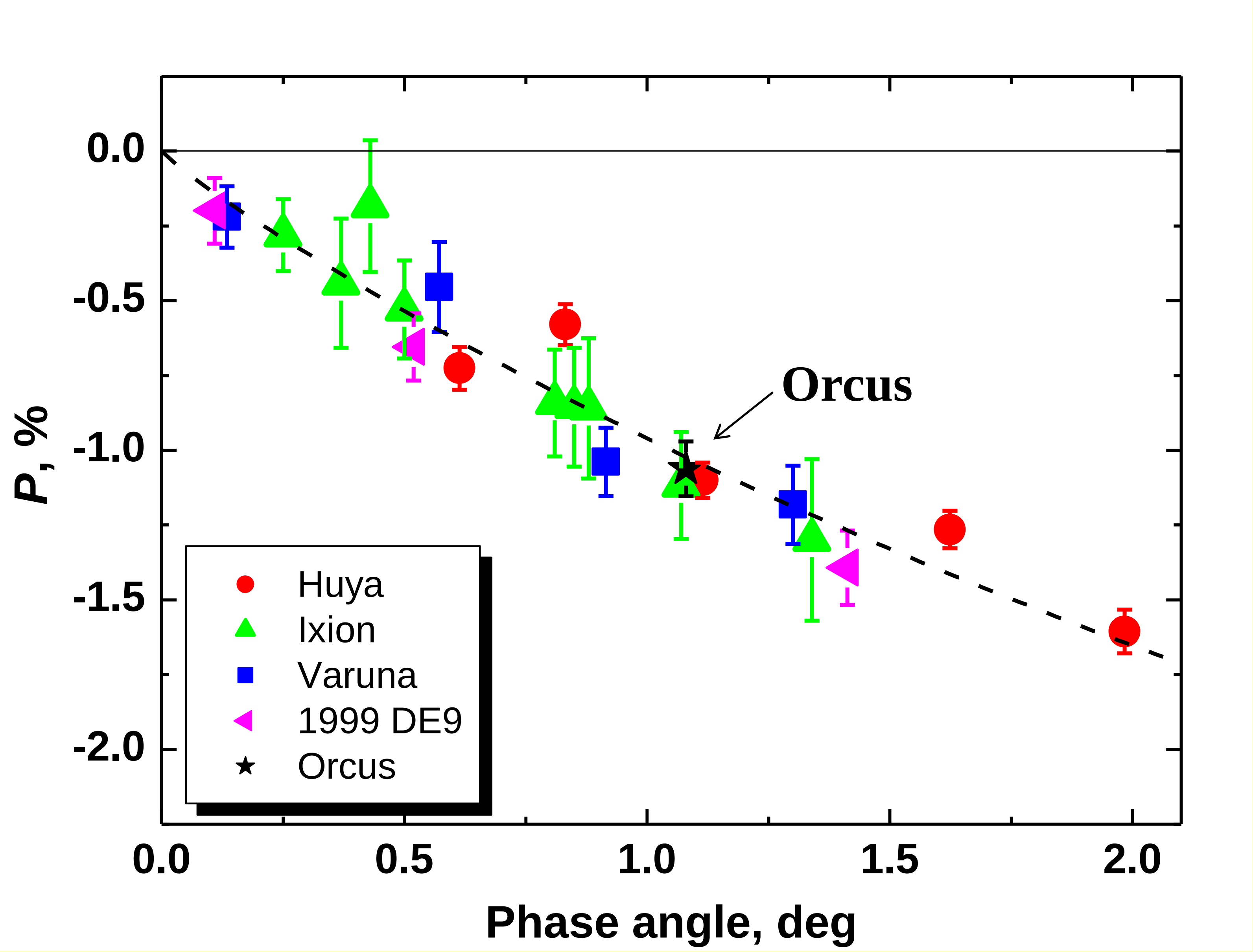
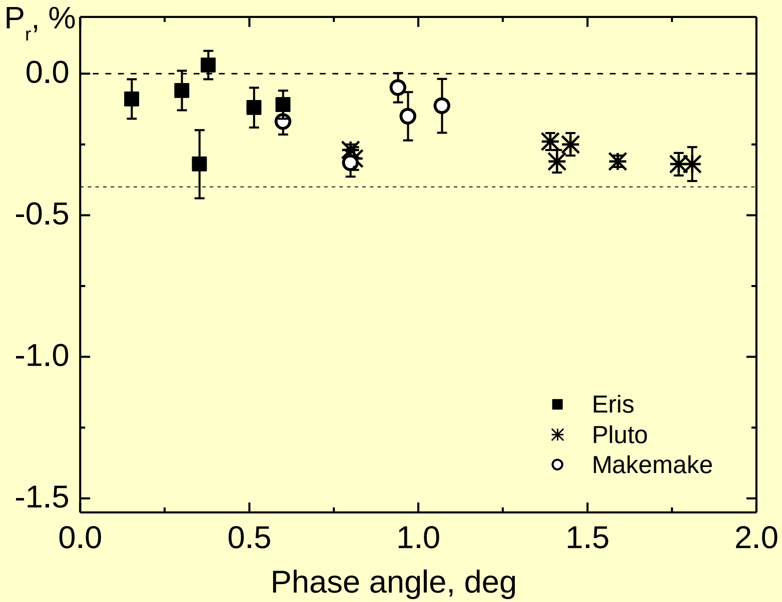


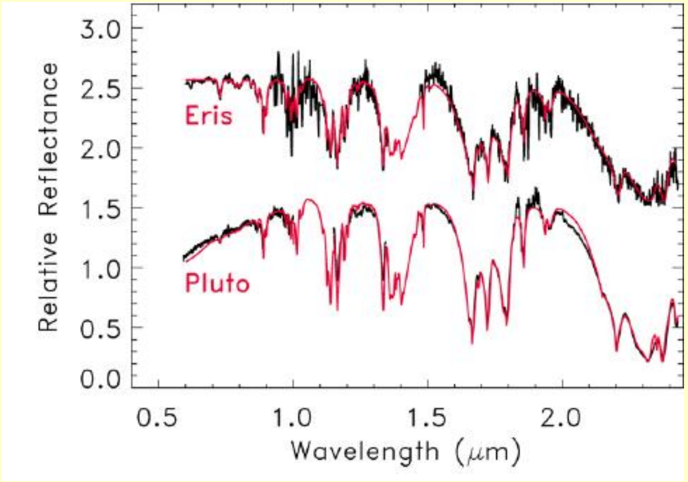
POLARIZATION-PHASE ANGLE DEPENDENCE OF THE SMALLER SIZE TNOs



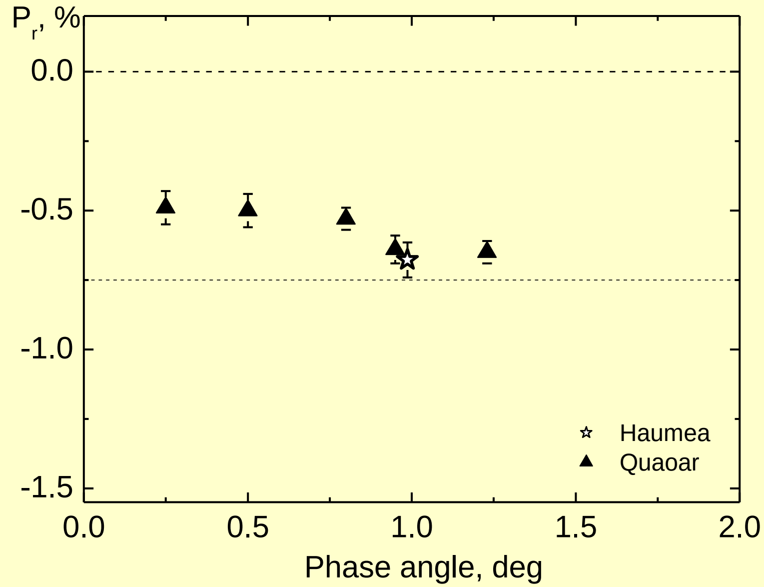
POLARIZATION OF SURFACES OF THE LARGEST TNOs

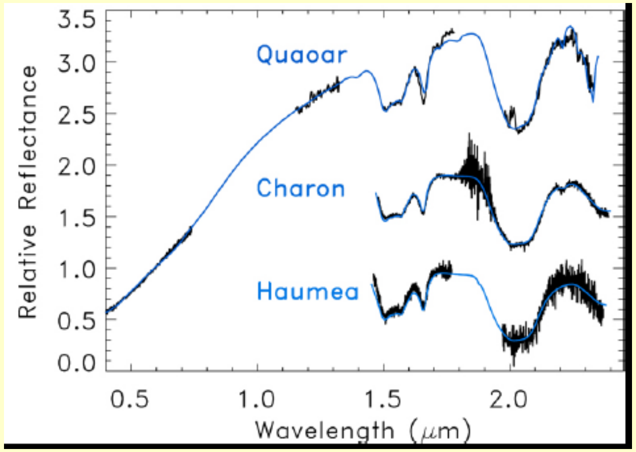
Methane-ice rich surfaces





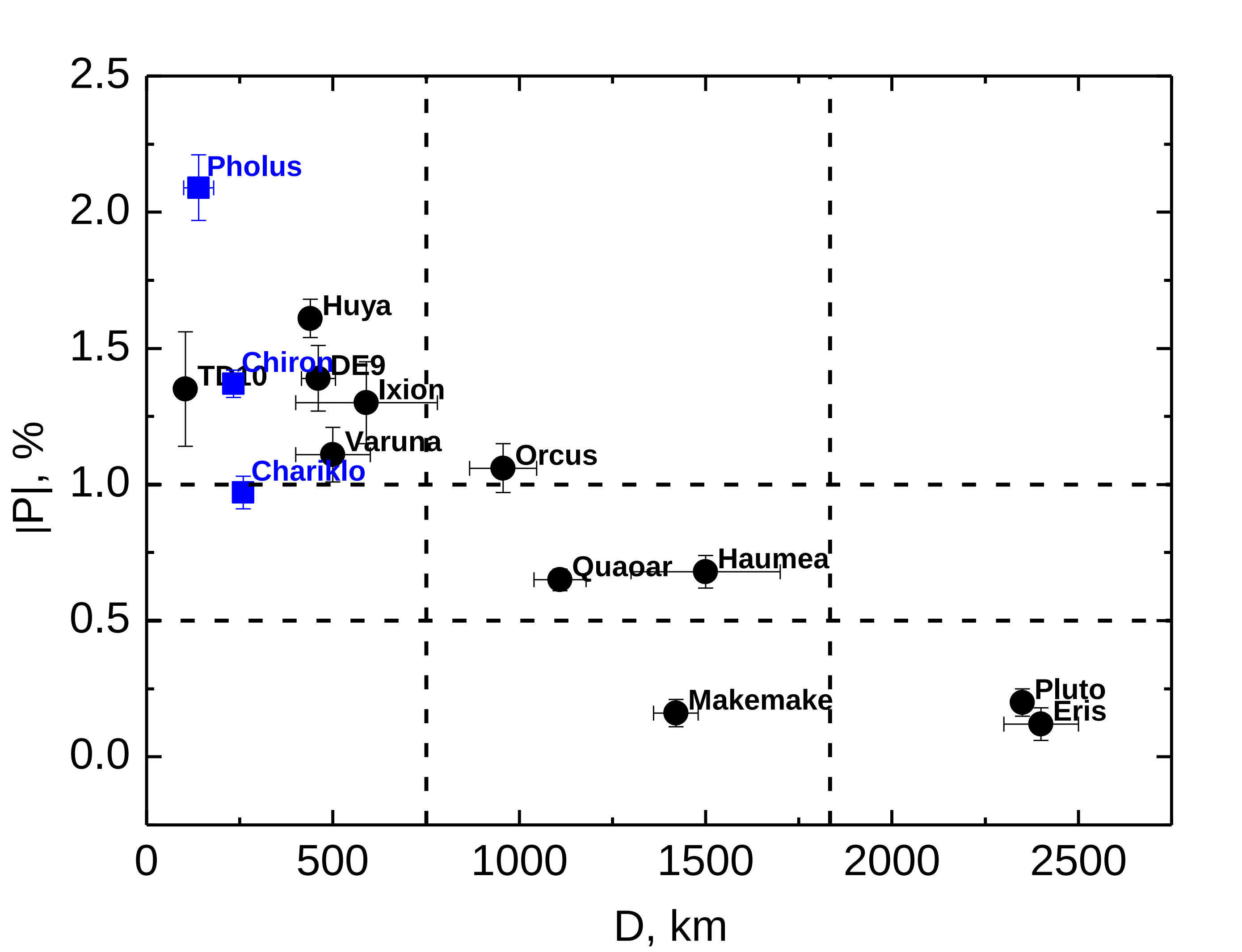
Water-ice rich surfaces





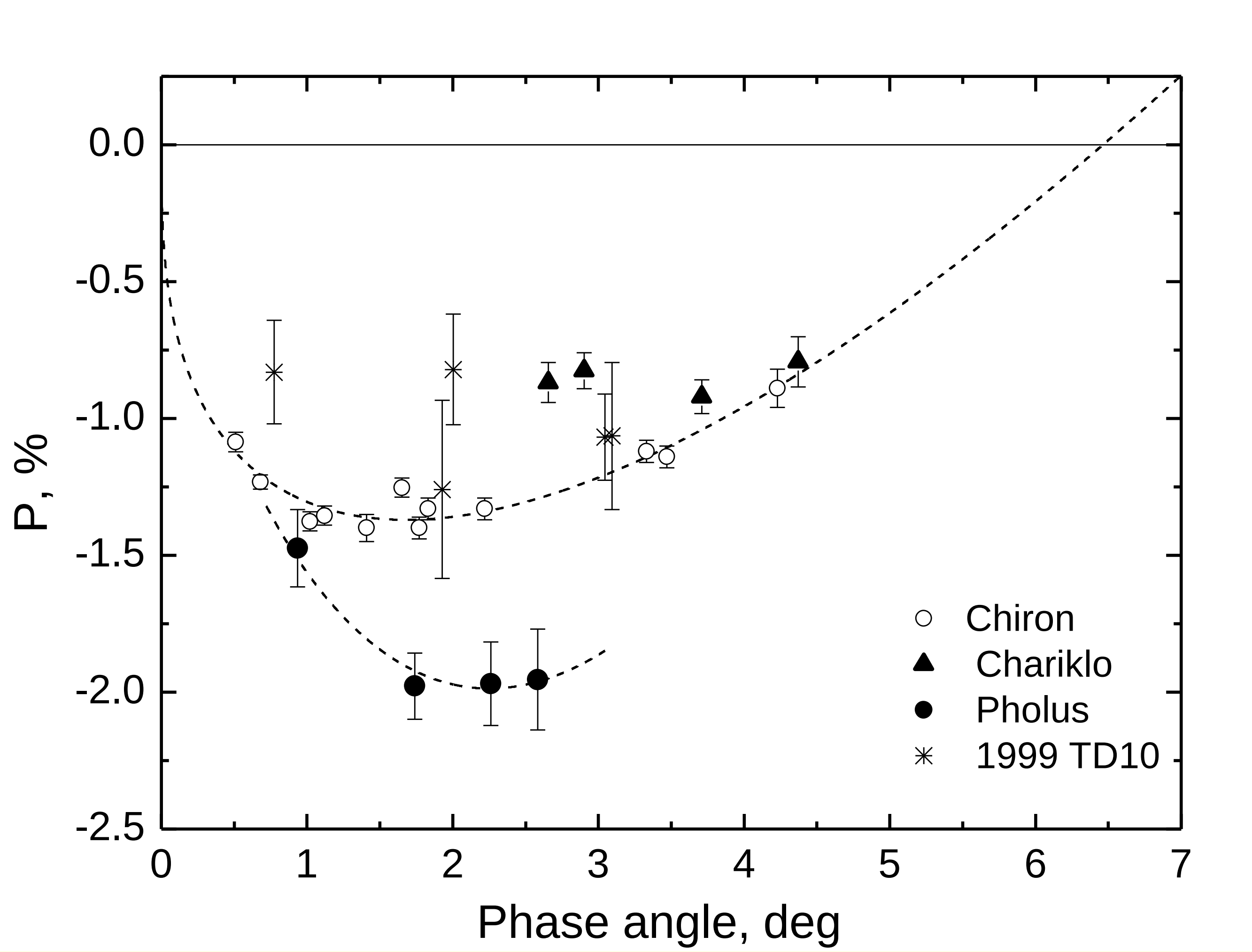
Barucci et al. (2010)

POLARIZATION DEGREE & DIAMETER



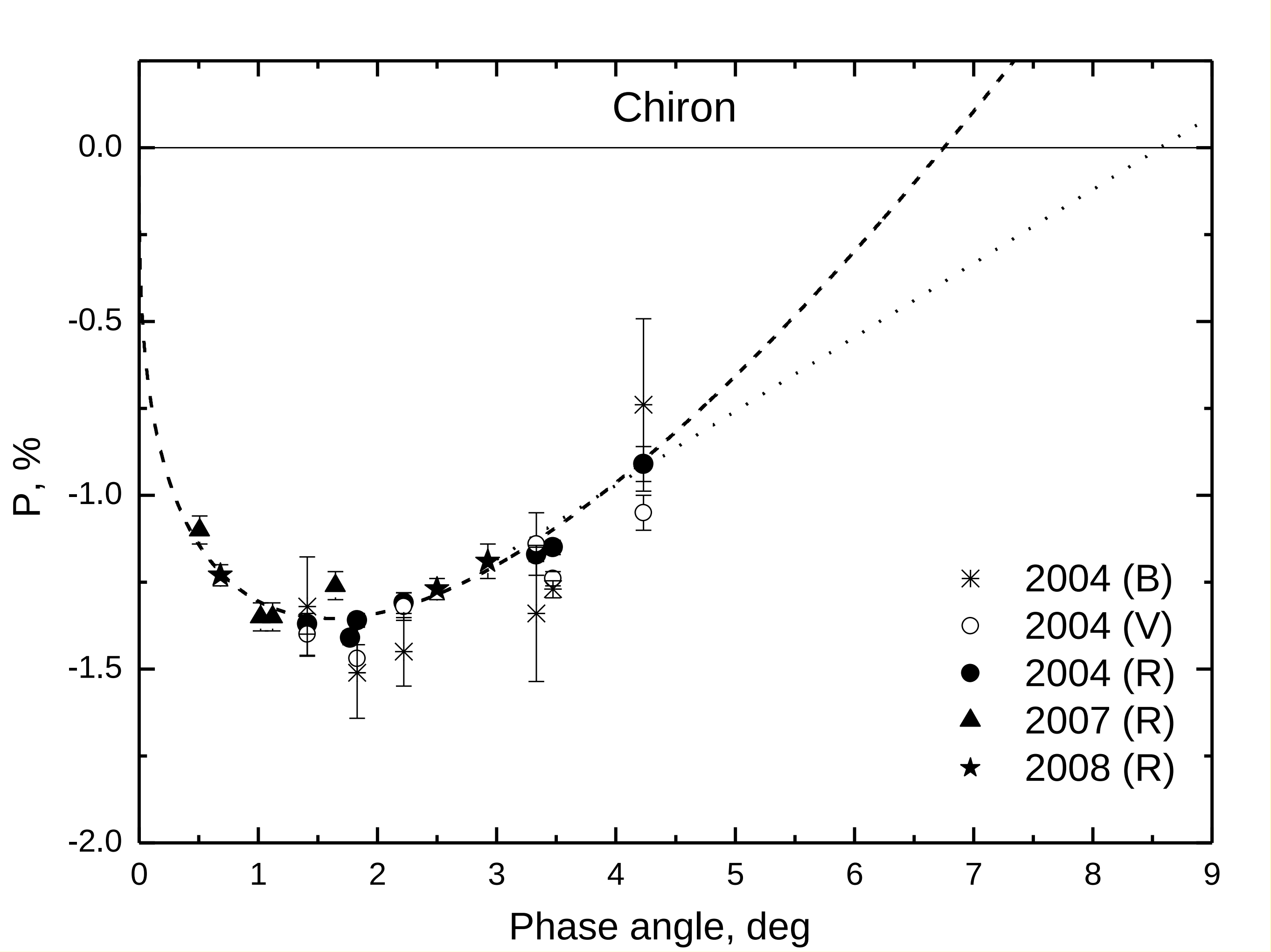
Vertical lines indicate the transition between volatile-free and volatile-rich surfaces according to Schaller & Brown (2007)

CENTAURS



• a great diversity in polarization properties with the negative polarization varying from -1% to -2%.

SPECTRAL DEPENDENCE OF POLARIZARION DEGREE

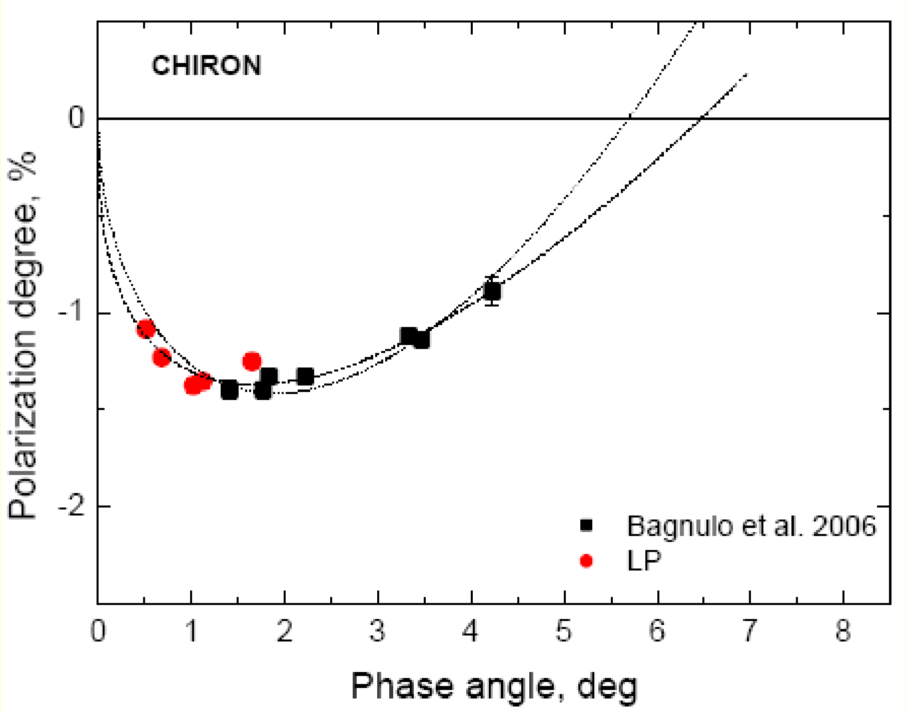


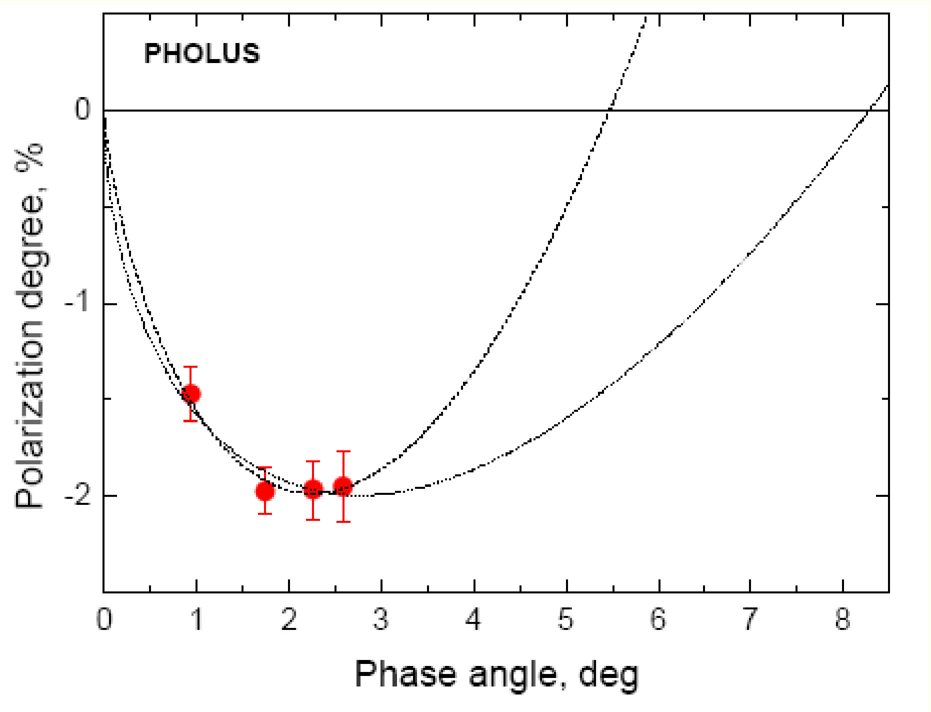
• a possible trend for deeper negative polarization in the B band

POSITION OF THE POLARIZATION MINIMUM

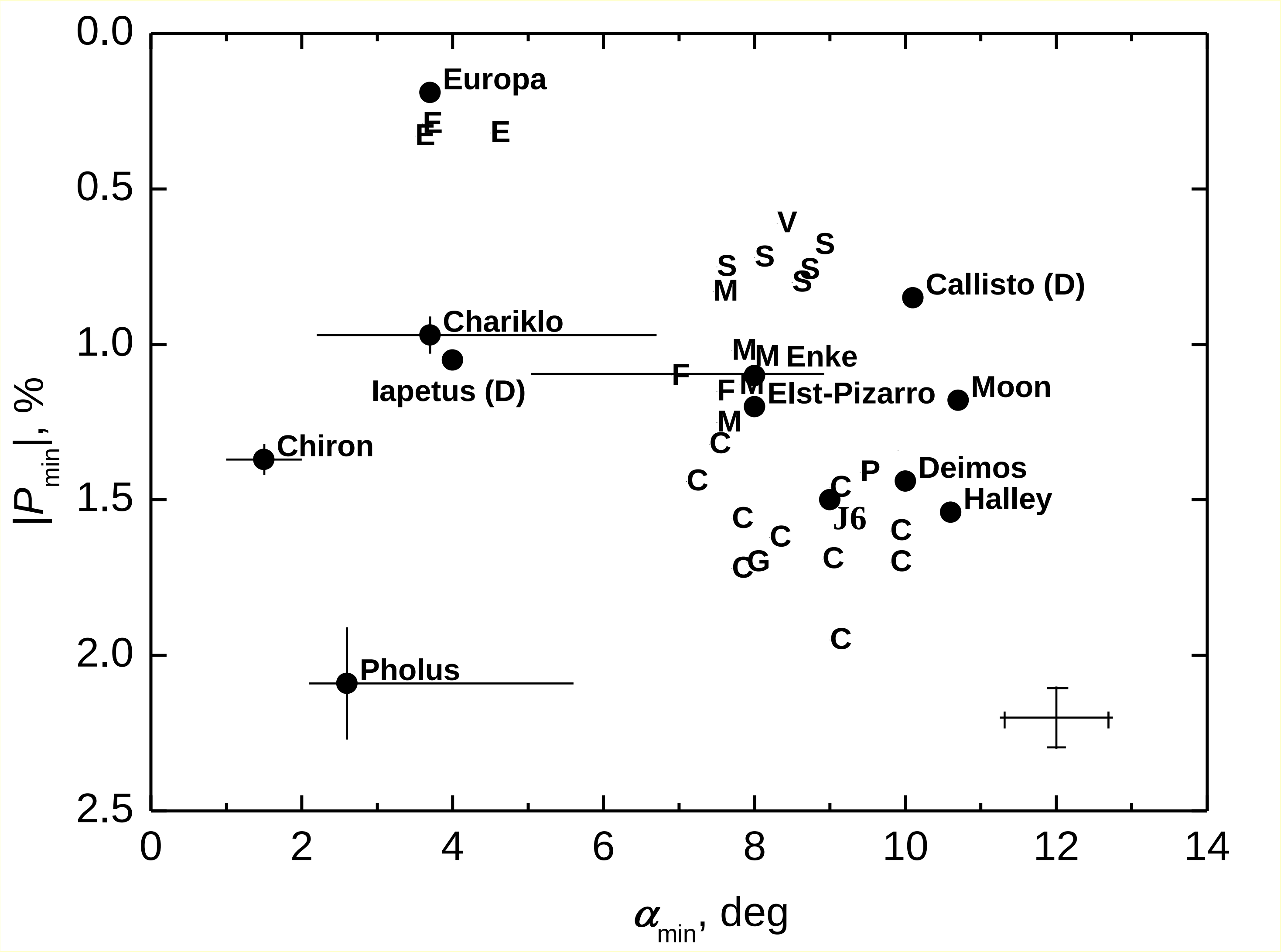
Chiron: P_{min}= –1.4%; α_{min} = 1.6°

Pholus: P_{min}=–2.1%; α_{min} ≥2.3°





POSITION OF THE MINIMUM OF NEGATIVE POLARIZATION BRANCH

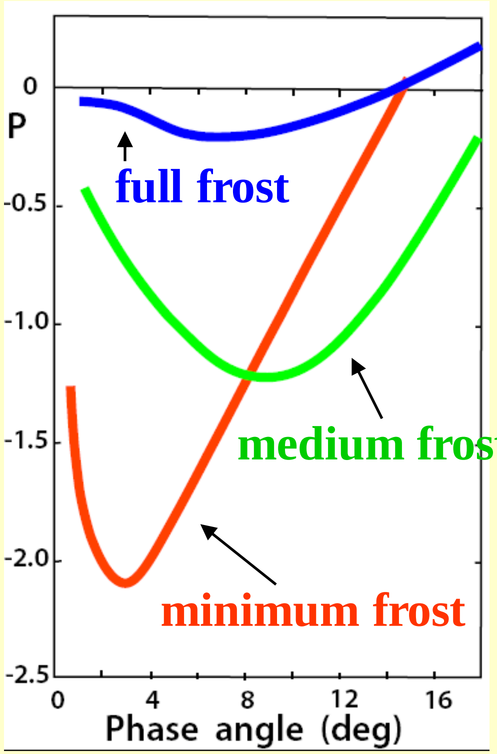


• Chiron shows the smallest phase angle of polarization minimum

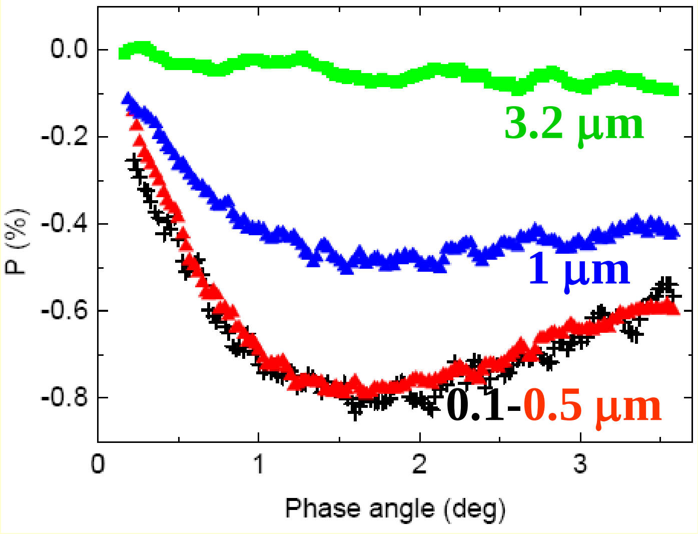
• Pholus shows the deepest negative polarization branch at small phase angles

POSSIBLE REASONS OF SHIFT OF POLARIZATION MINIMUM TOWARD SMALL PHASE ANGLES

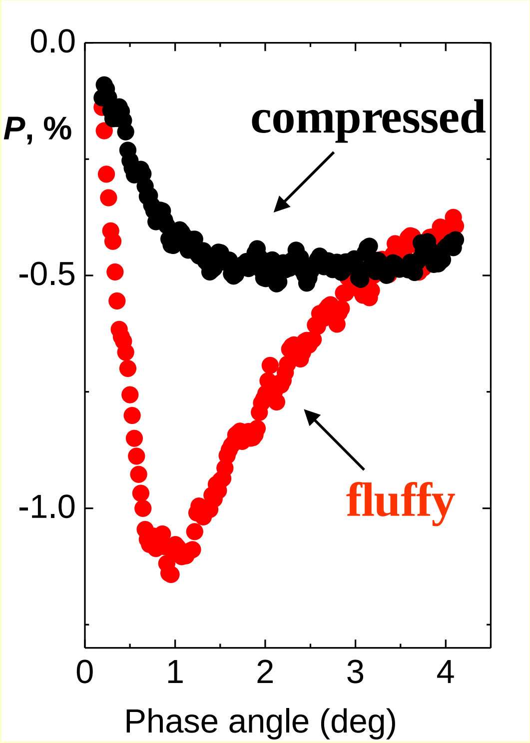
- fluffy surfaces with a large portion of submicron or micron-sized particles;
- inhomogeneous surface matter (scatterers with small and large single-scattering albedos).



Frost of submicron ice crystals on a dark surface (*Dougherty & Geake 1994*)

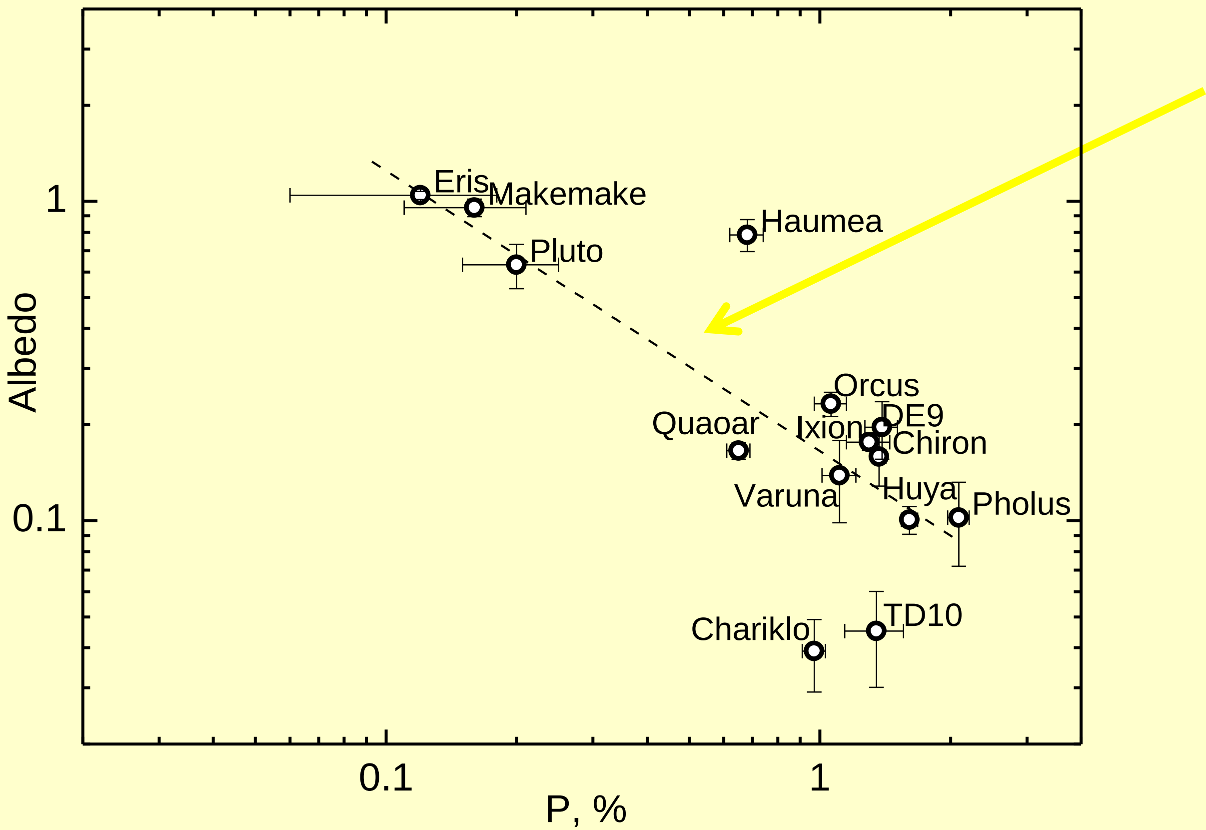


Measurements of size-separated Al_2O_3 (*Shkuratov et al. 2002*)



Fluffy and compressed MgO powder of ~1 μm (*Shkuratov et al. 2002*)

POLARIZATION DEGREE & ALBEDO



$\log(p_V) = c_1 * \log(P_{min}) + c_2$
found for asteroids

• the surface albedo does not play a dominant role in determining the polarization-phase behaviour of distant Solar system bodies.

• the interplay of the different physical parameters of the surfaces may destroy the correlation with albedo

SUMMARY

• **Main observational features can be summarized as following:**

- negative polarization have been measured for all observed objects, varying from -0.2% to -2.1%;
- two distinct polarization phase behaviours for large and small TNOs;
- different polarization properties of TNOs with methane ice and water ice rich surfaces;
- a deep negative polarization with a minimum shifted to small phase angles for small TNOs and Centaurs;
- diverse polarization behaviour among Centaurs with a minimum varying from -1% to -2.1% (albedo's range is 4-16%);
- $|P_{\rm min}|$ tends to decrease when surface albedo increases while the correlation weaker as compared to asteroids;

• **Interpretation is in progress...**