“Polarimetry of Solar System objects”

3: Polarimetry of asteroids, comets and TNOs

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Polarimetry of atmosphereless bodies

- The early 1970s were an era of quick progress in polarimetric studies of atmosphereless bodies due to the relevance of the Apollo missions.

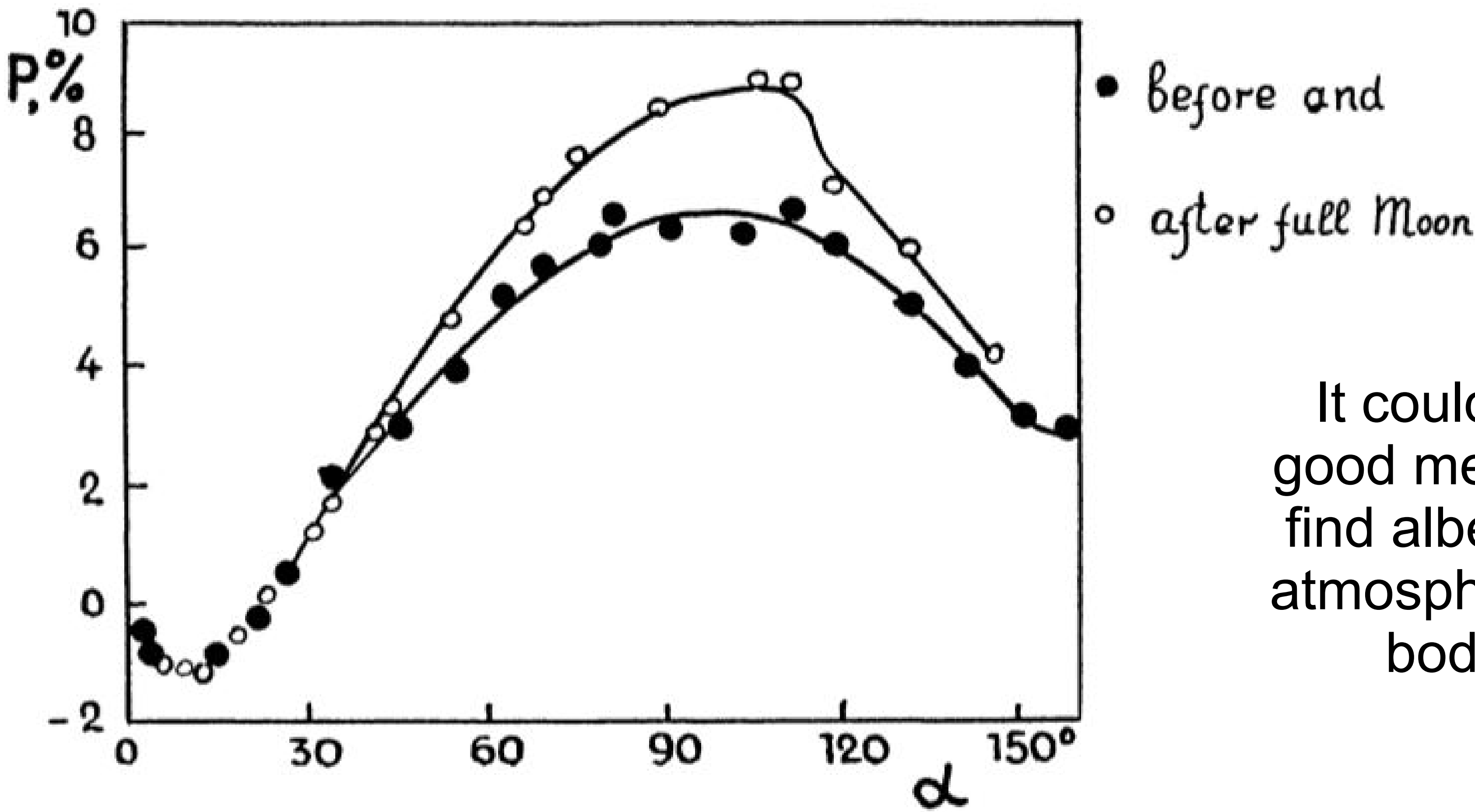
- T. Gehrels published "*Planets, Stars, and Nebulae Studied by Photopolarimetry*" in 1974.

- The main data sources at that time were a limited amount of asteroid measurements and laboratory studies using lunar samples and meteorites.

- Umov's law (1905) is a relationship between the albedo and the degree of polarization:

$$P_r \propto \frac{1}{p}, \qquad \alpha > 30^o$$

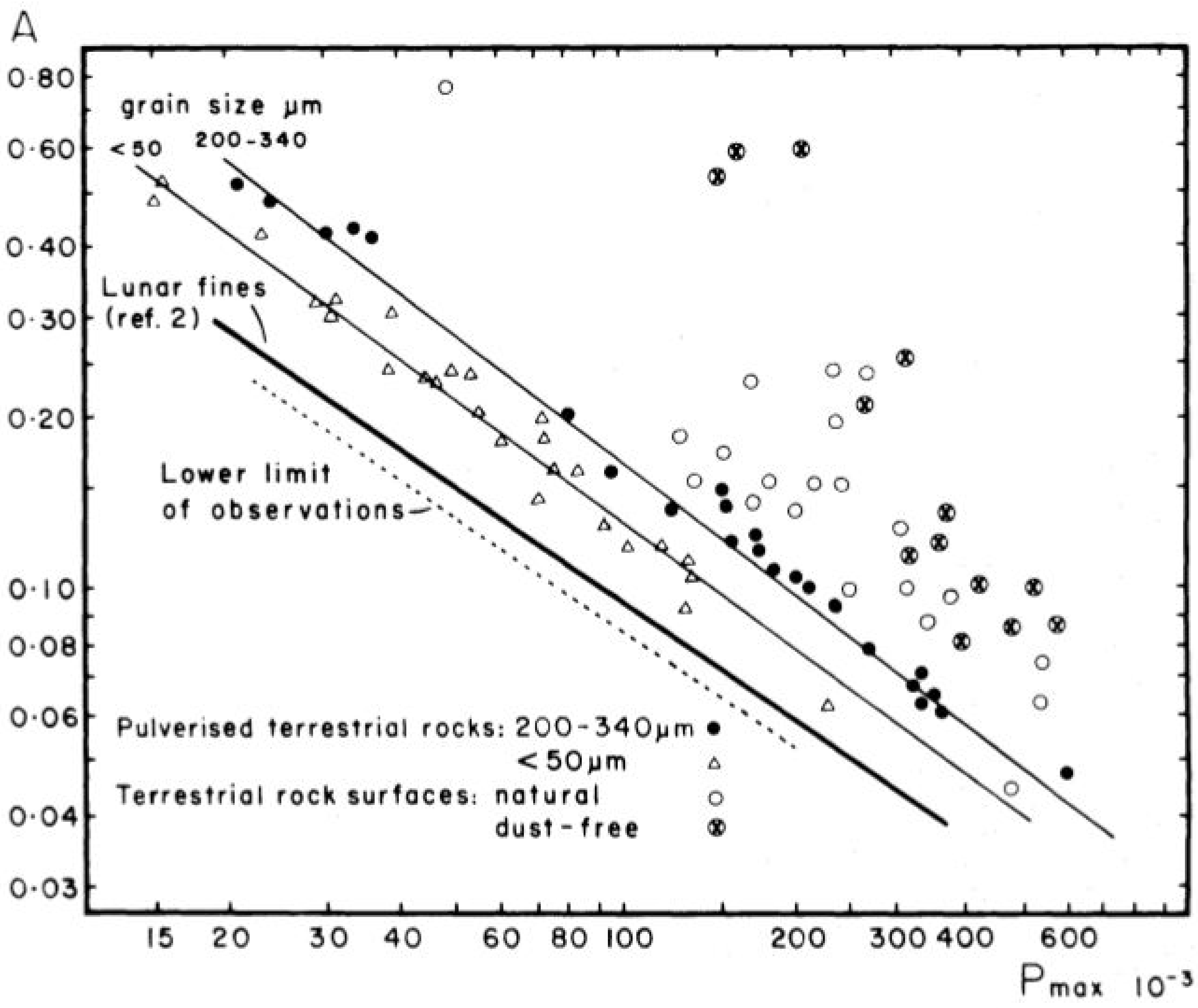
Polarimetry of atmosphereless bodies



It could be a good method to find albedos of atmosphereless bodies

Lyot (1929)

Polarimetry of atmosphereless bodies



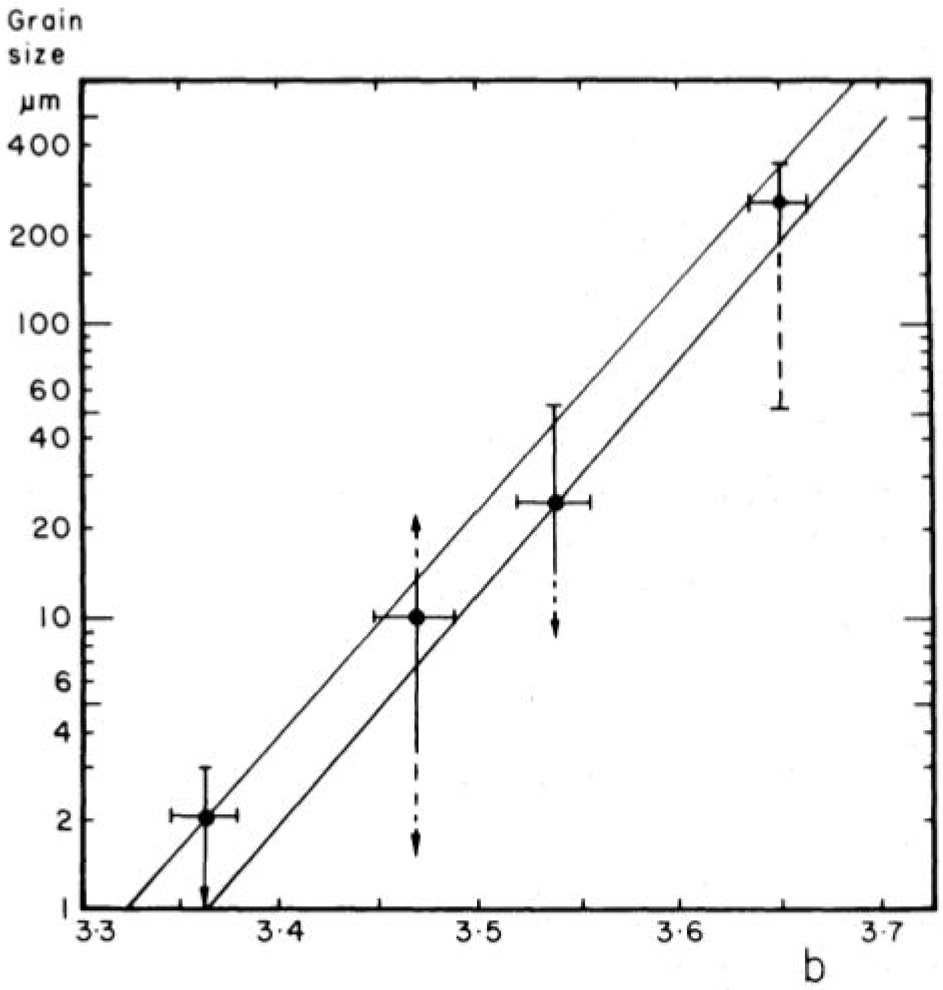
$$\log(p) = a\log(P_{max}) + b$$

a = 1.34 - 1.50

b is a function of grain size

Geake & Dollfus (1986)

Polarimetry of atmosphereless bodies



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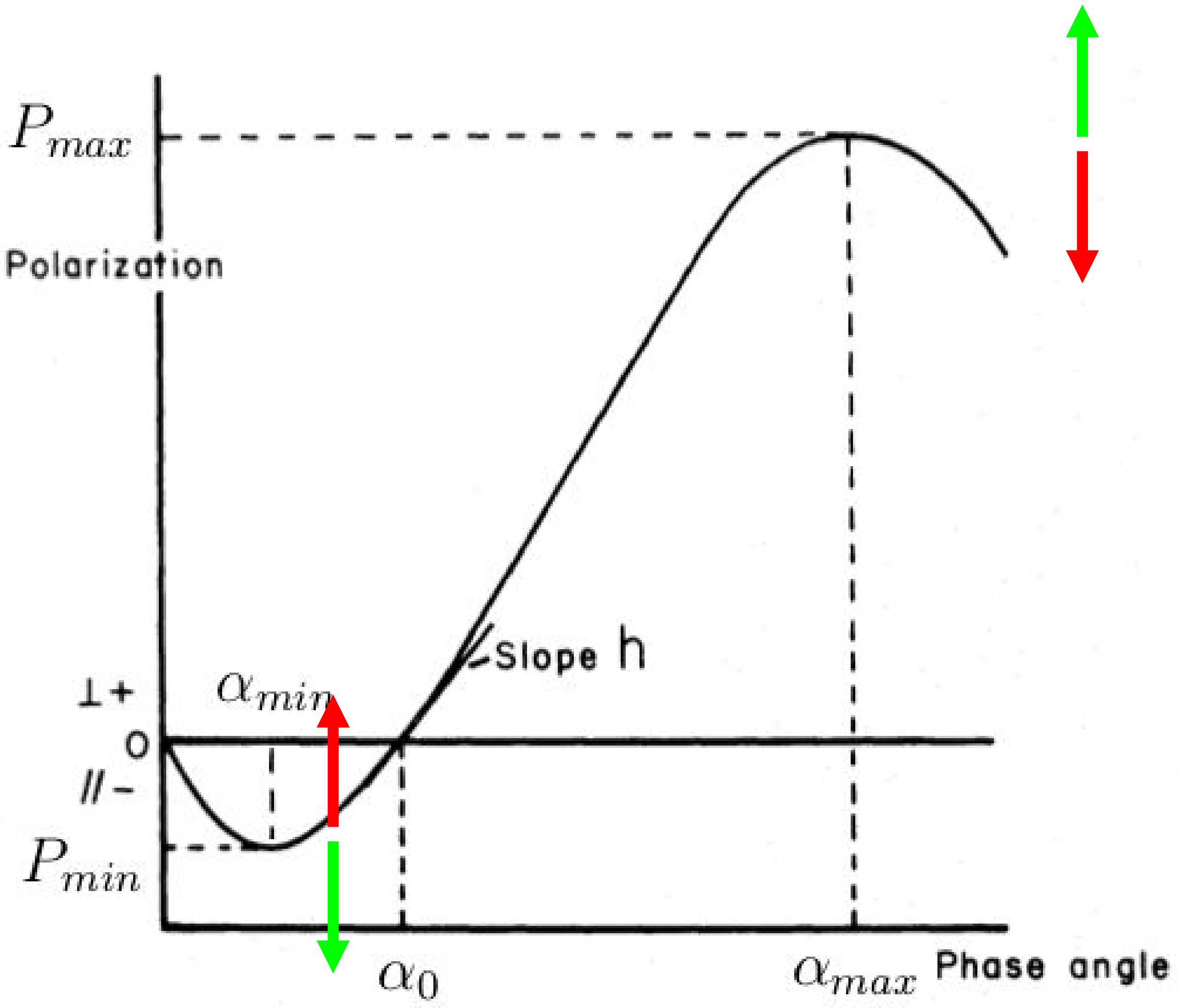
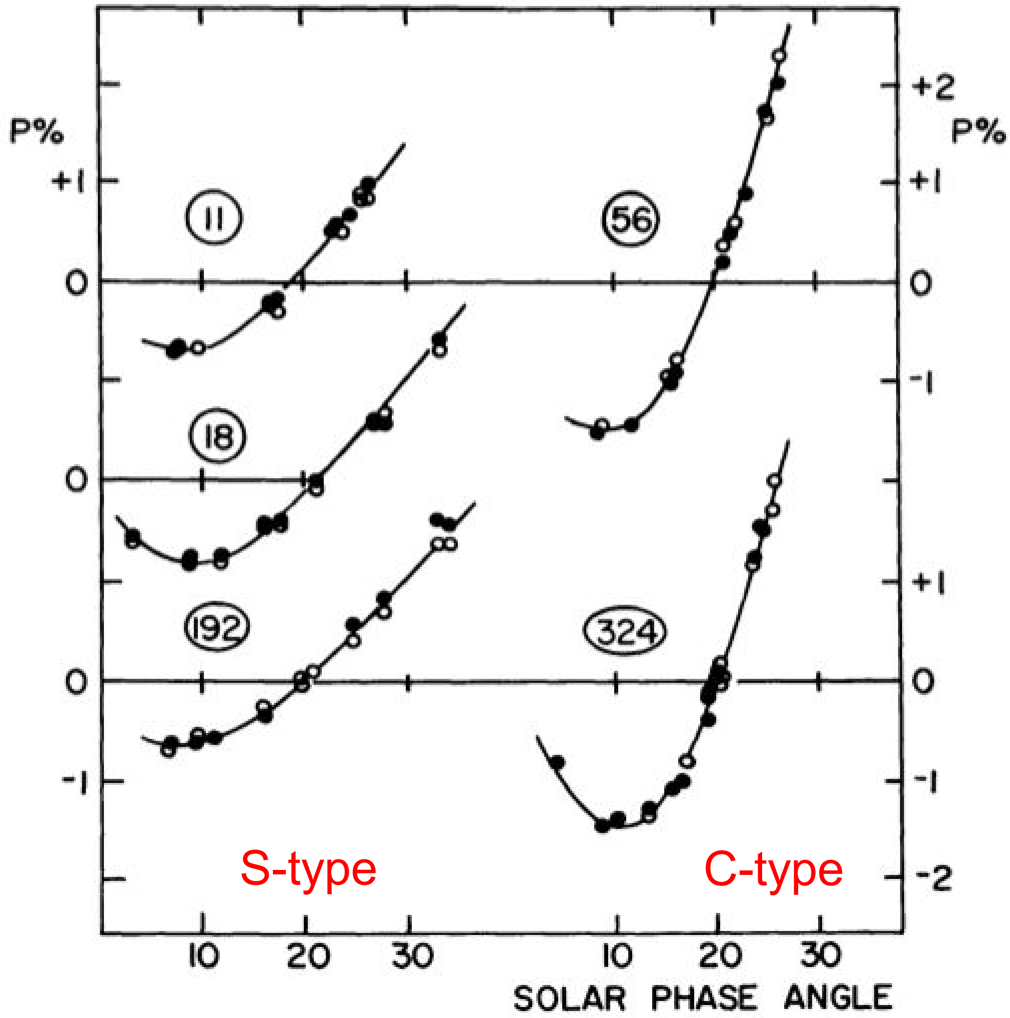
Polarimetry of atmosphereless bodies



Assuming that α_0 is almost stable, a change of P_{max} also produces a variation of h and P_{min}

$$P_r = \frac{(I_{\perp} - I_{\parallel})}{(I_{\perp} + I_{\parallel})}$$

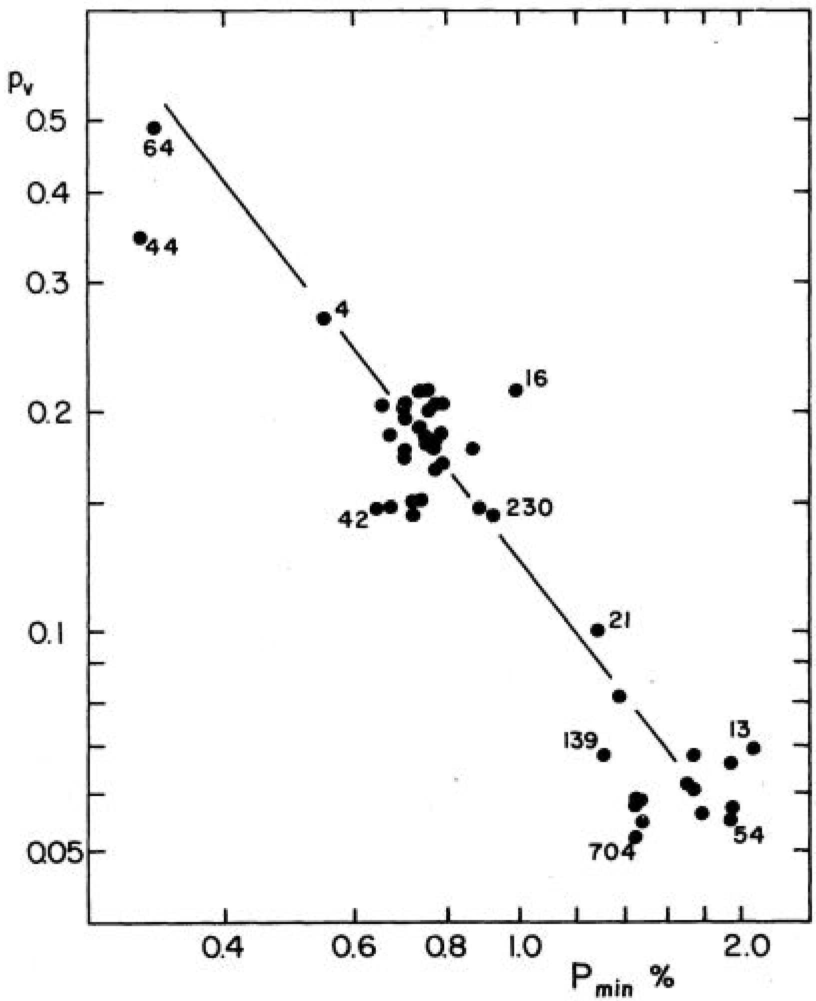
Polarimetry of atmosphereless bodies



differences between C- and S-type asteroids (Tholen taxonomy) for phase angles less than 30 degrees

Zellner & Gradie (1976)

Polarimetry of atmosphereless bodies



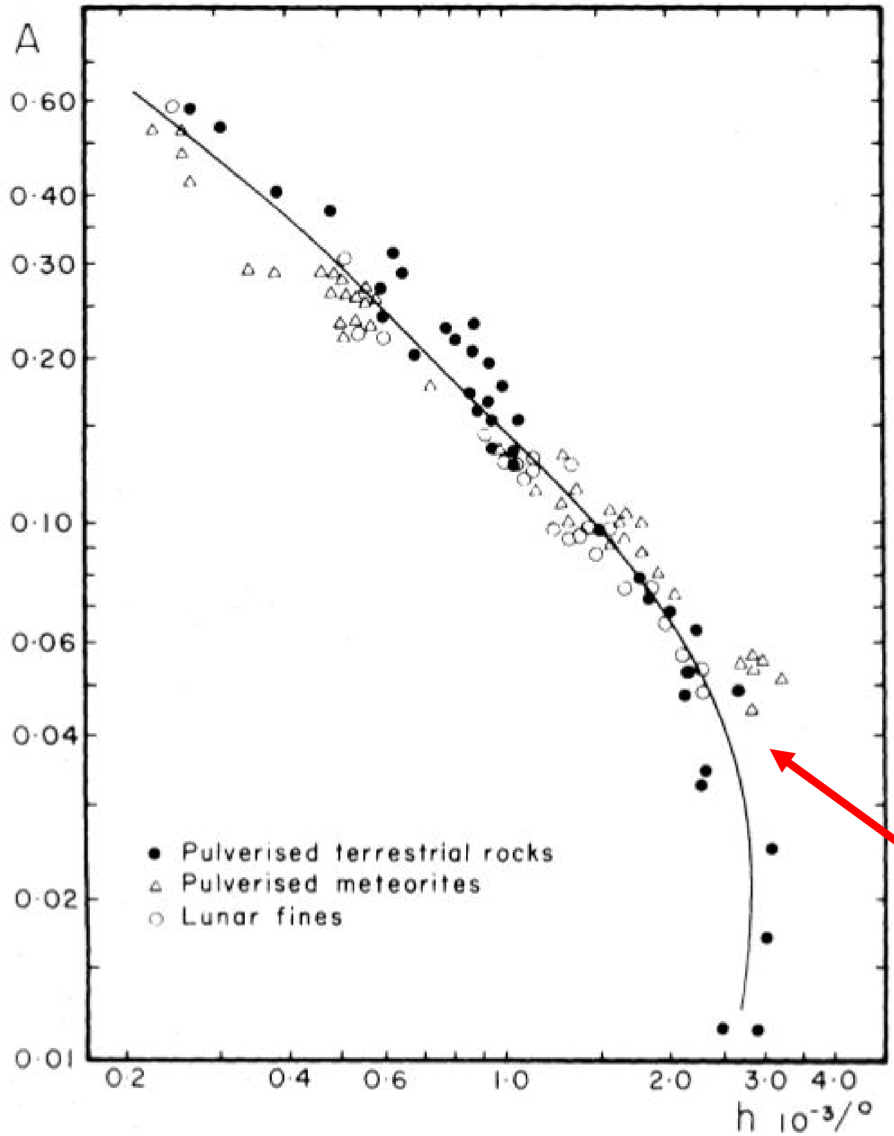
Empirical law relating P_{min} and albedo using asteroid data

$$\log(p_v) = C_1 \log(h) + C_2$$

$$\log(p_v) = C_3 \log(P_{min}) + C_4$$

Zellner & Gradie (1976)

Polarimetry of atmosphereless bodies



Empirical law relating h and albedo using meteorites and terrestrial rocks

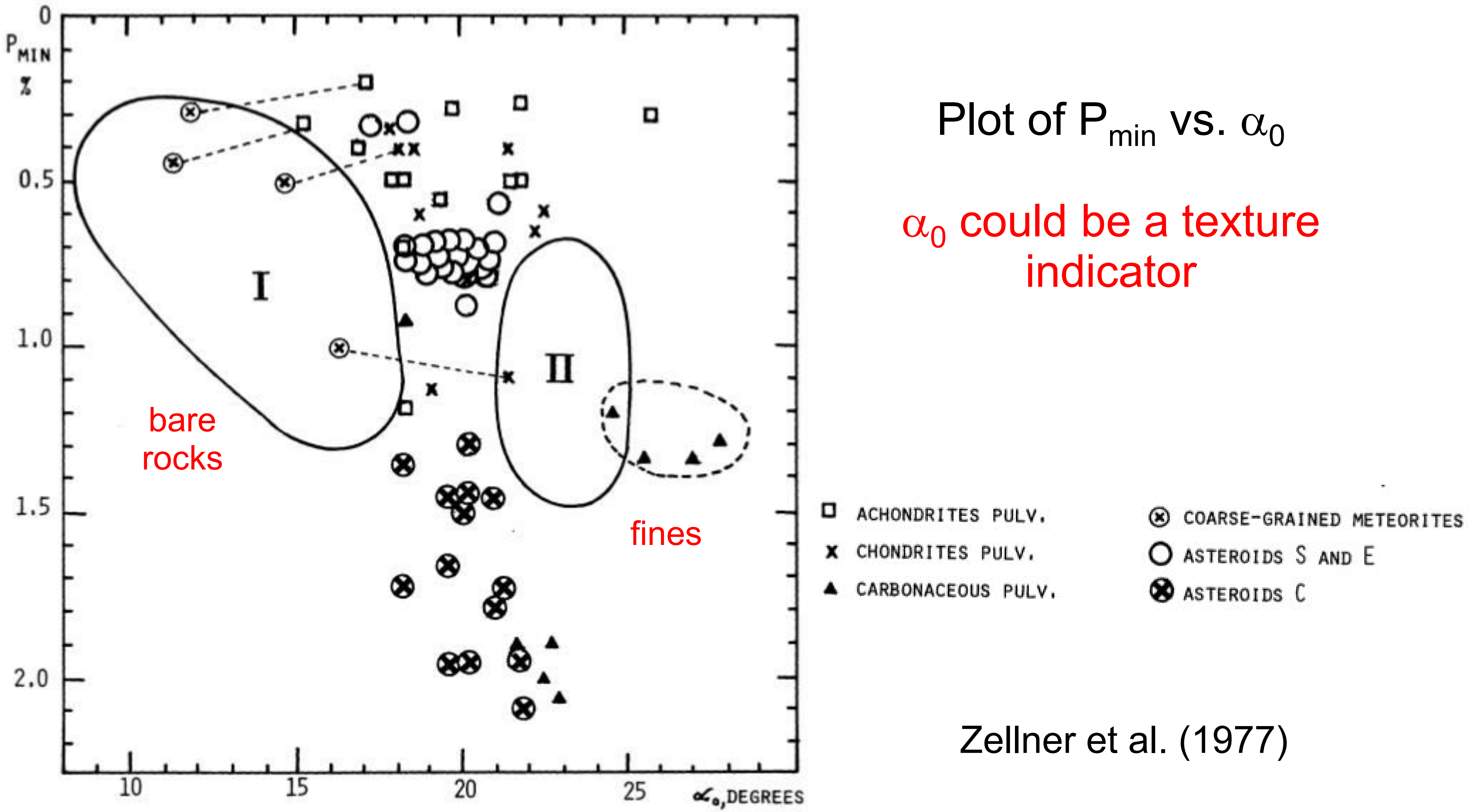
$$\log(p_v) = C_1 \log(h) + C_2$$

$$\log(p_v) = C_3 \log(P_{min}) + C_4$$

It fails for p < 6-8%

Zellner et al. (1977)
Geake & Dollfus (1986)

Polarimetry of atmosphereless bodies

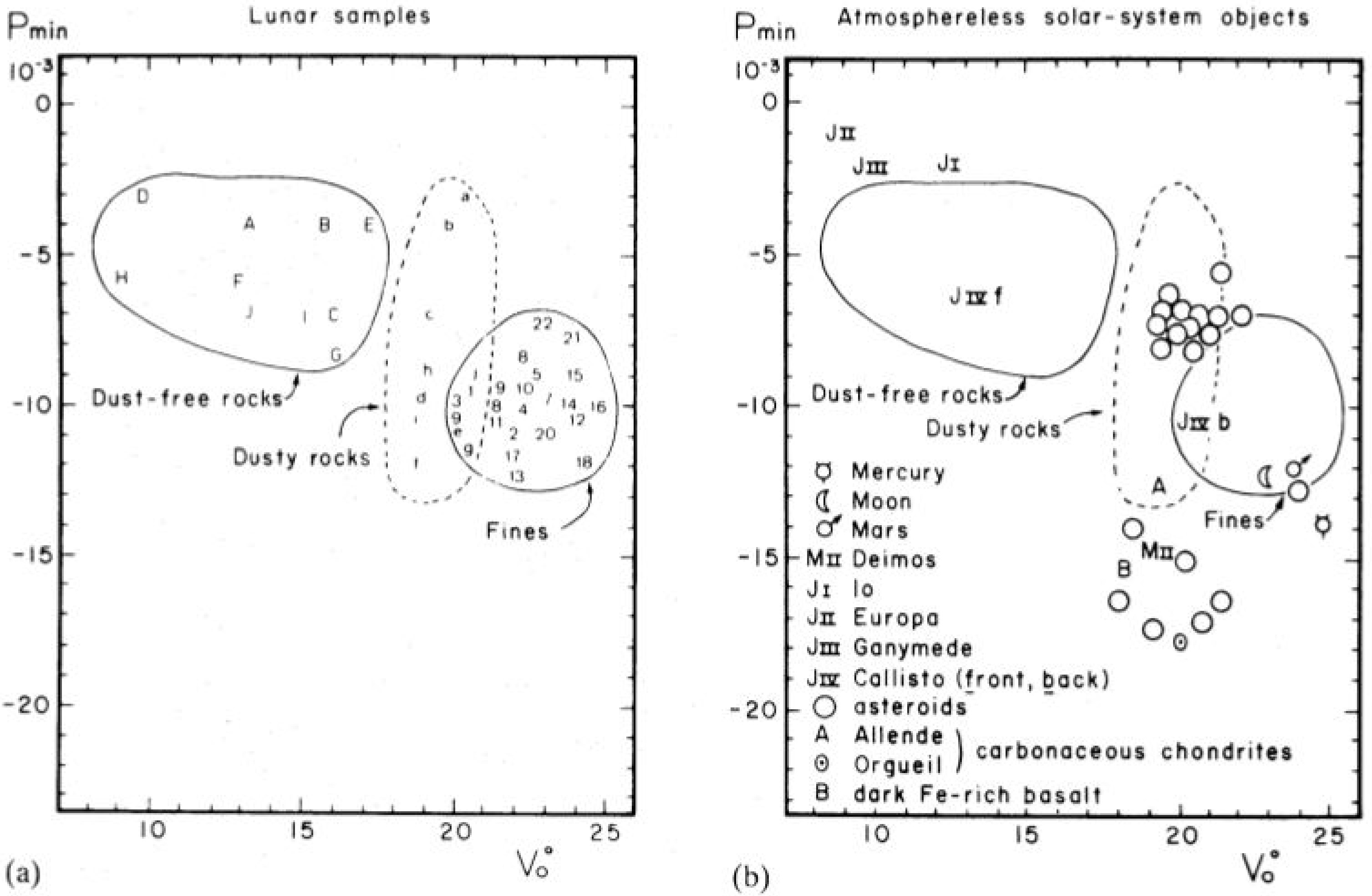


Plot of P_{min} vs. α_0

α_0 could be a texture indicator

Zellner et al. (1977)

Polarimetry of atmosphereless bodies



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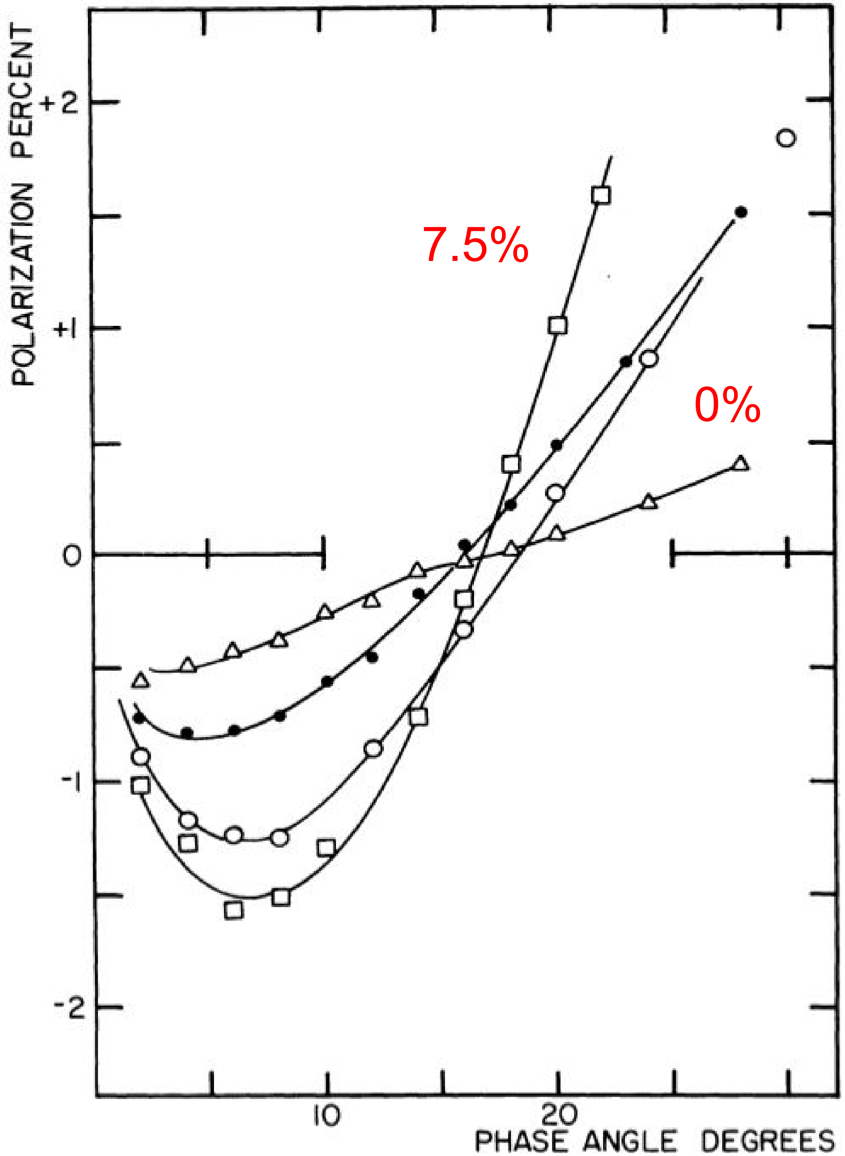


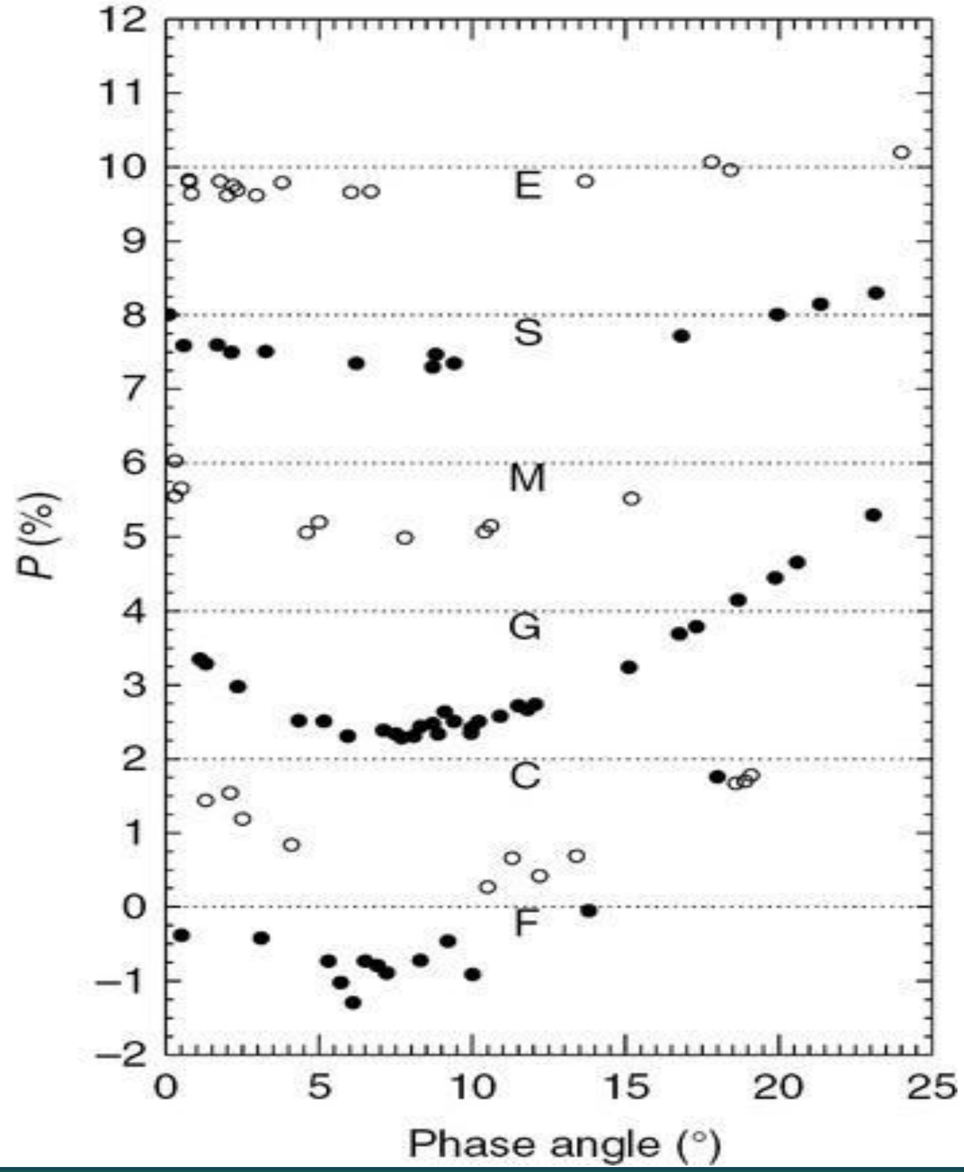
Polarimetric curves of silicates mixed with different amount of carbon

(0%, 1%, 5% and 7.5%)

Polarimetry is sensitive to composition

Zellner et al. (1977a)

Polarimetry of atmosphereless bodies

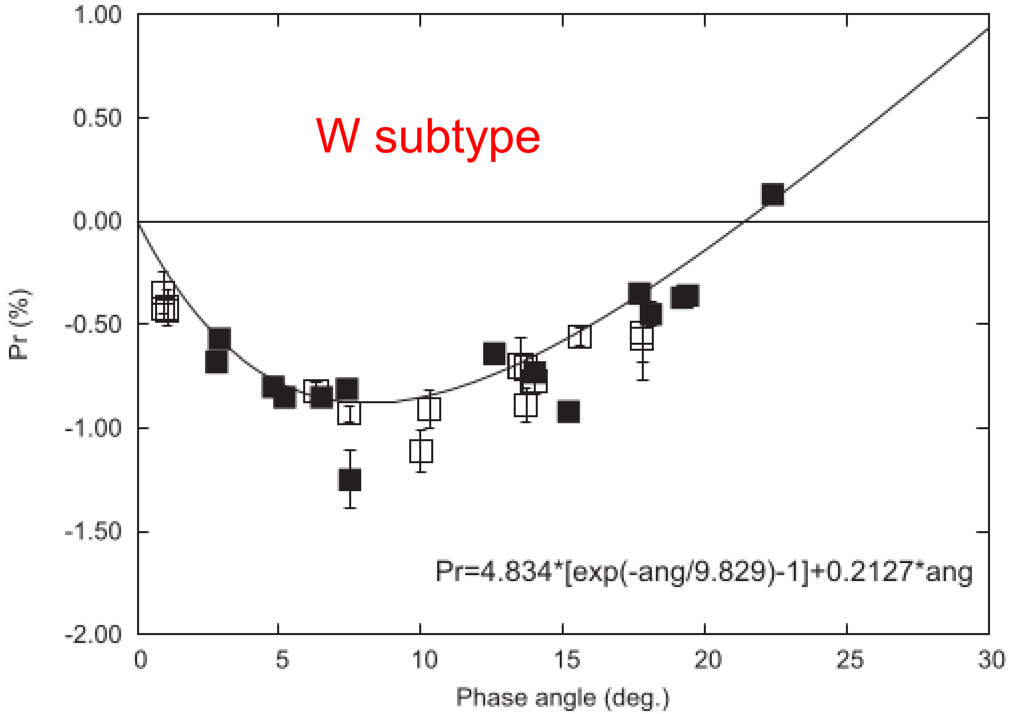


Polarimetric curves of several taxonomic types (Tholen 1984)

Polarimetry is sensitive to taxonomic type

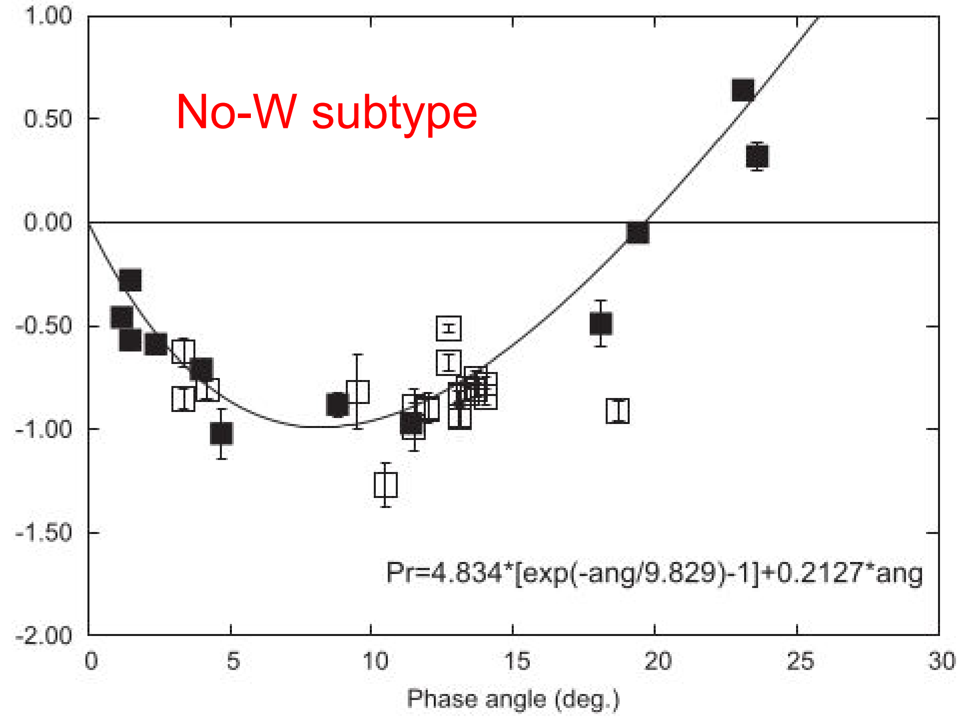
Zellner & Gradie (1976)
Lupishko et al. (1994)
Belskaya et al. (2003)

Polarimetry of M-type asteroids



Gil-Hutton (2007)

M-types
with or without 3 μm band
(Rivkin 1995, 2000)

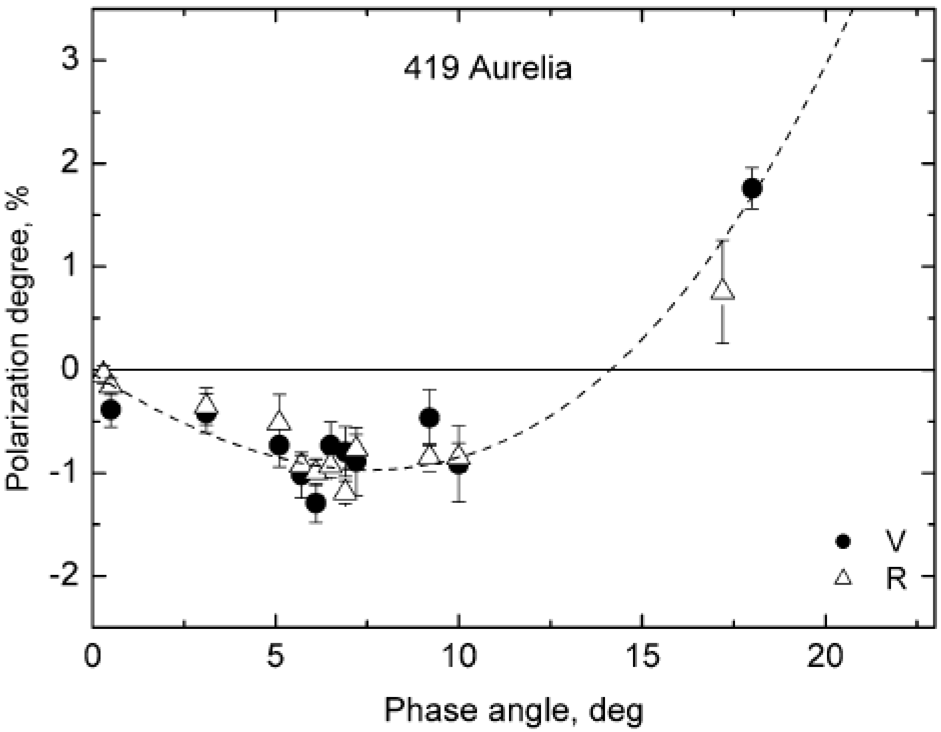


Polarimetry of M-type asteroids

Asteroid	$\|P_{min}\|$ %	α_{min} °	h %/°	α_0 °	Albedo Pol.	Albedo IRAS
16 Psyche	1.03 ± 0.02	7.99			0.13 ± 0.01	0.12
21 Lutetia	1.21 ± 0.01	8.67			0.11 ± 0.01	0.22
21 Lutetia			0.108 ± 0.001	24.83	0.20 ± 0.04	0.22
347 Pariana	0.78 ± 0.03	10.15			0.19 ± 0.02	0.18
347 Pariana			0.113 ± 0.001	22.59	0.19 ± 0.04	0.18
W-types (no 21)	0.88 ± 0.02	8.12			0.17 ± 0.01	
W-types (no 21)			0.101 ± 0.001	21.41	0.22 ± 0.05	
no W-types (no 16)	0.99 ± 0.08	8.24			0.14 ± 0.02	
no W-types (no 16)			0.146 ± 0.004	19.64	0.14 ± 0.03	
all M-types (no 16 or 21)	0.91 ± 0.07	8.57			0.16 ± 0.02	
all M-types (no 16 or 21)			0.121 ± 0.004	20.92	0.18 ± 0.04	

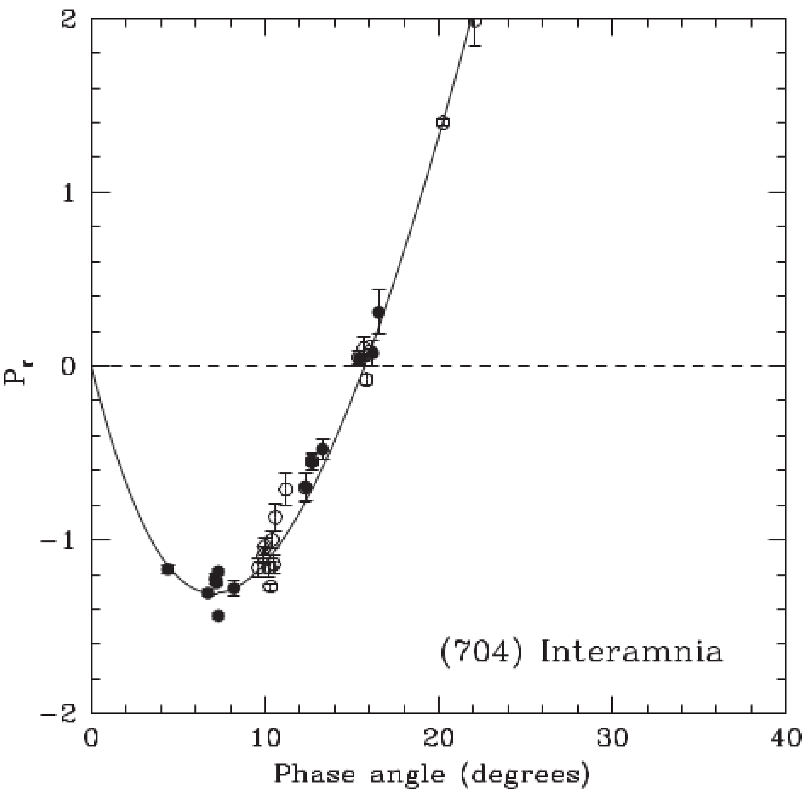
Gil-Hutton (2007)

Polarimetry of F-type asteroids



F-types of Tholen (1984) with small inversion angle

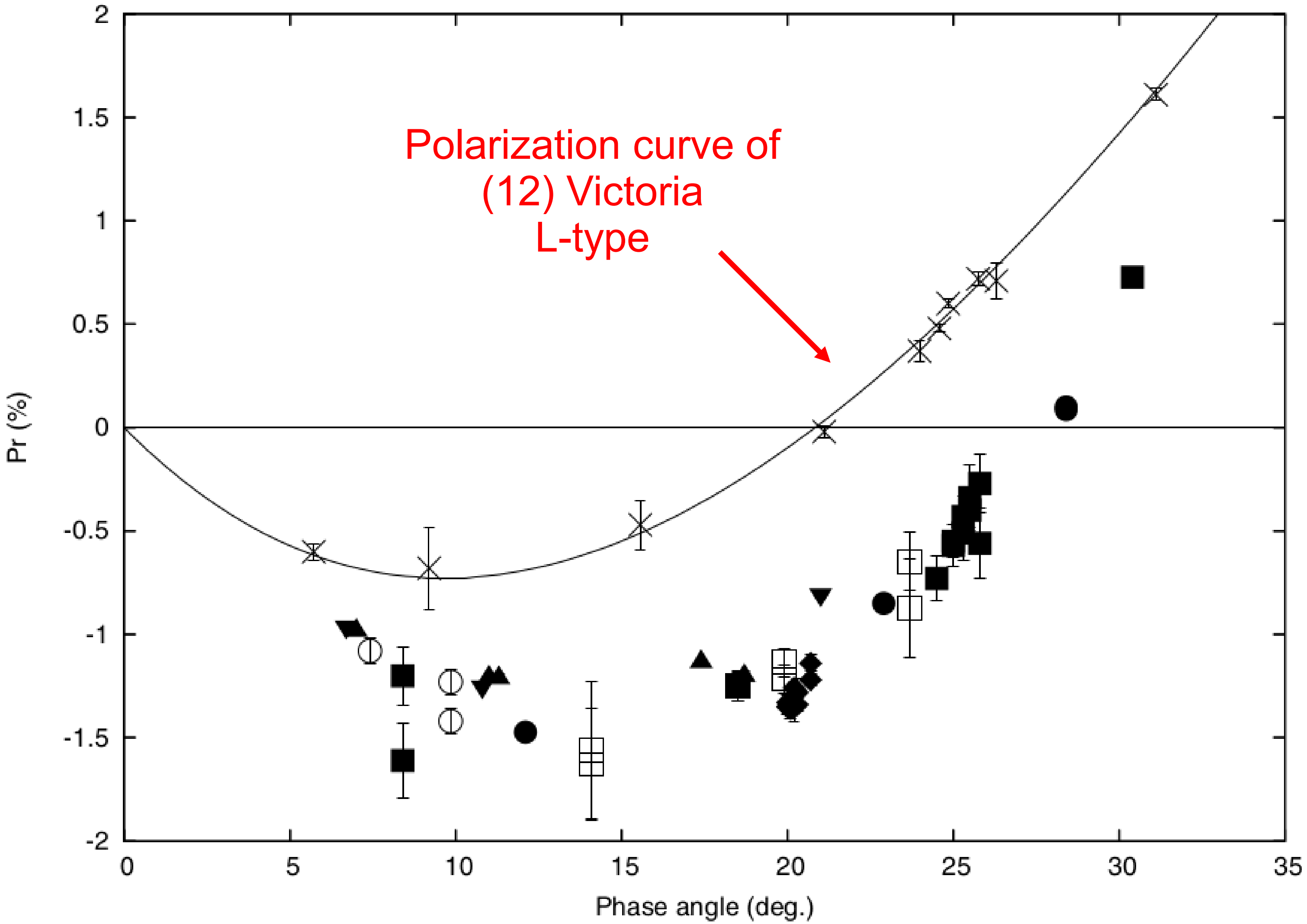
$\alpha_0 \sim 15^o$



Regolith of bare rocks?

Belskaya et al. (2005)

Polarimetry of Barbarians



Objects with large inversion angle (L-, Ld- and K-types)

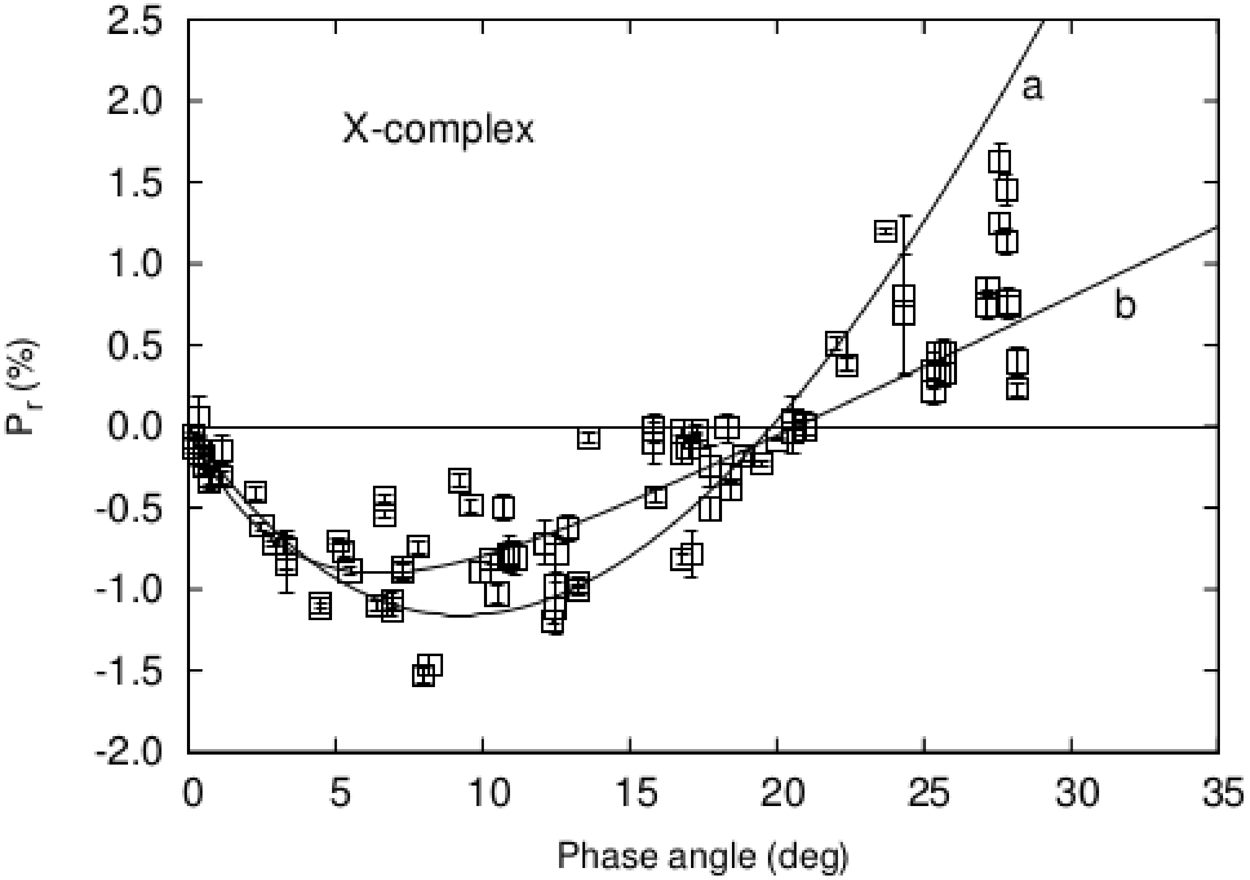
$\alpha_0 \sim 28^o$

CAIs on a black matrix?

Regolith of fine particles?

Cellino et al. (2006)
Gil-Hutton et al. (2008)

Polarimetry of X-class asteroids



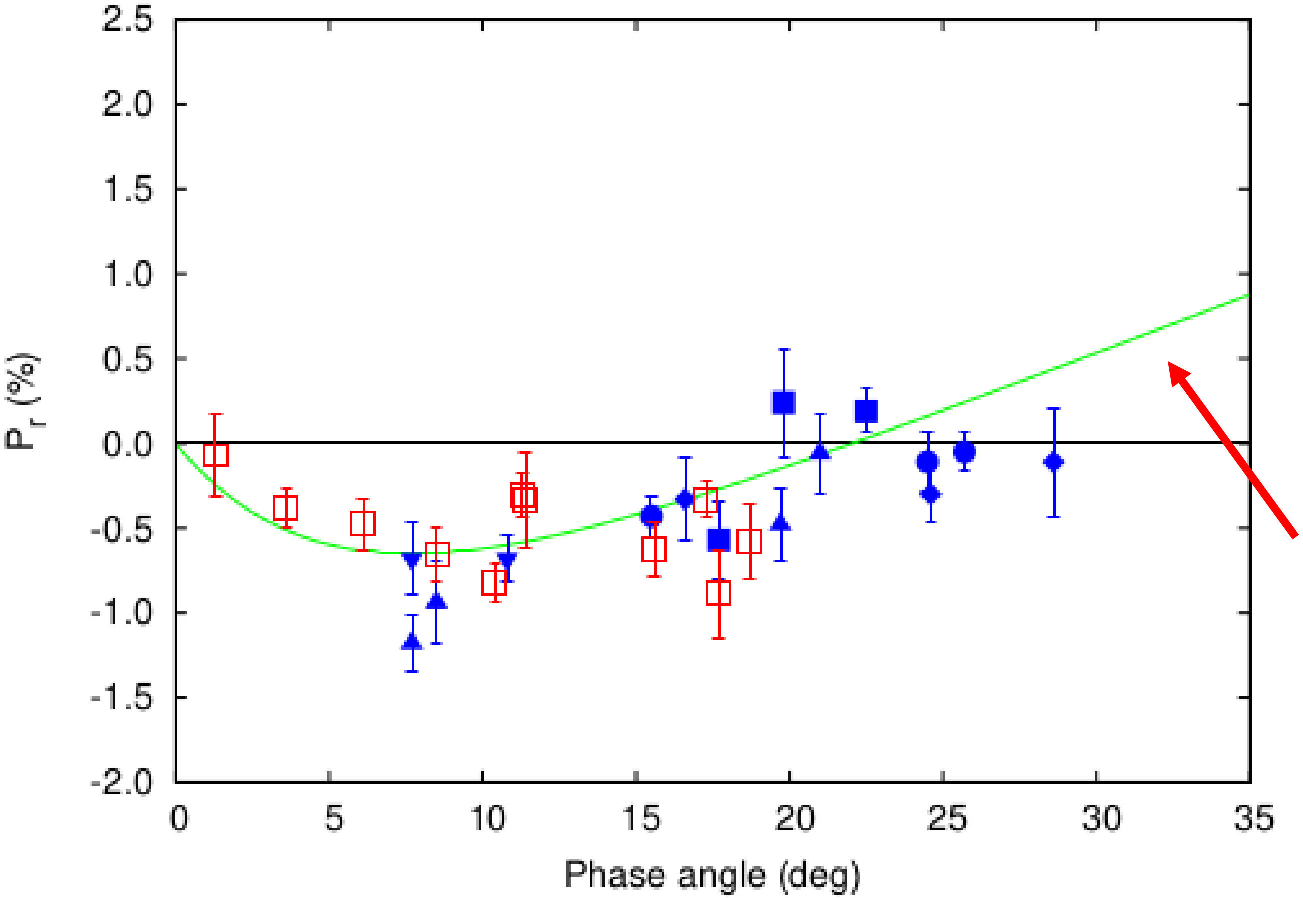
Objects in X-complex with different polarimetric properties

New taxonomies do not take into account the polarimetric properties

a: Polarization curve for P-type
b: Polarization curve for M-type

Cañada-Assandri et al. (2012)

Polarimetry of V-type asteroids



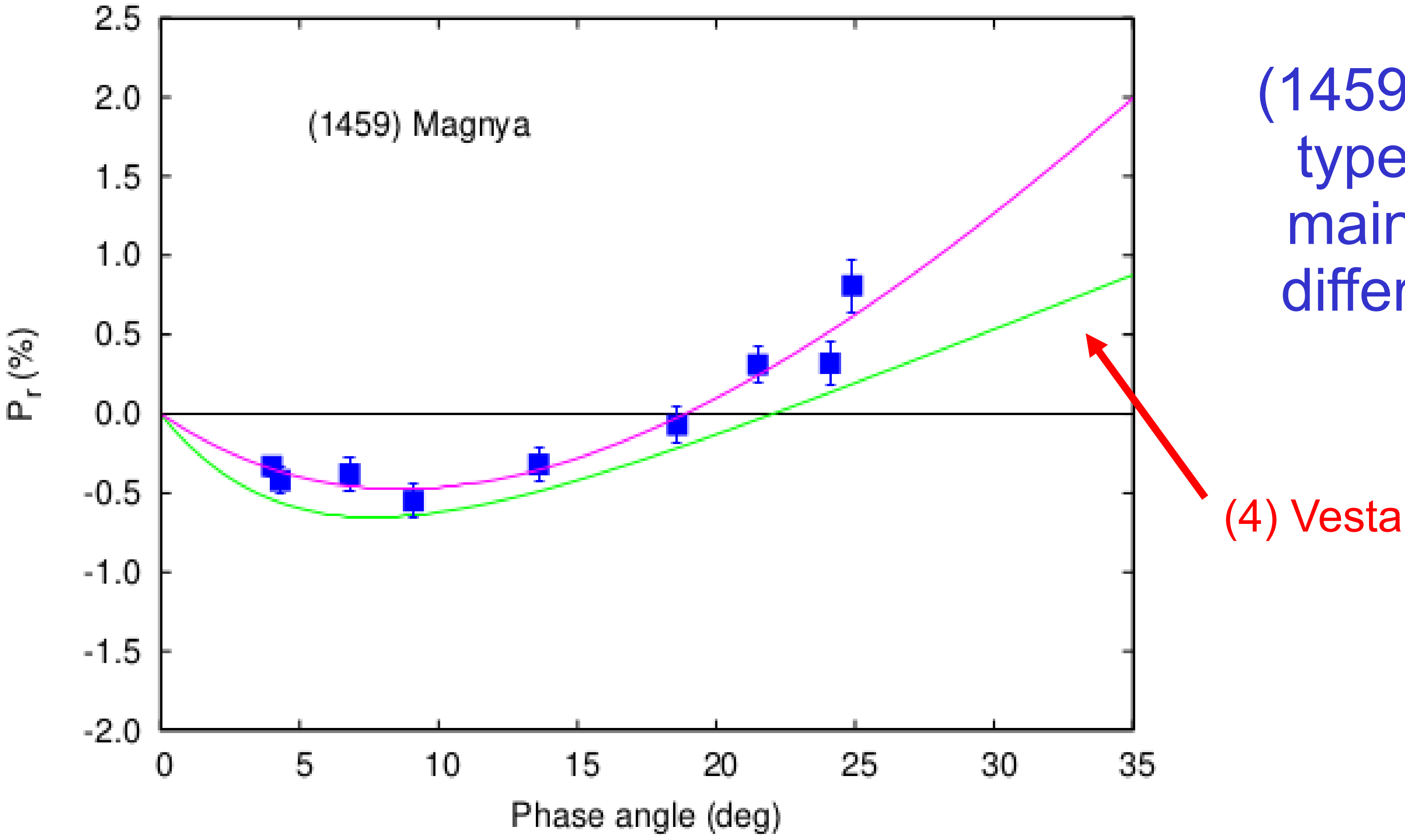
(4) Vesta

V-types in the main-belt

Several members of Vesta family follow the tipical V-type polarization curve

Gil-Hutton et al. (2017)

Polarimetry of V-type asteroids



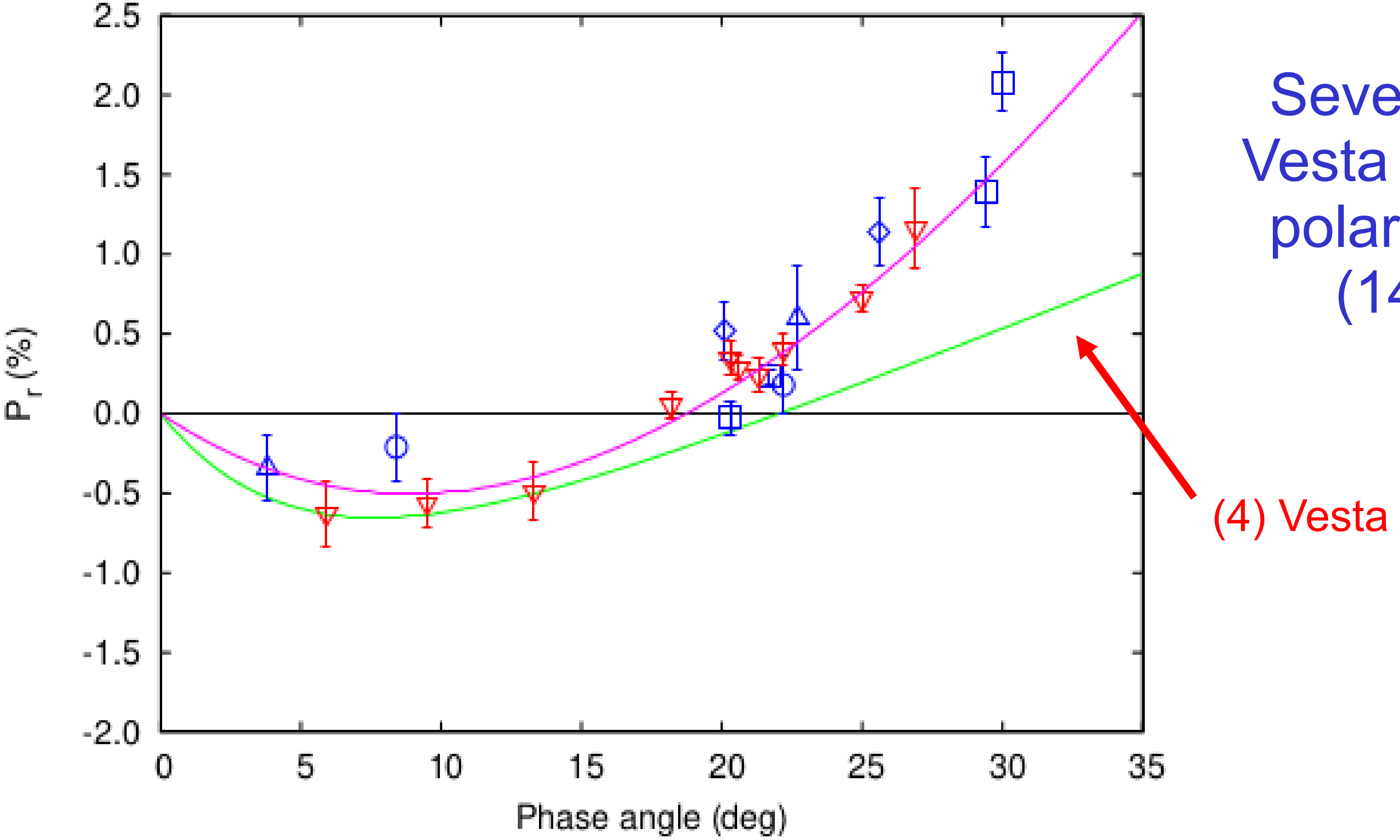
V-types in the main-belt

(1459) Magnya is a V-type in the external main-belt and has a different polarization curve

Gil-Hutton et al. (2017)

Polarimetry of V-type asteroids

V-types in the main-belt



Several members of Vesta family follow the polarization curve of (1459) Magnya

Gil-Hutton et al. (2017)

Catalogue of polarization curves

Grupo de Ciencias Planetarias

Planetary Science Group

U.N.S.J - San Juan - Argentina

GRUPO de CIENCIAS PLANETARIAS

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- Investigación
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Catalogue of asteroid polarization curves

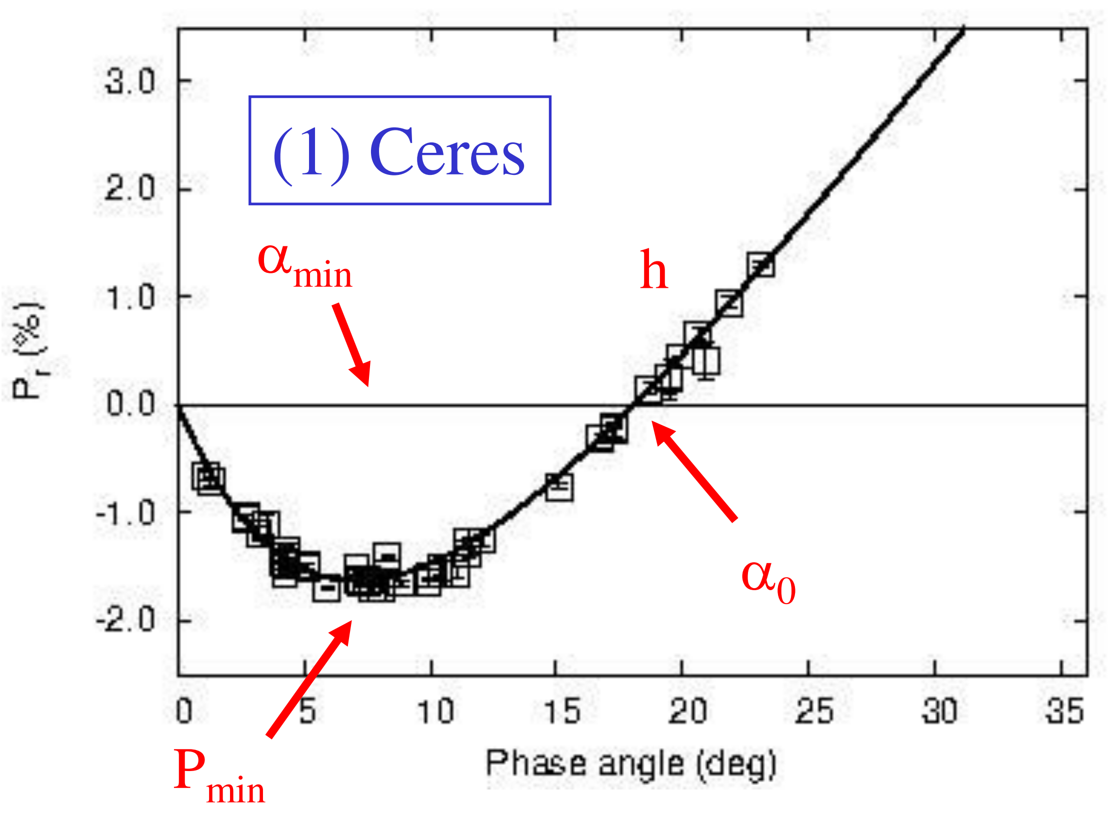
Please make reference to: **R. Gil-Hutton (2017)Catalogue of asteroid polarization curves, presented at "Asteroid, Comets, Meteors 2017", Montevideo, Uruguay**.

There are 8 groups:

- **Group A:** Asteroids with at least 5 measurements, excellent phase coverage and a polarization curve.
- **Group B, C and D:** Asteroids with at least 4 measurements, good phase coverage and a polarization curve.
- **Group E:** Asteroids with at least 4 measurements, regular phase coverage and tentative polarization curve.
- **Group F:** Asteroids with at least 3 measurements and regular phase coverage.
- **Group G:** Asteroids with at least 3 measurements and bad phase coverage.
- **Group H:** Asteroids with only 2 measurements.

Catalogue of polarization curves

Catalogue of polarization curves

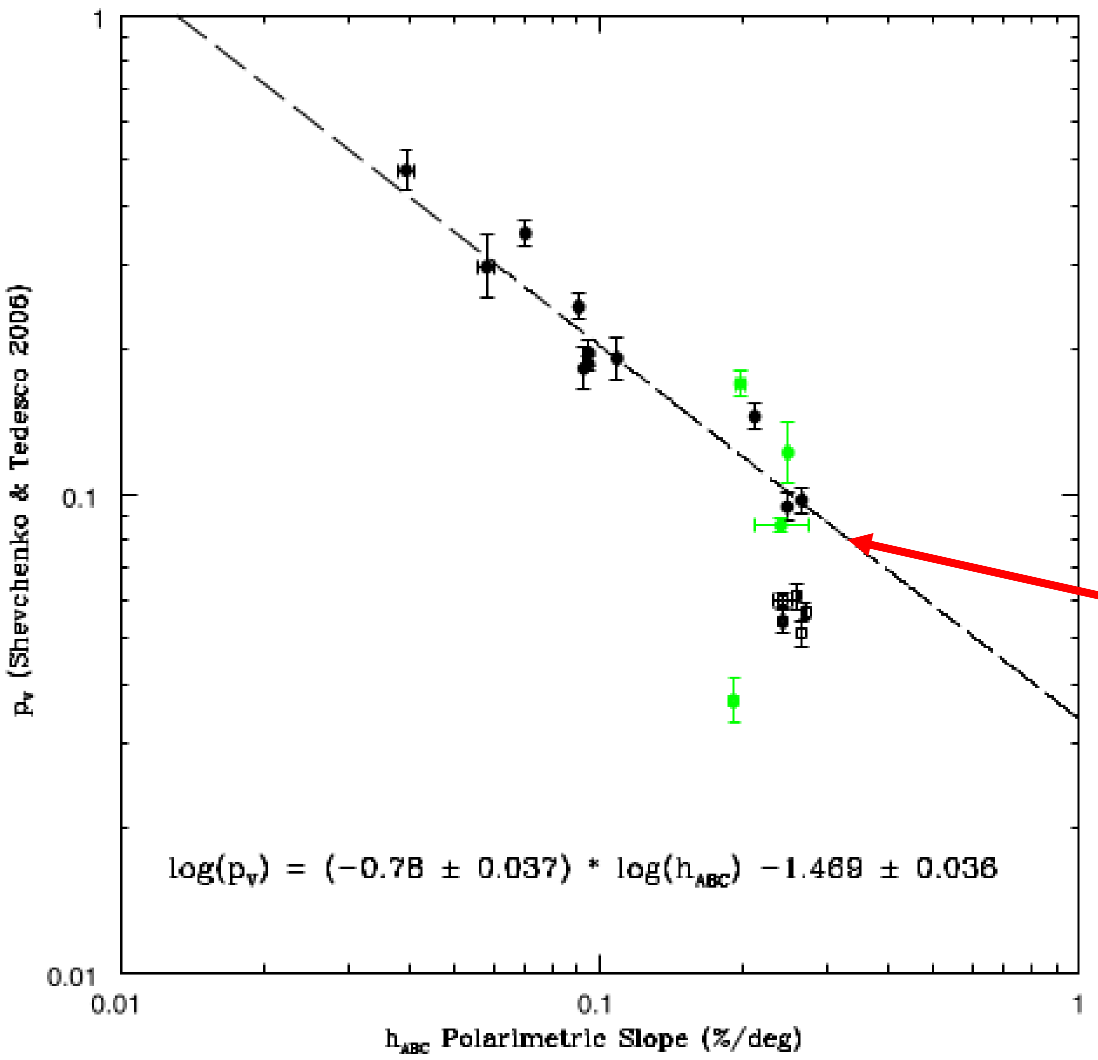


$$P_r = \frac{(I_\perp - I_\parallel)}{(I_\perp + I_\parallel)}$$

$$P_r(\alpha) = A_0\left[\exp\left(-\frac{\alpha}{A_1}\right) - 1\right] + A_2\alpha,$$

Kaasalainen et al. (2001, 2003)
Muinonen et al. (2009)

Catalogue of polarization curves



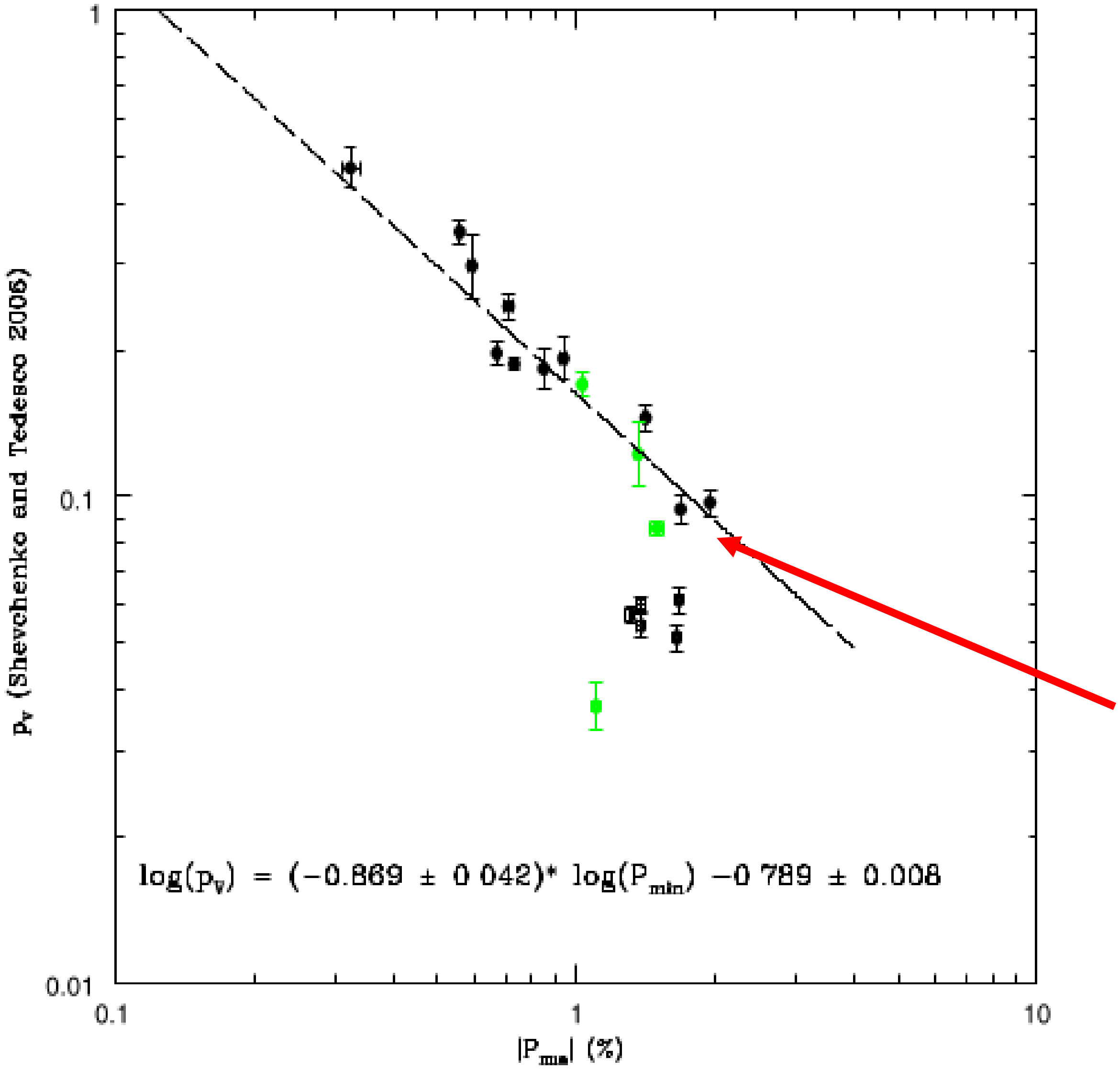
Albedo vs. slope

using diameters from the list of Tedesco & Sevchenko (2006)

It fails for p < 6-8%

Cellino et al. (2015)

Catalogue of polarization curves



Albedo vs. P_{min}

using diameters from the list of Tedesco & Sevchenko (2006)

It fails for p < 6-8%

Cellino et al. (2015)

Catalogue of polarization curves

- Other empirical laws were also tested

Masiero et al. (2012)

$$p^* = W_1 \log(h) + W_2 \log(P_{min})$$

$$\log(p_v) = C_1^* p^* + C_2^*$$

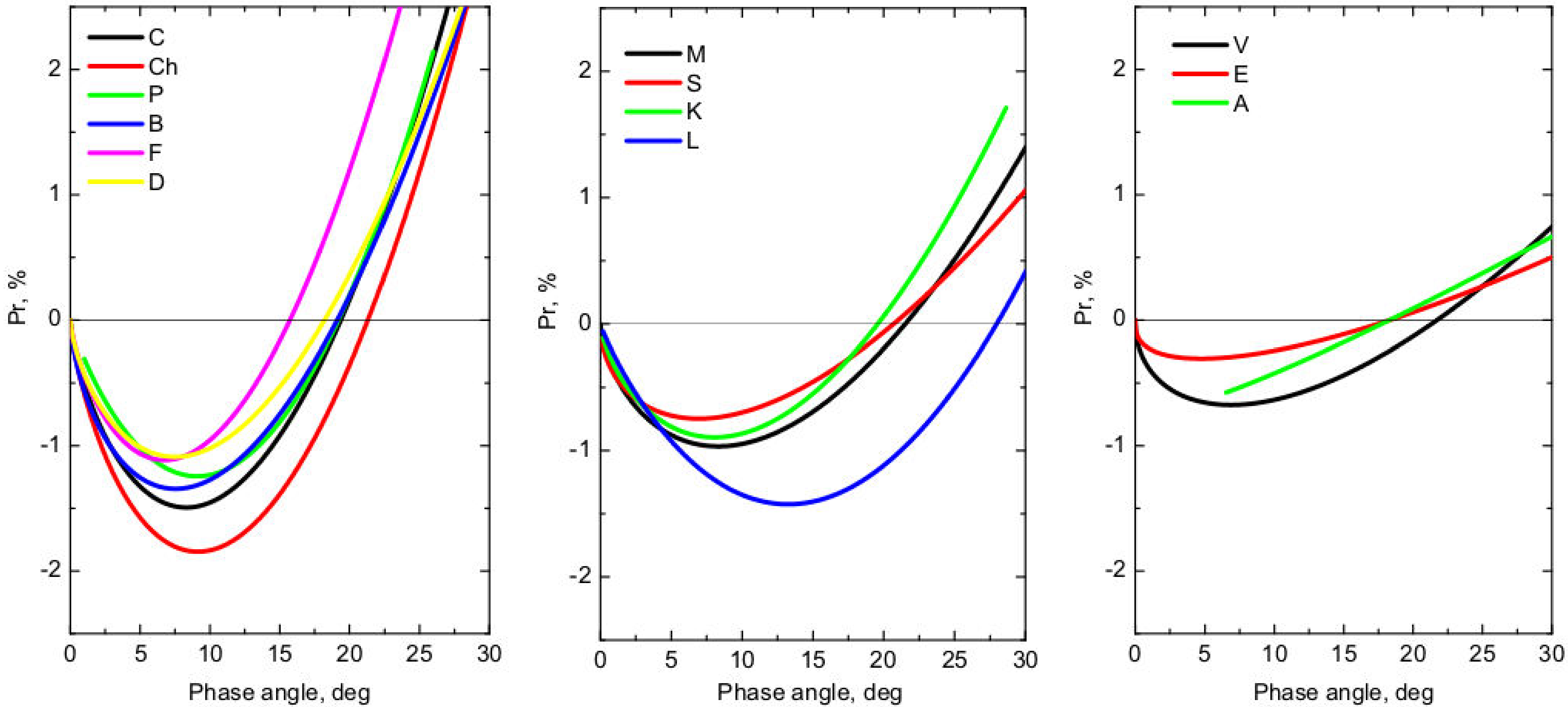
Cellino et al. (2015)

$$\psi = P_r(30^o) - P_r(10^o)$$

$$\log(p_v) = C_{\psi 1} \log(\psi) + C_{\Psi 2}$$

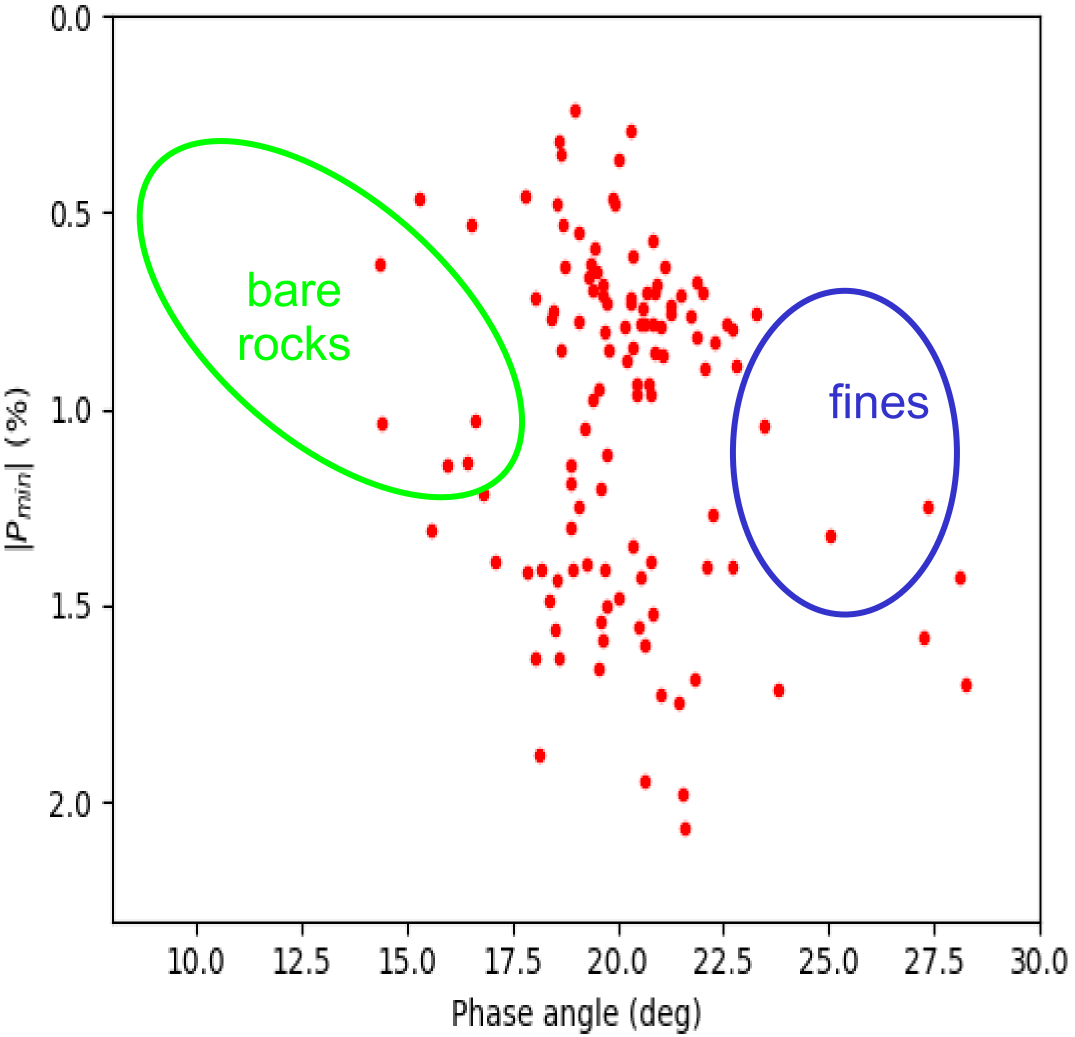
$\log(p_V) = C_1 \log(h) + C_2$	$C_1 = -1.111 \pm 0.031$	$C_2 = -1.781 \pm 0.025$
$\log(p_V) = C_1 \log(h) + C_2 \ (p_V \geq 0.08)$	$C_1 = -0.800 \pm 0.041$	$C_2 = -1.467 \pm 0.037$
$\log(p_V) = C_1 \log(h_{ABC}) + C_2$	$C_1 = -1.139 \pm 0.026$	$C_2 = -1.850 \pm 0.021$
$\log(p_V) = C_1 \log(h_{ABC}) + C_2 \ (p_V \geq 0.08)$	$C_1 = -0.780 \pm 0.037$	$C_2 = -1.469 \pm 0.036$
$\log(p_V) = C_3 \log(P_{\min}) + C_4$	$C_3 = -1.419 \pm 0.034$	$C_4 = -0.918 \pm 0.006$
$\log(p_V) = C_3 \log(P_{\min}) + C_4 \ (p_V \geq 0.08)$	$C_3 = -0.869 \pm 0.042$	$C_4 = -0.789 \pm 0.008$
$\log(p_V) = C_{\psi 1} \log(\Psi) + C_{\psi 2}$	$C_{\psi 1} = -0.987 \pm 0.022$	$C_{\psi 2} = -0.458 \pm 0.013$
$\log(p_V) = C^*{}_1 p^* + C^*{}_2$	$C^*{}_1 = -0.896 \pm 0.029$	$C^*{}_2 = -1.457 \pm 0.018$

Catalogue of polarization curves



Belskaya et al. (2017)

Catalogue of polarization curves



Plot of P_{min} vs. α_0

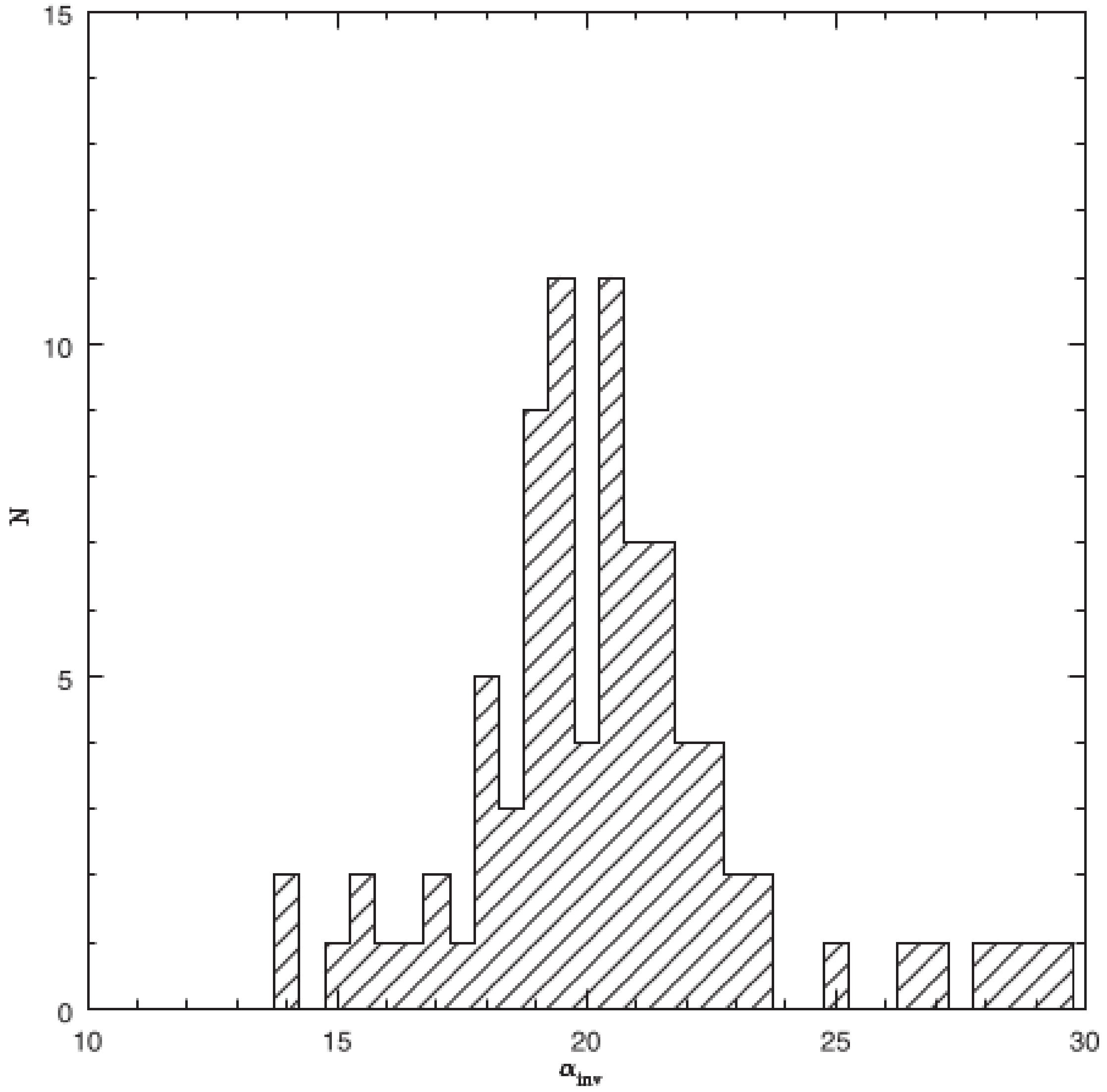
using the catalogue

It was expected that the surfaces have only rocks

α_0 is not a good indicator of texture

Gil-Hutton (2017)

Catalogue of polarization curves



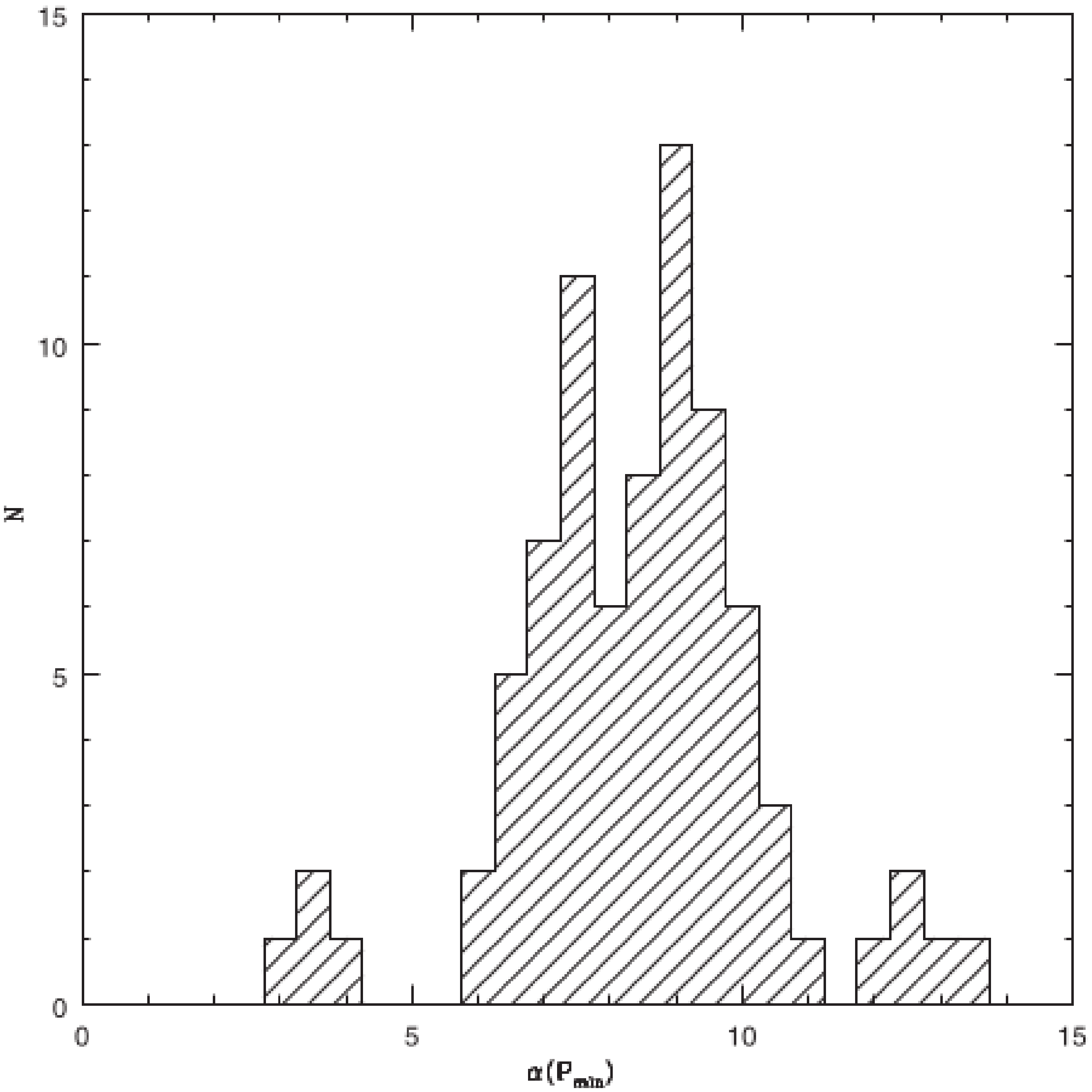
Inversion angle α_0

using the catalogue

It was expected that the surfaces have only rocks ($\alpha_0 < 17^o$)

Cellino et al. (2016)
Gil-Hutton (2017)

Catalogue of polarization curves

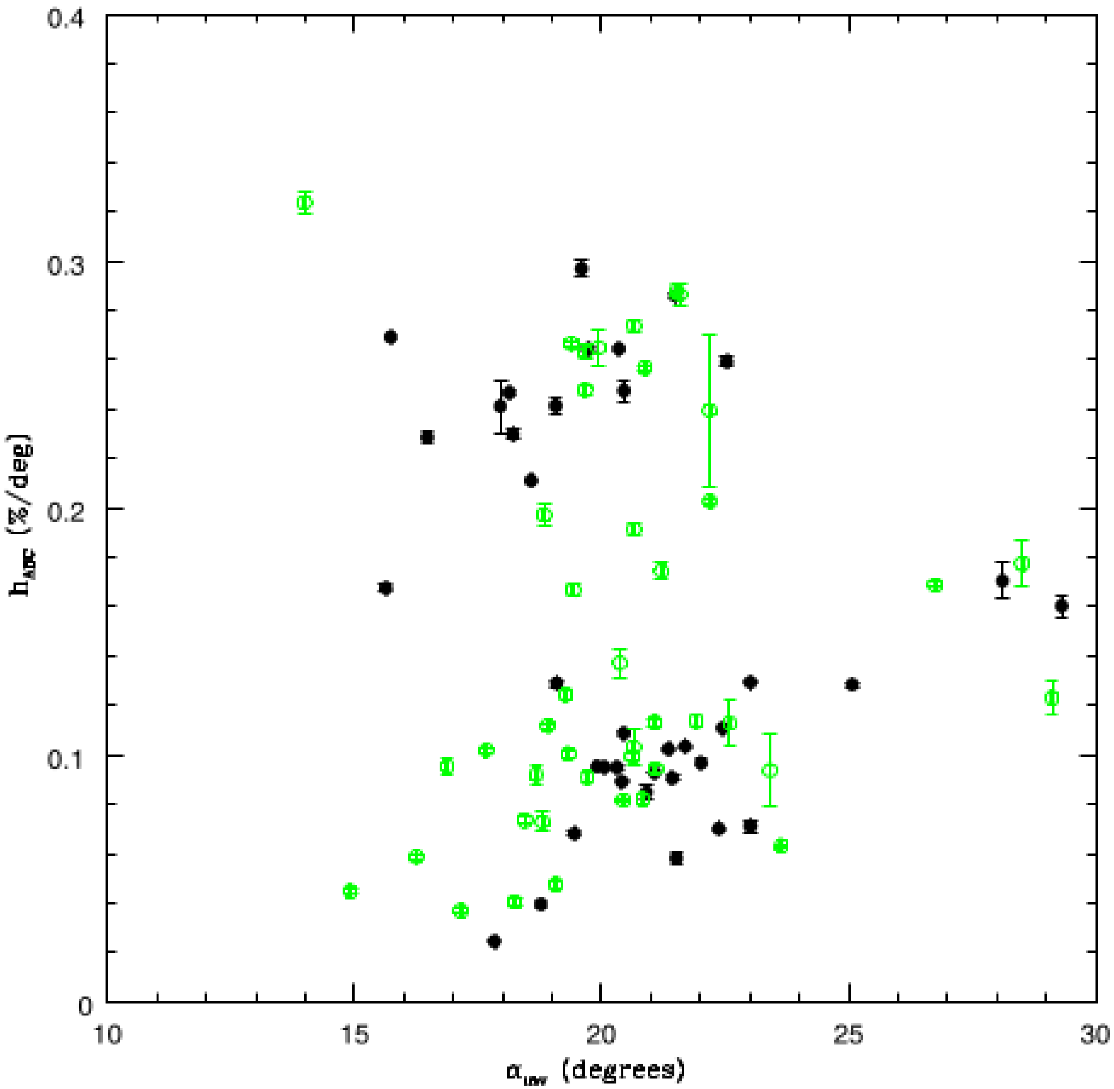


Phase angle of minimum α_{min}

using the catalogue

Cellino et al. (2016)
Gil-Hutton (2017)

Catalogue of polarization curves

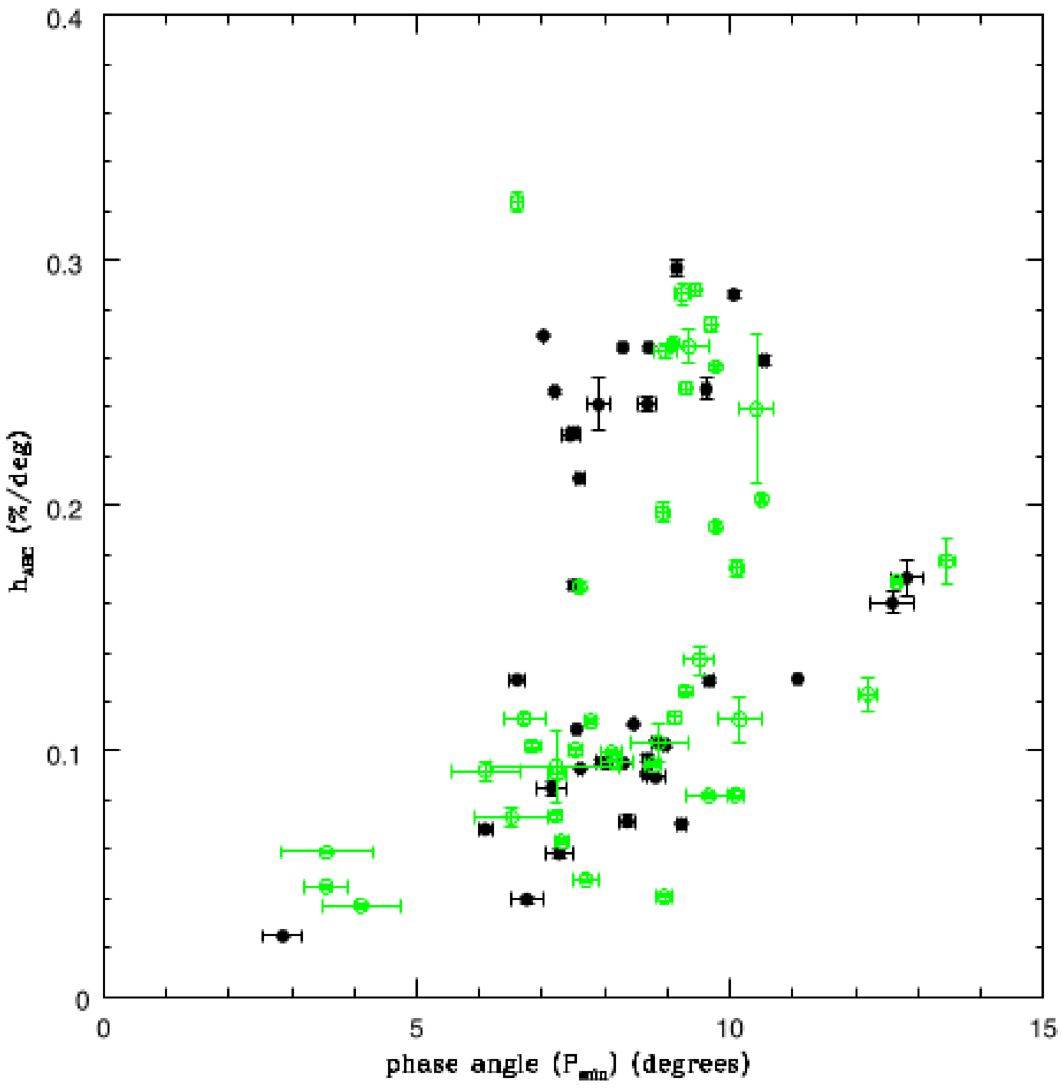


slope vs. α_0

using the catalogue

Cellino et al. (2016)
Gil-Hutton (2017)

Catalogue of polarization curves

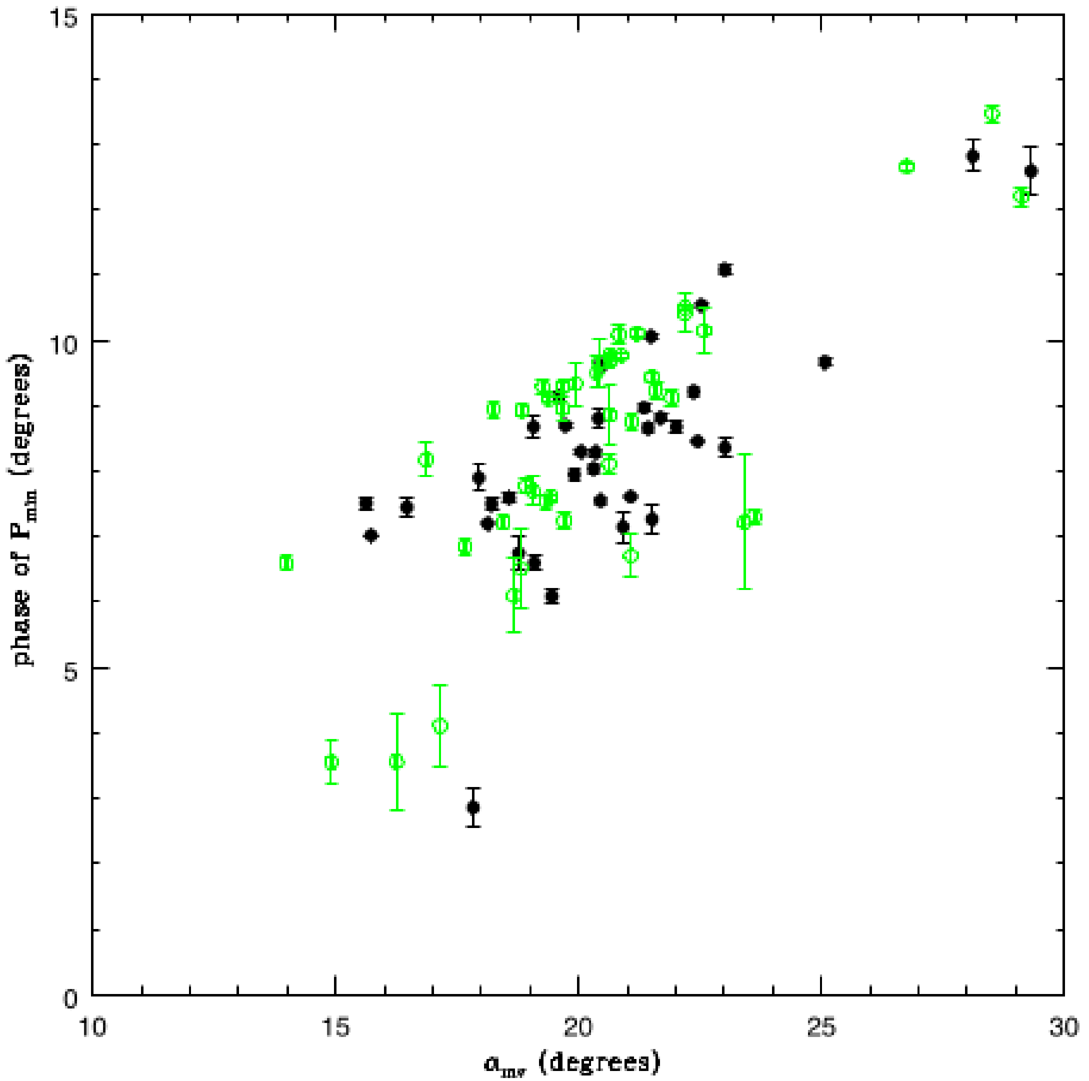


slope vs α_{min}

using the catalogue

Cellino et al. (2016)
Gil-Hutton (2017)

Catalogue of polarization curves

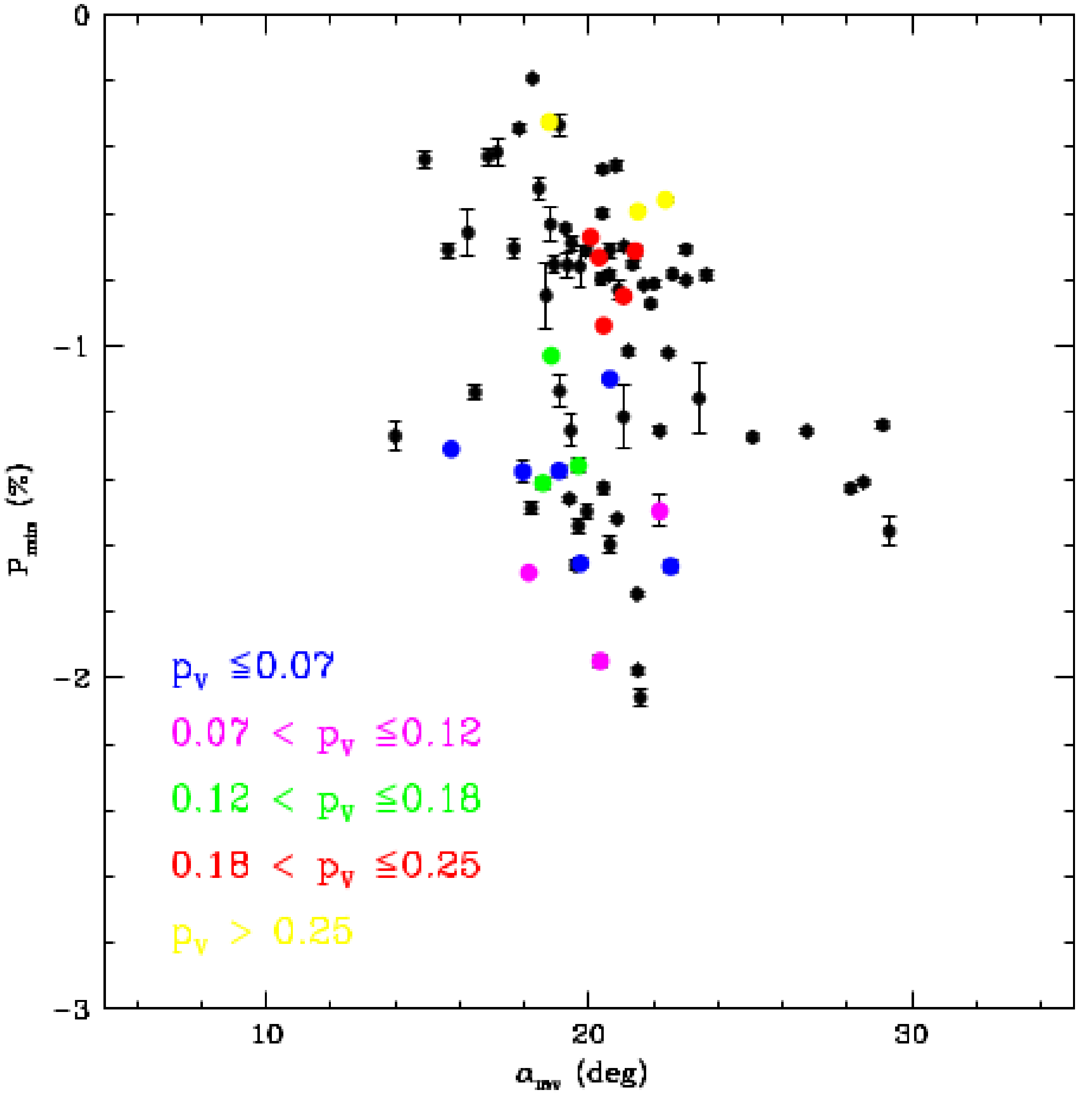


α_{min} vs. α_0

using the catalogue

Cellino et al. (2016)
Gil-Hutton (2017)

Catalogue of polarization curves

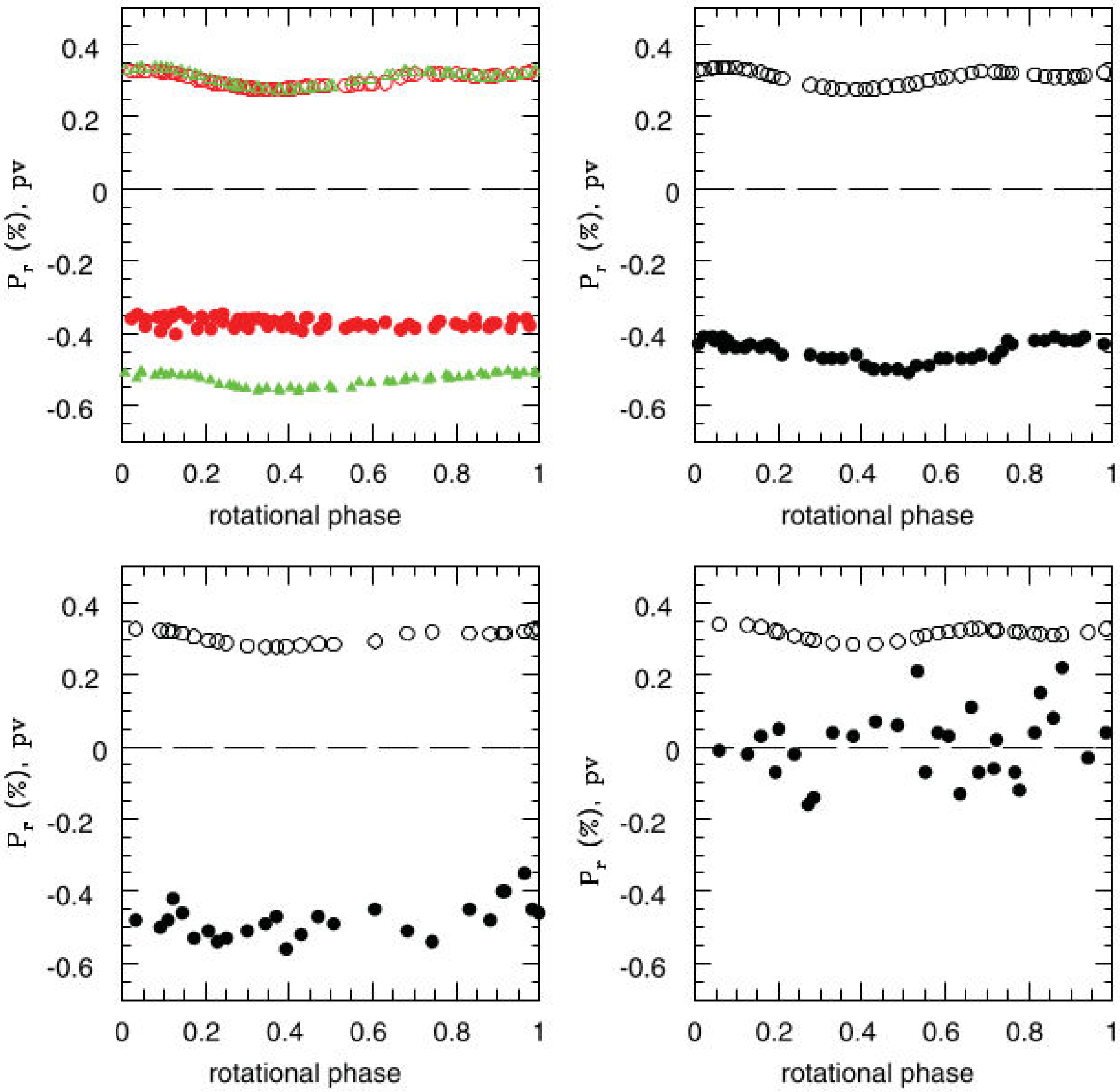


P_{min} vs. α_0

using the catalogue

Cellino et al. (2016)
Gil-Hutton (2017)

Albedo variation on (4) Vesta



Polarimetric light curves of (4) Vesta

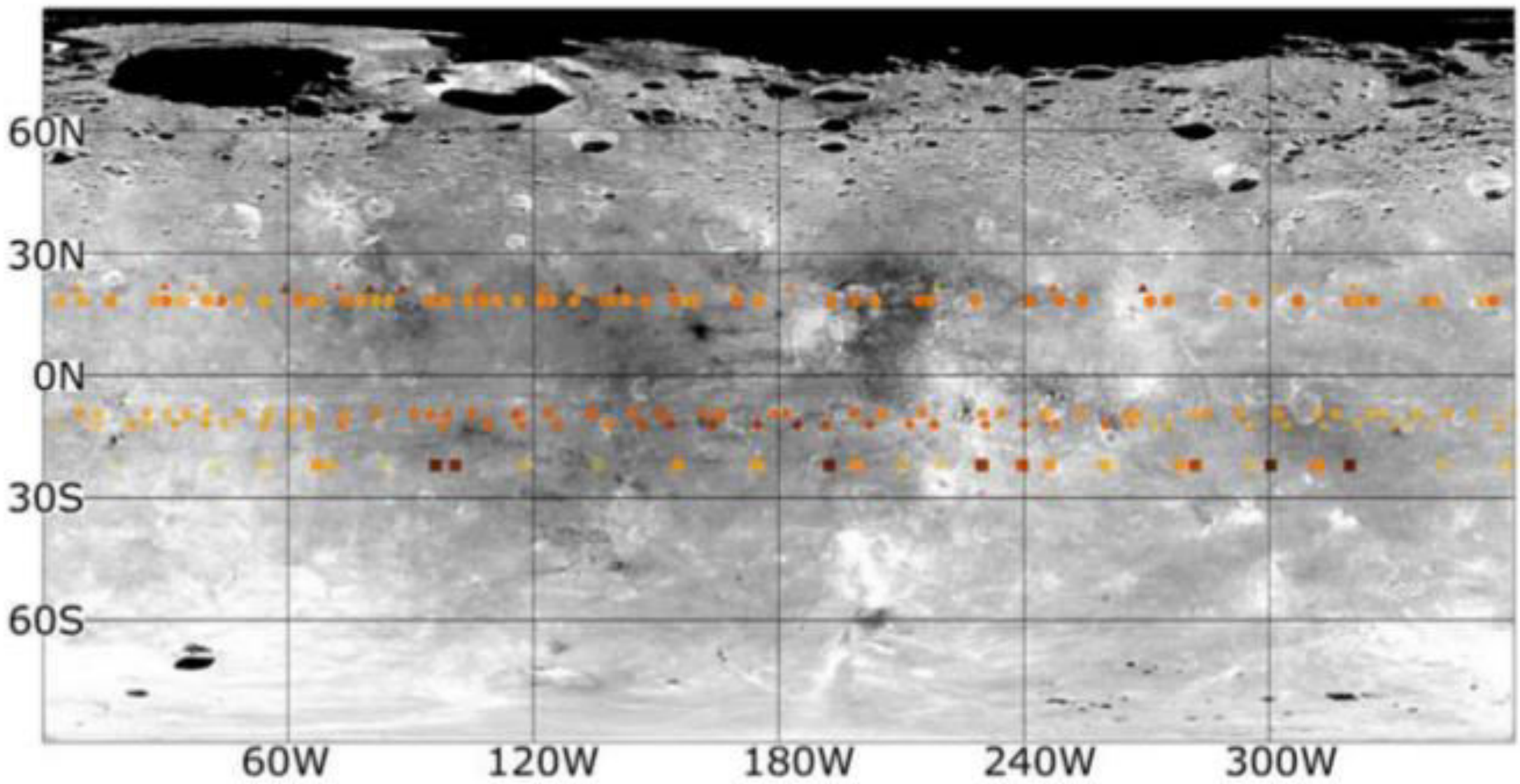
the albedo shows a variation around a value of about 0.30

data taken in 1977, 1978, 1986, 1988 and 2011

Cellino et al. (2016a)

Albedo variation on (4) Vesta

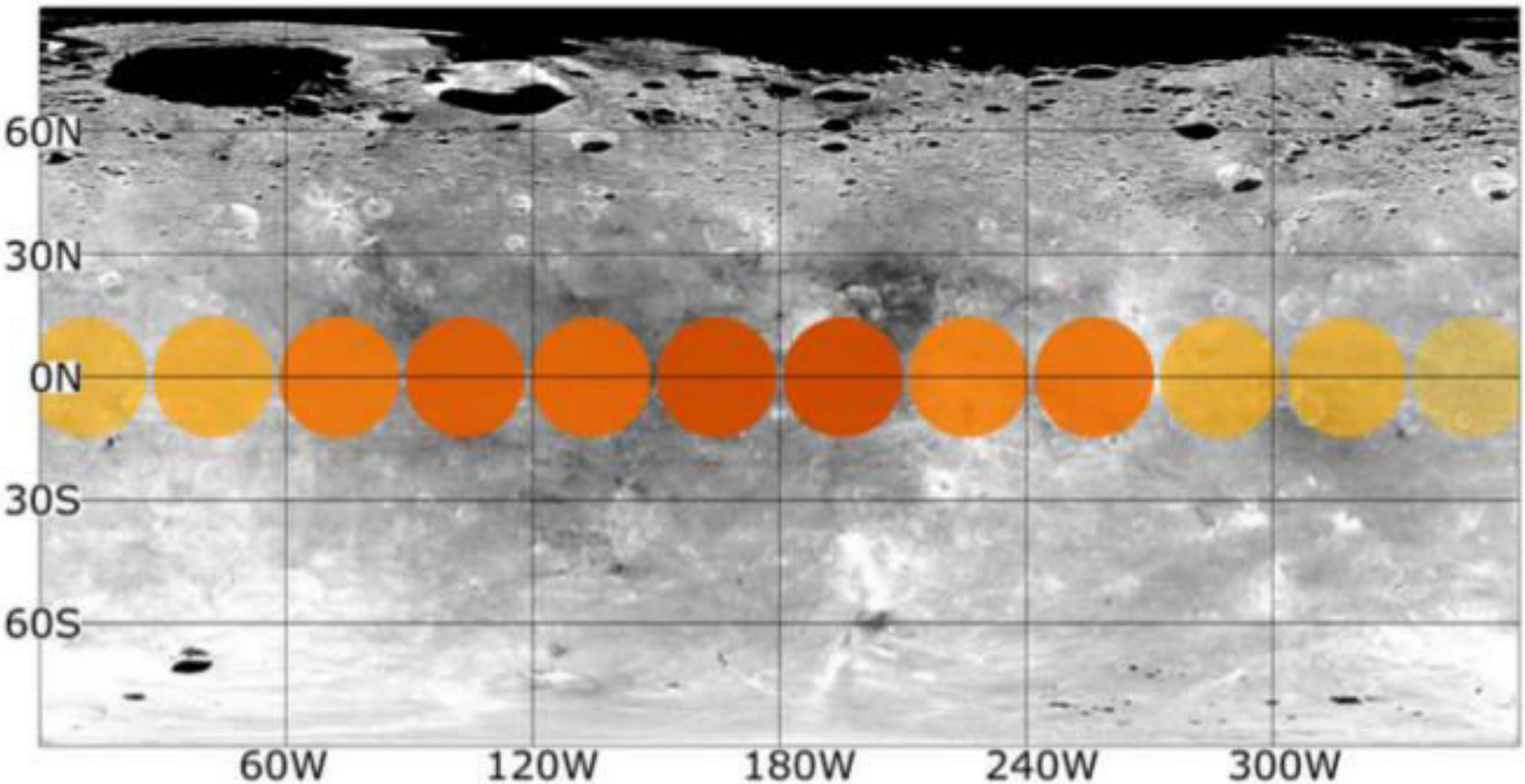
Agreement between polarimetry and albedo



Cellino et al. (2016a)

Albedo variation on (4) Vesta

Agreement between polarimetry and albedo



Cellino et al. (2016a)

New relationship between parameters

$$P_r(\alpha) \sim \frac{\alpha^2}{2n} - \left(\frac{n-1}{n+1}\right)^2 \frac{(kd\alpha)^2}{2\left[1+(kd\alpha)^2\right]},$$

$$\alpha_{\min} = \frac{1}{kd}\sqrt{kd\sqrt{n}\left(\frac{n-1}{n+1}\right) - 1},$$

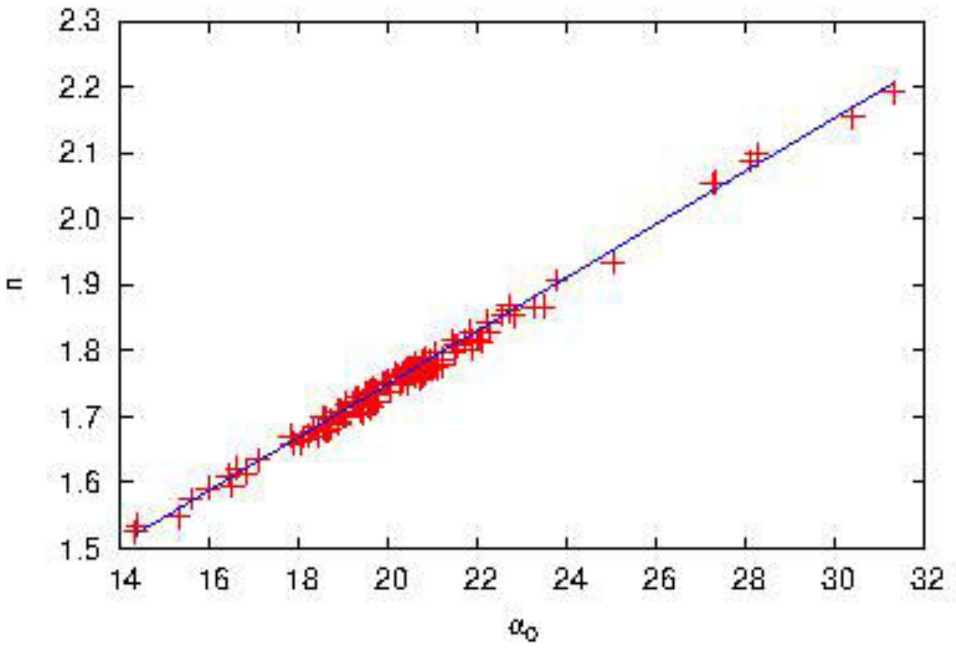
$$\alpha_0 = \sqrt{n\left(\frac{n-1}{n+1}\right)^2 - \frac{1}{(kd)^2}}.$$

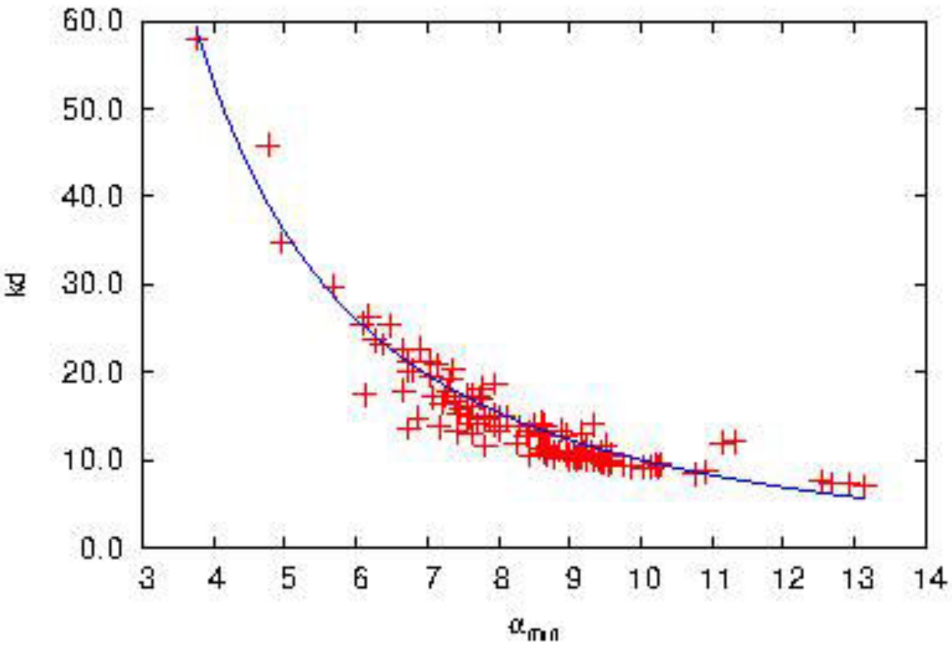
n = real part index of refraction

d = mean distance between particles in the regolith

Shkuratov (1989)
Muinonen (2002)

New relationship between parameters





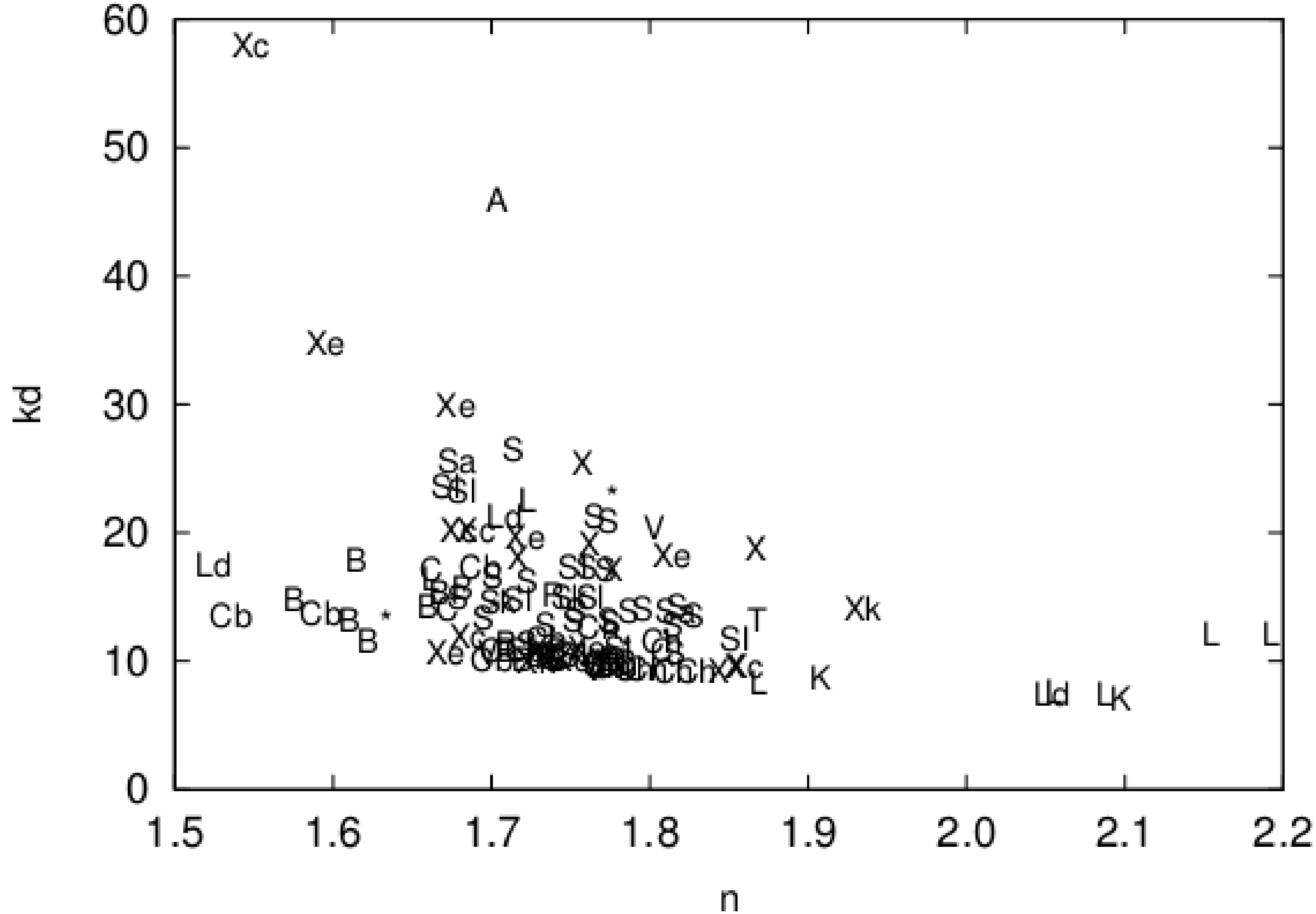
$$n = (0.0403 \pm 0.0082)\alpha_0 + (0.9438 \pm 0.1650),$$

$$kd = \frac{(558.1472 \pm 5.5233)}{\alpha_{\min}^{(1.67\pm0.01)}} - (1.9188 \pm 0.1926),$$

α_{min} provides information about the texture of the surface

Gil-Hutton & García-Migani (2017)

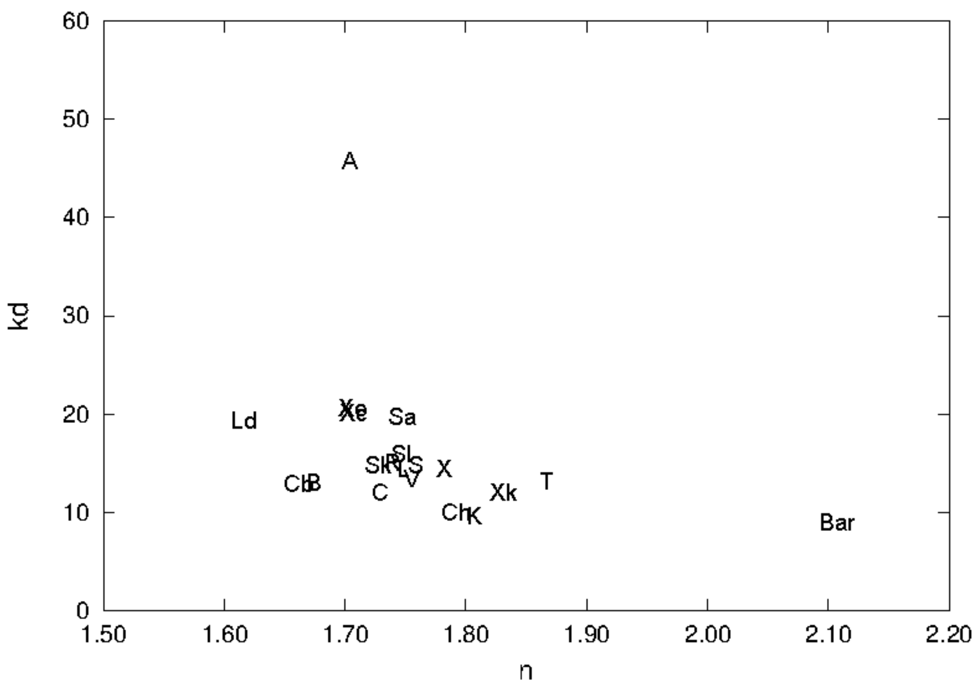
New relationship between parameters



Gil-Hutton & García-Migani (2017)

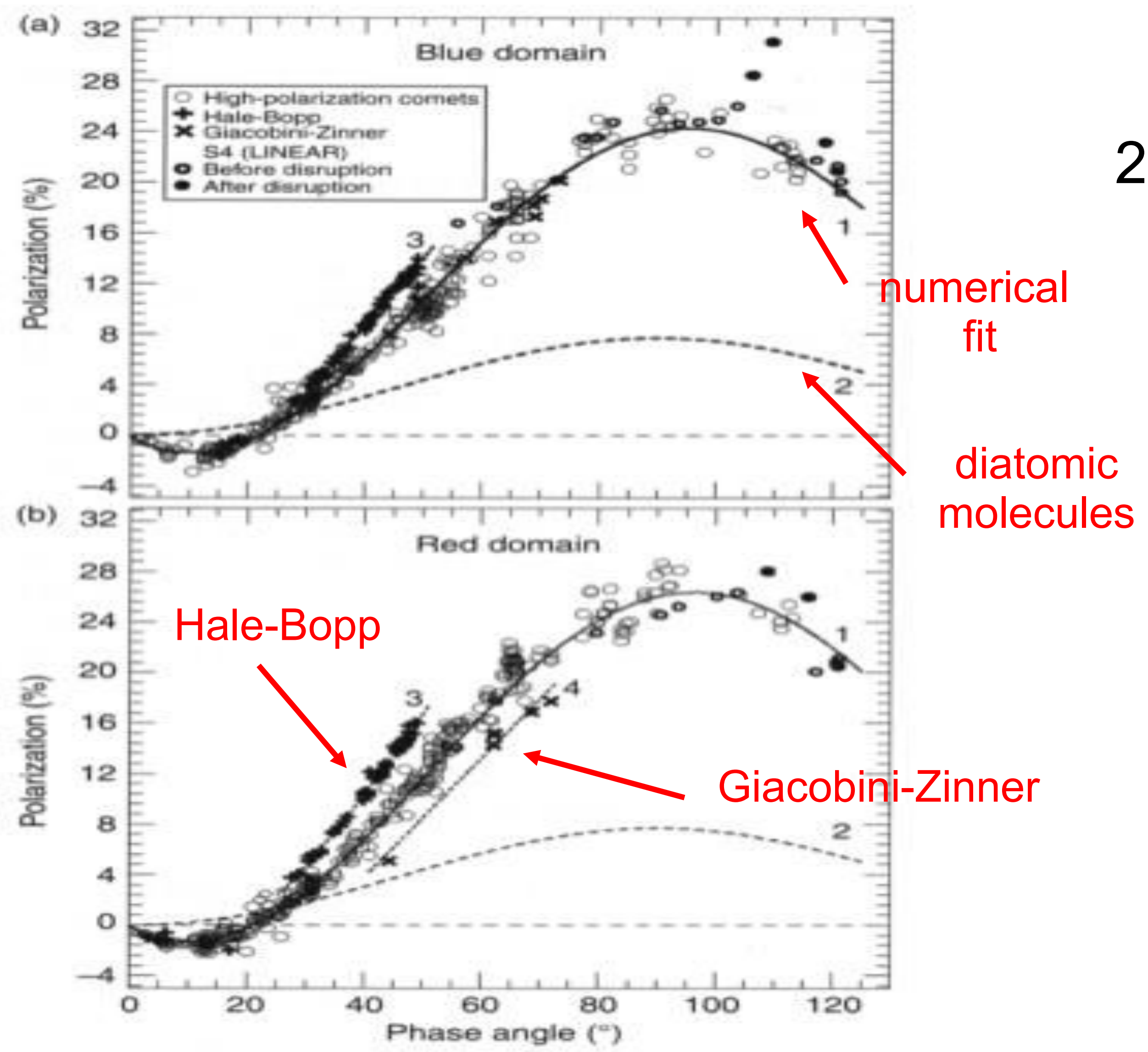
New relationship between parameters

Tax	N	n	σ_n	kd	σ_{kd}
A	1	1.704	0.000	45.795	0.000
B	12	1.674	0.058	12.932	2.514
C	7	1.729	0.051	11.961	2.461
Cb	6	1.662	0.073	12.871	2.356
Ch	9	1.792	0.020	10.015	1.159
K	3	1.807	0.073	9.530	0.639
L	4	1.748	0.075	14.375	5.564
Ld	2	1.616	0.092	19.361	1.960
R	1	1.739	0.000	15.066	0.000
S	23	1.758	0.041	14.794	3.774
Sa	2	1.747	0.069	19.728	5.784
Sk	2	1.727	0.022	14.811	0.165
Sl	8	1.746	0.054	15.848	4.865
T	1	1.867	0.000	13.115	0.000
V	3	1.755	0.043	13.412	4.857
X	11	1.782	0.047	14.328	5.237
Xc	7	1.707	0.087	20.104	16.037
Xe	6	1.706	0.070	20.637	8.995
Xk	2	1.831	0.103	11.974	2.023
Bar	6	2.107	0.051	8.898	2.221



Gil-Hutton & García-Migani (2017)

Polarimetry of comets

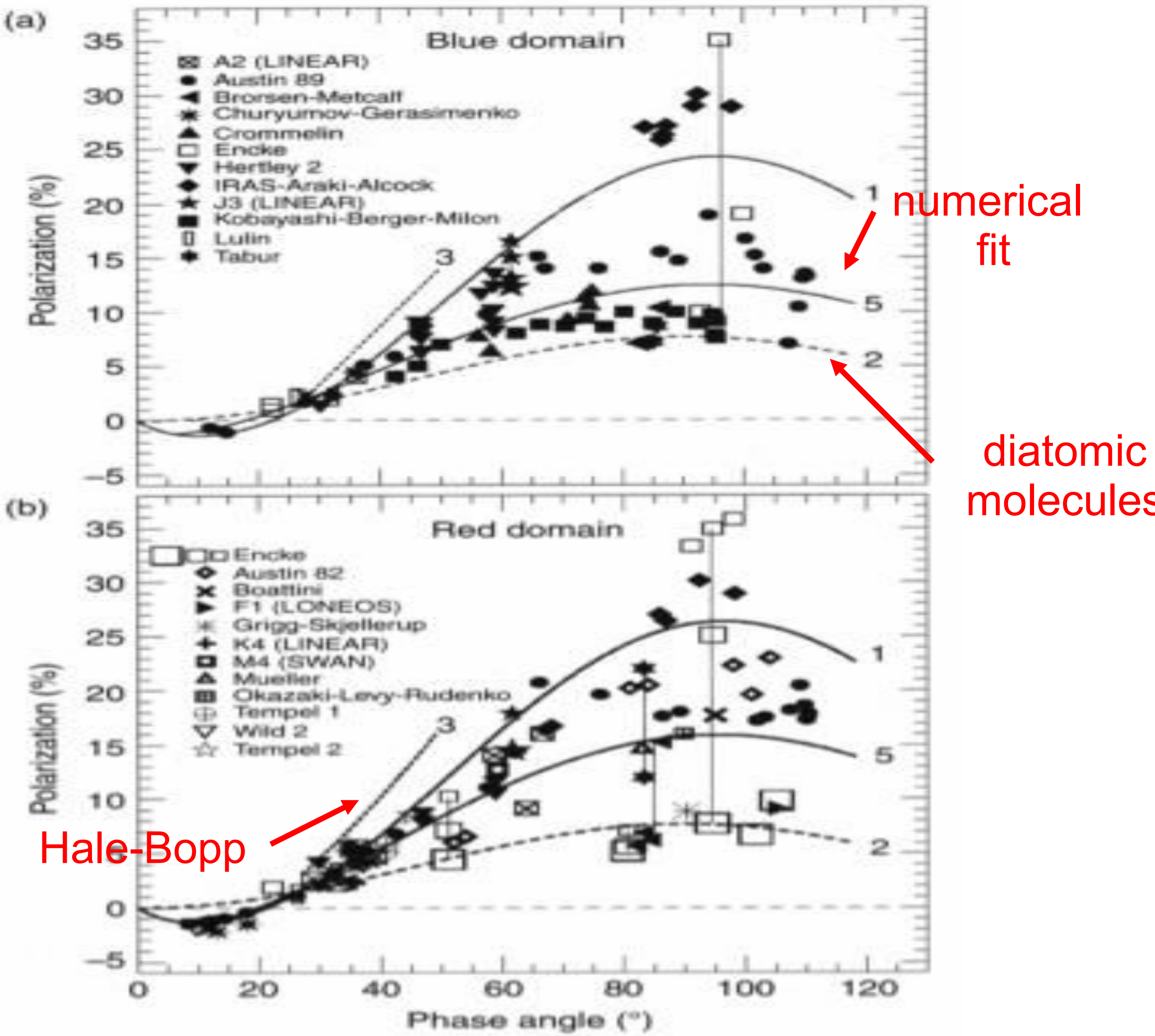


23 high - P_{max} comets

P_{max} ~ 25-30%
α_{max} ~ 95°
α_0 ~ 22°
P_{min} ~ -1.5%
α_{min} ~ 10°

Kiselev et al. (2015)

Polarimetry of comets

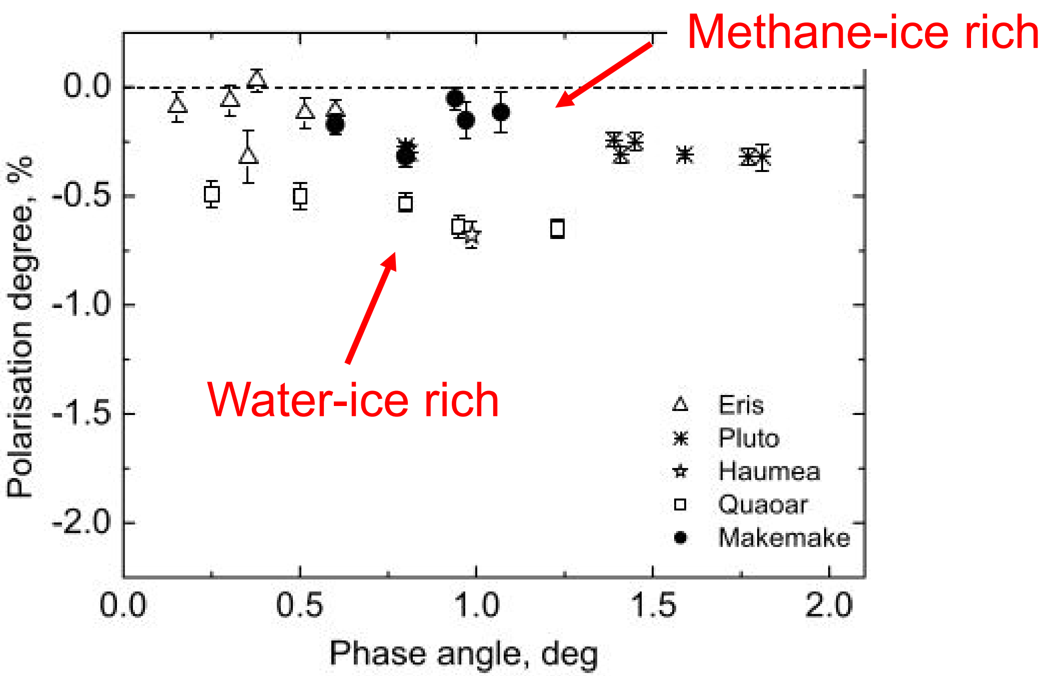


23 low - P_{max} comets

P_{max} ~ 8-22%
α_{max} ~ 90°
α_0 ~ 22°
P_{min} ~ -1.5%
α_{min} ~ 10°

Kiselev et al. (2015)

Polarimetry of TNOs

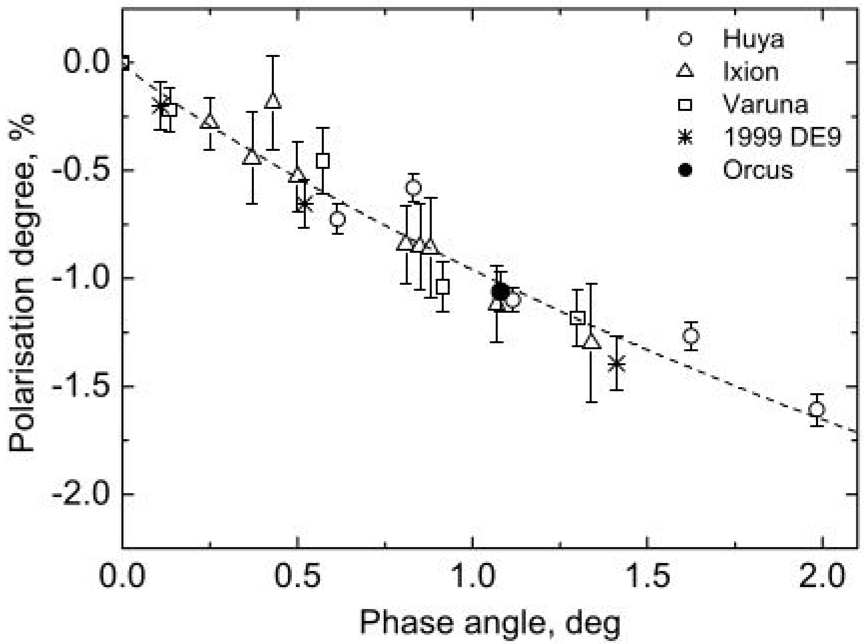


D > 1000 km

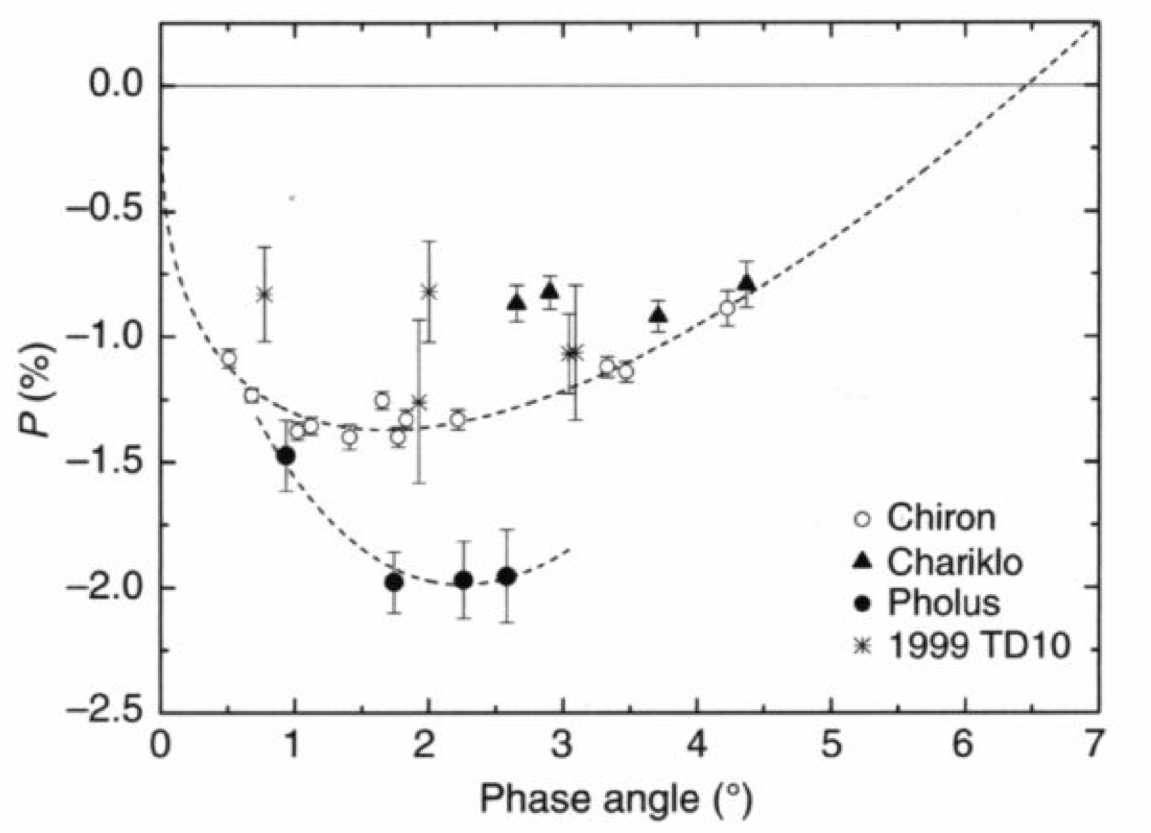
Belskaya & Bagnulo (2015)

Polarization has a strong dependency on size

D < 1000 km



Polarimetry of Centaurs



Polarization curve has a deep negative value at small phase angles.

Thin frost layer of water-ice over a dark surface can produce this result

Belskaya & Bagnulo (2015)