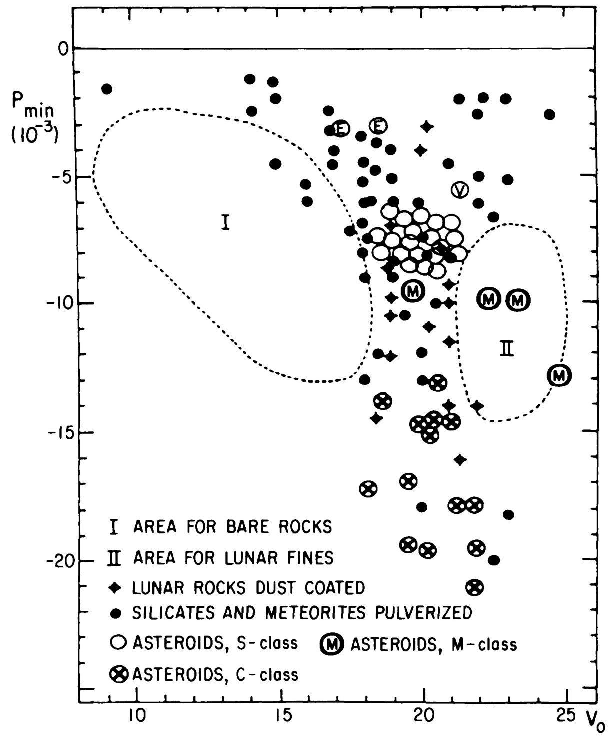
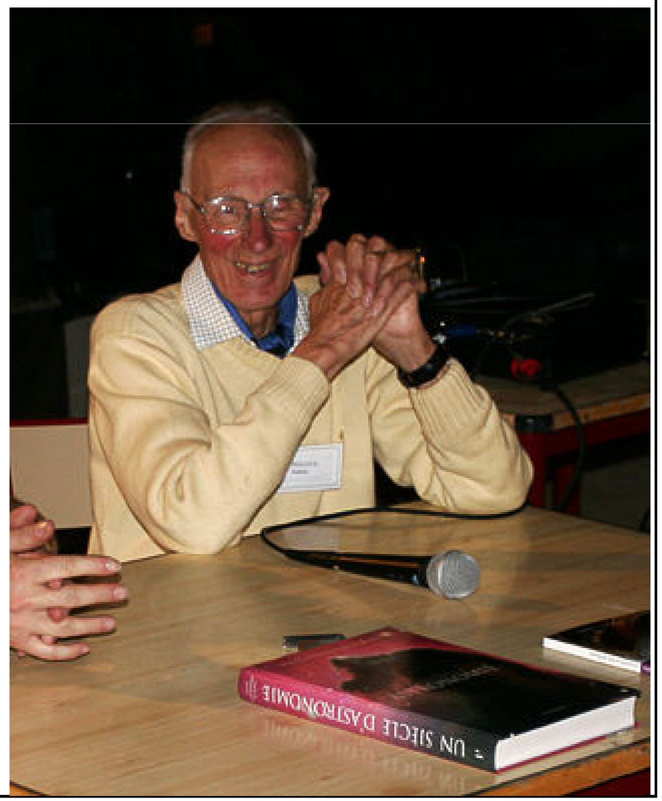
Asteroid Polarimetry: Paying homage to the memory of Prof. A. Dollfus

Alberto Cellino

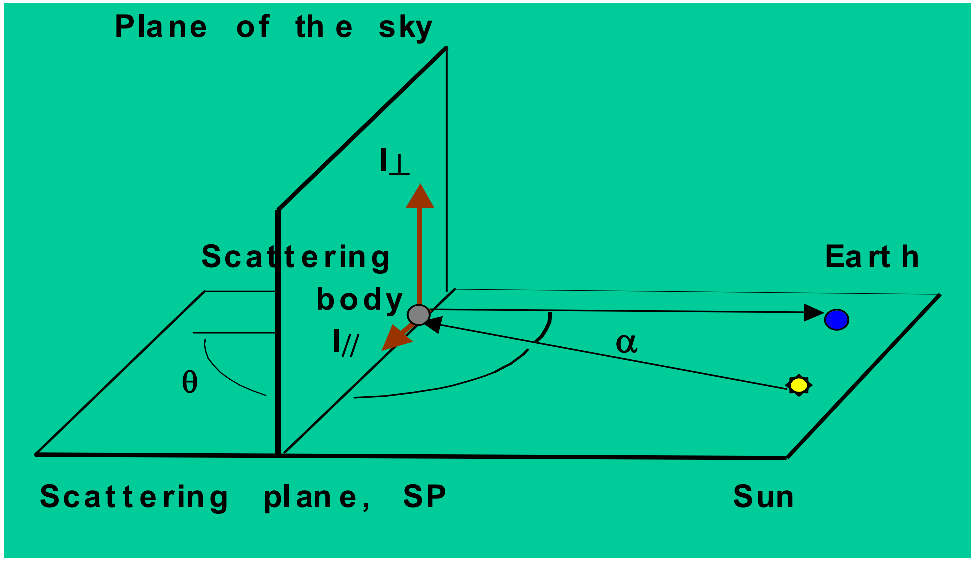
INAF - OATO





Asteroid Polarimetry: What do we measure ?

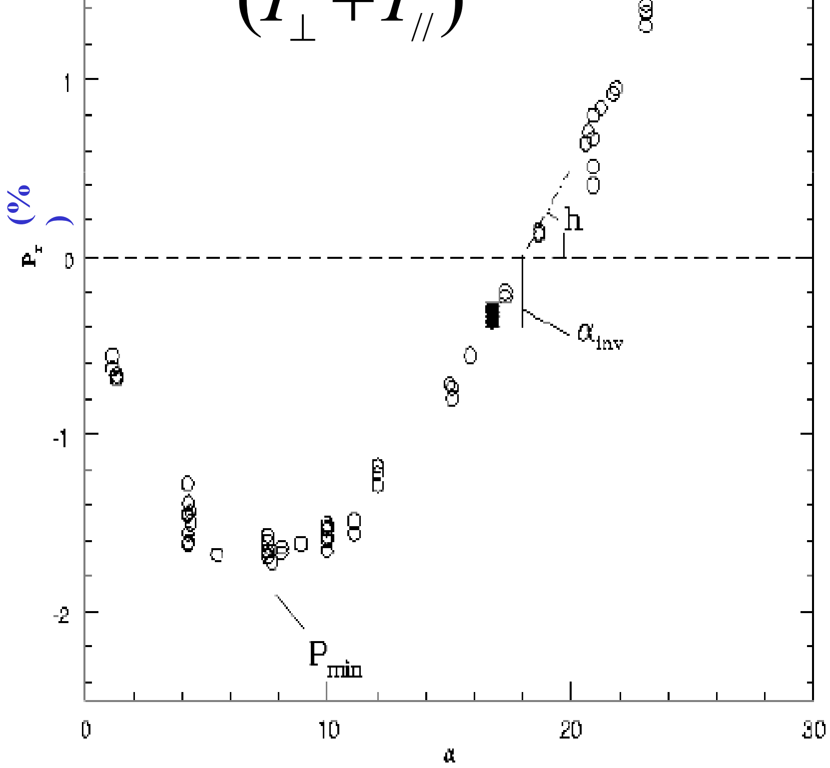
Partial linear polarization and polarization – phase curves.



- Presence of a "Negative polarization branch"
- Curve described by a few parameters

1 Ceres

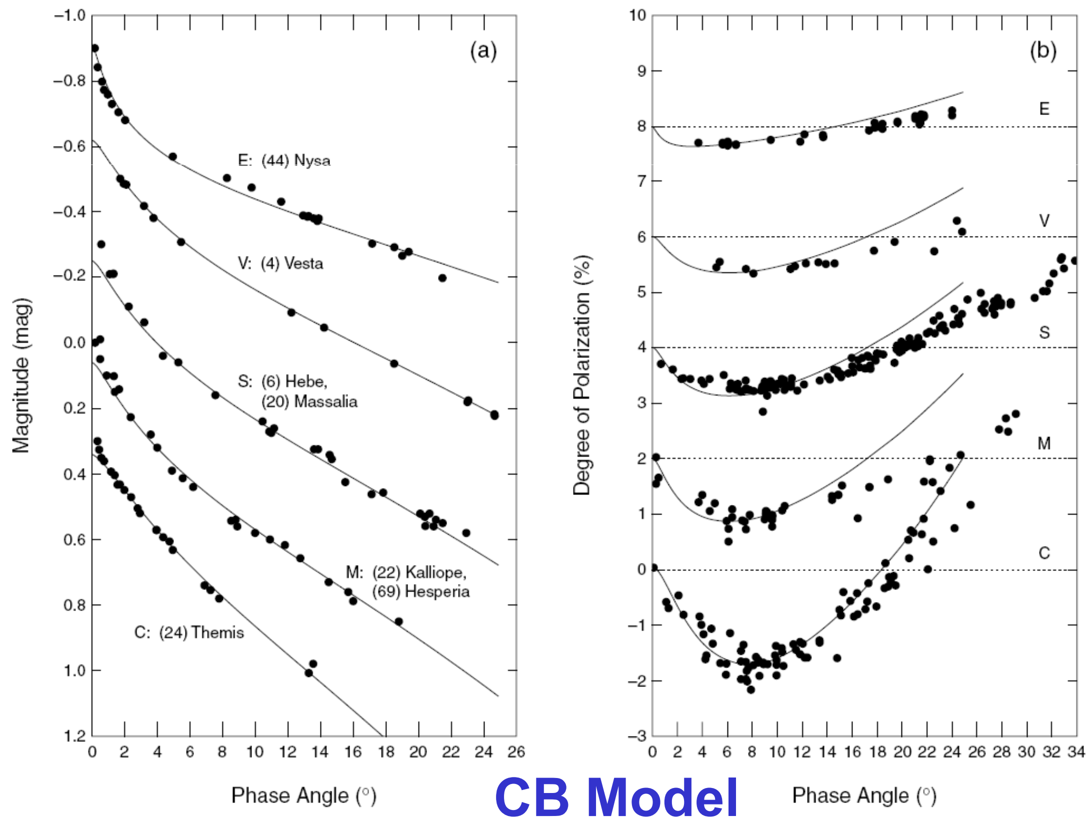
$$P_r = \frac{(I_\perp - I_{//})}{(I_\perp + I_{//})}$$



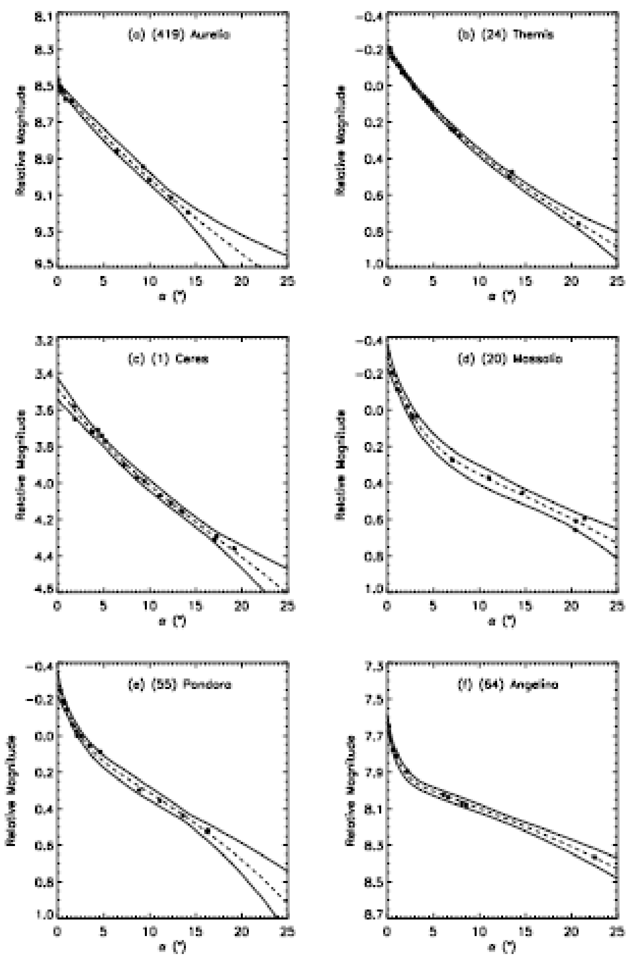
Phase – Pr curves are interpreted as scattering from irregular particles having sizes greater than the wavelength. *One* main mechanisms is currently thought to be at work here, namely coherent backscattering.

(Muinonen *et al.*, Asteroids III)

According to current models, CB may explain at least qualitatively both the phenomenon of negative polarization as well as the observed brightness - phase angle relationship, including the well known brightness opposition effect observed for many objects.



CB Model

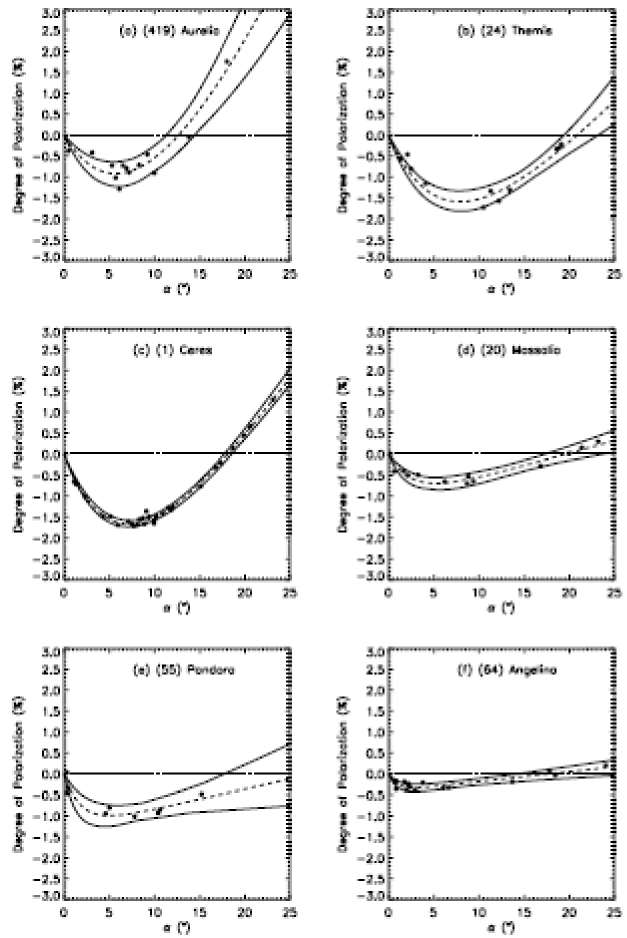


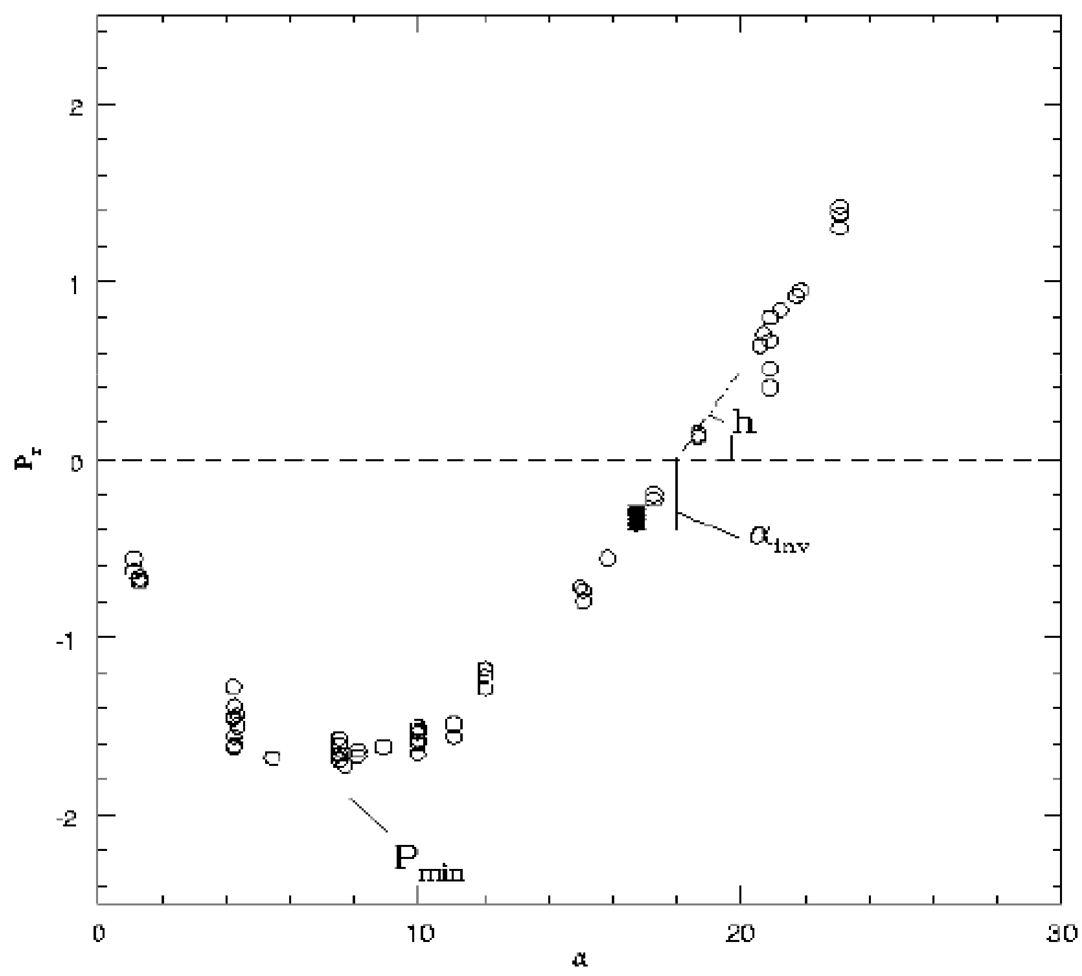
Linear - exponential model

$$f(\alpha) = a \exp\left(-\frac{\alpha}{d}\right) + b + k\alpha$$

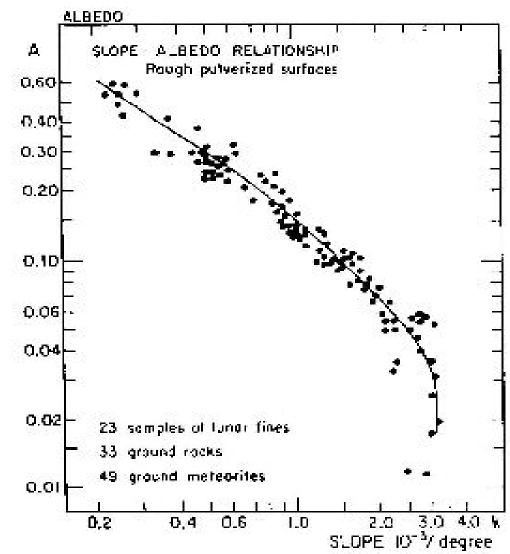
MCMC fitting

Muinonen et al., Meteoritics & Planetary Science, 44, 1937-1946





The derivation of the Albedo from polarimetric properties.



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

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

$$\log(D) = 3.1236 - 0.2H - 0.5\log(p_V)$$

Is a fundamental relation in asteroid science, where:

D is the equivalent diameter in km.

3.1236 is a wavelength-dependent constant (the indicated value is for V colour)

p_V is the geometric albedo in V. *It is defined as the ratio between the object brightness at zero phase angle and that of an ideal, flat and perfectly Lambertian disk, having the same projected surface of the object.* The albedo is an important physical parameter, being related to surface composition, texture and more in general to the history of the object.

H is the absolute magnitude in V, that is the apparent brightness that would be measured at unit distance from the Sun and the observer, and at zero phase angle. ***The IAU has adopted the (H,G) system to describe the variation of the magnitude as a function of the phase angle α:***

$$V(1,\alpha) = H - 2.5\log[(1-G)\Phi_1(\alpha) + G\Phi_2(\alpha)]$$

Polarimetry is in principle an excellent technique to derive the albedoes of main belt asteroids and NEOs of all sizes.

Used in the past in asteroid taxonomy to distinguish between E, M, P classes.

Some advantages over thermal radiometry, the most used technique for size and albedo determination. Albedo determination by thermal radiometry requires observations in different IR bands, and may suffer from poor knowledge of the absolute magnitude H.

Radiometric albedoes for small asteroids observed in one single IR band may have intrinsic uncertainties of the order of 60%, due to the uncertainty in the thermal model to be applied in different cases.

Some Problems of Polarimetry

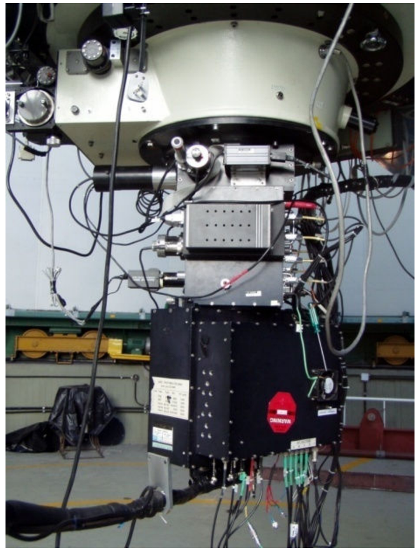
Polarimetry is not intrinsically efficient, since several observations of the same object at different phase angles are required.

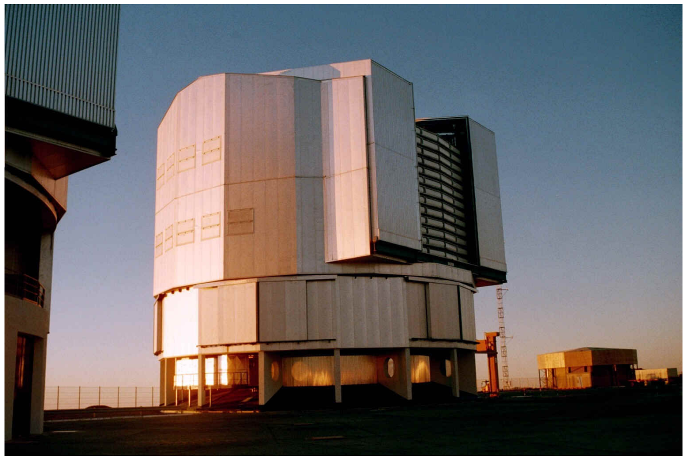
In the case of NEOs this problem is less severe, since the phase angle changes more quickly with respect to main belt asteroids. Moreover, NEOs can be observed at large phase angles, and the (positive) linear polarization of the objects at large phase angles is expected to be fairly different for low- and high-albedo objects.

Polarimetry is intrinsically demanding in terms of telescope size, since polarimeters split the incoming light into beams of radiation linearly polarized along different directions. Thus, a large collecting area is required.

In the case of NEOs this problem may be severe, since the objects are generally faint.

After the first pioneering era in the 70s, not very much was done in the next 20 years. Since mid-90s, there has been a phase of Renaissance of asteroid polarimetry due to the availability of new instruments and actively involved teams, mainly in Europe and Argentina





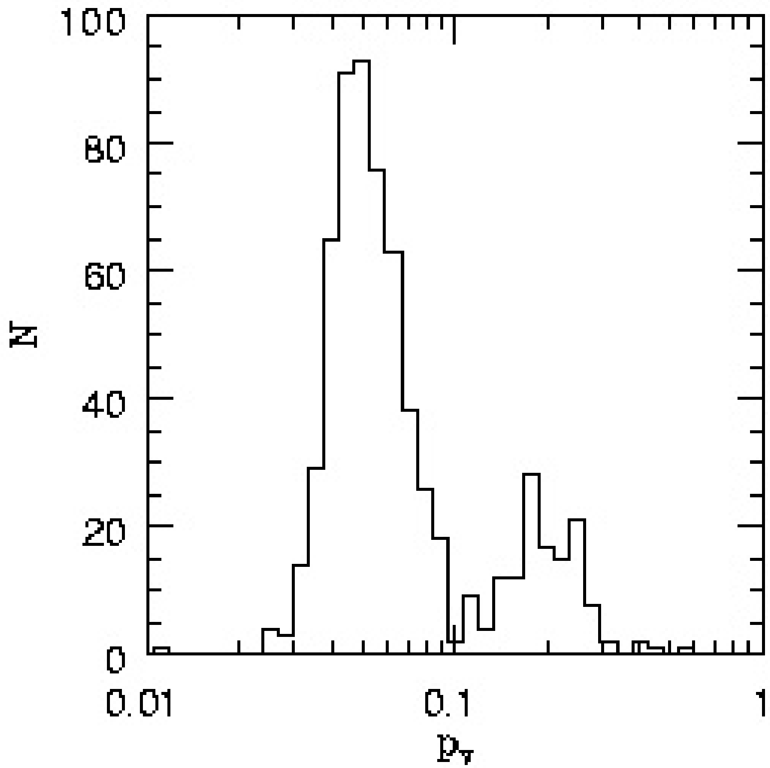
The Torino – CASLEO polarimetric programs, using FOTOR and CASPROF.

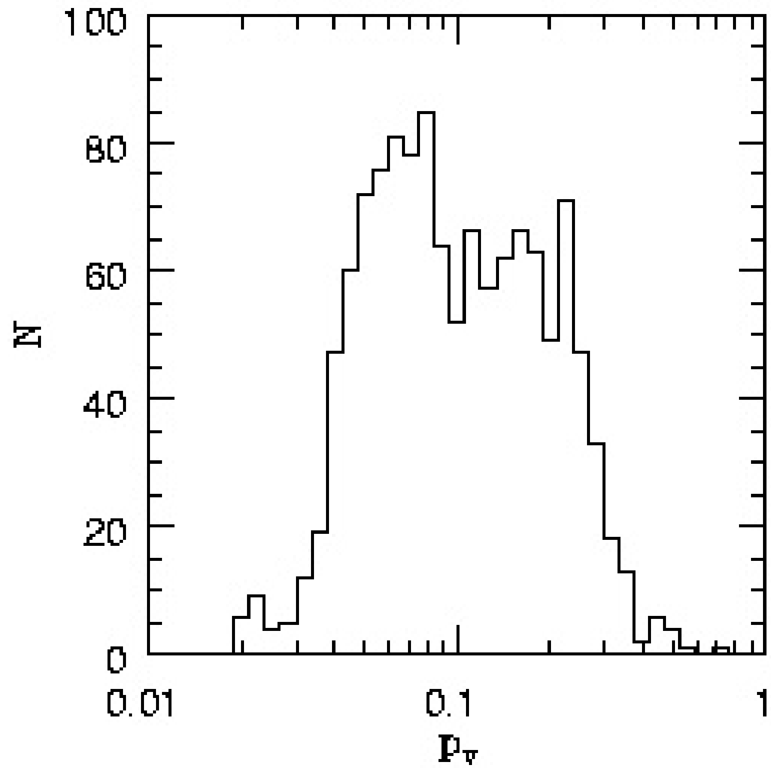
Both instruments attached at the 2.15 m telescope of the Complejo Astronomico El Leoncito (Argentina).

FOTOR: UBVRI photopolarimeter of the Torino Astronomical Observatory (now dead).

CASPROF: one-channel photopolarimeter of CASLEO.

IRAS albedo distributions





D > 50 km **D < 50 km**

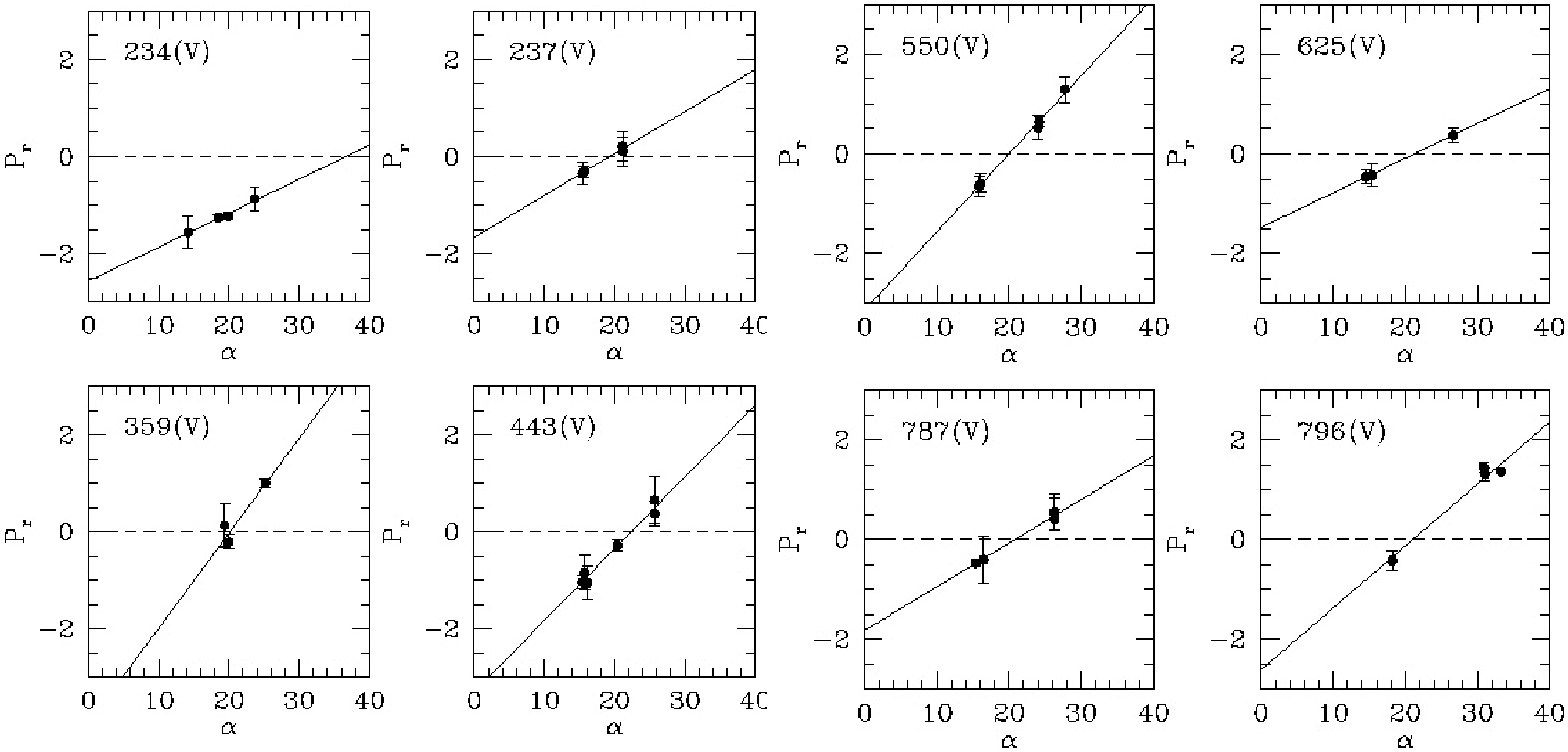
Problem: Is this true?

INAF --Osservatorio Astronomico di Torino

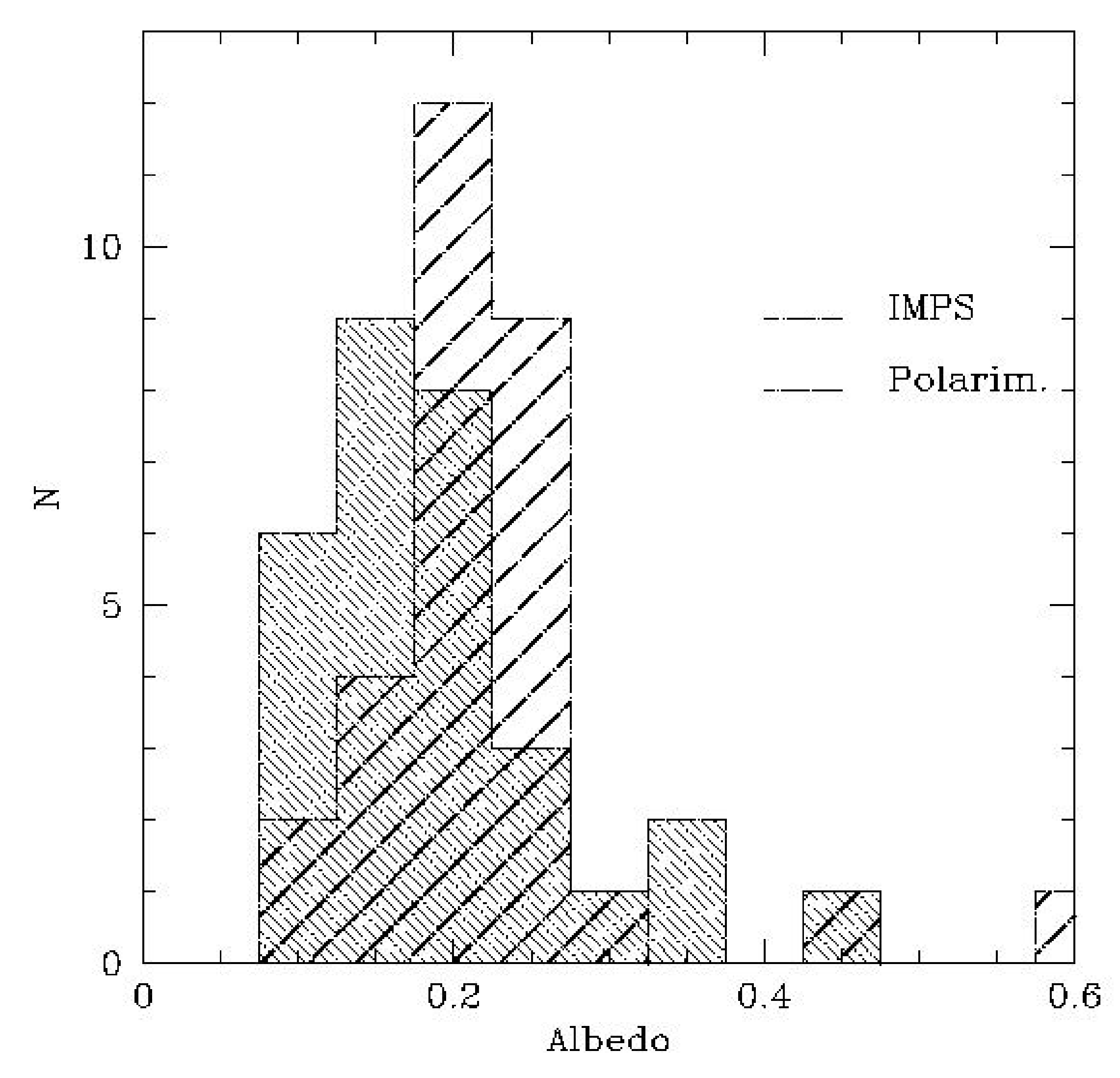
Recent Results in Asteroid Polarimetry

Alberto Cellino - Regolith in Solar System Bodies, 1/12/ 2010

At present, about 650 measurements for about 180 asteroids



Recent Results in Asteroid Polarimetry



Evidence for a slight systematic difference between IRAS and polarimetric albedoes (the latter being generally lower).

Analysis limited to intermediate-albedo objects, due to instrumental limitations at CASLEO.

Need of deriving polarimetric albedoes of fainter, low-albedo objects

No evidence of an "opposition effect" for polarimetry, occurring at phase angles larger than 0.4-0.5 degrees.

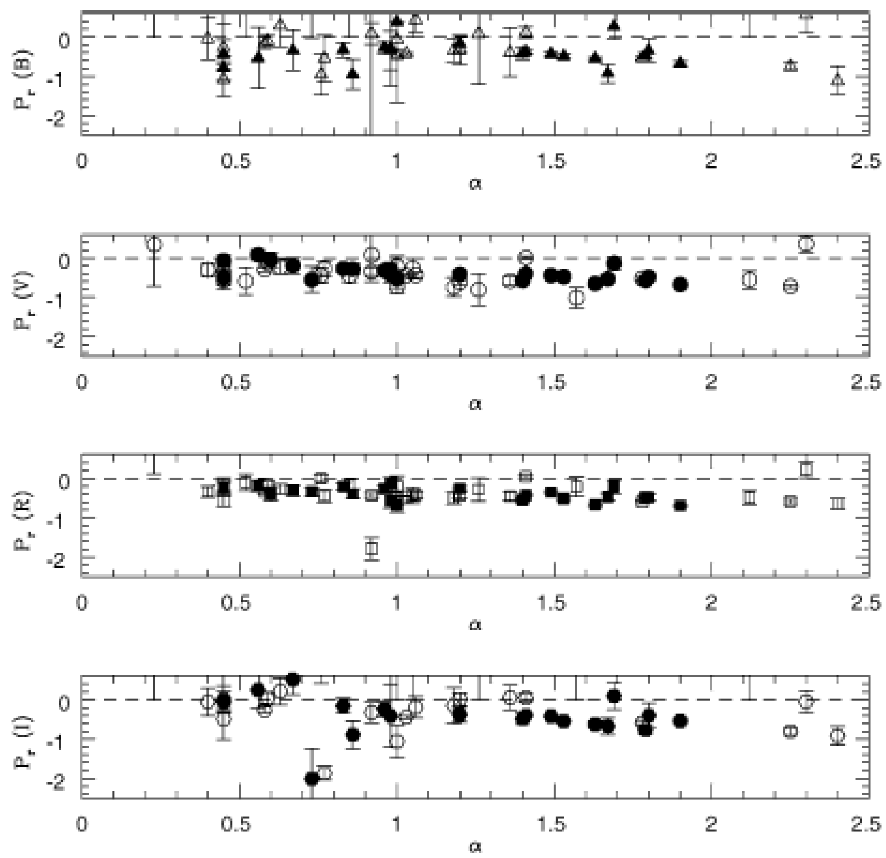
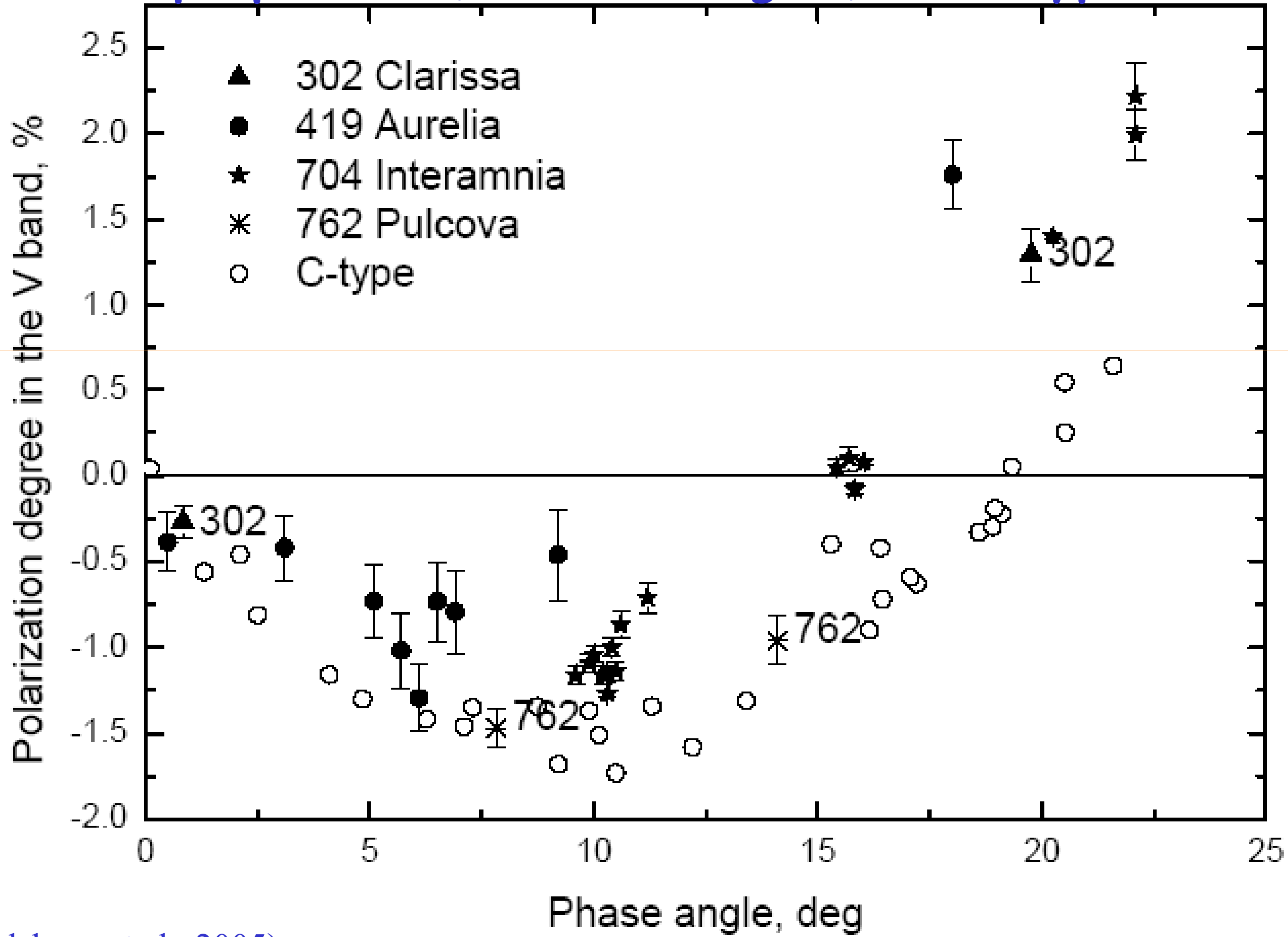


Fig. 17. Phase–polarization curve of all the objects of our sample observed at phase angles below 2.5°, in BVRI colors (from top to bottom, respectively). Filled symbols are used to indicate objects having IRAS albedo smaller than 0.08.

Cellino et al., Icarus 179, 304-324 (2005)

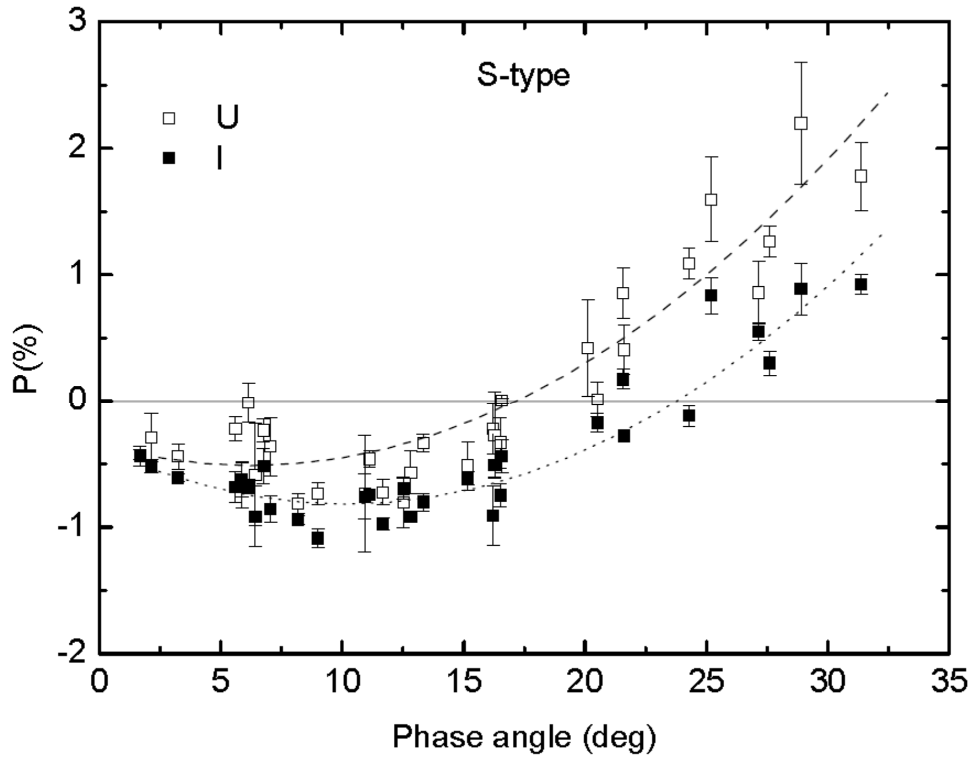
Peculiar properties (inversion angles) of F-type Asteroids



(Belskaya et al., 2005)

Some F-types exhibit evidence of a cometary nature (Phaeton, Wilson-Harrington).

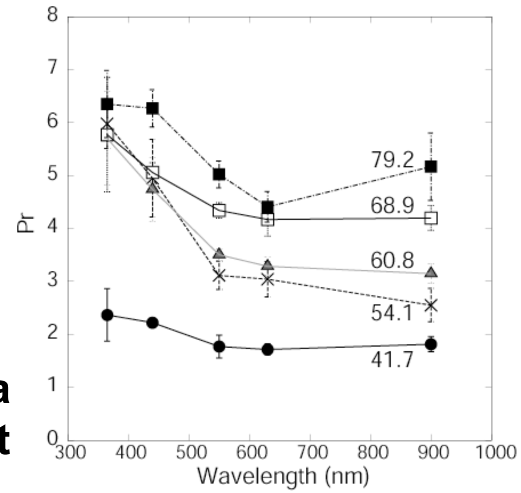
2008 TC3 was an F-type!!



Wavelength dependence of linear polarization

Opposite behaviour among moderate-albedo and low-albedo asteroids.

Similar effects observed also for comets.



UBVRI Itokawa observations at CASLEO

Belskaya *et al.*, Icarus 199, 97-105 (2009)

General problem and Recommendation by IAU Comm.15:

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

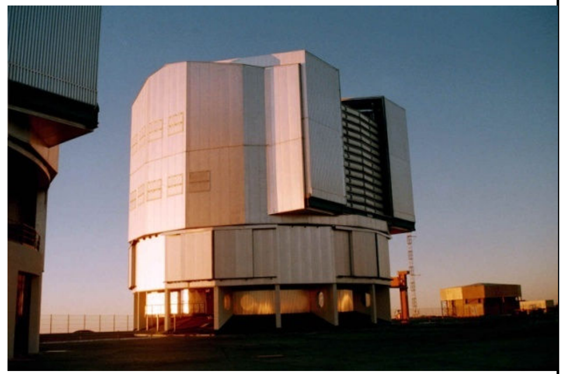
Different authors are using different sets of C_1 and C_2 coefficients:

- $C_1 = -1.0$ $C_2 = -1.78$ (Bowell & Zellner 1974)
- $C_1 = -0.983 \pm 0.082$ $C_2 = -1.731 \pm 0.066$ (Lupishko & Mohamed, 1996)
- $C_1 = -1.118 \pm 0.071$ $C_2 = -1.779 \pm 0.062$ (Cellino *et al.*, 1999)

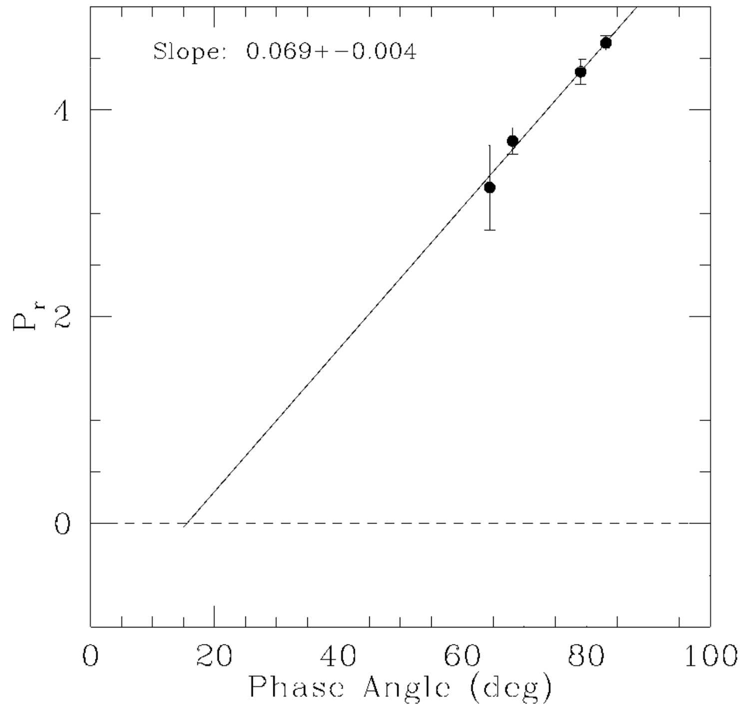
Among them, only the latter was derived using thermal IR data reduced using the (H,G) system, which takes into account the opposition brightness surge at zero phase.

It is urgent to converge to a new and unique choice of C_1 and C_2

Example: the determination of the albedo of the Potentially Hazardous Asteroid (99942) Apophis



Observations performed at the UT2 ESO VLT (8-m Kueyen) telescope. **(Delbò et al., 2007)**



Results: $p_v = 0.33 \pm 0.08$

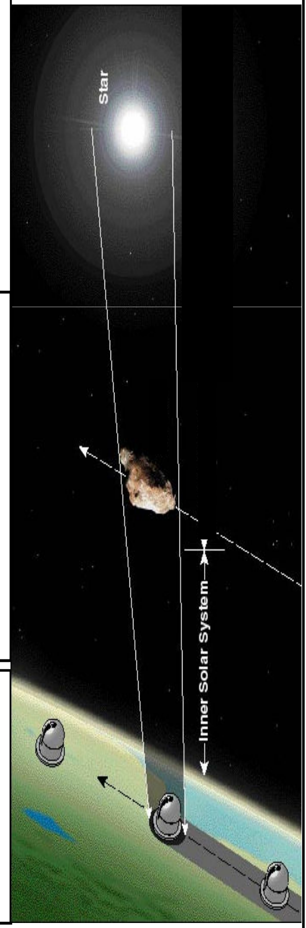
The error is mostly a consequence of the calibration uncertainty

Assuming G=0.25 (Q-type), H = 19.7, and the size of Apophis turns out to be D = 270 ± 30 m

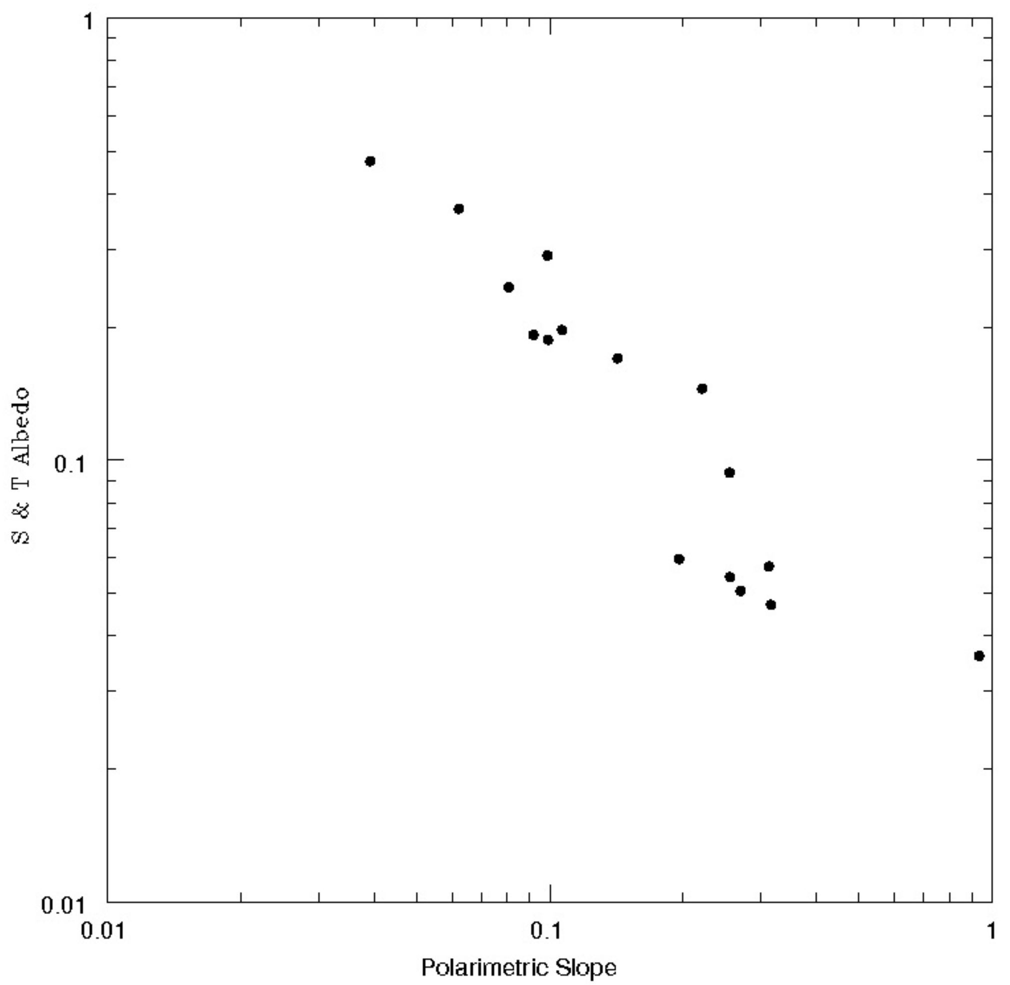
The slope-albedo relation must be recalibrated using only high-quality V-band polarimetry of asteroids with accurate albedoes. **The best object list at present is the one by Shevchenko and Tedesco (2006), consisting of albedoes derived from occultation and *in situ* (four objects) size measurements, coupled with accurate estimates of absolute magnitudes obtained using one unique photometric system (H,G). But see the report of the Absolute MagnitudeTask Group!**

Albedos determined using model-dependent fits to thermal spectra, and all results based on IRAS or single-wavelength radiometric observations, are **not** suitable for use as calibration objects, and **should be no longer used for these purposes**. Only albedoes derived by using diameters from radiometric spectra fit using detailed thermophysical models (e.g., Mueller and Lagerros, 1998; Harris et al., 2005) can still be acceptable for calibration.

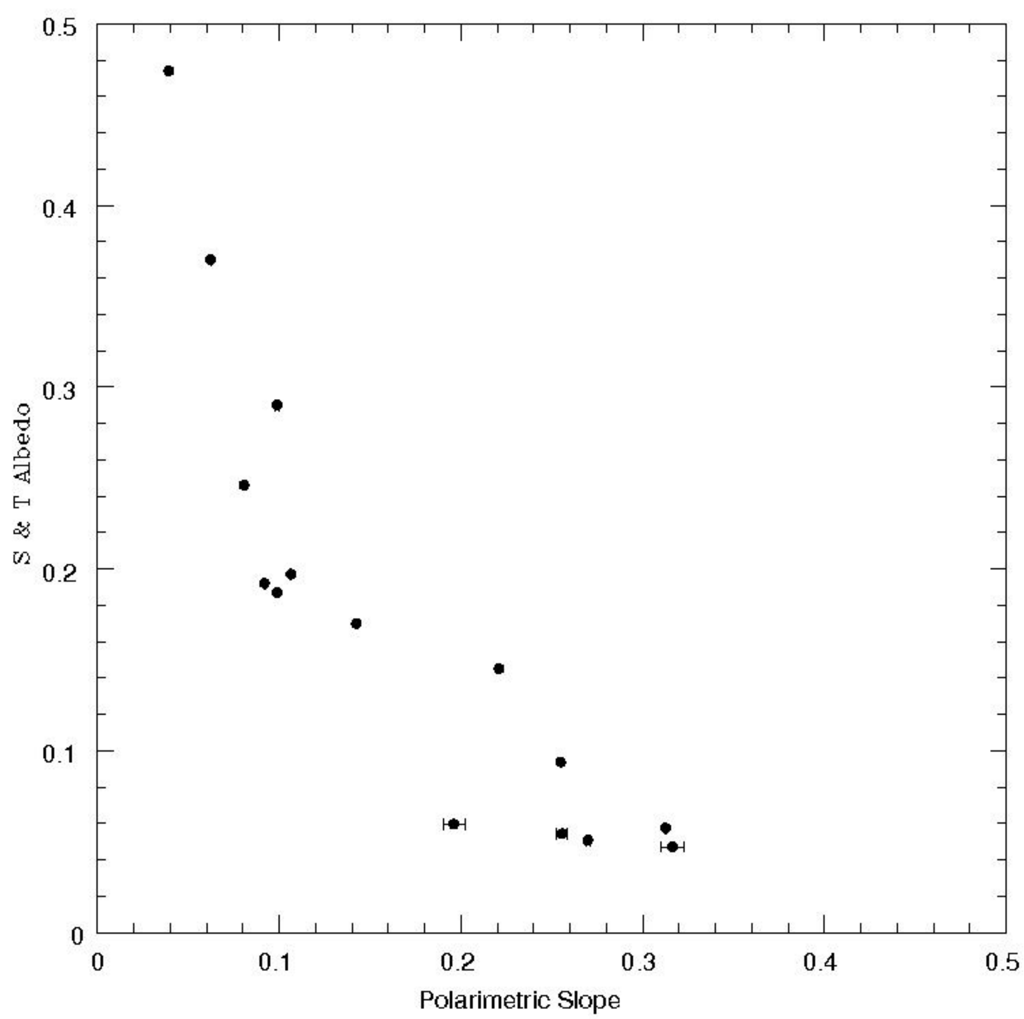
Albedos obtained in laboratory for meteorite samples should **not** be used to calibrate the slope-albedo relation because these are generally based on the visual brightness measured at 5° phase angle and on ground-up samples and not an actual regolith sample.



Asteroids	Date	α	λ_{2000}	β_{2000}	Class	D_{occ}	D_{IRAS}	p_{IRAS}	P_{pol}	H	p_H	$V(1,4)$[a]	$p_{V(1,4)}$	Qual[b]
1 Ceres	1984 Nov 13.19653	3.4	46.781	−8.657	G?,C	933	848	0.11	0.076	3.34	**0.0936**	3.73	0.0653	3e
2 Pallas	1978 May 29.22569	14.3	254.929	48.451	m,B	544	498	0.16	0.087	4.04	**0.145**	4.37	0.1066	3e
	1983 May 29.20674	15.4	293.711	43.351	m,B	522	498	0.16	0.087	4.13	**0.145**	4.46	0.1067	4e
3 Juno	1979 Dec 11.38229	18.6	117.719	−20.458	S,Sk	269	234	0.24	0.22	5.29	**0.187**	5.61	0.139	4e
4 Vesta	1991 Jan 4.01097	19.1	44.771	−6.108	r,V	503	468	0.42	0.35	3.19	**0370**	3.49	0.280	3e
8 Flora	2004 Oct 29.30389	30.1	117.245	−3.047	S,S	160.8	135.9	0.24	0.21	6.35	**0.197**	6.70	0.143	3g
27 Euterpe	1993 Oct 9.29132	5.0	5.224	−2.847	-,S	96.9	–	–	0.22	7.0	0.298	7.35	0.216	1e
39 Laetitia	1998 Mar 21.79271	20.6	91.625	−7.887	S,S	177.9	149.5	0.29	0.25	5.89	**0.246**	6.33	0.164	3e
41 Daphne	1999 Jul 02.94722	20.5	241.742	26.729	C,Ch	185.9	174.0	0.083	0.059	7.31	**0.0609**	7.51	0.0507	3g
47 Aglaja	1984 Sep 06.10063	1.9	348.158	−2.345	C,B	138.0	127.0	0.098	0.085	7.98	**0.0596**	8.20	0.0487	4e
51 Nemausa	1983 Sep 11.29298	1.8	352.425	1.424	G,Ch	142.6	147.9	0.093	0.066	7.38	**0.0970**	7.72	0.0709	3e
64 Angelina	2004 Jul 03.47156	19.3	38.130	1.105	E,Xe	50.3	60.0	0.43	0.66	7.92	0.474	8.17	0.376	2g
78 Diana	1980 Sep 04.46792	19.4	41.658	8.748	C,Ch	103.9	120.6	0.071	–	8.20	**0.0859**	8.36	0.0742	4g
85 Io	1995 Dec 10.02653	10.1	52.218	−11.490	C,B	163.7	154.8	0.067	0.091	7.71	**0.0543**	7.87	0.0469	3g
	2004 Dec 12.87882	7.1	94.287	−16.475	C,B	175.9	154.8	0.067	0.091	7.65	0.0497	7.81	0.0429	2g
94 Aurora	2001 Oct 12.58072	17.6	134.018	6.710	C,C	187.5	204.9	0.040	–	7.63	0.0446	7.83	0.0371	2e
105 Artemis	1997 Dec 04.50479	15.0	107.487	−30.933	C,Ch	103.7	119.1	0.047	–	8.86	0.0470	9.02	0.0406	2e
106 Dione	1983 Jan 19.79146	2.2	122.991	5.899	G,Cgh	140.3	146.6	0.089	–	7.66	**0.0775**	7.86	0.0645	3g
109 Felicitas	2003 Mar 29.46400	27.5	79.148	7.327	C,Ch	88.2	89.4	0.070	–	8.96	**0.0592**	9.12	0.0511	3g
124 Alkeste	2003 Jun 24.44155	24.0	177.176	0.695	S,S	65.4	76.4	0.17	–	8.09	0.240	8.45	0.172	1g
129 Antigone	2001 Sep 09.17918	3.3	345.140	−9.323	–,X	129.5	113.0	0.16	0.16	6.90	0.183	7.25	0.132	2g
134 Sophrosyne	1980 Nov 24.17826	13.1	35.035	16.858	C,Ch	112.2	123.3	0.036	–	8.89	**0.0390**	9.04	0.0339	4g
139 Juewa	1988 Apr 21.77319	7.0	196.934	−7.028	–,X	160.2	156.6	0.056	0.075	8.10	0.0396	8.3	0.0330	2g
141 Lumen	2005 Jan 05.53504	7.5	91.518	13.113	–,C	137.1	131.0	0.054	0.063	8.20	0.0493	8.61	0.0338	1g
208 Lacrimosa	2003 Dec 31.29307	11.0	132.627	2.247	S,Sk	44.3	41.3	0.27	–	9.07	0.212	9.42	0.154	2g
210 Isabella	2003 Apr 21.42907	4.0	223.160	−0.854	CF,Cb	66.8	86.7	0.044	–	9.33	0.0733	9.74	0.0503	1g
216 Kleopatra	1980 Oct 10.29167	12.7	351.951	12.465	M,Xe	104.3	135	0.12	0.10	7.45	**0.170**	7.80	0.123	3g
230 Athamantis	1991 Jan 21.18634	20.1	180.833	−12.455	S,Sl	101.8	109	0.17	0.15	7.37	0.192	7.72	0.139	2g
238 Hypatia	2001 Mar 06.29785	3.8	177.342	−3.373	C,Ch	146.5	148.5	0.043	–	8.12	**0.0465**	8.28	0.0401	3g
	2005 Feb 23.36314	19.3	85.182	−14.842	C,Ch	145.3	148.5	0.043	–	8.15	0.0460	8.31	0.0397	2g
243 Ida[c]	–	–	–	–	–,S	–	28.0	0.24	–	–	0.21			4e
248 Lameia	1998 Jun 27.87822	9.7	298.406	4.603	–	54.0	48.7	0.062	–	10.21	0.0500	10.62	0.0343	1g
253 Mathilde[c]	–	–	–	–	–,Cb		58.1	0.044	–		0.036			4e



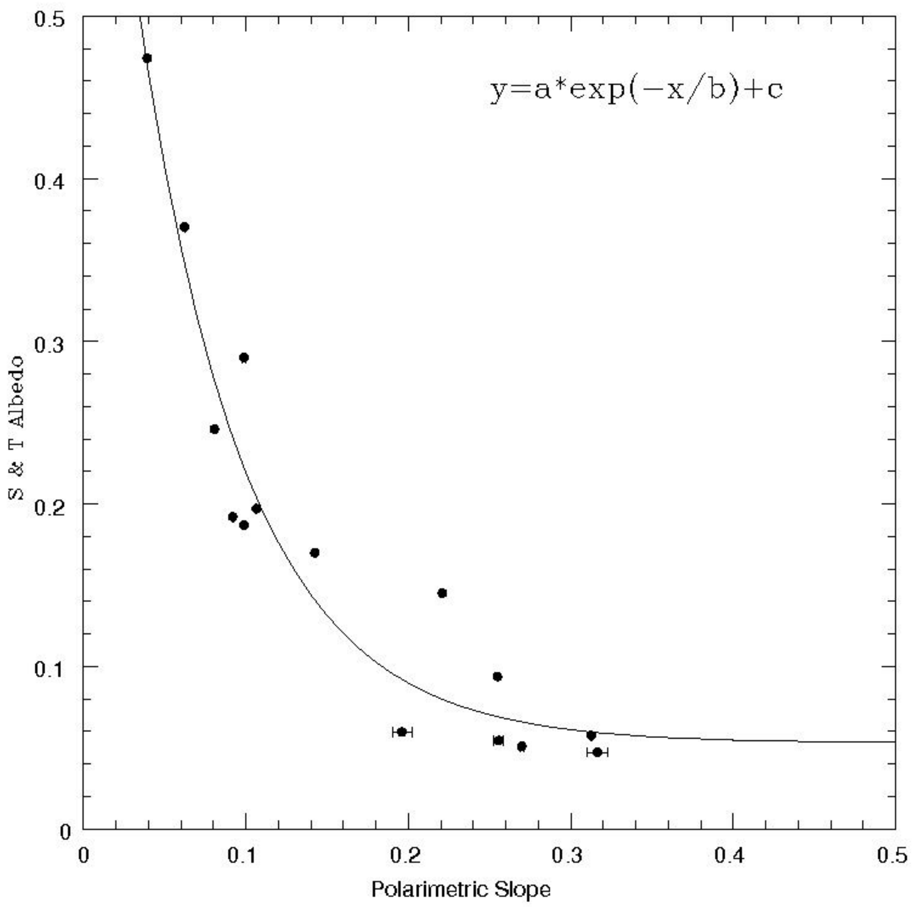
The available sample of « optimal » objects with good polarization measurements is still fairly small. Need of improving the data-set .



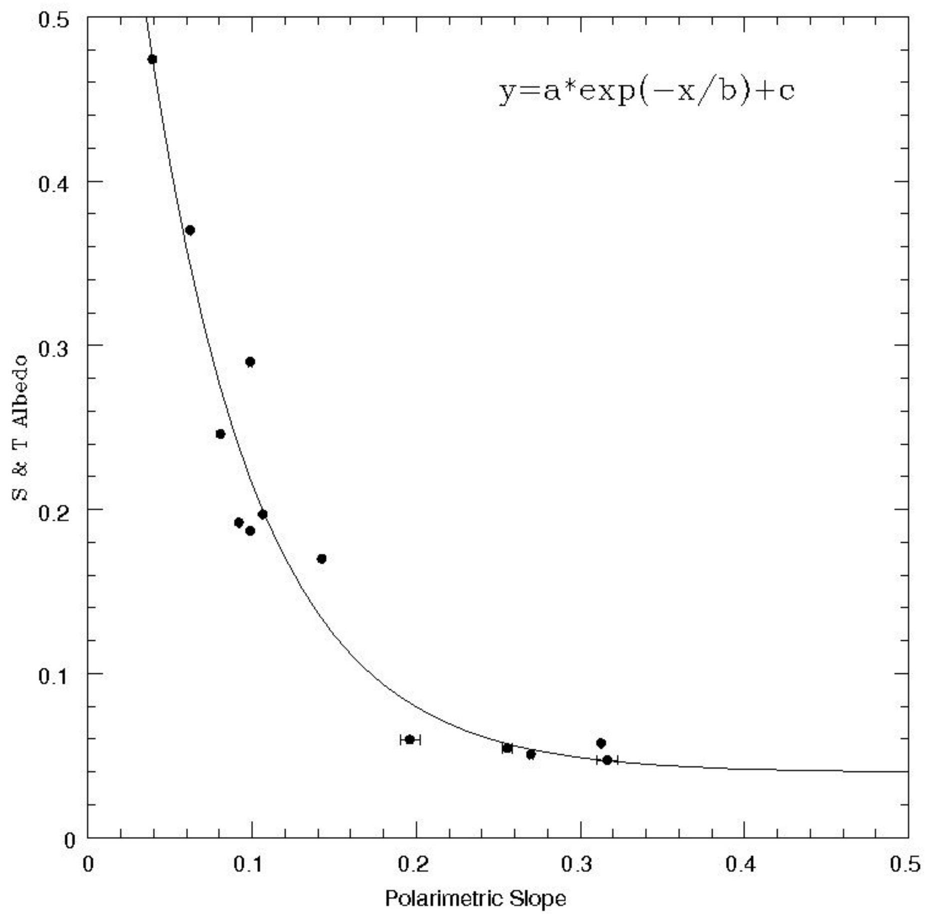
Slope-albedo data in a linear scale

Note that errors in polarimetric slopes are small for these (few) objects, whereas the albedo errors in the Shevchenko & Tedesco asteroid sample are not shown here, and depend on the errors in size determinations and in H.

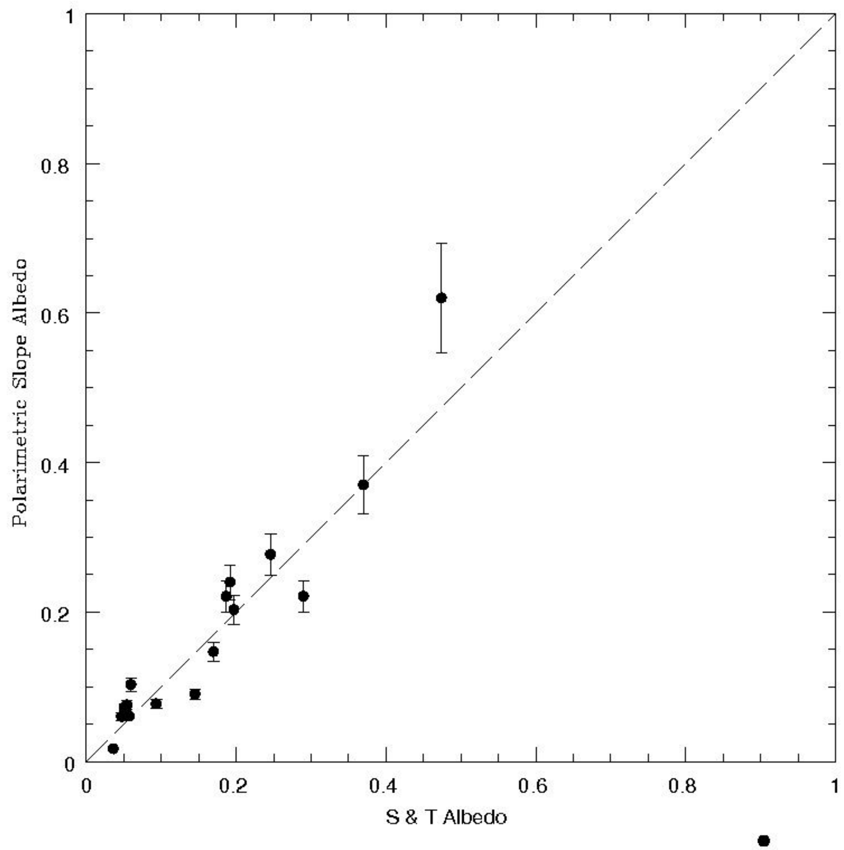
Whole sample



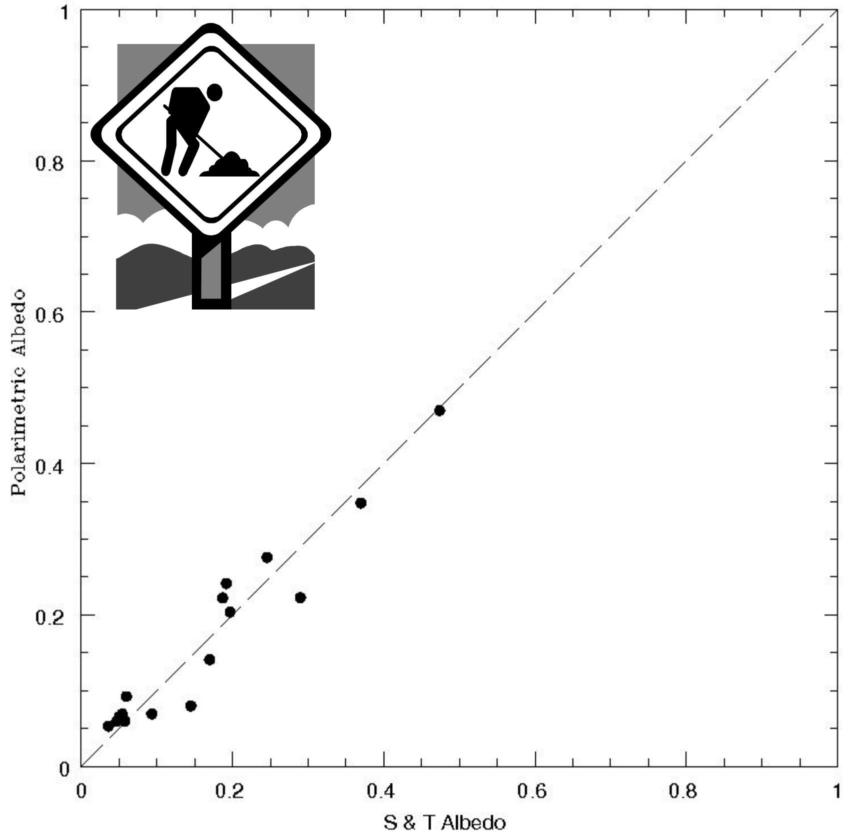
No Ceres, no Pallas



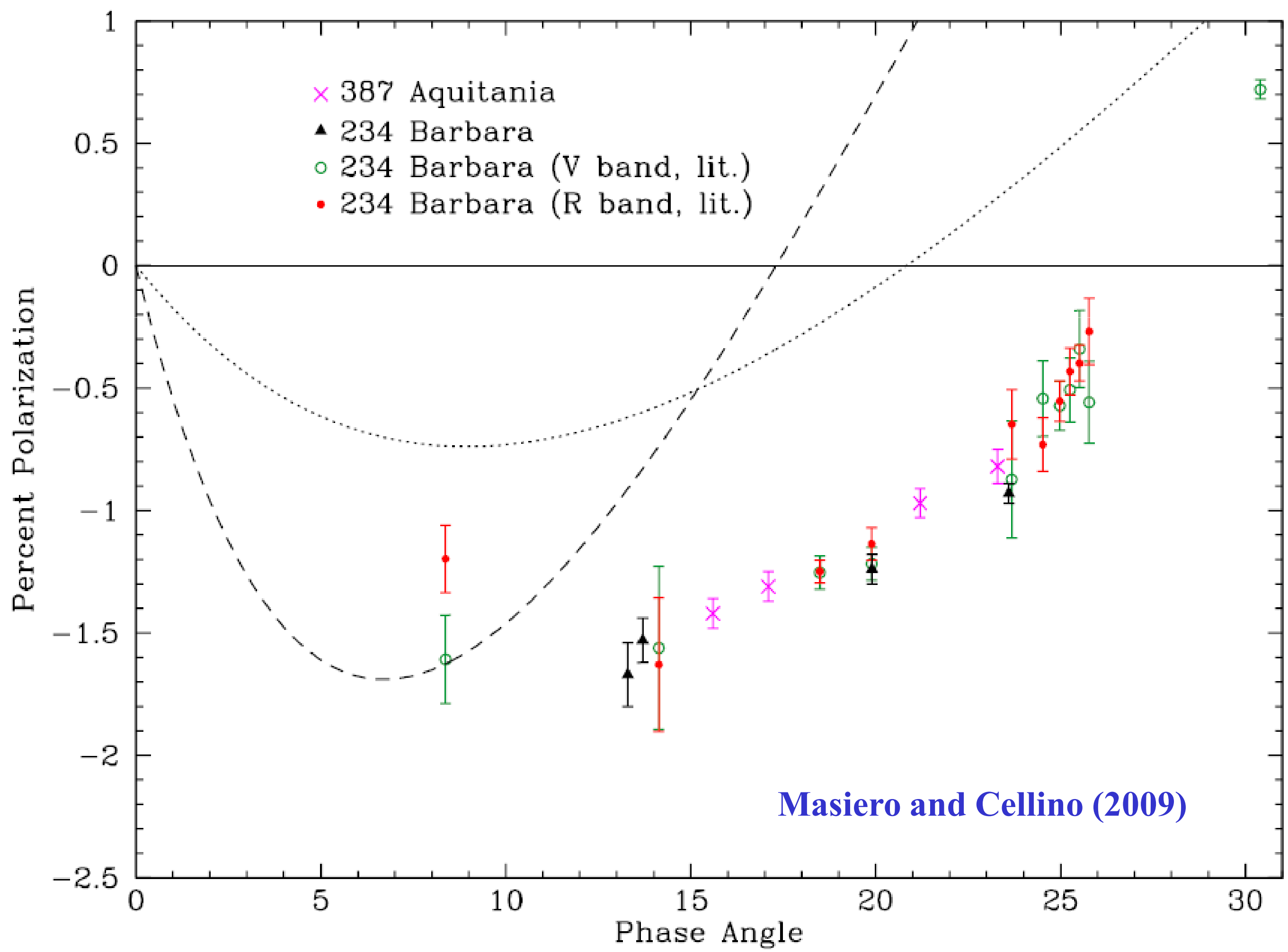
Current situation (classical calibration, best-fit coefficients)



Example of a possible re-definition



A new, exciting problem: The discovery of the "Barbarians"



(dashed and dotted lines show, for a comparison, typical polarization-phase curves for B-type ((24) Themis) and L-type ((12) Victoria) asteroids, respectively)

The search for "Barbarians": First results

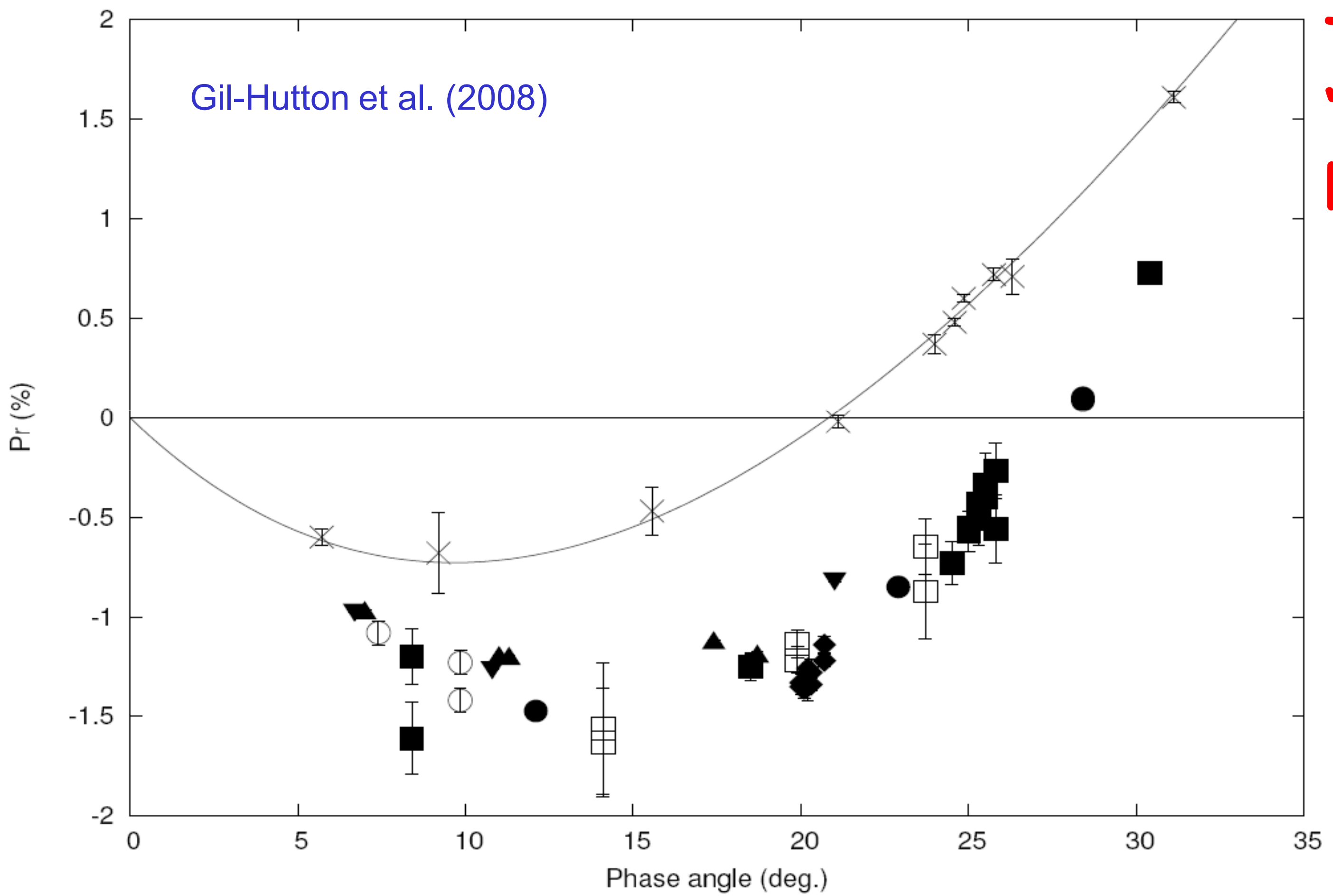


Fig. 1. Polarimetric observations of asteroids with anomalous polarimetric properties. Data for (172) Baucis are indicated by circles, for (234) Barbara by squares, for (236) Honoria by triangles, for (679) Pax by diamonds, and for (980) Anacostia by inverted triangles. Filled symbols indicate data taken during our campaigns. For comparison, data for (12) Victoria are indicated by crosses, and its phase-polarization curve are also included.

Known objects:

234 (Ld),

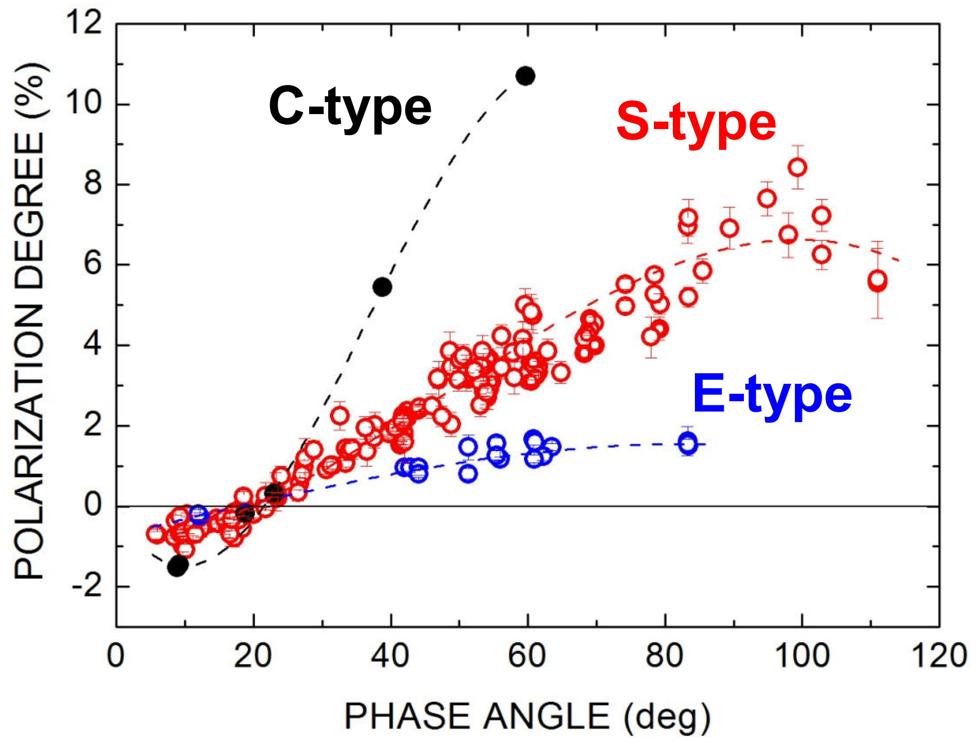
172, 236, 387, 980

(L -types)

679 (K-type)

Presence of thin, high- reflectivity particles on the surface?!

NEA Polarimetry

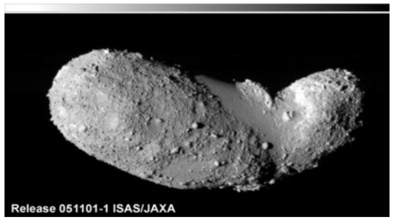


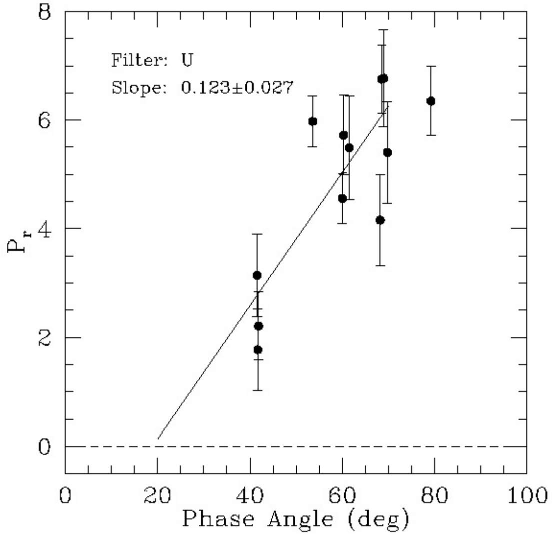
Presence of a wide branch of positive polarization with a maximum near 90°

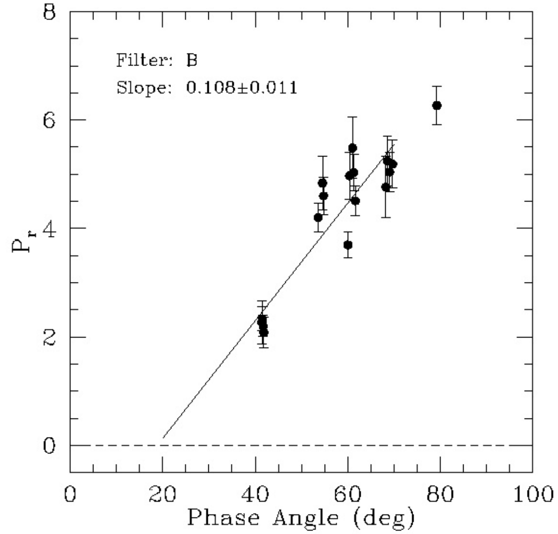
NEO polarimetry is inherently efficient, since the rate of variation of the phase angle is fast for these objects, and a polarimetric slope can be obtained in a short time.

Even a single measurement of polarization at phase > 40 deg can be sufficient to obtain an overall albedo estimation! **Very small (faint) NEAs are observable with the VLT (as shown by the case of Apophis).**

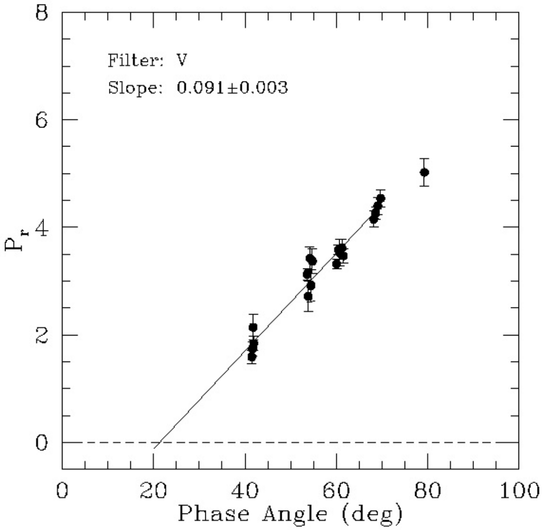
EXAMPLE: POLARIMETRIC OBSERVATIONS OF (25143) ITOKAWA AT LARGE PHASE ANGLES in 2004 at CASLEO

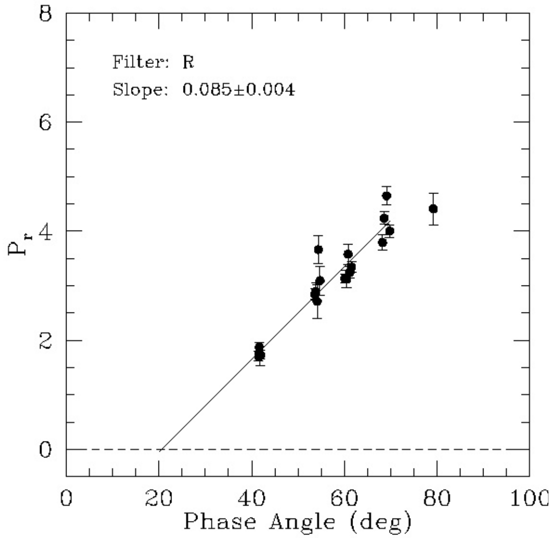


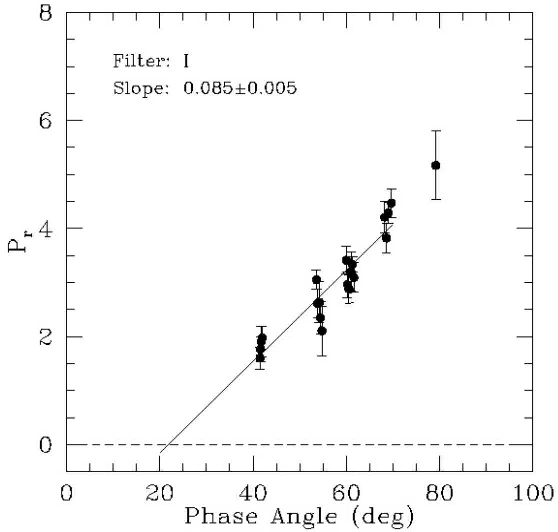




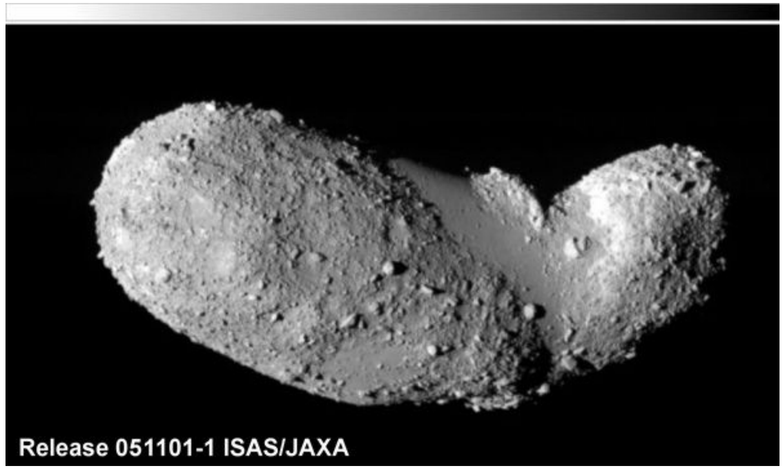
Linear fits of UBVRI data obtained in five consecutive nights, covering a large interval of phase angles



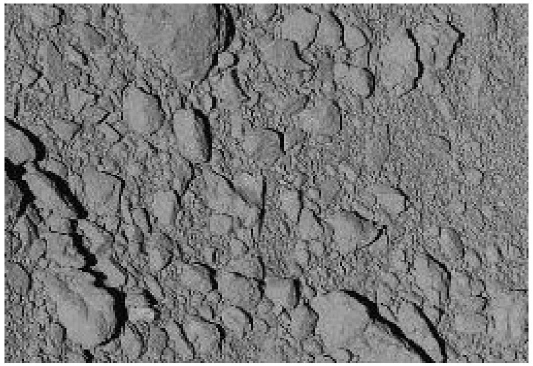




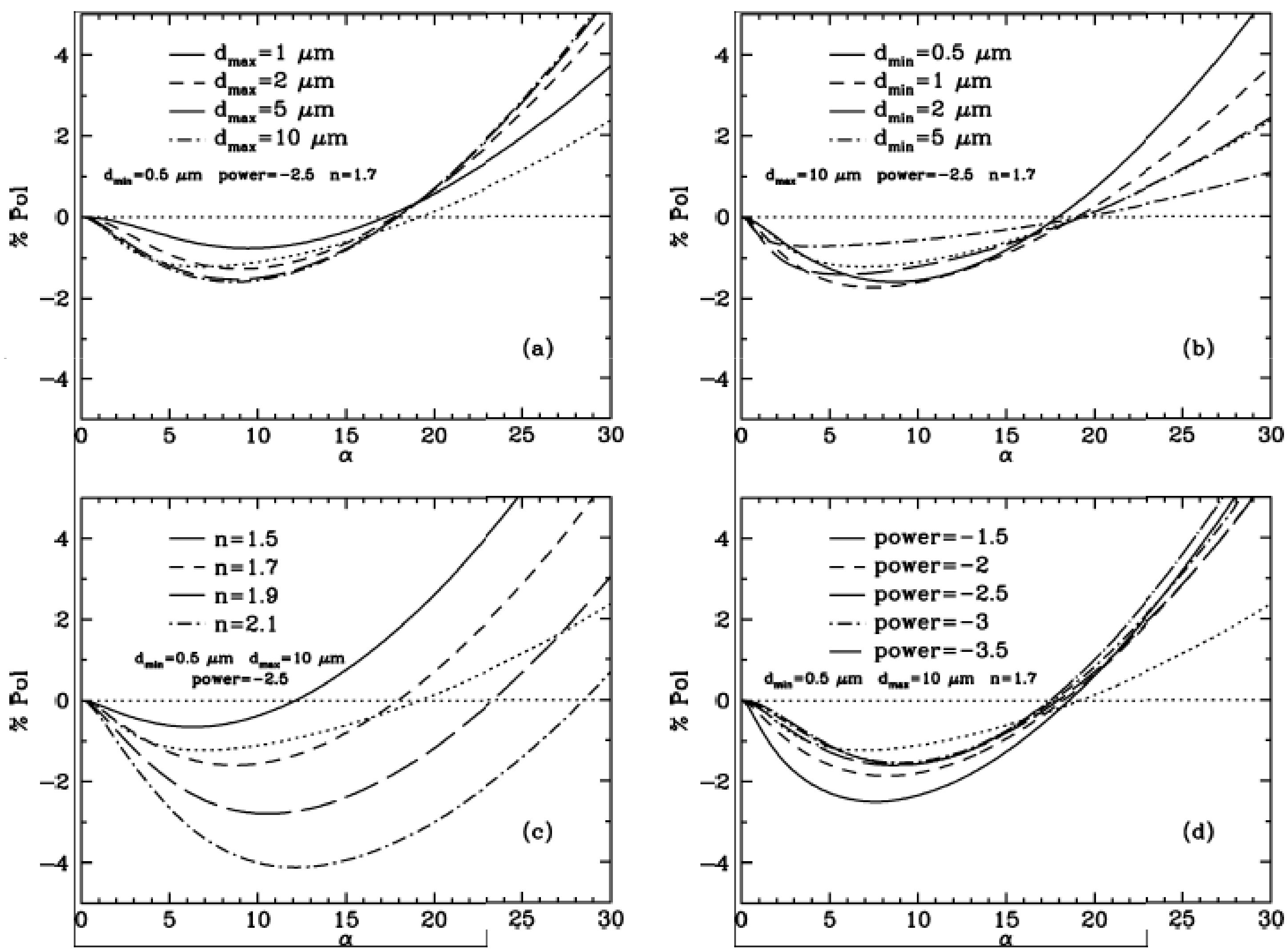
From the obtained polarimetric slope, the geometric albedo of Itokawa turns out to be: $p_v = 0.24 \pm 0.03$



The size obtained from the polarimetric albedo pv = 0.24 and H, derived from an extensive set of observations by different authors, gives a size which agrees within 7% with the Hayabusa results.



But... How is it possible? Itokawa seems to be very depleted in regolith particles. How can it behave like much larger, and regolith-rich main belt asteroids?



Dust grain between d_{min} and d_{max} are assumed be present on the surface, and different objects retain different d_{min}. However, there is no consequence on the phase-polarization curve. Possibly, there might be no difference even if there is not dust at all. What seems to really matter is mainly the distance between scattering elements

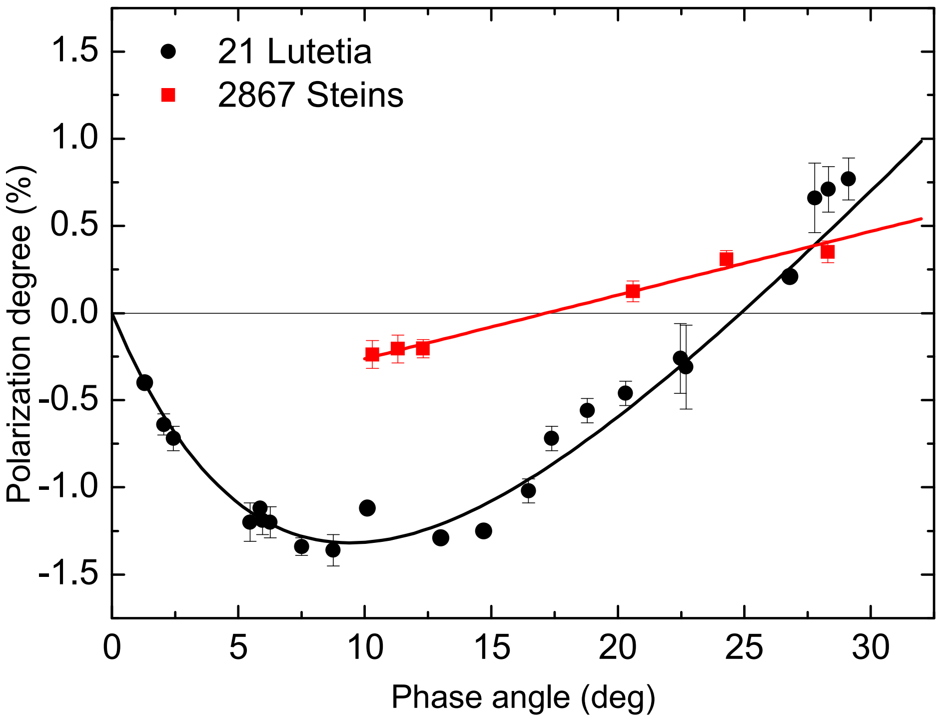
Masiero et al., 2009

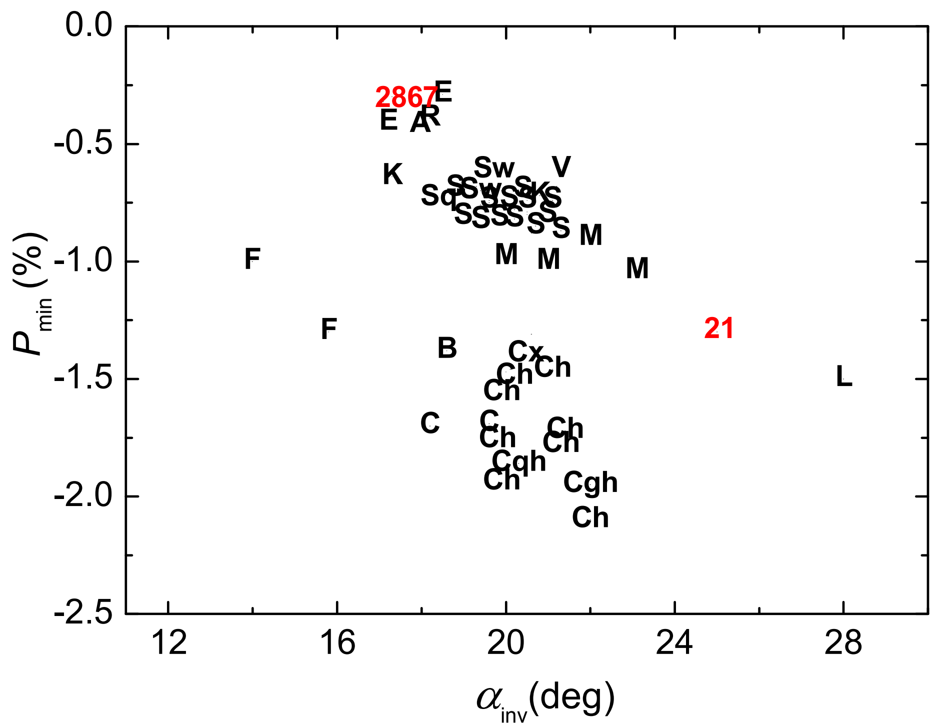
Another new result: VLT polarimetric observations of members of the Karin and Koronis families

No statistically relevant difference has been found for the polarimetric phase curves of objects belonging to the Koronis family (> 1 Gyrs old) and to the "children" objects belonging to the Karin family (5.8 Myrs old). This suggests that the space-weathering mechanism acts very quickly in affecting the albedo of S-type asteroid surfaces

Hot stuff: Steins and Lutetia

(see ACLR presentation)





A tentative "road map" for the future:

- **Primary goal: New data for albedo calibrations aimed at obtaining very accurate polarization measurements of the Shevchenko-Tedesco target list.**
- **Theoretical work certainly needed**
- **Peculiar objects (Barbarians, F-class,...)**
- **Need of new instruments. Good use of telescopes in the 2 - 4 m class.**