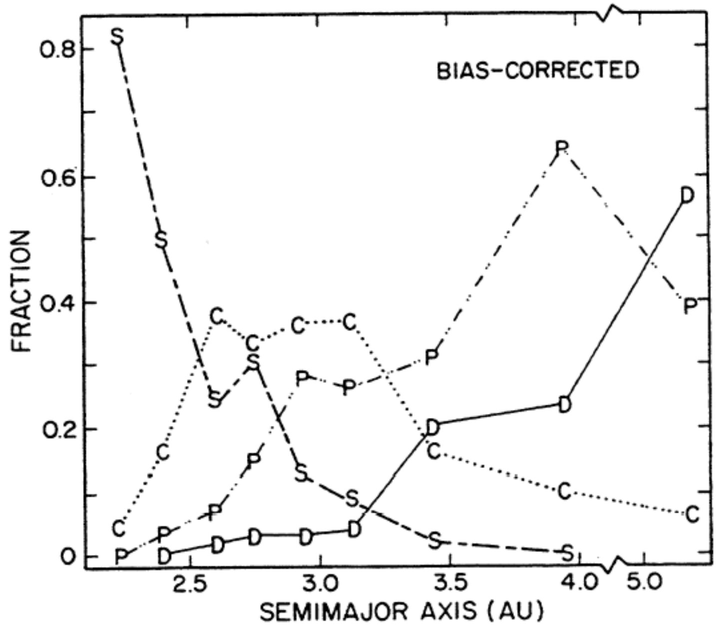
Some fundamental problems in current asteroid science:

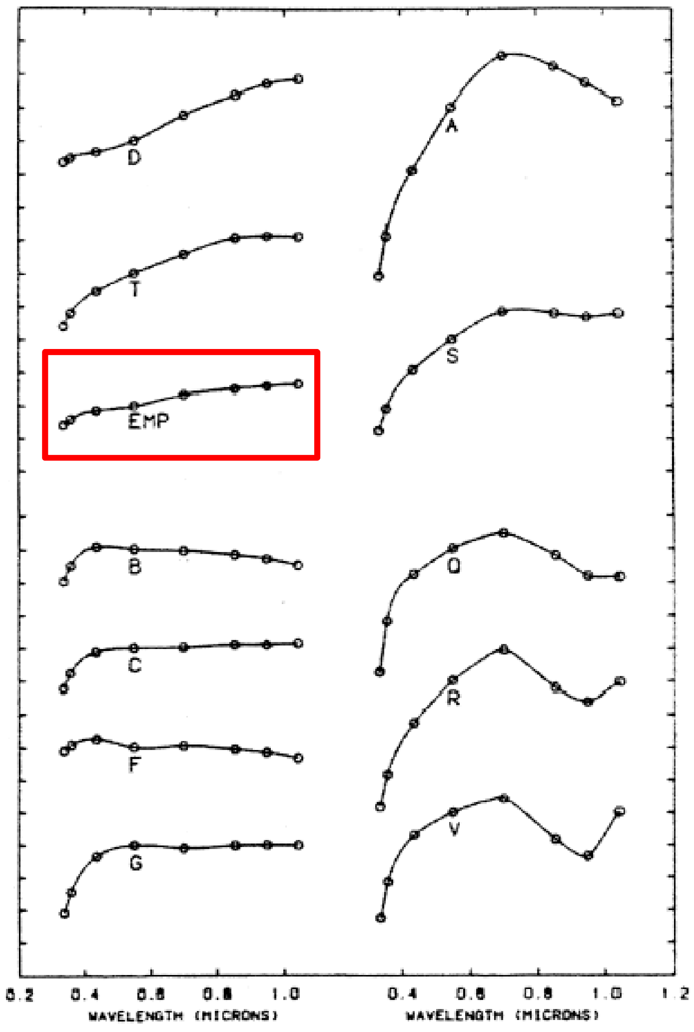
- The determination of asteroid masses and densities
- The measurement of asteroid sizes and shapes
- The determination of the relation between composition and taxonomic classification
- The physical characterization of potential Earth impactors

In all the above problems a crucial role is played by the problem of determining asteroid albedos

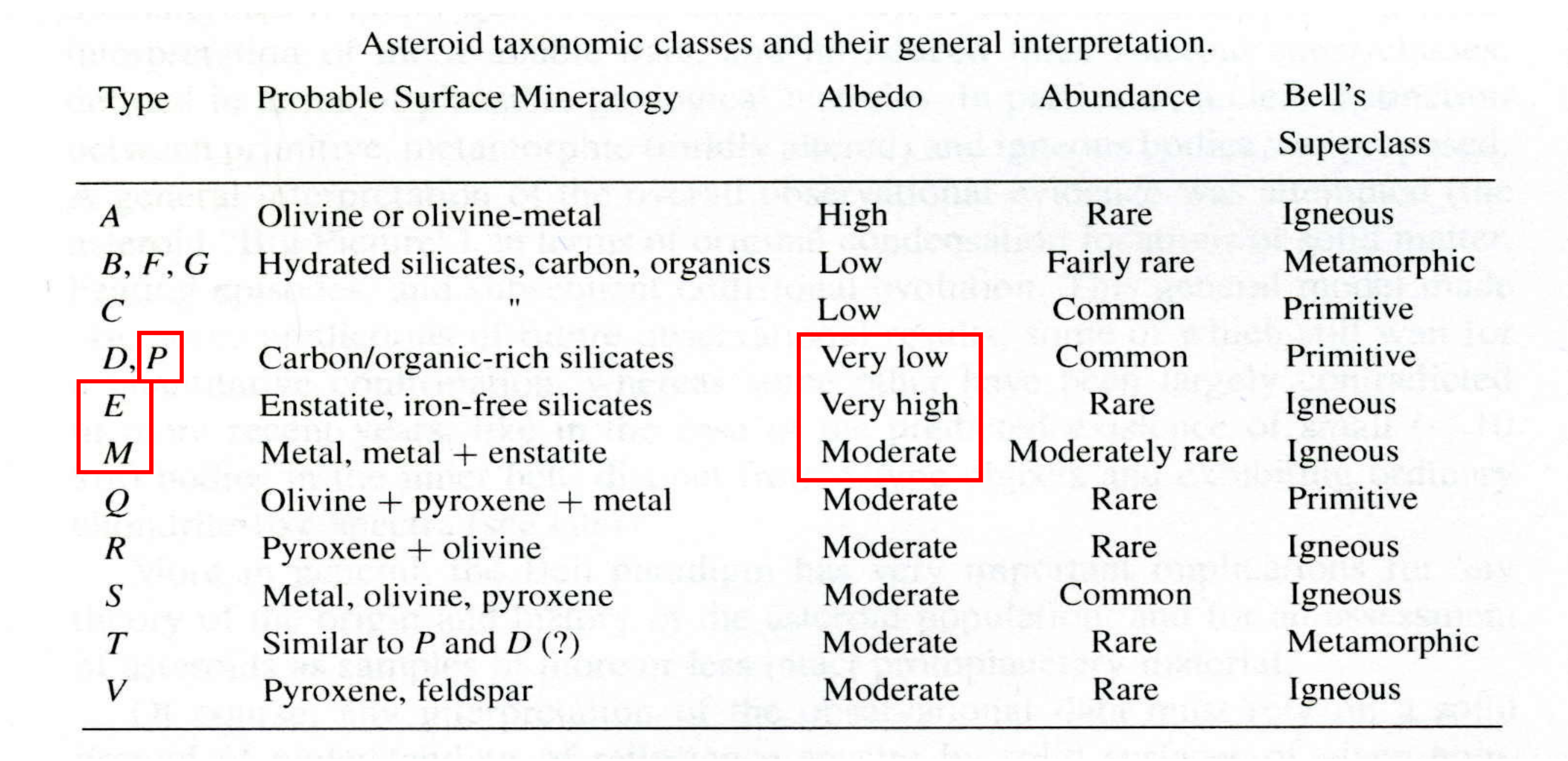
Asteroid taxonomy has been traditionally based on spectrophotometric properties at visible wavelengths. Near-IR added recently.

The distribution of different taxonomic classes as a function of heliocentric distance is related to the general composition gradient of our Solar System





The mineralogical interpretation of reflectance spectra



Asteroid taxonomic classes and their general interpretation.

Type	Probable Surface Mineralogy	Albedo	Abundance	Bell's Superclass
A	Olivine or olivine-metal	High	Rare	Igneous
B, *F*, *G*	Hydrated silicates, carbon, organics	Low	Fairly rare	Metamorphic
C	"	Low	Common	Primitive
D, *P*	Carbon/organic-rich silicates	Very low	Common	Primitive
E	Enstatite, iron-free silicates	Very high	Rare	Igneous
M	Metal, metal + enstatite	Moderate	Moderately rare	Igneous
Q	Olivine + pyroxene + metal	Moderate	Rare	Primitive
R	Pyroxene + olivine	Moderate	Rare	Igneous
S	Metal, olivine, pyroxene	Moderate	Common	Igneous
T	Similar to *P* and *D* (?)	Moderate	Rare	Metamorphic
V	Pyroxene, feldspar	Moderate	Rare	Igneous

E, M and P classes are characterized by very different albedo

Primitive objects have generally low albedoes, as shown by meteorite analyses in the lab.

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

Is a fundamental relation in asteroid science, where:

D **is the equivalent diameter** in km.

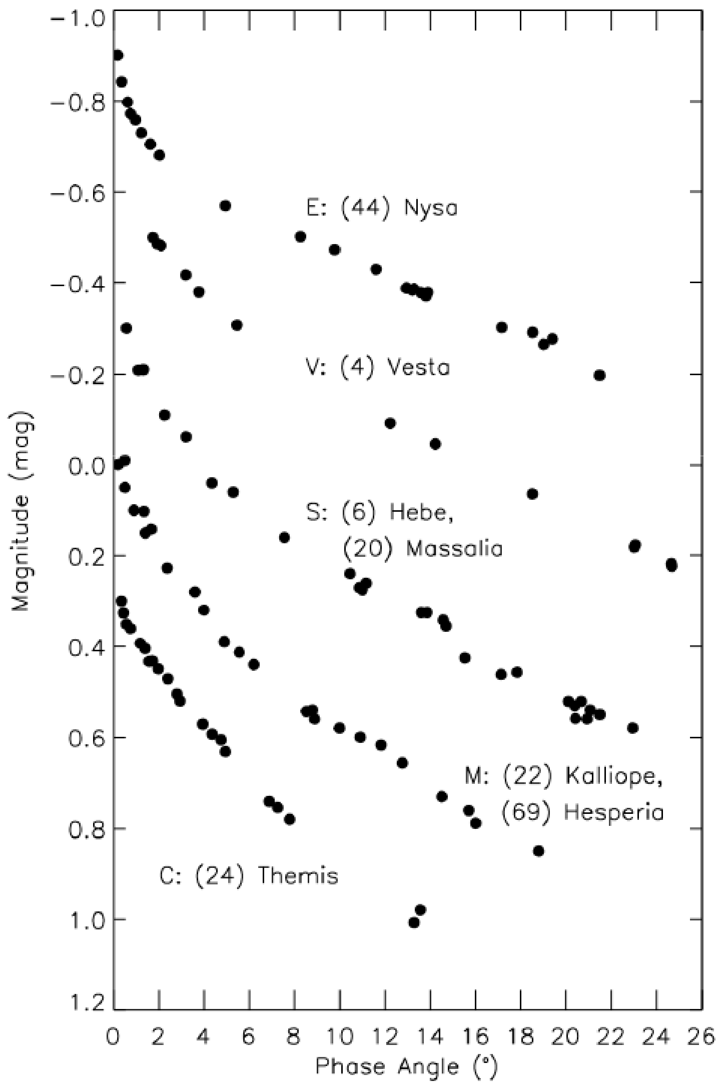
3.1236 is a wavelength-dependent constant (the indicated value is for V colour)

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. It varies at different solar oppositions of the same object**.

THE BRIGHTNESS OPPOSITION EFFECT

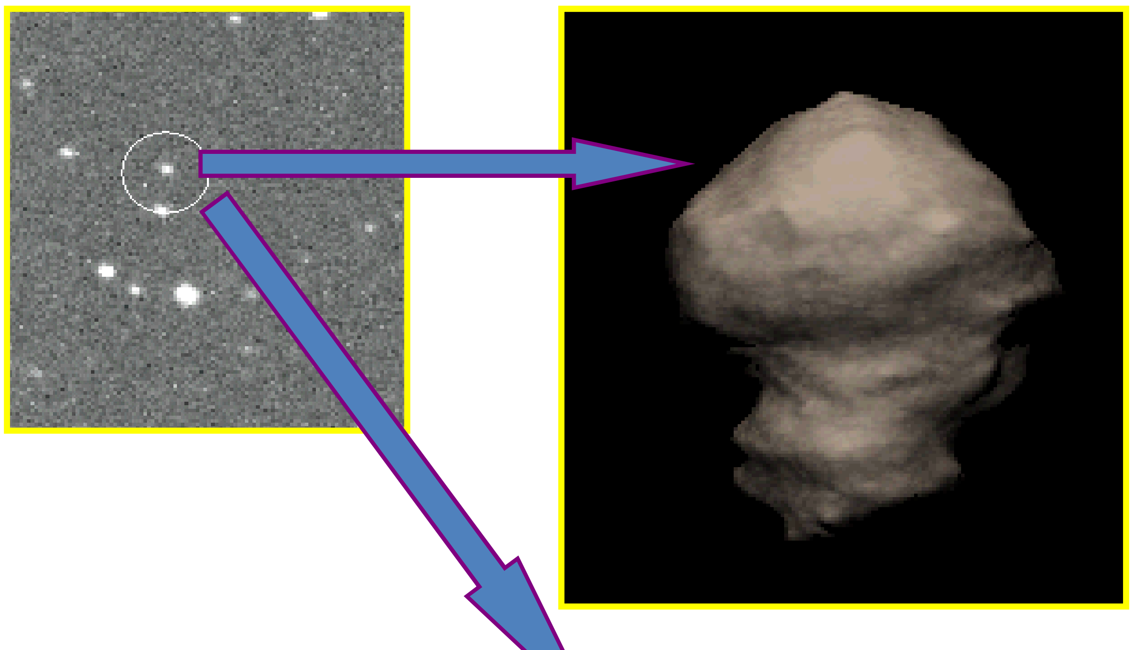
- sharp increase in brightness at small phase angles

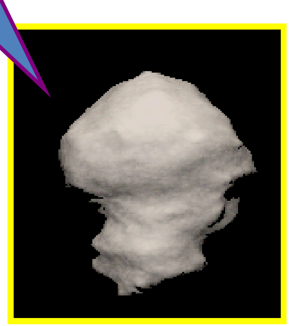


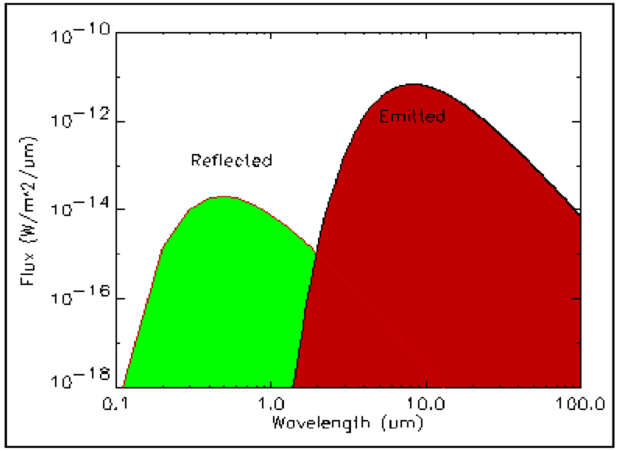
Muinonen et al., Asteroids III (2002)

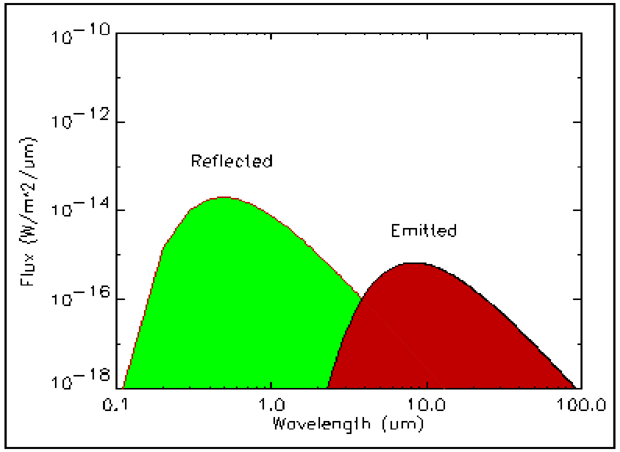
According to its zero-phase angle definition, the value of the absolute magnitude H strongly depends on the extent of the non-linear brightness opposition effect, which **can hardly** be predicted *a priori*.

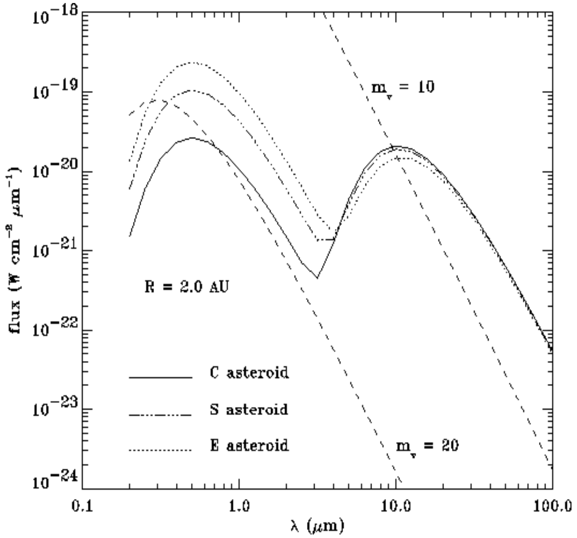
This is a problem, because the absolute magnitude is a very important parameter!







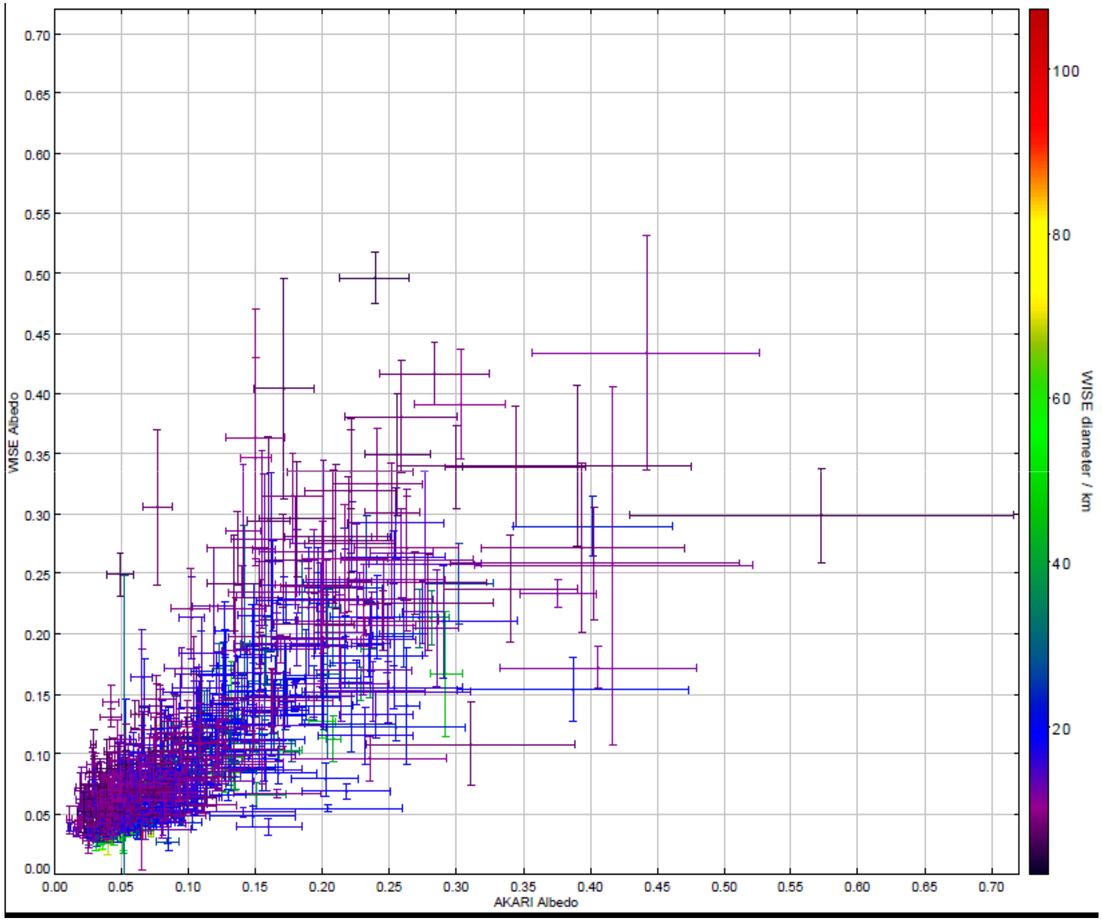




A well-known technique: Thermal Radiometry

Thermal radiometry results, however, are model-dependent and, particularly for albedo, suffer from poor knowledge of the value to assign to the absolute magnitude H. The thermal flux depends only weakly on the albedo!

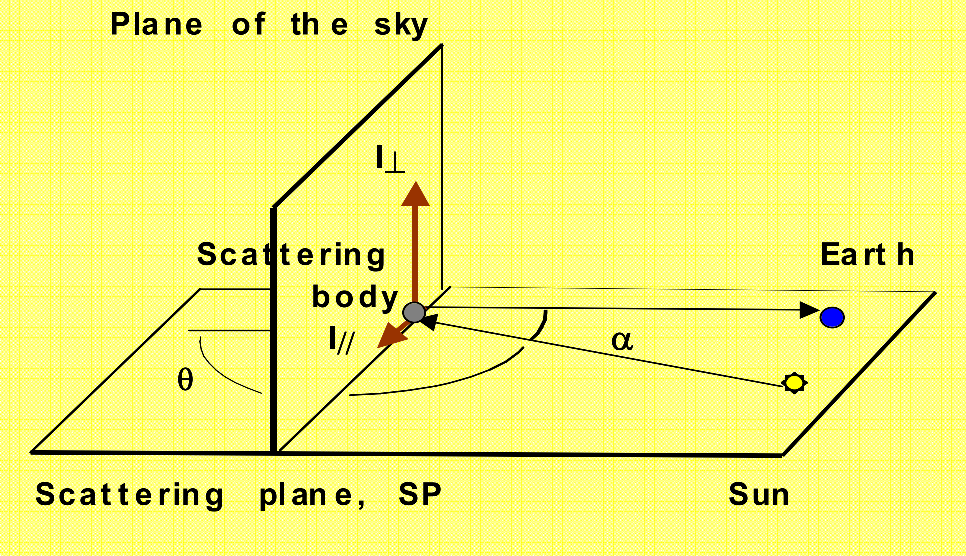
Radiometric albedoes for small asteroids observed in one single IR band have intrinsic uncertainties which may be of the order of 60% or larger.



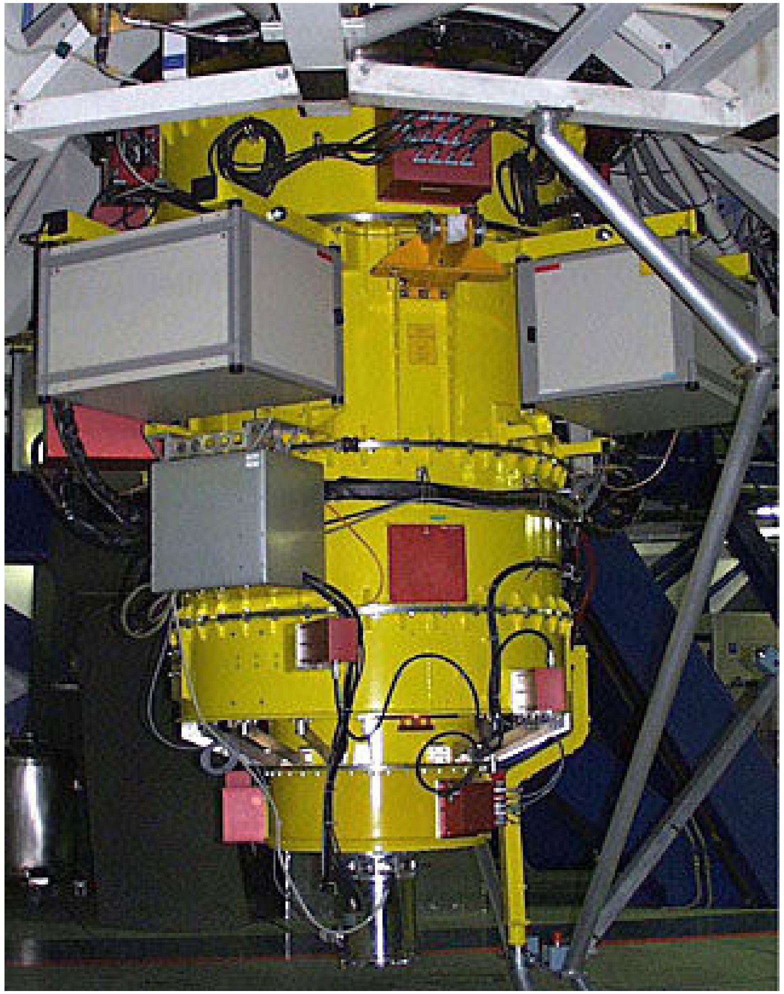
Akari *versus* Wise albedoes

Asteroid Polarimetry: What do we measure ?

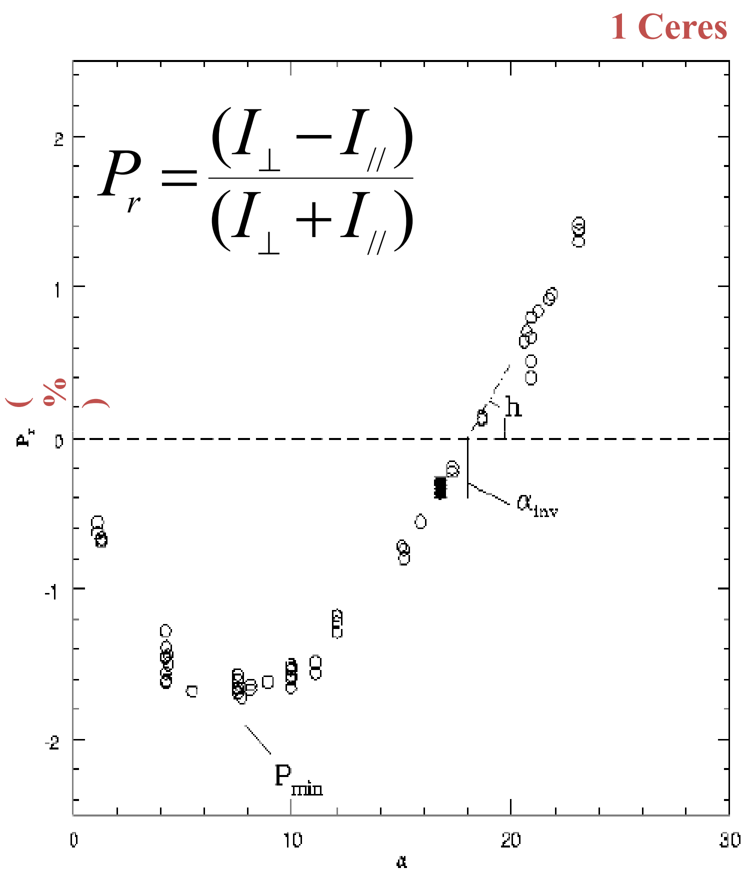
Partial linear polarization and polarization – phase curves.



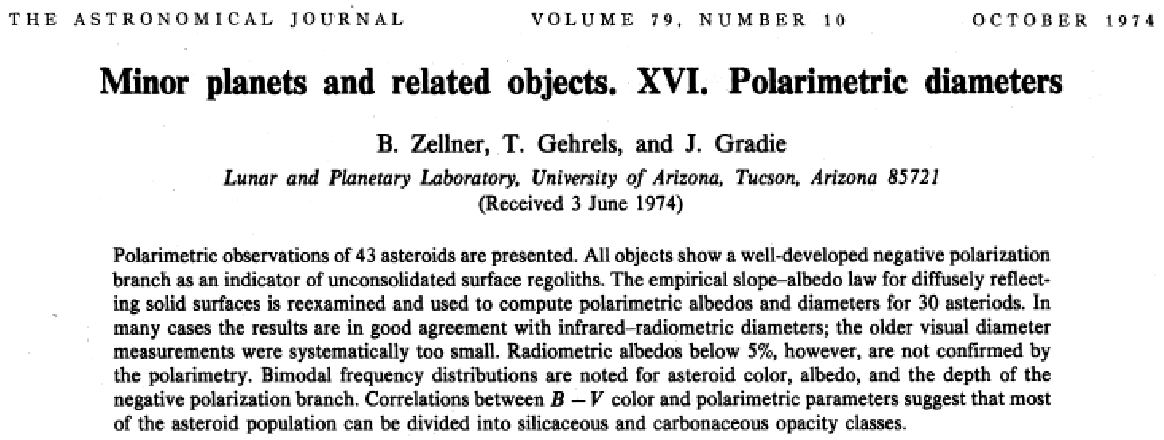
- Presence of a “Negative polarization branch”
- Curve described by a few parameters



The derivation of the Albedo from polarimetric properties: the "slope – albedo law".



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



THE ASTRONOMICAL JOURNAL VOLUME 79, NUMBER 10 OCTOBER 1974

Minor planets and related objects. XVI. Polarimetric diameters

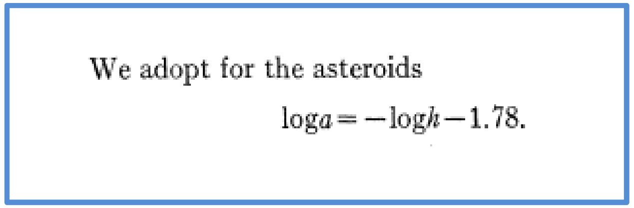
B. Zellner, T. Gehrels, and J. Gradie

Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721

(Received 3 June 1974)

Polarimetric observations of 43 asteroids are presented. All objects show a well-developed negative polarization branch as an indicator of unconsolidated surface regoliths. The empirical slope–albedo law for diffusely reflecting solid surfaces is reexamined and used to compute polarimetric albedos and diameters for 30 asteroids. In many cases the results are in good agreement with infrared–radiometric diameters; the older visual diameter measurements were systematically too small. Radiometric albedos below 5%, however, are not confirmed by the polarimetry. Bimodal frequency distributions are noted for asteroid color, albedo, and the depth of the negative polarization branch. Correlations between $B-V$ color and polarimetric parameters suggest that most of the asteroid population can be divided into silicaceous and carbonaceous opacity classes.

…



We adopt for the asteroids

$$\log a = -\log h - 1.78.$$

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:

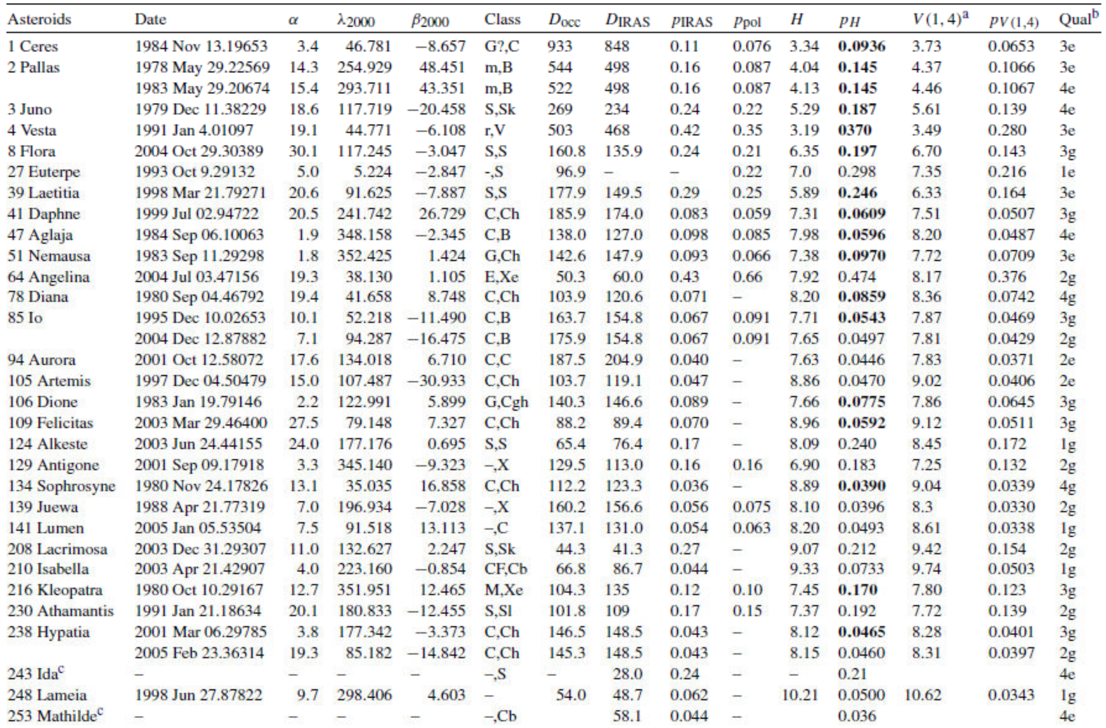
- $C_1 = -1.0$ $C_2 = -1.78$ (Zellner *et al.*, 1974)
- $C_1 = -0.983 \pm 0.082$ $C_2 = -1.731 \pm 0.066$ (Lupishko & Mohamed, 1996)
- $C_1 = -1.118 \pm 0.071$ $C_2 = -1.779 \pm 0.062$ (Cellino *et al.*, 1999)
- $C_1 = -0.970 \pm 0.071$ $C_2 = -1.677 \pm 0.083$ (Cellino *et al.*, 2012)

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

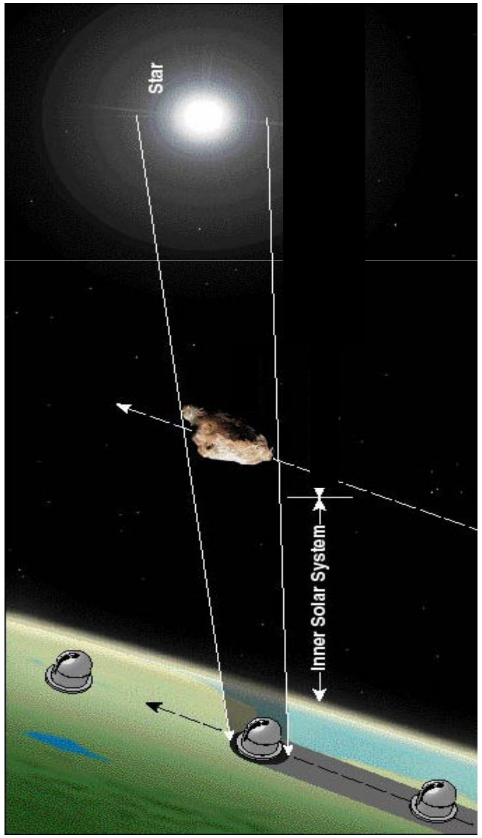
It is urgent to converge to a new and unique choice choice of C_1 and C_2

The slope-albedo relation must be recalibrated using only high-quality V-band polarimetry of asteroids having accurately derived albedoes. The best target list at present is the one by **Shevchenko and Tedesco (2006)**, including objects whose albedoes were derived from both occultation and *in situ* (four objects) size measurements, coupled with accurate estimates of absolute magnitudes **(obtained using H,G, so let us keep our fingers crossed! ☺)**.

First objects of the Shevchenko & Tedesco (2006) list

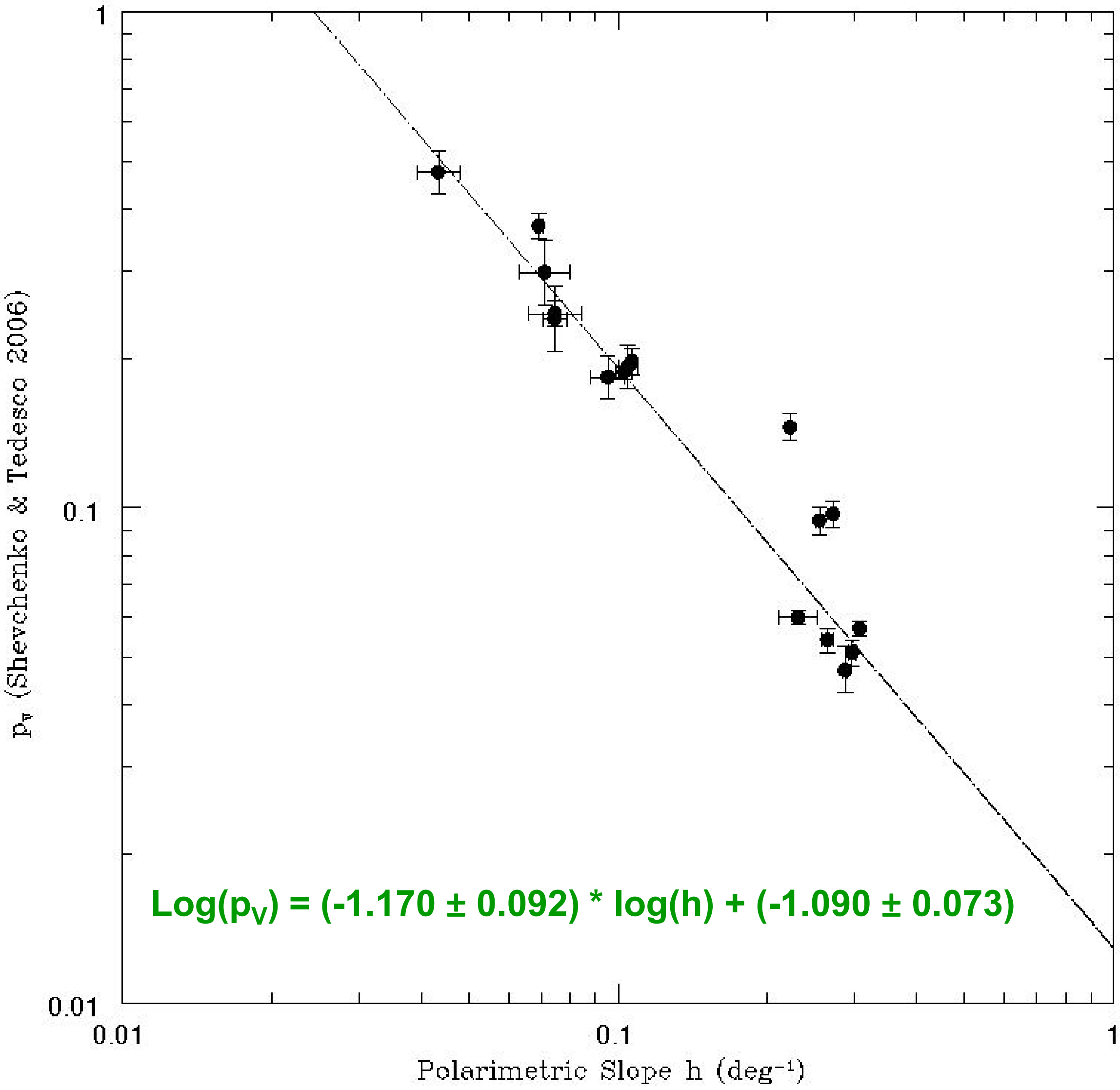


Asteroids	Date	α	λ_{2000}	β_{2000}	Class	D_{occ}	D_{IRAS}	p_{IRAS}	p_{pol}	H	p_H	$V(1,4)$[a]	$p_{V(1,4)}$	Qual[b]
1 Ceres	1984 Nov 13.19653	3.4	46.781	−8.657	G?,C	933	848	0.11	0.076	3.34	**0.0936**	3.73	0.0653	3e
2 Pallas	1978 May 29.22569	14.3	254.929	48.451	m,B	544	498	0.16	0.087	4.04	**0.145**	4.37	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

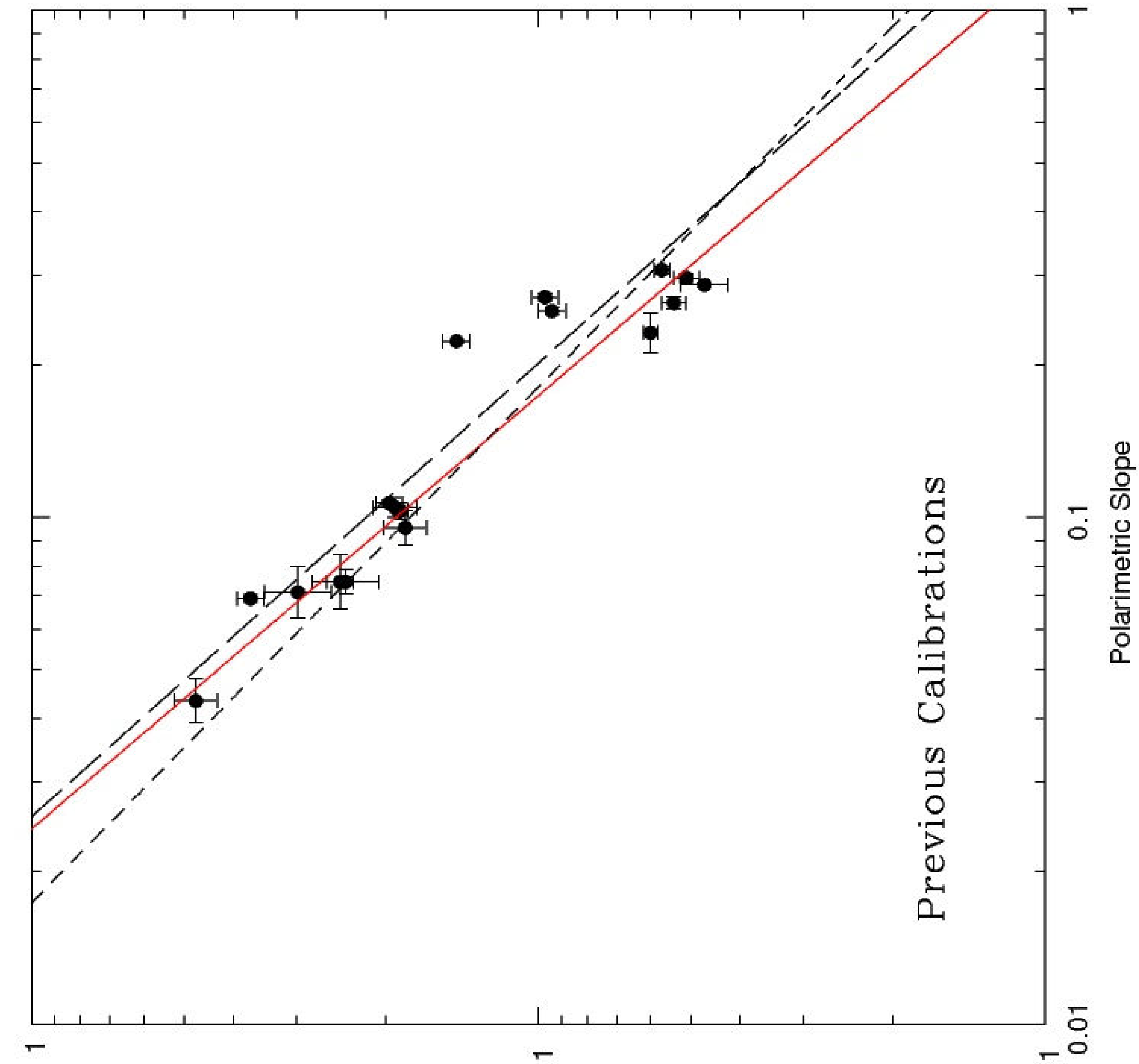


An updated list is going to be produced soon using a larger data-set

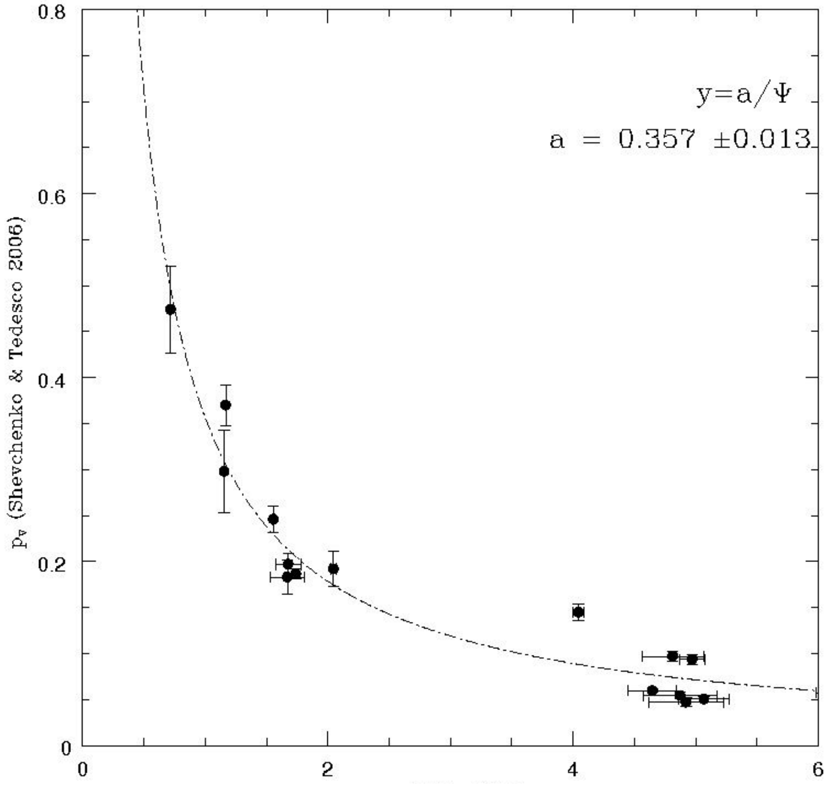
Results of an extensive analysis of all data available in the literature, as well as of many still unpublished observations carried out at the CASLEO observatory (to be submitted soon for publication)



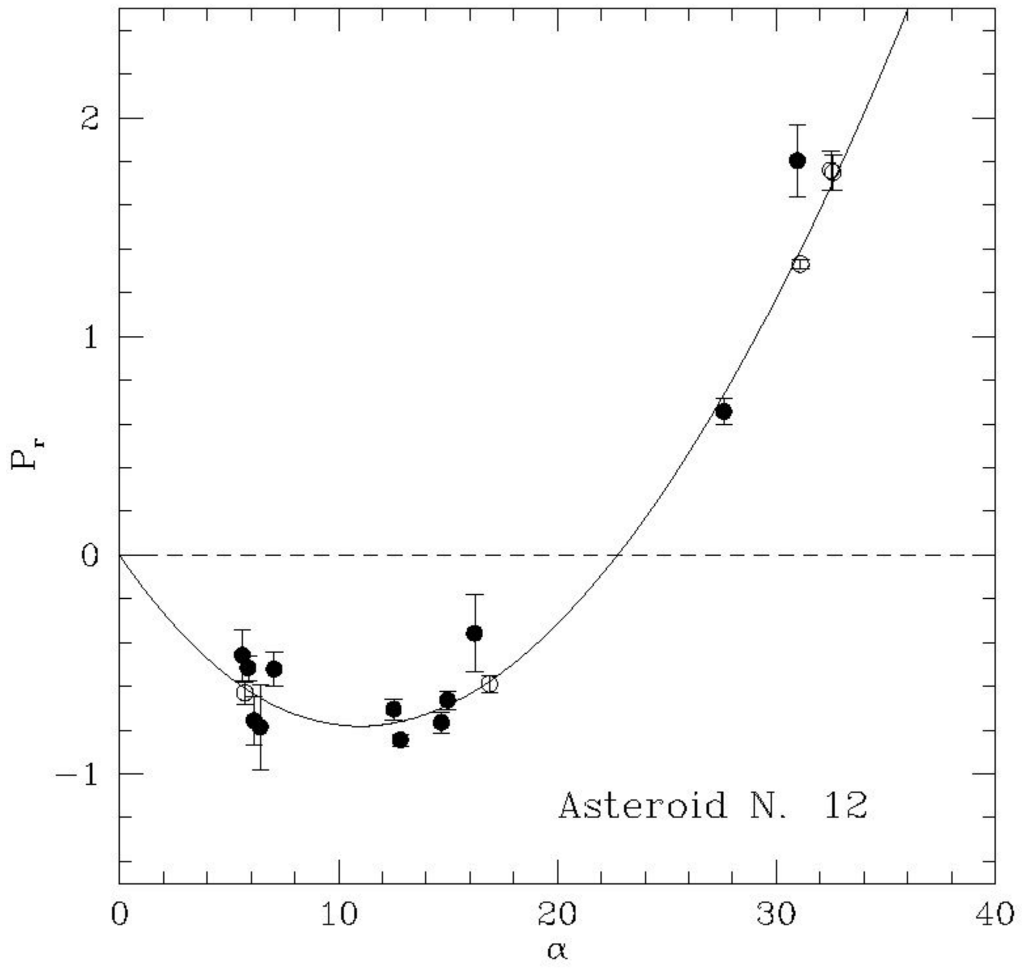
Nominal errors of resulting albedoes are generally better than 10%.


Previous Calibrations
Polarimetric Slope
p_V (Shevchenko & Tedesco 2006)
0.01
0.1
1
0.01
0.1
1

Looking also for new relations not purely based on the polarimetric slope only, but on more global fits of the whole phase – polarization curve.



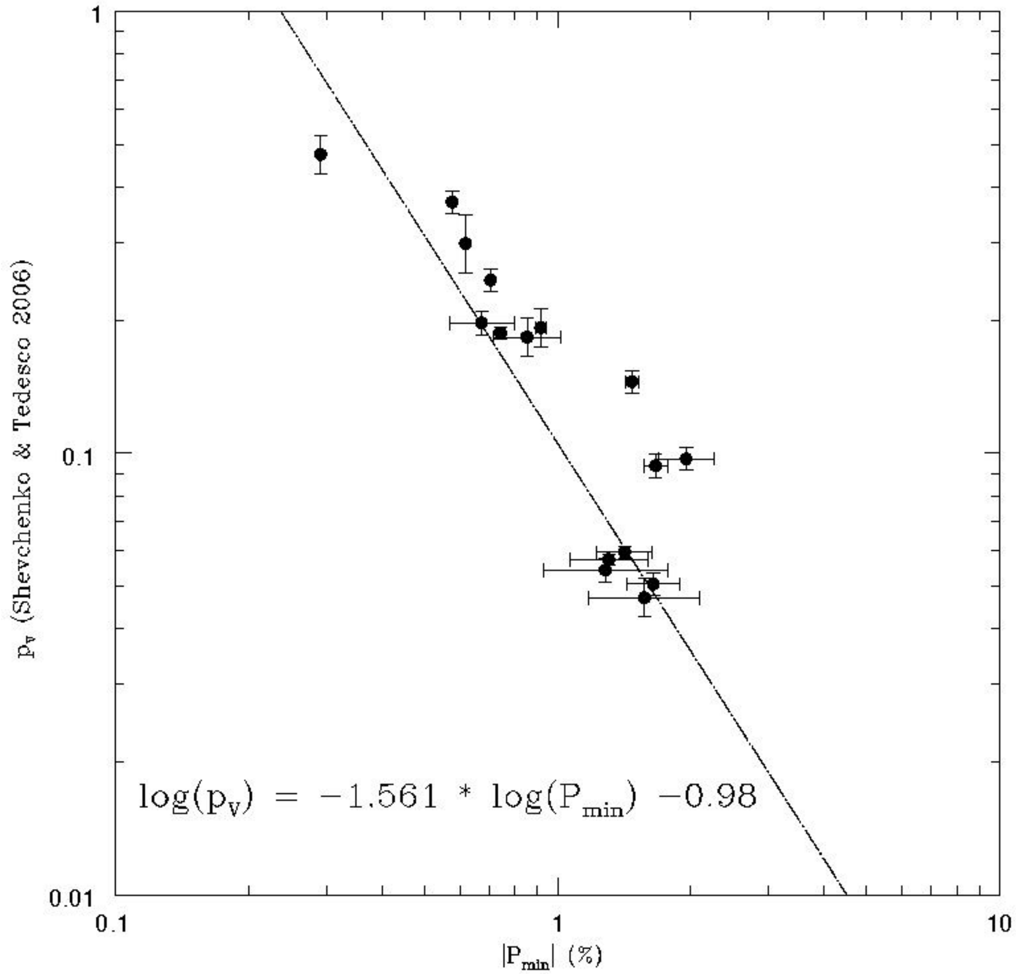
$\Psi = Pr(30) - Pr(10)$



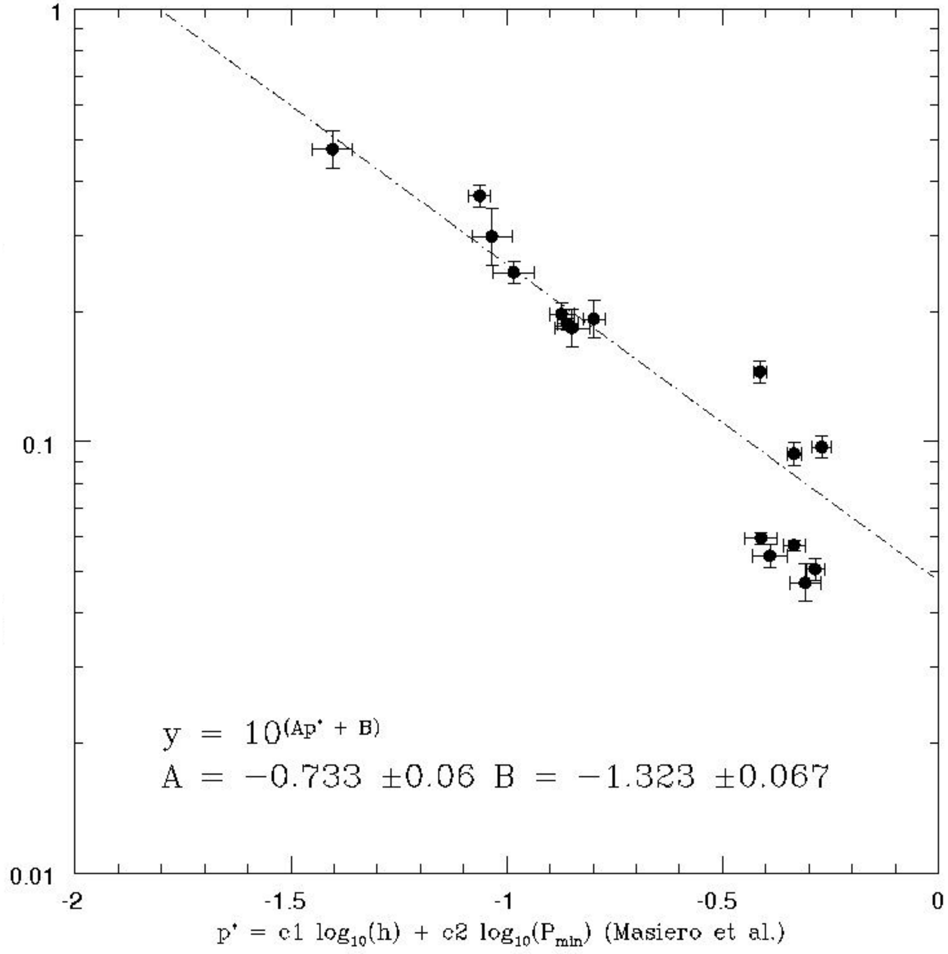
$$P_r = a \cdot \left(e^{(-\alpha/b)} - 1 \right) + c \cdot \alpha$$

α: phase angle; a,b,c: coefficients to be determined

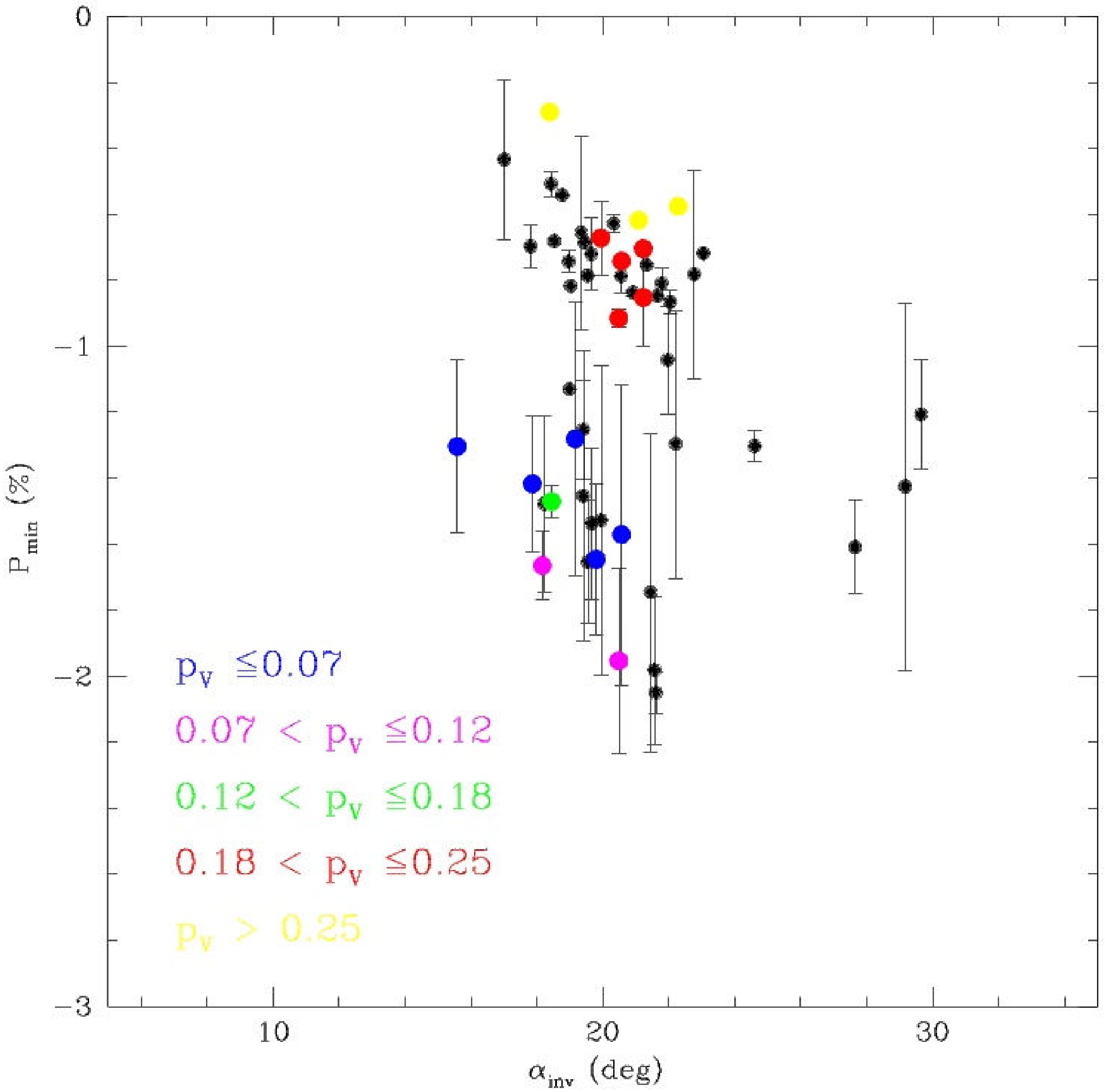
The “classical” P_{min} – p_V relation … and the recently proposed p^* - p_V

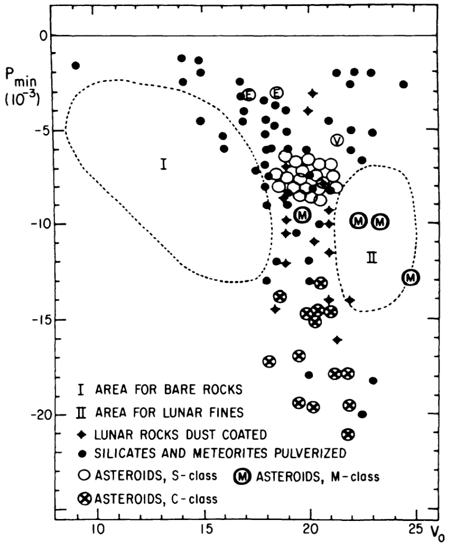


(new calibration) ↑



(new calibration) ↑





New version of the classical Figure by Dollfus *et al.*, 1989
Note the locations of three known Barbarians (172, 234, 387) and of (21) Lutetia.

Pros:

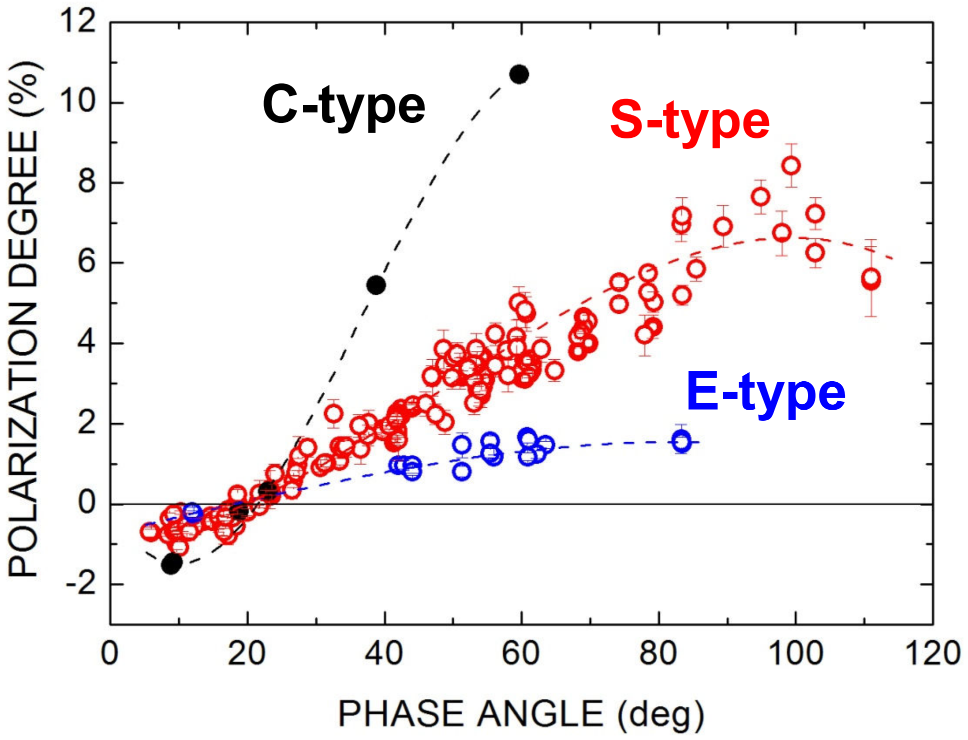
Polarimetry is in principle an excellent technique to derive the albedoes of main belt asteroids and NEOs of all sizes. No dependence on absolute magnitude!

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

Cons:

Time consuming! You need weeks to get a satisfactory coverage of the phase- polarization curve of a main belt asteroid! (much less time is needed for near-Earth asteroids).

NEA Polarimetry



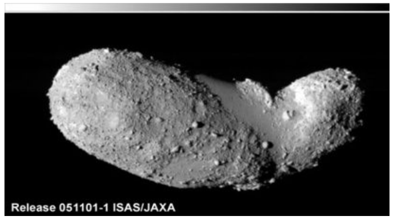
Courtesy of I.N. Belskaya

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

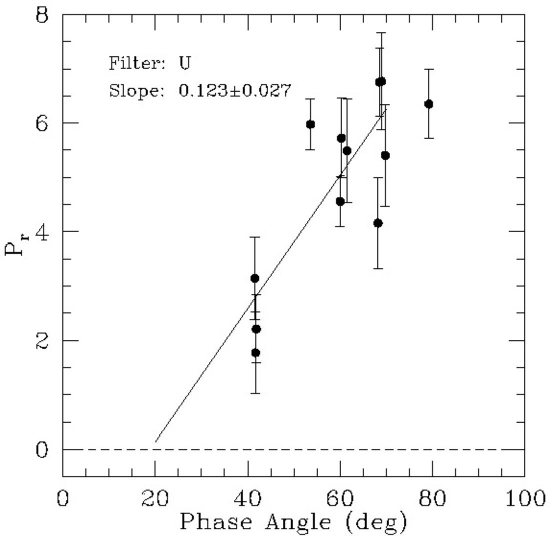
NEO polarimetry is inherently efficient, since the rate of variation of the phase angle is fast for these objects, and a polarimetric slope can be obtained in a short time. Interesting for the purposes of ESA SSA program

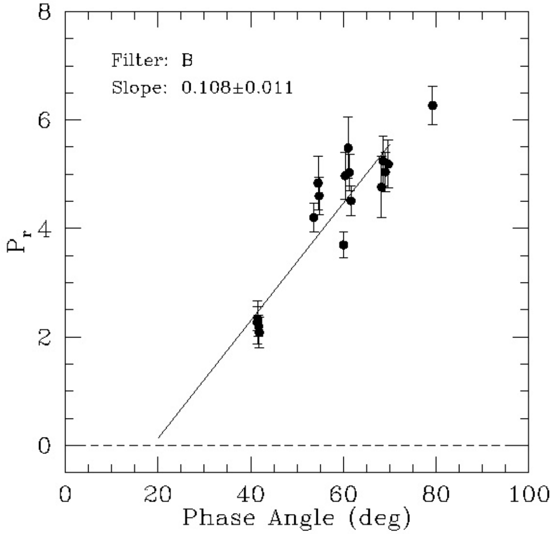
Even a single measurement of polarization at phase > 40 deg can be sufficient to obtain an overall albedo estimation! **Very small (faint) NEAs are observable with the VLT (as shown by the case of Apophis).**

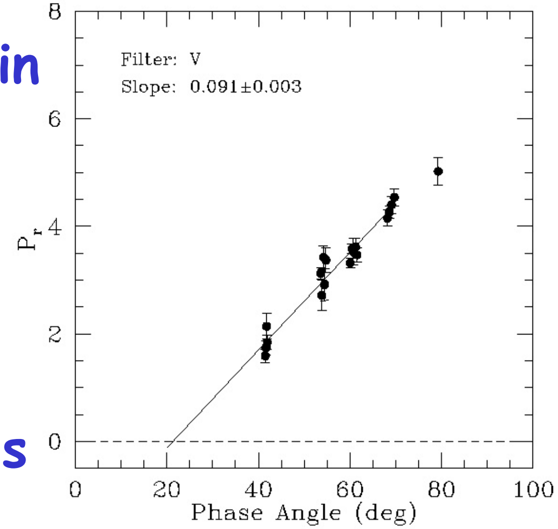
EXAMPLE: POLARIMETRIC OBSERVATIONS OF (25143) ITOKAWA AT LARGE PHASE ANGLES in 2004 at CASLEO

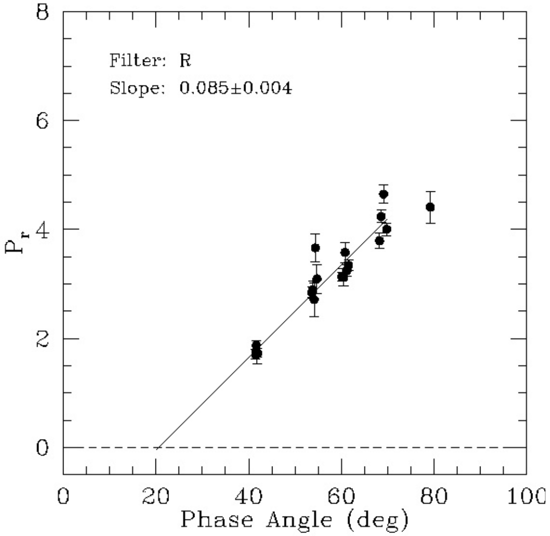


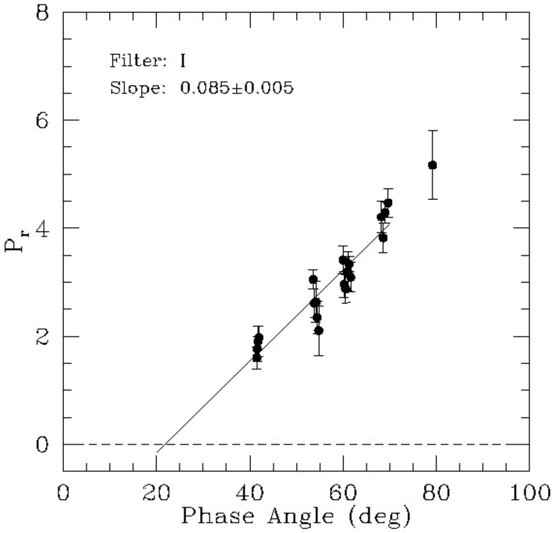
Linear fits of UBVRI data obtained in five colors in consecutive nights, covering a large interval of phase angles

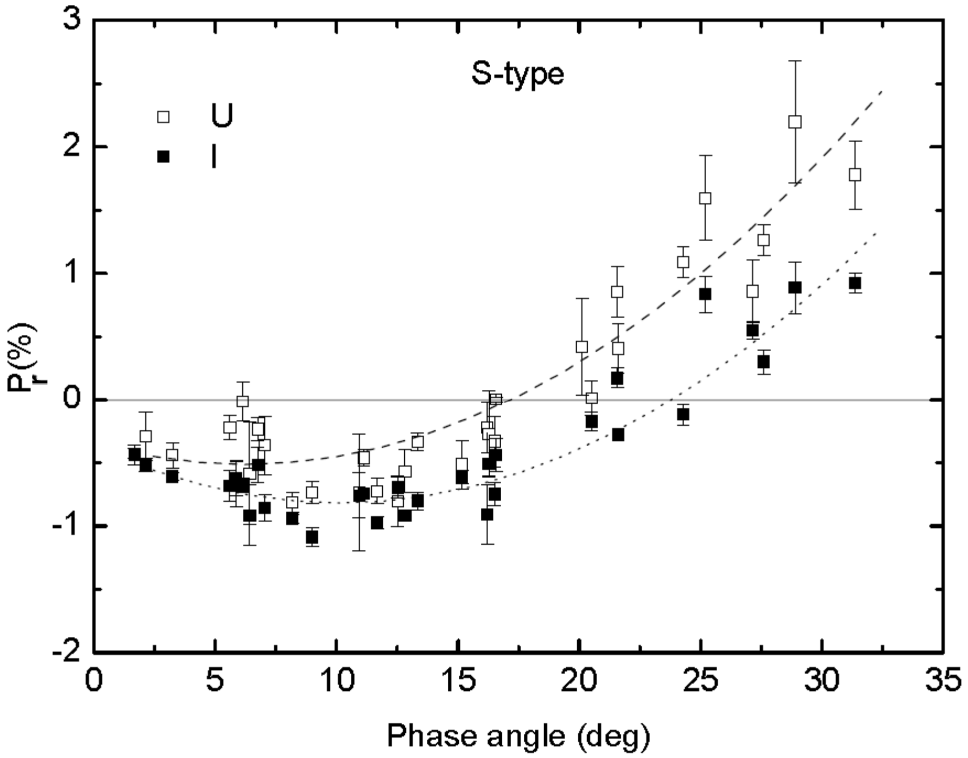










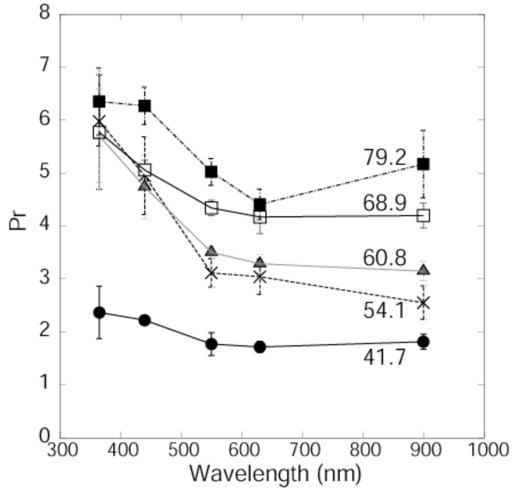


Belskaya *et al.*, Icarus 199, 97-105 (2009)

First results about wavelength dependence of linear polarization

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

Similar effects observed also for comets.

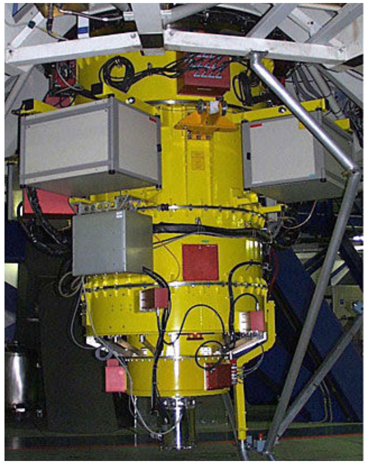


UBVRI **Itokawa observations at CASLEO**

Full spectro-polarimetry never attempted so far for asteroids!

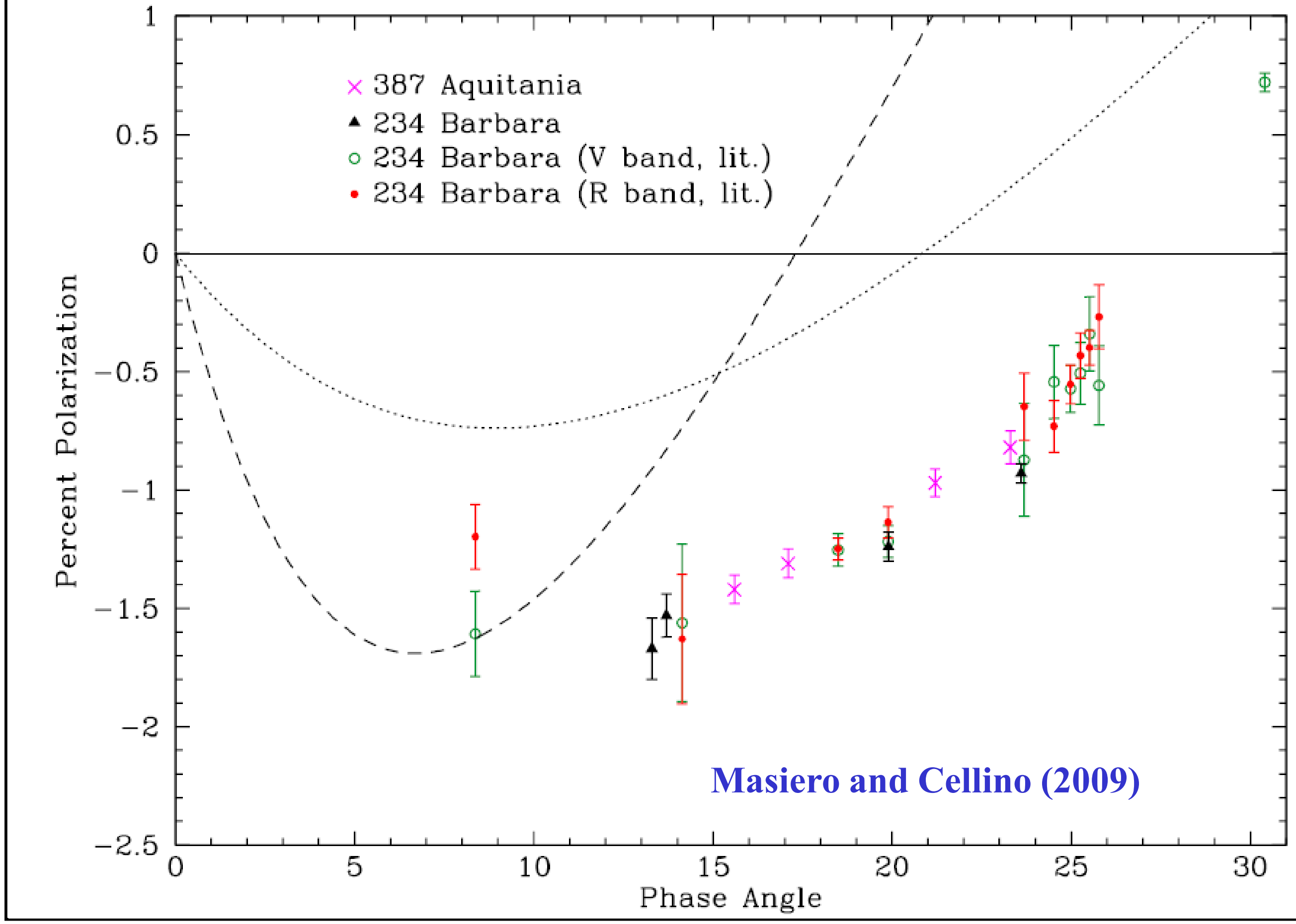
The preliminary results obtained so far, if confirmed, would imply that one single spectro-polarization measurement obtained at different wavelengths either at large phase angles (> 20°) or at a phase angle around 10° could be sufficient to distinguish between asteroids belonging to different albedo and taxonomic classes

Stay tuned! We have been awarded the first observing run of asteroid spectro-polarimetry at VLT in the next observing semester !



Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info
2 Pallas	09 45 00.0	-20 00 00	1.0	8.2		Low-albedo,B-class
4 Vesta	13 40 00.0	-01 45 00	1.0	7.5		High-albedo,V-class
7 Iris	21 00 00.0	-08 00 00	1.0	9.2		Intermediate albedo,S-class
8 Flora	20 00 00.0	-24 00 00	1.0	10.4		Intermediate albedo,S-class
21 Lutetia	12 30 00.0	01 10 00	1.0	11.5		Intermediate albedo,M-class(?)
24 Themis	12 00 00.0	01 00 00	1.0	11.5		Low-albedo,C-class
44 Nysa	00 20 00.0	-03 00 00	1.0	10.4		High-albedo,E-class
44 Nysa	00 20 00.0	-02 00 00	1.0	11.0		High-albedo,E-class
51 Nemausa	06 57 00.0	11 00 00	1.0	12.0		Low-albedo,CU-class
51 Nemausa	06 60 00.0	06 15 00	1.0	11.0		Low-albedo,CU-class
208 Lacrimosa	10 05 00.0	13 43 00	1.0	13.5		Intermediate albedo,S-class
HD147935	16 25 49.1	-27 49 09	0.5	9.2		solar analogue
HD210990	22 14 24.2	-16 36 34	0.5	9.5		solar analogue

Other very interesting targets for future observations: the "Barbarians"



Masiero and Cellino (2009)

Known objects:

234 (Ld - class),

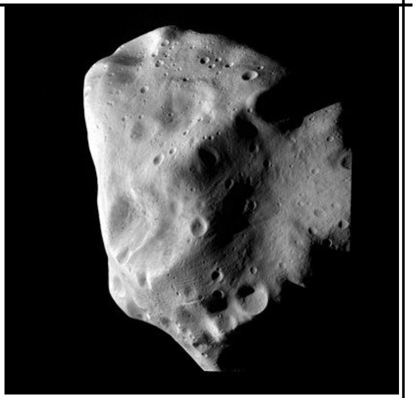
172, 236, 387, 980 (L – class)

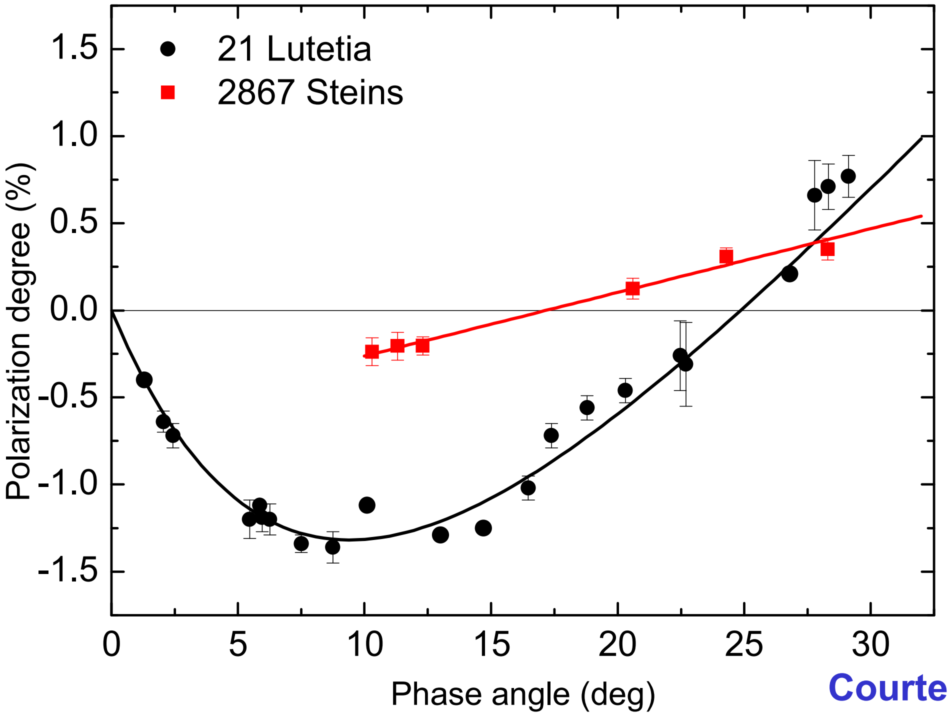
679 (K - class)

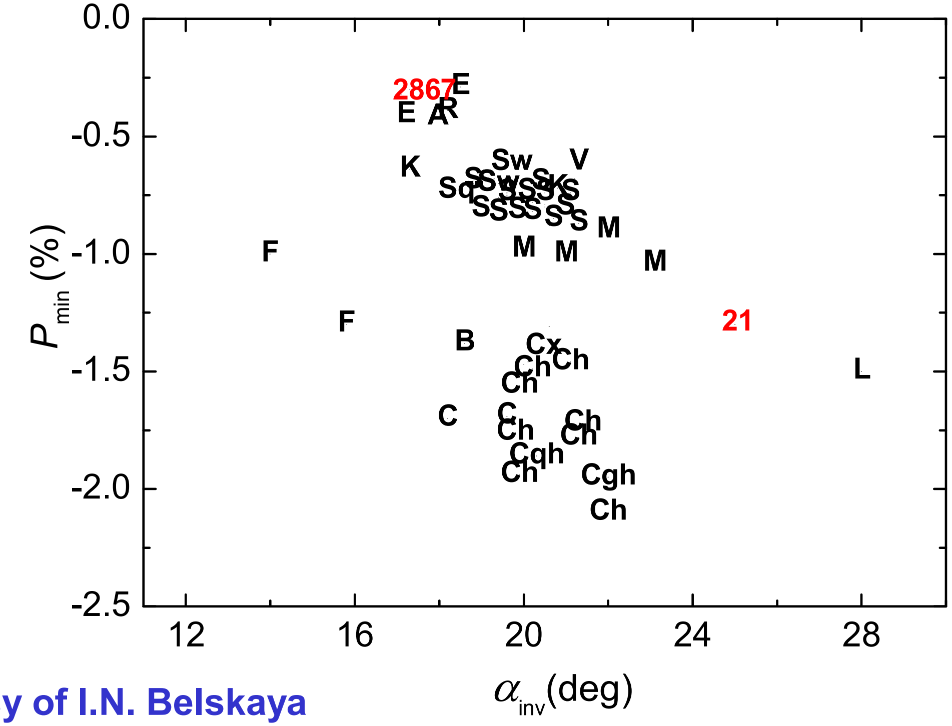
Wait for Paolo Tanga's talk for exciting news!

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

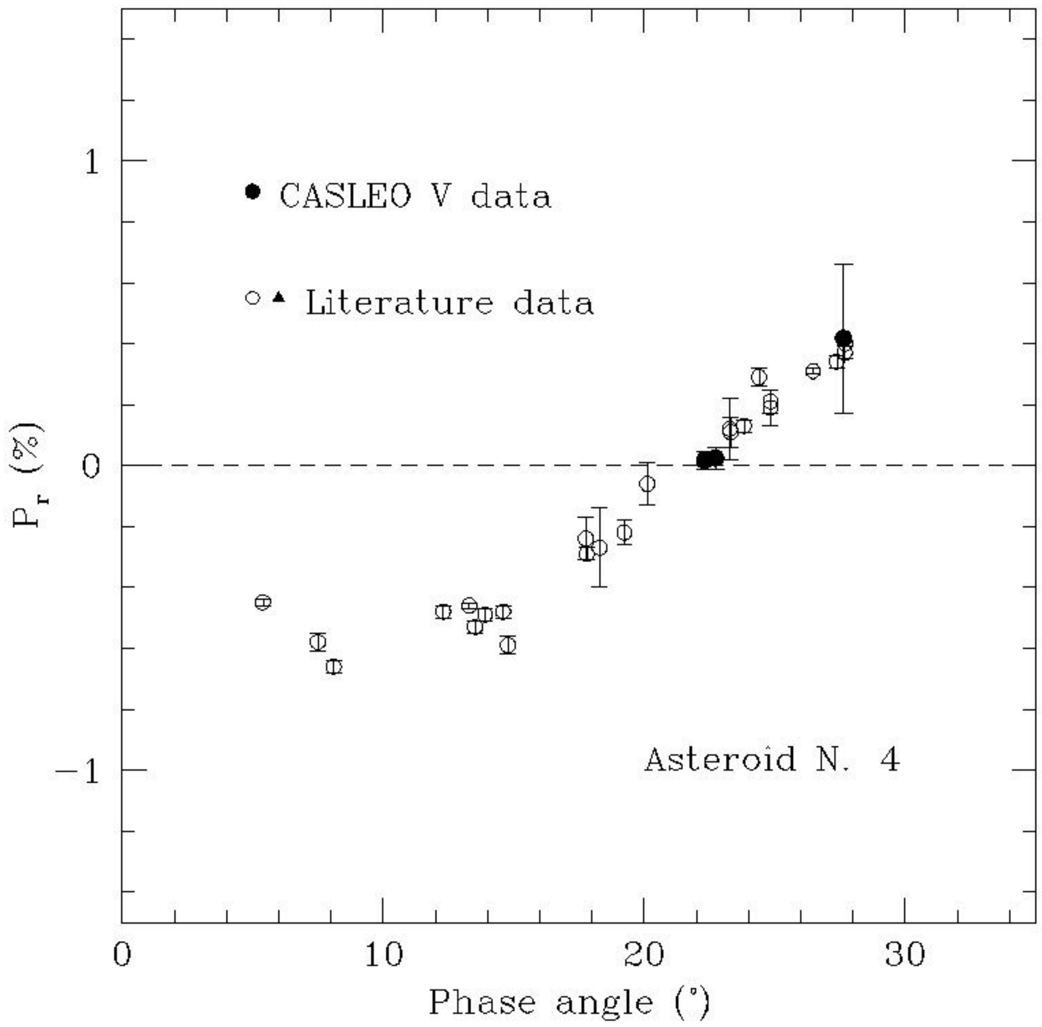
Asteroid polarimetry as a support to space missions: the examples of Steins and Lutetia



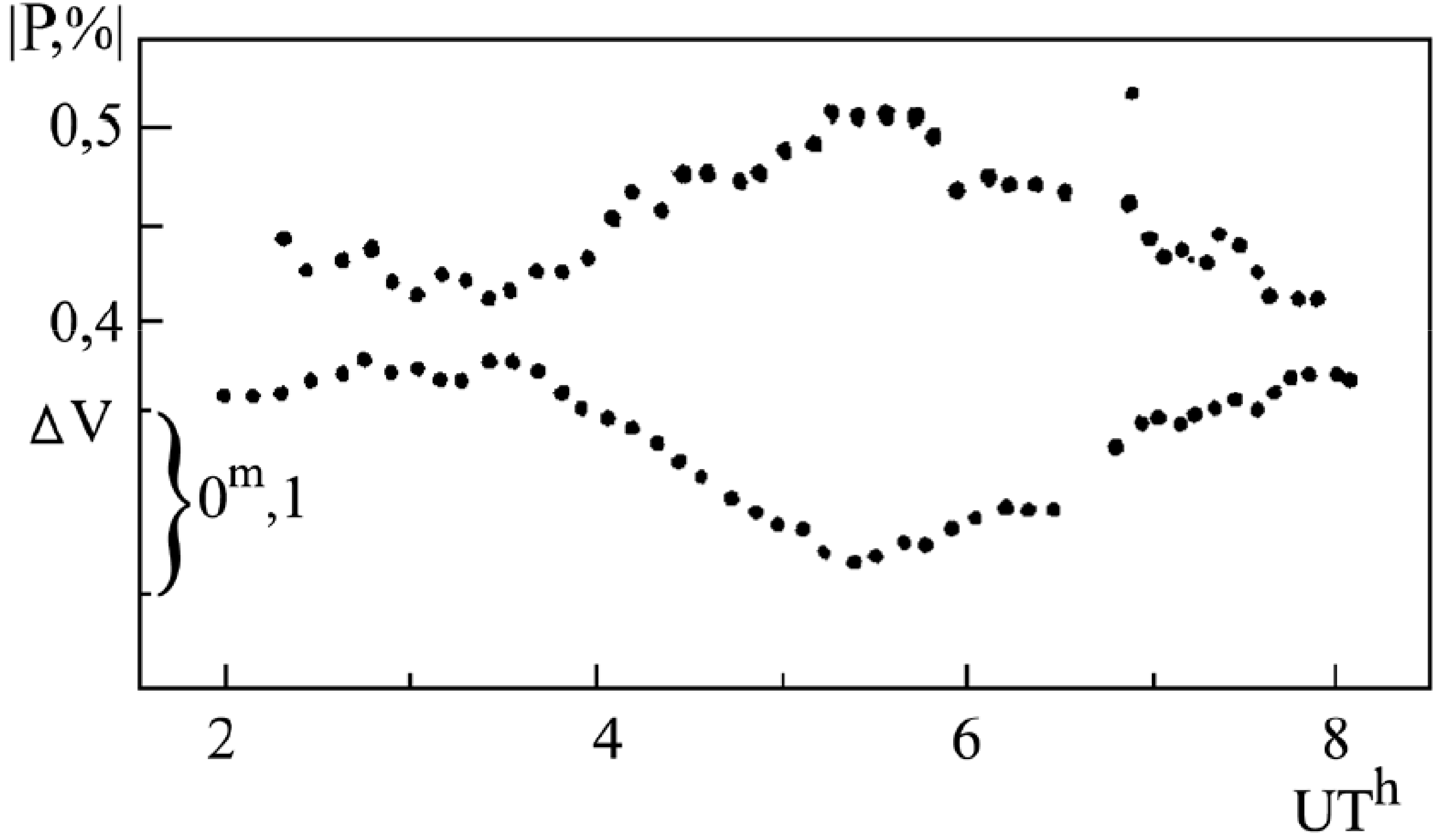




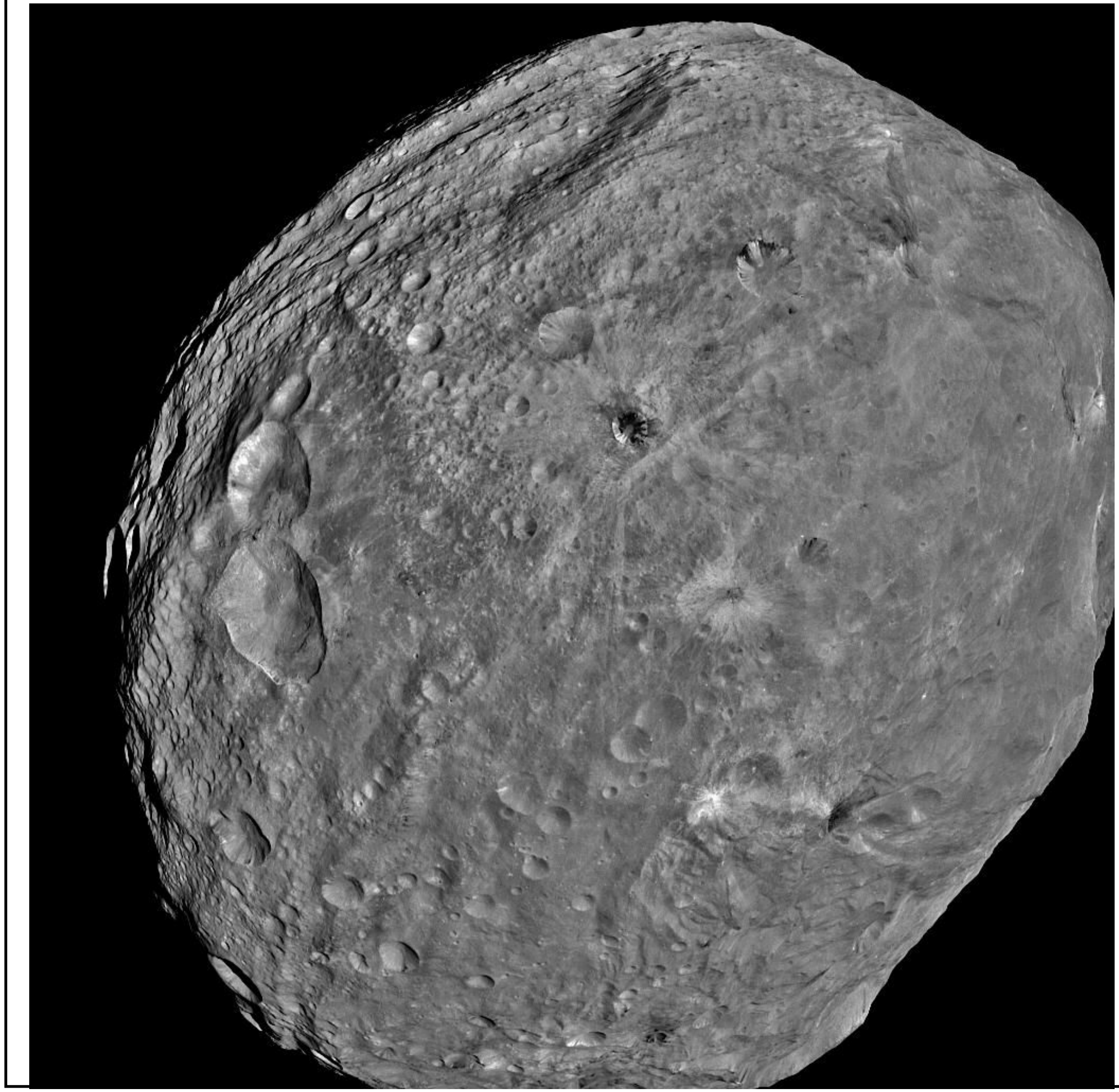
Courtesy of I.N. Belskaya



The importance of Vesta after the in situ exploration by DAWN



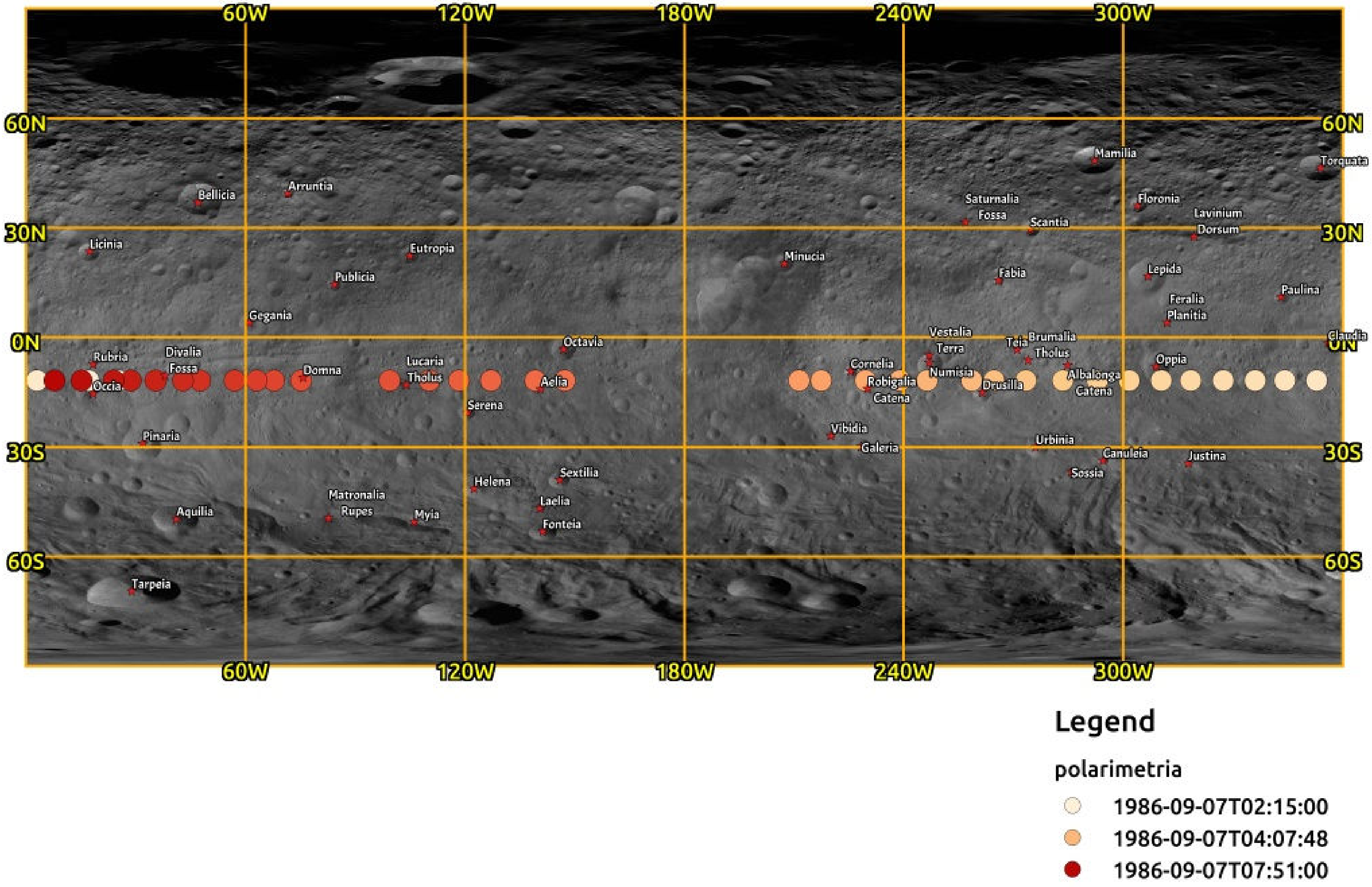
Vesta photometry and polarimetry, 1986



The next step:

Linking remote-sensing polarization measurements to local surface properties observed in situ, by computation of sub-Earth points at the epochs of ground-based observations.

Project funded by the Italian INAF.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120W
180W
240W
300W
60N
30N
0N
30S
60S
Mamilia
Torquata
Bellicia
Arruntia
Saturnalia Fossa
Floronia
Lavinium Dorsum
Scantia
Licinia
Eutropia
Minucia
Publicia
Fabia
Lepida
Paulina
Feralia Planitia
Gegania
Vestalia Terra
Teia
Brumalia Tholus
Claudia
Octavia
Rubria
Divalia Fossa
Lucaria Tholus
Domna
Cornelia
Numisia
Oppia
Occia
Aelia
Robigalia Catena
Drusilla
Albalonga Catena
Serena
Vibidia
Urbinia
Pinaria
Galeria
Canuleia
Justina
Sextilia
Helena
Sossia
Matronalia Rupes
Laelia
Aquilia
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Fonteia
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polarimetria
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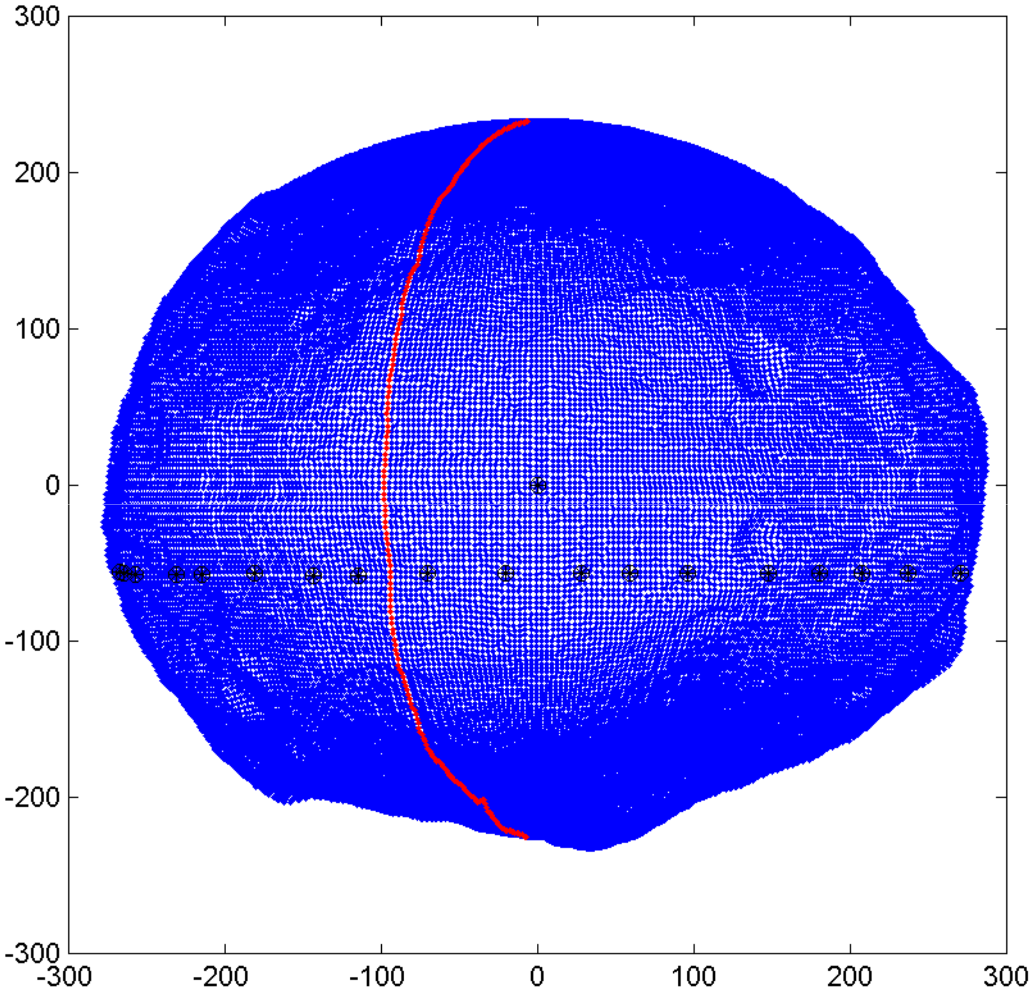
300
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-200
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300

Thank you