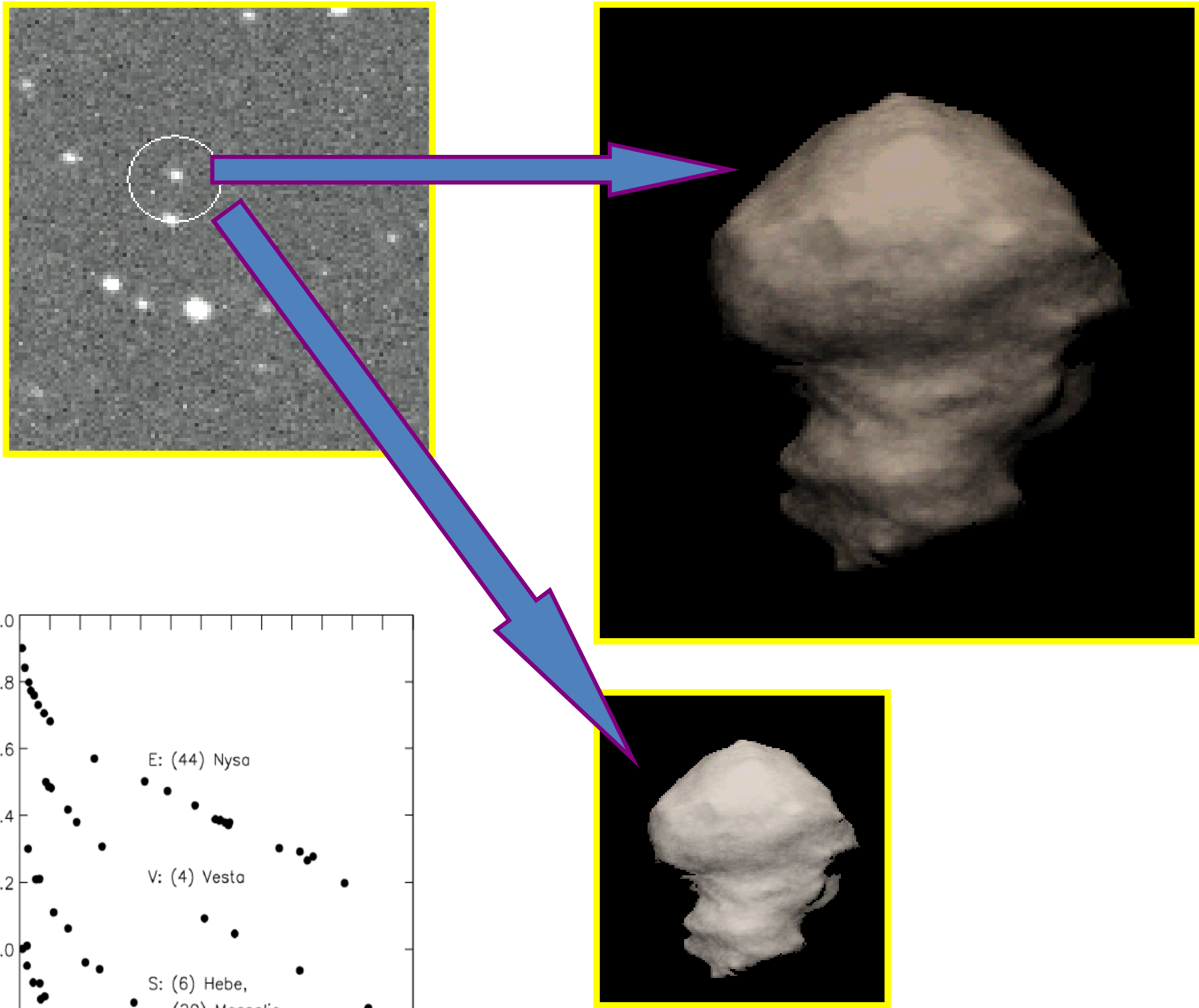
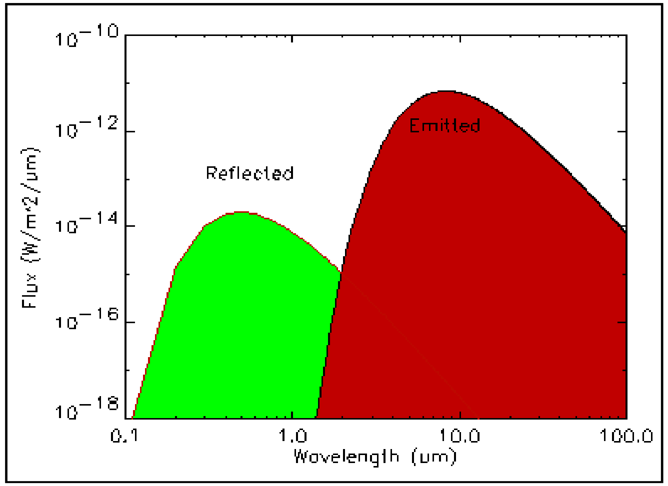
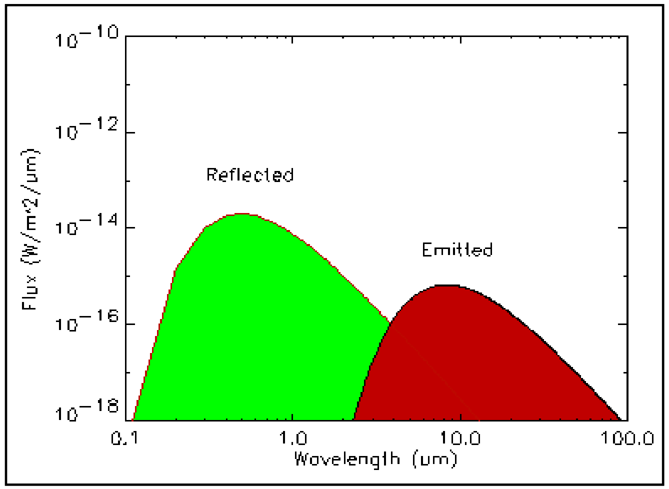
# Some fundamental problems in current asteroid science:

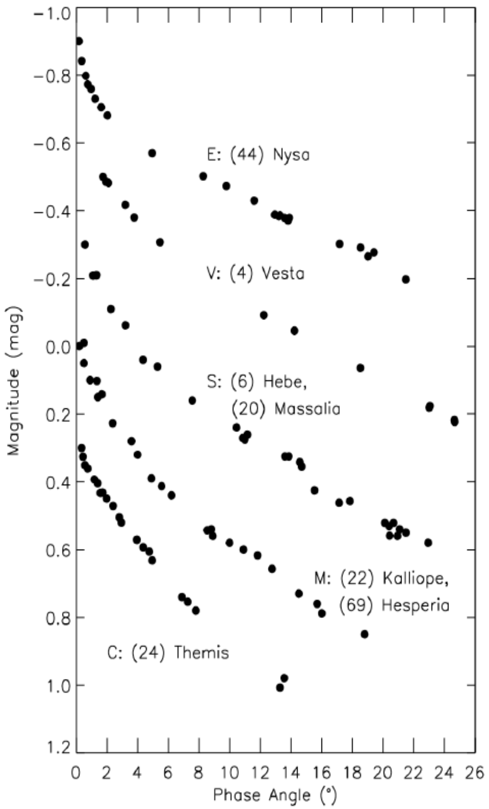
- The determination of asteroid masses and densities
- The measurement of asteroid sizes and shapes
- The determination of the relation between composition and taxonomic classification
- The physical characterization of potential Earth impactors

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



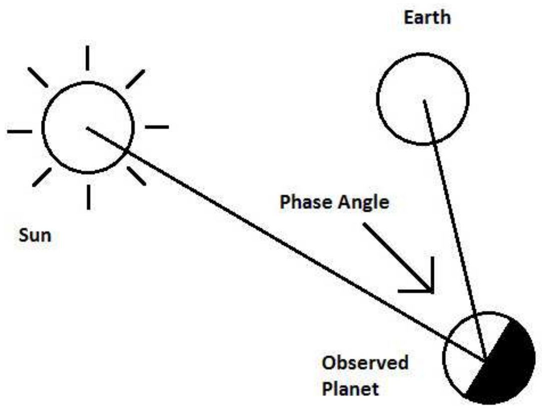


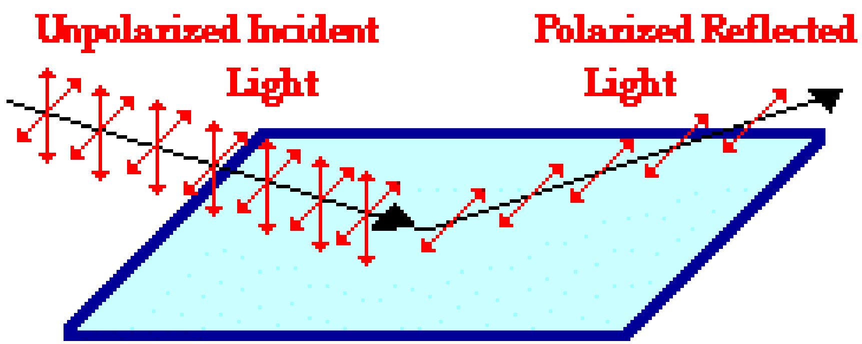



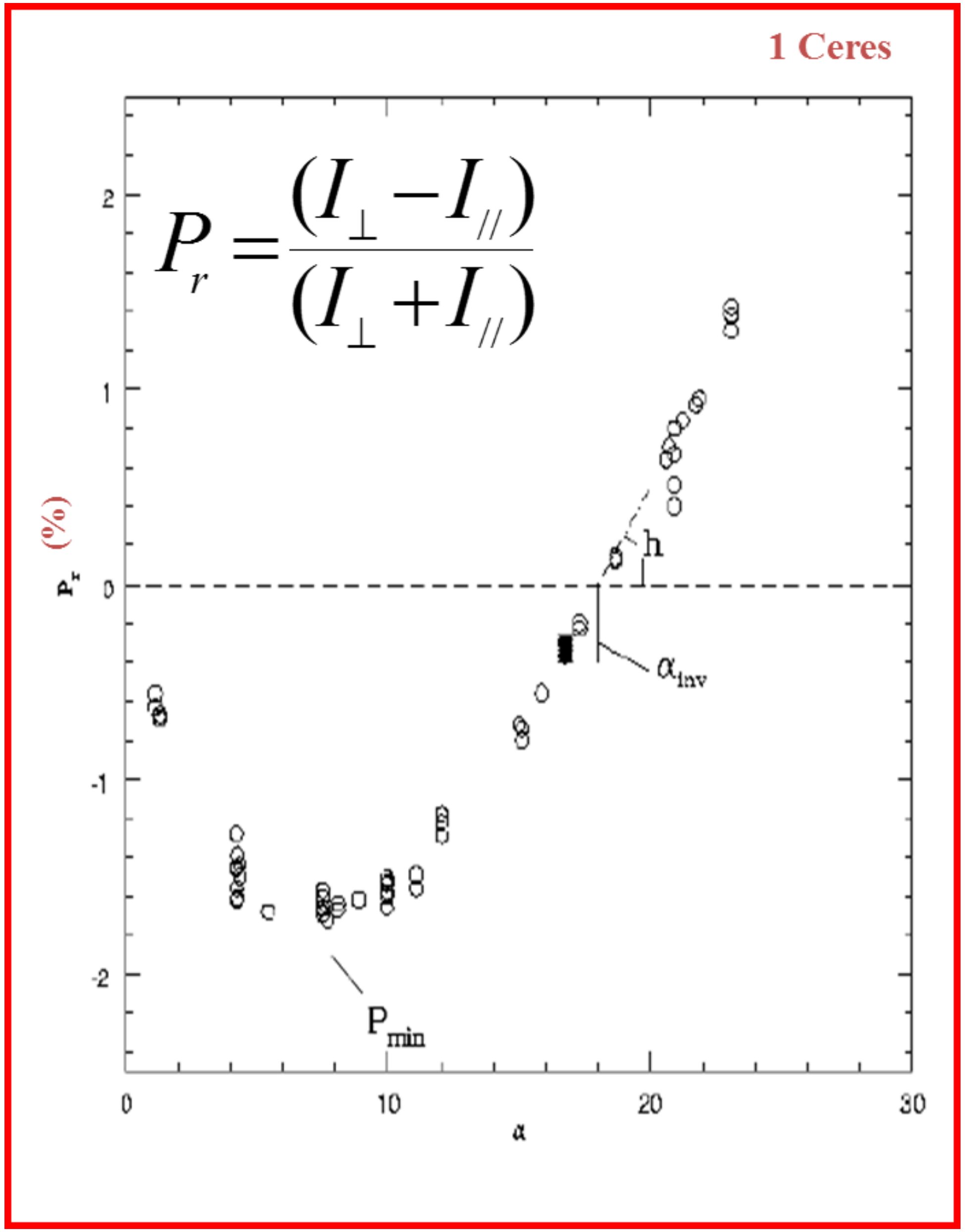




The Thermal Radiometry technique.
Good for sizes, less good for albedo.

# The derivation of the Albedo from polarimetric properties: the “slope - albedo law”.



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

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

**Different authors are using different values for the $C_1$ 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)

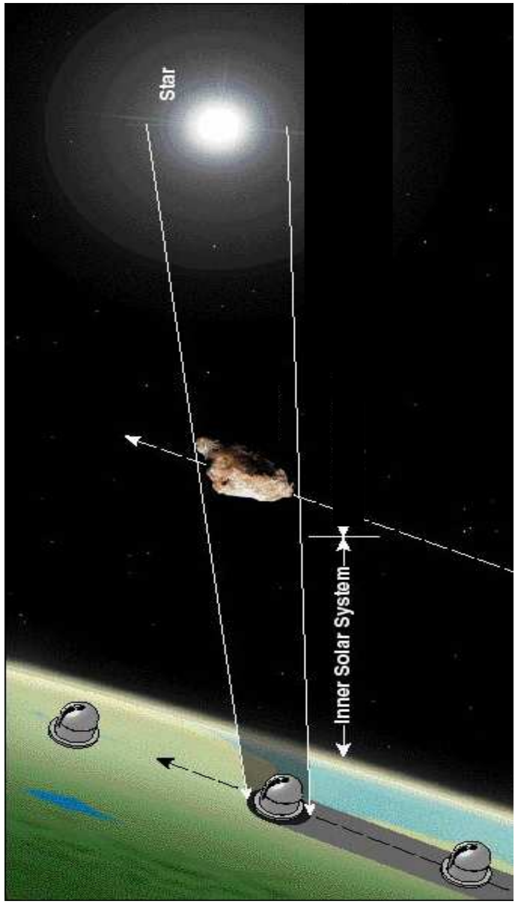
***Among them, only the latter two ones were derived using thermal IR data reduced using the (H,G) system, which takes into account the opposition brightness surge at zero phase.***

**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 albedos.** The best target list at present is the one by Shevchenko and Tedesco (2006), including objects whose albedos were derived from both occultation and *in situ* (four objects) size measurements, coupled with accurate estimates of absolute magnitudes (obtained using H,G).

## First objects of the Shevchenko & Tedesco (2006) list

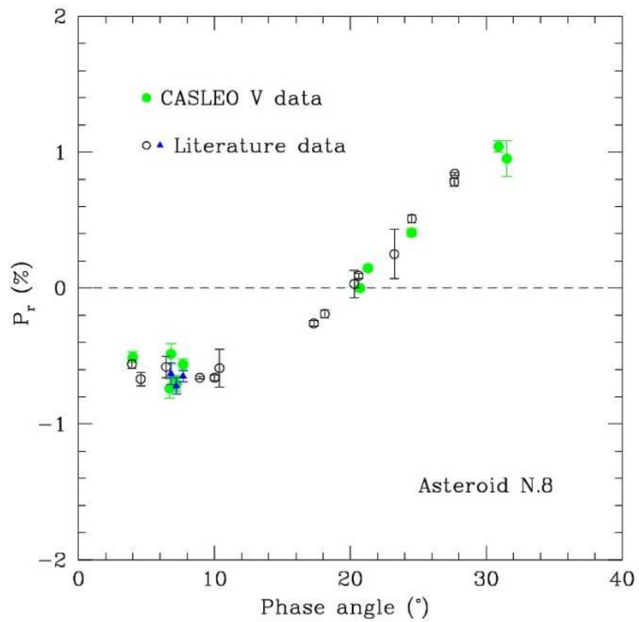
| Asteroids | Date | $\alpha$ | $\lambda_{2000}$ | $\beta_{2000}$ | Class | $D_{occ}$ | $D_{IRAS}$ | $p_{IRAS}$ | $p_{pol}$ | $H$ | $p_H$ | $V(1,4)$[a] | $p_{V(1,4)}$ | Qual[b] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 Ceres | 1984 Nov 13.19653 | 3.4 | 46.781 | −8.657 | G?,C | 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 |

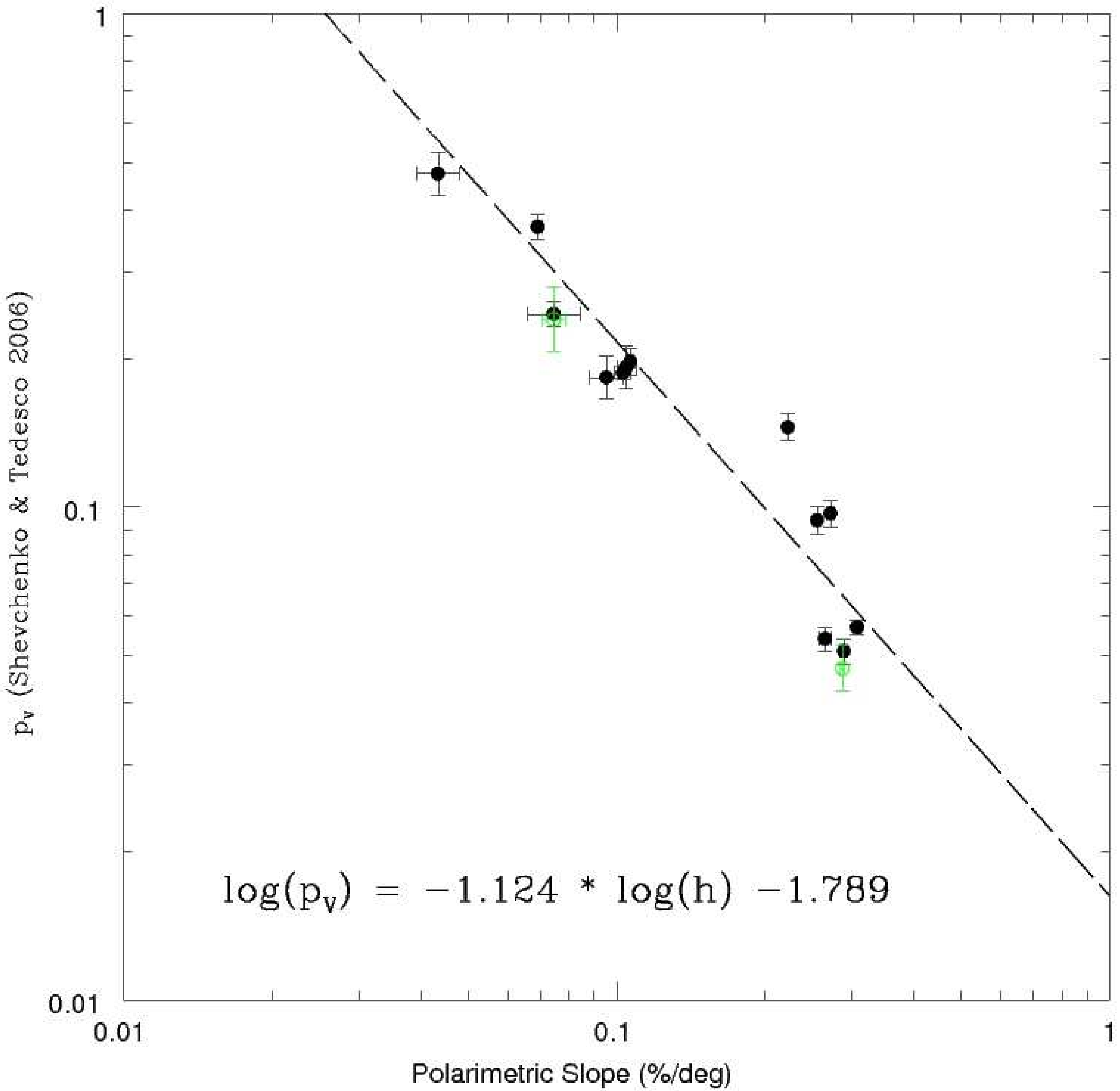



An updated list is going to be produced soon using a larger data-set

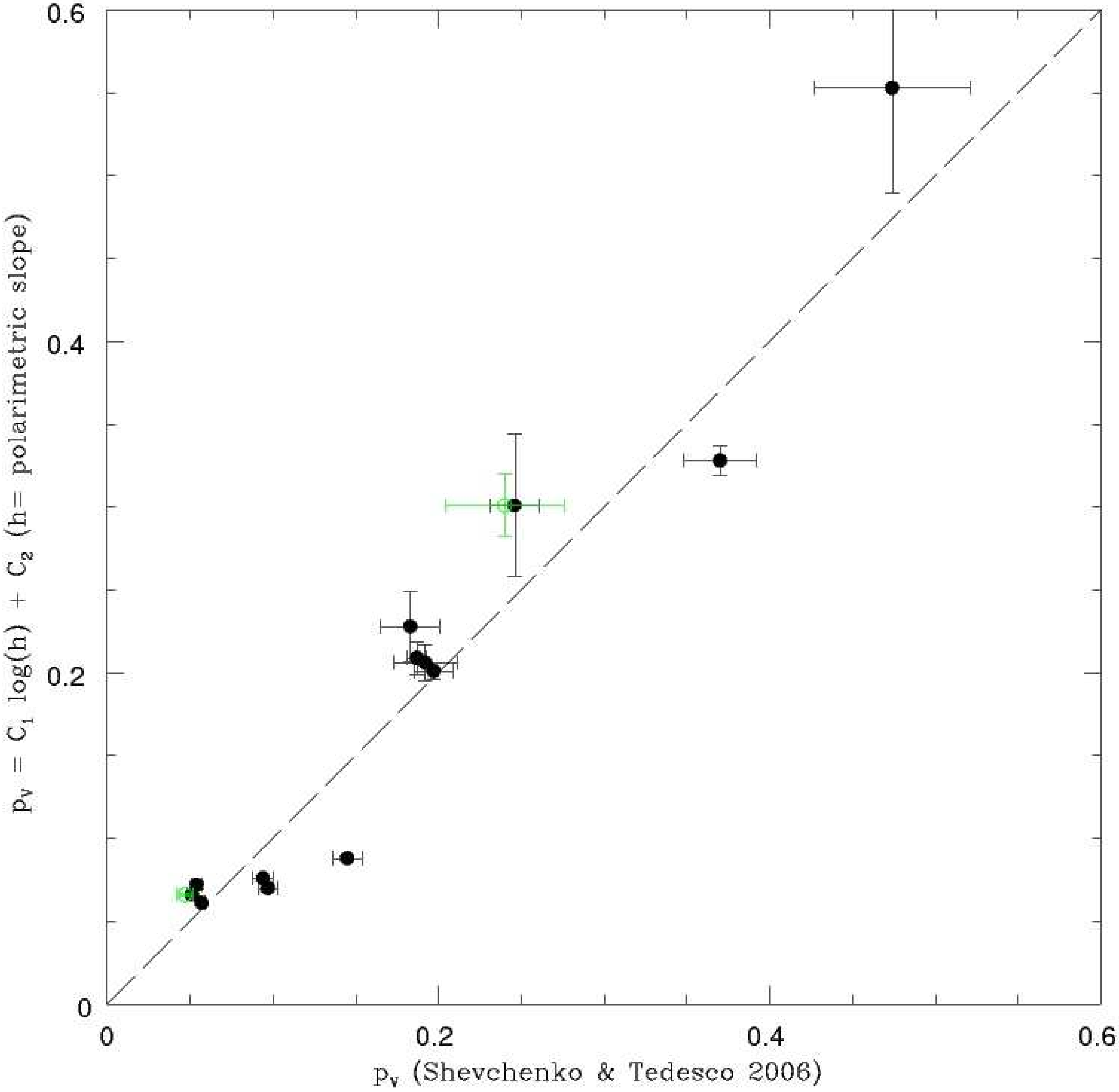
We have used all the polarimetric measurements available in the literature for asteroids belonging to the Shevchenko & Tedesco list, and a number of previously unpublished data obtained by us at the CASLEO observatory (Argentina)

- We limit our analysis to polarimetric measurements obtained in the standard *V* filter.
- we only use values of linear polarization *Pr* having nominal errors less than 0.2.
- We use only polarimetric measurements obtained at phase angles larger than or equal to 14 degrees of phase, a value generally well beyond the phase corresponding to *Pmin*, and in a region of the negative polarization branch where *Pr* starts to increase linearly with phase.
- We require to have at least 5 available measurements, and that the interval of phase angles covered by the data is not less than 3 degrees.





1
0.1
0.01
0.01
0.1
1
$p_V$ (Shevchenko & Tedesco 2006)
Polarimetric Slope (%/deg)
$\log(p_V) = -1.124 * \log(h) - 1.789$

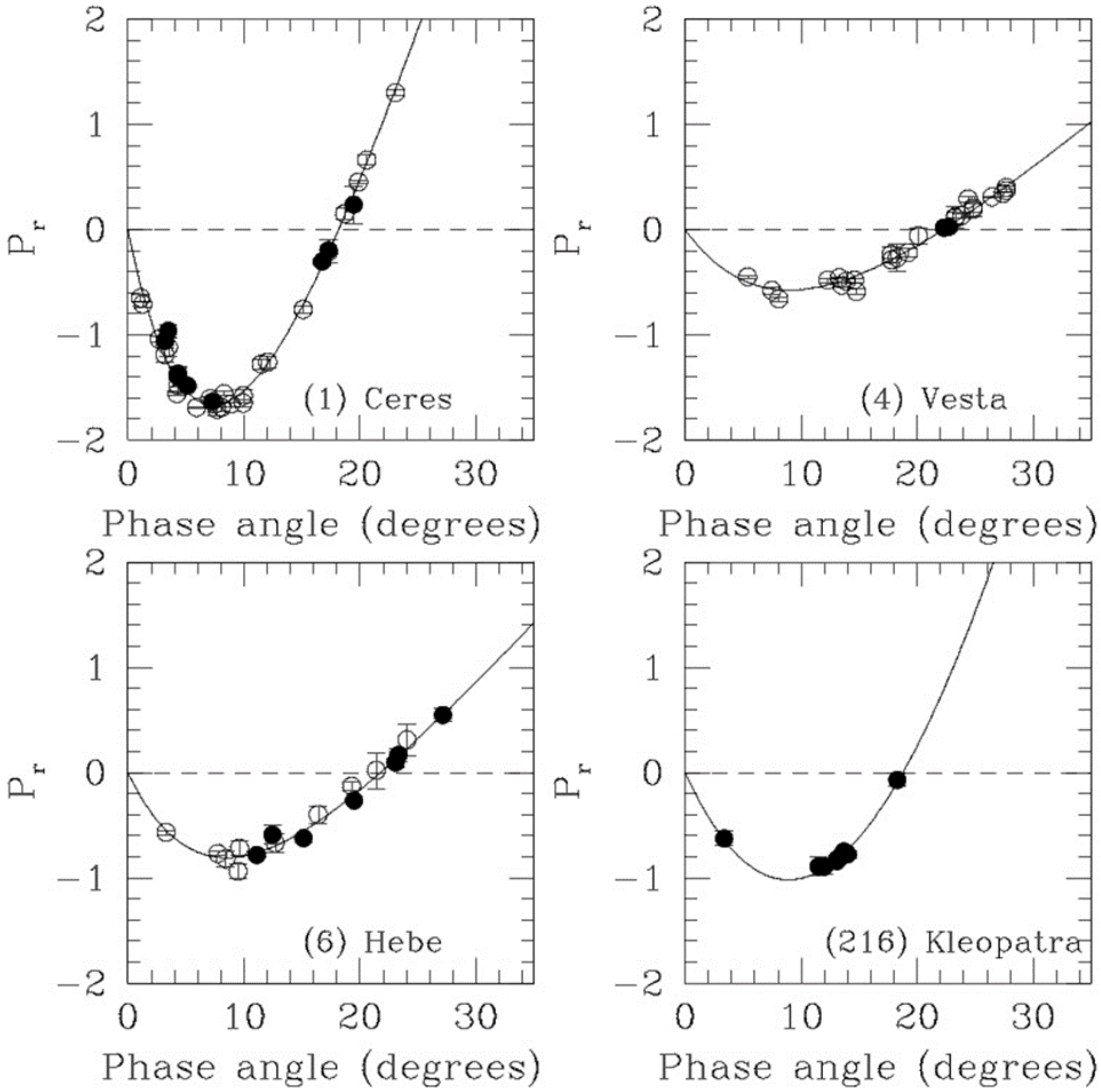


0.6
0.4
0.2
0
0
0.2
0.4
0.6
p_v = C_1 log(h) + C_2 (h= polarimetric slope)
p_v (Shevchenko & Tedesco 2006)

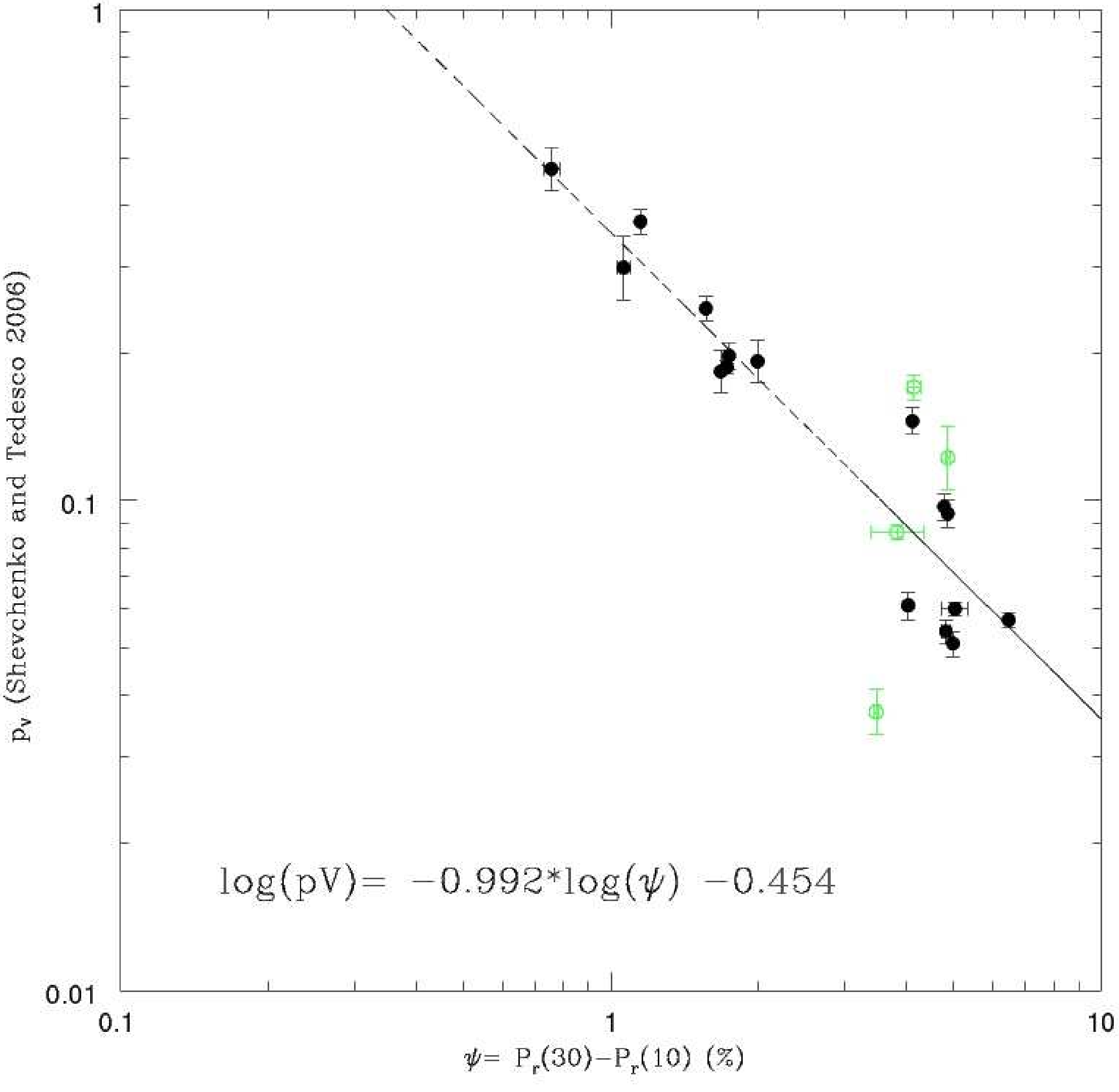
**The phase – polarization curves of asteroids can be adequately fit by a exponential – linear relation:**

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

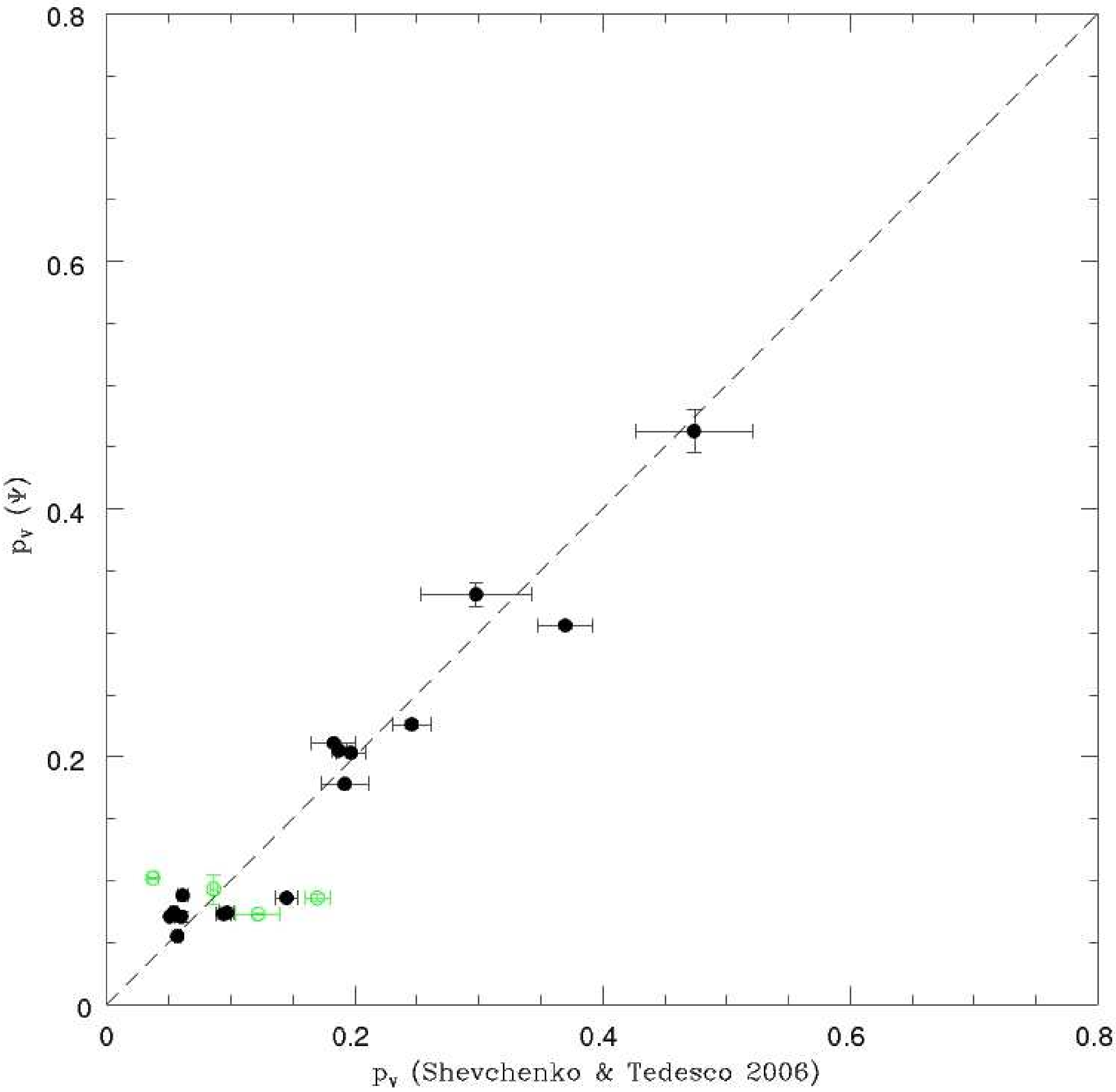
**Where α is the phase angle and *a, b, c* are three parameters to be determined by best-fit procedures**




**This allows us to better determine "old" parameters like $P_{min}$ and h, and also to build new polarimetric parameters**

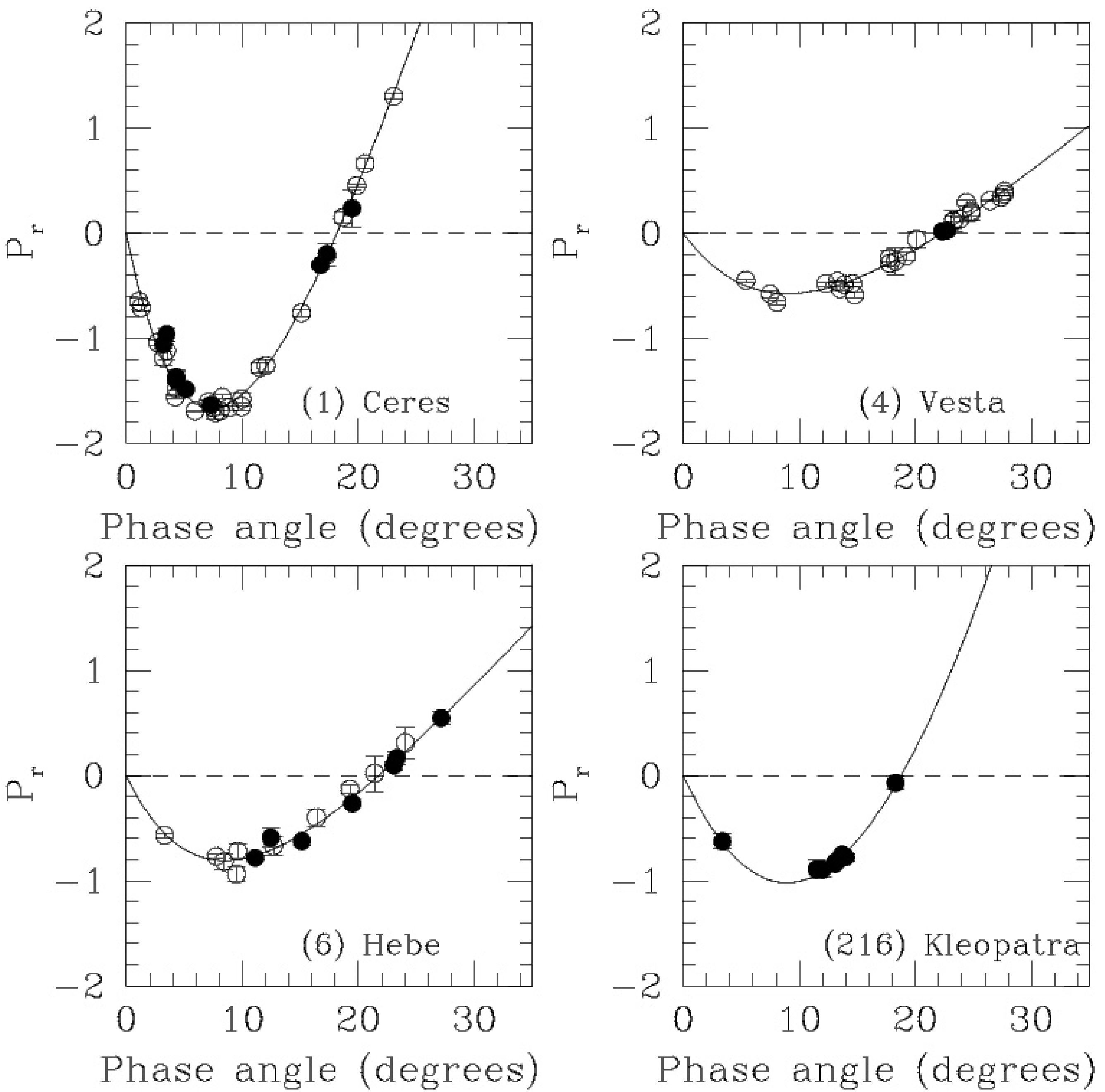


1
0.1
0.01
0.1
1
10
$p_V$ (Shevchenko and Tedesco 2006)
$\psi$= $P_r(30)-P_r(10)$ (%)
log(pV)= −0.992*log($\psi$) −0.454



0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
$p_V$ ($\Psi$)
$p_V$ (Shevchenko & Tedesco 2006)

# This is what "normal" asteroids do...

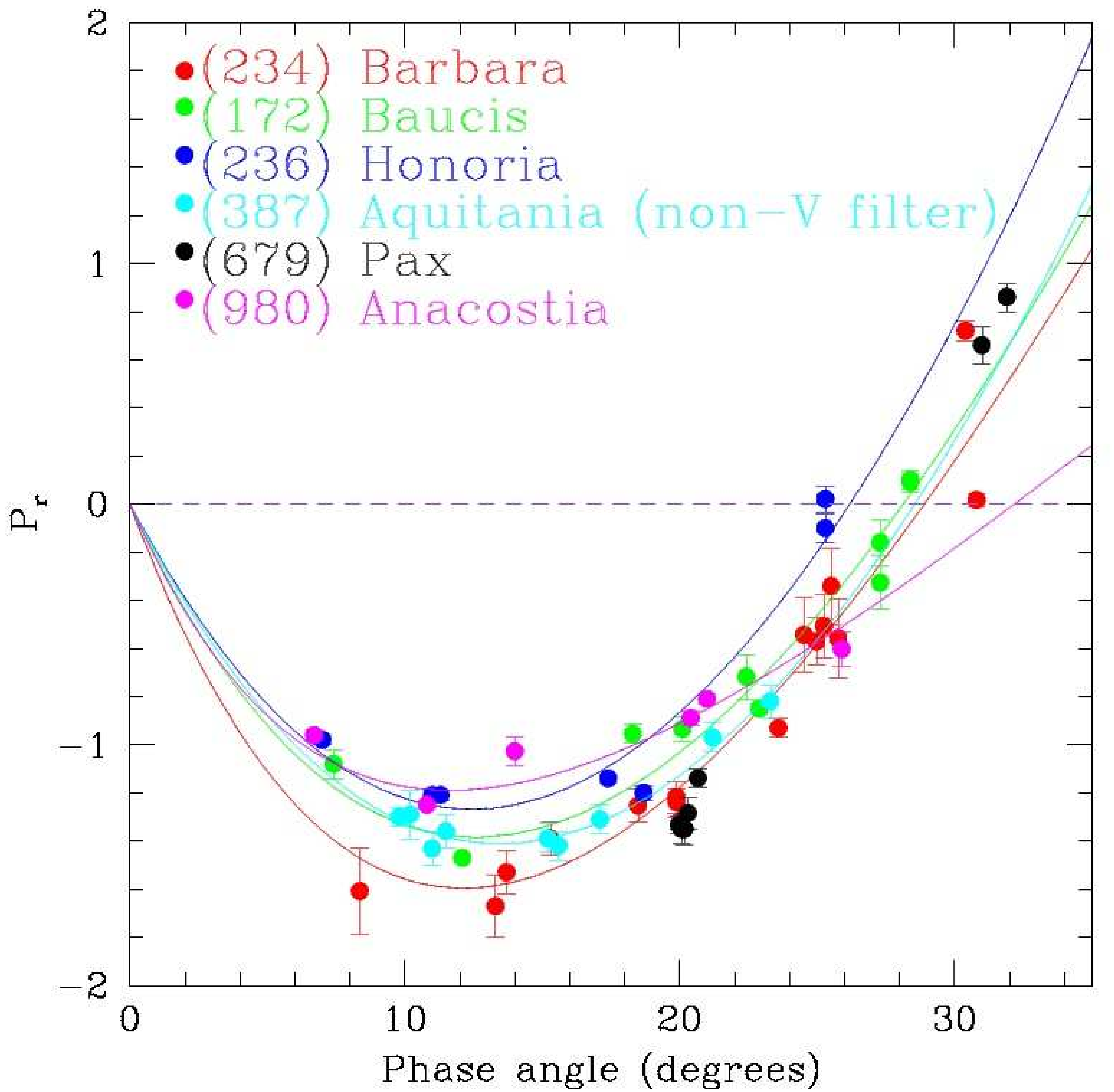


... And these are Barbarians, so-called after the prototype, (234) Barbara (Cellino et al., 2006).

Strong negative polarization around 20° of phase.

Very high values of the inversion angle!

Only six objects mentioned in the literature until a few months ago.



# Sunshine et al., 2008, Science, 320, 514

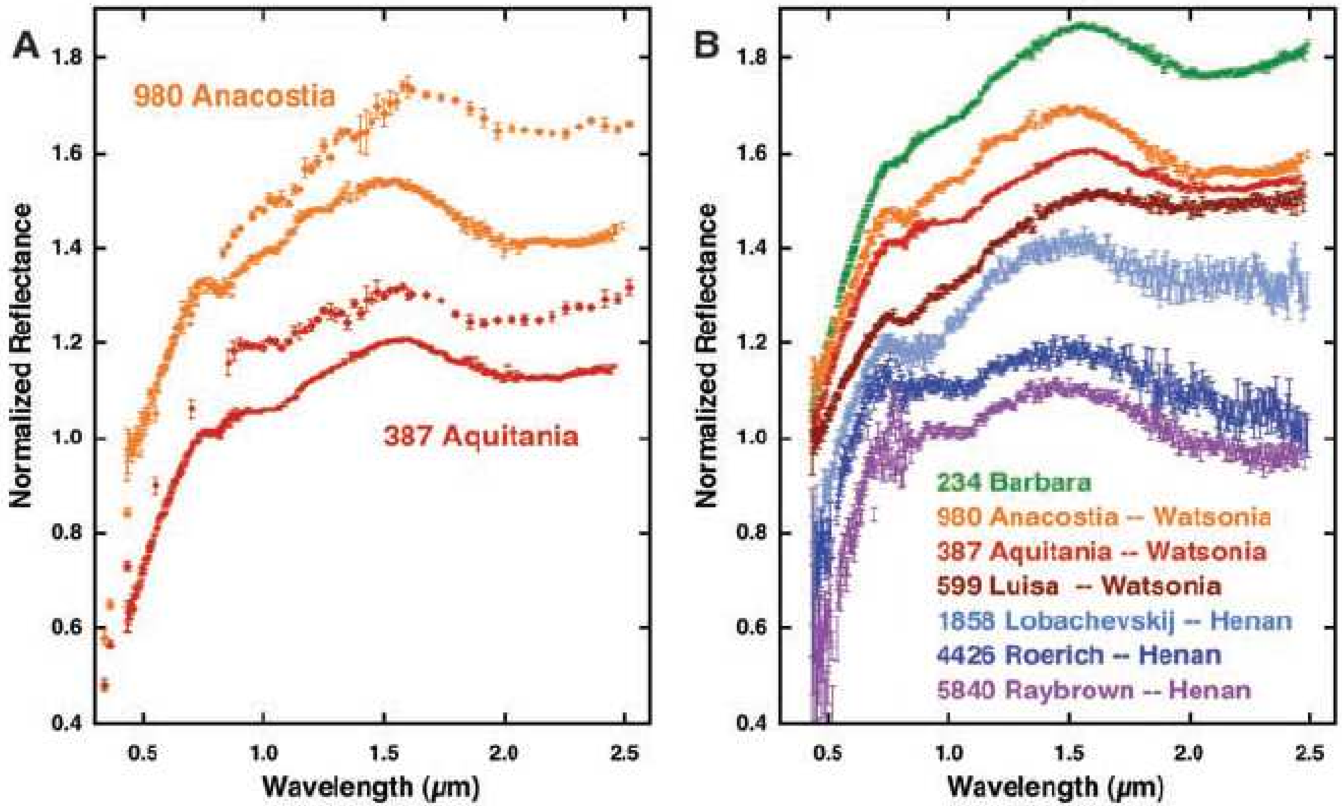



**Fig. 3.** (**A**) Visible near-infrared spectra of asteroids 387 Aquitania (red) and 980 Anacostia (orange) from Burbine *et al.* (*3*) compared with the current higher–spectral resolution Small Main-Belt Asteroid Spectroscopic Survey (SMASSII) (visible) (*11*, *12*) and SpeX (near-infrared) (*13*) data. (**B**) Combined SMASSII and SpeX data for the asteroid 234 Barbara (green) and representative asteroids from the Watsonia and Henan families (table S1). All spectra are dominated by strong 2-μm absorptions. The observing conditions for these data and other members of the Watsonia and Henan families are given in table S1.

**Spinel: [Fe,Mg]$Al_2O_4$ abundant in Calcium-Aluminum rich Inclusions (CAI)**

**To model the available near-IR spectra of spinel-rich asteroids, it is necessary to assume abundances of the order of up to 30% of CAI material on the surface.**

**This extreme abundance, which causes a high refractive index, might also be responsible for the anomalous polarization properties. Such high CAI abundances have never been found in meteorite on Earth (so far, the richest CAI abundance, found on CV3 meteorites, is about 10 per cent).**

**Therefore, Sunshine et al. (2008) conclude that spinel – rich asteroids "might be more ancient than any known sample in our meteorite collection, making them prime candidates for sample return' missions".**

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# Families among high-inclination asteroids

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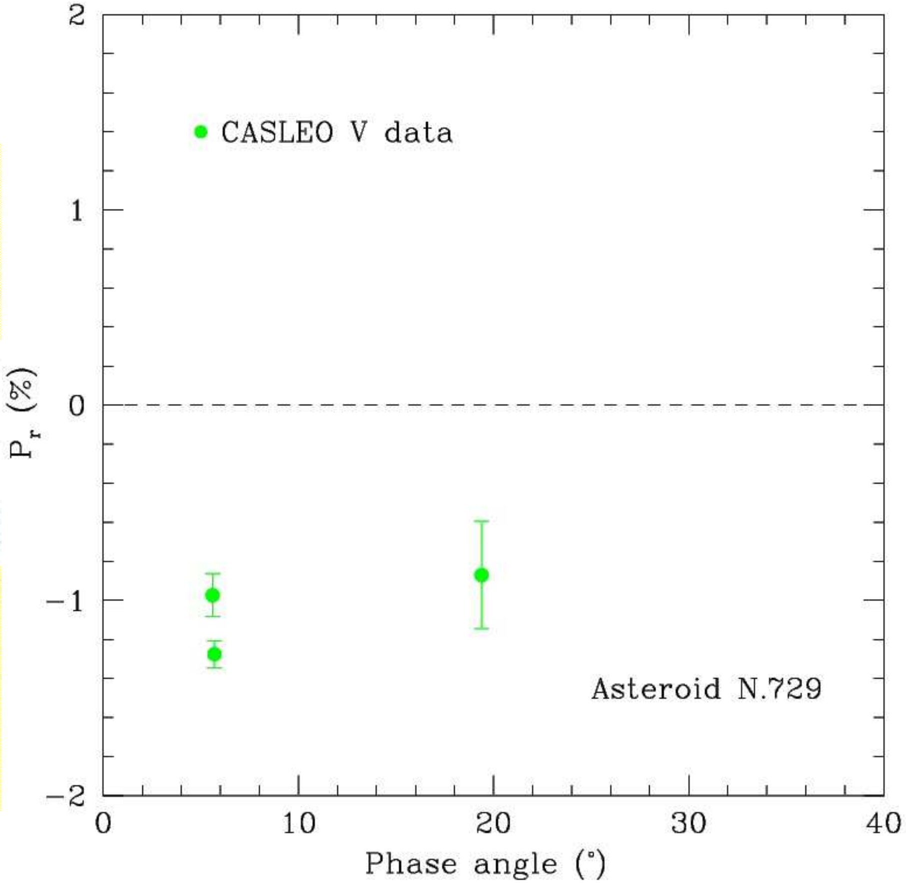
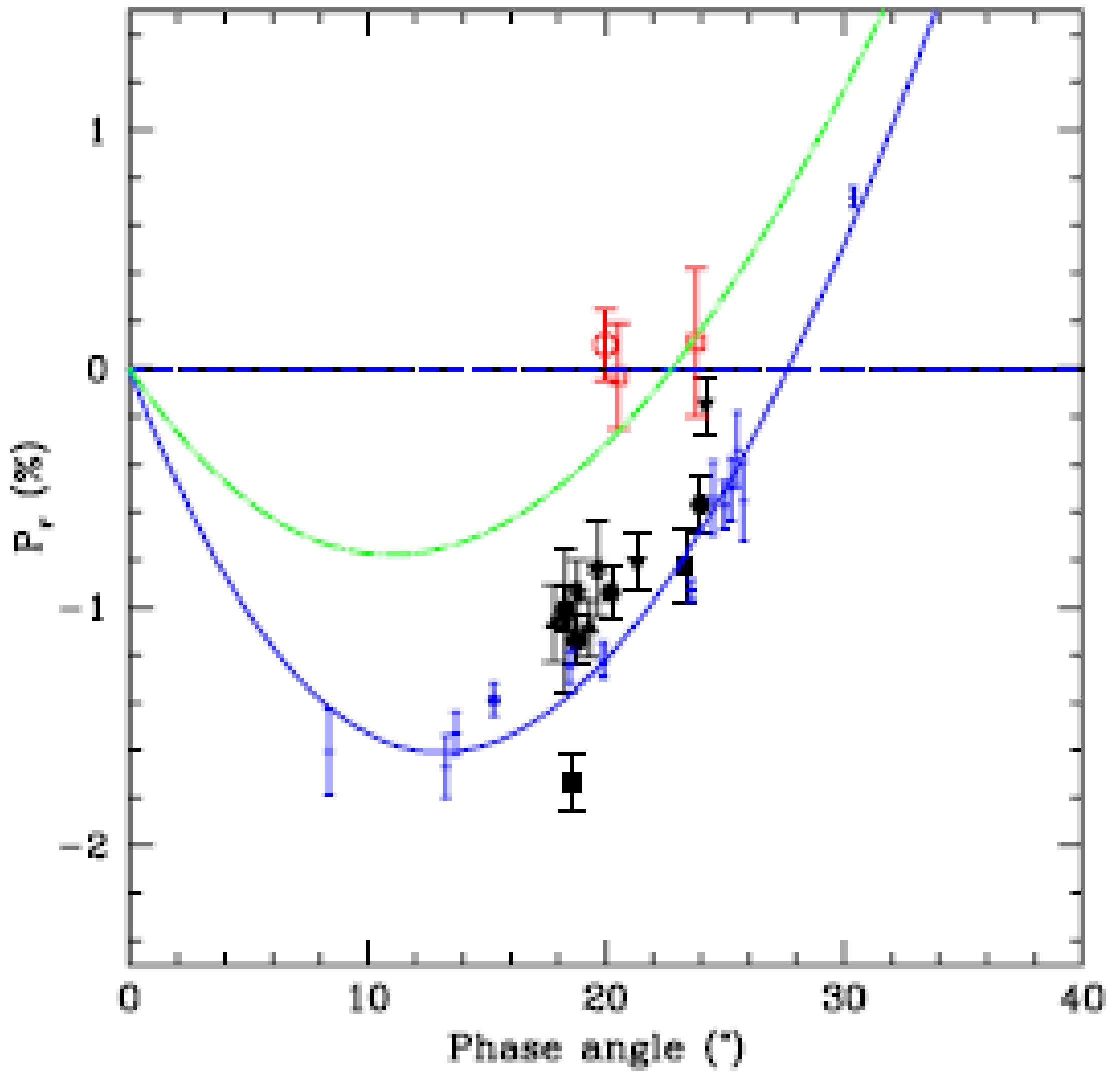
We also confirm the existence of a Watsonia family, mentioned by Cellino et al. (2002) on the basis of spectroscopic properties pointed out by Burbine et al. (1992) and Bus (1999). According to still unpublished observations (Cellino, 2011, in preparation) (729) Watsonia belongs to a rare group of objects, called *Barbarians* after their prototype, the Asteroid (234) Barbara, which exhibit unusual polarimetric properties (Cellino et al., 2006; Masiero and Cellino, 2009). Very interestingly, we found in this region another family, whose lowest-numbered member is (980) Anacostia, which is also a Barbarian (Gil-Hutton et al., 2008). The Watsonia and Anacostia families merge together well above the QRL.



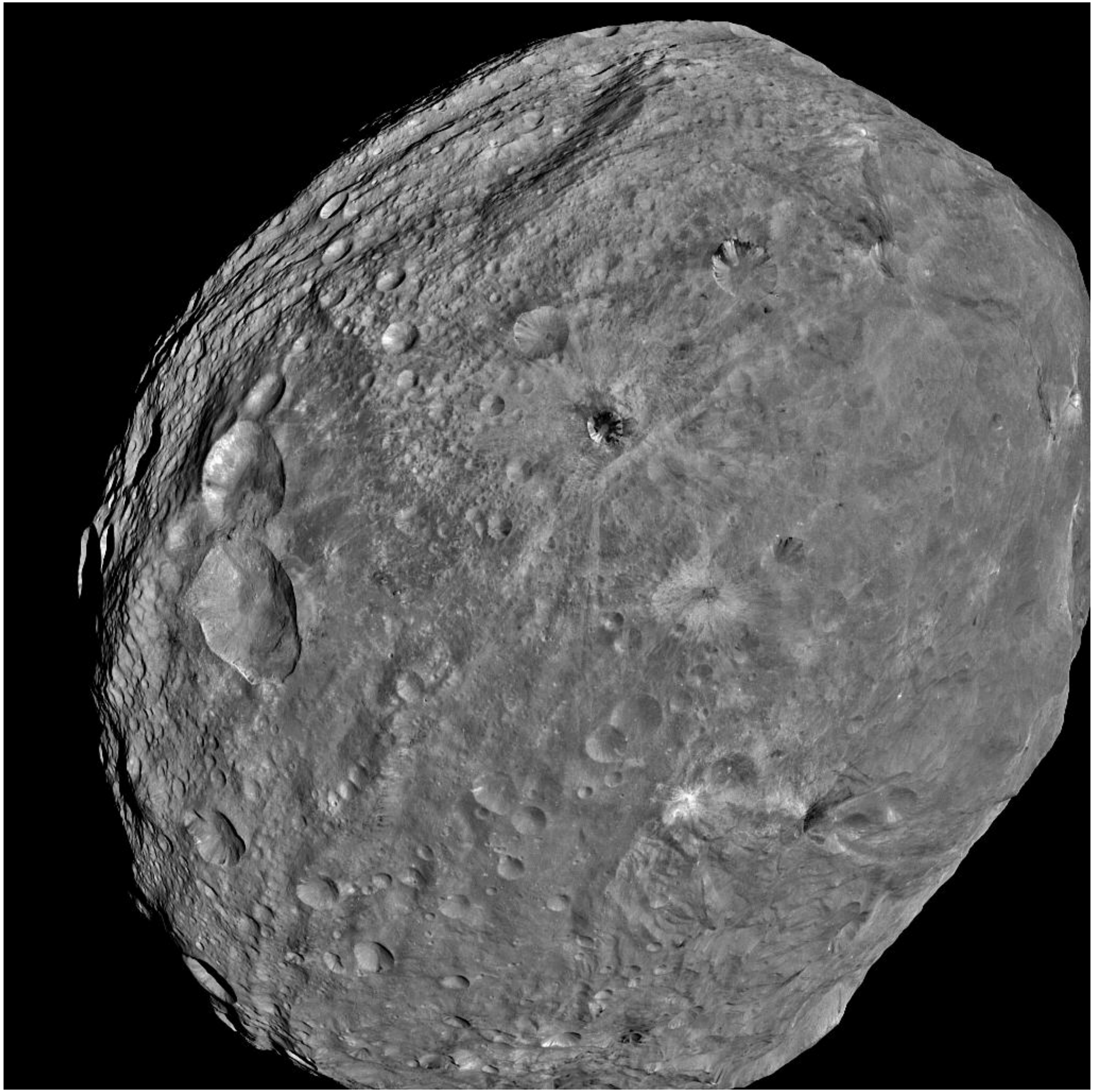



# 7 out of 9 observed Watsonia members are Barbarians !

**Phase-polarization data (in R light) for the targets of our investigation, compared with the polarization curves (in V light) of the (234) Barbara, and of (12) Victoria, a large L-class asteroid which does not exhibit the Barbarian behaviour. Black symbols: the seven targets exhibiting the Barbarian polarimetric behaviour; red symbols: our two targets that display a 'normal' polarimetric behaviour; small blue symbols and blue curve: available data for (234) Barbara (Masiero & Cellino 2009), and the corresponding best-fitting curve using the linear exponential relation Pr = A[eα/B − 1] + C · α, where α is the phase angle in degrees; dashed green curve: the best-fitting curve for the L-class asteroid (12) Victoria (for the sake of clearness, individual observations of this asteroid are not shown).**

# Current list of known Barbarians

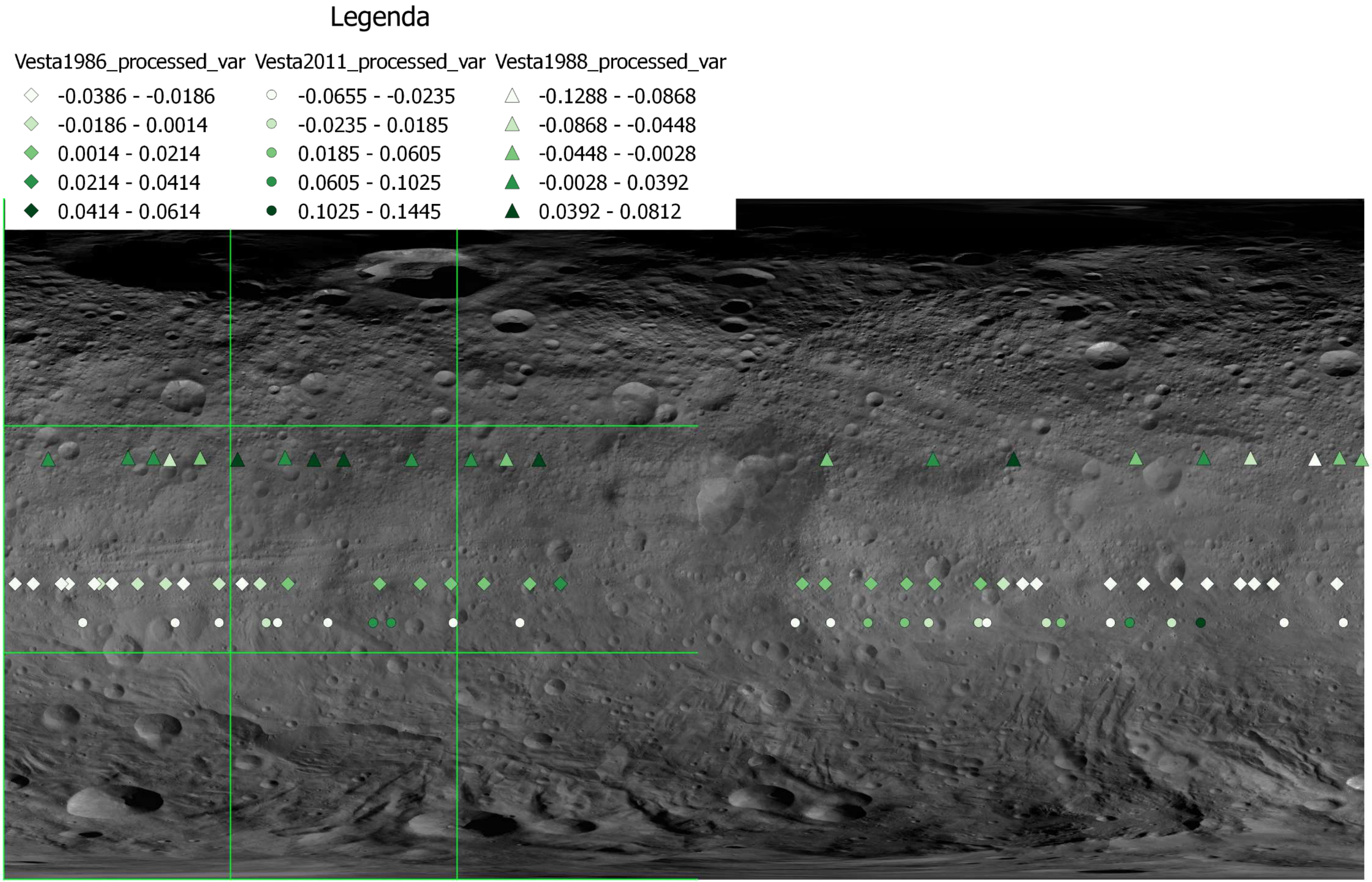
| Id | Taxonomic classification Bus & Binzel (2002)/DeMeo et al. (2009) |
|---|---|
| (234) Barbara | Ld / L |
| (172) Baucis | L / - |
| (236) Honoria | L / L |
| (387) Aquitania | L / L |
| (402) Chloe | K / L |
| (599) Luisa | K / L |
| (679) Pax | K / L |
| (729) Watsonia | L / L |
| (980) Anacostia | L / - |
| (5492) Thoma (*Watsonia family member*) | L / - |
| (42365), (56233), (106059), (106061), (144854), (236408) (*Watsonia family members*) | Unknown |

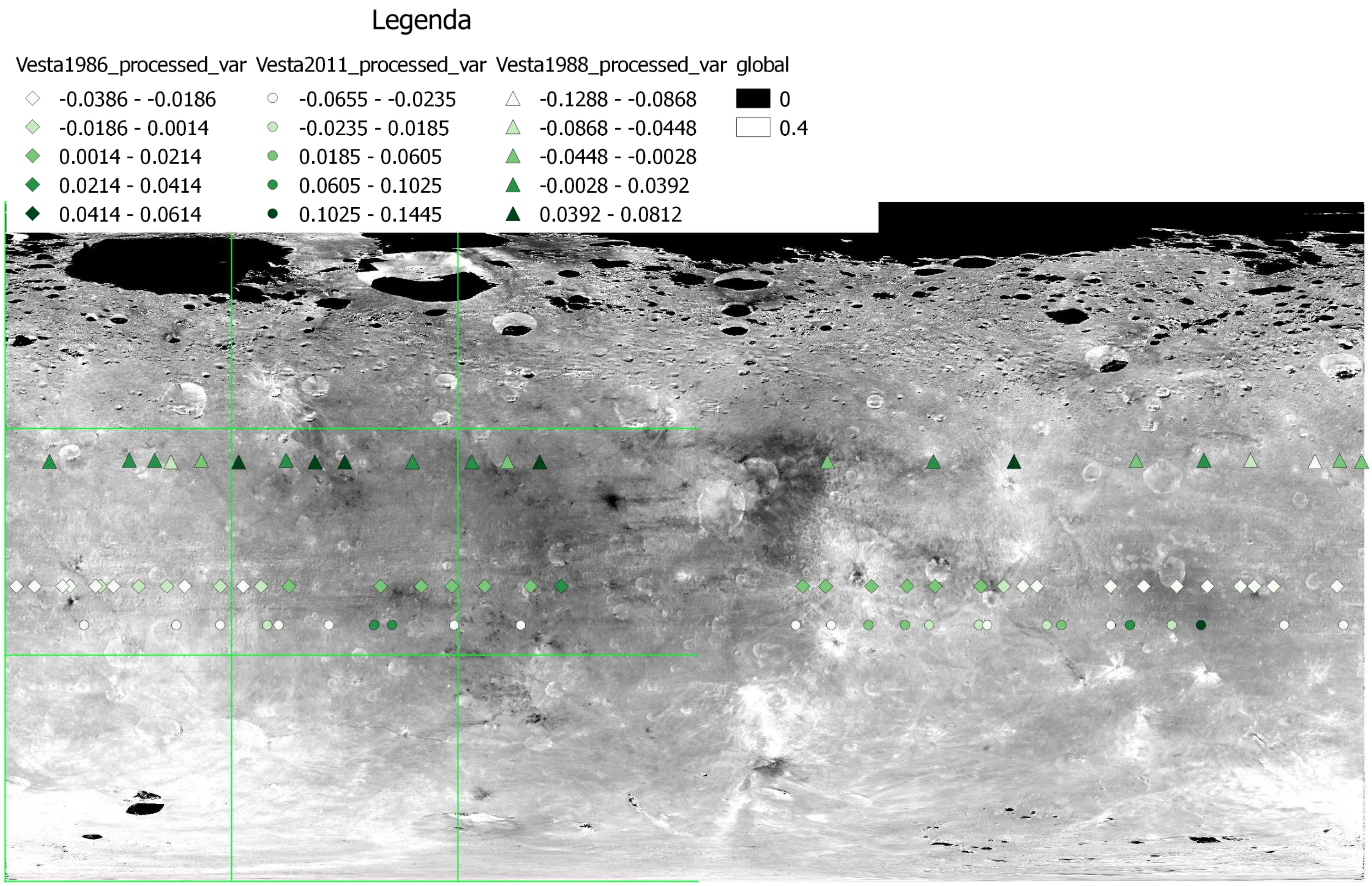


# The next step:

**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.**

The case of (4) Vesta


Legenda
Vesta1986_processed_var
-0.0386 - -0.0186
-0.0186 - 0.0014
0.0014 - 0.0214
0.0214 - 0.0414
0.0414 - 0.0614
Vesta2011_processed_var
-0.0655 - -0.0235
-0.0235 - 0.0185
0.0185 - 0.0605
0.0605 - 0.1025
0.1025 - 0.1445
Vesta1988_processed_var
-0.1288 - -0.0868
-0.0868 - -0.0448
-0.0448 - -0.0028
-0.0028 - 0.0392
0.0392 - 0.0812



Legenda
Vesta1986_processed_var
-0.0386 - -0.0186
-0.0186 - 0.0014
0.0014 - 0.0214
0.0214 - 0.0414
0.0414 - 0.0614
Vesta2011_processed_var
-0.0655 - -0.0235
-0.0235 - 0.0185
0.0185 - 0.0605
0.0605 - 0.1025
0.1025 - 0.1445
Vesta1988_processed_var
-0.1288 - -0.0868
-0.0868 - -0.0448
-0.0448 - -0.0028
-0.0028 - 0.0392
0.0392 - 0.0812
global
0
0.4

# Summary and Questions (1)

- We have now new coefficients for the classical slope-
  - albedo slope.  New, useful polarimetric parameters, can
  also be used  to derive reliable albedo estimates.
- We will produce soon an updated list of calibration
  asteroids, using currently available sizes coming from
  occultation observations, and absolute magnitudes
  in the new H, $G_1$, $G_2$ photometric system.
- DAWN observations of Vesta can provide  a first “ground
  truth” for the calibration of the polarimetry – albedo
  relations.

# Summary and Questions (2)

- **Why are Barbarians so rare? What's their origin?**
- **Polarimetric behaviour very likely linked to spinel abundance**
- **The Watsonia family is a Barbarian repository**
- **The Barbarian properties are not limited to the surface of the objects. The parent body of Watsonia was "homogeneously Barbarian".** *(A really wild asteroid!)*
- **Is the Watsonia family the result of a second-generation impact involving a parent body which was possibly, a first-generation member of a much older, and now dispersed, family?**
- **Polarimetry and Spectroscopy nicely complement each other!**
- **See Bagnulo's presentation to better understand the advantages of a marriage of Spectroscopy and Polarimetry!**