Polarimetry as a tool for physical characterization of potentially hazardous NEOs

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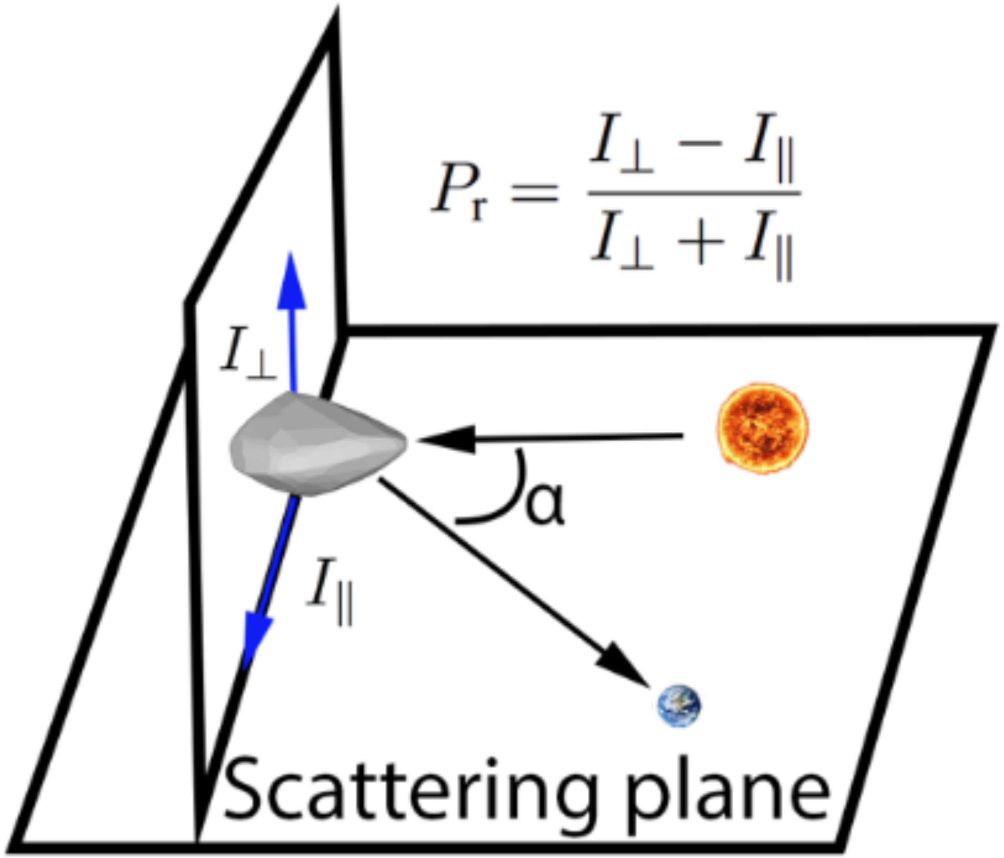
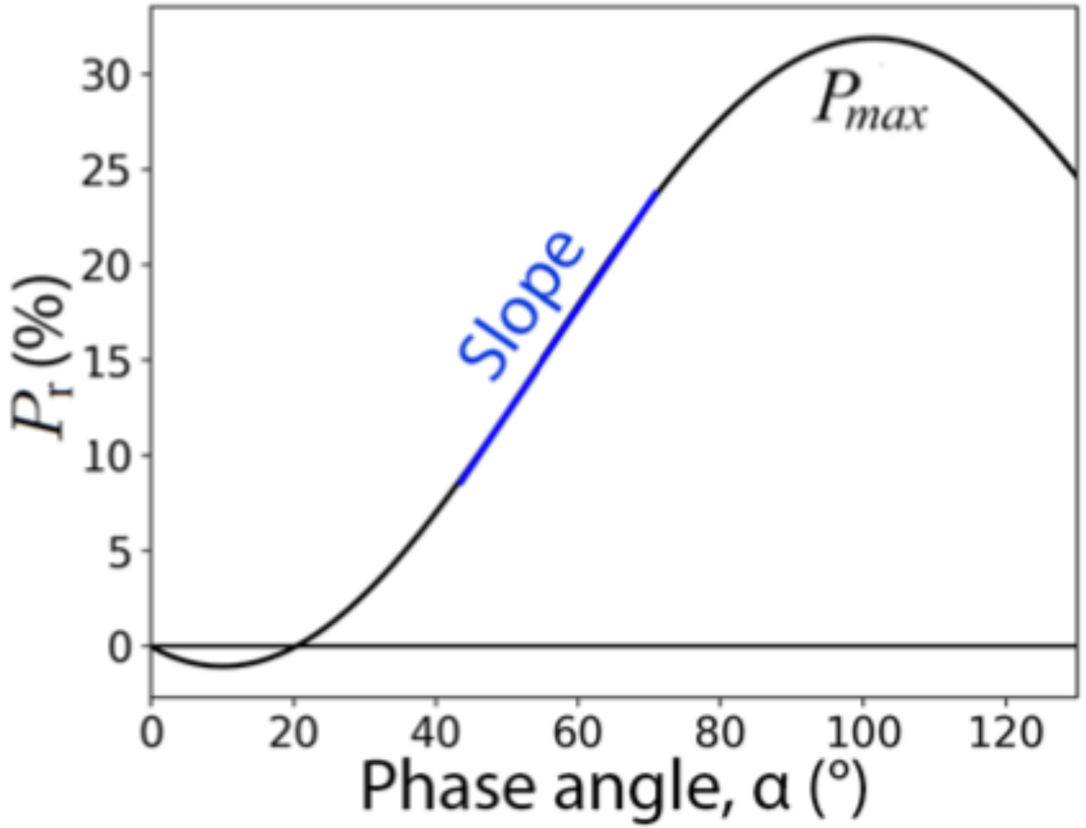
13/11/2024

Introduction





The degree of linear polarization is inversely proportional to the albedo of the scattering surface (Umov law 1905) $P \propto \frac{1}{A}$

$$\log A + a \log P_{max} = b,$$

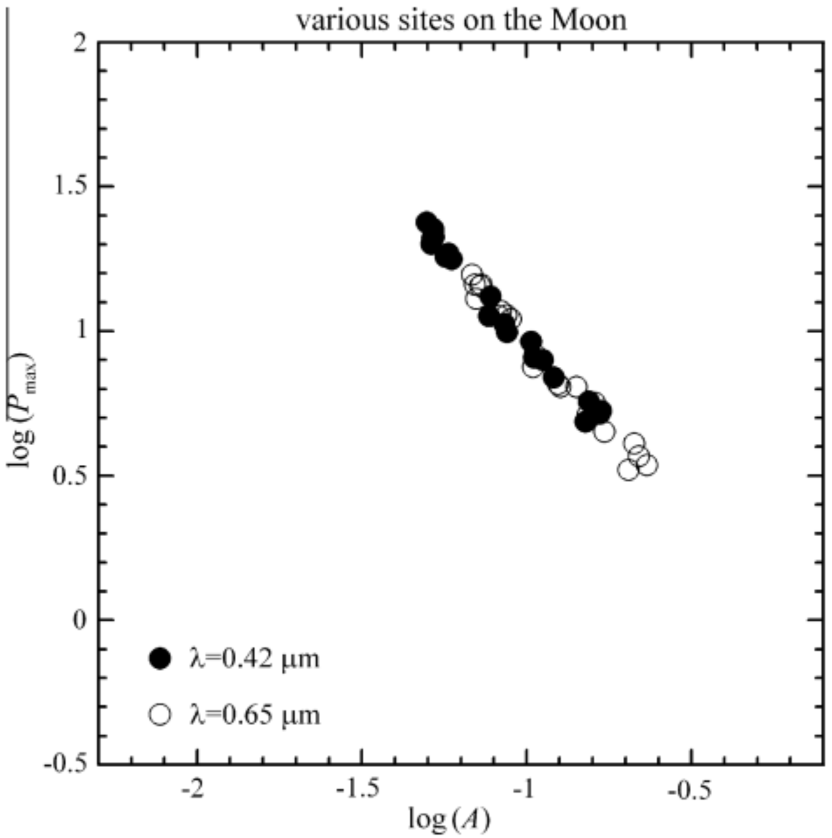
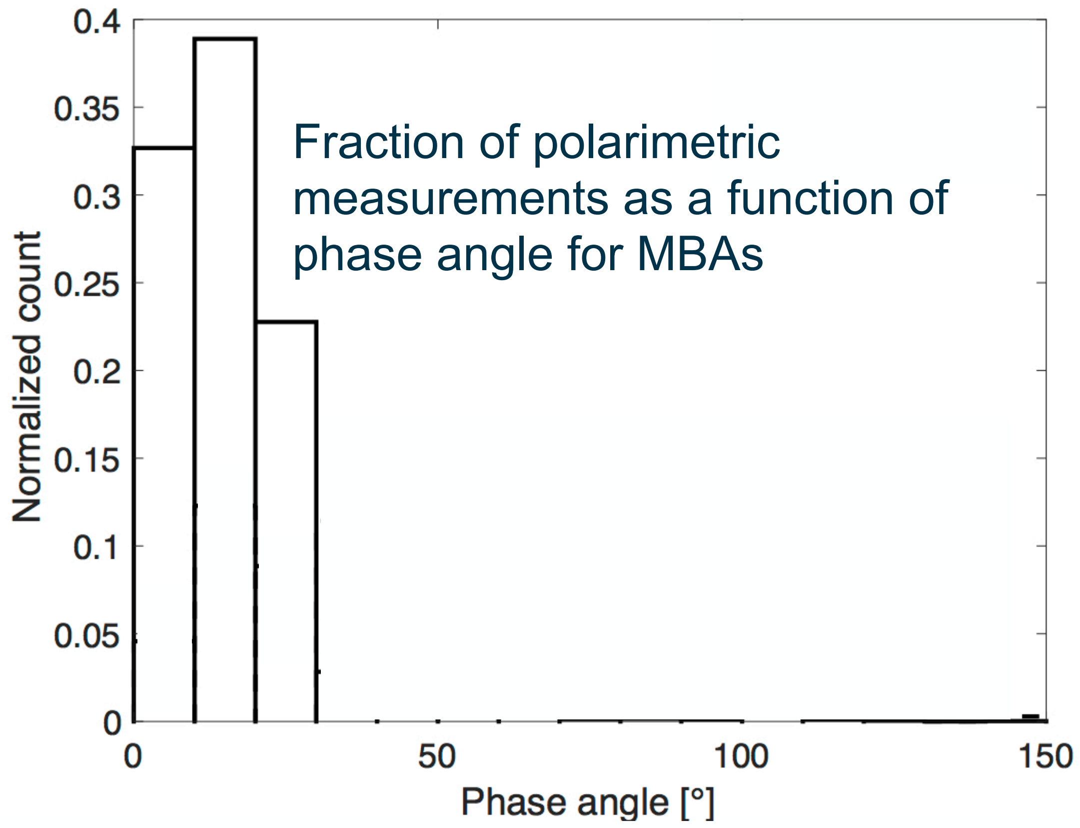


Fig. 1. Log(P_{max}) vs. log(A) diagram for 22 sites on the Moon (adapted from Shkuratov et al. (1992)).

How to determine P_{max} ?

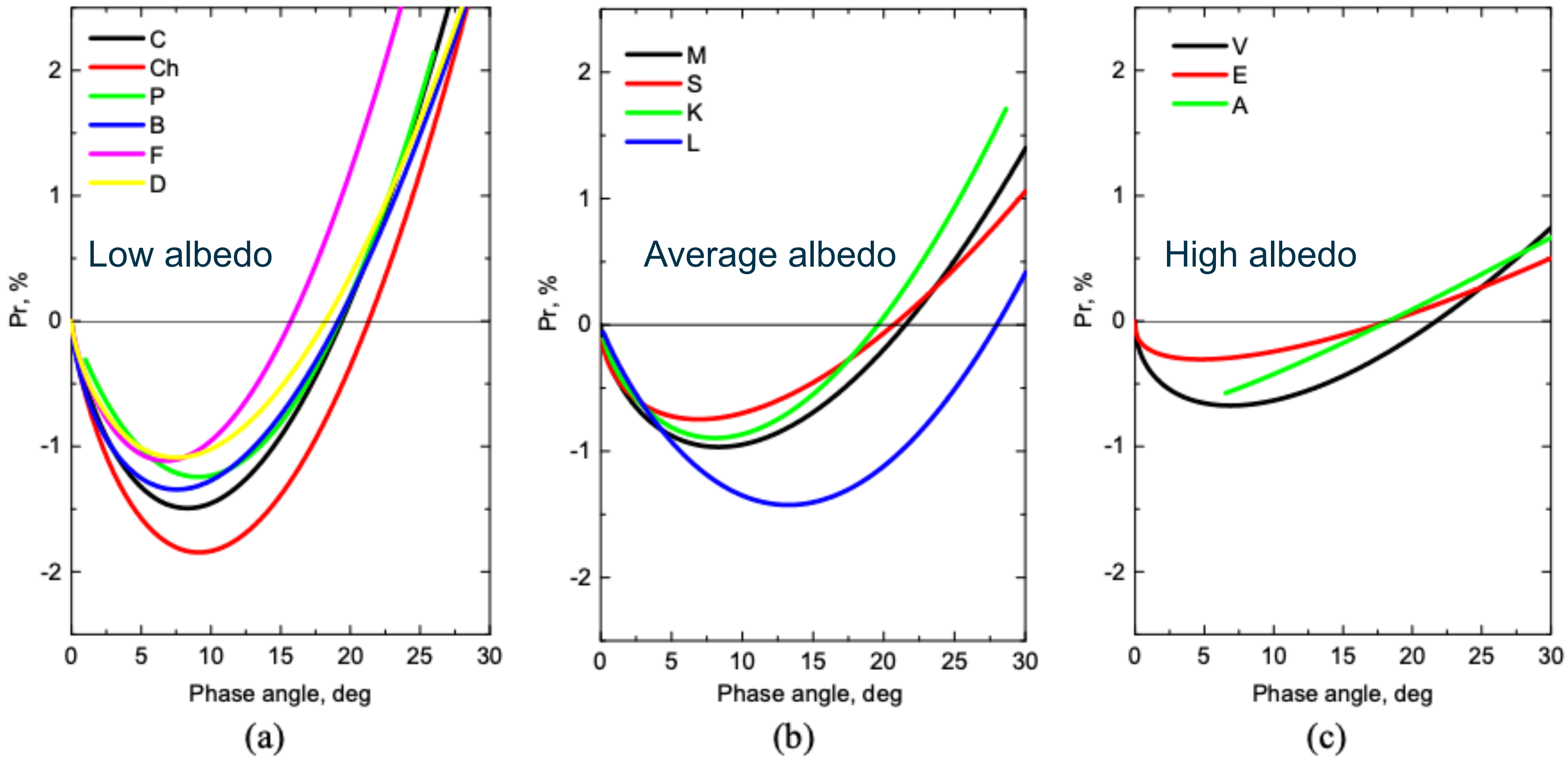
The umov law is based on P_{max} which is occurring at phase angle higher than 80°



P_{max} is unreachable, there is the need of a proxy to the umov law at low phase angles

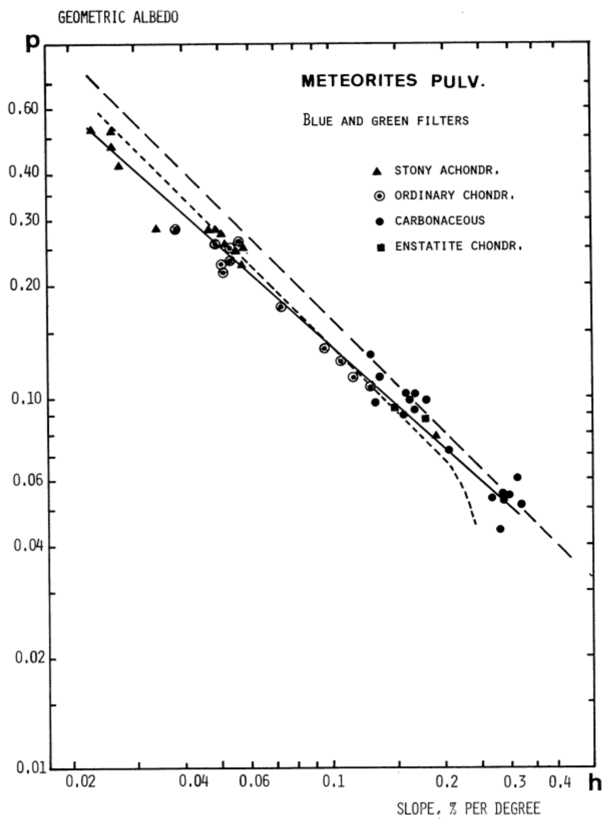
Proxy at low phase angles?

Belskaya et al. 2017



Umov law at low phase angles

Zellner et al. 1974: $log_{10}p_V = -\,log_{10}h - 1.78$



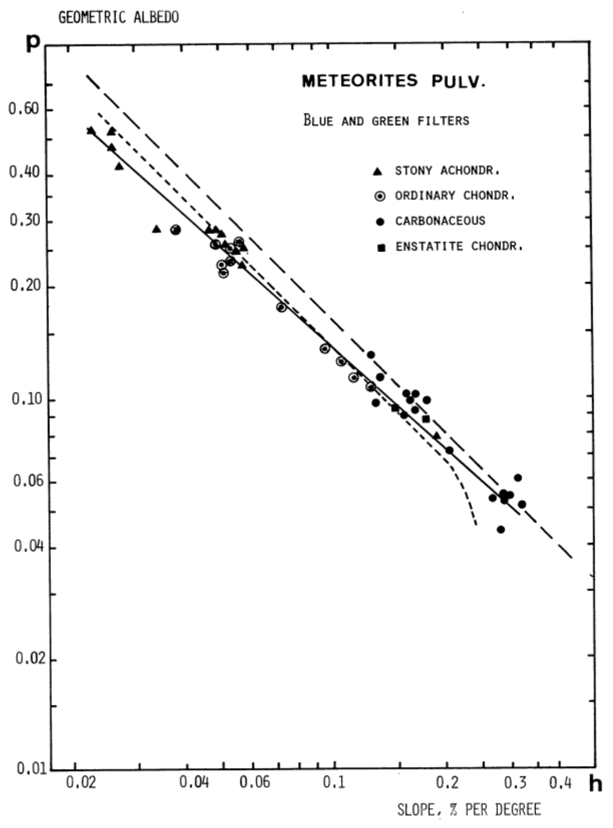
Umov law at low phase angles

Zellner et al. 1974: $\log_{10} p_V = -1.000 \log_{10} h - 1.78$

Cellino et al. 1999: $\log_{10} p_V = -1.118 \log_{10} h - 1.779$

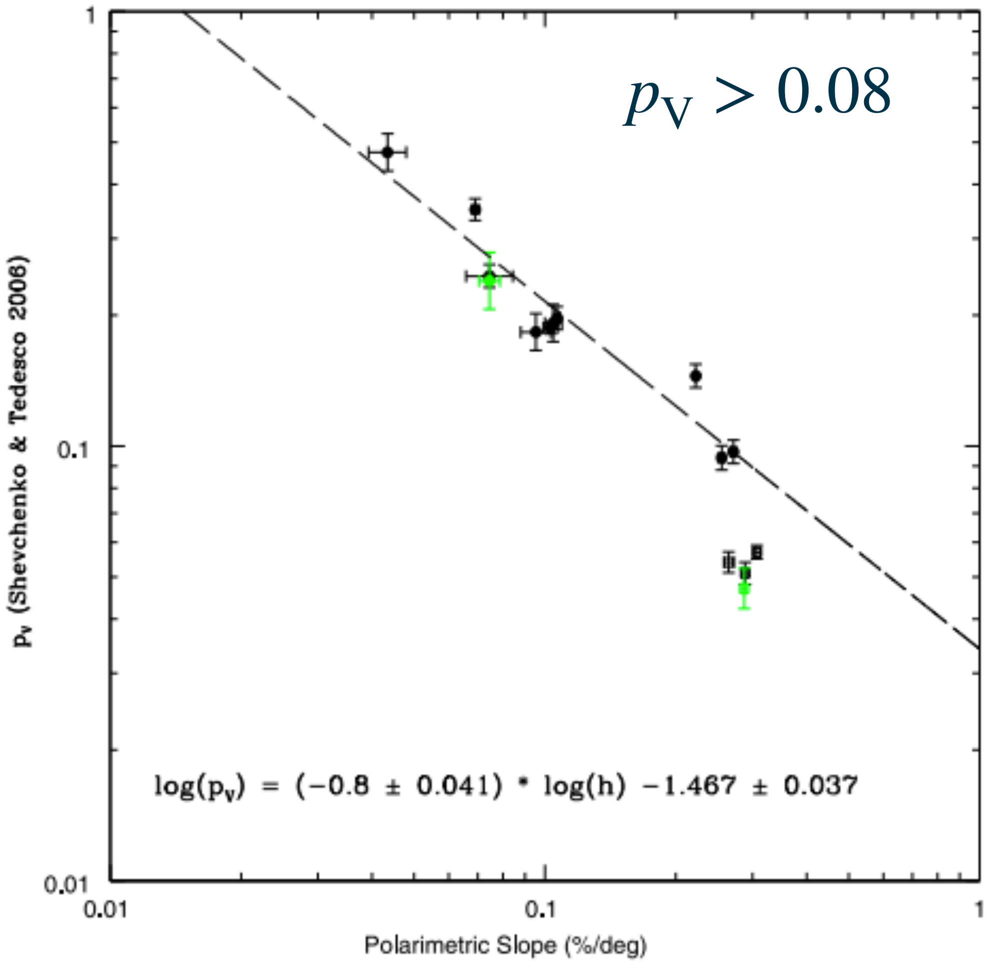
Masiero et al. (2012): $\log_{10} p_V = -1.207 \log_{10} h - 1.892$

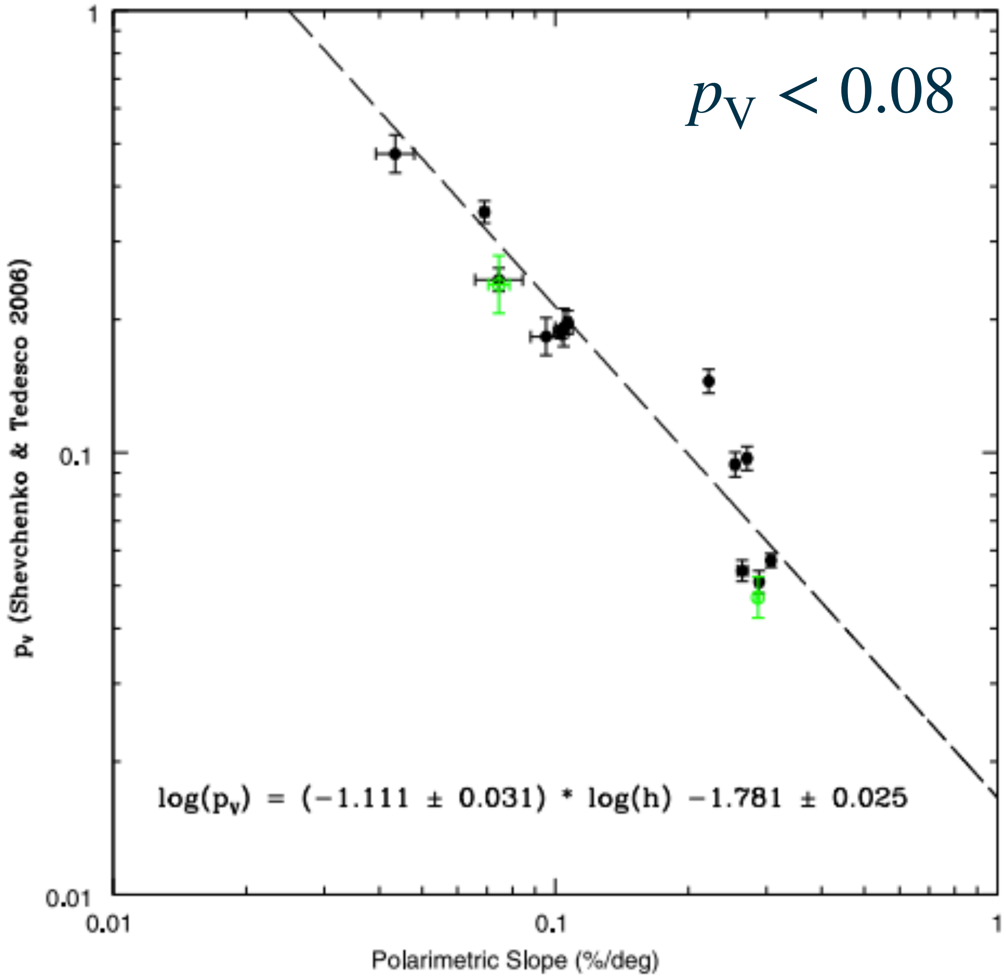
Cellino et al. (2015): $\log_{10} p_V = -1.111 \log_{10} h - 1.781$



Umov law at low phase angles

Cellino et al. (2015)



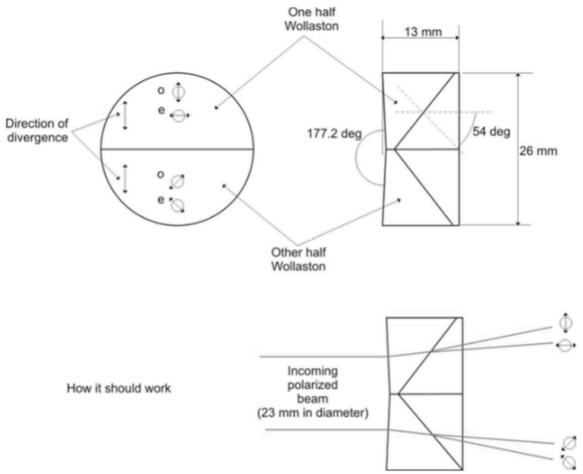


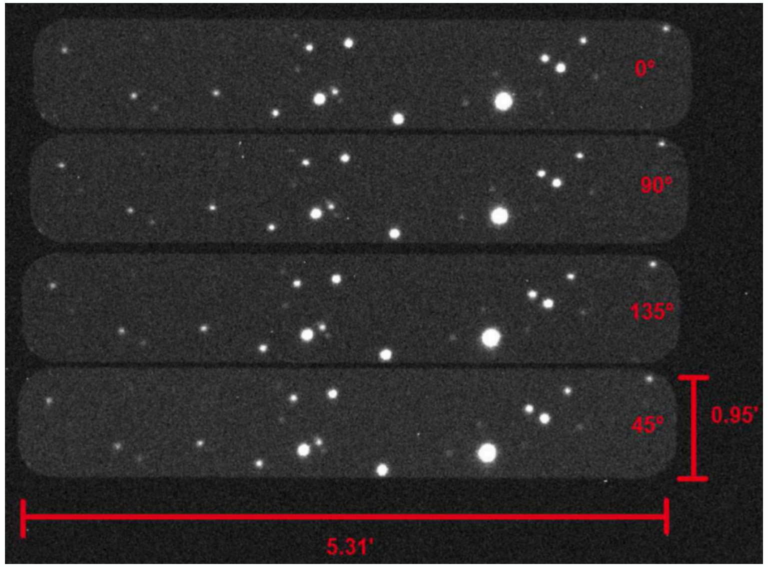
CAPS survey with ToPol

The Calern Asteroid Polarimetric Survey

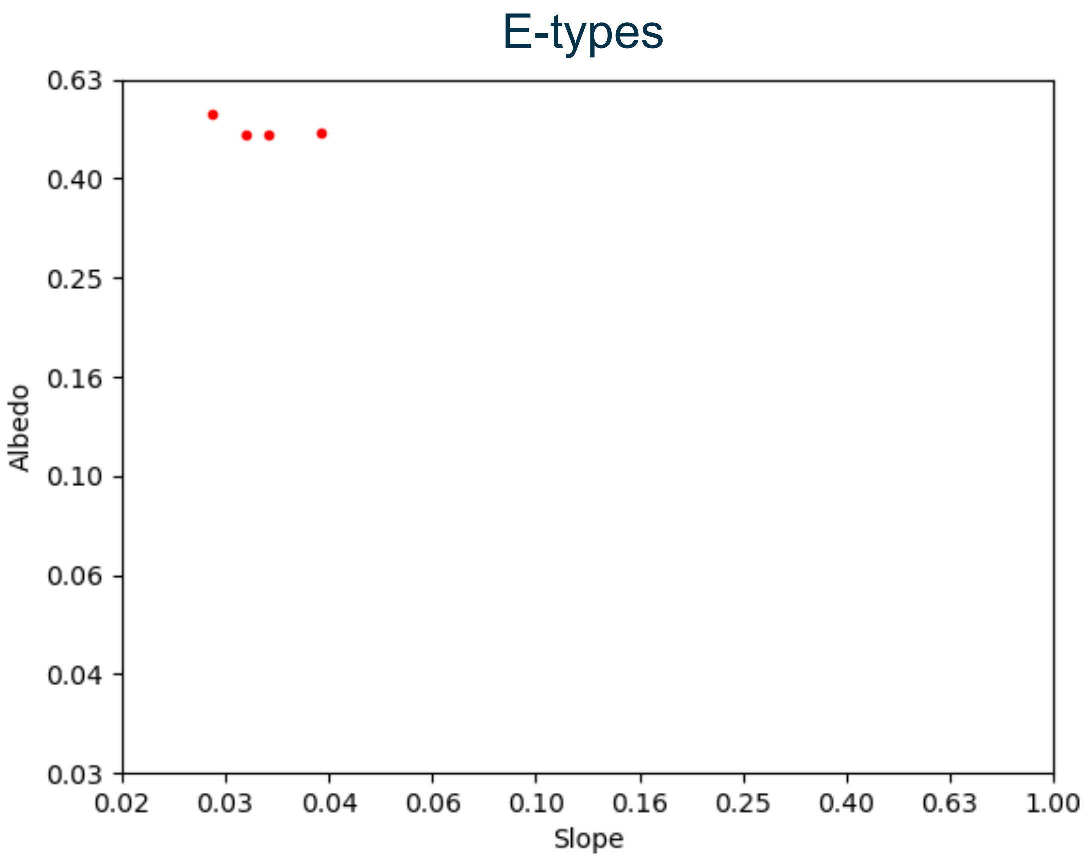
Released more than 2000 measurements of 568 individual asteroids in Bendjoya et al. 2022

Increased the number of measurements for asteroids by ~1/3 (Lupishko 2022)



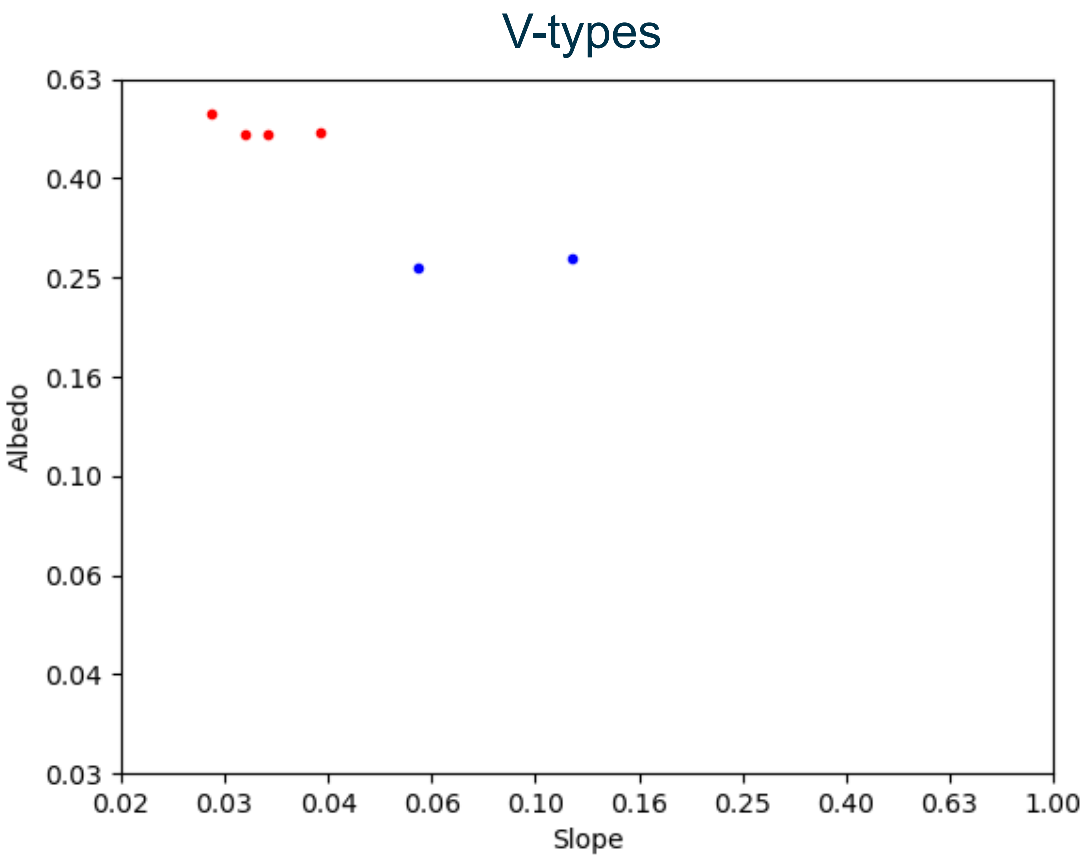


CAPS survey with ToPol



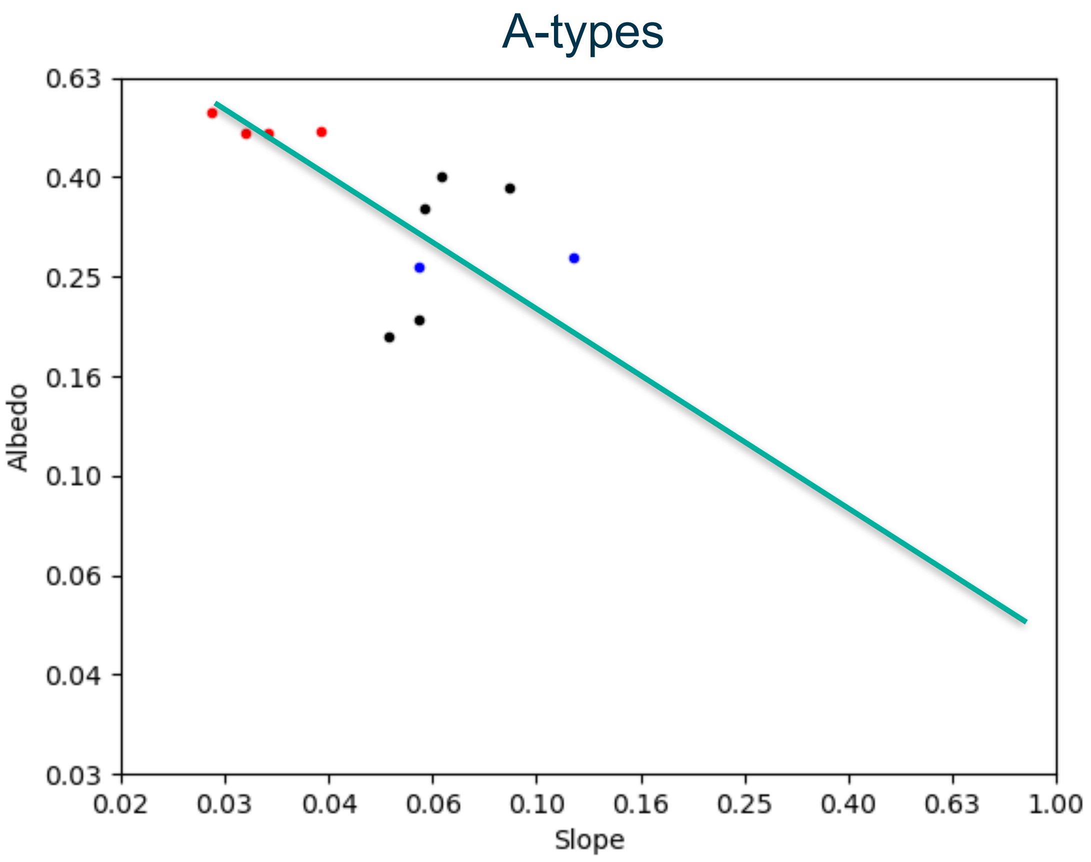
Albedos from SsODNet retrieved with Rock python package

CAPS survey with ToPol



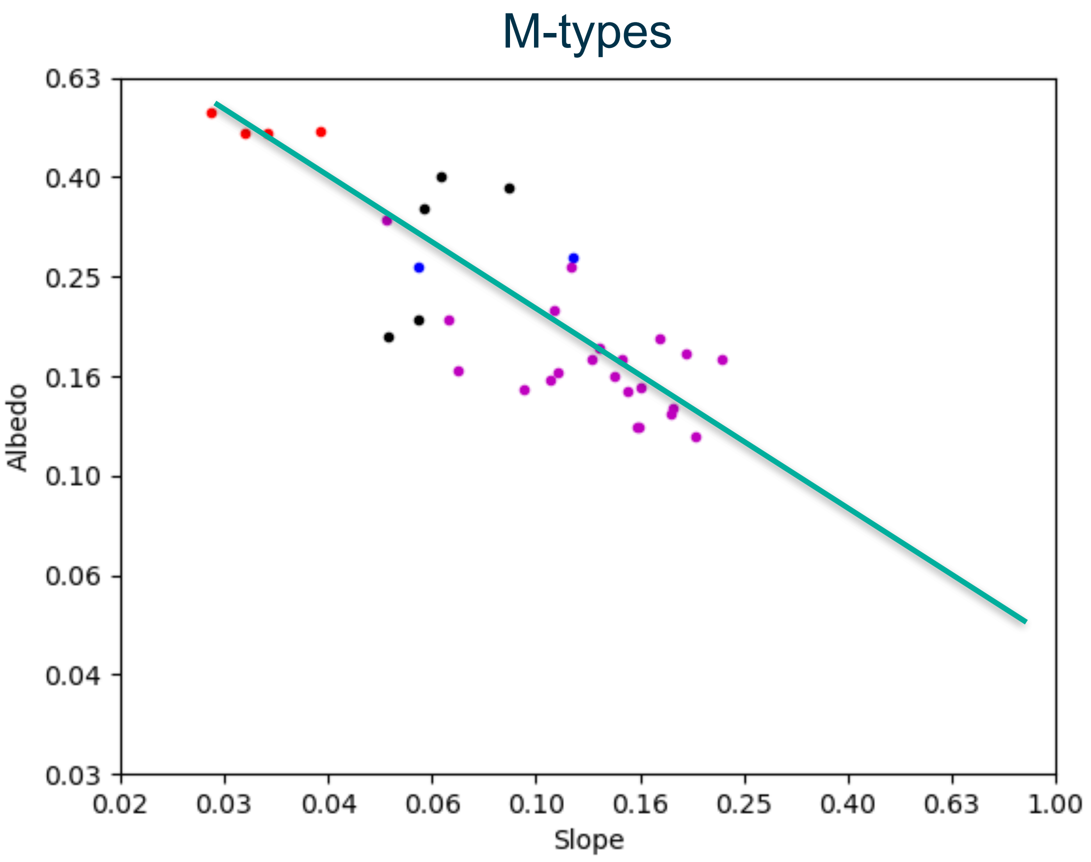
Albedos from SsODNet retrieved with Rock python package

CAPS survey with ToPol



Albedos from SsODNet retrieved with Rock python package

CAPS survey with ToPol



Albedos from SsODNet retrieved with Rock python package

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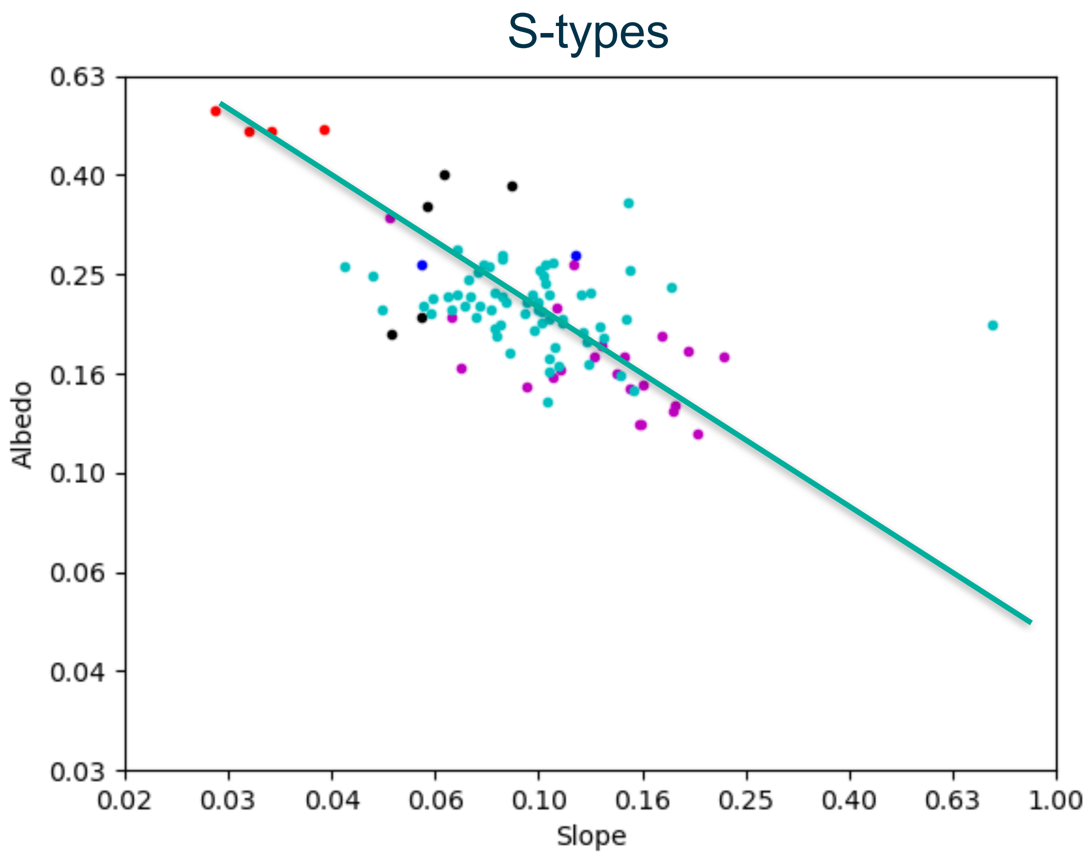
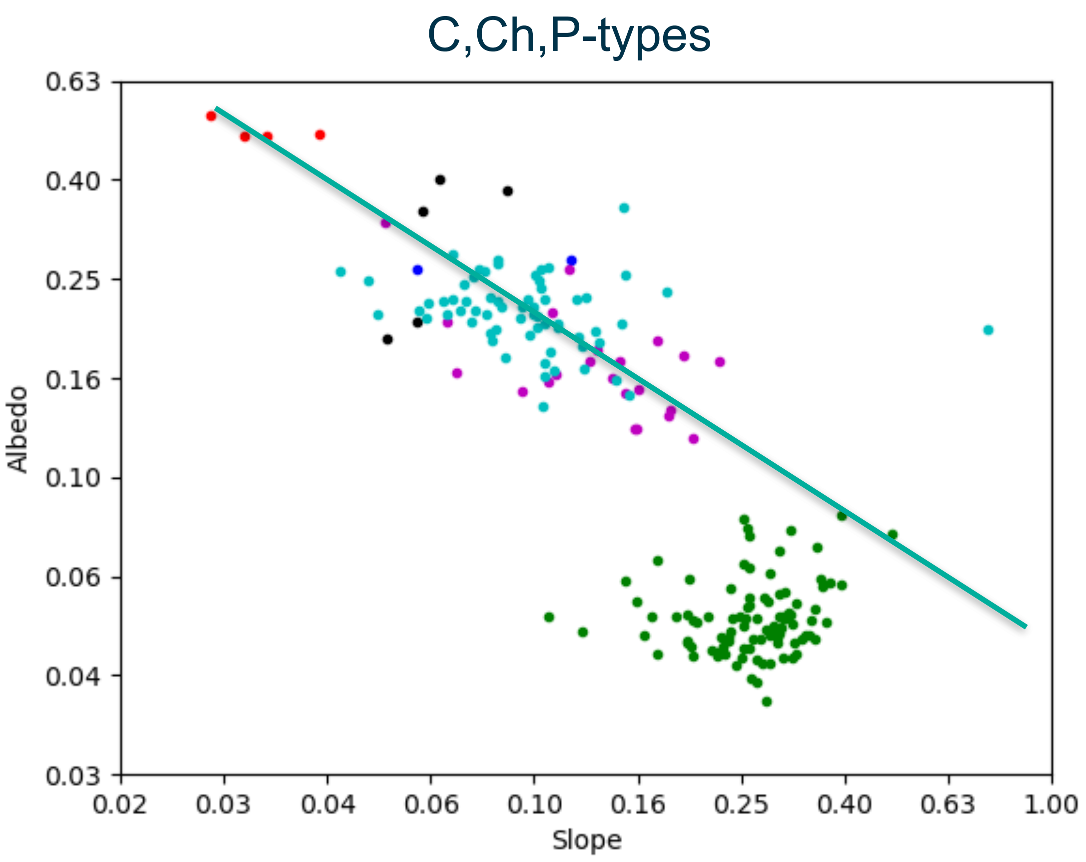


Albedos from SsODNet retrieved with Rock python package

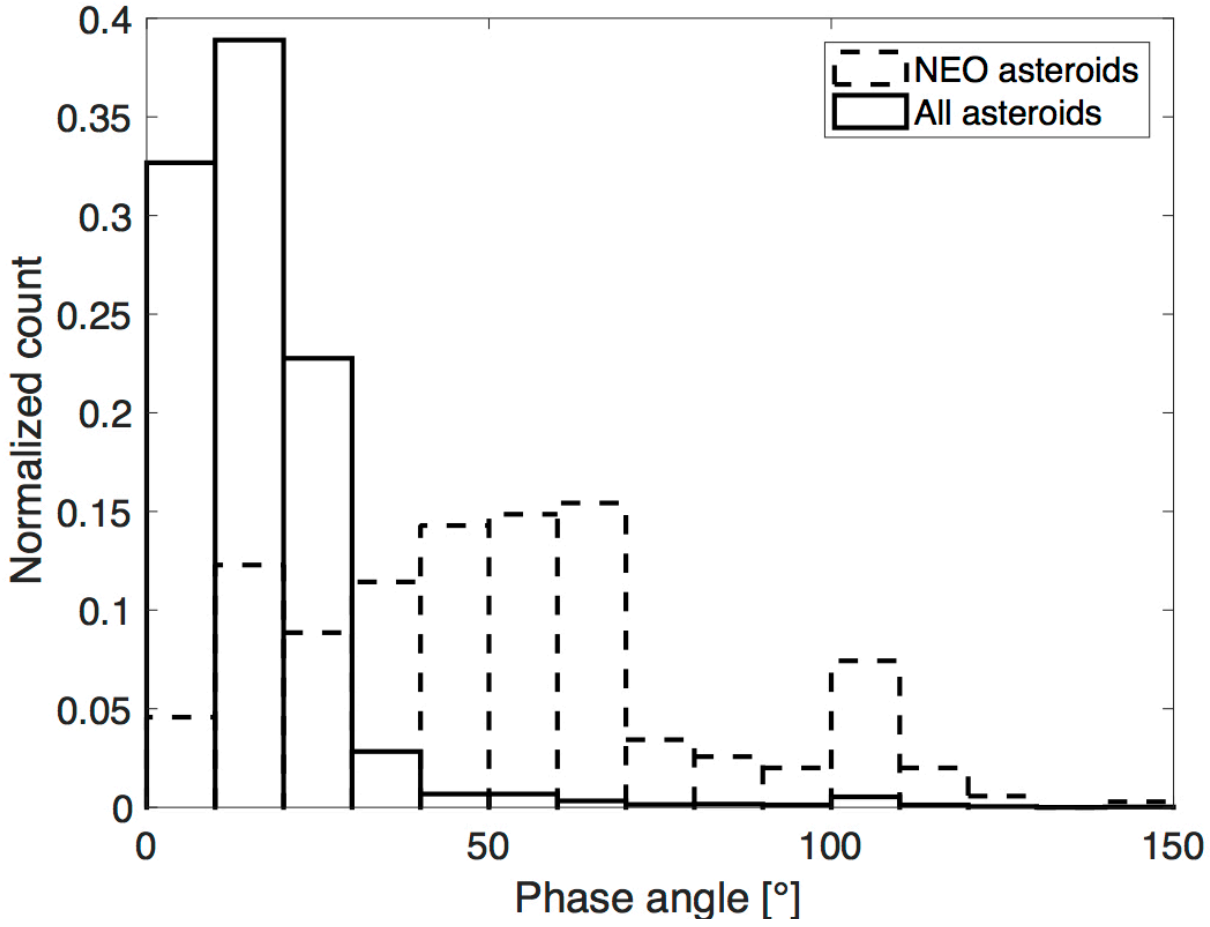
CAPS survey with ToPol



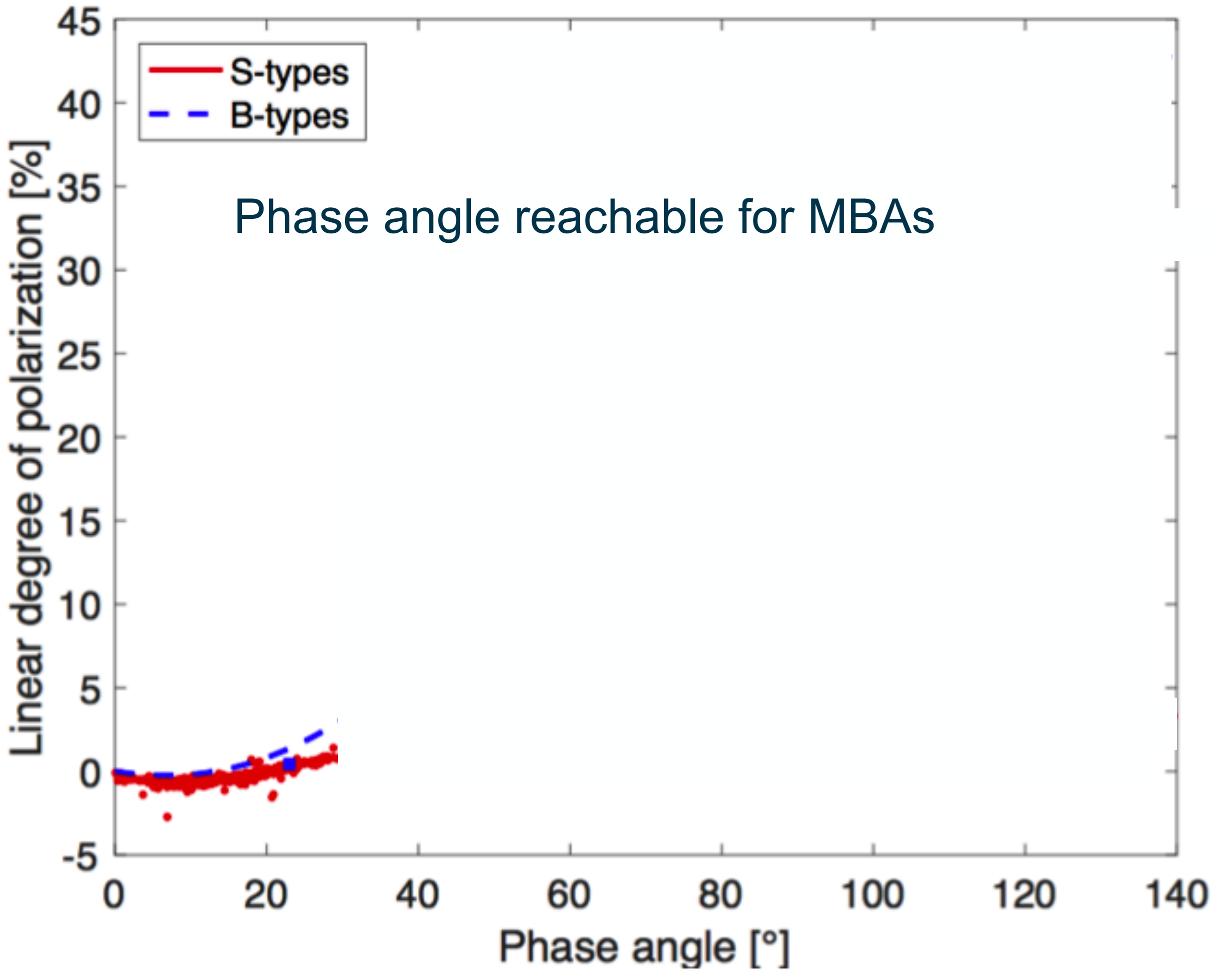
Albedos from SsODNet retrieved with Rock python package

How to improve the albedo-polarization calibration for NEOs?

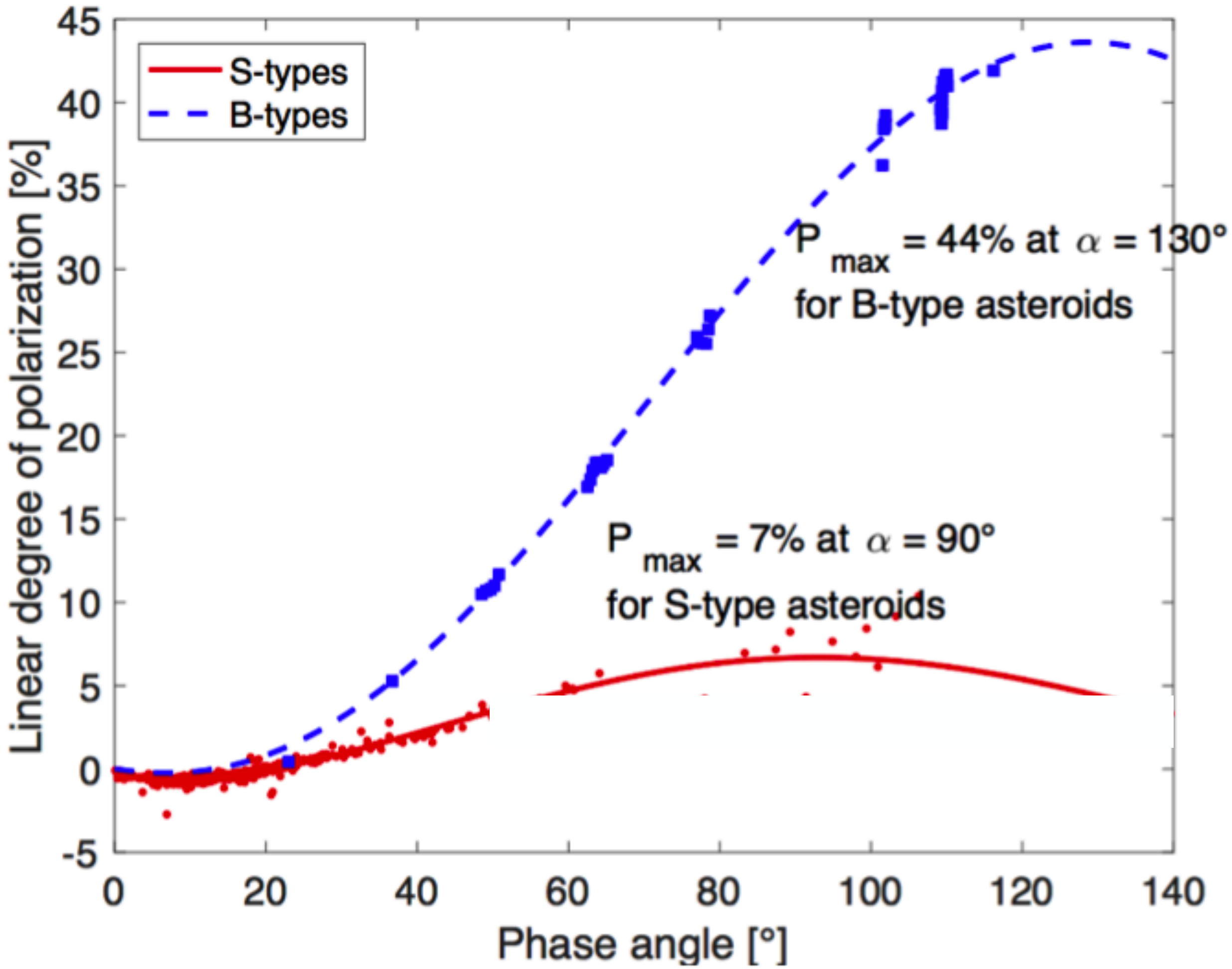
NEOs are usually observed a much higher phase angles than MBAs



High phase angles polarimetric observations



High phase angles polarimetric observations

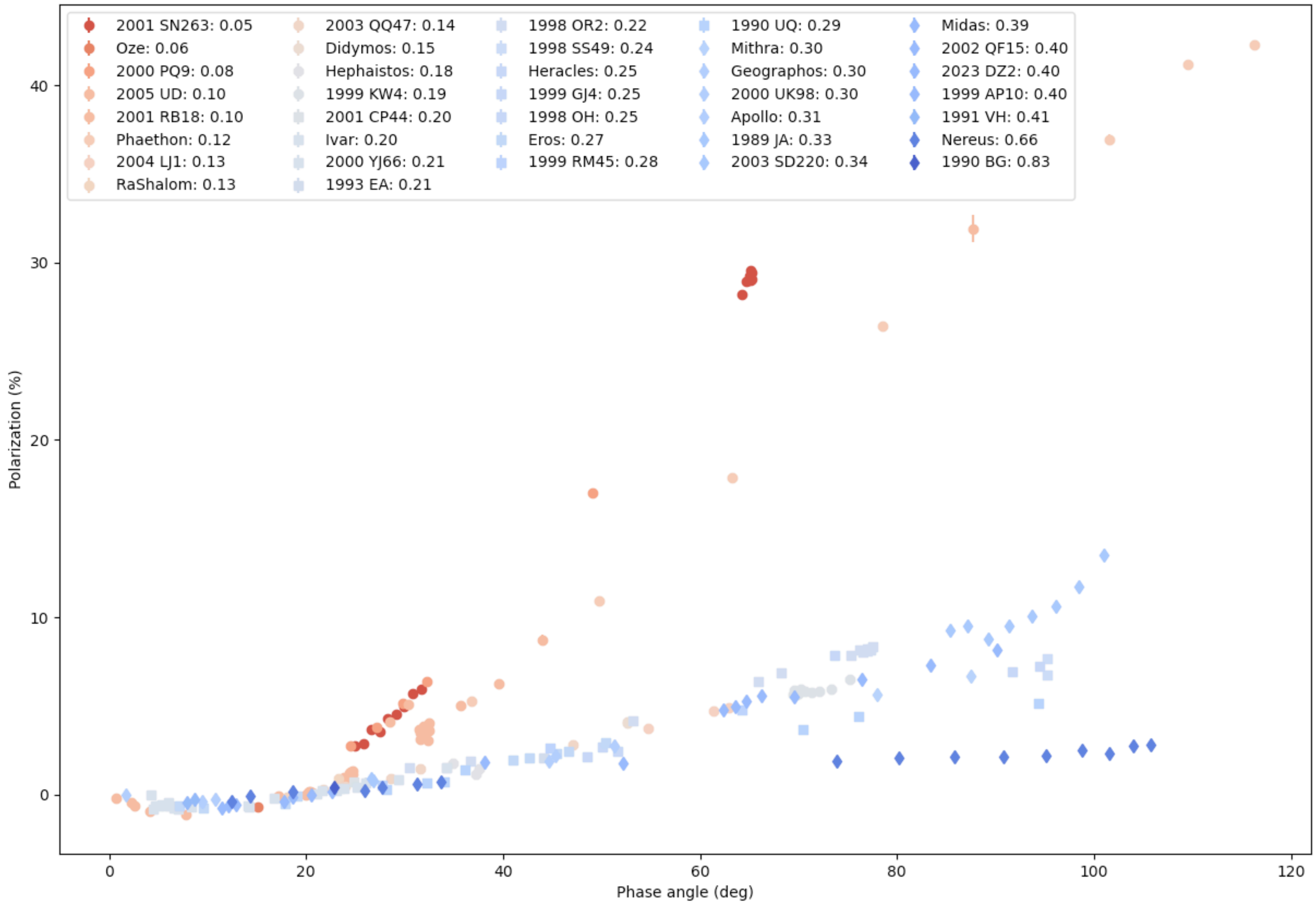


We can directly use the value of Pr at a given phase angle to obtain an estimation of the albedo, but we need to calibrate the albedo vs polarization for all the phase angles

Polarimetry as a tool for physical characterization of potentially hazardous NEOs

Project funded by the NASA YORPD (Yearly Opportunity for Research in Planetary Defense) since 2022:

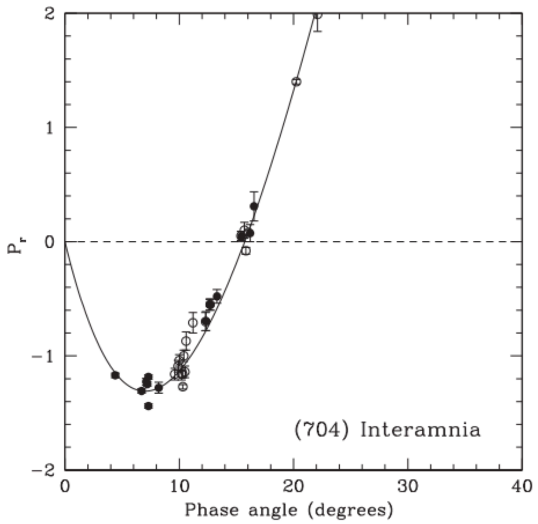
- Survey of NEOs in polarimetry
  - ToPol @ Calern 1m telescope V<15 mag
  - FoReRo2 @ Rozhen 2m telescope V<17 mag
  - FORS2 @ VLT 8m telescope V<22 mag
- Study of the observed NEOs in photometry, spectroscopy, and thermal infra-red to improve our knowledge of their albedos
- Final goal:
  - Producing a calibration of the form $\log_{10}(p_V) = A(\alpha)\log_{10}(p_r(\alpha)) + B(\alpha)$
  - Being able to get an estimation of the albedo for an NEOs with a single polarimetric measurement at high phase angle


2001 SN263: 0.05
Oze: 0.06
2000 PQ9: 0.08
2005 UD: 0.10
2001 RB18: 0.10
Phaethon: 0.12
2004 LJ1: 0.13
RaShalom: 0.13
2003 QQ47: 0.14
Didymos: 0.15
Hephaistos: 0.18
1999 KW4: 0.19
2001 CP44: 0.20
Ivar: 0.20
2000 YJ66: 0.21
1993 EA: 0.21
1998 OR2: 0.22
1998 SS49: 0.24
Heracles: 0.25
1999 GJ4: 0.25
1998 OH: 0.25
Eros: 0.27
1999 RM45: 0.28
1990 UQ: 0.29
Mithra: 0.30
Geographos: 0.30
2000 UK98: 0.30
Apollo: 0.31
1989 JA: 0.33
2003 SD220: 0.34
Midas: 0.39
2002 QF15: 0.40
2023 DZ2: 0.40
1999 AP10: 0.40
1991 VH: 0.41
Nereus: 0.66
1990 BG: 0.83
Polarization (%)
Phase angle (deg)
0
10
20
30
40
0
20
40
60
80
100
120

Fitting the phase polarization curves

Phase-polarization curve models:

- Exponential-linear model (Muinonen et al. 2002): $P_r(\alpha) = A\left(\exp\left(-\alpha/B\right) - 1\right) + C\alpha$
  - Pr=0 at α=0°
  - Exponential behavior at low phase angles
  - Linear trend at high phase angles
  - Pros:
    - Fit well low phase angle observations
  - Cons:
    - Cannot model non-linearities around Pmax
    - Parameters are not diagnostics (i.e. Pmin, h, α_{inv} are not parameters)
    - Parameters are heavily correlated



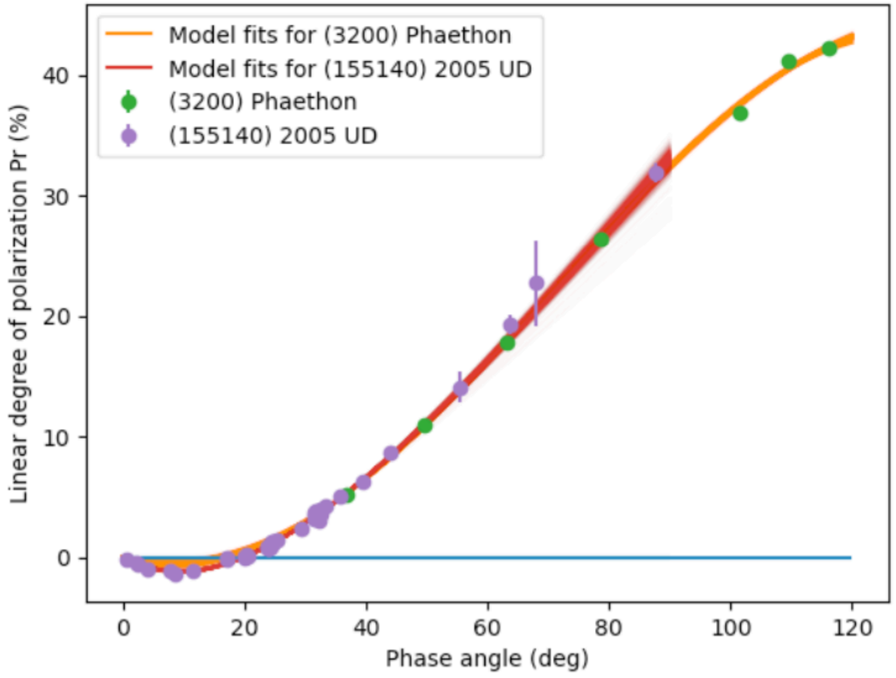
Fitting the phase polarization curves

Phase-polarization curve models:

- Lumme and Muinonen trigonometric model (Goidet-Devel et al. 1995 ; Lumme and Muinonen 1993):

$$P_r(\alpha) = a \sin(\alpha)^b \cos\left(\frac{\alpha}{2}\right)^c \sin(\alpha - \alpha_{inv})$$

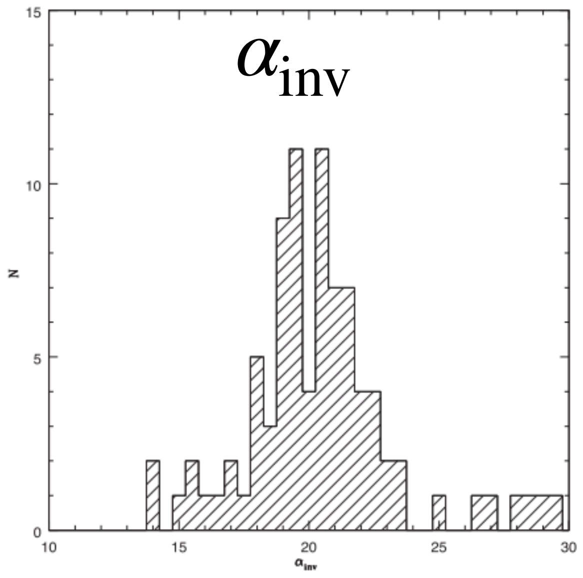
  - Pr=0 at α=0°
  - Pros:
    - Allows to model the non-linearities at high phase angles
    - α_{inv} is a parameter of the model
  - Cons:
    - Can introduce false non-linearities at low phase angles

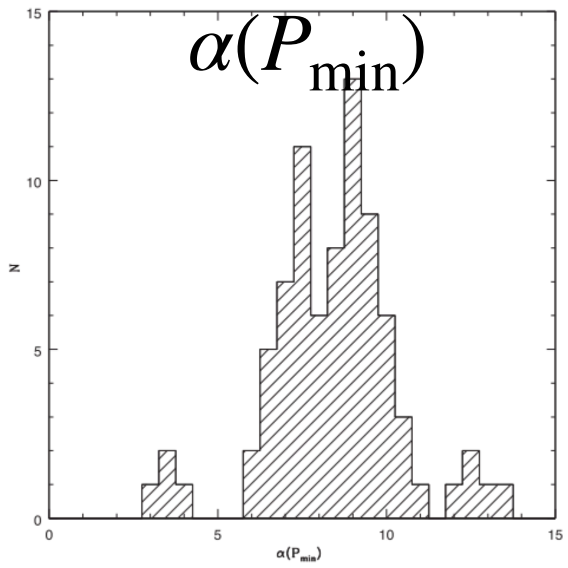


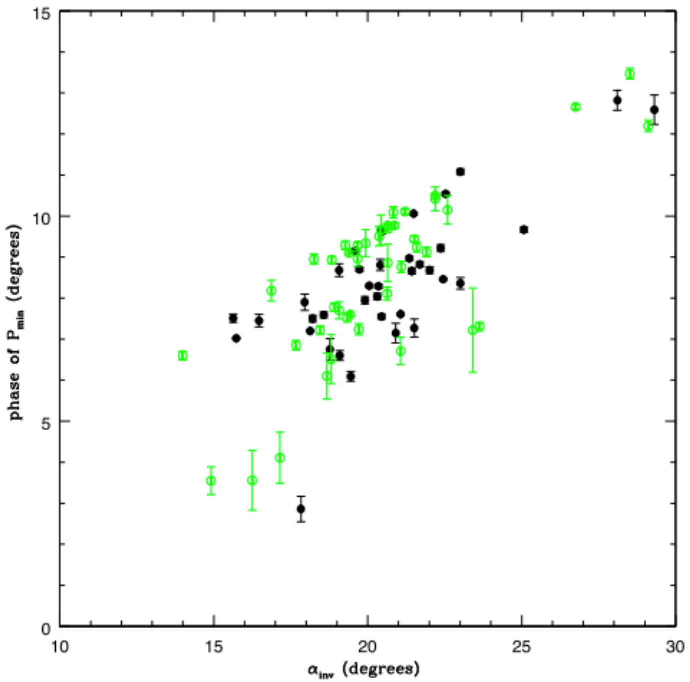
Fitting the phase polarization curves

Use of prior information:

- Pmin, $\alpha(P_{min})$, α_{inv}, h are not random and are correlated



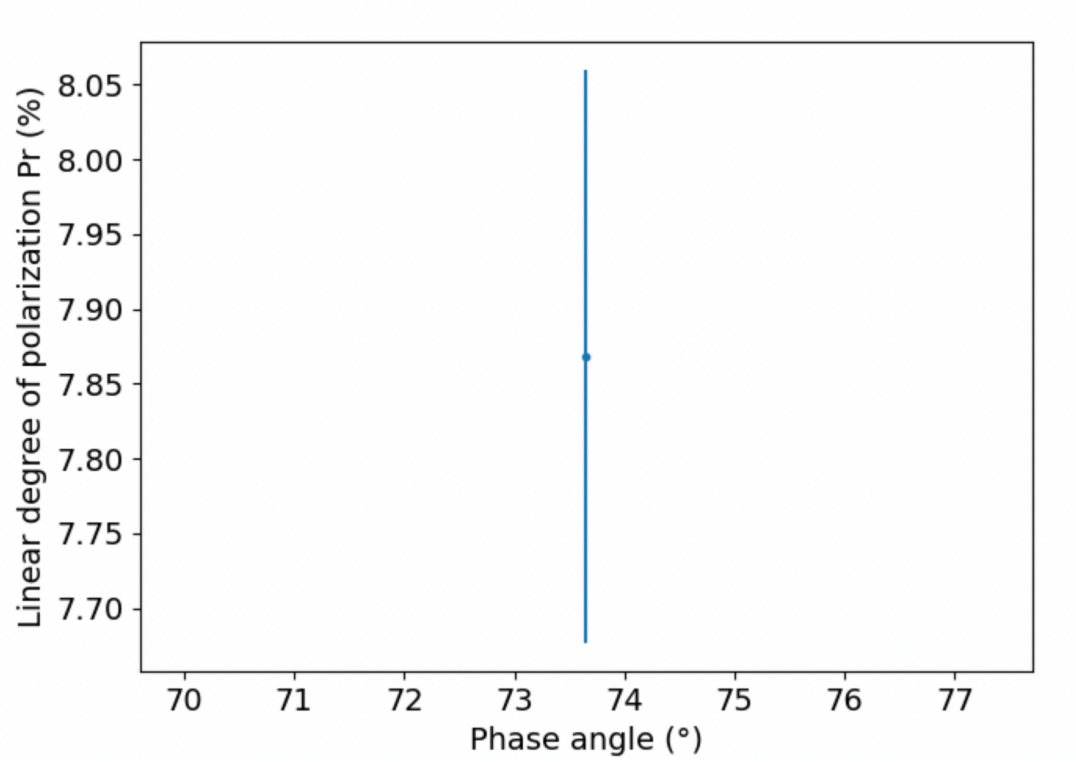




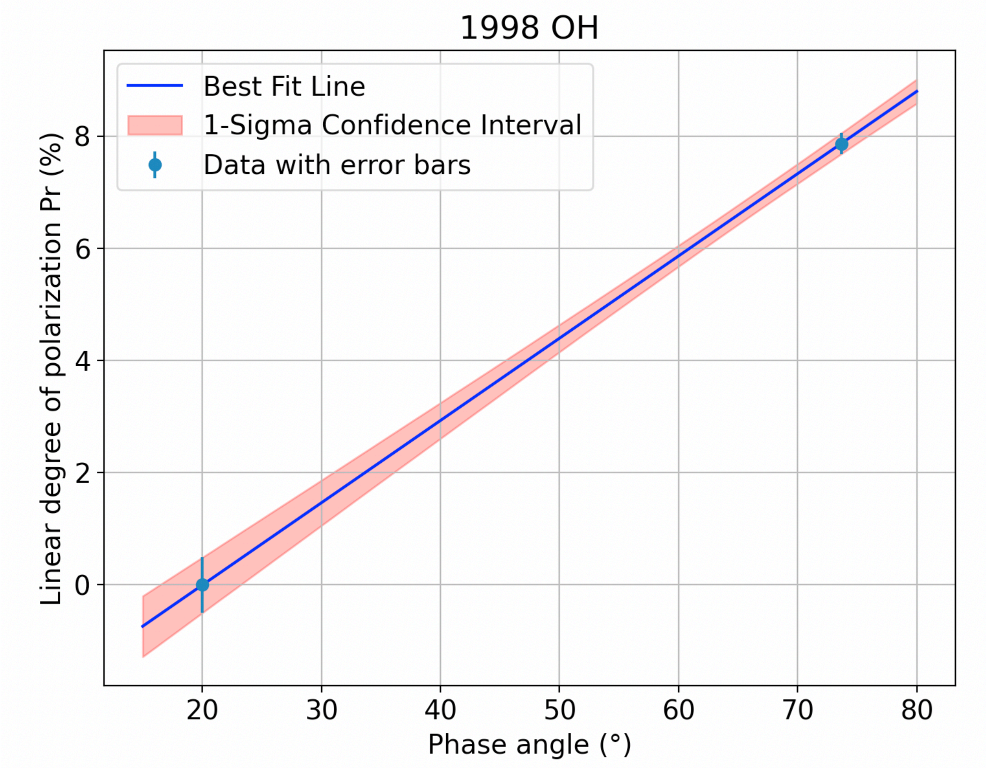
We can use that information to constrain the fit even when no observations are available at low phase angles

Example of fit

Observation of 1998 OH

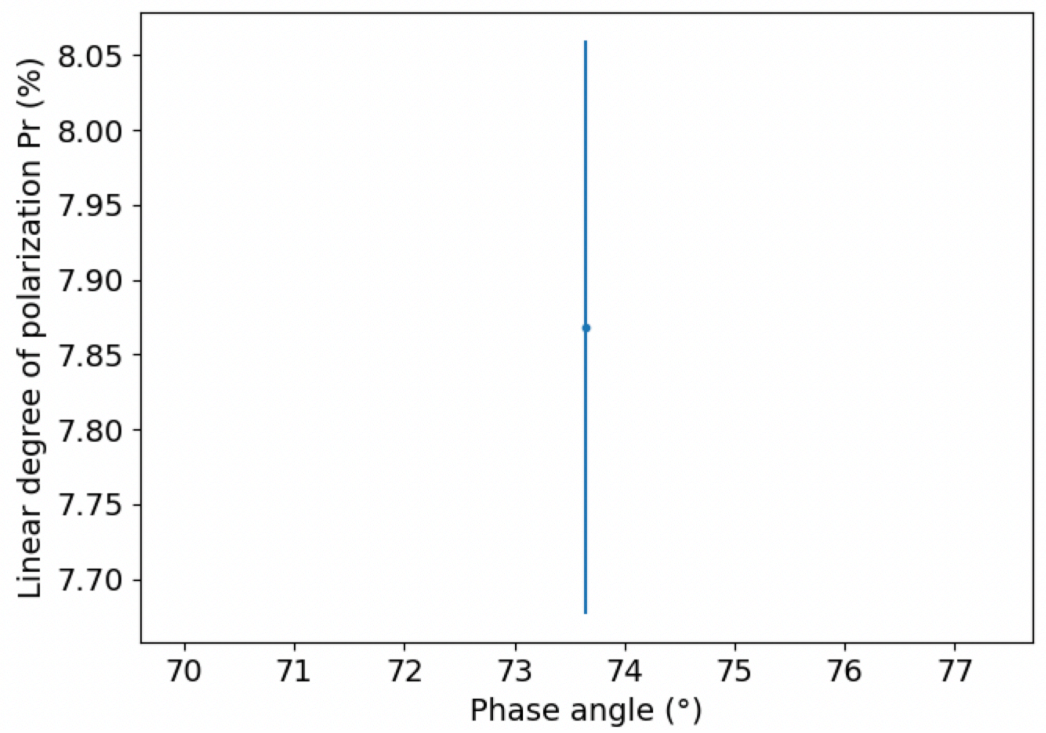


Fit of a linear model with assumptions of inversion angle at 20°

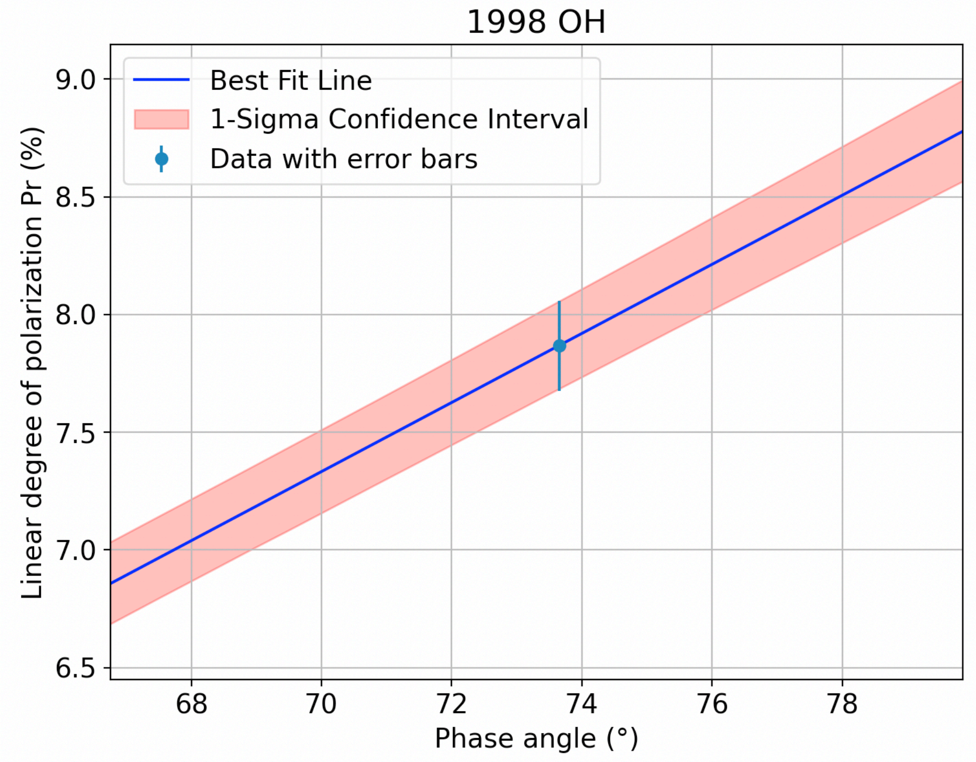


Example of fit

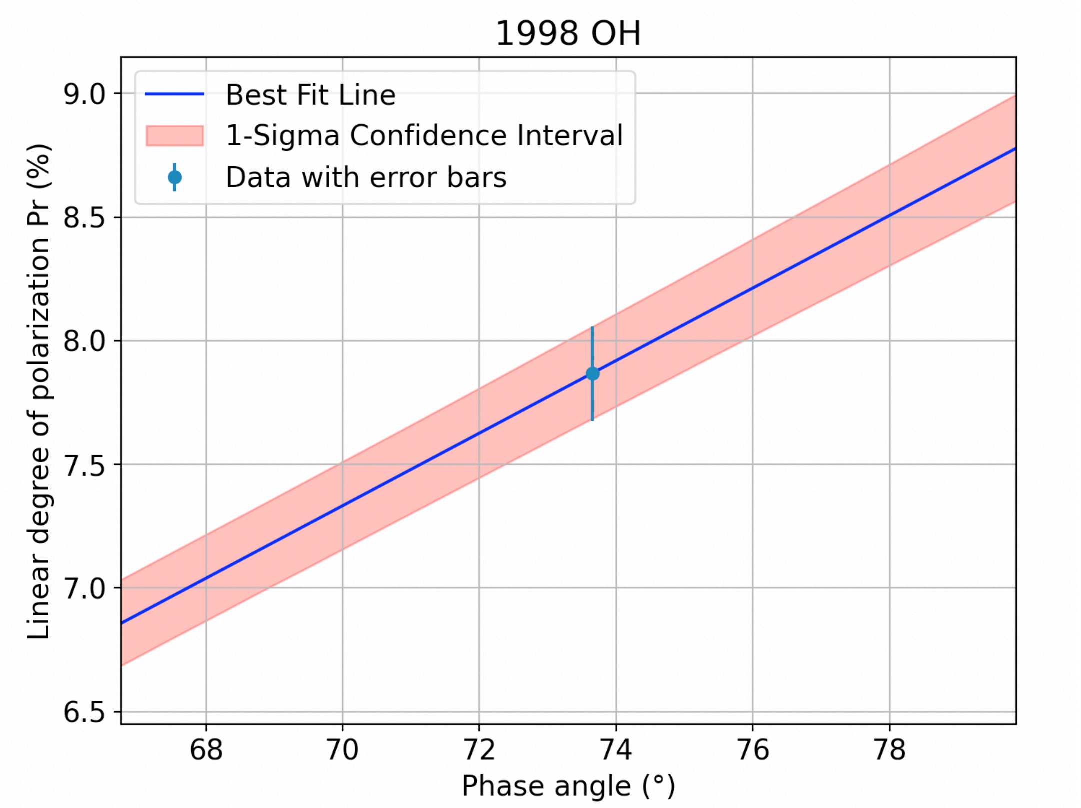
Observation of 1998 OH



For our calibration, we only consider +-5° around the observation



1998 OH characteristics



Albedo of 1998 OH?

- 0.382 (Trilling et al., 2010)
- 0.232 +- 0.116 (Mainzer et al., 2011)

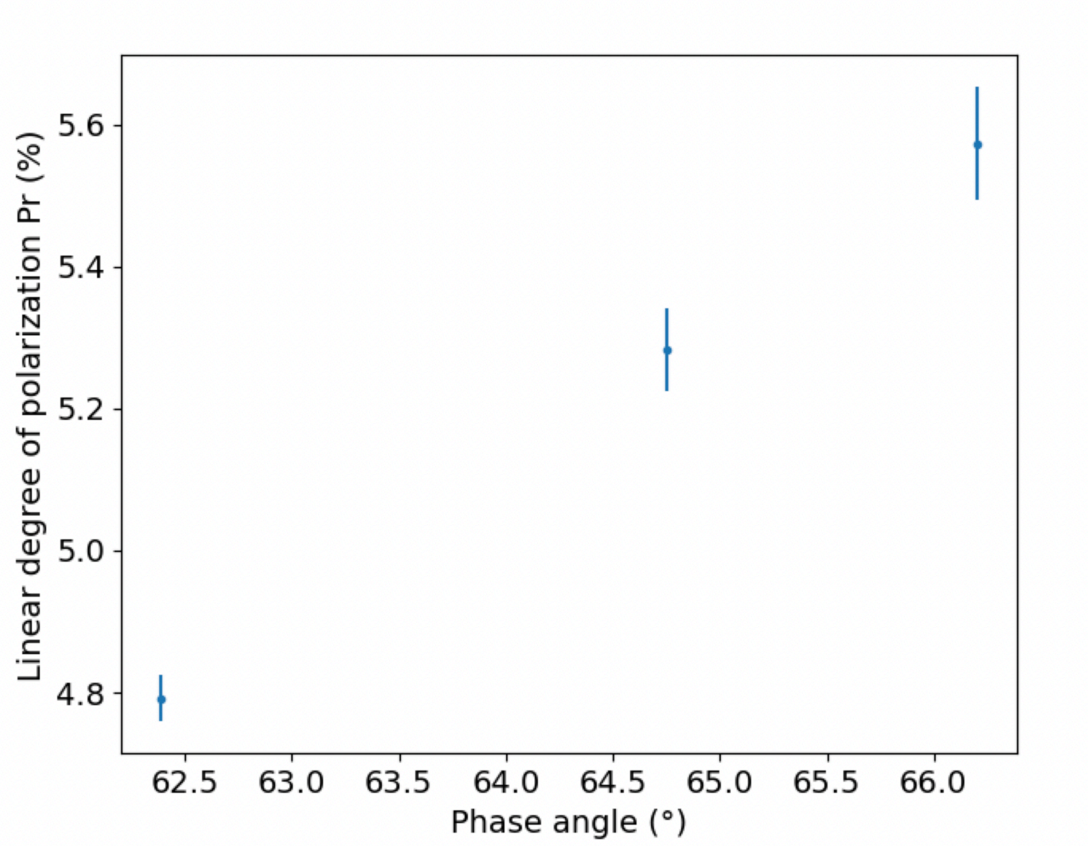
Assuming an uncertainty of 0.2 for ExploreNEOs albedo, we have:

- Pv = 0.27 +- 0.10

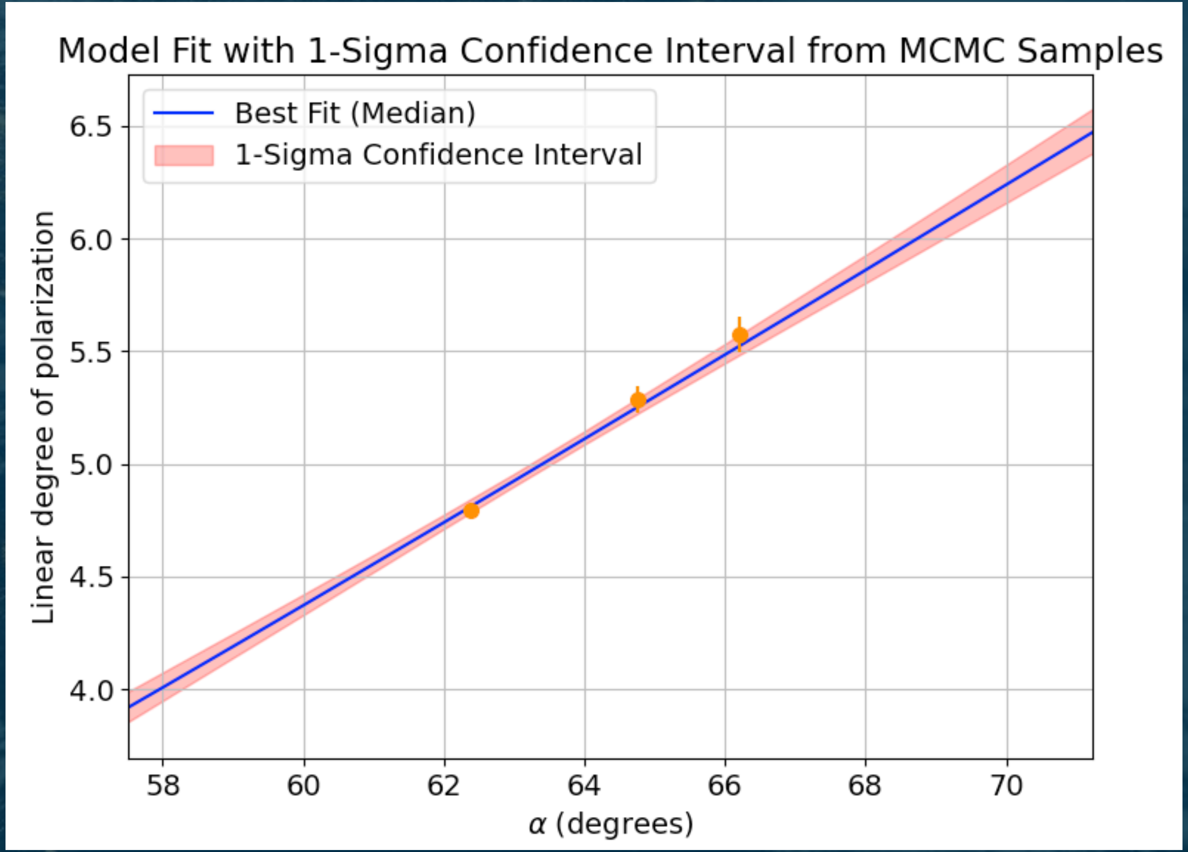
Consistent with the Sq taxonomy from the MITHNEOS survey (Binzel et al. 2019)

Steps to get the best calibration

Observations of 2002 QF15

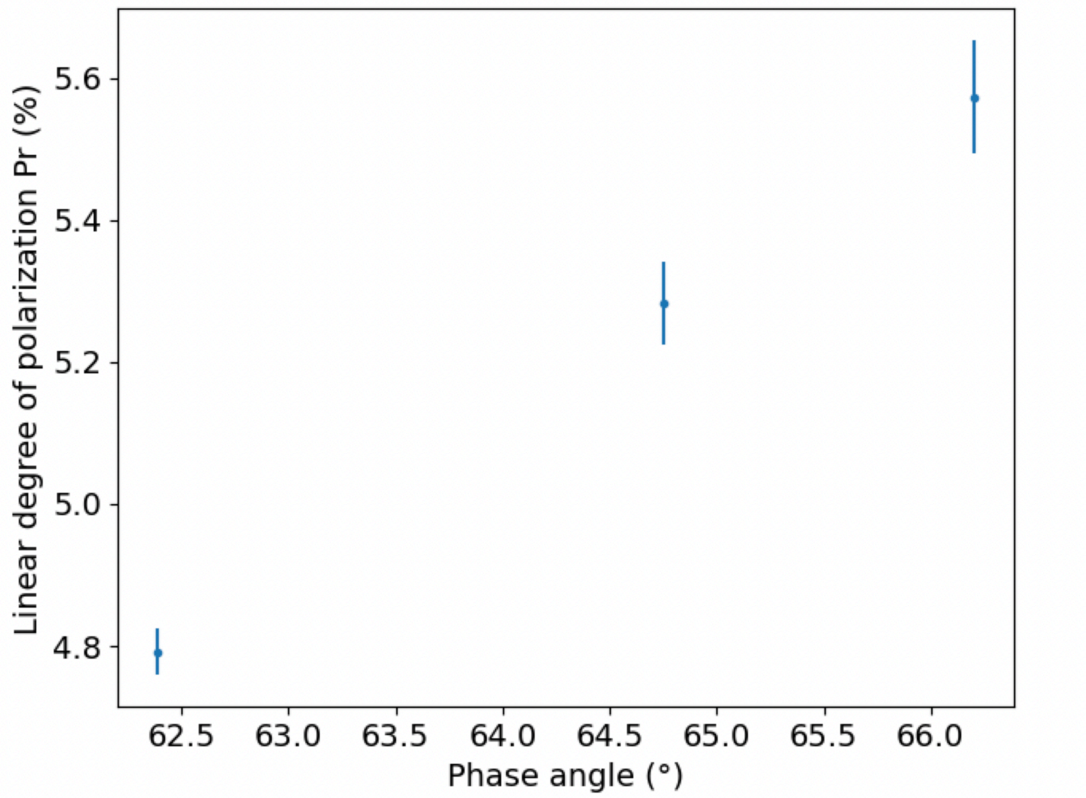


Fit of the exponential-linear model to the data using MCMC routine



Example of fit

Observations of 2002 QF15



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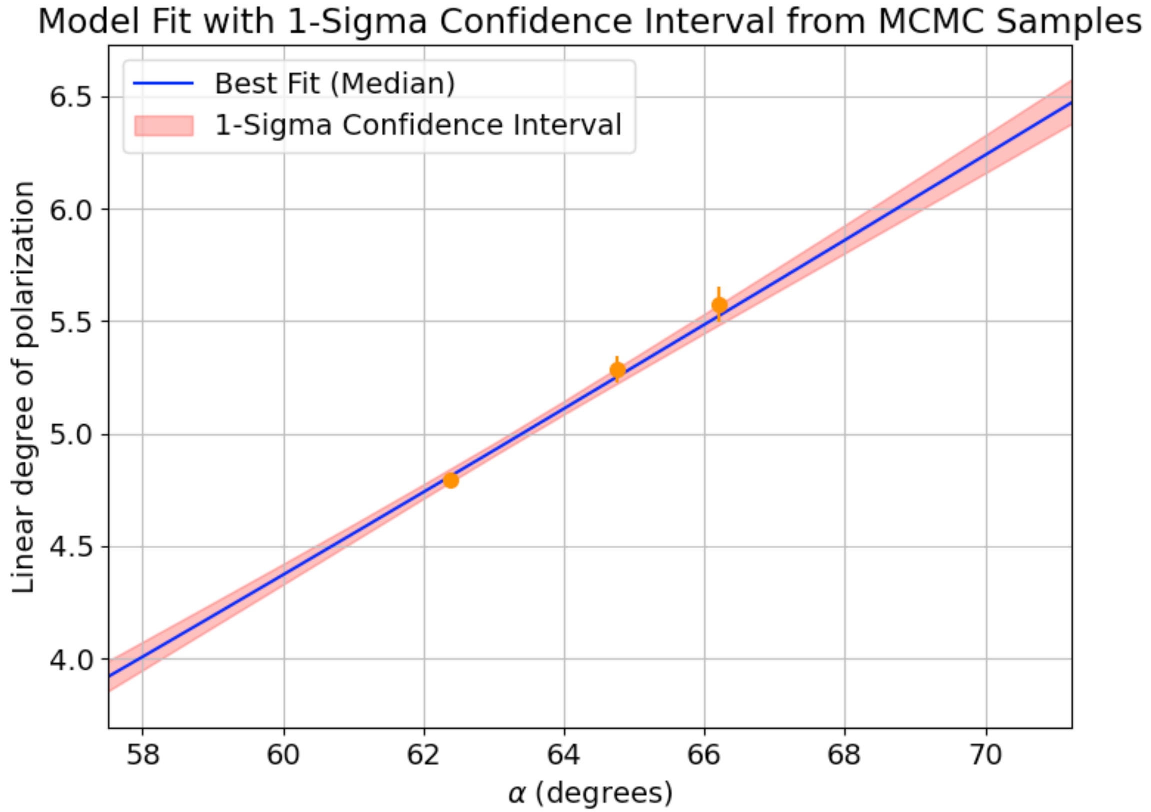
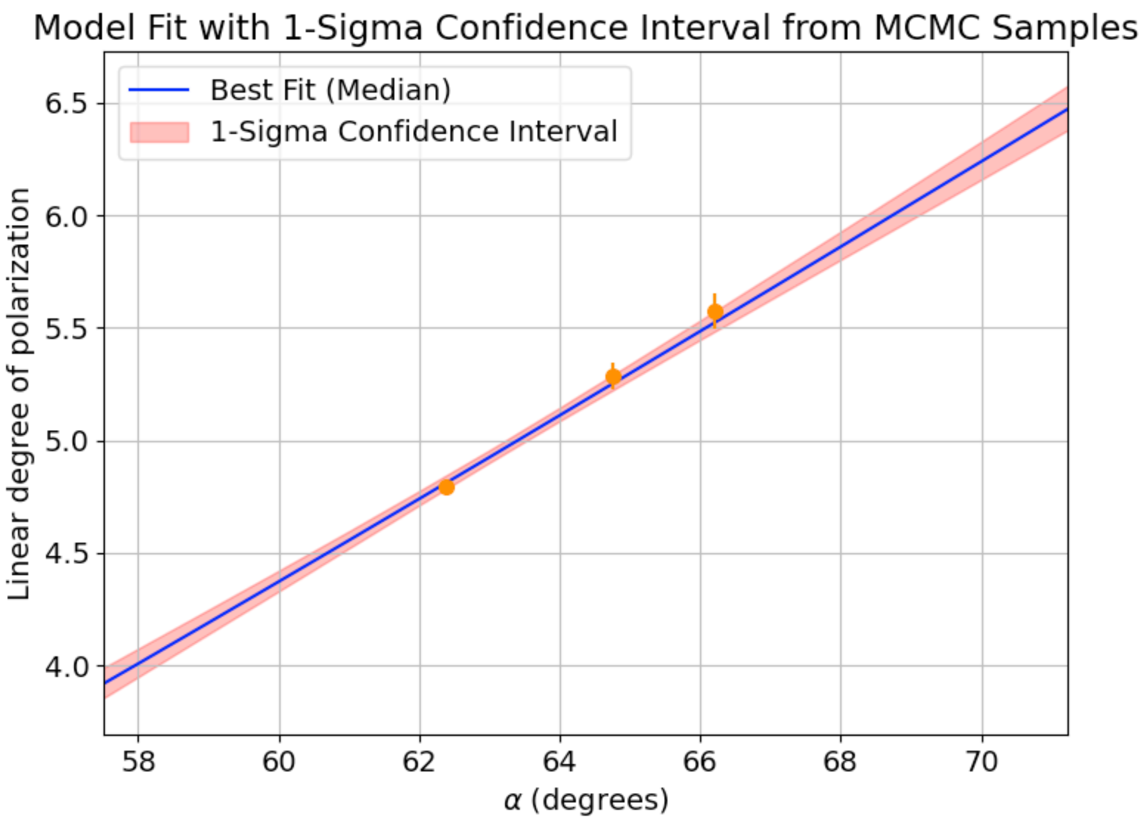


Properties of 2002 QF15

Fit of the exponential-linear model to the data using MCMC routine



Albedo of 2002 QF15?:

- $0.358^{+0.264}_{-0.152}$ Masiero et al. 2020b
- $0.428^{+0.029}_{-0.029}$ Usui et al. 2011
- $0.249^{+0.209}_{-0.144}$ Masiero et al. 2021
- $0.241^{+0.206}_{-0.111}$ Masiero et al. 2020b
- $0.341^{+0.136}_{-0.136}$ Lagoa et al. 2018
- $0.178^{+0.140}_{-0.078}$ Masiero et al. 2017

Average albedo:

- 0.30 +- 0.04 (simple average)
- 0.32 +- 0.06 (Monte Carlo taking into account uncertainties

Radar observations of 2002 QF15

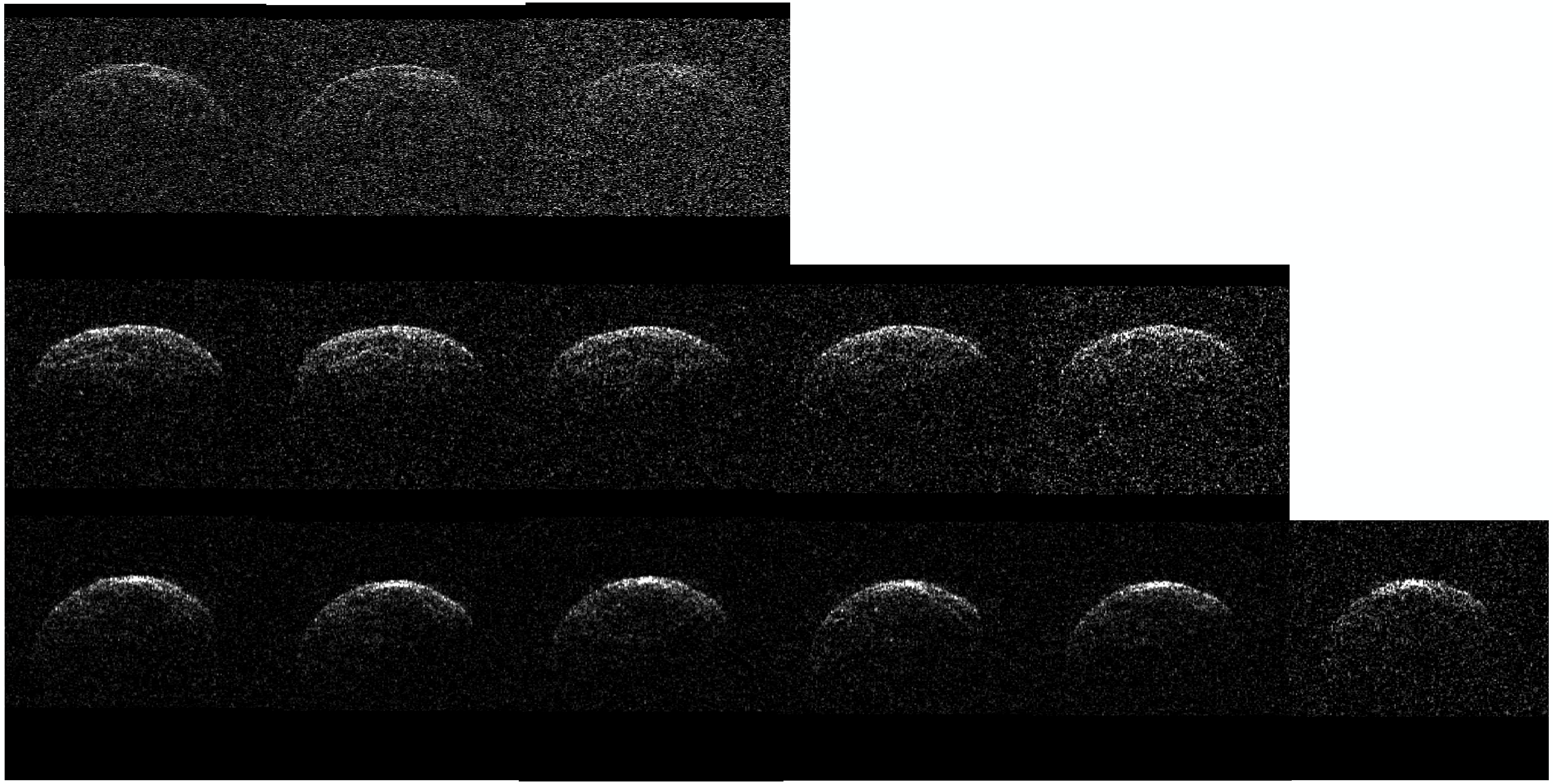
Can we improve the albedo?

2002 QF15 was observed in radar by Arecibo

May 5 2019

May 21 2019

May 22 2019



Radar observations of 2002 QF15

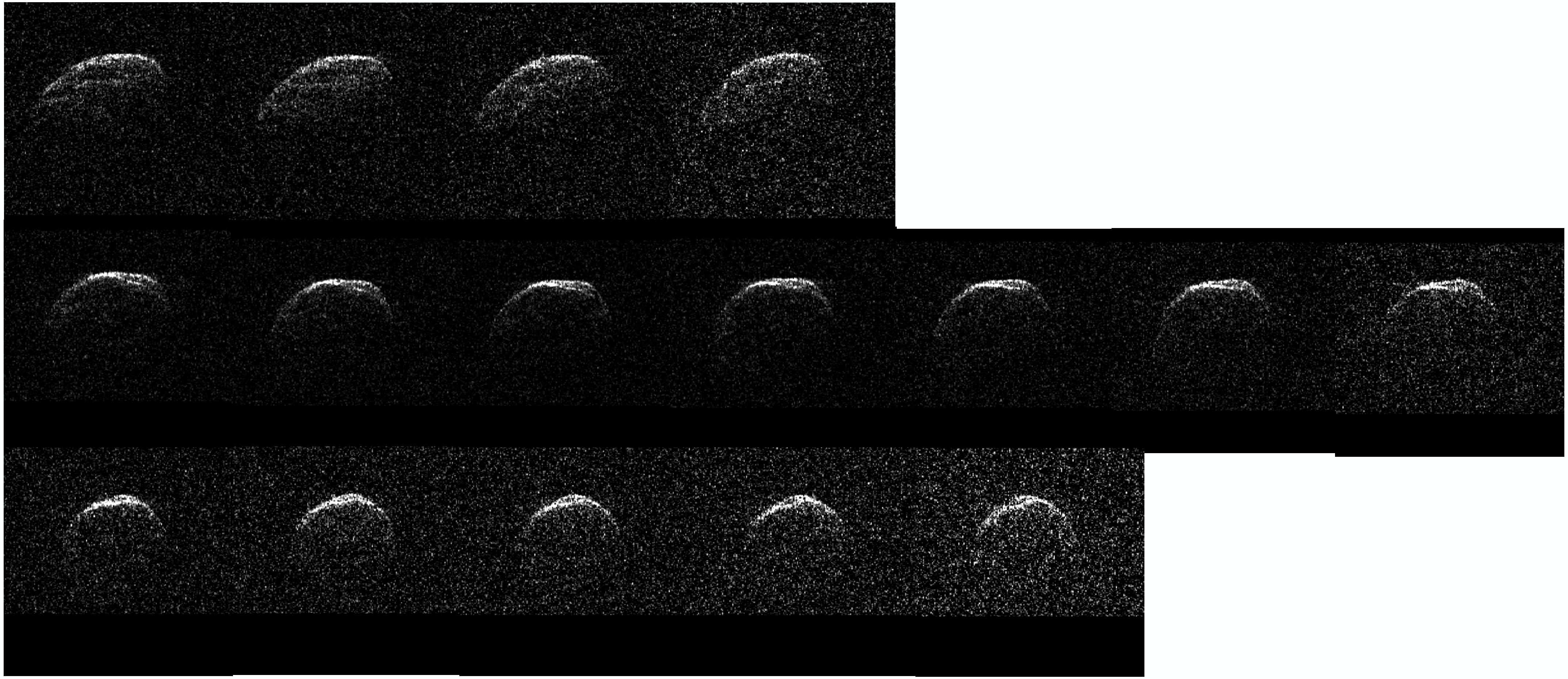
Can we improve the albedo?

2002 QF15 was observed in radar by Arecibo

May 23 2019

May 24 2019

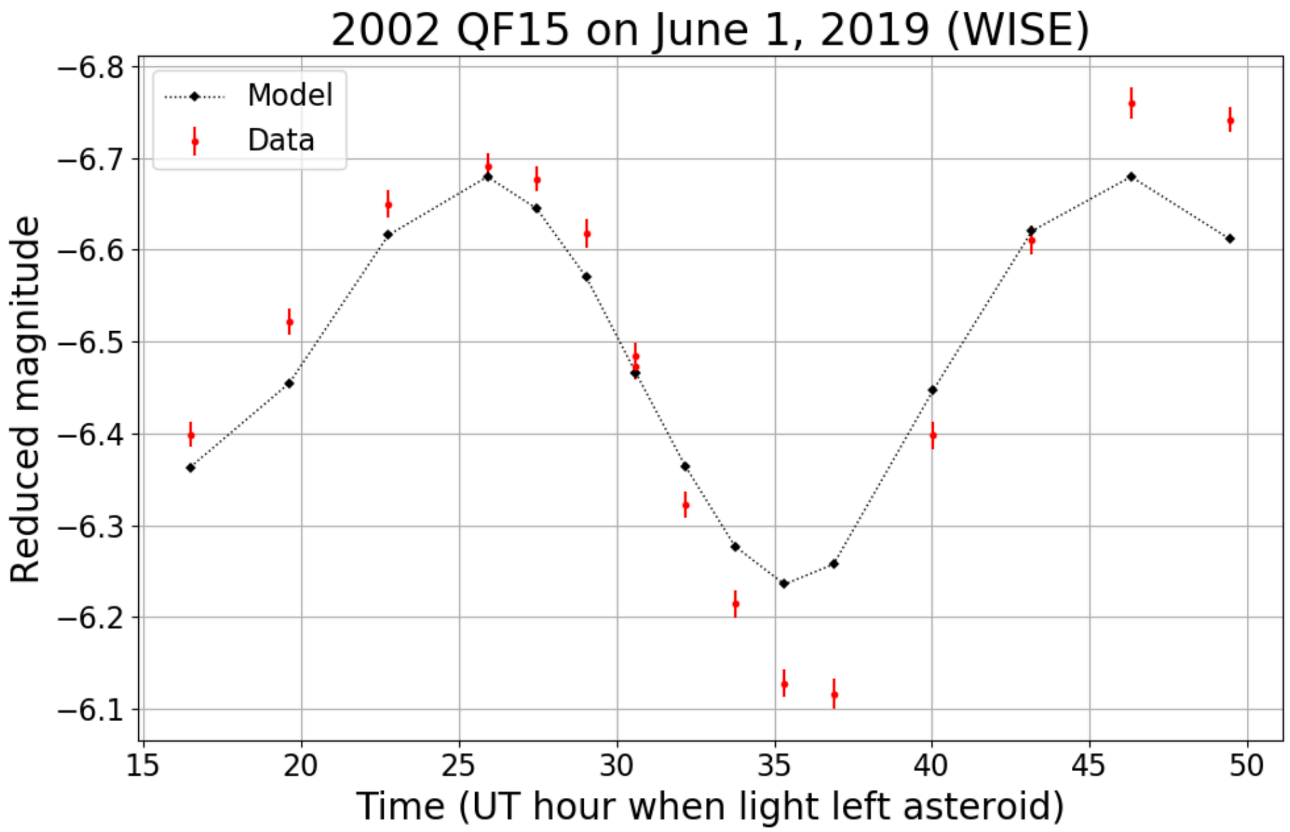
May 25 2019



NEOWISE Observations of 2002 QF15

Can we improve the albedo?

Lightcurves from NEOWISE



Highly useful to confirm the 46.05 hours rotation period

Reese L Williams results

Results of the radar shape model of 2002 QF15

Can we improve the albedo?

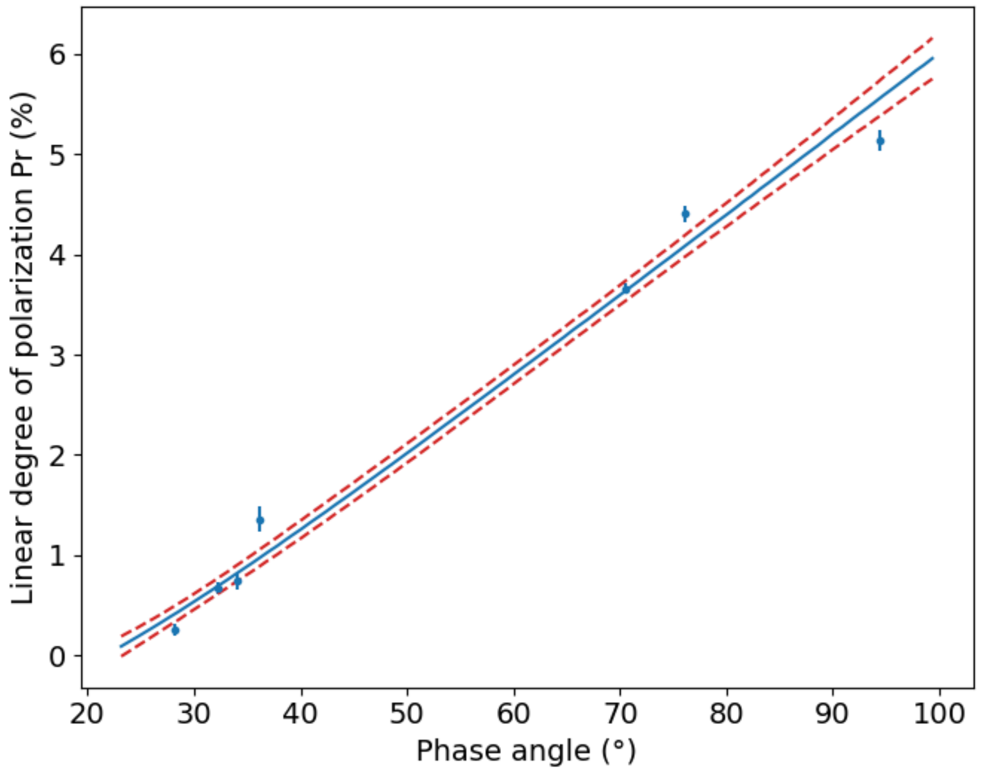
Final results:

- Ellipsoidal shape of dimensions: 2.2x1.7x1.7 km
- Equivalent diameter: 1.85 km
- Considering H=16.39 (MPC) => pv = 0.15

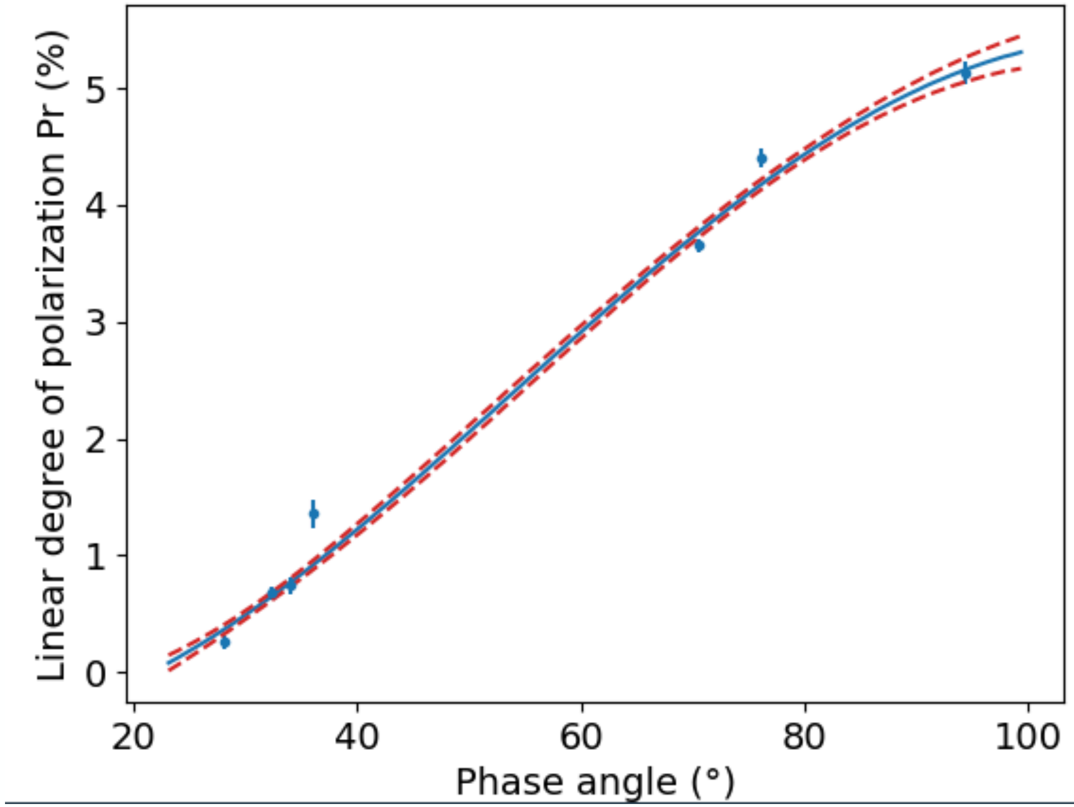
Reese L Williams results

Example of fit

Observations of 1990 UQ

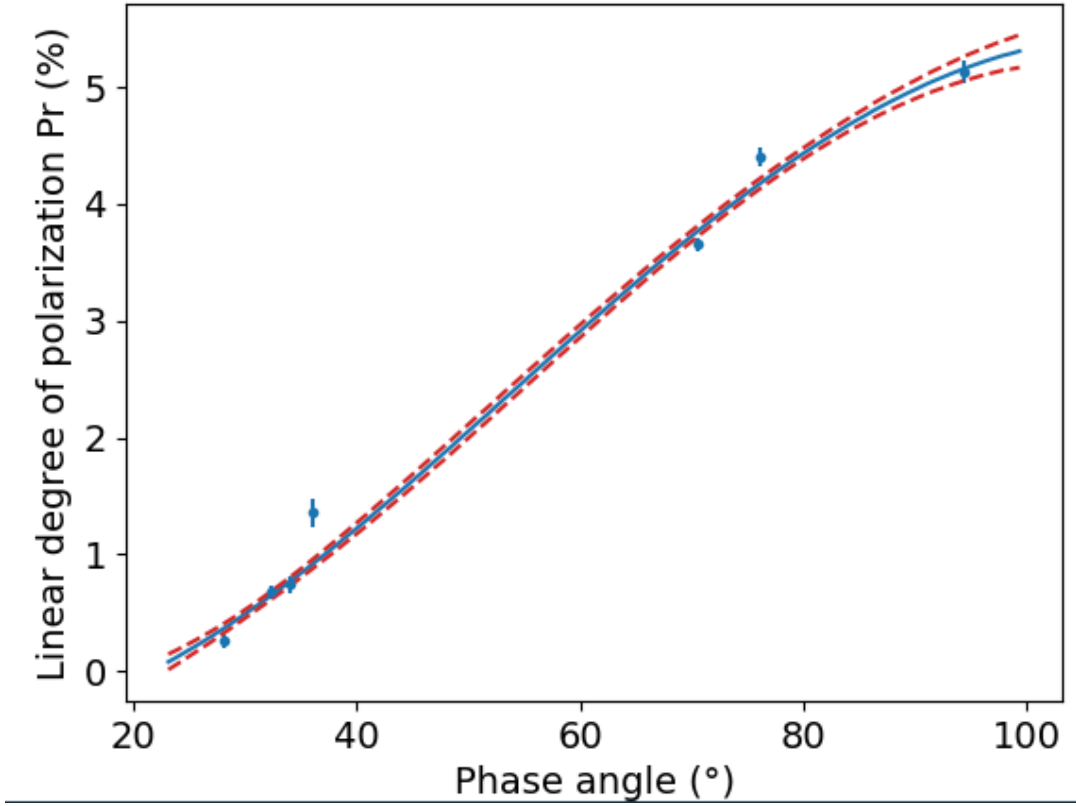


Fit using the trigonometric model model with prior information



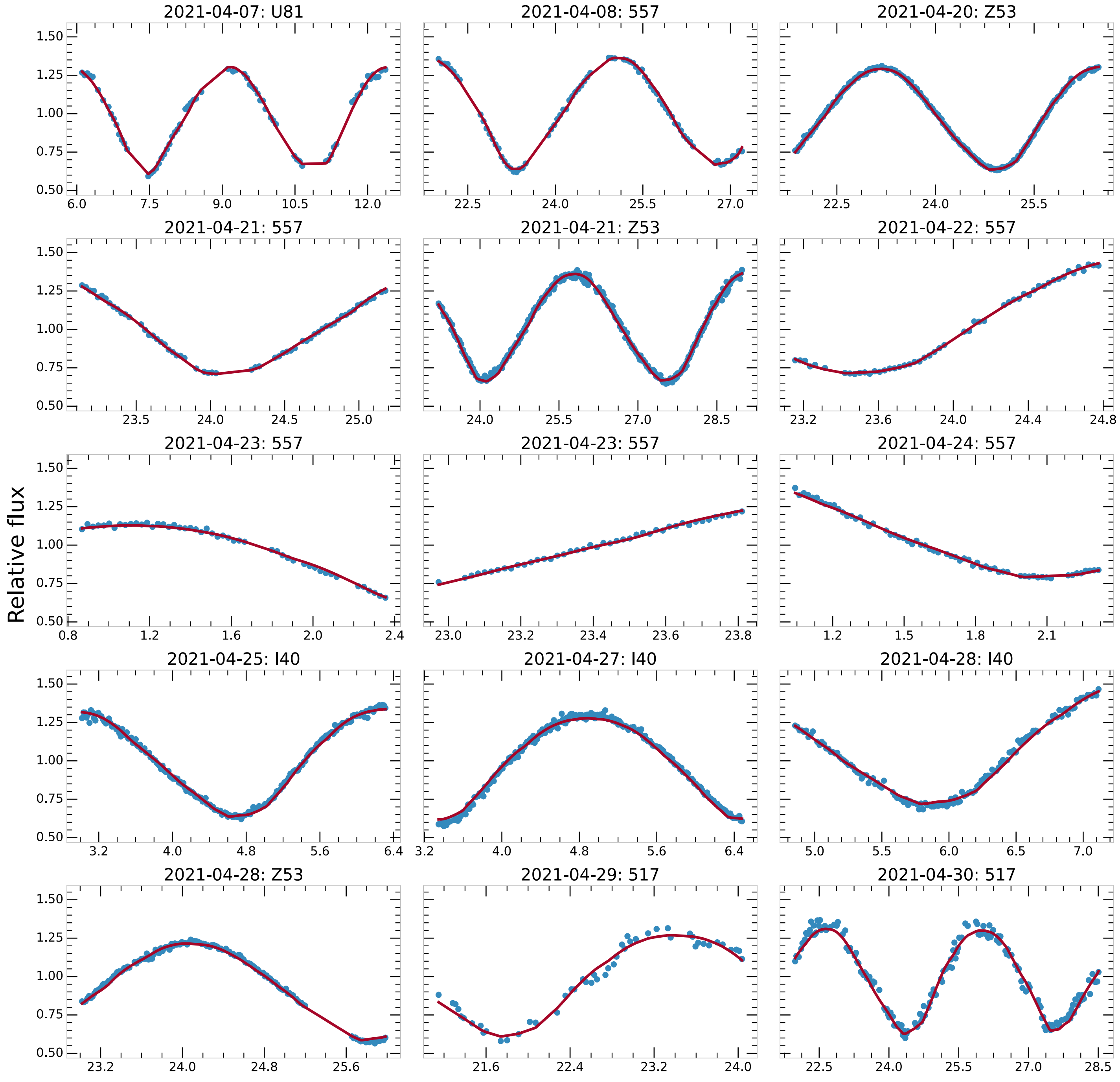
Example of fit

Observations of 1990 UQ

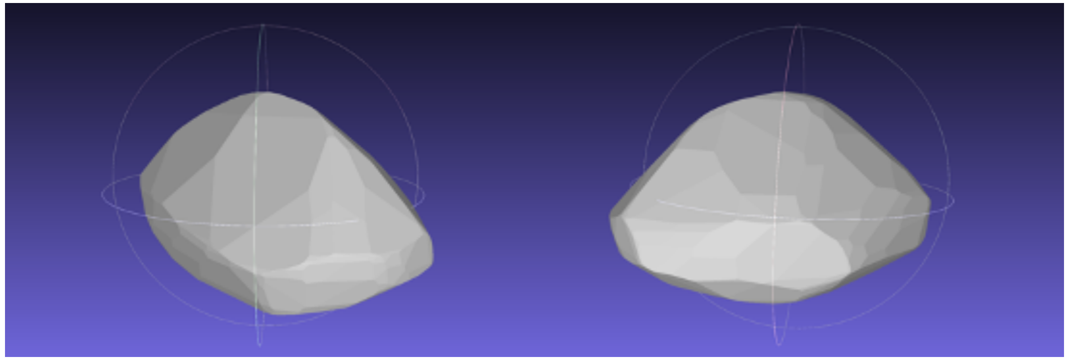


What do we know about Apollo's albedo:

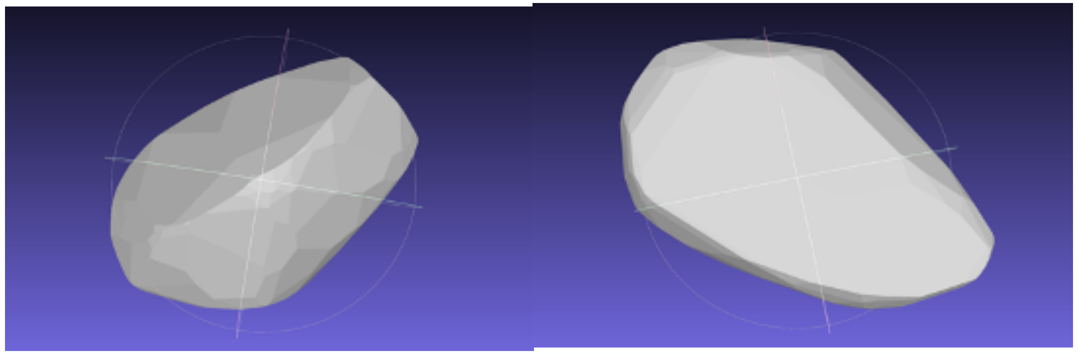
- 0.203 (Trilling et al. 2010)
- $0.448^{+0.332}_{-0.188}$ (Masiero et al. 2021)



X axis X axis



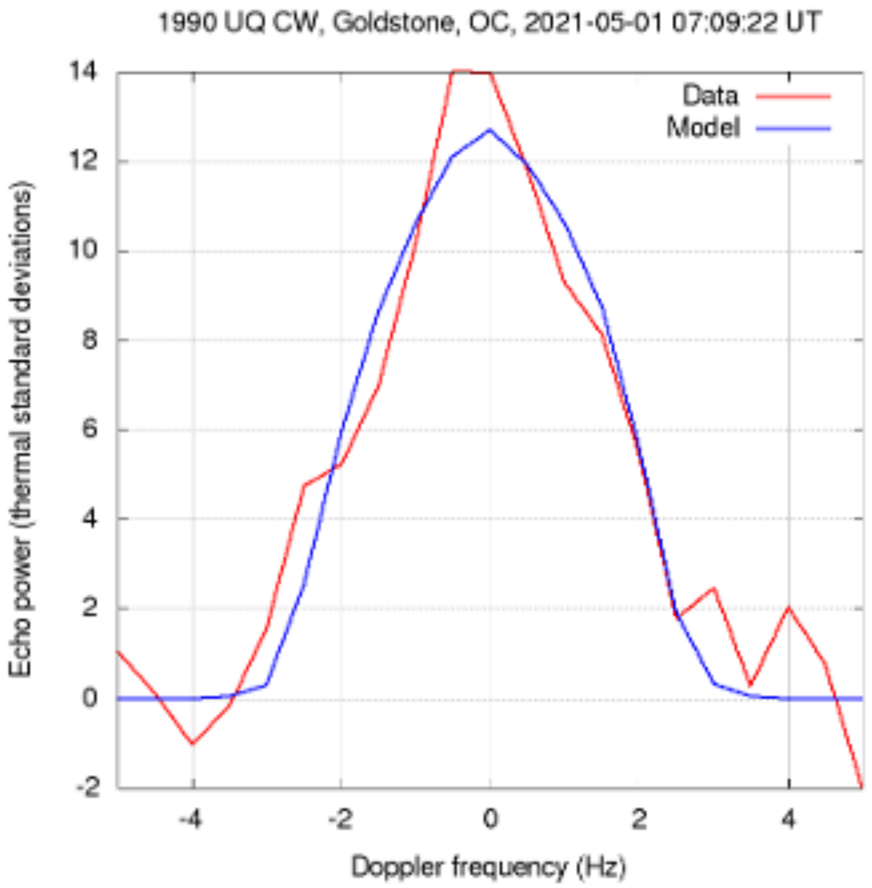
North pole South pole

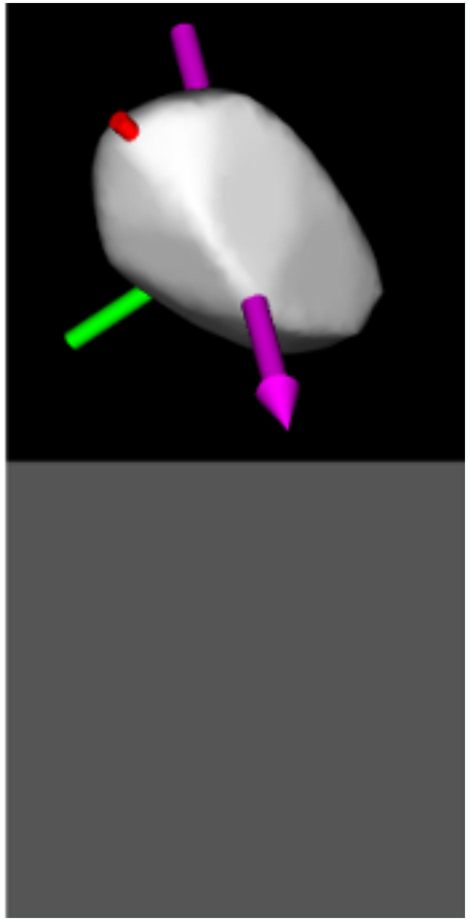


Xavier Inosencio shape modeling results

→ THE EUROPEAN SPACE AGENCY

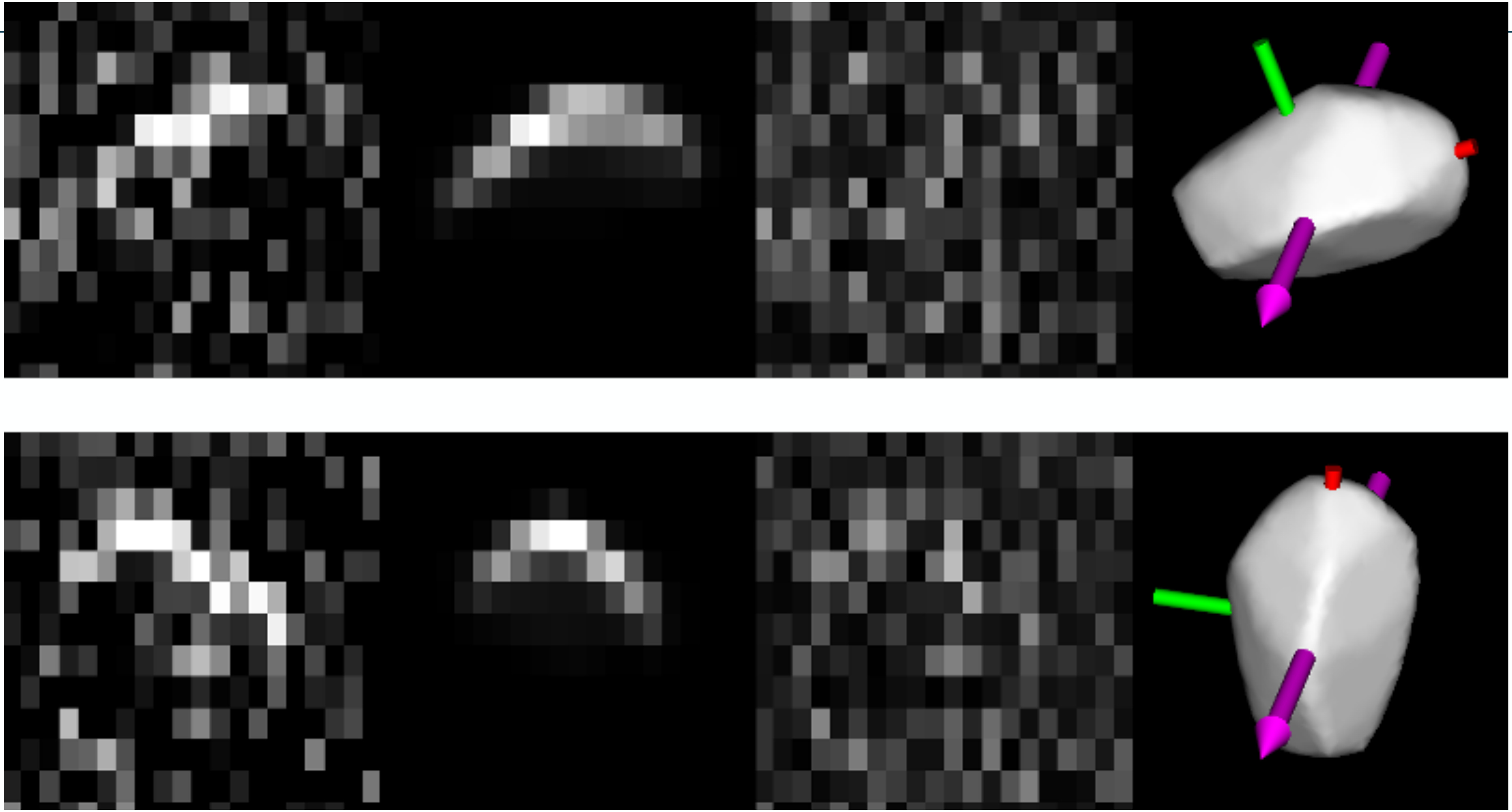
CW observation on 1990 UQ





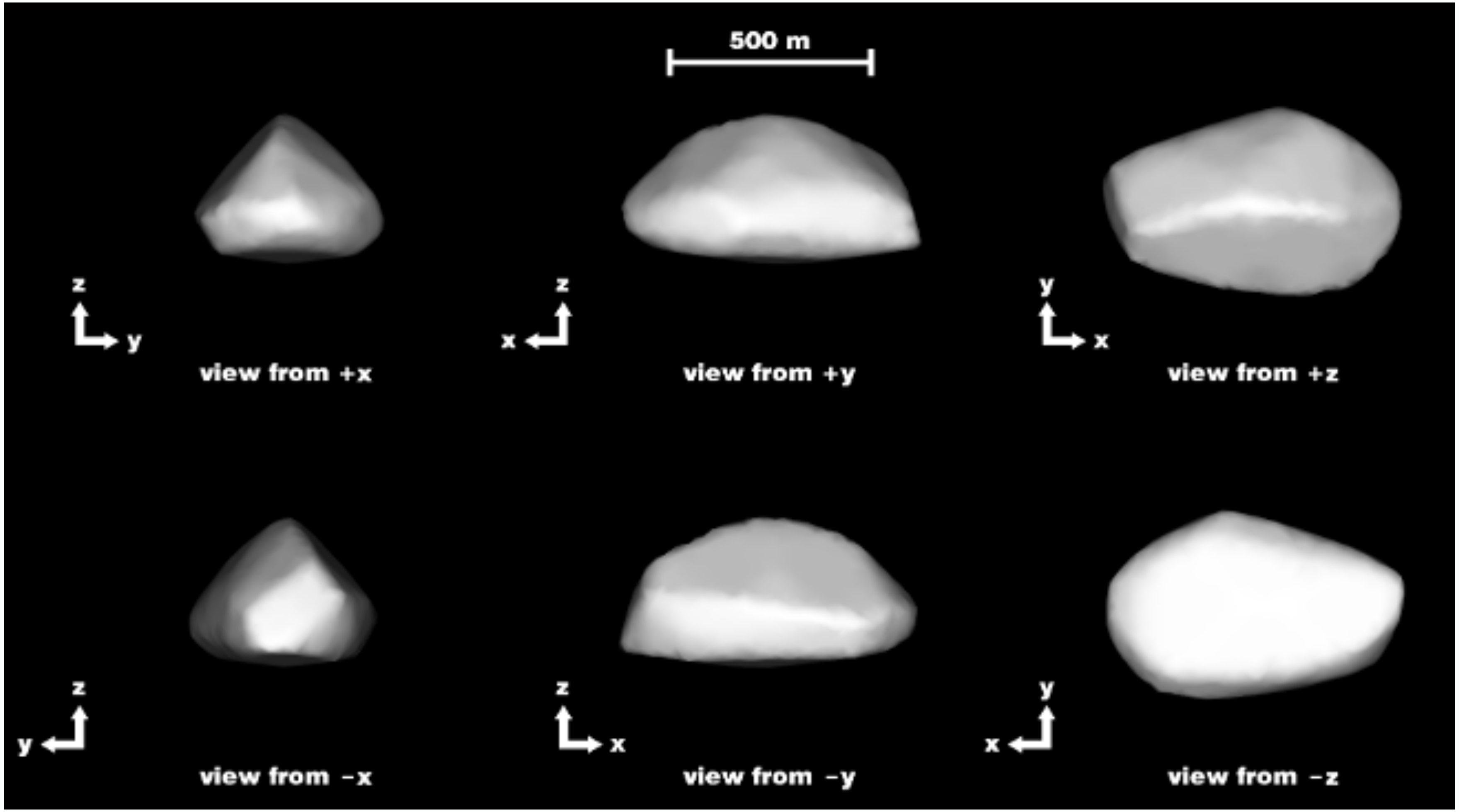
Xavier Inosencio shape modeling results

Delay-Doppler observations of 1990 UQ



Xavier Inosencio shape modeling results

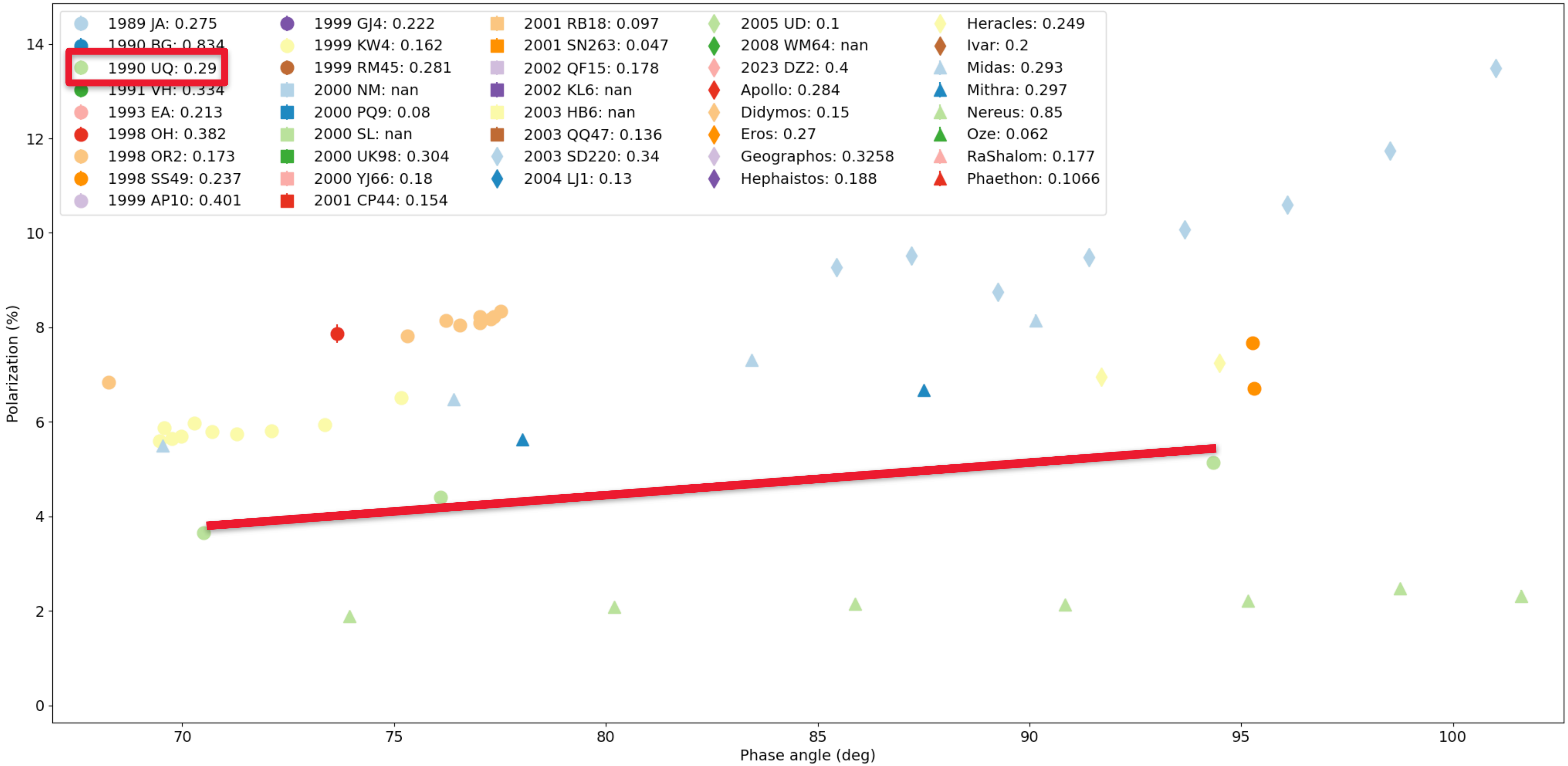
Radar shape model of 1990 UQ

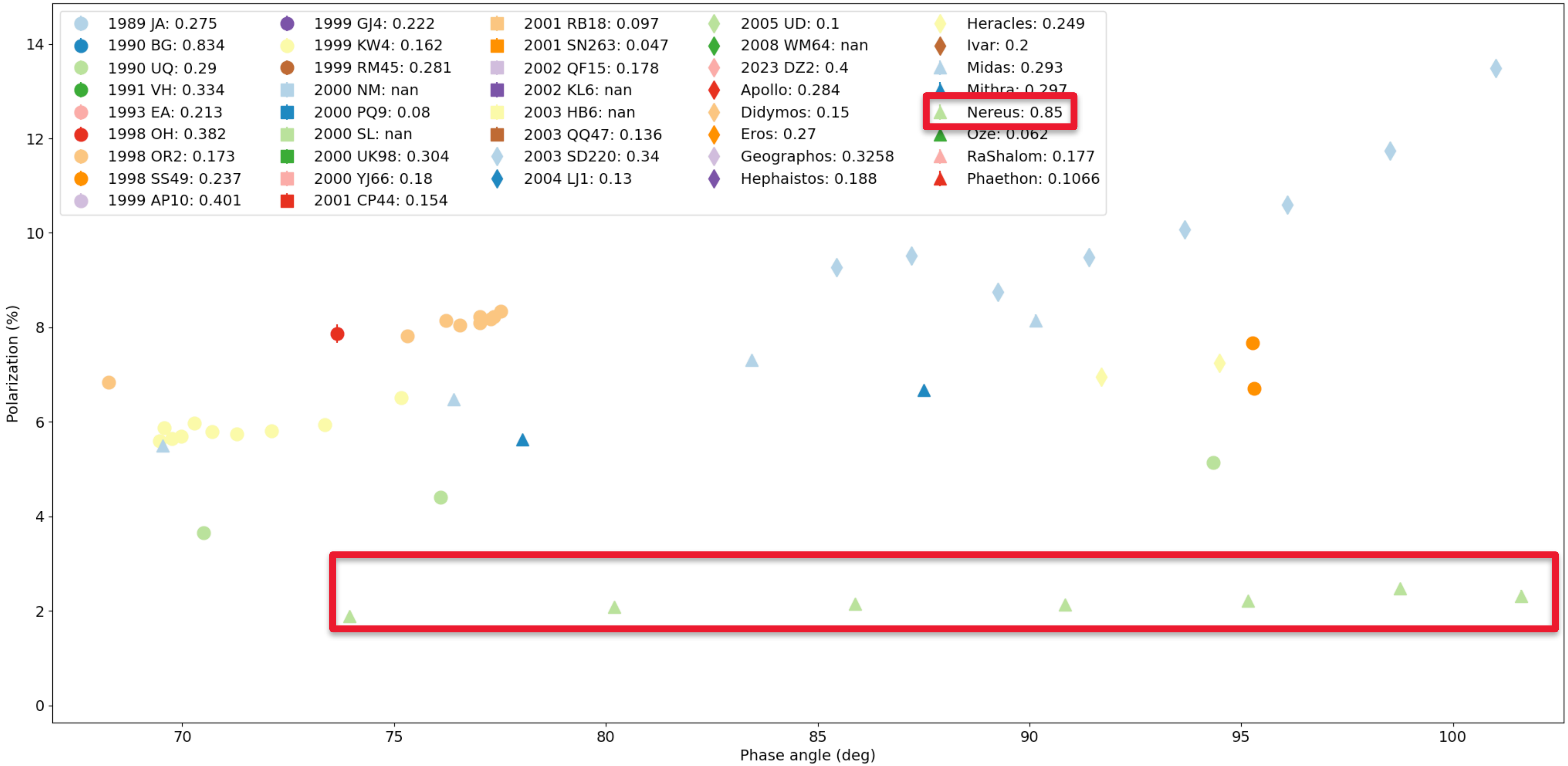


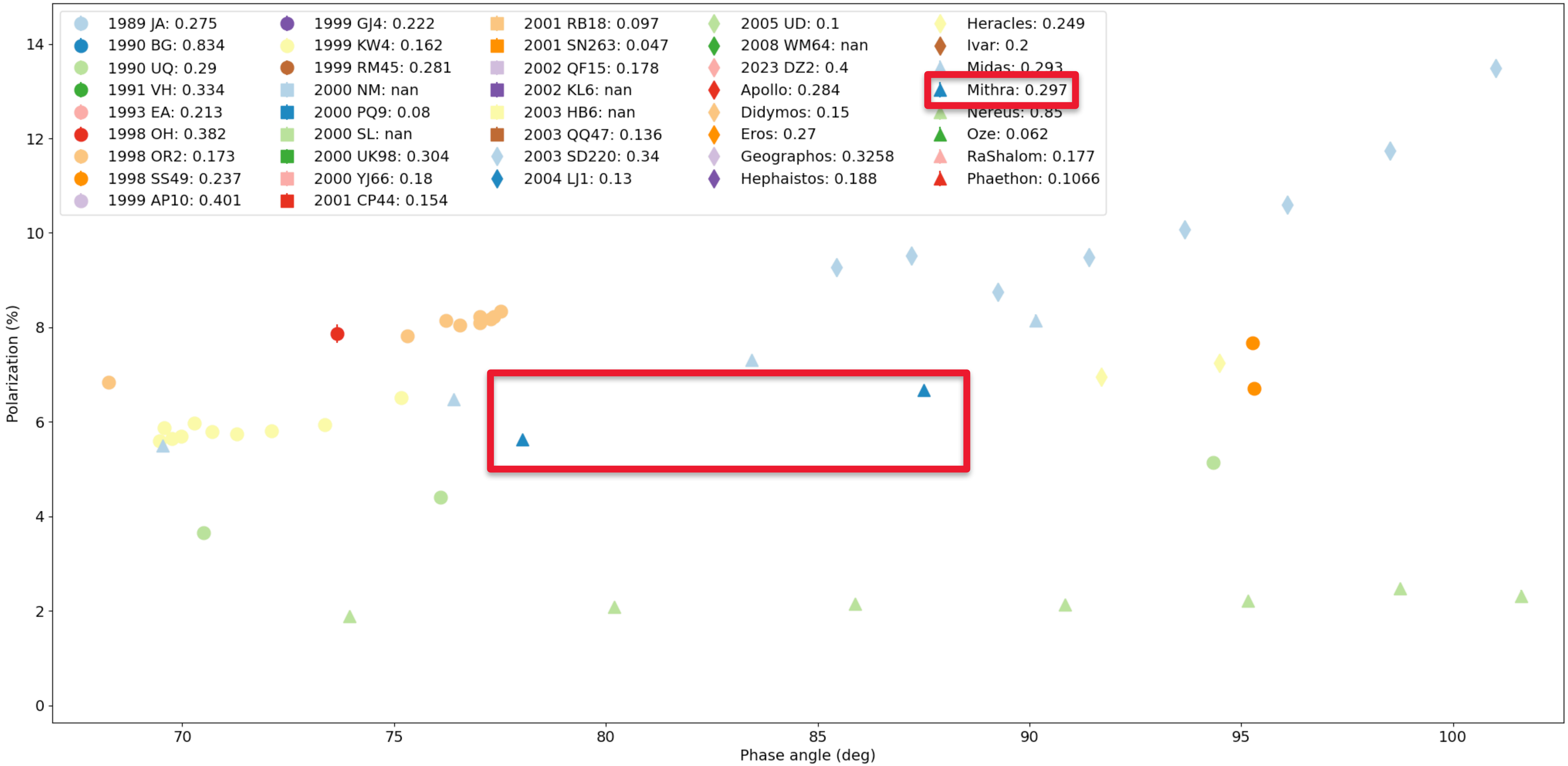
D = 0.48 km

H = 17.94 => pv = 0.51

Xavier Inosencio shape modeling results


1989 JA: 0.275
1990 BG: 0.834
1990 UQ: 0.29
1991 VH: 0.334
1993 EA: 0.213
1998 OH: 0.382
1998 OR2: 0.173
1998 SS49: 0.237
1999 AP10: 0.401
1999 GJ4: 0.222
1999 KW4: 0.162
1999 RM45: 0.281
2000 NM: nan
2000 PQ9: 0.08
2000 SL: nan
2000 UK98: 0.304
2000 YJ66: 0.18
2001 CP44: 0.154
2001 RB18: 0.097
2001 SN263: 0.047
2002 QF15: 0.178
2002 KL6: nan
2003 HB6: nan
2003 QQ47: 0.136
2003 SD220: 0.34
2004 LJ1: 0.13
2005 UD: 0.1
2008 WM64: nan
2023 DZ2: 0.4
Apollo: 0.284
Didymos: 0.15
Eros: 0.27
Geographos: 0.3258
Hephaistos: 0.188
Heracles: 0.249
Ivar: 0.2
Midas: 0.293
Mithra: 0.297
Nereus: 0.85
Oze: 0.062
RaShalom: 0.177
Phaethon: 0.1066
Polarization (%)
Phase angle (deg)
0
2
4
6
8
10
12
14
70
75
80
85
90
95
100


1989 JA: 0.275
1990 BG: 0.834
1990 UQ: 0.29
1991 VH: 0.334
1993 EA: 0.213
1998 OH: 0.382
1998 OR2: 0.173
1998 SS49: 0.237
1999 AP10: 0.401
1999 GJ4: 0.222
1999 KW4: 0.162
1999 RM45: 0.281
2000 NM: nan
2000 PQ9: 0.08
2000 SL: nan
2000 UK98: 0.304
2000 YJ66: 0.18
2001 CP44: 0.154
2001 RB18: 0.097
2001 SN263: 0.047
2002 QF15: 0.178
2002 KL6: nan
2003 HB6: nan
2003 QQ47: 0.136
2003 SD220: 0.34
2004 LJ1: 0.13
2005 UD: 0.1
2008 WM64: nan
2023 DZ2: 0.4
Apollo: 0.284
Didymos: 0.15
Eros: 0.27
Geographos: 0.3258
Hephaistos: 0.188
Heracles: 0.249
Ivar: 0.2
Midas: 0.293
Mithra: 0.297
Nereus: 0.85
Oze: 0.062
RaShalom: 0.177
Phaethon: 0.1066
Polarization (%)
Phase angle (deg)



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Polarization (%)
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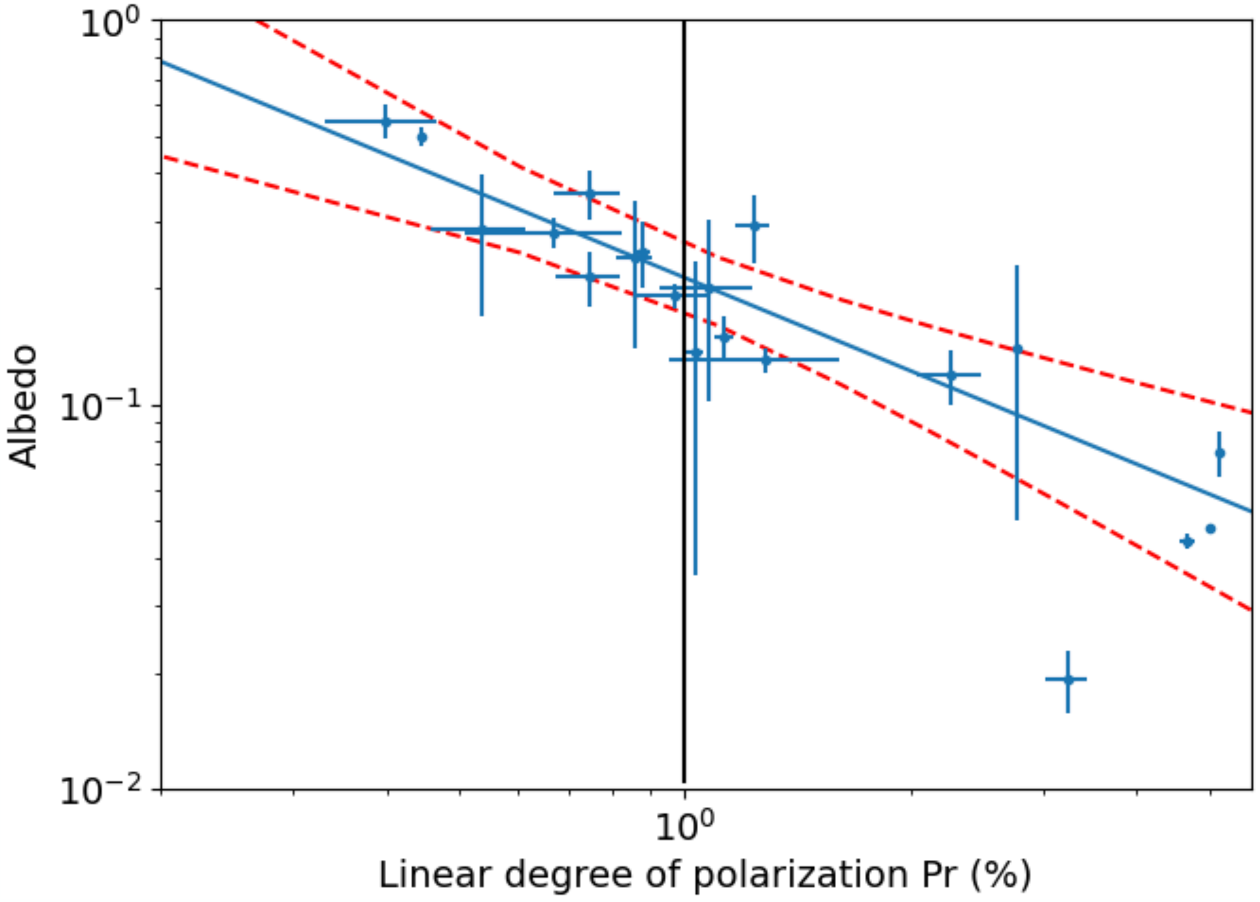
Calibration of the albedo-polarization relation

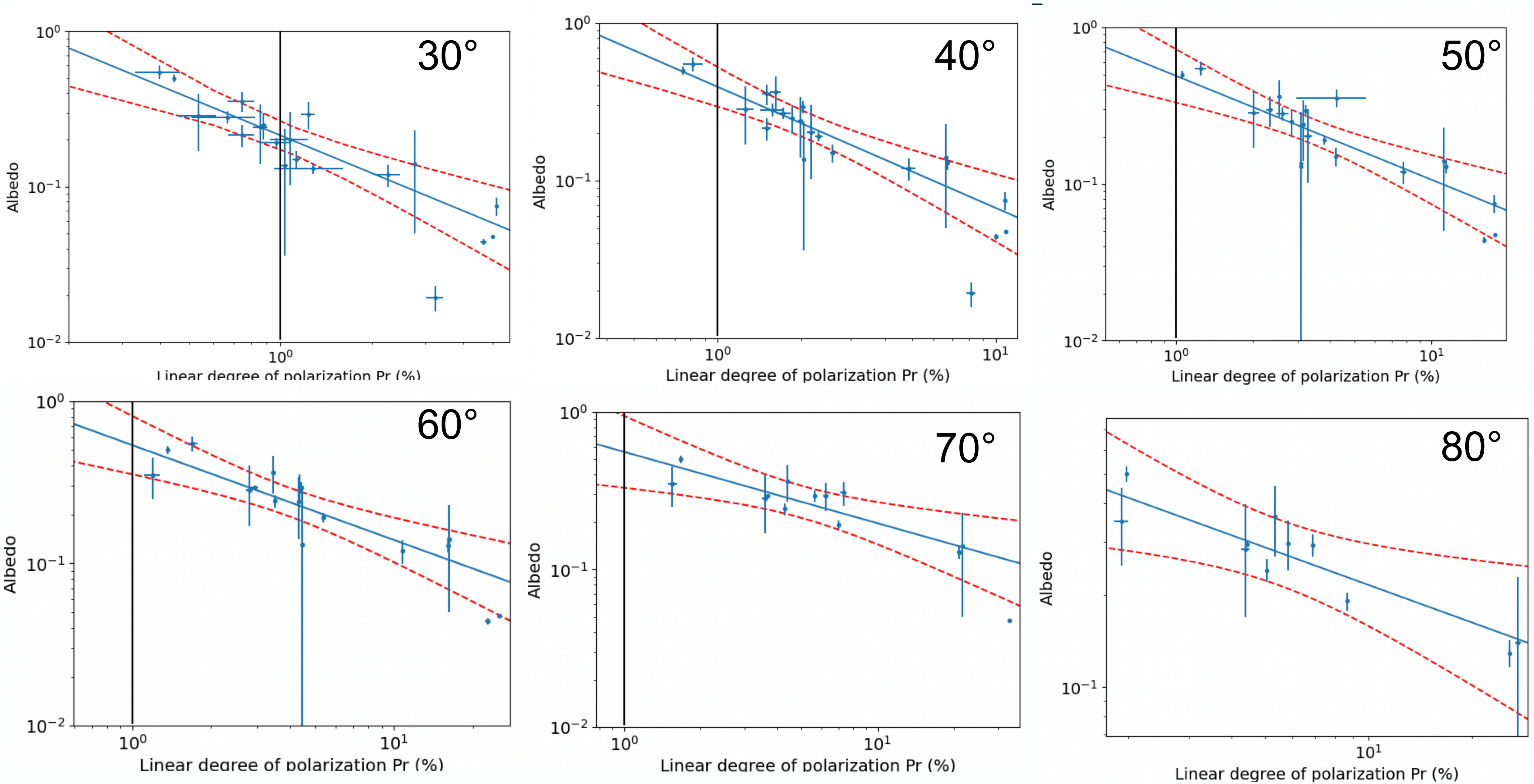


Example for a phase angle of 30°

- Pr = 0.6 => pv = 0.32 (0.25-0.41)
- Pr = 1% => pv = 0.21 (0.17-0.26)
- Pr = 1.6% => pv = 0.14 (0.11-0.19)
- Pr = 2.1% => pv = 0.11 (0.08-0.16)
- Pr = 3.1% => pv = 0.08 (0.06-0.13)
- Pr = 5.6% => pv = 0.05 (0.03-0.10)

Not defined for Pr > 5.6% (no data)

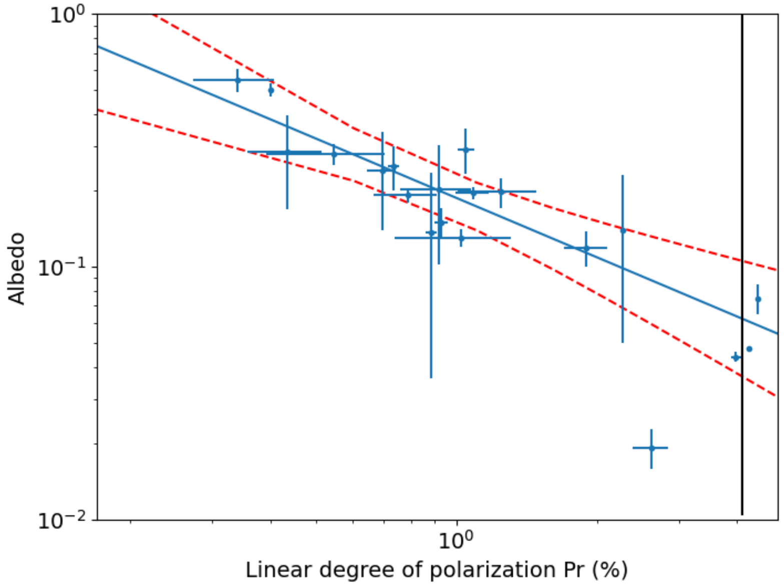
Calibration of the albedo-polarization relation



Application of the new calibration

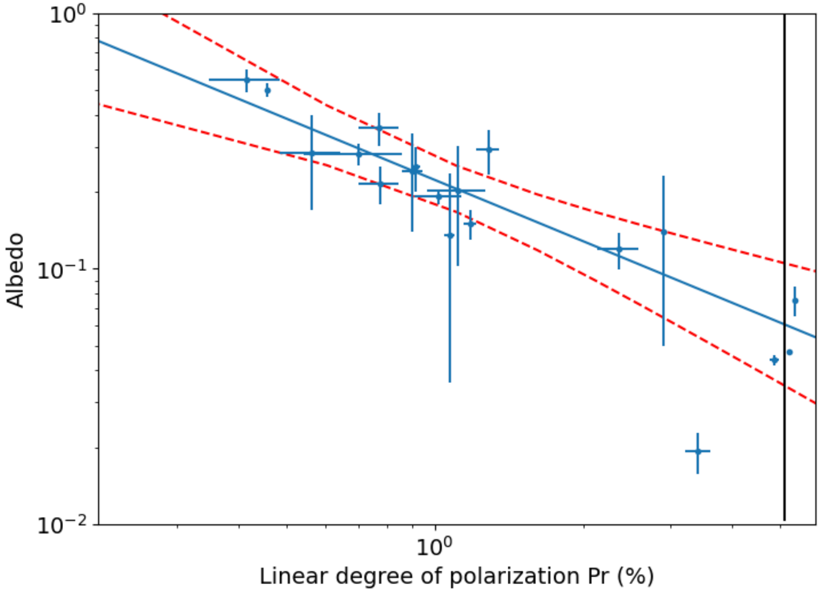
2001 RB18:

Pr = 4.09% (α = 28.5°)



pv = 0.06 (0.04-0.11)

Pr = 5.1% (α = 30.4°)

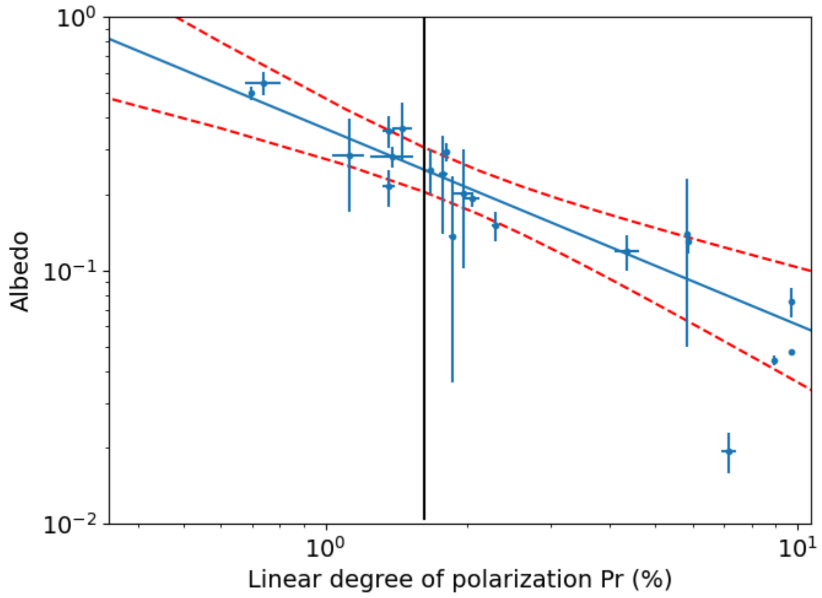


pv = 0.06 (0.03-0.11)

Application of the new calibration

2000 NM:

Pr = 1.62% (α = 38.15°)



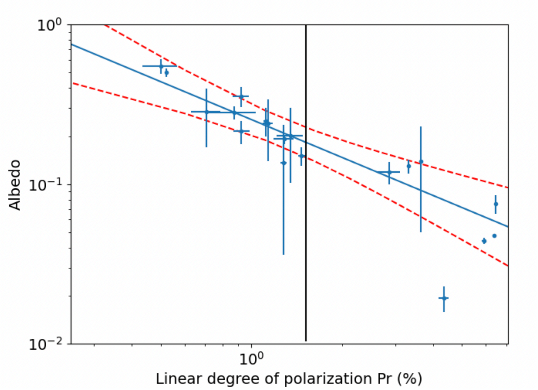
pv = 0.25 (0.20-0.31)

Taxonomy: V-type => Expected to have a high albedo

Application of the new calibration

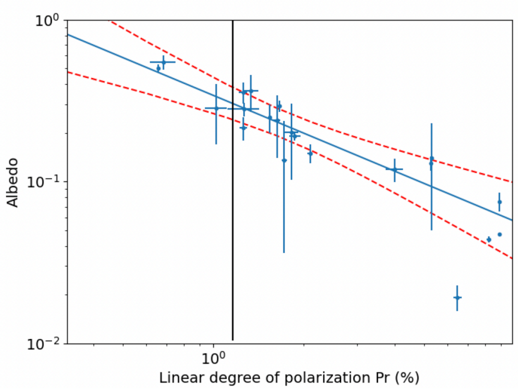
2002 KL6:

Pr = 1.52% (α = 32.49°)



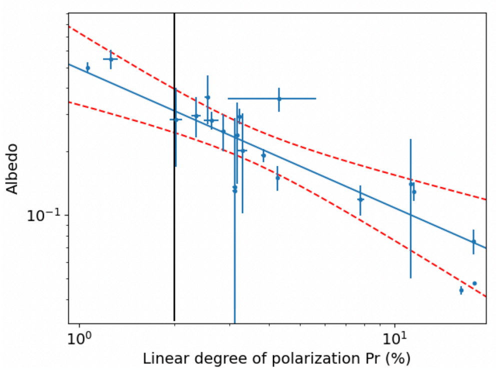
Pv = 0.18 (0.15-0.23)

Pr = 1.16% (α = 36.85°)



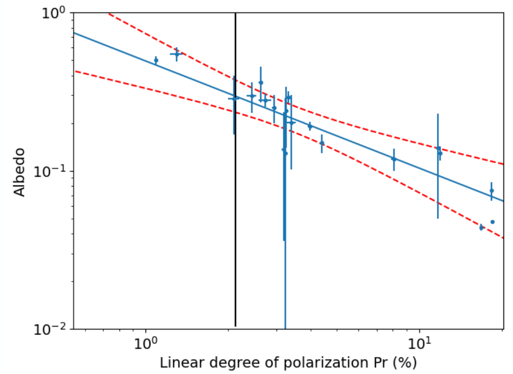
Pv = 0.30 (0.24-0.38)

Pr = 2.0% (α = 50.18°)



Pv = 0.31 (0.25-0.40)

Pr = 2.13% (α = 51.05°)



Pv = 0.30 (0.23-0.37)

Conclusions

- Polarimetry can be used obtain information on the albedo of atmosphereless objects
- In the past, the slope at inversion angle has been used
- NEOs can be observed at much higher and more diagnostic phase angles
- We started a survey of polarimetric observations of NEOs
- We developed a calibration for any phase angles that can be use with single polarimetric observations