ASTEROID PHOTOMETRIC AND POLARIMETRIC MODELLING

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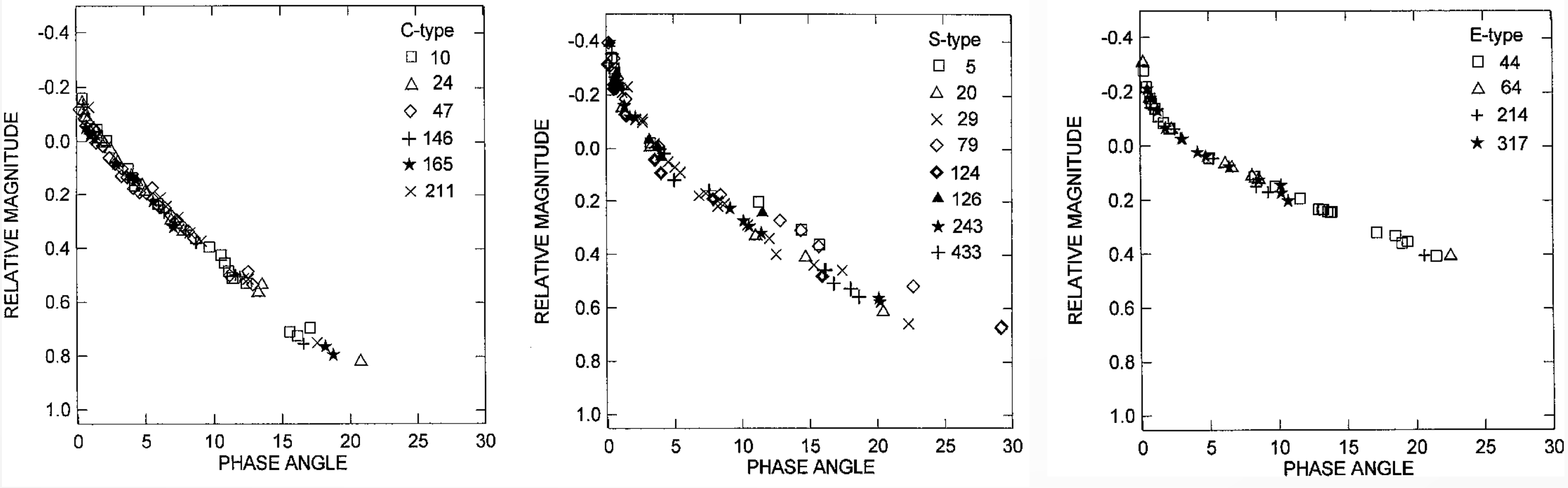
PHOTOMETRIC OBSERVATIONS

- Atmosphereless Solar System objects (SSOs), such as asteroids, exhibit special features in the way they scatter unpolarized incident sunlight:
  - nonlinear increase in brightness at small phase angles (the angle between the Sun and the observer seen from the object, α), i.e. the opposition effect (amplitude and angular width)
  - A linear photometric slope at $\alpha = 10° - 50°$ (in the magnitude scale)

Low albedo → High albedo



Belskaya & Shevchenko (Icarus, 2000)

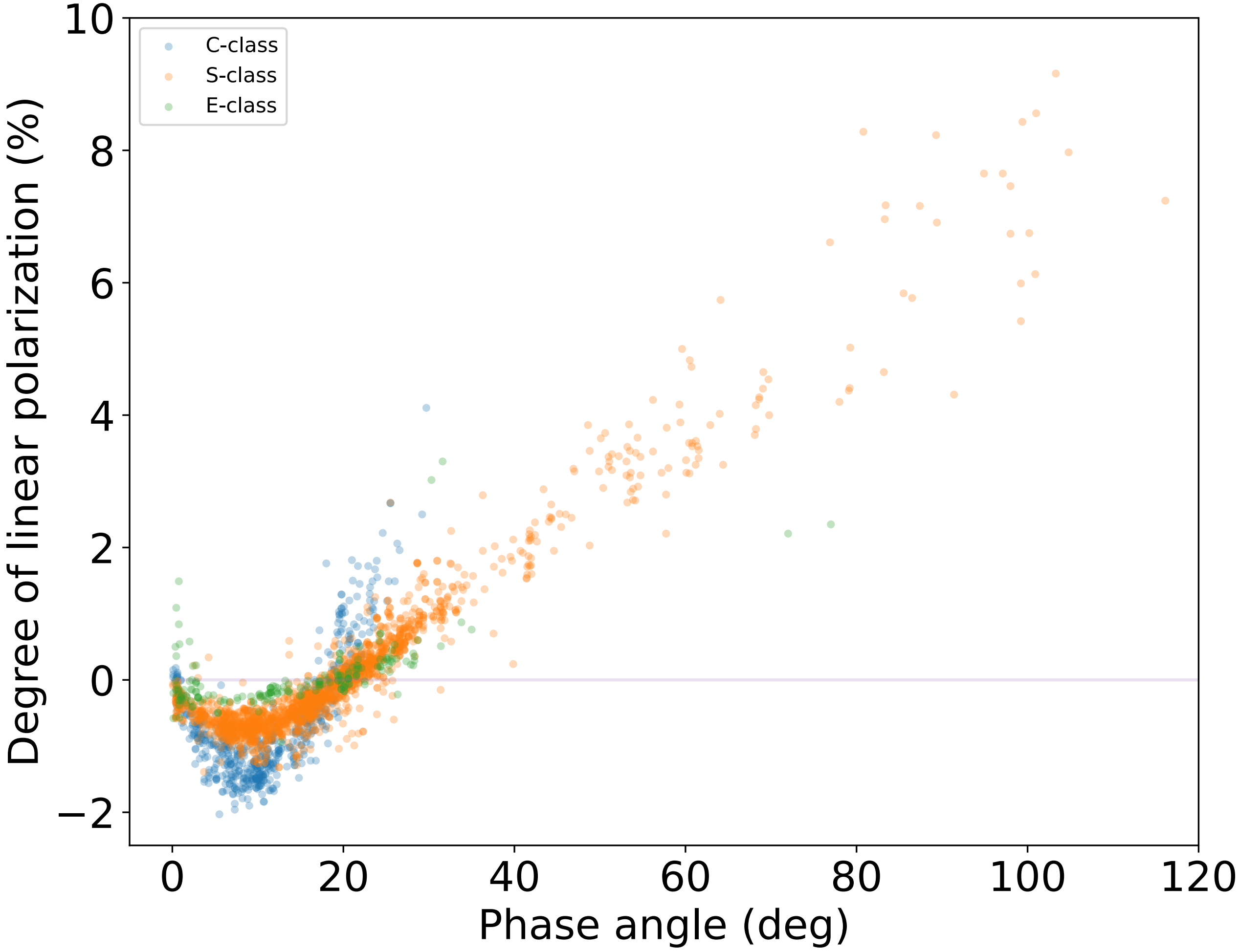
POLARIMETRIC OBSERVATIONS

- Negative degree of linear polarization at $\alpha \leq 15°$-$30°$
  - Degree of linear polarization describes how much of the incident flux is either perpendicularly polarized ($P_r > 0$) or parallel ($P_r < 0$) to the scattering plane (Sun-asteroid-observer):

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

- Positive polarization with a maximum at $\alpha > 90°$

Catalogue of asteroid polarimetric observations, Gil-Hutton 2023: http://gcpsj.sdf-eu.org/catalogo.html



ASTEROID OBSERVATIONS

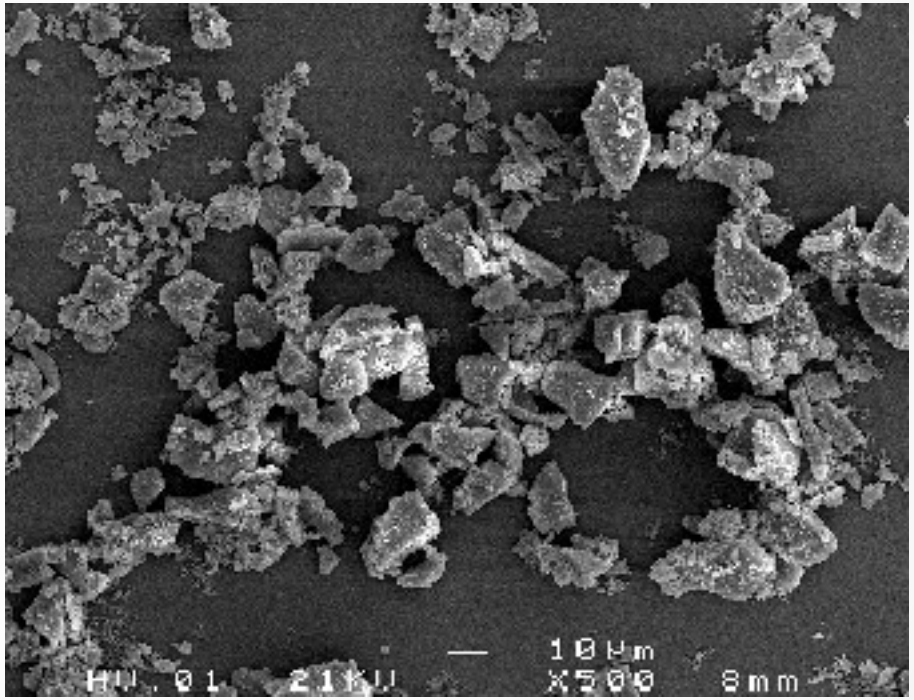
- The phenomena near backscattering are likely due to the surface regolith consisting of closely packed small particles

- Models producing the photometric and polarimetric phase angle dependence of different asteroid classes:
  - Constrain size distribution, shape, refractive indices of the particles (→ information about composition)

EMPIRICAL SCATTERING MATRIX

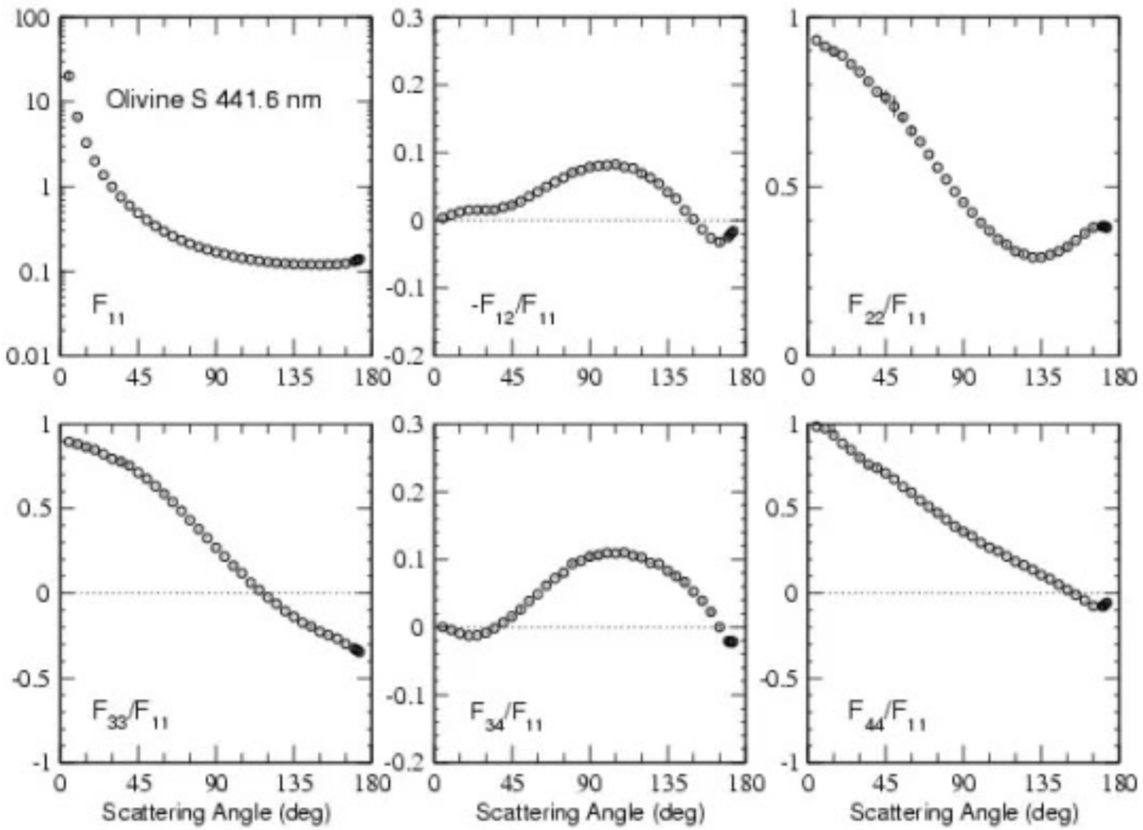
- Starting point for modelling the photometric and polarimetric phase curves is to use scattering phase matrices measured from a size distribution of particles (ensemble-averaged) as the single-scattering input

- Measurement data available in the Granada-Amsterdam Light Scattering Database (Muñoz et al., JQSRT, 2025; https://scattering.iaa.es/)
- E.g. olivine, refractive index 1.62 + *i0.0001-i*0.001



EMPIRICAL SCATTERING MATRIX

$$\theta = \pi - \alpha$$



If used as is in a multiple-scattering computation, the resulting polarization curve would have too much negative polariztion and not large enough maximum for e.g. S-class

Also, the single-scattering albedo would be too high

SMALL AND LARGE PARTICLES

- Combine small and large particles (compared to λ)
  - Large particles create more positive polarization and shift the maximum
  - Compute scattering phase matrix and scattering and extinction cross sections for a size distribution of large Gaussian particles with the geometric optics approximation
  - With appropriate weights of the small and large particles (taking into account cross sections and number densities), the combined single-scattering albedo and the phase matrix to represent single scattering is computed

- Radiative transfer and coherent backscattering (RT-CB):
  - Numerical multiple scattering method for computing scattering and absorption in a densely packed random medium of nonspherical particles (Muinonen et al., JQSRT 2025)

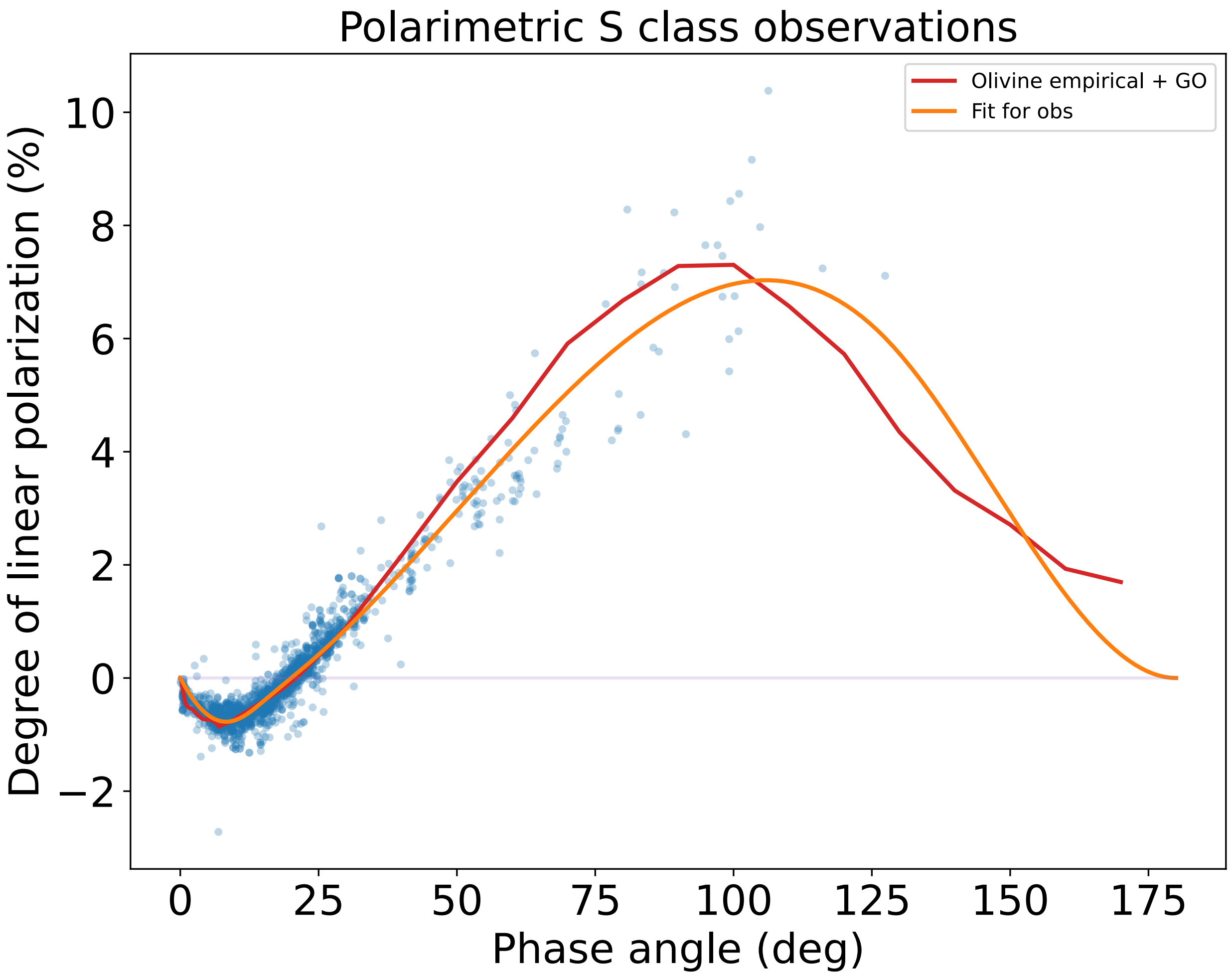
RT-CB RESULTS: S-CLASS

First, S-class:

- Measured olivine, refractive index 1.62 + *i*0.001, 1μm volume element at 20% packing density
- Size distribution 10-110 μm (power law r^{-3}) particles with same refractive index

Multiple-scattering result:

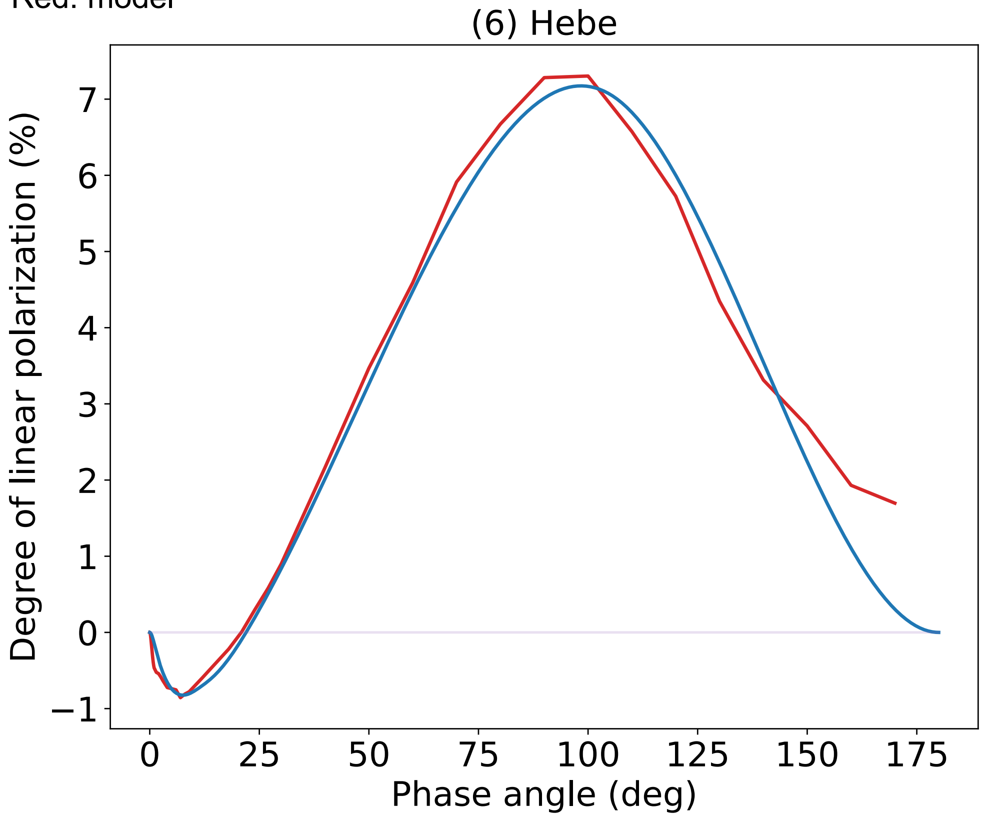
- Geometric albedo p_V = 0.175



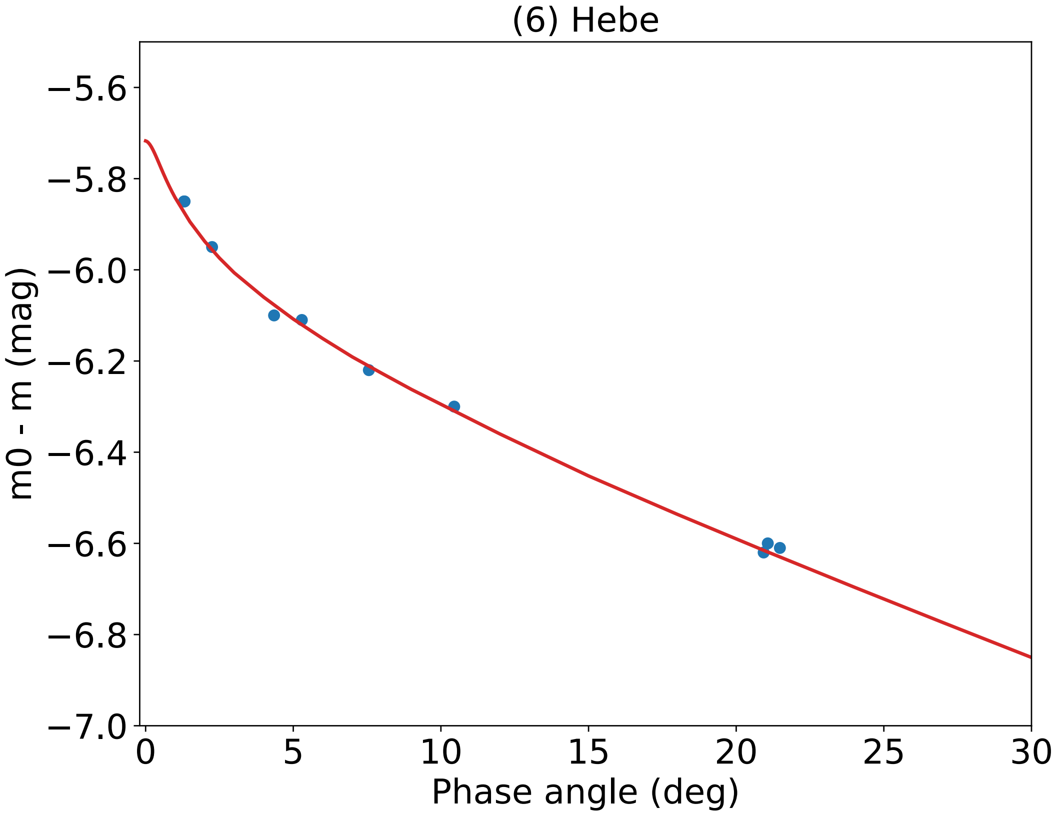
RT-CB RESULTS: (6) HEBE

Polarimetric phase curve

Blue: fit to obs
Red: model



Photometric phase curve



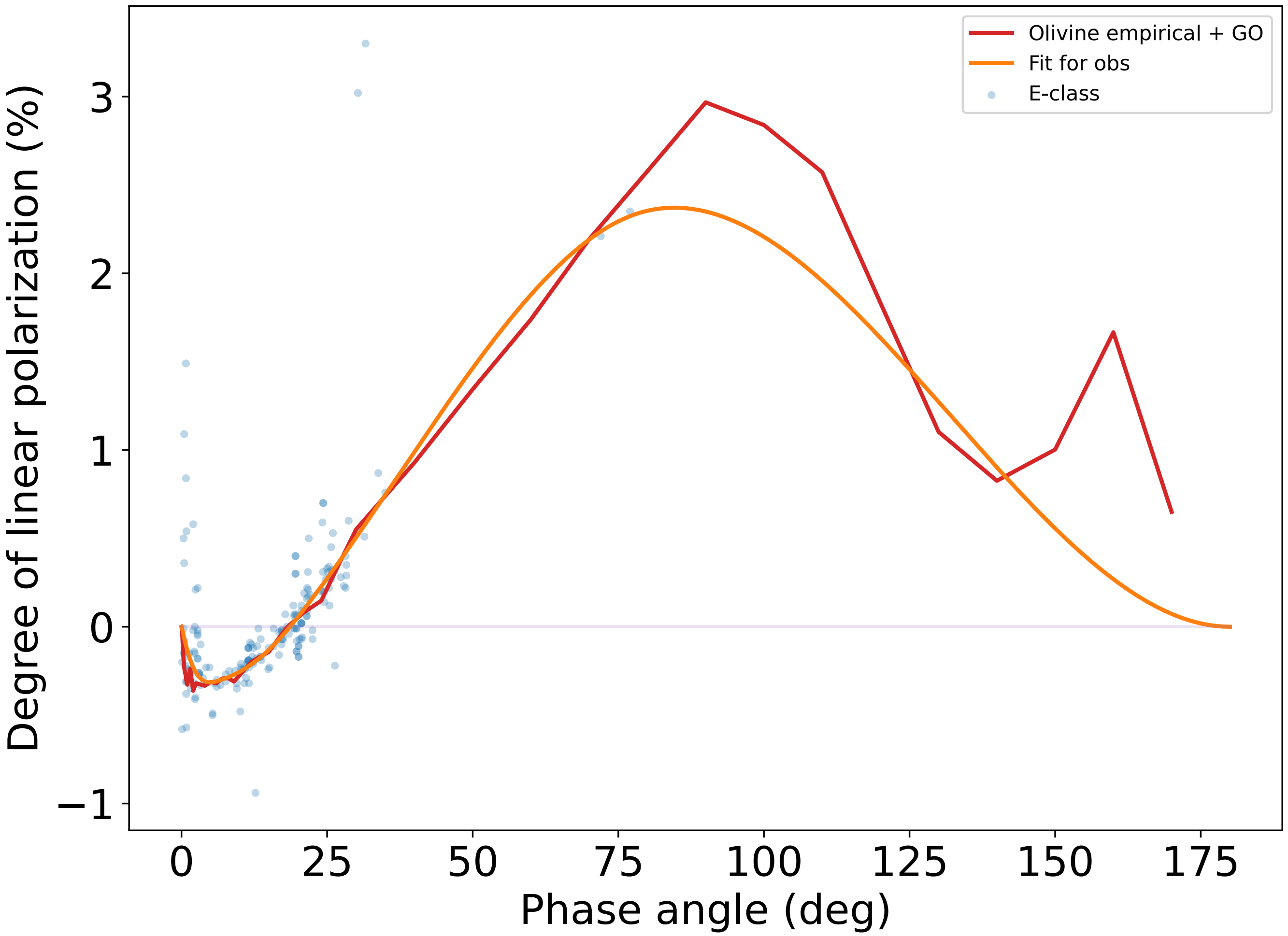
RT-CB RESULTS: E-CLASS

E-class:

- Need a low max and small min
- Same olivine, except imaginary part of the refractive index is 10^{-4}
- Large particles 10-80 μm (same power law r^{-3})

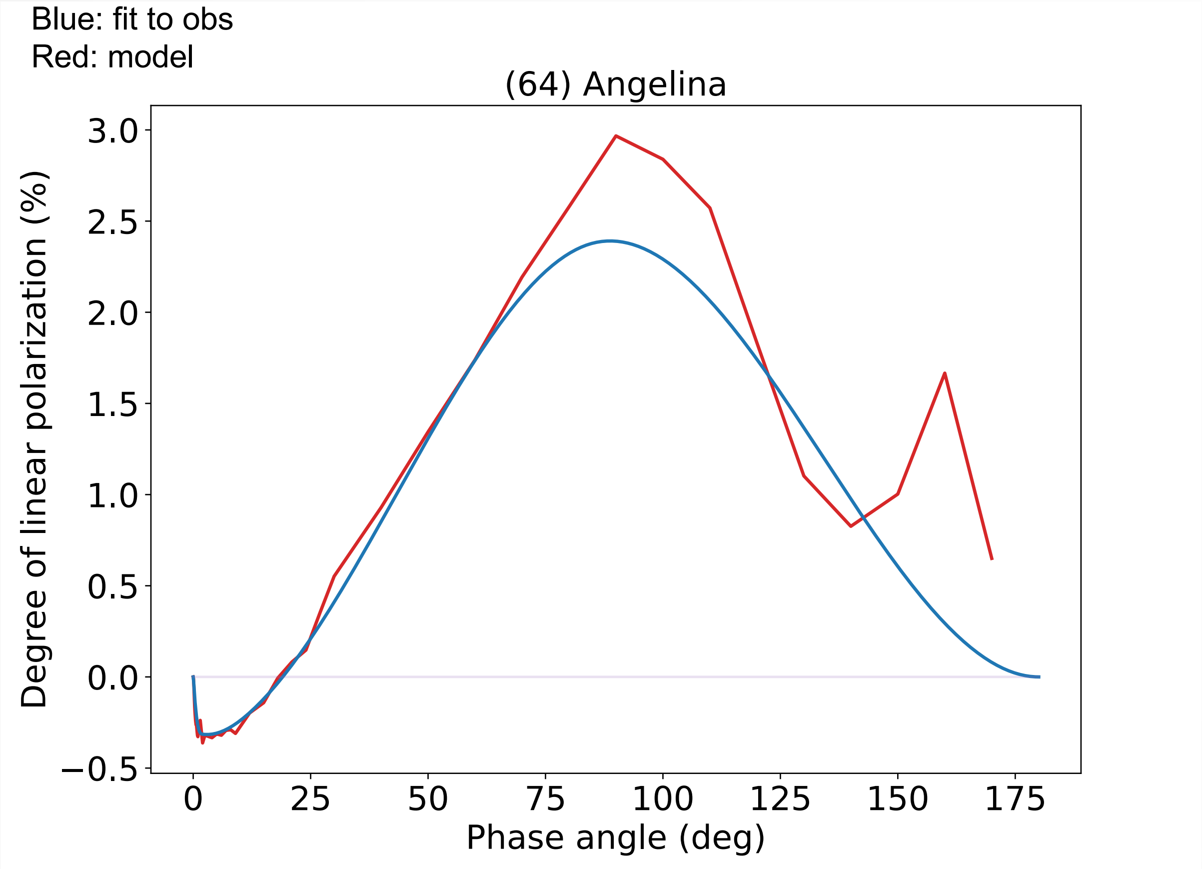
Multiple-scattering result:

- geometric albedo p_V = 0.535

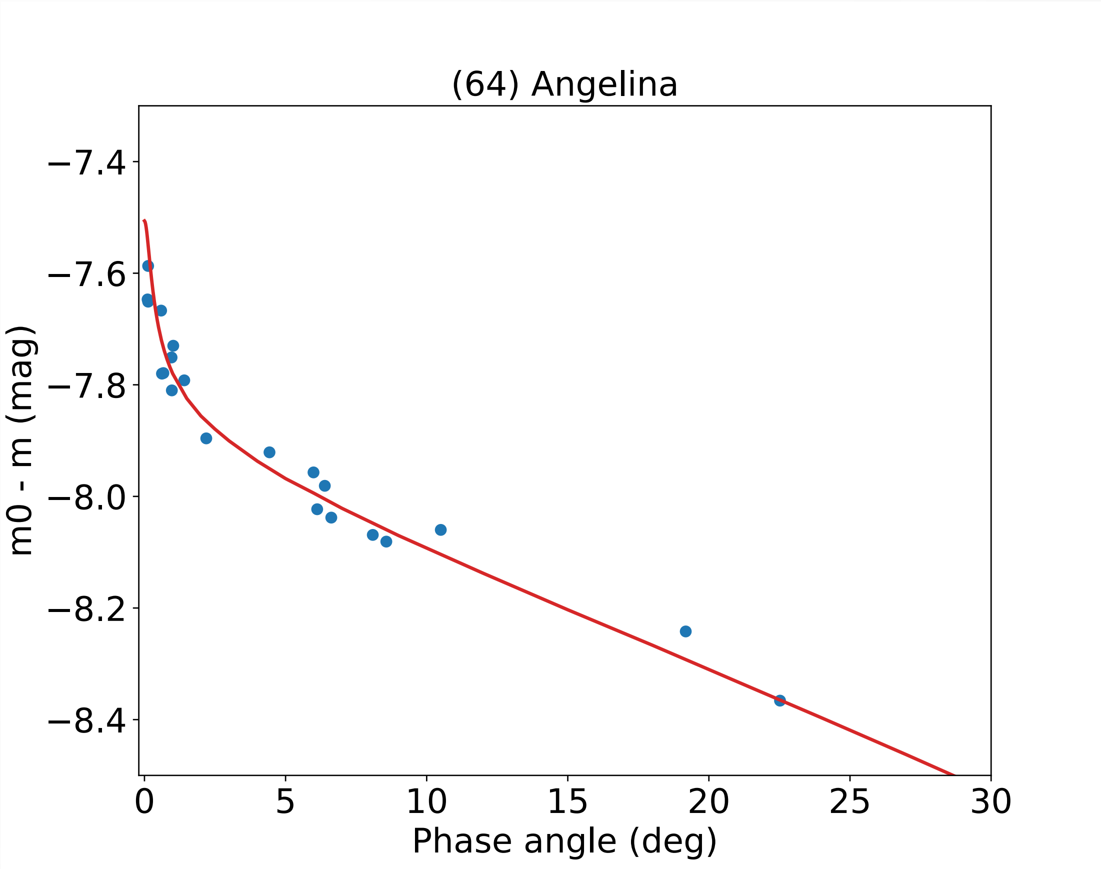


RT-CB RESULTS: (64) ANGELINA

Polarimetric phase curve



Photometric phase curve



GAUSSIAN PARTICLES

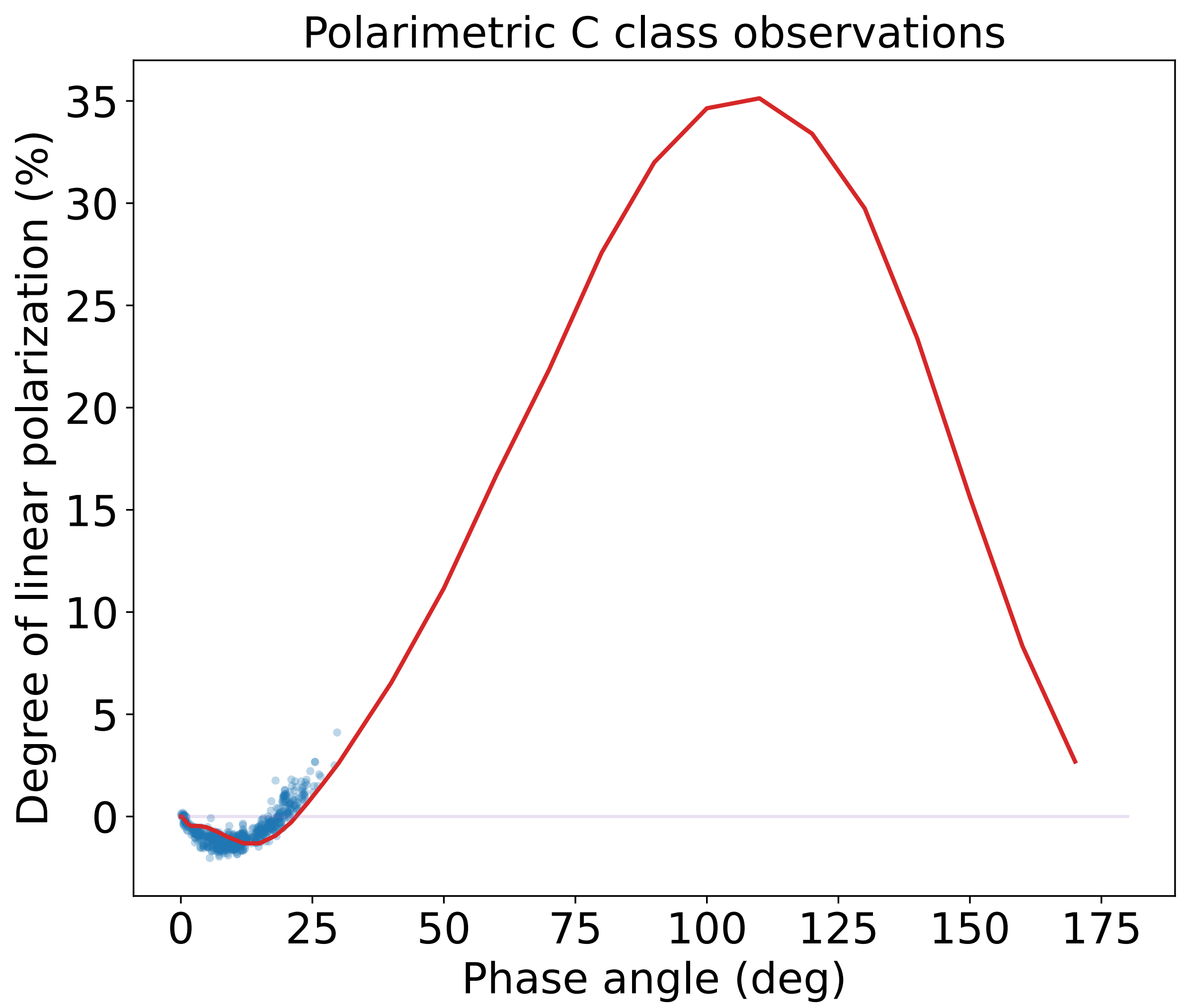
- C-class remained a challenge: low min (-1.5%) and high max (up to 53%)
  - To achieve the high max (and featureless spectra, Vuori et al. in preparation), large only externally reflecting particles are needed
  - Kills a significant proportion of the negative polarization (at least the amount present in the ensemble of measured small particles)
  - Tried combining small measured olivine with small graphite spheres, but it did not work without deepening the minimum by hand
    - → unknown size distribution and scattering quantities

GAUSSIAN PARTICLES

- Small Gaussian particles can exhibit extreme low negative polarization (Lumme & Rahola, JQSRT, 1998 and Muinonen et al., JQSRT, 2007)
- Scattering computations of randomly orientated Gaussian particles using SIEM (Markkanen, JQSRT 2025)
- C-class model
  - Power law size distribution of the Gaussian particles ($r \approx 0.1$-1.3 μm) with refractive index of olivine
  - Combined with small graphite spheres → 1 μm volume element
  - Combined with large externally reflecting olivine (150 μm)

RT-CB RESULTS: C-CLASS

- Preliminary result, p_V = 0.032
- Need to modify size distribution to fix inversion angle



CONCLUSIONS AND FUTURE WORK

- **We have shown that physics-based modelling is now able to explain the phase angle dependence of asteroid observations**
- **The models constrain the size distributions and refractive indices of the particles on the surface of the asteroids**
  - Information about composition, not just particle sizes

- Gaussian particles to construct a relevant input for S- and E-class
- Improve the photometric results
  - Regolith geometry model (Björn et al, PSJ 2024) to correct for shadowing by surface roughness