Astrophysical light scattering problems (PAP316)

Lecture 4a

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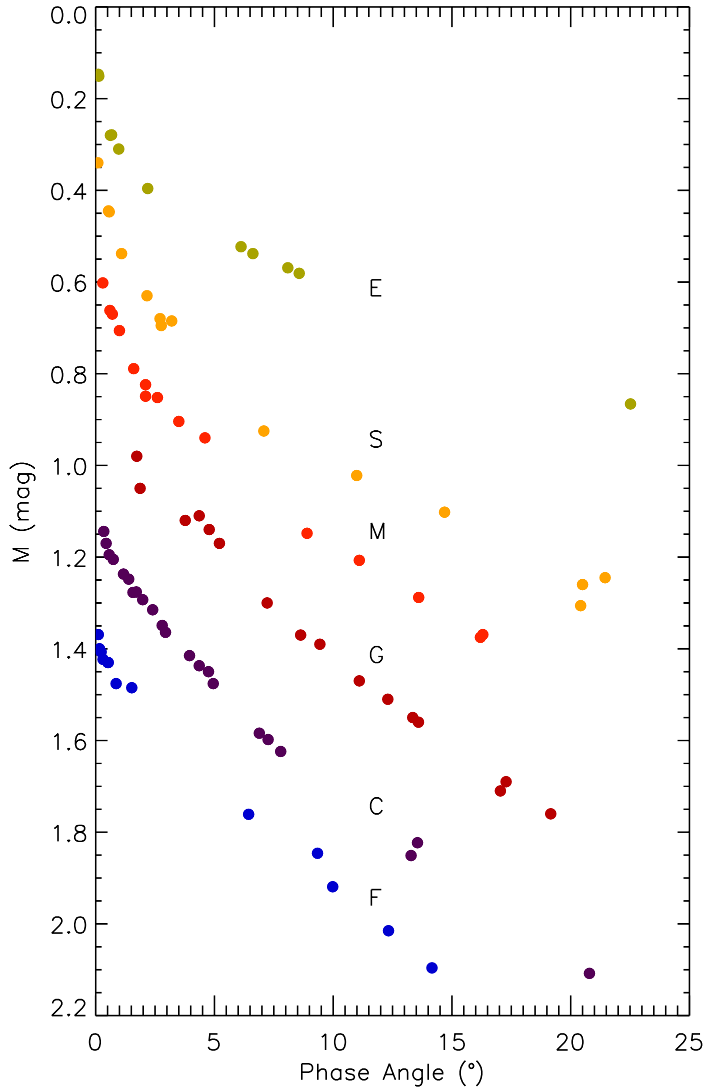
Contents

Introduction

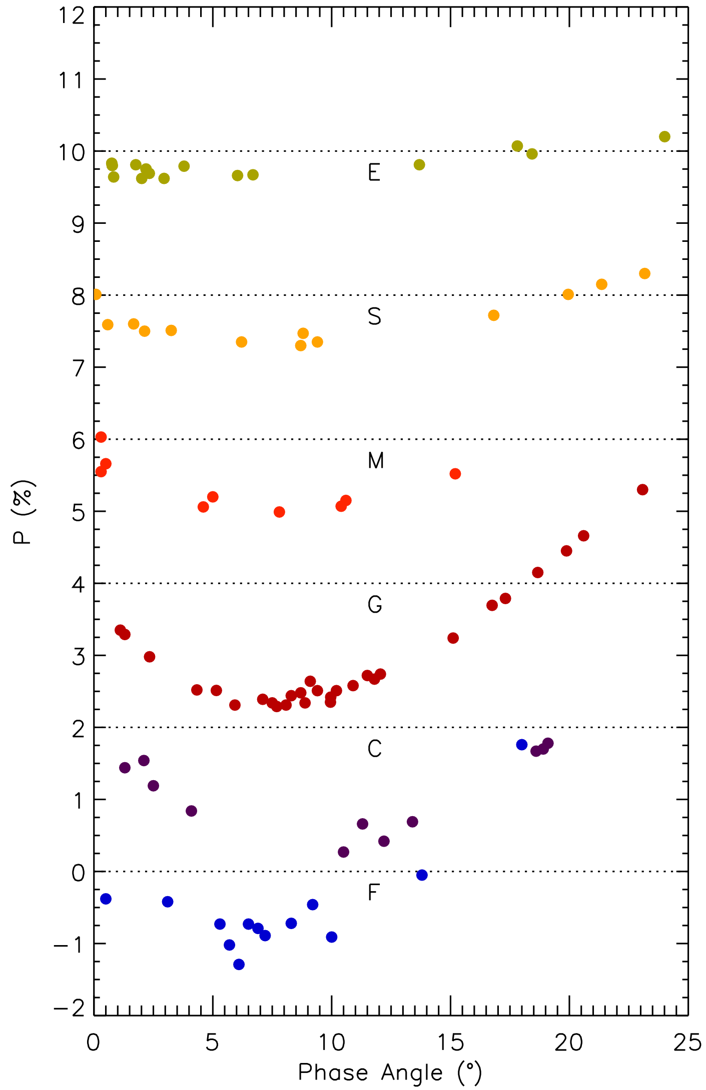
- Physical characterization of astronomical objects (e.g., surfaces of airless planetary objects)
- Direct problem of light scattering by particles with varying particle size, shape, refractive index, and spatial distribution
- Inverse problem based on astronomical observations and/or experimental measurements
- Plane of scattering, scattering angle, solar phase angle, degree of linear polarization

Asteroids

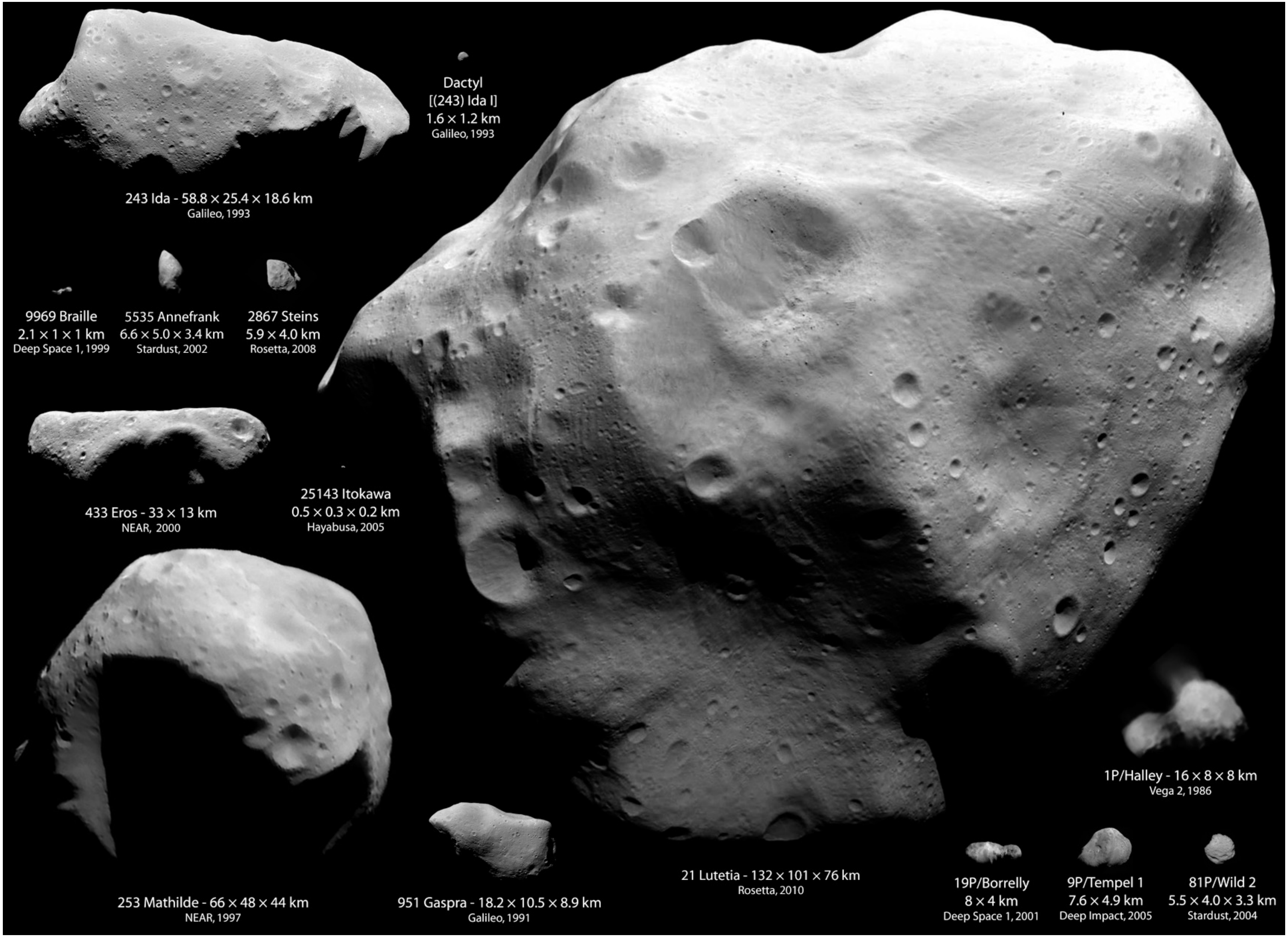
Photometry

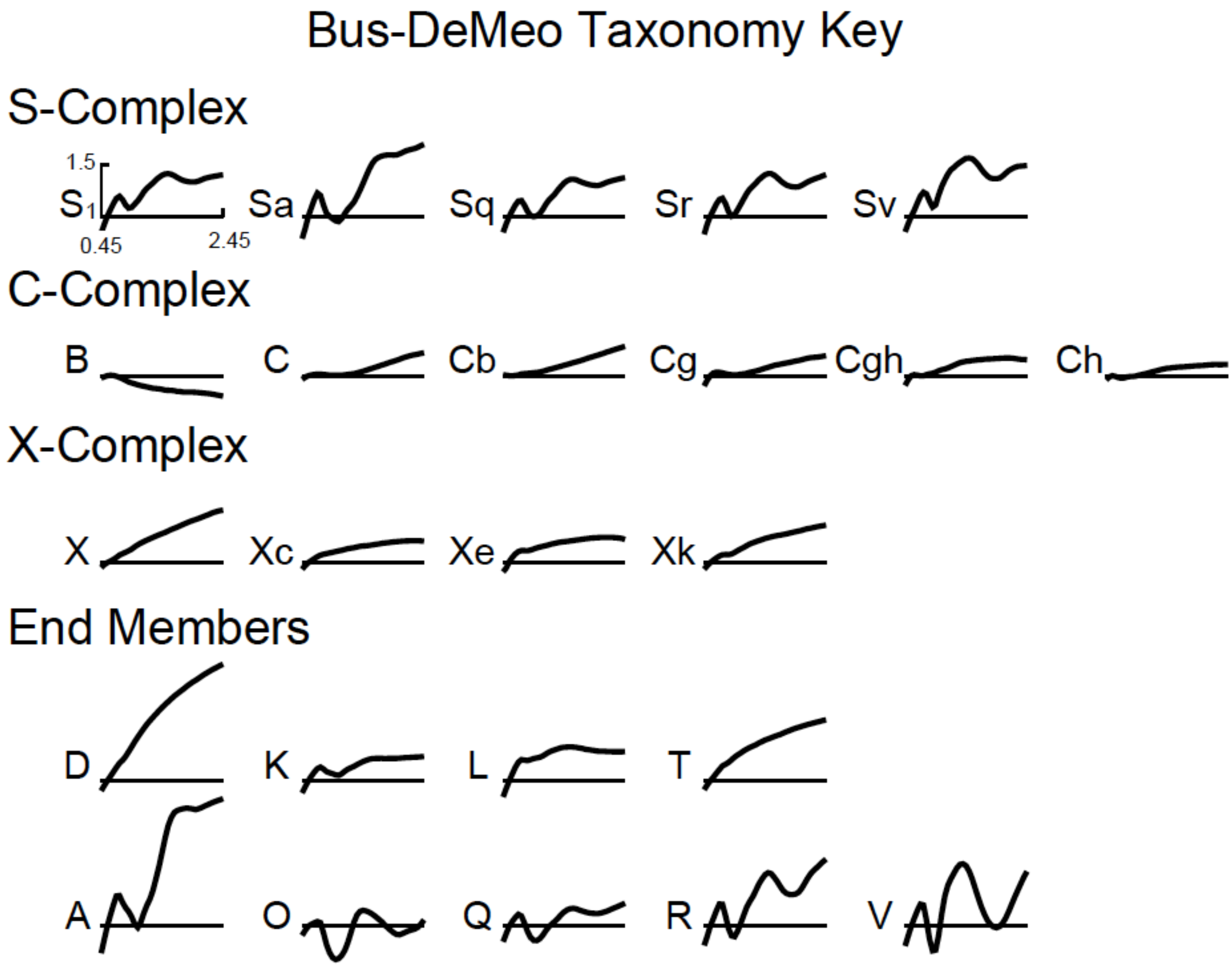


Polarimetry



Muinonen et al., in Polarimetry of Stars and Planetary Systems, 2016 (obs. ref. therein)


243 Ida - 58.8 × 25.4 × 18.6 km
Galileo, 1993
Dactyl
[(243) Ida I]
1.6 × 1.2 km
Galileo, 1993
9969 Braille
2.1 × 1 × 1 km
Deep Space 1, 1999
5535 Annefrank
6.6 × 5.0 × 3.4 km
Stardust, 2002
2867 Steins
5.9 × 4.0 km
Rosetta, 2008
433 Eros - 33 × 13 km
NEAR, 2000
25143 Itokawa
0.5 × 0.3 × 0.2 km
Hayabusa, 2005
253 Mathilde - 66 × 48 × 44 km
NEAR, 1997
951 Gaspra - 18.2 × 10.5 × 8.9 km
Galileo, 1991
21 Lutetia - 132 × 101 × 76 km
Rosetta, 2010
1P/Halley - 16 × 8 × 8 km
Vega 2, 1986
19P/Borrelly
8 × 4 km
Deep Space 1, 2001
9P/Tempel 1
7.6 × 4.9 km
Deep Impact, 2005
81P/Wild 2
5.5 × 4.0 × 3.3 km
Stardust, 2004



Bus-DeMeo Taxonomy Key
S-Complex
1.5
S
1
0.45
2.45
Sa
Sq
Sr
Sv
C-Complex
B
C
Cb
Cg
Cgh
Ch
X-Complex
X
Xc
Xe
Xk
End Members
D
K
L
T
A
O
Q
R
V

Polarimetric data

- Disk-integrated observations only
- Asteroid Polarimetric Database
- (1) Ceres most extensively observed
- Main-belt, near-Earth, transneptunian objects

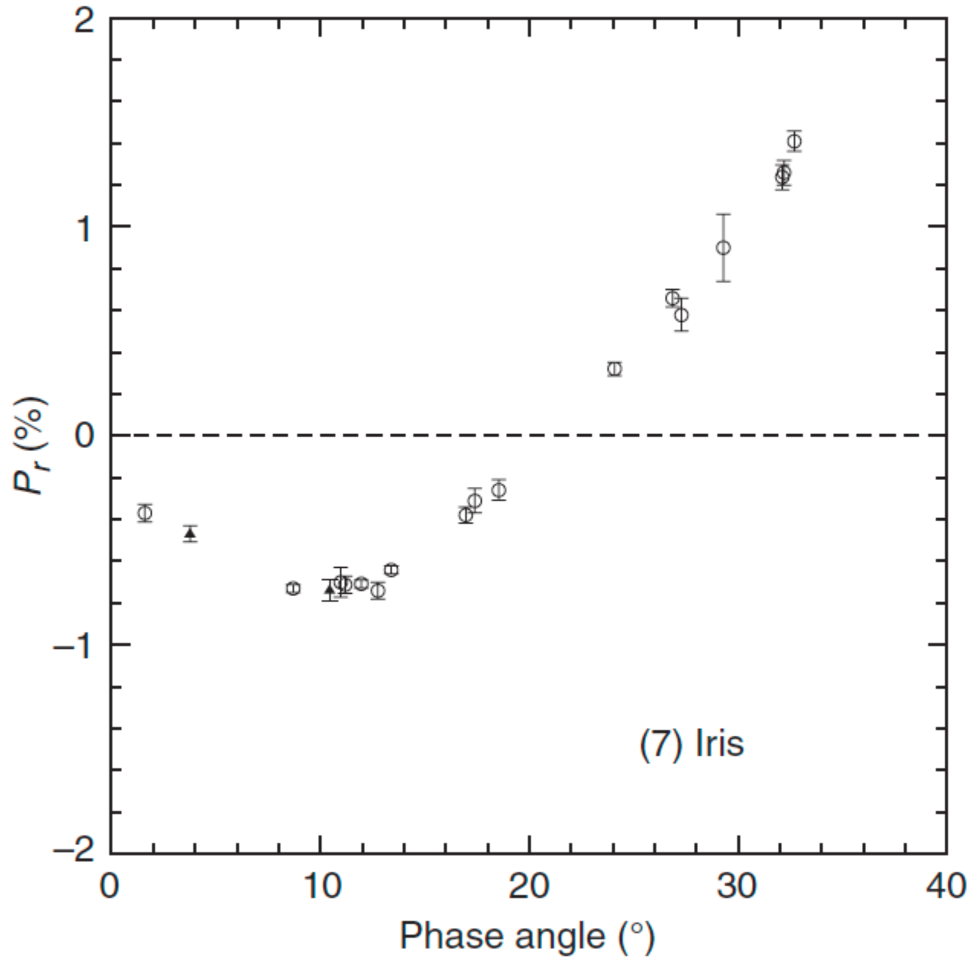


FIGURE 21.1 Phase–polarization curve for the asteroid (7) Iris. Open symbols: data from the Asteroid Polarimetric Database at PDS website; full symbols: other data obtained at CASLEO.

Telescopes and instruments

- Crimean Astrophysical Observatory (UBVRI polarimeter by Vilppu Piirola)
- Complejo Astronomico El Leoncito (CASLEO)
- Nordic Optical Telescope (NOT)
- Nice Observatory in Calern with Torino Observatory
- University of Hawaii, Mauna Kea
- Very Large Telescope, Focal Reducer and Spectrograph (FORS)

Interpretation of data

- Theoretical and numerical light-scattering methods maturing
- Still no widely accepted modeling approach
- Empirical rules utilized to relate polarimetric parameters to geometric albedo
- Thermal emission measurements offer sizes, challenges due to nonspherical shapes!

Polarization vs. taxonomy

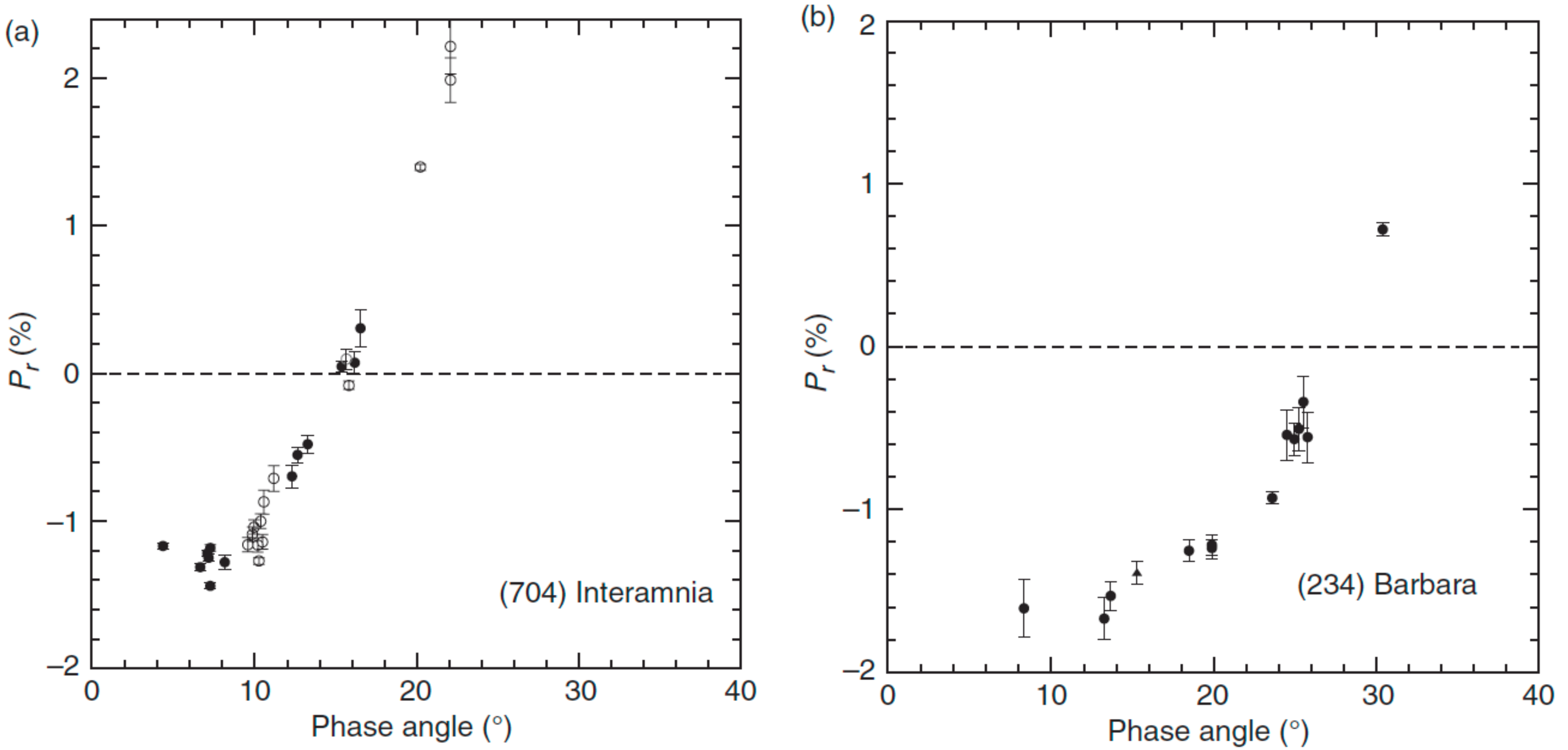


FIGURE 21.2 Two extreme cases of asteroid phase–polarization curve. (704) Interamnia (top) belongs to the F taxonomic class, and is characterized by a low value of the inversion angle, around 15°. In contrast, (234) Barbara (bottom), the prototype of the "Barbarian" polarimetric class, exhibits a very large inversion angle, close to 28°. Note also a strong negative polarization at phase angle around 20°, where most asteroids display their inversion angle. The meaning of the symbols is as in Fig. 21.1.

Properties of F-class asteroids

- Low-albedo objects with flat spectra across 0.3-1.1 microns (hence class F)
- Unusually low inversion angles
- Possibly similar to CI1-CM2 meteorites
- (3200) Phaethon, Comet Wilson-Harrington, (419) Aurelia
- Earth-impactor 2008 TC_3 predicted to be of F class
- Almahatta Sitta meteorites discovered were polymict ureilites!
- F-class now within C or B classes due to omission of UV in classifications

Barbarians

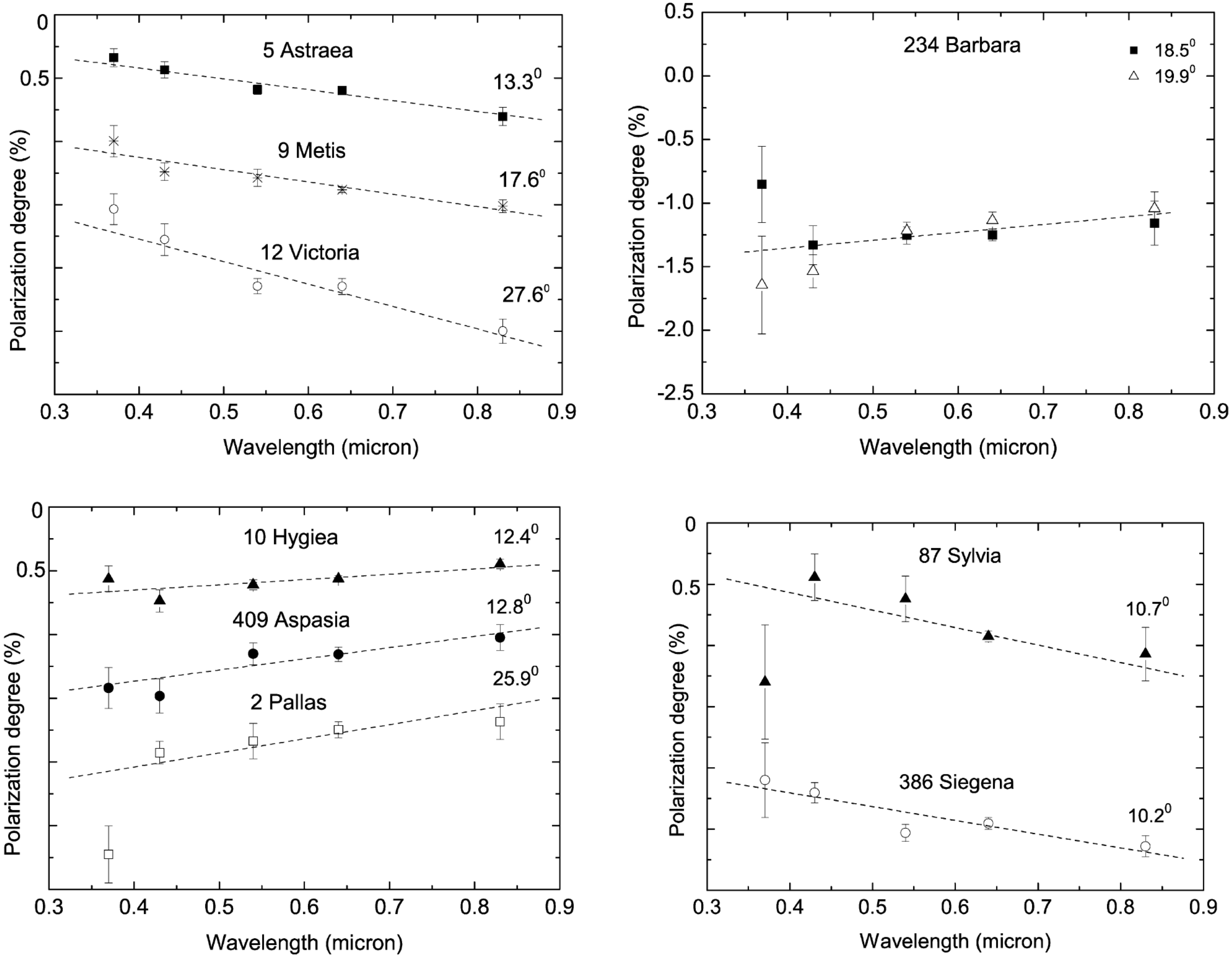
- Asteroid (234) Barbara shows exceptionally extended negative polarization
- Rare L class asteroids with reddish spectral slopes
- 2-micron feature suggests spinel, a key mineral in primitive Calcium Aluminum rich Inclusions (CAIs, potentially pre-solar)

- Why are there so few Barbarians?
- Theoretical modeling suggest small particles and/or wavelength-scale inhomogeneities

Wavelength dependence

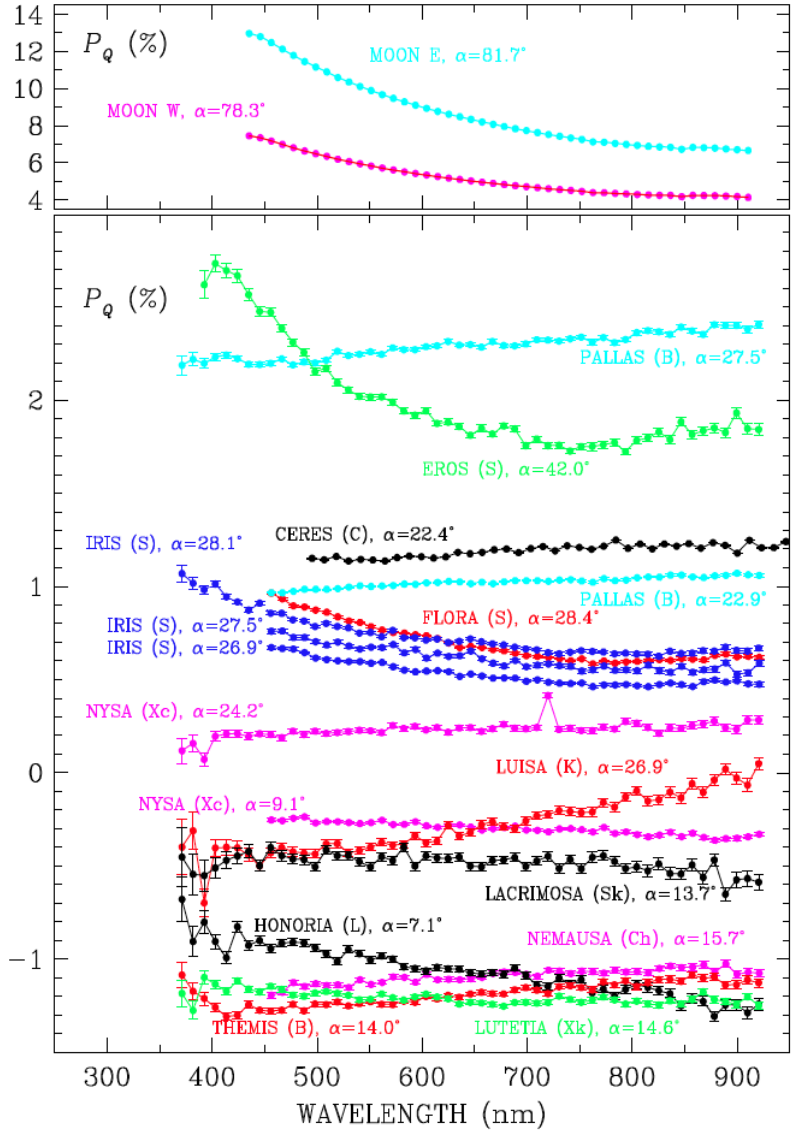
- Towards longer wavelengths
  - Moderate-albedo S and M classes show weaker/stronger positive/negative polarization
  - Low-albedo classes show stronger/weaker positive/negative polarization
- There are exceptions to the predominating trends
  - for example, (234) Barbara

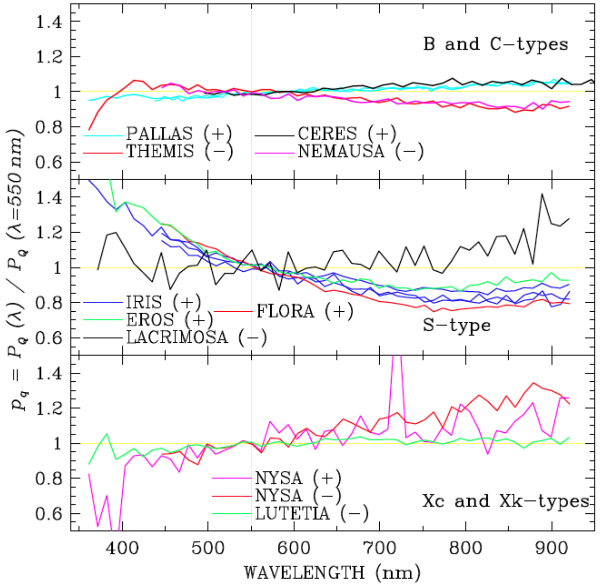
Asteroid spectropolarimetry

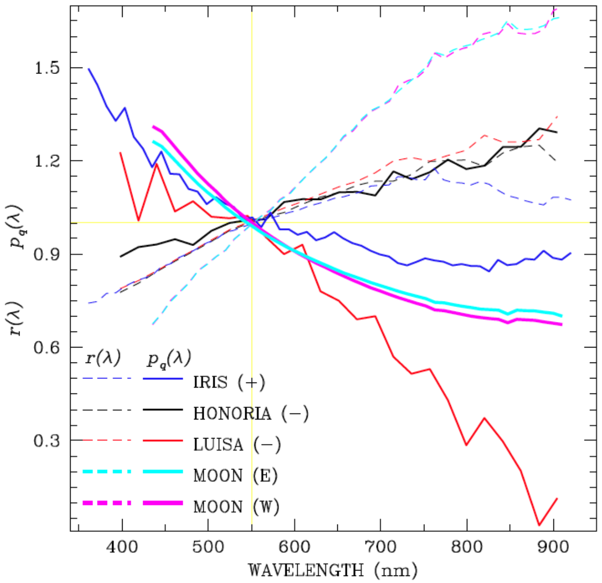


Belskaya et al. 2009

Asteroid spectropolarimetry







Bagnulo et al. 2015

Near-Earth asteroids

- Large phase-angle ranges possible
- S-class objects show maximum polarizations of 7.7-8.5% at 103-110^{o}
- E-class objects show polarizations of 1.7-2.3% at 80^{o}
- A single low-albedo asteroid (2100) Ra Shalom observed at 60^{o}, polarization 10.7-11.1%

- Possible proxies for modeling main-belt asteroid polarimetry
- Useful as pointers for project tasks

Space weathering phenomena

- Origin of ordinary chondrite meteorites at S-class asteroids explained by space weathering effects on regolith particles
  - Overall spectral reddening
  - Decrease of depth in the 1-micron silicate absorption band
- Polarimetric studies of space weathering have produced inconclusive results

Comparison of albedos

- Polarimetric vs. thermal radiometric geometric albedos $p = A_g$
- Thermal radiometry sensitive to asteroid sizes (cf. $1 - A$, where A spherical albedo and typically smallish)
- Phase integral q relates albedos, $A = pq$
- Substantial discrepancies, long-term controversy
- Challenges due to nonspherical shapes
- Note that albedo differences turn into differences in predicted population numbers (diameter D vs. absolute magnitude H)

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

Open problems

- Polarization albedo rule, what are the optimum coefficients?

$$\log\left(A_g\right) = C_1 \log(h) + C_2,$$

$$C_1 = -0.97 \pm 0.07$$

$$C_2 = -1.68 \pm 0.08.$$

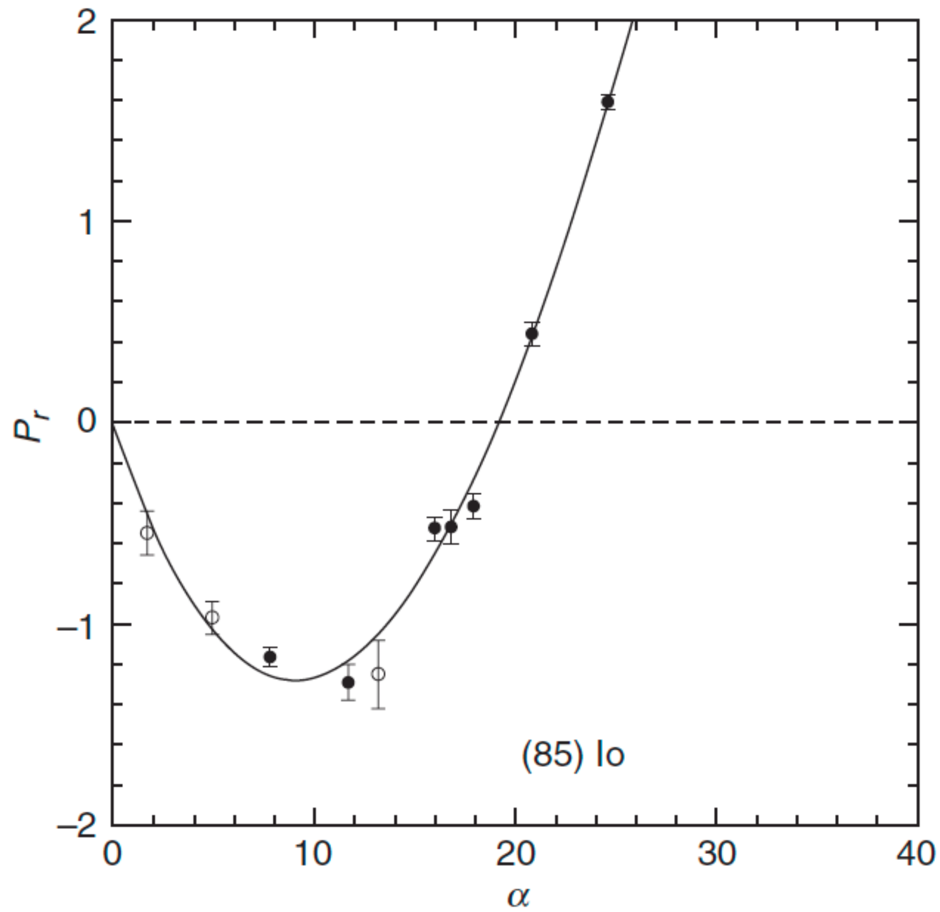


FIGURE 21.3 A fit of the phase–polarization curve of asteroid (85) Io using the linear-exponential relation described in the text. Meanings of the symbols as in Fig. 21.1.

Polarimetry in asteroid science

- Observational challenges due to the need to observe at different epochs
- Under-exploited in albedo retrieval
- Gaia mission spectroscopy and photometry offers outstanding complementary data
- Polarimetric data depend on wavelength-scale properties of regolith particles
- Requires photometry and/or spectroscopy as a companion
- Potential treasure trove!

Subjects for future investigation

- Albedo-polarization rule needs to be calibrated
- May provide a powerful tool for large numbers of objects in spite of "outliers"
- Theoretical methods to be brought to practical applications
- Novel observational capabilities to be promoted (cf. NTE, Nordic Optical Telescope Transient Explorer)

Intermediate conclusions

- Exciting times ongoing and ahead in asteroid polarimetry, photometry, and spectroscopy
- Asteroids offer an outstanding laboratory for numerical methods in light scattering

Projects

- C-class asteroids
- S-class asteroids
- E-class asteroids (KM)
- Ceres
- Mercury
- The Moon (KM)