Astrophysical light scattering problems (PAP316)

Lecture 10a

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Transneptunian objects and Centaurs, Contents

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Introduction (1/2)

- 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

Introduction (2/2)

- Classical objects
  - low eccentricities and semimajor axes 42-46 au
- Resonant objects
  - mean-motion resonances with Neptune
- Scattered disk
  - high eccentricities and high inclinations
- Detached objects
  - highly elliptical orbits beyond Neptune's influence with semimajor axes <2000 au (cf. Oort cloud)
- Centaurs
  - Giant-planet crossers with unstable orbits with semimajor axes 5-28 au

Instruments and method of observations

- ESO Very Large Telescope
- Focal Reducer and Spectrographs FORS1 and FORS2
- Service mode
- For Pluto, other instruments earlier on
- FORS1&2, series of exposures with $\lambda/2$ retarder plate at position angles 0^o, 22.5^o, …, 337.5^o
- Integration times from a few minutes to two hours

Accuracy of FORS polarimetric measurements and quality checks

- Narrow phase angle range of <1.5^{o} at 40-au distance
- One expects small polarization, thus high accuracy required
- 0.03% emerging as the practical limit of photon noise no matter how bright the target is
- 0.1% realistic for the faintest objects

Results of the observations
Dwarf planets and large TNOs

- TNOs larger than ~1000 km in diameter
- Pluto, resonant
  - rich in methane and nitrogen ices
- Eris, detached
  - composition similar to Pluto
- Makemake, classical
  - methane detected
- Haumea, classical
  - amorphous and crystalline water ice detected
  - elongated, fast rotator
- Quaoar, classical
  - water ice detected
- Orcus, resonant
  - water ice detected

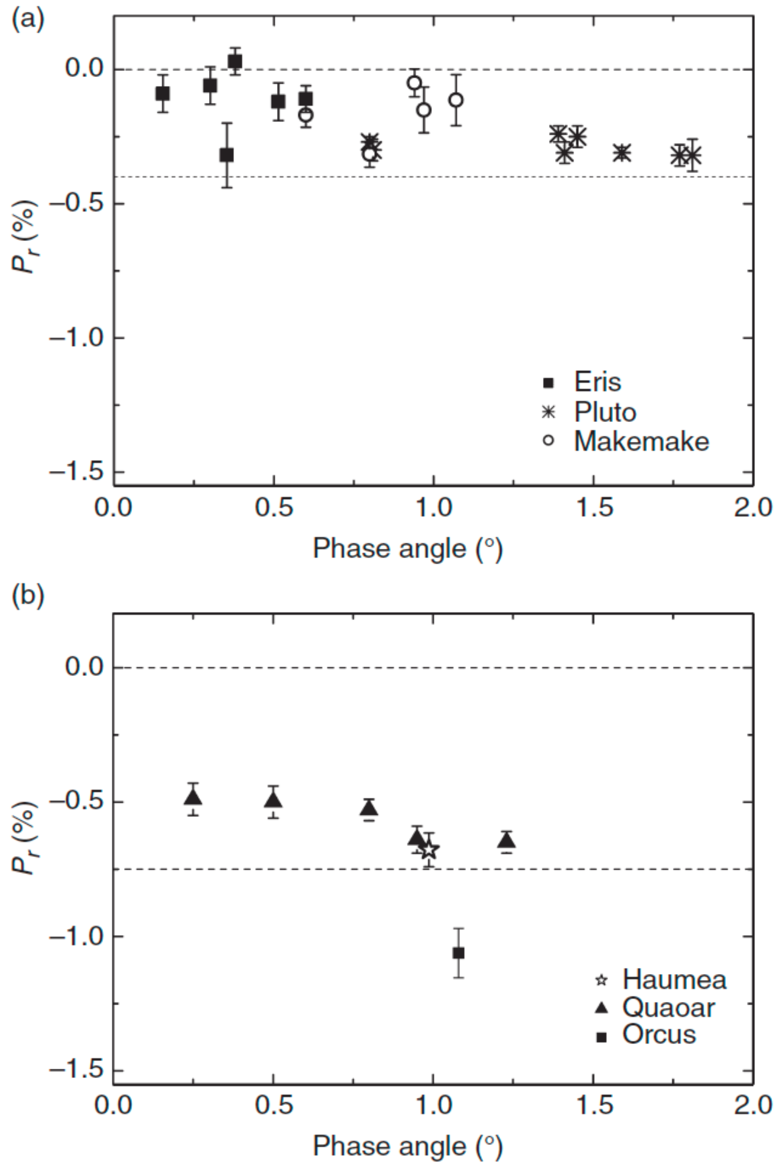

FIGURE 23.1 Polarization (R filter) versus phase angle for the largest TNOs with (a) methane-ice and (b) water-ice rich spectra.

TNOs of smaller size

- Varuna, classical
  - water ice plausible
- Ixion, resonant
  - water ice
- Huya, resonant
  - water ice
- 1999 DE9, resonant
  - water ice

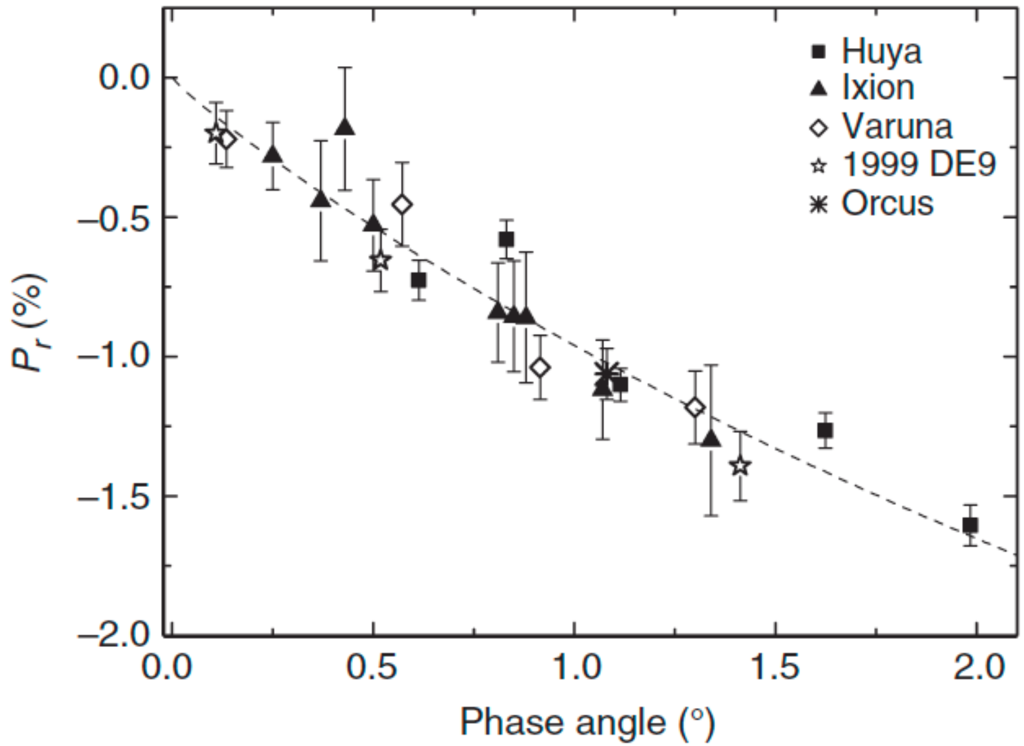

FIGURE 23.2 Polarization phase-angle dependences for smaller size TNOs. The measured polarization of Orcus, which is larger in size, is similar to other plutinos Huya and Ixion.

Centaurs

- Chiron
  - weak bands of water ice
  - cometary activity
  - cf. icy satellites of Saturn
- Pholus, primitive
  - water ice, methanol
- Chariklo
  - water ice bands
  - rings
- 1999 TD10
  - no detection of water ice

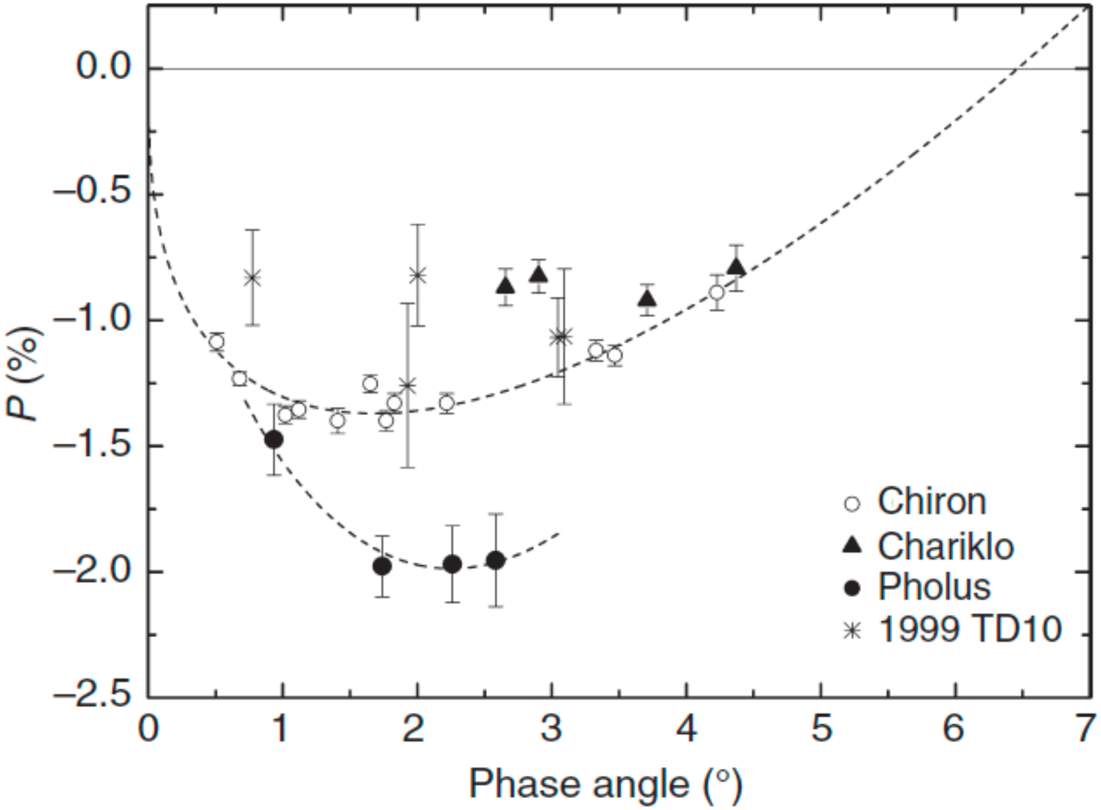

FIGURE 23.3 Polarization vs. phase angle in the R band for Centaurs.

- Spectral dependence of Chiron's polarization

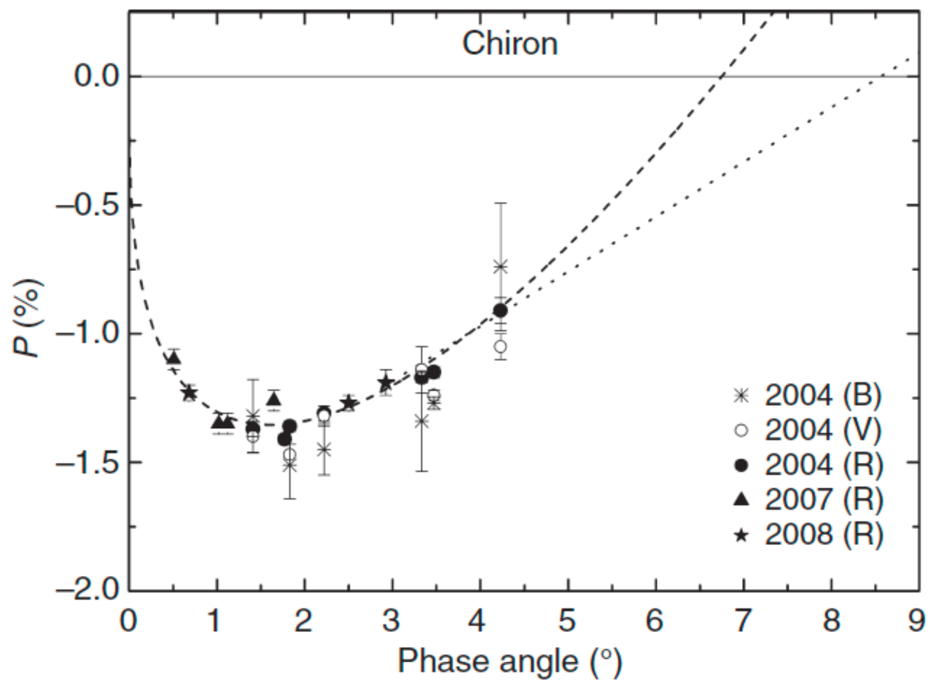

FIGURE 23.4 Polarization vs. phase angle for Chiron measured in 2004–2008 in the BVR bands. The dashed line shows a fit to the R-band data with a Lumme and Muinonen function. The dotted line shows a linear fit to the R-band data at phase angles >2°.

TABLE 23.1 The list of TNOs and Centaurs for which polarimetric measurements are available

Name	Orbital group[1]	Spectral class[2]	Diameter, km	Albedo	Range of phase angles	P_{min}	σ_{Pmin}	Reference
(2060) Chiron	Centaur	BB	218[3]	0.16[3]	0.51–4.23	−1.37	0.05	Bagnulo *et al*. (2006), Belskaya *et al*. (2010)
(5145) Pholus	Centaur	RR	107[4]	0.13[4]	0.93–2.58	−2.09	0.12	Belskaya *et al*. (2010)
(10199) Chariklo	Centaur	BR	248[3]	0.04[3]	2.66–4.37	−0.97	0.06	Belskaya *et al*. (2010)
(20000) Varuna	Classical	IR	668[5]	0.13[5]	0.14–1.30	−1.18	0.13	Bagnulo *et al*. (2008)
(26375) 1999 DE9	Resonant	IR	311[5]	0.16[5]	0.11–1.41	−1.39	0.12	Bagnulo *et al*. (2008)
(28978) Ixion	Resonant	IR	617[5]	0.14[5]	0.25–1.34	−1.30	0.15	Boehnhardt *et al*. (2004)
(29981) 1999 TD10	Cent/SDO	BR	104[6]	0.04[6]	0.77–3.10	−1.35	0.21	Rousselot *et al*. (2005)
(38628) Huya	Resonant	IR	458[3]	0.08[3]	0.61–1.98	−1.61	0.07	Bagnulo *et al*. (2008)
(50000) Quaoar	Classical	RR	1074[3]	0.13[3]	0.25–1.23	−0.65	0.04	Bagnulo *et al*. (2006)
(90482) Orcus	Resonant	BB	958[3]	0.23[3]	1.08	−1.06	0.09	Belskaya *et al*. (2012)
(134340) Pluto	Resonant	BR	2350[7]	0.61[7]	0.75–1.81	−0.28	0.05	Kelsey and Fix (1973), Breger & Cochran (1982), Avramchuk *et al*. (1992)
(136108) Haumea	Classical	BB	1240[3]	0.80[3]	0.99	−0.68	0.06	Bagnulo *et al*. (2008)
(136199) Eris	Detached	BB	2400[8] 2454[9]	0.96[8] 0.85[9]	0.15–0.60	−0.11	0.05	Belskaya *et al*. (2008a), Bagnulo *et al*. (2008)
(136472) Makemake	Classical	BR	1430[10]	0.77[10]	0.60–1.07	−0.16	0.05	Belskaya *et al*. (2012)

[1]Gladman *et al*. (2008); [2]Fulchignoni *et al*. (2008); [3]Fornasier *et al*. (2013); [4]Duffard *et al*. (2014); [5]Lellouch *et al*. (2013); [6]Stansberry *et al*. (2008); [7]Albrecht *et al*. (1994); [8]Sicardy *et al*. (2011); [9]Santoz-Sans *et al*. 2012; [10]Ortiz *et al*. (2012).

Possible influence of atmospheres, comae, and satellites

- Expect no effect from atmosphere for Pluto
- Comae checked for each case, no detection
- Rings?
- Satellite contributions expected for Pluto and Huya

Polarization-albedo relationship

- Polarization-albedo relation shows trends seen for asteroids
- However, empirical rules may well be distorted by physical and chemical conditions of the surfaces

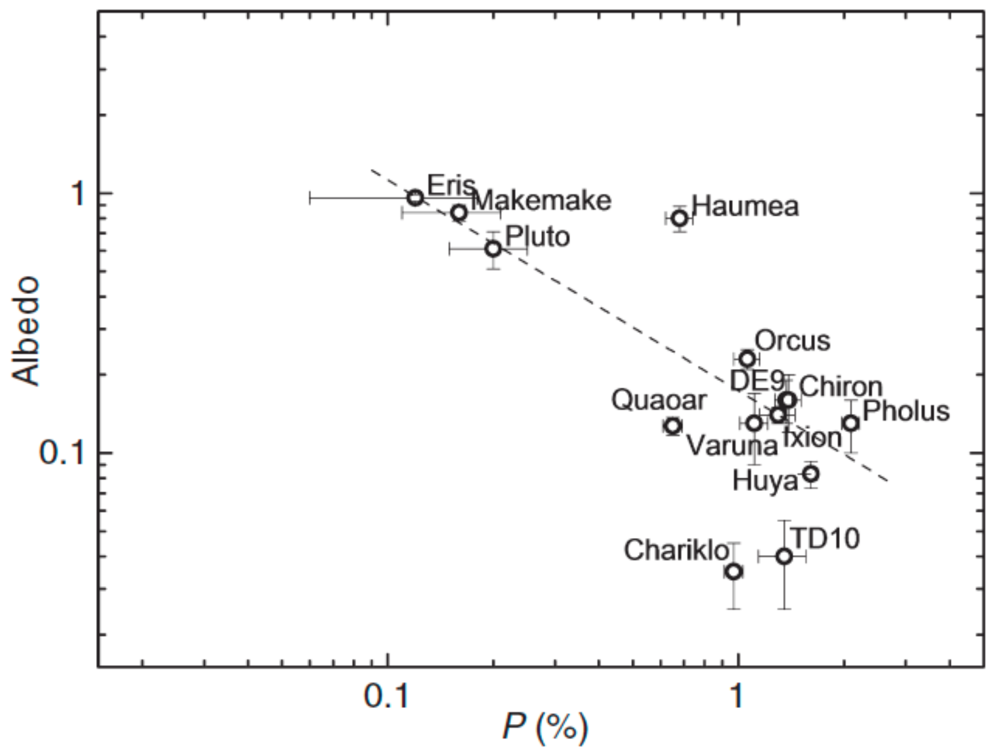

FIGURE 23.5 The relationship of minimal polarization degree measured for TNOs and Centaurs and their albedos. The dashed line corresponds to the linear fit in a log-log scale. References for albedos are given in Table 23.1.

Constraints on surface properties

- Water ice vs. methane and nitrogen ices revealed by polarimetry?
- Surface structure and composition remain open
- What is produced in condensation of gases from tenuous atmospheres onto the surfaces?
- Combinations of bright and dark materials enhance polarimetric signals

Conclusions

- Tentative RT-CB models based on two-component media of bright and dark Rayleigh scatterers offered and successful in explaining the data
- More advanced models remain to be developed in accordance with the photometric and spectroscopic observations
- It is realistic to launch such a modelling effort for the unique polarimetric data

Light-scattering experiment: Rainbows at home

- Equipment
  - Source of light, e.g., headlamp
  - Circular-cylindrical glass bottle, e.g., water bottle
  - Detector screen
- Measurement
  - Fill in the bottle with water
  - Illuminate horizontally with light source
  - Detect rainbows on the screen
- Question
  - Rainbow angles for water or for glass?
  - Provide argumentation