

Contents

List of contributors	<i>page</i> xvii
I Introduction	I
1 Preface	3
<i>Ludmilla Kolokolova, James Hough, and Anny-Chantal Levasseur-Regourd</i>	
2 The life of Tom Gehrels	5
<i>Neil, George, Jo-Ann, and Aleida Gehrels</i>	
II Theory, instrumentation, and laboratory studies	II
3 Measurement and modeling of electromagnetic scattering by particles and particle groups	13
<i>Michael I. Mishchenko</i>	
3.1 Introduction	13
3.2 Polarization-sensitive well-collimated radiometers	14
3.3 Electromagnetic scattering by a fixed object	16
3.4 Far-field scattering	18
3.5 Response of a polarization-insensitive far-field WCR	19
3.6 Response of a polarization-sensitive far-field WCR	22
3.7 Derivative quantities	24
3.8 Far-field scattering by a “random” object	25
3.9 Foldy equations and their far-field version	25
3.10 First-order-scattering approximation	27
3.11 Discrete random media	29
3.12 Concluding remarks	32
4 Instrumentation	35
<i>Christoph U. Keller, Frans Snik, David M. Harrington, and Chris Packham</i>	
4.1 Introduction	35
4.1.1 Mathematical tools	35
4.1.2 Sensitivity and accuracy	36

4.2	Optical components for polarimetry	36
4.2.1	Polarizers	36
4.2.2	Fixed retarders	38
4.2.3	Variable retarders	39
4.2.4	Detectors	39
4.3	Polarimeter design	40
4.3.1	Spatial, temporal, and spectral modulation	40
4.3.2	Optimization	40
4.3.3	Instrumental polarization	41
4.3.4	Calibration	42
4.4	Modern polarimeters	44
4.4.1	High-sensitivity polarimeters	44
4.4.2	High spectral-resolution polarimeters	50
4.4.3	High-contrast polarimeters	51
4.4.4	High time resolution polarimeters	51
4.4.5	Space-based polarimeters	52
4.5	Conclusions	55
5	Laboratory studies	62
<i>Anny-Chantal Levasseur-Regourd, Jean-Baptiste Renard, Yuriy Shkuratov, and Edith Hadamcik</i>		
5.1	Introduction	62
5.1.1	Need for experimental simulations	62
5.1.2	First experimental simulations on particulate surfaces	62
5.1.3	First experimental simulations on hovering particles	63
5.2	Linear polarization for surfaces and dust clouds	64
5.2.1	Overview of available observations	64
5.2.2	Polarimetric parameters	64
5.2.3	Types of samples	65
5.2.4	Instrumental developments	65
5.3	Measurements on surfaces	66
5.3.1	Kharkov instruments	66
5.3.2	PROGRA2-surf instrument	66
5.3.3	Measurements on surfaces and their significance	67
5.4	Measurements on clouds	70
5.4.1	Instrumentation in laboratory and microgravity conditions	70
5.4.2	Measurements on clouds and their significance	71
5.4.3	CODAG-LSU instrument	73
5.5	Discussion	73
5.5.1	Comparison between measurements on surfaces	73
5.5.2	Comparison between measurements on surfaces and clouds	73
5.5.3	Comparison with numerical simulations	74
5.5.4	Significance for other scientific domains	75
5.6	Conclusions and perspectives	75
5.6.1	Conclusions	75
5.6.2	Measurements under reduced gravity conditions	76
5.6.3	Long duration measurements under microgravity	76
6	Grain alignment: Role of radiative torques and paramagnetic relaxation	81
<i>Alexander Lazarian, B-G Andersson, and Thiem Hoang</i>		
6.1	Introduction	81
6.2	RAT quantitative theory: Analytical model for radiative torques	83

6.2.1	Introducing the model for RATs	83
6.2.2	AMO: Description	83
6.2.3	LH07a study: Main results	84
6.3	Properties of RAT alignment	85
6.4	Complexities of dust dynamics	89
6.4.1	Effects of internal relaxation	89
6.4.2	Purcell's pinwheel torques	89
6.4.3	Thermal trapping of grains	90
6.5	Alignment of large grains	91
6.6	Astrophysically important implications	92
6.6.1	Molecular clouds and diffuse/dense cloud interface	92
6.6.2	Polarization of zodiacal light	93
6.6.3	Alignment of dust in comets	94
6.7	Alignment by paramagnetic relaxation	94
6.7.1	Alignment of small grains	94
6.7.2	Alignment of ultra-small grains and polarized spinning dust	95
6.8	Observational tests of interstellar grain alignment	96
6.8.1	Observational methodology	97
6.8.2	Observational considerations	100
6.8.3	Observational tests of grain-alignment theories	101
6.8.4	Why aren't the carbonaceous grains aligned?	106
6.9	Discussion	107

7 Multiple scattering of light in particulate planetary media

114

Karri Muinonen, Antti Penttilä, and Gorden Videen

7.1	Introduction	114
7.2	Multiple scattering in theory and numerics	117
7.2.1	Polarization mechanisms	117
7.2.2	Superposition T-matrix method (STMM)	119
7.3	Radiative-transfer coherent-backscattering method (RT-CB)	119
7.4	Discussion	120
7.4.1	STMM computations for volumes of spheres	120
7.4.2	Comparison of RT-CB and STMM	121
7.4.3	RT-CB in planetary applications	123
7.5	Conclusions	125

8 Experimental scattering matrices of clouds of randomly oriented particles

130

Olga Muñoz and Joop W. Hovenier

8.1	Introduction	130
8.2	Basic concepts	131
8.3	Experimental techniques	131
8.4	Results of measurements	133
8.4.1	Instrumental performance	133
8.4.2	Measurements using ensembles of small irregular particles	135
8.5	The Amsterdam–Granada light-scattering database	137
8.6	Applications	138

III Stars and their environment	145
9 Interstellar polarization	147
<i>Terry Jay Jones and Douglas C. B. Whittet</i>	
9.1 Introduction	147
9.2 Extinction by non-spherical particles	148
9.3 Polarization in emission	150
9.4 Wavelength dependence	150
9.5 Grain alignment	153
9.6 Turbulence in the ISM	154
9.7 Conclusions and future work	157
10 Young stellar objects and their environment	162
<i>Motohide Tamura and Jungmi Kwon</i>	
10.1 Introduction to young stellar objects and polarimetry in star-forming regions	162
10.1.1 Wide-field near-IR imaging	163
10.1.2 High-spatial resolution near-IR imaging	163
10.1.3 Wide-field near-IR imaging polarimetry	164
10.2 History of YSO polarimetry	164
10.2.1 Aperture polarimetry	164
10.2.2 Imaging polarimetry	165
10.2.3 Thermal polarimetry at far-IR, submillimeter, and millimeter wavelengths	165
10.3 Advanced techniques for YSO polarimetry	165
10.4 Highlights of recent polarimetry on YSOs	166
10.4.1 Polarimetry of a transitional YSO and protostars	166
10.4.2 Young stellar cluster polarimetry	166
10.4.3 Disk–planet relationship from YSO polarimetry	167
10.4.4 Circular polarimetry of YSOs	168
10.4.5 Submillimeter and millimeter polarimetry of YSOs	170
10.5 Conclusions	172
11 T Tauri and Herbig Ae/Be stars	176
<i>Pierre Bastien</i>	
11.1 Introduction	176
11.2 Linear polarization properties	177
11.2.1 Wavelength dependence	177
11.2.2 Polarization frequency distributions	178
11.2.3 Polarimetric variability	179
11.3 Correlations between linear polarization and other stellar properties	183
11.4 Circular polarization	184
11.5 Spectro-polarimetry	184
11.6 Binary stars	189
11.7 Spatially resolved observations	190
11.7.1 Historical perspective: Polarization maps and their Interpretation	190
11.7.2 More recent results	191
11.7.3 Example of a source with complex structures: R Monocerotis	192
11.8 Conclusions	193

12 Magnetic fields in high-mass star-forming regions	199
<i>Antonio Chrysostomou, Martin Houde, and Brenda C. Matthews</i>	
12.1 Introduction	199
12.2 Support mechanisms for molecular clouds	199
12.3 Polarimetry techniques	200
12.3.1 Single-beam polarimeters	200
12.3.2 Dual-beam polarimeters	201
12.4 Grain alignment and magnetic fields	201
12.5 Investigating the environments of star-forming regions	201
12.5.1 Circular polarimetry and magnetic fields	202
12.5.2 Observations in the submillimeter	204
12.5.3 Models	205
12.6 Conclusions	206
13 Evolved stars	210
<i>Tim Gledhill</i>	
13.1 Introduction	210
13.2 Early polarimetry of evolved stars	211
13.3 Detecting dust outflows in scattered light	212
13.3.1 Aperture polarimetry	212
13.3.2 Ground-based imaging polarimetry	212
13.3.3 Optical/IR interferometric polarimetry	214
13.3.4 Polarimetry with HST	214
13.4 Polarized emission from aligned dust grains	215
13.4.1 Mid-IR polarimetry	216
13.4.2 Submillimeter polarimetry	216
13.5 Molecular line polarimetry	217
13.5.1 Maser transitions	217
13.5.2 Thermal (non-maser) transitions	219
13.6 Future steps	219
14 Stellar magnetic fields	224
<i>Stefano Bagnulo and John D. Landstreet</i>	
14.1 Introduction	224
14.2 Basic principles	224
14.2.1 The Zeeman effect on the Stokes profiles of a spectral line	224
14.2.2 Line formation and radiative transfer in a magnetic atmosphere	226
14.2.3 Field detection in non-Zeeman regime	228
14.3 Instruments	228
14.4 Detection of stellar magnetic fields	229
14.4.1 Mean longitudinal magnetic field	229
14.4.2 Constraints from the second-order moment of the Stokes V profile about the line center	230
14.4.3 Line addition techniques	230
14.4.4 Broadband polarization	230
14.4.5 Mean magnetic field modulus	231
14.4.6 Modeling of stellar magnetic fields	231
14.5 Magnetic fields across the Hertzsprung–Russell diagram	232
14.5.1 Dynamo fields	232
14.5.2 Fossil fields	234
14.5.3 Stars in which surveys report no firm evidence of magnetic field	237
14.6 Conclusions	238

15 Imaging of protoplanetary and debris disks	244
<i>Marshall D. Perrin, Dean C. Hines, John P. Wisniewski, and Glenn Schneider</i>	
15.1 Introduction	244
15.1.1 Polarimetry for high contrast	245
15.1.2 Polarimetry for insight into scattering particle properties	246
15.2 History and methods	247
15.2.1 Initial history	247
15.2.2 The rise of AO	248
15.2.3 The Hubble Space Telescope	249
15.2.4 Other recent developments	249
15.2.5 Expectations for next-generation AO	249
15.3 Polarimetry results for debris disks	251
15.3.1 Beta Pictoris and AU Microscopii	251
15.3.2 Other debris disks	252
15.4 Protoplanetary disks	253
15.4.1 Case study: AB Aur	253
15.4.2 Protoplanetary disks observed with AO	254
15.4.3 Subaru SEEDS	255
15.4.4 Protoplanetary disks observed with HST	256
15.5 The future: Exozodiacal debris as background for terrestrial exoplanet studies	257
15.6 Conclusions and outstanding problems	258
IV Solar system	265
16 The Sun	267
<i>Jan O. Stenflo</i>	
16.1 Introduction	267
16.2 Instrumentation for solar polarimetry	267
16.2.1 Trade-offs and S/N ratio limitations	267
16.2.2 Compatibility of large array detectors with fast modulation schemes	268
16.3 Zeeman effect	268
16.3.1 Fourier transform spectrometers polarimetry	270
16.3.2 Line-ratio technique	271
16.4 Scattering polarization	273
16.4.1 Continuum polarization	273
16.4.2 The Second Solar Spectrum	273
16.5 Hanle effect	276
16.5.1 Forward-scattering Hanle effect	278
16.6 Hyperfine structure and Paschen–Back effect	279
16.7 Optical pumping and lower-level polarization	281
16.8 Resolution-independent magnetic-field diagnostics	281
16.8.1 Line ratio, intermittency, kG flux tubes	282
16.8.2 Hanle depolarization and the hidden ocean of turbulent fields	283
16.8.3 Symmetry properties of the transverse Zeeman effect and the angular field distribution	283
16.9 Concluding remarks	285
17 Terrestrial planets	289
<i>Vadym Kaydash, Yuriy Shkuratov, Michael Wolff, and Gorden Videen</i>	
17.1 Introduction	289

17.2	Mercury	289
17.3	Venus	292
17.3.1	Earth-based observations of Venus	292
17.3.2	Spaceborne polarimetry of the Venus atmosphere	293
17.4	Mars	296
17.4.1	Earth-based observations of Mars	296
17.4.2	Spaceborne polarimetry of Mars	297
17.5	Conclusion and perspectives	299
18	The Moon	303
<i>Yuriy Shkuratov, Nikolay Opanasenko, Viktor Korokhin, and Gorden Videen</i>		
18.1	Introduction	303
18.2	Negative polarization	305
18.3	Positive polarization	308
18.4	Spectro-polarimetry	310
18.5	Other polarimetric parameters	313
18.5.1	Polarization-plane orientation at large phase angles	313
18.5.2	Polarization-plane orientation at small phase angles	315
18.5.3	Circular polarization	315
18.5.4	Depolarization	316
18.6	Conclusion and future work	317
19	Gas giant planets, Saturn's rings, and Titan	320
<i>Robert A. West, Padma A. Yanamandra-Fisher, and Viktor Korokhin</i>		
19.1	Introduction	320
19.2	Ground-based observations and interpretations	320
19.2.1	Jupiter	321
19.2.2	Saturn, Titan, Uranus, and Neptune	322
19.2.3	Circular polarization	324
19.2.4	Saturn's rings	324
19.3	Spacecraft missions to Jupiter, Saturn, and Titan: Mission characteristics and instrument descriptions	324
19.3.1	Pioneer 10 and 11 missions and IPP description	325
19.3.2	Voyager 2 mission and PPS description	325
19.3.3	Galileo mission and PPR description	326
19.3.4	Cassini mission and ISS description	327
19.3.5	Huygens probe mission and DISR description	327
19.4	Data and interpretation: Jupiter	328
19.4.1	IPP maps at red and blue wavelengths	328
19.4.2	Galileo PPR scans and laboratory work on ammonia ice crystals	331
19.5	Data and interpretation: Saturn and rings	332
19.5.1	IPP maps in red and blue	332
19.5.2	Voyager PPS scans in the UV and near-IR	333
19.5.3	Cassini ISS polarization images	333
19.6	Data and interpretation: Titan	334
19.6.1	IPP maps in red and blue	334
19.6.2	Voyager PPS integrated disk measurements	334
19.6.3	DISR observations inside the atmosphere	335
19.7	Uranus and Neptune	335
19.8	Summary and future work	335

20 Icy moons of the outer planets	340
<i>Vera Rosenbush, Nikolai Kiselev, and Viktor Afanasiev</i>	
20.1 Introduction	340
20.2 Random and systematic errors of observations	342
20.3 Jovian system: The Galilean moons	344
20.3.1 Summary of polarimetric observations	344
20.3.2 Phase-angle and longitude dependences of polarization for Callisto	345
20.3.3 Phase-angle and longitude dependences of polarization for Io, Europa, and Ganymede	347
20.3.4 Opposition effects for Io, Europa, and Ganymede	348
20.3.5 Polarimetric data of the Galilean moons from space probes	349
20.3.6 Spectral dependence of polarization for the Galilean satellites	349
20.4 Saturnian system: Enceladus, Dione, Rhea, Iapetus, and Tethys	350
20.4.1 Enceladus, Dione, Rhea, and Tethys	350
20.4.2 Iapetus	351
20.5 Uranian system: Ariel, Umbriel, Titania, and Oberon	353
20.6 Final notes on polarization of satellites	354
20.7 Conclusion and perspectives	355
21 Asteroids	360
<i>Alberto Cellino, Ricardo Gil-Hutton, and Irina Belskaya</i>	
21.1 Introduction	360
21.2 Asteroid polarimetry: Data and instruments	361
21.2.1 Asteroid polarimetric data	361
21.2.2 The telescopes and instruments used in asteroid polarimetry	363
21.3 Interpretation of asteroid disk-integrated polarimetric data	364
21.4 Recent advances and most important achievements	365
21.4.1 Polarimetric behavior of different taxonomic classes	366
21.4.2 The properties of F-class asteroids	367
21.4.3 The discovery of Barbarians	368
21.4.4 Wavelength dependence	368
21.4.5 Polarimetric properties of near-Earth asteroids	369
21.4.6 Applications to space-weathering phenomena	369
21.4.7 Comparisons with thermal radiometry results for asteroid albedos	370
21.5 Some open problems	371
21.6 On the role of polarimetry in asteroid science	373
21.7 Some promising subjects for future investigation	375
22 Comets	379
<i>Nikolai Kiselev, Vera Rosenbush, Anny-Chantal Levasseur-Regourd, and Ludmilla Kolokolova</i>	
22.1 Introduction	379
22.1.1 Preamble	379
22.1.2 Historical background	380
22.2 Methods of modern observations	380
22.2.1 Aperture polarimetry	380
22.2.2 Imaging polarimetry	381
22.2.3 Spectro-polarimetry	381
22.2.4 Near-IR polarimetry	381
22.2.5 Spaceborne and in situ polarimetry	381
22.3 Main trends in linear polarization	381
22.3.1 Phase-angle dependence of linear polarization in the visible	382

22.3.2 Phase-angle dependence of linear polarization in the near IR	384
22.3.3 Spectral dependence of polarization	384
22.4 In situ measurements	386
22.5 Distribution of polarization over the coma	387
22.6 Specific phenomena in linear polarization	388
22.6.1 Outburst and fragmentation events	388
22.6.2 Stellar occultations	389
22.7 Interpretation of linear polarization data	389
22.7.1 Phase-angle dependence of polarization	389
22.7.2 Spectral dependence of polarization	391
22.8 Comet nuclei	392
22.9 Circular polarization	393
22.9.1 Observations	393
22.9.2 Interpretation	395
22.10 Similarity and diversity of comets: Classification issues	396
22.11 Conclusions	397
22.12 Perspectives	397

23 Transneptunian objects and Centaurs 405

Irina Belskaya and Stefano Bagnulo

23.1 Introduction	405
23.2 Instrument and method of observations	405
23.3 Accuracy of FORS polarimetric measurements and quality checks	406
23.4 Results of the observations	407
23.4.1 Dwarf planets and large TNOs	407
23.4.2 TNOs of smaller size	410
23.4.3 Centaurs	411
23.5 Possible influence of atmospheres, comae, and satellites	412
23.6 Polarization–albedo relationship	413
23.7 Constraints on surface properties	414
23.8 Conclusions	415

24 Interplanetary dust 419

Jérémie Lasue, Anny-Chantal Levasseur-Regourd, and Alexander Lazarian

24.1 Introduction	419
24.2 Polarimetric observations of the zodiacal light	419
24.2.1 Historical background	419
24.2.2 Zodiacal light intensity and polarization	420
24.2.3 Solar F-corona observations	424
24.2.4 Circular polarization observations	425
24.3 Local values of the zodiacal polarization	425
24.3.1 The inversion method	425
24.3.2 Radial variation of local polarization	426
24.3.3 Polarization–phase curve	426
24.4 Analysis of the observations and interpretations	427
24.4.1 Properties of the interplanetary dust particles	427
24.4.2 Numerical simulations of the polarization of the zodiacal light	428
24.4.3 Possible origin of circular polarization	430
24.5 Discussion	430
24.5.1 Thermal equilibrium of the dust population	430
24.5.2 Experimental simulations	430

24.5.3 Dust particle physical properties and their sources	431
24.5.4 Perspectives	432

V Exoplanets and exobiology **437**

25 Exoplanets **439**

Sloane J. Wiktorowicz and Daphne M. Stam

25.1 Searching for exoplanets	439
25.1.1 Polarimetry for exoplanet detection	440
25.1.2 Polarimetry for exoplanet characterization	445
25.2 Flux and polarization signals of exoplanets	445
25.2.1 Signals of gaseous exoplanets	446
25.2.2 Signals of rocky exoplanets	449
25.2.3 Signals of fluid-surface exoplanets	449
25.2.4 Transit polarimetry	449
25.2.5 Signals of planetary rings and moons	451
25.3 The first polarimetric observations of exoplanets	451
25.3.1 HD 189733	451
25.3.2 τ Boötis and 55 Cancri	452
25.3.3 ν Andromedae	453
25.3.4 The role of systematic effects	453
25.4 Polarimetry of Earthshine	455
25.5 The near future	456
25.5.1 Spatially unresolved exoplanets	456
25.5.2 Spatially resolved exoplanets	456
25.6 The intermediate future	457
25.7 The future	457

26 Astrobiology **462**

William Sparks, James Hough, and Ludmilla Kolokolova

26.1 Introduction	462
26.2 Linear polarization	463
26.2.1 Detection of terrestrial exoplanets	463
26.2.2 Liquid water and rainbows	463
26.2.3 Astrobiological characterization of exoplanets with linear polarimetry	463
26.2.4 Extrazodiacal disks	463
26.3 Circular polarization	464
26.3.1 Chirality	464
26.3.2 The origin of homochirality	465
26.3.3 The weak nuclear force	466
26.3.4 Circular polarization in star-forming regions	466
26.4 Searches for extraterrestrial life and evidence of prebiological chemistry	467
26.4.1 Biosignatures	467
26.4.2 Polarimetric remote sensing of microbial photosynthesis	468
26.4.3 Remote sensing of macroscopic vegetation	471
26.4.4 Modeling of laboratory data	471
26.4.5 Observational results	473
26.5 Summary	475

Appendix: Polarimetric definitions for astronomy **479**

Ludmilla Kolokolova, James Hough, and Anny-Chantal Levasseur-Regourd

Index **482**