

Contents

4 The stars

4.1 Physical parameters of the stars (Th. SCHMIDT-KALER)	1
4.1.0 General remarks	1
4.1.1 Classification of stellar spectra	1
4.1.1.1 The (improved and extended) Harvard classification	1
4.1.1.2 The (Yerkes or) MK system: spectral type and luminosity class	4
4.1.1.3 Abundance effects in spectral classification	5
4.1.1.4 Other spectral classification systems	9
4.1.1.5 Spectral catalogues and surveys	10
4.1.1.6 Spectral classification and interstellar extinction from wide band photometry	10
4.1.1.7 References for 4.1.1	13
4.1.2 Intrinsic colors and visual absolute magnitudes (calibration of the MK system)	14
4.1.2.1 Intrinsic colors of normal galactic stars	14
4.1.2.2 The absolute magnitudes of the stars	17
4.1.2.3 Calibration of special luminosity criteria	22
4.1.2.4 References for 4.1.2	23
4.1.3 Hertzsprung-Russel diagram, color-magnitude diagrams	25
4.1.3.1 The Hertzsprung-Russel diagram, stellar populations, stellar ages and metal contents	25
References for 4.1.3.1	27
4.1.3.2 Color diagrams	449
4.1.3.2.1 Color and spectral types	449
4.1.3.2.2 Color and extinction	449
4.1.3.2.3 Color-magnitude and color-color diagrams	450
4.1.3.2.4 References for 4.1.3.2	451
4.1.4 Effective temperatures T_{eff} , bolometric corrections B.C. and luminosities L	451
References for 4.1.4	456
4.1.5 Mass \mathfrak{M} , radius R , density ϱ , surface gravity g	28
4.1.5.1 Determination of the mass	28
4.1.5.2 Radius, density and surface gravity of the stars	29
4.1.5.3 References for 4.1.5	32
4.1.6 Rotation of stars	32
4.1.6.1 Individual values of the rotational velocity	32
4.1.6.2 Stellar rotation as a function of spectral type, luminosity class, and stellar evolution	32
4.1.6.3 References for 4.1.6	33
4.1.6.4 Catalogues of rotational velocities	34
4.2 Magnitudes and colors (E. LAMLA)	35
4.2.0 General remarks	35
4.2.1 Data dissemination centers	35
4.2.2 Definitions	35
4.2.2.1 Symbols	35
4.2.2.2 Definition of the apparent magnitude	35
4.2.2.3 Isophotal and effective wavelength	36
4.2.2.4 Passband width	37
4.2.2.5 Definition of the color index	37
4.2.2.6 Definition of the absolute magnitude	38
4.2.2.7 Definitions of the bolometric magnitude and the bolometric correction	38
4.2.3 General problems in photometry of stars	38

4.2.4 Photographic photometry	40
4.2.4.1 Methods and catalogues	40
4.2.4.2 <i>RGU</i> system Basel	41
4.2.5 Photoelectric photometry	44
4.2.5.0 Introduction	44
4.2.5.0.1 Extinction of the earth's atmosphere	45
4.2.5.0.2 Response function of receivers	47
4.2.5.1 The original <i>UBV</i> color system, reconstructed in USA	48
4.2.5.2 The original <i>UBV</i> color system, reconstructed at Vilnius	51
4.2.5.3 The DDO color system	55
4.2.5.4 The Strömgren <i>uvby</i> color system and H β	57
4.2.5.5 The 7 color system of Borgman (<i>RQPNMLK</i>)	59
4.2.5.6 The 4 color system <i>uvgr</i>	60
4.2.5.7 The Geneva 7 color system	61
4.2.5.8 The Wood 12 color system (Strömgren extension)	63
4.2.5.9 The Vilnius <i>WBVR</i> color system	64
4.2.5.10 The Vilnius <i>UPXYZVS</i> color system	66
4.2.5.11 The 13 color system (Johnson, Mitchell, Latham)	68
4.2.5.12 The Johnson color system <i>UBVRIJK...Q</i>	71
4.2.5.13 The color system used in the southern hemisphere	74
4.2.5.14 The Walraven <i>VBLUW</i> color system	76
4.2.5.15 The <i>UBVRI</i> color system	79
4.2.5.16 The Cousins (Cape) <i>VRI</i> color system	82
4.2.5.17 Graphs of some response functions $S(\lambda)$	83
4.2.6 References for 4.2	85
4.3 Physics of stellar atmospheres (B. BASCHEK/M. SCHOLZ).	91
4.3.1 General references	91
4.3.2 List of generally and frequently used symbols	91
4.3.3 Basic equations	92
4.3.3.1 Assumptions and parameters	92
4.3.3.2 Equation of hydrostatic equilibrium	93
4.3.3.3 Equation of energy conservation	93
4.3.3.4 Equations of kinetic equilibrium	94
4.3.3.5 Equation of radiation transport	94
4.3.3.6 Boundary conditions	95
4.3.3.7 Mean extinction coefficients and optical depths	95
4.3.3.8 Stellar radius and atmospheric extension	95
4.3.3.9 Compact model atmosphere	96
4.3.4 Statistical equilibrium and cross-sections	96
4.3.4.1 Distribution functions	96
4.3.4.2 Statistical (rate) equations	97
4.3.4.3 Collisional processes	98
4.3.4.3.1 Collisional ionization by electrons and three-body recombination	98
4.3.4.3.2 Collisional excitation and de-excitation by electrons	99
4.3.4.3.3 Other collisional processes	100
4.3.4.4 Radiative processes	100
4.3.4.4.1 Photo-ionization and photo-recombination (bound-free transitions)	100
4.3.4.4.2 Electron-ion bremsstrahlung (free-free transitions)	101
4.3.4.4.3 Line absorption and emission (bound-bound transitions)	101
4.3.4.4.4 Scattering of photons	102
4.3.4.5 Line broadening	106
4.3.4.5.1 Gauss, Lorentz, and Voigt profile	106
4.3.4.5.2 Doppler line broadening	107
4.3.4.5.3 Radiation (natural) line broadening	108
4.3.4.5.4 Collision (pressure, Stark) line broadening	108
4.3.4.6 LTE approximation in radiation transport	113
4.3.4.7 Multi-level approach in radiation transport	114

4.3.4.8 Continuous opacity in stellar atmospheres	115
4.3.4.9 References for 4.3.4	120
4.3.5 Thermodynamic properties	122
4.3.5.1 Internal partition functions	122
4.3.5.2 Occupation numbers of internal states	124
4.3.5.3 Equation of state	124
4.3.5.4 Chemical equilibrium (mass-action law)	124
4.3.5.5 Some thermodynamic quantities and relations	125
4.3.5.6 Some thermodynamic functions for the normal element mixture	127
4.3.5.7 References for 4.3.5	135
4.3.6 Methods of computation of stellar model atmospheres	136
4.3.6.1 Approximations in radiation transport theory	136
4.3.6.2 Convective energy transport	137
4.3.6.3 Model computation with given parameters	140
4.3.6.4 Spectral analysis	143
4.3.6.5 References for 4.3.6	144
4.3.7 “Non-standard” stellar model atmospheres	146
4.3.7.1 Moving atmospheres	146
4.3.7.2 Chromospheres and coronae	148
4.3.7.3 “Turbulent” motions	148
4.3.7.4 Depth-dependent abundances (diffusion)	149
4.3.7.5 Deviations from spherical symmetry	150
4.3.7.6 References for 4.3.7	151
4.4 Stellar structure and evolution (E. MEYER-HOFMEISTER)	152
4.4.0 List of symbols	152
4.4.1 Equation of stellar structure	154
4.4.2 Properties of stellar matter	155
4.4.2.1 The equation of state	155
4.4.2.2 Functions ∇_{ad} and c_p	159
4.4.2.3 Stellar opacities	159
4.4.2.3.1 Opacity tables	159
4.4.2.3.2 Electron conduction	178
4.4.2.4 Energy generation	181
4.4.2.4.1 Hydrogen burning	181
4.4.2.4.2 Helium burning	185
4.4.2.4.3 Carbon burning	186
4.4.2.4.4 Advanced burning stages	186
4.4.2.4.5 Screening factors	187
4.4.2.4.6 Neutrino loss rates	187
4.4.3 Model computations	188
4.4.3.1 Main-sequence stars	188
4.4.3.2 Evolved stars	190
4.4.3.3 Stars with special properties	193
4.4.4 References for 4.4	194

5 Special types of stars

5.1 Variable stars (H. W. DUERBECK/W. C. SEITTER)	197
5.1.0 Abbreviations and notations	197
5.1.1 Definitions and general remarks	198
5.1.1.1 General catalogues and bibliographies	198
5.1.1.2 Monographs on general aspects of variable stars	198
5.1.1.3 Notation and classification	198
5.1.1.4 Statistical, kinematical, and evolutionary status	198
5.1.1.5 Position of variable stars in the Hertzsprung-Russell diagram	201
5.1.1.6 References for 5.1.1	202

5.1.2 Pulsating and rotating variables	203
5.1.2.1 Long period Cepheids—C	204
5.1.2.2 RR Lyrae stars—RR	208
5.1.2.3 Dwarf Cepheids—RRs	210
5.1.2.4 δ Scuti stars—δ Sct	212
5.1.2.5 RV Tauri stars—RV	213
5.1.2.6 Mira stars (long period variables)—M	215
5.1.2.7 Semiregular variables—SR	219
5.1.2.8 Irregular variable stars—L	219
5.1.2.9 β Cephei stars—βC	220
5.1.2.10 ZZ Ceti stars—ZZ	221
5.1.2.11 α ² Canum Venaticorum variables—αCV	222
5.1.2.12 BY Draconis variables—BY	223
5.1.2.13 References for 5.1.2	224
5.1.3 Eruptive and depression variables	228
5.1.3.1 Supernovae—SN	229
5.1.3.2 Novae—N	240
5.1.3.3 Dwarf novae—DN	250
5.1.3.4 Nova-like stars—NL	253
5.1.3.5 Z Andromedae stars or symbiotic stars—Z And	254
5.1.3.6 R Coronae Borealis stars—RCB	255
5.1.3.7 S Doradus variables—SD	257
5.1.3.8 γ Cassiopeiae variables—γC	258
5.1.3.9 Orion and RW Aurigae type variables—In and Is	258
5.1.3.10 UV Ceti stars—UV	261
5.1.3.11 References for 5.1.3	262
5.2 Peculiar stars (W. C. SEITTER/H. W. DUERBECK)	269
5.2.0 Introduction, general remarks	269
5.2.1 Peculiar stars of early spectral classes (O···A)	272
5.2.1.1 Of stars	272
5.2.1.1.1 General characteristics, classification	272
5.2.1.1.2 Physical parameters	274
5.2.1.1.3 Evolution	277
5.2.1.1.4 Statistics and galactic distribution	278
5.2.1.2 Wolf-Rayet stars—WR	278
5.2.1.2.1 General characteristics, classification	278
5.2.1.2.2 Variability	281
5.2.1.2.3 Physical parameters	281
5.2.1.2.4 Evolution	286
5.2.1.2.5 Galactic distribution and statistics	287
5.2.1.3 P Cygni type stars	288
5.2.1.4 Be, shell and related stars	290
5.2.1.4.1 Classification criteria and phenomena	291
5.2.1.4.2 Variability	294
5.2.1.4.3 Physical parameters	294
5.2.1.4.4 Models of Be and shell stars	299
5.2.1.4.5 Statistics and galactic distribution	302
5.2.1.5 CNO stars	303
5.2.1.6 Helium strong, helium weak, helium variable stars	305
5.2.1.7 References for 5.2.0 and 5.2.1	311
5.2.2 Peculiar stars in the range B···F	318
5.2.2.1 Peculiar A stars—Ap (Bp)	318
5.2.2.1.1 General characteristics	318
5.2.2.1.2 Variability	321
5.2.2.1.3 Rotation, pulsation	322
5.2.2.1.4 Magnetic fields	322
5.2.2.1.5 Physical parameters	326

5.2.2.1.6 Theories of Ap stars	330
5.2.2.1.7 Statistics and galactic distribution	332
5.2.2.2 Metallic line stars—Am (Fm)	333
5.2.2.2.1 General characteristics, nomenclature	333
5.2.2.2.2 Variability	335
5.2.2.2.3 Rotation	336
5.2.2.2.4 Physical parameters	337
5.2.2.2.5 Models, theories of Am stars	340
5.2.2.2.6 Statistics and galactic distribution	341
5.2.2.3 λ Bootis stars—weak line population I stars	341
5.2.2.4 References for 5.2.2	342
5.2.3 Peculiar stars of late spectral classes (G...M)	347
5.2.3.1 Peculiar G and K stars	348
5.2.3.1.1 Stars with CH anomalies	348
5.2.3.1.2 Stars with CN anomalies	349
5.2.3.1.3 Ba stars	350
5.2.3.2 C stars (Carbon stars)	351
5.2.3.3 S stars	352
5.2.3.4 References for 5.2.3	355
5.3 Protostars, pre-main sequence objects (I. APPENZELLER)	357
5.3.1 Definitions	357
5.3.2 List of symbols	357
5.3.3 Distribution of protostars and pre-main sequence objects	358
5.3.4 Low mass protostars and pre-main sequence stars ($M \gtrsim 3 M_{\odot}$)	358
5.3.4.1 Evolutionary tracks	358
5.3.4.2 The T Tauri stars	360
5.3.5 Massive protostars ($M \gtrsim 4 M_{\odot}$)	361
5.3.6 Other very young objects related to the final stages of star formation or very early stellar evolution	362
5.3.7 References for 5.3	362
5.4 Planetary nebulae (L. H. ALLER)	364
5.4.1 Introduction	364
5.4.2 General references and review articles	364
5.4.3 References for special topics	364
5.4.4 Data for representative planetary nebulae	368
5.5 White dwarfs (V. WEIDEMANN)	373
5.5.1 General	373
5.5.2 Luminosity function, space density	373
5.5.3 Spectral type	374
5.5.3.1 Spectral classification	374
5.5.3.2 Magnetic white dwarfs	374
5.5.3.3 Variable DA (or ZZ Ceti) stars	374
5.5.4 Catalogues, observation lists	375
5.5.5 Atmospheres, HR diagram	376
5.5.6 Radii, masses	377
5.5.7 Interior, envelopes	378
5.5.8 Evolution, age	379
5.5.9 References for 5.5	379
5.6 Compact objects	
5.6.1 Neutron stars (M. GREWING)	} see Subvolume c, p. 1ff.
5.6.2 Radiopulsars (M. GREWING)	
5.6.3 Pulsating X-ray sources (J. TRÜMPER/H. H. FINK)	
5.6.4 X-ray bursters (J. TRÜMPER/H. H. FINK)	
5.6.5 Black holes (J. TRÜMPER/H. H. FINK)	
5.7 X-ray and γ-ray sources (H. H. FINK/J. TRÜMPER)	

6 Double stars and star clusters

6.1 Double stars (T. HERCZEG)	381
6.1.0 General remarks	381
6.1.0.1 Classification	381
6.1.0.2 Orbital elements	382
6.1.0.3 Some binary systems of special interest	383
6.1.0.4 Binary frequencies, distribution of separations	384
6.1.0.5 Double and multiple stars in the solar neighborhood ($r \leq 10$ pc)	385
6.1.0.6 References for 6.1.0	386
6.1.1 Visual double stars	387
6.1.1.1 Limits of separation; detectability	387
6.1.1.2 Catalogues of visual double stars	388
6.1.1.3 Apparent magnitudes	389
6.1.1.4 Statistical relationships	389
6.1.1.5 Wide pairs	391
6.1.1.6 Multiple systems	391
6.1.1.7 References for 6.1.1	392
6.1.2 Astrometric binaries and systems with unseen companions	393
References for 6.1.2	394
6.1.3 Spectroscopic binaries	395
6.1.3.1 Orbital elements and catalogues	395
6.1.3.2 Statistical relationships	396
6.1.3.3 Spectral duplicity, composite spectra	397
6.1.3.4 Rotation in close binaries	398
6.1.3.5 Binaries among special types of stars	398
6.1.3.6 Cataclysmic variables as close binaries	400
6.1.3.7 References for 6.1.3	401
6.1.4 X-ray binaries	403
References for 6.1.4	407
6.1.5 Photometric or eclipsing binaries	408
6.1.5.1 Catalogues	408
6.1.5.2 Classification	409
6.1.5.3 Close binary evolution	409
6.1.5.4 Statistical relationships	410
6.1.5.5 Contact systems	412
6.1.5.6 The group of RS Canum Venaticorum stars	413
6.1.5.7 Period changes of eclipsing binaries	413
6.1.5.8 Apsidal motion	414
6.1.5.9 Ellipsoidal variables	415
6.1.5.10 Close binaries in star clusters and nearby galaxies	415
6.1.5.11 Radioemission in close binary systems	417
6.1.5.12 References for 6.1.5	417
6.2 Star clusters and associations (W. SEGGEWISS)	420
6.2.1 Globular clusters	420
6.2.1.1 Definition and classification	420
6.2.1.2 Catalogues	420
6.2.1.3 Literature compilations	421
6.2.1.4 Dimensions and structure of globular clusters	421
6.2.1.5 Brightness and colour	422
6.2.1.6 Integrated spectra of globular clusters	423
6.2.1.7 Mass and luminosity function	423
6.2.1.8 Colour-magnitude diagrams (CMDs)	424
6.2.1.9 Evolution of globular clusters	424
6.2.1.10 Variable stars and X-ray sources in globular clusters	425
6.2.1.11 Gas and dust content of globular clusters	426
6.2.1.12 Abundances of chemical elements in globular clusters	427

6.2.1.13 Motions and dynamics	427
6.2.1.14 Distances and galactic distribution of globular clusters	428
6.2.1.15 References for 6.2.1	429
6.2.2 Open clusters	432
6.2.2.1 Definition and classification	432
6.2.2.2 Catalogues, atlases and literature	433
6.2.2.3 Dimensions of open clusters	433
6.2.2.4 Brightness and colours of open clusters	434
6.2.2.5 Spectra of cluster stars	434
6.2.2.6 Mass and luminosity	434
6.2.2.7 Colour-magnitude diagrams (CMDs) of open clusters	435
6.2.2.8 Evolution and ages of open clusters	436
6.2.2.9 Variable and peculiar stars in open clusters	437
6.2.2.10 Gas and dust content of open clusters	437
6.2.2.11 Abundances of chemical elements in open clusters	438
6.2.2.12 Motions and dynamics of open clusters	438
6.2.2.13 Distances and galactic distribution of open clusters	440
6.2.2.14 References for 6.2.2	441
6.2.3 Associations	445
6.2.3.1 Definitions and designations	445
6.2.3.2 OB associations	445
6.2.3.3 T associations	446
6.2.3.4 R associations	447
6.2.3.5 References for 6.2.3	447

