

Contents

<i>Preface</i>	<i>page</i> xiii
1 The wind from the Sun: an introduction	1
1.1 A brief history of ideas	1
1.1.1 Intermittent particle beams?	2
1.1.2 Permanent solar corpuscular emission?	4
1.1.3 The modern solar wind	6
1.2 Looking at the Sun	8
1.2.1 Basic solar properties	9
1.2.2 The solar spectrum	10
1.2.3 The solar disc	13
1.2.4 Sunspots, magnetic fields and the solar cycle	15
1.2.5 Around the Sun: chromosphere and corona	18
1.3 Observing the solar wind	24
1.3.1 Observing near the ecliptic	24
1.3.2 Exploring the third dimension with Ulysses	28
1.3.3 A simplified three-dimensional picture	33
References	37
2 Tool kit for space plasma physics	41
2.1 What is a plasma?	42
2.1.1 Gaseous plasma	44
2.1.2 Quasi-neutrality	44
2.1.3 Collisions of charged particles	48
2.1.4 Plasma oscillations	54
2.1.5 Non-classical plasmas	56
2.1.6 Summary	57
2.2 Dynamics of a charged particle	58
2.2.1 The key role of the magnetic field	58
2.2.2 Basic charge motion in constant and uniform fields	59
2.2.3 Non-uniform magnetic field	62
2.2.4 Adiabatic invariants	65
2.2.5 Summary	66
2.3 Many particles: from kinetics to magnetohydrodynamics	66
2.3.1 Elements of plasma kinetics	66

2.3.2	First-aid kit for space plasma fluids	72
2.3.3	Elements of magnetohydrodynamics	85
2.3.4	Waves and instabilities	96
2.3.5	Summary	100
2.4	Basic tools for ionisation	101
2.4.1	Energy of ionisation and the size of the hydrogen atom	101
2.4.2	Ionisation by compressing or heating	102
2.4.3	Radiative ionisation and recombination	103
2.4.4	Non-radiative ionisation and recombination	105
2.5	Problems	107
2.5.1	Linear Debye shielding in a non-equilibrium plasma	107
2.5.2	Mean free path in a plasma	108
2.5.3	Particles trapped in a planetary magnetic field	108
2.5.4	Filtration of particles in the absence of equilibrium	109
2.5.5	Freezing of magnetic field lines	110
2.5.6	Alfvén wave	110
2.5.7	Why is the solar wind ionised?	110
	References	110
3	Anatomy of the Sun	113
3.1	An (almost) ordinary star	113
3.1.1	Hydrostatic equilibrium of a large ball of plasma	114
3.1.2	Luminosity	116
3.1.3	Energy source and timescales	118
3.1.4	The mass of a normal star	121
3.2	Structure and dynamics	123
3.2.1	Modelling the solar interior	124
3.2.2	Convective instability	125
3.2.3	Convective energy transfer	128
3.2.4	The quiet photosphere	132
3.2.5	Solar rotation	135
3.3	Some guesses on solar magnetism	137
3.3.1	Elements of dynamo theory	138
3.3.2	Solar kinematic dynamos	142
3.3.3	Concentrating and expelling the magnetic field	145
3.3.4	Lorentz force restriction on dynamo action	148
3.3.5	Elementary physics of magnetic flux tubes	149
3.3.6	Surface magnetic field	154
3.4	Problems	158
3.4.1	Conductive heat transfer in the solar interior	158
3.4.2	Timescale for radiative transport	158
3.4.3	Solar differential rotation	158
3.4.4	Twisted magnetic flux tube	159
3.4.5	The heat flux blocked by sunspots	159
	References	160

4	The outer solar atmosphere	165
4.1	From the photosphere to the corona	166
4.1.1	The atmosphere in one dimension	166
4.1.2	One more dimension	168
4.1.3	Three dimensions in space	169
4.1.4	... and one dimension in time	169
4.1.5	A (tentative) look at the solar jungle	172
4.2	Force balance and magnetic structures	174
4.2.1	Forces	175
4.2.2	Force-free magnetic field	177
4.2.3	Magnetic helicity	181
4.2.4	Inferences on magnetic structure in the low corona	185
4.3	Energy balance	186
4.3.1	Radiative losses	186
4.3.2	Radiative and conductive timescales	187
4.3.3	Temperature structure	188
4.4	Some prominent species	190
4.4.1	Spicules	190
4.4.2	Magnetic loops	191
4.4.3	Prominences	193
4.5	Time variability	194
4.5.1	Empirical facts	194
4.5.2	Hints from physics	197
4.5.3	Further difficult questions	200
4.6	Coronal heating: boojums at work?	203
4.6.1	The energy budget and how to balance it	204
4.6.2	Heating through reconnection events	205
4.6.3	Heating by waves	206
4.6.4	Filtration of a non-Maxwellian velocity distribution	209
4.7	Hydrostatic instability of the corona	214
4.7.1	Simplified picture of a static atmosphere	214
4.7.2	Magnetic field effects	215
4.8	Problems	217
4.8.1	Elementary temperature profile	217
4.8.2	Helicity of a string wrapped around a doughnut	217
4.8.3	A static solar atmosphere?	218
	References	218
5	How does the solar wind blow?	223
5.1	The basic problem	225
5.1.1	The solar wind on the back of an envelope	225
5.1.2	Nasty questions, or why it is complicated	227
5.2	Simple fluid theory	228
5.2.1	The isothermal approximation	228
5.2.2	Breeze, wind or accretion?	232
5.3	Letting the temperature vary	237

5.3.1	Energy balance	237
5.3.2	Polytrope approximation	239
5.3.3	Changing the geometry	246
5.3.4	Further pushing or heating the wind	247
5.3.5	What about viscosity?	249
5.4	A mixture of fluids	250
5.4.1	Simple balance equations	251
5.4.2	Observed proton and electron temperatures	253
5.4.3	The role of collisions	254
5.4.4	Heat flux	256
5.4.5	The electric field	257
5.4.6	Fluid picture balance sheet and refinements	261
5.5	Kinetic descriptions	262
5.5.1	Some notations	262
5.5.2	Observed proton and electron velocity distributions	263
5.5.3	Non-collisional electron heat flux	267
5.5.4	Exospheric models	268
5.5.5	Kinetic models with collisions and wave-particle interactions	273
5.6	Building a ‘full’ theory?	274
5.6.1	More and better observations (beware of hidden assumptions)	274
5.6.2	Difficult theoretical questions	275
5.7	Problems	277
5.7.1	Transonic flows in ducts: the de Laval nozzle	277
5.7.2	The hysteresis cycle of an isothermal flow	279
5.7.3	Spherical accretion by a star: the Bondi problem	280
5.7.4	A wind with polytrope protons and electrons	281
5.7.5	Playing with the kappa distribution	282
5.7.6	‘Temperature’ or ‘temperatures’?	283
5.7.7	Non-collisional heat flux	284
5.7.8	An imaginary wind with charges of equal masses	285
	References	286
6	Structure and perturbations	291
6.1	Basic large-scale magnetic field	291
6.1.1	Parker’s spiral	291
6.1.2	Basic heliospheric current sheet and other currents	296
6.1.3	Magnetic field effects on the wind	299
6.2	Three-dimensional structure during the solar cycle	300
6.2.1	Warped heliospheric current sheet	301
6.2.2	Observed large-scale structure	301
6.2.3	Connecting the Sun and the solar wind, or: where do the fast and slow winds come from?	305
6.3	Major perturbations	308
6.3.1	Interaction between the fast and slow winds	308

6.3.2	Coronal mass ejections in the solar wind	309
6.3.3	Associated shocks	311
6.4	Waves and turbulence	315
6.4.1	Waves	315
6.4.2	Turbulence	318
6.5	Minor constituents	326
6.5.1	Abundances: from the Universe to the solar wind	326
6.5.2	Helium and heavier solar wind ions	327
6.5.3	Pick-up ions	328
6.6	Problems	329
6.6.1	Parker's spiral	329
6.6.2	Heliospheric currents	329
6.6.3	Coplanarity in MHD shocks	330
6.6.4	Kraichnan's spectrum in magnetofluid turbulence	330
	References	330
7	Bodies in the wind: dust, asteroids, planets and comets	335
7.1	Bodies in the wind	336
7.1.1	Various bodies	336
7.1.2	Mass distribution	338
7.1.3	Mass versus size	341
7.1.4	Atmospheres and how they are ionised	344
7.1.5	Planetary magnetic fields and ionospheric conductivity	347
7.2	Basics of the interaction	348
7.2.1	Properties and spatial scales of the flow	348
7.2.2	Being small: electrostatic charging and wakes	352
7.2.3	Being large: the importance of conductivity	358
7.2.4	Large objects with a conducting atmosphere	362
7.2.5	Large magnetised objects	365
7.2.6	Bow shocks	368
7.2.7	Not being constant: sputtering and evaporation	371
7.3	The magnetospheric engine	372
7.3.1	Basic structure	375
7.3.2	Energy, coupling and timescales	378
7.3.3	Storms, substorms and auroras	385
7.4	Physics of heliospheric dust grains	390
7.4.1	Forces	390
7.4.2	Evaporation	394
7.5	Comets	394
7.5.1	Producing an atmosphere	397
7.5.2	Ionising the atmosphere	400
7.5.3	Pick-up of cometary ions	401
7.5.4	Magnetic pile-up	403
7.5.5	The plasma tail	404
7.5.6	X-ray emission	406
7.5.7	The dust tail	408

7.6	Problems	409
7.6.1	Electrostatic charging in space	409
7.6.2	Magnetic pile-up	409
7.6.3	Chapman–Ferraro layer	410
7.6.4	Interaction of the solar wind with Venus and Mars	411
7.6.5	Ring current	411
7.6.6	Does Vesta have a magnetosphere?	412
7.6.7	Gas–dust drag in a comet: another nozzle problem	412
	References	413
8	The solar wind in the Universe	419
8.1	The frontier of the heliosphere	419
8.1.1	The Local Cloud	420
8.1.2	Basics of the interaction	421
8.1.3	The size of the solar wind bubble	424
8.2	Cosmic rays	425
8.2.1	Cosmic rays observed near Earth	426
8.2.2	Rudiments of the acceleration of particles	430
8.2.3	Modulation of galactic cosmic rays by solar activity	436
8.2.4	‘Anomalous cosmic rays’	439
8.3	Examples of winds in the Universe	440
8.3.1	Some basic physical processes in mass outflows	441
8.3.2	Some empirical results on stellar winds	443
8.3.3	The efficiency of the wind engine	445
8.4	Problems	448
8.4.1	Energy density of cosmic rays	448
8.4.2	Power law distribution of accelerated particles	448
8.4.3	The size of an astrosphere	448
8.4.4	Instability of a star’s atmosphere produced by radiation pressure	448
	References	449
	<i>Appendix</i>	451
	<i>Index</i>	457