Contents

	Preface	page xi
	Acknowledgements	xii
1	A brief history and background	1
1.1	Overview of some early results and concepts	1
1.2	Observational techniques and results: past, present, and future prospects	5
2	Methods for probing magnetic fields in diffuse astrophysical plasmas	9
2.1	Introduction	9
2.2	Some basics of polarised EM waves	9
2.3	Zeeman splitting of spectral lines	10
2.4	Polarisation of optical starlight and dust radiation as a probe of	
	interstellar fields	12
2.5	Radio telescope techniques for polarimetry	12
2.6	Faraday rotation	13
2.7	The concept of Faraday depth and magnetic field probes	
	in the 3rd dimension	17
2.8	The Crab Nebula as a 3-D Faraday synthesis model	21
2.9	Some instrumental and measurement effects involved in Faraday	
	rotation imaging	24
2.10	Faraday tomography to model magnetic structures in the	
	3rd dimension	25
2.11	Total energy and magnetic field estimates for	
	synchrotron-radiating clouds	27
2.12	Prospects for magnetic field measurement in other energy bands	29
3	Mechanisms for magnetic field generation and regeneration	33
3.1	Introduction	33
3.2	Some basic equations and the magnetic induction equation	34
3.3	Battery processes and seed fields	36
3.4	The role of cosmic ray pressure in galactic magnetic fields	42
3.5	Magnetic reconnection	43
3.6	Effects of neutral gas	52

viii	Contents

4	Galactic "microcosms" of extragalactic magnetic systems	55
4.1	Introductory comments	55
4.2	The Sun	56
4.3	Magnetic fields in other stars	57
4.4	Jets from Galactic stars	59
4.5	Molecular clouds and the role of magnetic fields in star formation	61
4.6	The generation and regeneration of magnetic fields	
	in supernova remnants	62
4.7	A magnetised jet in the Galactic centre	68
5	Magnetic field configurations in large galaxies	72
5.1	Introduction	72
5.2	Our Milky Way – a spiral galaxy from within	73
5.3	Magnetic structures of spiral galaxies	80
5.4	Some dynamical and energetic aspects of galaxies	88
5.5	Basic principles of the galactic α - ω dynamo	89
6	Magnetic field outflow from dwarf and starburst galaxies	100
6.1	Introduction	100
6.2	Star formation in galaxies and associated magnetised outflows	101
6.3	IGM seeding due to "conventional" stellar processes in galaxies	109
7	Extragalactic jets and lobes – I	117
7.1	How much energy and from where?	117
7.2	Jets as electromagnetically driven systems	119
7.3	Representative model simulations of radio lobes fed by a	
	Poynting flux jet	120
7.4	Tests of kpc scale jet-lobe systems in different environments	126
7.5	Some specific ideas on extraction of magnetic energy at the	
	central BH	130
7.6	Electromagnetic extraction of collimated power flow at the	
	black hole	131
7.7	Another concept: Extraction of BH energy from the inner	
	accretion disc, outside the ergosphere	132
7.8	Summary of two SMBH jet models	136
7.9	Simulations of protostellar jets	137
8	Extragalactic jets and lobes - II. More on magnetic energy	
	flows into the IGM from galaxy nuclei	140
8.1	Introduction	140
8.2	An electric circuit model for energy flow from a supermassive	
	black hole	140
8.3	Plasma parameter estimates for a "typical" BH-driven jet-lobe	
	system outside of a large galaxy cluster	143

Co	ntent	nts	ix

8.4	Extragalactic jets as transmission lines and CR accelerators	146
8.5	Probes of the internal gas physics in magnetised radio lobes and halos	148
8.6	SMBH masses and magnetisation of the IGM	151
8.7	Some basic calculations relating to BH-powered outflow	152
8.8	Observational/experimental quantification of BH energy output to the IGM	153
8.9	Implications of constraints imposed by the energy gap in Fig. 8.2	155
8.10	Additional calculations of global energy release from galactic BHs	
	into the IGM and estimates of the photon energy component	155
8.11	Some consequences of "captured" energy release from galactic BHs	157
8.12	Summary of some questions	158
9	Magnetic fields associated with clusters and groups of galaxies	162
9.1	Introduction	162
9.2	Methods for probing galaxy cluster magnetic fields	166
9.3	Magnetic fields and cluster cooling	174
9.4	Energy components of the intracluster medium (ICM)	176
9.5	Regeneration and amplification of magnetic fields in the	
	intracluster medium	178
9.6	The Sunyaev-Zel'dovich effect as a probe of intracluster gas physics	182
9.7	Inverse-Compton emission and implications for intracluster	
	magnetic field strength	185
9.8	Hadronically produced CR electrons, CR protons, and related magnetic	
	field energy	187
9.9	Summary	187
10	Magnetic fields beyond galaxy clusters	192
10.1	Low frequency radio emission as a tracer of extragalactic	
	magnetic fields	192
10.2	Large scale intergalactic shocks and "fossil" radio galaxies	194
10.3	γ-Ray probes for weak intergalactic fields in cosmic voids	197
10.4	$B_{\rm IG}$ from the angular broadening of a γ -ray cascade	202
10.5	Intergalactic magnetic field γ -ray flux probes down to 10^{-20} G	205
10.6	Summary remarks	207
11	Intergalactic cosmic rays, gamma rays, and magnetic fields	210
11.1	A brief introduction	210
11.2	Magnetic effects on UHECR propagation in intergalactic space	211
11.3	Energy losses of UHECR nucleons in intergalactic space	214
11.4	CR nuclei of helium and heavier nuclei	218
11.5	Candidate production sites for UHECRs	219
11.6	γ -Rays, neutrons, and neutrinos at high energies	221
11.7	Detection instruments for UHECRs	222
11.8	Some additional comments on UHECR detection	223
11.9	The Pierre Auger UHECR telescope	226
11.10	Recent astrophysical results from UHECR observations	226

X	Contents

11.11	An intergalactic magnetic field probe based solely on UHECR measurements	229
11.12	Concluding comments on the high energy universe of	227
11.12	Chapters 10 and 11	232
12	Magnetic fields in cosmologically distant galaxy systems	235
12.1	Magnetic fields associated with absorption line systems in quasars	235
12.2	Probes of cosmological magnetic field evolution using quasar	
	Faraday rotation statistics	238
12.3	Magnetic field estimates from transverse probes of quasar intervenors	245
12.4	Transverse B probes and gravitational lensing	249
12.5	Rotation measure searches for a widespread, cosmologically	
	co-expanding intergalactic magnetic field	251
12.6	Importance of the global star formation rate (SFR) over all	
	galaxy redshifts	253
12.7	Post-amplification of existing IGM fields	254
12.8	Seed fields produced during and following the appearance of the	
	first stars and galaxies: some general, basic calculations	256
12.9	Indirect observational indicators of extragalactic magnetic fields	
	at large cosmological distances	258
12.10	Seed fields between Recombination and the early galaxy	
	formation epoch	259
13	Cosmic magnetic fields and our ultimate origins	263
13.1	Introduction: Why pre-Recombination magnetic fields are of interest	263
13.2	CMB fluctuations	264
13.3	The problem of foreground CMB fluctuations	265
13.4	Faraday rotation at the last scattering surface	265
13.5	Ideas and theories on seed fields originating around the QCD and/or	
	electroweak phase transitions in the primordial fluid	266
13.6	Summary and conclusion	270
	Abbreviations	272
	Symbols	273
	Object Index	278
	Subject Index	279