

PHYSICS 426 NOTES: PLASMA ASTROPHYSICS

Original version (2008): Jean Eilek
 Physics Department, New Mexico Tech
 Socorro, NM 87801, U.S.A.
 JEILEK@AOC.NRAO.EDU

revised (2009): Lisa Young

Note to my students: These notes continue what we started in Physics 425. Our goal is still to explore the “physics of astrophysics”. This term we’ll develop the radiation-physics tools we’ll need, and focus more on galaxies, their interstellar medium, and high-energy astrophysics .

Contents

1 Galaxies, normal and otherwise	1	3 Some Radiation Basics	12
1.1 Normal galaxies: spirals	1	3.1 Radiation: some important definitions	12
1.2 Normal galaxies: ellipticals	2	3.2 Thermal equilibrium: an ideal gas . . .	12
1.3 Query: why are they different?	3	3.3 Thermal equilibrium: radiation	13
1.4 Interlude: stellar dynamics	3	3.4 Radiative transfer	14
1.5 The not-so-normal ones: active galaxies	4	3.4.1 More definitions	14
1.6 The beast in the core	5	3.4.2 Transfer analysis	15
1.6.1 Techniques: normal galaxies	5	3.4.3 Optically thick and thin limits	15
1.6.2 Techniques: extend to AGN	5	3.5 Appendix I: some examples with in-	
1.6.3 The galactic center: stellar orbits	6	tensity	16
2 The Interstellar Medium	8	3.5.1 Isotropic radiation field	16
2.1 The diffuse ISM in our galaxy	8	3.5.2 Intensity is constant along a ray	16
2.1.1 How we observe the ISM	8	3.5.3 Flux from a sphere	16
2.1.2 A multi-phase equilibrium?	8	3.6 Appendix II: more on pressure	17
2.1.3 Other components of the ISM	9	3.6.1 Ideal gases: the pressure integral	17
2.2 “Star stuff” in our galaxy	9	3.6.2 Radiation pressure	17
2.3 Galactic ecology	10	4 Bremsstrahlung radiation	19
2.4 The ISM in Ellipticals	10	4.1 Some basic tools	19
2.4.1 Everything that isn’t the hot		4.1.1 Power; Larmor formula	19
phase	10	4.1.2 Spectrum: Fourier analysis	19
2.4.2 The hot phase – the x-ray loud		4.2 Bremsstrahlung I: single particle	20
gas	11	4.3 Bremsstrahlung II: from a plasma	21
		5 Thermal state of the ISM	24
		5.1 Heating and cooling: general consid-	
		erations	24
		5.1.1 Cooling	24
		5.1.2 Heating	24
		5.2 HII regions	25
		5.2.1 Ionization structure	26

5.2.2	Energy balance and temperature	27	8.6.2	Plasma turbulence: Alfven waves	45
5.3	The diffuse ISM: multiphase equilibrium	28	8.6.3	Turbulent shock acceleration .	46
5.3.1	Cooling: what dominates here?	28	8.6.4	Energy limits for Alfven acceleration	46
5.3.2	Heating: by cosmic rays? . . .	29			
5.3.3	Thermal balance and multiphase equilibrium	29	9	Synchrotron radiation	47
5.3.4	Is the thermal balance solution stable?	30	9.1	Total power	47
6	Dynamics of the ISM: energetics & shocks	32	9.2	Single particle spectrum	47
6.1	Fluids: energetics	32	9.3	Spectrum from a distribution of particle energies	48
6.2	Supersonic flow and shock fronts . . .	33	9.4	Polarization	49
6.2.1	Adiabatic shocks	33	9.5	Synchrotron self-absorption	49
6.2.2	Isothermal shocks	34	9.6	Total synchrotron spectrum	50
6.2.3	Magnetized shocks	34	10	Pair plasmas in Astrophysics	52
6.2.4	Oblique shocks	34	10.1	Pair annihilation	52
7	Stellar Winds & Supernovae Remnants	36	10.2	Pair creation	52
7.1	Stellar winds and the surrounding ISM	36	10.2.1	Two-photon pair production .	52
7.1.1	The basic solution	36	10.2.2	Pair production in pion decay	53
7.1.2	The outer shock	36	10.3	Magnetic pair production	53
7.1.3	What about the inner shock? .	37	11	(Inverse) Compton scattering	55
7.2	Supernova remnants	38	11.1	Basic Tools	55
7.2.1	Early: energy conserving (Sedov) phase.	38	11.1.1	One event seen in the ERF . .	55
7.2.2	Late: momentum conserving (snowplow) phase.	39	11.1.2	Cross sections	55
7.3	Plerions, a.k.a. pulsar wind nebulae .	39	11.1.3	Remember your relativity . .	55
8	Relativistic particles in astrophysics	41	11.2	Scattering as seen in the lab	56
8.1	Recap: basics for relativistic particles	41	11.2.1	Single particle radiation . . .	56
8.2	Quick overview of the observations . .	41	11.2.2	Single particle spectrum . . .	57
8.3	Cosmic rays in the galactic setting . .	42	11.3	Composite spectra	57
8.4	Particle acceleration, overview	42	11.3.1	Nonrelativistic electrons . . .	57
8.5	Particle acceleration, first stage mechanisms	42	11.3.2	Relativistic electrons, single scattering	57
8.5.1	Magnetic reconnection	43	11.3.3	Scattering from power-law electrons	57
8.5.2	Unipolar dynamos	43	12	Pulsars: overview and some physics	59
8.6	Particle acceleration, second stage mechanisms	44	12.1	The basic picture	59
8.6.1	Fermi acceleration	44	12.1.1	The cartoon	59
			12.1.2	And some details	59
			12.2	Spin a magnetic field	60

12.2.1	Star in vacuum	60	14.3.1	Zoom in: the central kpc and within	74
12.2.2	Filled magnetosphere	61	14.3.2	Zoom in further: the central pc and within	74
12.3	Radio emission and the pair cascade	61	14.3.3	Why radio-loud vs. radio-quiet?	74
12.4	High altitudes and currents	62	14.3.4	Why are only some galaxies “active”?	74
12.4.1	High energy emission	62	14.4	Unification Models	74
12.4.2	The pulsar circuit?	62	14.4.1	Relativistic beaming	75
12.5	Winds and nebulae	62	14.4.2	Obscuration and tori	75
12.5.1	Pulsar winds	63	14.5	AGN demographics	75
12.5.2	Pulsar wind nebulae	63	14.5.1	Was there a “quasar era?”	75
12.6	Magnetars and Anomalous pulsars	63	14.5.2	What about galaxy formation?	76
13	Radio jets and radio galaxies	65	14.6	Ending with questions	76
13.1	Jets: the observational constraints	65	14.7	Appendix: a little practical cosmology	77
13.2	Some useful relativity	66	14.7.1	Just what is the redshift?	77
13.2.1	Superluminal motion	66	14.7.2	The Hubble diagram	77
13.2.2	Doppler beaming	66	14.7.3	The lookback time	77
13.3	Some useful physics	66			
13.3.1	Collimation	67			
13.3.2	Jet transport	67			
13.4	Larger Scales: the Radio Galaxy	67			
13.4.1	Classical Double radio galaxies (FR II’s)	67			
13.4.2	Tailed radio galaxies (FR I’s)	68			
13.5	Unresolved issues	69			
13.5.1	What is the life cycle of a RG?	69			
13.5.2	How does a jet affect its environment?	69			
13.6	How are jets made?	70			
13.6.1	Wind (fluid-based) models	70			
13.6.2	MHD models	70			
13.6.3	Duty cycles?	70			
14	Quasars and Active Galactic Nuclei	72			
14.1	Basic properties: observations	72			
14.1.1	Spectral lines	72			
14.1.2	Continuum emission	72			
14.2	The AGN zoo	73			
14.2.1	The radio-quiet ones	73			
14.2.2	The radio-loud ones	73			
14.2.3	Blazars and friends	73			
14.2.4	Parent galaxies	73			
14.3	The usual model: a massive BH	74			