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Plasma Astrophysics (Vols. I and II)

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Plasma Astrophysics, appropriately subtitled "Nonthermal Processes in Diffuse Magnetized Plasmas," is divided into two volumes titled "The Emission, Absorption, and Transfer of Waves in Plasmas (Vol. I)" and "Astrophysical Applications (Vol. II)."

The first volume is devoted to general theory and was obviously written as a textbook for graduate students in astrophysics and astronomy. It has all the trappings of a textbook, including problem sets at the end of each chapter, answers to many of the problems, and an appendix on Bessel functions. The second volume is an almost homogeneous mixture of basic theory, phenomenological discussion of radiation processes in astrophysics (cosmic rays, solar radio bursts, decametric radio emission from Jupiter, and the like), and an application of the theory to explain the observations. Together the books present a fairly thorough theoretical treatment of radiation processes in uniform plasmas. The coverage is very similar to that in Bekefi's *Radiation Processes in Plasmas*.[1] However, much more material is included and the approach is entirely different. Another reasonable comparison would be with the encyclopedic two-volume set *Plasma Electrodynamics* by Akhiezer et al.[2]

There is an introductory chapter that summarizes the radiation processes thought to be of importance in astrophysics and radio astronomy and that introduces the basic ideas of plasma physics: the Vlasov equation, Debye shielding, Langmuir waves, transverse electromagnetic waves, sound waves, and Alfven waves. There is also the usual discussion of characteristic plasma parameters, such as plasma frequency, collision frequency, and beta, with typical values given for plasmas of astrophysical interest.

The second chapter, titled "Waves in Plasmas," sets forth the formal properties of linear waves in a magnetized plasma. At the outset, Maxwell's equations are expressed in Fourier-transformed form with the plasma current described by a Fourier-transformed conductivity tensor, $j(\boldsymbol{k},w) = \boldsymbol{\sigma}(\boldsymbol{k},w)\cdot \boldsymbol{E}(\boldsymbol{k},w)$. Not including a convolution integral, of course, eliminates any effects of plasma inhomogeneity from consideration. However, there is no discussion of this restriction. The field of view is further restricted by considering only weakly damped (or growing) waves, i.e., waves for which the anti-Hermitian or dissipative part of the dielectric tensor $\boldsymbol{\epsilon}^A$ is small compared with the Hermitian or reactive part $\boldsymbol{\epsilon}^H$. It is not mentioned that $|\boldsymbol{\epsilon}^A| \ll |\boldsymbol{\epsilon}^H|$ is a sufficient but not a necessary condition for weak damping. Therefore, there are weakly damped waves for which the formal theory does not apply, such as ordinary mode waves near the fundamental cyclotron resonance. Within the context of weak damping, a detailed discussion is given of the general wave properties that are independent of the particular wave mode considered. These include symmetry properties of the dielectric tensor, transformation properties under reflection and time reversal, polarization vectors, the form for the wave energy, and relations between wave energy and group velocity. Finally, there are very brief discussions of the basic plasma wave modes. Waves in warm unmagnetized plasmas, Langmuir waves, and ion sound waves (including Landau damping) are discussed in two pages. Waves in cold magnetized plasmas are given four pages, and waves in warm magnetized plasmas are dispensed with in two pages.

Chapters 3 and 4 cover the theory of radiation due to single particle effects: Cerenkov emission, bremsstrahlung, Thompson scattering, synchrotron emission, and inverse Compton scattering. A unified treatment of all these phenomena is obtained by relating $u^{\sigma}(\boldsymbol{k})$, the energy radiated in mode σ with wave vector $\boldsymbol{k}$, to the time average of $\boldsymbol{J}^{ext}\cdot\boldsymbol{E}^{\sigma}$, where $\boldsymbol{J}^{ext}(\boldsymbol{k},w)$ is the Fourier transform of the current due to the moving particle and $\boldsymbol{E}^{\sigma}(\boldsymbol{k},w)$ is the electric field of mode σ induced in the plasma by the $\boldsymbol{J}^{ext}$. In each case, the calculation proceeds by solving for the particle orbit at the appropriate level of approximation, Fourier transforming the associated current, and then determining the plasma response from the wave equation with $\boldsymbol{J}^{ext}(\boldsymbol{k},w)$ as an inhomogeneous term. The discussion of Cerenkov radiation, bremsstrahlung, and Thompson scattering in Chap. 3 is somewhat less detailed than is available elsewhere (for example, in *Classical Electrodynamics*[3] by J. D. Jackson). There is, however, some mention of plasma effects, such as emission of Langmuir waves and bremsstrahlung from thermal plasmas.

The discussion of synchrotron emission in Chap. 4 begins with a derivation of general formulas for gyromagnetic radiation by particles of arbitrary energy in a plasma. Melrose uses the term "gyromagnetic emission" for radiation by particles due to the spiraling motion in a magnetic field, with the term "synchrotron emission" being reserved for radiation from ultrarelativistic particles, $\gamma \gg 1$. The presentation of synchrotron emission is very detailed including the frequency spectrum, polarization, emission at low frequencies, emission at small pitch angles, and many mathematical derivations. The chapter concludes with a section on inverse Compton scattering, i.e., the scattering of soft photons by hard (relativistic) electrons as opposed to the scattering of soft electrons by hard photons in Compton scattering. Several interesting exotic electron-photon processes are mentioned, such as scattering of Langmuir waves into transverse waves, nonlinear inverse Compton scattering, and nonlinear Thompson scattering. Unfortunately, neither the material on synchrotron radiation nor that on inverse Compton scattering is of much direct relevance for fusion applications since ultrarelativistic particles are not anticipated even in advanced fuel-fusion reactors.

Some nonlinear theory is also included. In Chap. 5 quasi-linear theory and the theory of nonlinear wave kinetic equations are developed from a semi-classical formalism. There is a sketchy discussion of the quantum mechanical ideas required, such as the relation between wave frequency and wavelength to particle energy and momentum, the occupation number, the quantum analog of the Doppler-shifted resonance condition, and the principle of detailed balance. Master equations describing the time evolution of the wave and particle occupation numbers are introduced that in the classical limit yield the usual quasi-linear equations and wave kinetic equations. The treatment here is similar to that in Harris' article in *Advances in Plasma Physics*,[4] but it is much more intuitive and much less detailed. A major weakness here is the lack of an adequate discussion of the conditions under which the theory would be valid. There is some mention of the random phase approximation; however, it is discussed in terms of the Heisenberg uncertainty principle and appears as if it were a purely quantum effect. Requirements on wave amplitude or width of the wave spectrum necessary for validity of the quasi-linear theory are not discussed.

Volume I concludes with a chapter on radiation absorption and transport. In a preliminary section, Kirchoff's law is presented, and the equations of geometrical optics are derived, including a transport equation for the wave specific intensity. In the next section there is a very detailed discussion of methods used to calculate field amplitude transport in situations of high frequency ($\omega \gg \omega_{pe},\Omega_e$), where the two electromagnetic modes are nearly degenerate. In an inhomogeneous or absorbing medium, the modes do not propagate independently but are coupled together. This necessitates an extension of geometrical optics if the wave polarizations are to be accurately computed. The formalism is then applied to synchrotron radiation in media with absorption and with induced Compton scattering.

Chapters 7 and 8 (Vol. II) are devoted to scattering and acceleration of single particles. Orbit theory, guiding center drifts, and adiabatic invariants are covered in three pages. About five pages are devoted to Coulomb collisions and Fokker-Planck theory. This is just enough to support the conclusion that Coulomb collisions are of negligible importance for the high-energy electrons of interest in astrophysics. Of course, that conclusion is not valid for plasmas of fusion interest. There are good discussions of the theory of resonant scattering by plasma modes and acceleration of particles by Langmuir or hydromagnetic turbulence. Most of the remainder of these chapters is devoted to strictly astrophysical topics: cosmic rays, acceleration of particles in the magnetosphere, the solar corona, and the Crab Nebula.

In Chap. 9, synchrotron radiation is taken up again with the object of interpreting measured properties of synchrotron radiation to give information about the radiating source. There is also a discussion of the influence that synchrotron radiation has on the time evolution of the particle distribution function.

Chapter 10 is devoted to several theoretical topics needed to understand how electromagnetic waves are produced at the plasma frequency in meter wavelength solar bursts. This is a two-stage process that involves first generation of Langmuir turbulence and conversion of the electrostatic waves to transverse waves. Several turbulence generation phenomena are presented, of which the most complete discussion is given to the two-stream instability. Then, there is a sudden shift back to basic nonlinear plasma theory. Although nonlinear wave kinetic equations were previously derived in Chap. 5, the author gives an additional formalism based on nonlinear response tensors. Perhaps this method leads most quickly to expressions for the particular processes needed to explain Langmuir wave conversion, namely, nonlinear scattering by thermal ions and coalescence of two Langmuir waves into a transverse wave. However, the presentation is very compressed and not likely to be of much value in a more general context.

Chapter 11 is about solar radio bursts. This is one of the author's primary research interests, and, indeed, much of the previous theory is oriented to the purposes of this chapter. A large amount of material on the phenomenology of the various types of solar bursts is included as well as a discussion of the theoretical success in explaining their observed features. The emphasis is on a type III solar radio burst for which theory has apparently been most successful.

In Chap. 12 there is an excellent discussion of magnetoionic theory (theory of cold plasma waves). In addition to the usual material on the propagation and polarization properties of the cold plasma waves, there is some discussion of finite-temperature effects and extensive coverage of mode coupling effects.

The final chapter is about radiation from rotating magnetospheres. It is again a mixture of theory and observation related to radio emission from Jupiter and from pulsars. The chapter and book conclude with a section on relativistic quantum electrodynamics for plasmas.

The presentation of material in these books is at a uniformly advanced level. The discussion of physical ideas is intuitive and very succinct. The organization tends to be fragmented with the logical flow interrupted by frequent references back as well as forward to uncovered material. An extreme example of this is the statement without derivation in Chap. 2 of the mathematical formula for the warm plasma dielectric tensor. The reader is referred to Chap. 10 (a section in Vol. II on nonlinear wave interactions) for the relevant calculations, to Chap. 3 (a section on solutions of the wave equation) for an explanation of the handling of resonant denominators, to Chap. 4 (a section on gyromagnetic emission) for the mathematical definition of one of the factors in the equation, and to Appendix B for a discussion of methods for calculating dielectric tensors. A positive feature is that often after highly mathematical or complicated presentations, the author gives a summary listing the main points of the discussion.

There is a wealth of material here on plasma waves, but it would not be advisable to learn plasma waves—for the first time—from these books. The semi-classical approach of nonlinear theory is very interesting and as far as I know unique in a textbook. However, one would not want to learn nonlinear plasma theory from these books. All applications and all experimental observations discussed are astrophysical in nature to the total exclusion of laboratory or fusion-related plasmas. Therefore, these books are likely to be useful as textbooks only for students of astrophysics having a solid background in plasma physics and quantum mechanics. The division of the two volumes into theory and applications is not really achieved since much of the basic theory actually appears in Vol. II, e.g., scattering of particles, part of the material on synchrotron radiation, and part of the material on nonlinear theory, especially the magnetoionic theory. Therefore, it would not be appropriate to use Vol. I alone as a text for a general course in plasma waves. I can recommend these books to specialists for the coverage of synchrotron radiation, transport of radiation, limiting polarization, and as an alternative point of view on a wide collection of topics. However, the price, $109.50, is too high to casually recommend these volumes for a general audience.

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