Lecture no.11

Optical Properties of Nonideal Plasmas

Introduction

The optical properties of plasma are also of great interest because the plasma radiation contains information concerning the temperature and concentration of particles, elastic and inelastic collisions, and ionization and recombination processes. Nowadays we have extensive data about optical properties of rarefied plasma where the elementary processes are easily separated. With increasing of plasma density (at the weakly nonideal regime) we have such effects as a spectral line shift and broadening, as well as shift of photoionization continua. With a further increase of nonideality, these effects do not change in their behavior but only increase quantitatively (we have so called "spectroscopic stability"). At high density regime (in laser-condensed matter interaction, in pinched electric discharges, in dynamical experiments etc.) the electron spectrum is deformed in a highly compressed plasma.

Basic radiation processes in rarefied weakly ionized plasma

Let us introduce the basic concepts of the radiation theory. The spectral absorption coefficient κ_ν is determined in terms of the attenuation dI_ν which is experienced by the radiation intensity I_ν passing through a layer of matter of thickness dl :

$$dI_\nu = -\kappa_\nu I_\nu dl \tag{1}$$

In the case of thermodynamic equilibrium κ_ν is related to the radiation intensity I_ν by the following Kirchhoff's law:

$$I_\nu = \kappa_\nu B_\nu(T)\,; \quad B_\nu(T) = 2h\nu^3 c^{-2}\left[\exp\left(\frac{h\nu}{k_B T}\right) - 1\right]^{-1} , \tag{2}$$

where $B_\nu(T)$ is the Planck's function. The quantity $I_\nu d\nu$ is the energy emitted by volume dV per unit time in unit solid angle in the frequency interval $d\nu$.

The radiation processes in weakly nonideal plasma have been studied very well and can be divided into two groups:

1) Bound–bound transitions in atoms which provide a series of spectral lines. These lines converge at the photoionization thresholds.
2) Bound–free and free–free transitions which define the photoionization and bremsstrahlung processes with the continuous spectrum.

It should be noted that this division is not absolute, for instance, in strongly nonideal and high–pressure plasma the spectral lines are overlapped with the continuous spectrum.

The integrated intensity of the spectral line is defined by the oscillator strength $f_{nn'}$:

$$\int \kappa_\nu d\nu = \left(\pi e^2 / mc\right) f_{nn'} n_n \, , \tag{3}$$

where κ_ν is the absorption coefficient in a spectral line due to the $n \to n'$ transition. n_n is the concentration of absorbing atoms. According to (2) and (3) the integrated intensity of the spectral line is

$$I = \int I_\nu d\nu = \frac{2\pi h e^2}{m\lambda^3} \frac{g_n}{g_{n'}} \cdot n_{n'} f_{nn'} \, , \tag{4}$$

where $n_{n'}$ is the concentration of radiating atoms; g_n and $g_{n'}$ are the statistical weights of the low–lying and high–lying states, respectively.

The oscillator strength of absorption line is defined by the Einstein probability of spontaneous transition:

$$f_{nn'} = \frac{g_{n'}}{g_n} \frac{mc^3}{8\pi^2 e^2 \nu^2} \cdot A_{n'n} \, . \tag{5}$$

The factor $A_{n'n}$ is equal to the inverse lifetime of an atom in the state n relative to the $n \to n'$ transition. The complete data for $f_{nn'}$ and $A_{n'n}$ are provided by special books (for instance, see Wiese W., e.a. Atomic transitions probabilities. Washington. 1966).

For hydrogen–like atom we have the well known quaziclassical Kramers formula:

$$f_{n'n} = \frac{32}{3\pi\sqrt{3}} \frac{1}{(n')^5 n^3} \left[(n')^{-2} - n^{-2} \right]^{-3} = \frac{1{,}96}{(n')^5 n^3} \left(\frac{E_{n'} - E_n}{Z^2 Ry} \right)^{-3}, \quad (6)$$

where $E_{n'}$ and E_n are the binding energies of the n'-th and n-th levels. In Kramers formula (6) the transition is considered between states with the main quantum numbers n' and n averaged over the remaining quantum numbers. The line spectral intensity fully depends on the absorption coefficient because the Planck function varies slightly within the line (see, formula (2)). The dependence κ_ν on frequency ν is defined by the behavior of the line broadening. In a rarefied (weakly nonideal) plasma, the line broadening is defined by radiation damping and the Doppler effect. The broadening in a nonideal plasma is mainly defined due to the interparticle interactions.

Let us consider the bound–free and free–free transitions:

- Free–bound transitions in the field of a ion (recombination radiation):

$$A^+ + e \to A + h\nu \quad (7)$$

- Free–free transitions in the field of the ion (bremsstrahlung in the field of the ion):

$$A^+ + e\left(\frac{m\upsilon_1^2}{2}\right) \to A^+ + e\left(\frac{m\upsilon_2^2}{2}\right) + h\nu \quad (8)$$

- Free–free transitions in the field of the atom (bremsstrahlung in the field of the atom):

$$A + e\left(\frac{m\upsilon_1^2}{2}\right) \to A + e\left(\frac{m\upsilon_2^2}{2}\right) + h\nu \quad (9)$$

In the case of absorption we distinguish the following transitions.

- Bound–free transitions in the field of ions (photoionization of atoms):

$$A + h\nu \rightarrow A^{+} + e \tag{8}$$

- Free–free transitions in the field of the atom and ion (the expressions of (8) and (9)).
- Photodetachment of the electron (the absorption process):

$$A^{-} + h\nu \rightarrow A + e \tag{9}$$

- Photoattachment of the electron (the radiation process):

$$A + e \rightarrow A^{-} + h\nu \tag{10}$$

It should be noted that the final (resultant) continuous spectra represent the superposition of several continua due to individual processes. Therefore, the determination and analysis of the resultant spectrum are a complicated problem.

In the case of plasma with developed ionization, the greatest contribution to the continuous spectrum intensity is made by free–free transitions of electrons in the fields of ions. The absorption coefficient, including the correction for stimulated radiation, is given by Kramers' formula:

$$\kappa_\nu = \frac{2\sqrt{2}e^6 Z^2}{3\sqrt{3\pi}c\hbar m^{3/2}\sqrt{k_B T}}\frac{g}{\nu^3} n_e n_i \left(1 - e^{-h\nu/k_B T}\right), \tag{11}$$

where Z is the ion charge; g is the Gaunt factor.

L.Biberman and G.Norman (1967, UFN-Physics Uspekhi) developed an approximate calculation technique for the calculation of absorption and radiation coefficients in both free–free and bound–free transitions in the plasma of complex atoms and ions. This technique takes into account the following effects:

- The merging of spectral lines near the continuous spectrum boundary.
- The lowering of the ionization potential ΔI.
- The complex atoms are not hydrogen–like.

Optical properties of nonideal plasma

The influence of the interparticle interaction on the optical properties causes the well–known effects of spectral line broadening and shift. In the case of a dense plasma, both broadening and shift effects are caused by the interaction between a radiating atom or ion and surrounding particles.

The scheme of calculating line broadening through the interaction of atoms with ions and electrons in a weakly nonideal plasma is follows (Baranger 1962). The electric field generated by ions is assumed to be constant and the Stark broadening is determined for an atom in this field. The broadening of each Stark component is then calculated within the impact approximation. After that, the resultant distribution of intensity is averaged over all the possible values of intensity of the ion microfield. In this case with taking into account these effects for absorption coefficient we have the following expression:

$$\kappa_\nu = \kappa_0 \left[1 + \left(\left(\nu - \nu_0 \right) - \Delta^2 \right) \Big/ \left(\delta / 2 \right)^2 \right]^{-1} , \qquad (12)$$

where δ is the line width; Δ is the line shift; The absorption coefficient at the line center is $\kappa_0 = (8\pi)^{-1} \lambda^2 (g_2 / g_1) A_{21} n_1 (2/\pi\delta)$; λ is the radiation wavelength; n_1 is the number density of absorbing atoms. The shift and width of spectral line are expressed in terms of the amplitude of elastic forward scattering $f(0)$:

$$\Delta = -\frac{h}{m} n_e \operatorname{Re}\left[f(0) \right]_{av} ; \quad \delta = \frac{h}{m} n_e \operatorname{Im}\left[f(0) \right]_{av} = \frac{1}{2} n_e (\upsilon_e q_{tot})_{av} , \qquad (13)$$

where q_{tot} is the total scattering cross section.

As a rule the Holtsmark distribution of ion microfields is used for calculation of the absorption coefficient in lines. From the other hand it is known that the Holtsmark distribution is valid for rarefied weakly nonideal plasma. Therefore it should be noted that nowadays the systematic studies have not yet been performed with taking into account the effect of strong nonideality on the spectral lines. For this purpose it is necessary to use the adequate microfield distribution functions which take into account both quantum and screening effects in dense (nonideal) plasma and results of recent experiments (Griem 2000).

Figure 1 represents the spectral absorption coefficient of air plasma. The broken line indicates the contribution made by continua. With increasing the density, the lines broaden considerably and merge to form quasi–continua, thus making significant contribution to the integral optical characteristics.

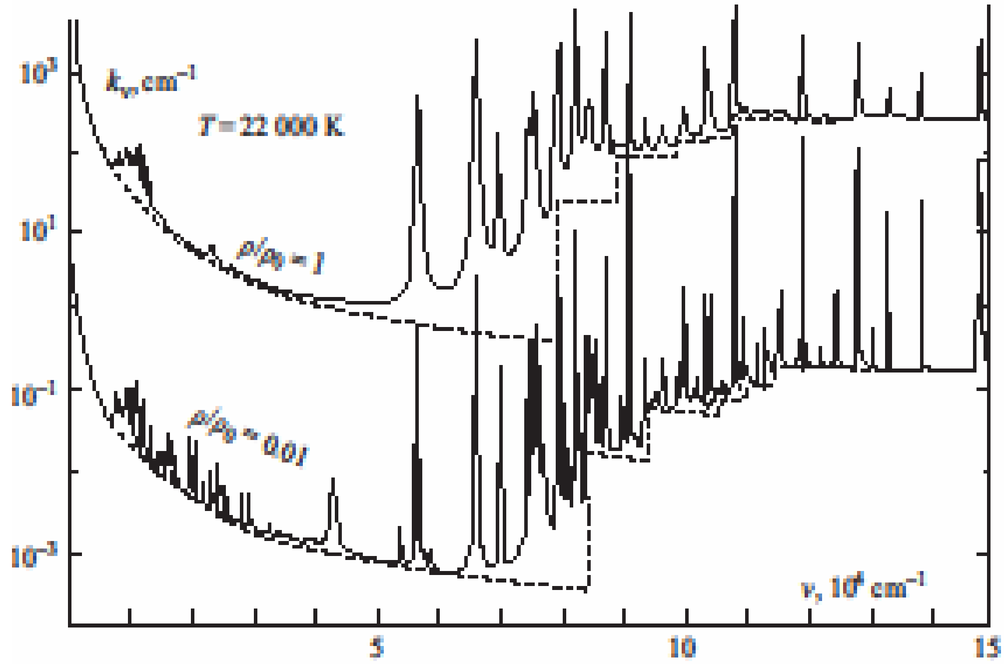

Figure 1. The absorption coefficient of air plasma for $T = 2,2 \cdot 10^4\,K$ *at two values of relative density* ρ/ρ_0*;* ρ_0 *is the normal density of air.*

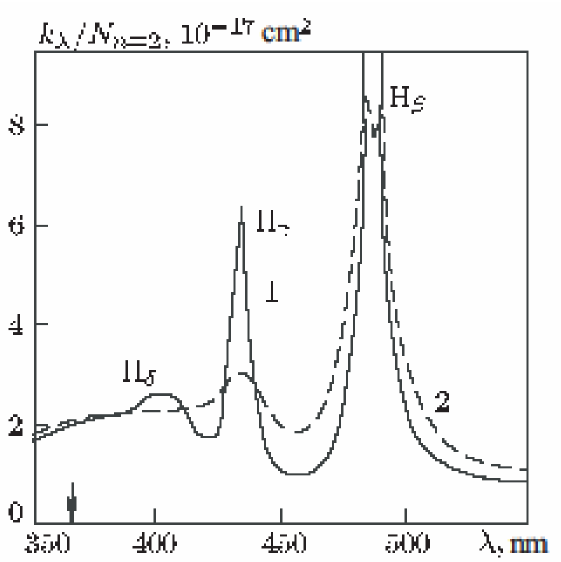

Figure 2. The absorption coefficient of the Balmer series per single absorbing atom as a function of wavelength λ (Guenter et al. 1985). Experimental results:

1: $n_e = 1,7 \cdot 10^{17}\,sm^{-3}$; $T = 1,6 \cdot 10^4\,K$

2: $n_e = 8,4 \cdot 10^{17}\,sm^{-3}$; $T = 2,22 \cdot 10^4\,K$

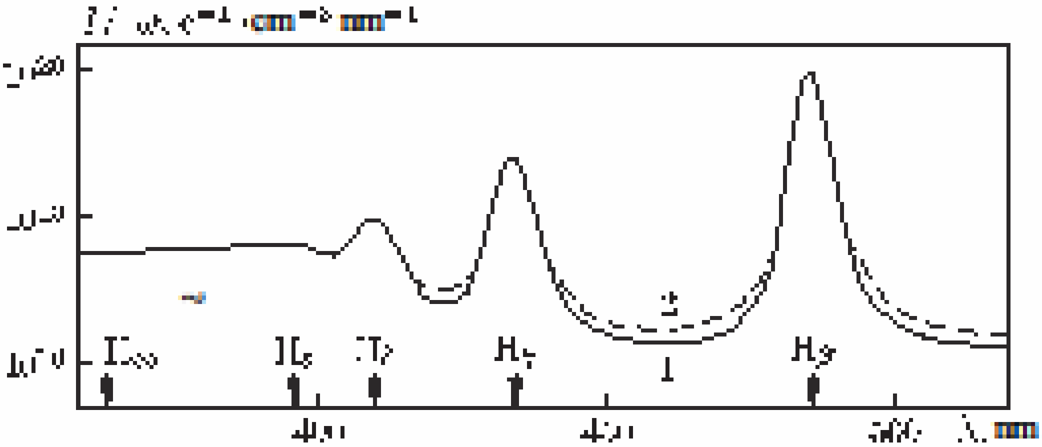

Figure 3. The radiation spectrum of a hydrogen plasma. $n_e = 9,3\cdot 10^{16}\, sm^{-3}$; $T = 1,41\cdot 10^{4}\, K$. *Solid line is the experimental data (Wiese e.a., 1972). Dashed line represents the theoretical results of D'yachkov et al., 1987.*