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Nonthermal effects on hydrogen Stark profiles

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Abstract. Plasma waves in nonthermal conditions can be strongly amplified by instabilities. We consider plasma conditions where a velocity-space instability amplifies the oscillating electric field magnitude of electron plasma waves up to several times the average plasma microfield. For a wide range of plasma conditions, the first Lyman and Balmer lines of hydrogen are then affected by both the dynamic plasma microfield and the oscillating field. We present computer simulations of line shapes showing the changes expected in such nonthermal conditions.

1. Introduction

The collective behaviour of a plasma is favored by the long range of electric and magnetic fields, and is well known to be able to excite oscillating waves which can affect the plasma radiation [1,2]. As an example, Langmuir waves are ubiquitous in many types of laboratory, fusion, and astrophysical plasmas. Using a classical equipartition theorem for a plasma in equilibrium, attributing half of the wave energy in the oscillating field, and half in kinetic energy, one can estimate the electric field magnitude of the wave to be one order of magnitude smaller than the average plasma microfield [3], e.g. for a plasma with a temperature T of the order of one eV, and an electronic density $N_e = 10^{21} \text{ m}^{-3}$. In a nonthermal plasma, the waves may be amplified by an instability, allowing them to rise above thermal fluctuations, and to reach electric field magnitudes larger than the average plasma microfield. Instabilities can be induced by an energetic particle stream created or injected in the plasma, as it is common in many different types of plasmas. Starting from an equilibrium Maxwellian velocity distribution, a beam of fast electrons creates a double-humped velocity distribution, with a peak appearing in a region of large velocity. Using kinetic theory with the Vlasov equation, we can use the physical picture of inverse Landau damping [4], which predicts an unstable electron plasma wave. The magnitude of such an unstable mode increases exponentially in time in a linear analysis, but some nonlinear effects arise that will limit the perturbation. A first study of such nonlinear effects is provided by a quasi-linear approach [5], which provides a description of how waves and particles exchange energy, and also an estimate for the saturation of the instability. For the beams encountered in different plasma devices, estimates for the oscillating electric field magnitude are indeed often larger than the plasma microfield. Early observations of spectra in nonthermal plasma have indicated the appearance of satellite like structures near the multiples of the oscillation frequency which is assumed to be monochromatic [6,7,8,9]. Observations of Balmer lines in nonthermal plasma revealed the presence of first and second order satellites with intensities reaching a significant fraction of the central intensity [8]. We propose in the following a calculation taking both an oscillating electric field and a dynamic plasma microfield into account for an accurate calculation of the line shape.

2. Nonthermal Langmuir waves

We consider the excitation of a large number of Langmuir waves with a random direction and phase φ [10]. Each wave is supposed to act on an emitter with an electric field $\vec{E}_L = \vec{E}_w \cos(\omega_p t + \varphi)$, where



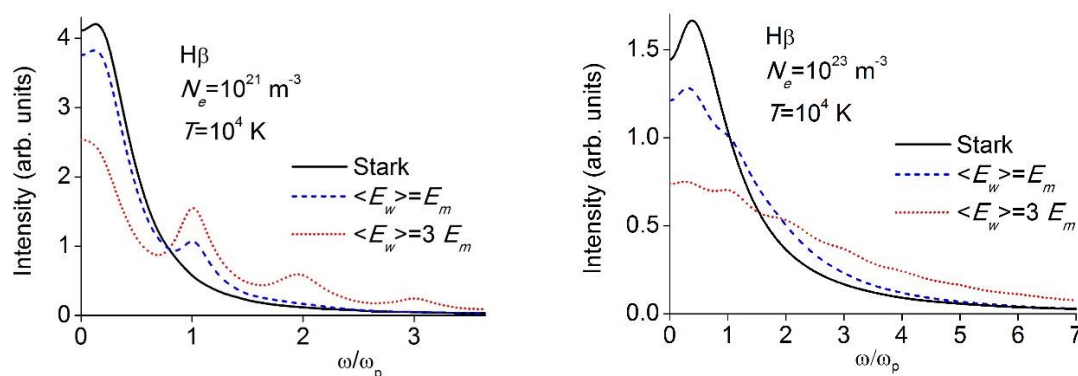
$\omega_p = \sqrt{N_e e^2 / m \epsilon_0}$ is the plasma frequency, with e and m the electron charge and mass, and ϵ_0 the permittivity of free space. The electric field magnitude has been taken to obey a half-normal probability density function (PDF), as predicted for turbulent plasmas [11] and measured in experiments [12]. We thus sample the oscillating electric field magnitude E_w with a PDF:

$$P(F) = \frac{2}{\pi \langle E_w \rangle} \exp\left(-\frac{F^2}{\langle E_w \rangle^2}\right)$$

where $\langle E_w \rangle$ is the mean value of the oscillating electric field. This quantity will be compared to the mean plasma microfield E_m , a quantity approximately equal to $3.4 E_0$ for weakly coupled plasmas [3], where E_0 is the electric field created by a charged particle at the average interparticle distance.

3. Line shape calculations

We use a computer simulation of the ion motion and a numerical integration of the Schrödinger equation to obtain the dipole autocorrelation function [13]. We plot in the following the line shapes without Doppler effect, a broadening mechanism which can be included by a simple convolution when comparing to experimental profiles. In figures 1a and 1b we plot pure Stark profiles, and line shapes affected by oscillating electric fields with $\langle E_w \rangle = E_m$ (dashed line), $\langle E_w \rangle = 3 E_m$ (dotted line), in a plasma of temperature $T=10^4$ K. For a density $N_e=10^{21} \text{ m}^{-3}$, and $\langle E_w \rangle = E_m$ (figure (1a)), the half width at half maximum (HWHM) of the Stark profile is about half of the plasma frequency, and a satellite clearly appears at ω_p , with an intensity of the order of a quarter of the maximum central intensity. At least three satellites appear for $\langle E_w \rangle = 3 E_m$, with a first satellite reaching about two thirds of the maximum central intensity. This results in a significant intensity transfer from the central regions of the line to frequencies close and above the plasma frequency. For $N_e=10^{23} \text{ m}^{-3}$ (figure (1b)) the HWHM of the Stark profile is almost equal to the plasma frequency, and the structure of the satellites is hardly visible, but there is clearly an intensity transfer from the central part of the line toward several satellites, thus increasing the HWHM by 36% for $\langle E_w \rangle = E_m$, and a factor 2.4 for $\langle E_w \rangle = 3 E_m$.



(1a)

(1b)

Figure 1. H β line shapes for pure Stark profile (solid line), and with account of an oscillating electric field with $\langle E_w \rangle = E_m$ (dashed line), $\langle E_w \rangle = 3 E_m$ (dotted line), in a plasma of temperature $T=10^4$ K, and for densities $N_e=10^{21} \text{ m}^{-3}$ (figure (1a)) and $N_e=10^{23} \text{ m}^{-3}$ (figure (1b)).

It is interesting to perform calculations in the condition of the early spectroscopic measurements obtained by Gallagher and Levine [8] in a toroidal TORMAC device. In particular, two satellites at ω_p and $2\omega_p$ on each side of H β , with a surprising intensity of about a half and a third of the central

intensity had been observed for a plasma density $N_e=3.4 \times 10^{21} \text{ m}^{-3}$ and temperature $T=7 \times 10^4 \text{ K}$. We plot in figure 2 the Stark profile (dashed line) for such a plasma, and the profile in the presence of an oscillating electric field with $\langle E_w \rangle = 3.5 E_m$ (solid line), corresponding to the estimate of 10^7 V/m given in reference 8 for the oscillating electric field magnitude. In our calculations the intensities of the first two satellites are respectively about two thirds and 35% of the central intensity, suggesting that the observations of reference 8 can be explained with our model.

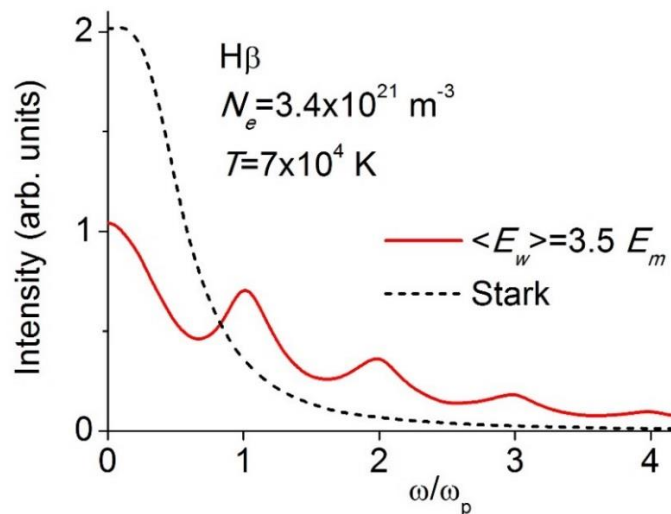


Figure 2. H β line shapes for a Stark profile (dashed line), and the effect of an oscillating electric field with $\langle E_w \rangle = 3.5 E_m$ (solid line), in a plasma of temperature $T=7 \times 10^4 \text{ K}$, and density $N_e=3.4 \times 10^{21} \text{ m}^{-3}$.

4. Conclusion

We have applied a computer simulation method to the calculation of line shapes in the presence of an oscillating electric field. The calculations presented assume a constant impact operator for the electron contribution, and use a numerical integration of the Schrödinger equation for an emitter submitted to the simultaneous effect of ion dynamics and wave field. For increasing values of the oscillating field magnitude our calculations show accurately how the two dynamic fields transfer the intensity from the central part of the line to an increasing number of satellites at multiples of the plasma frequency.

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