LIGHT-PRESSURE EFFECTS ON ION SPECTRA IN TWO-ION LASER PLASMAS

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In plasmas produced by high-power lasers, the electron temperature T_e may be so high that the ion temperature trail well behind (slow relaxation), and T_e be spatially uniform (large heat conductivity). Then a simple, often used, model, having initially $n=n_o$ ($x<0$), $n=0$ ($x>0$), involves ion continuity, and ion and electron momentum equations

$$\frac{Dn}{Dt} + n\frac{\partial v}{\partial x} = 0 \quad , \quad \frac{D}{Dt} \equiv \frac{\partial}{\partial t} + v\frac{\partial}{\partial x} \quad , \qquad (1)$$

$$mn\frac{Dv}{Dt} = ne\,ZE \quad , \quad 0 = -\frac{\partial P_e}{\partial x} - n_e e E \qquad (2)$$

where n, v, m, Z refer to ions, E is the charge separation field, and we take $n_e=Zn$. If electrons are Maxwellian ($P_e=n_e kT_e$), and T_e=const, we obtain

$$\frac{d\ln n}{d\eta} = -\frac{1}{M}\left(1 + \frac{dM}{d\eta}\right) \quad , \quad (M^2-1)\left(1 + \frac{dM}{d\eta}\right) = 0 \quad , \qquad (3)$$

where $\eta = x/c_s t$, $M = v/c_s - \eta$ and $c_s^2 = kT_e/m$. Solutions to (3) are $dM/d\eta = -1$ (v=const, n=const) and M=1. The solution then is

$$M=1 \quad (v = c_s + x/t), \quad n = n_o \exp(-v/c_s) \, , \quad \text{for } \eta > -1$$

(isothermal rarefaction wave) [1]. The number of ions in the interval v, $v+\delta v$ is $\delta N \propto n\delta x \propto n\delta\eta$, and the ion velocity spectrum is then

$$\frac{dN}{dv} = C\frac{n}{dv/d\eta} \propto \frac{n}{1+dM/d\eta} \quad (C \equiv \text{const}) \; ; \qquad (4)$$

here,

$$\frac{dN}{dv} \propto \exp(-v/c_s) \; ,$$

a well known result [1].

In some experiments where two species with different Z/m ratio (H^+, C^{6+} in Ref. 1) are involved, dN/dv for that one with larger Z/m presents a large peak superposed to the exponential decay law. It may be shown that using a two- temperature electron population (which explains the shape of the current registered by a remote collector in certain cases [2]), does not lead to a peak in dN/dv, as required. On the other hand, it is clear from (4) that if a spatial region exists where v=const$\equiv v_o$, dN/dv will present a peak around v_o. In this respect it should be noted that Gurevich et al. [3] claimed that when two species 1,2 exist, where $Z_1/m_1 > Z_2/m_2$ say, n_2 vanishes at some point and a plateau (n_1=const) appears, where v_1=const. Let us consider the two-species case; the continuity equations read

$$\frac{d\ln n_j}{d\eta} = -\frac{1}{M_j}\left(1 + \frac{dM_j}{d\eta}\right) \quad , \qquad (j=1,2) \qquad (5)$$

while the momentum equations (using $n_e = \Sigma n_j Z_j$) additionally yield

$$\frac{M_2}{\bar{c}_2^2}\left(1 + \frac{dM_2}{d\eta}\right) = \frac{M_1}{\bar{c}_1^2}\left(1 + \frac{dM_1}{d\eta}\right) \quad , \qquad (6)$$

$$\Sigma\frac{Z_j n_j}{m_j}\left(1 + \frac{dM_j}{d\eta}\right)\left(\frac{M_j^2}{c_j^2} - 1\right) = 0 \qquad (7)$$

where $\bar{c}_j^2 = c_j^2/c_s^2$, $c_j^2 = Z_j kT_e/m_j$. Unless $d\ln n_j/d\eta \equiv 1 + dM_j/d\eta \equiv 0$, from (6) and (7) there results [3]

$$\Sigma n_j Z_j\left(\frac{\bar{c}_j^2}{M_j^2} - 1\right) = 0 \; . \qquad (8)$$

From (5), (6) and (8) we finally get

$$\frac{dM_2}{dM_1} = \frac{M_2(\bar{c}_1^2 M_2 - \bar{c}_2^2 M_1)(M_1^2 - 3\bar{c}_1^2) + \bar{c}_2^2 M_1(M_2 - M_1)(M_1^2 - \bar{c}_1^2)}{M_1(\bar{c}_2^2 M_1 - \bar{c}_1^2 M_2)(M_2^2 - 3\bar{c}_2^2) + \bar{c}_1^2 M_2(M_1 - M_2)(M_2^2 - \bar{c}_2^2)} \; \frac{M_2^2 - \bar{c}_2^2}{M_1^2 - \bar{c}_1^2} \qquad (9)$$

The figure shows the singular points E (degenerated node), S (saddle) and N (node) of Eq. (9) in the nonshaded regions where the solution must remain [see Eq. (8)]; making the disturbance front to occur at $\eta=-1$, we have there $M_j=1$, and from (8), $c_s^2 = kT_e(\Sigma Z_j n_{jo} Z_j/m_j)(\Sigma Z_j n_{jo})^{-1}$. The solution to (9) starts at point I, crosses E, turns around [near S for $Z_2 n_{2o} >> Z_1 n_{1o}$], and finally reaches N, where

$$M_1 \equiv (v/c_1 - x/c_1 t)c_1/c_s = \bar{c}_1 \equiv c_1/c_s \quad ,$$

and, from (8), $n_2=0$ (at some point η_N). Since 1 is the only species from there on, no plateau appears [see the discussion following (3)] (in opposition to [3]), the solution being of the type

$$v_1 = c_1 + x/t, \quad n_1 = n_1(\eta_N)\exp\{[v_1(\eta_N) - v_1]/c_1\}, \quad \text{for } \eta > \eta_N \, .$$

Gurevich et al. [4] claimed that a nearly-flat range observed in experimental ion spectra provide support for the n-profile plateau predicted in [3]; as pointed out above however, a plateau leads, contrariwise, to a peak in dN/dv.

It appears that light-pressure is the cause of the peak in Ref. 1. When the light-to-thermal pressure ratio is not small (∿ 3 in Ref. 1), a plateau develops in the overdense region of a one-species plasma with T_e=const, in order to satisfy some appropiate conditions in the thin layer around critical density [5]; if T_e grows slowly with time, a near-plateau develops leading to a peak in dN/dv. However, the area under that peak is too small:

$$\int_{v>v_o} \frac{dN}{dv}\,dv = \int Cn\,d\eta = -C\int d(nM) = CnM\big|_{v_o} \; , \qquad (10)$$

where the continuity equation and Eq. (4) have been used; for T_e=const, (10) gives $Cn(v_o)$, which equals an area of width $\Delta v = c_s$ and height $dN/dv|_{v_o}$

$$\frac{dN}{dv}\Big|_{v_o} \times \Delta v = Cn\Big/\frac{dv}{d\eta}\Big|_{v_o} \times c_s = Cn(v_o)$$

much less than that observed. Moreover the above discussion makes no distinction between plasmas with ions of equal (D^+, C^{6+} in Ref. 1) and different (H^+, C^{6+}) values of Z/m, whereas results for D^+ in Ref 1 show no peak comparable to that for H^+. [The reasoning around Eq. (10) also shows that finite Debye effects [1] cannot explain the large peak in dN/dv for H^+].

Nonetheless, consider light-pressure for one species, when T_e decreases with time; then an isothermal shock appears, to adjust the plasma to conditions in the critical layer [5], carrying the flow from values ahead n_a, v_a (supersonic) to $n_b > n_a$, v_b (subsonic)$<v_a$. Clearly, a large peak in dN/dv will appear around v_b. Now, for two species with different Z/m ratio, and T_e=const (or even slowly increasing), the dominant, lowest Z/m, species will be supersonic in a broad flow region ($M_1 > \bar{c}_1$ in between points E and N of the figure), and light-pressure will produce a shock leading again to a peak in dN/dv for that species. An estimate of the peak area for H^+ in Ref. 1 is in reasonable agreement with the observed data.

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