[1] W. Corner, W. Roe, and K. Taylor, Proc. Phys. Soc. 80, 927 (1962).
[2] C. Craham, Proc. Intern. Confer. on Magnetism, Nottingham, 1964.
[3] N. A. Babushkina, DAN SSSR 155, 1290 (1960), Soviet Phys. Doklady 9, 299 (1960).
[4] K. P. Belov, Yu. V. Ergin, A. A. Katsnel'son, and A. V. Ped'ko, JETP Letters 1, No. 2, 8 (1965), transl. 1, 43 (1965).
[5] K. P. Belov, Yu. V. Ergin, and A. V. Ped'ko, JETP 49, 414 (1965), Soviet Phys. JETP 22, 291 (1966).

SELF-FOCUSING OF A LIGHT BEAM UPON EXCITATION OF THE ATOMS AND MOLECULES OF THE MEDIUM IN THE BEAM

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Submitted 16 August 1966
ZhETF Pis'ma 4, No. 10, 400-403, 15 November 1966

The increase in the refractive index of a medium in a powerful light beam causes self-focusing of the beam [1-3]. This increase can be connected with various processes, such as striction [1,2], heating [1,4], optic Kerr effect [3], hydrodynamic scattering [7], etc.

We note in this article that the vibrational, rotational, and electronic excitation of the molecules and atoms of the medium and disintegration of their associations under the influence of the light beam or processes accompanying it can contribute to the self-focusing of the beam.

Indeed, any excitation of the atom or the molecule makes their electronic structure more friable and increases their polarizability. Thus, for example, electronic excitation of a very simple atom to the n-th level increases its dimensions by n^2 times ($a_n \simeq n^2 a_1$) and its polarizability by n^6 times ($\kappa_n \sim e^2/m\omega_n^2 \sim a_n^3 \sim n^6\kappa_1$), making the change in the dielectric constant $\Delta\epsilon = \sum N_n(n^6 - 1)\kappa_1$, where N_n is the number of particles in the state n. Even when $n \simeq 2 - 3$ the polarizability can increase by a factor $\sim 10^2 - 10^3$, and even more for resonance levels (the resonance polarizability is $\kappa \simeq e^2/m[(\omega^2 - \omega_2^2)^2 + \gamma^2\omega^2]^{1/2} \to e^2/m\gamma\omega$ as $\omega \to \omega_r$).

When rotational and vibrational motions are excited in the molecule, the increase in its optical polarizability is smaller in magnitude (since the electron shells of the atom are squeezed less when their mutual attraction decreases), but this can result in a noticeable change in the dielectric constant, in view of the larger fraction of the molecules which are excited in this manner. The disintegration of molecule associations can also increase the polarizability of the medium.

It must be noted that these processes can occur not only when the medium is heated, but also when the probability of excitation by the temperature rise ($\Delta N_n^T \simeq N_n \mathcal{E}_n \Delta T/kT^2$) is much smaller than the probability of direct optical excitation, and certainly in the case when the excitation relaxation time is much longer than the duration of the light pulse, as is frequently the case in gases. Self-focusing by heating, for media with $d\epsilon/dT > 0$ was considered recently in [4]. The possibility that heating can affect self-focusing was noted already in [1]. A change in $\epsilon(T)_{\rho=\text{const}}$ is indicated, for example, in [5], where data on $(\partial\epsilon/\partial T)_\rho > 0$ are also given.

The dynamics of the variation of the optical penetrability can be estimated from the equation for the number of excited particles $\dot{N}_n + N_n/\tau_n = \alpha_n(\omega, E)N_{10}$ if $N_n + N_1 = N_{10}$. From this we obtain for the simplest case when the field is switched on instantaneously

$$N_n(t) = \alpha_n\tau_n N_{10}[1 - \exp(-t/\tau_n)],$$

where $\tau_n(E, \omega)$ is the lifetime of the n-th excited state with allowance for the reversible transitions, N_{10} the initial concentration of the unexcited particles, and E and ω the intensity and frequency of the beam field. Then $\Delta\epsilon \simeq 4\pi(\kappa_n - \kappa_1)\Delta N_1$.

When $t \gtrsim \tau_n$, a value $\Delta N_n \simeq \alpha_n\tau_n N_{10} \sim \Delta\epsilon$ is established. For $t < \tau_n$ we obtain $\Delta N \simeq \alpha_n N_{10}t$ and $\Delta\epsilon \sim t$. The excitation cross section can be greatly increased by adjusting the resonant frequency of the beam and by mixing the frequencies so as to enhance the exciting action by the difference frequency [6].

We can estimate the condition under which the effect of heating on the excitation can be neglected in comparison with the direct excitation. For equilibrium conditions

$$(\partial\epsilon/\partial T)_\rho\Delta T < N_n^E(\kappa_n - \kappa_1)4\pi;$$

or from $N_n \simeq N_1\exp(\mathcal{E}_n/kT)$

$$\Delta N_n^T \sim N_n\mathcal{E}_n\Delta T/kT^2;$$

then $\Delta N_n^T < \Delta N_n^E$ for $\Delta T/T < \alpha_n\tau_n(kT/\mathcal{E}_n)\exp(\mathcal{E}_n/kT)$, which is satisfied under a wide range of conditions.

We note that excitation of molecules and atoms and dissociation of molecules can occur not only under the influence of light, but also under the influence of light-induced processes, such as the electrons of many-photon or cascade ionization, ultraviolet, etc. The increase in the refractive index due to these effects may weaken and in some cases it may even exceed the decrease due to the appearance of plasma ($\Delta\epsilon_p \simeq -\omega_p^2/\omega^2$), so that the number of excited molecules may exceed by many times the number of ionized or electron-excited molecules at a low degree of ionization ($\Delta N_n\kappa_n \gg N_e|\kappa_e|$, where the polarizability of the free electron is $\kappa_e \simeq -e^2/m\omega^2$ and $\kappa_n \simeq a_n^3$).

The small resultant differentials $\Delta\epsilon$ are sufficient to offset the divergence angles $\Delta\theta \sim \sqrt{\Delta\epsilon}$ and can cause elimination of the divergence of "flopping" of the light beam at distances $L_f \sim d/\Delta\theta$, where d is the radius of the beam. In this case the differential $\Delta\epsilon$ due to the excitation of the medium on the path of the beam may be produced with small time lag, in contrast to such focusing processes as striction, thermal expansion, etc.

I am grateful to Yu. P. Raizer for a discussion of the article.

[1] G. A. Askar'yan, JETP 42, 1567 (1962), Soviet Phys. JETP 15, 1088 (1962).

[2] V. I. Talanov, Izv. Vuzov Radiofizika 7, 564 (1964).

[3] R. Y. Chiao, E. Garmire, and C. H. Townes, Phys. Rev. Lett. 13, 479 (1964).
[4] A. G. Litvak, JETP Letters 4, 341 (1966), transl. p. 230.
[5] L. M. Levin, Izv. AN SSSR, ser. fiz. 4, 111 (1940).
[6] G. A. Askar'yan, JETP 48, 666 (1965), Soviet Phys. JETP 21, 439 (1965).
[7] Yu. P. Raizer, JETP Letters 4, 124 (1966), transl. p. 85.

GENERATION OF COLLISIONLESS SHOCK WAVES PROPAGATING ALONG A MAGNETIC FIELD

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Submitted 22 August 1966
ZhETF Pis'ma 4, No. 10, 403-409, 15 November 1966

An experimental investigation of the conditions for the excitation of shock waves propagating in a rarefied plasma along the magnetic field is of fundamental significance at the present time.

As is proposed in [1,2], the possible generation of shock waves in an interplanetary plasma as streams of charged particles ("solar wind") move toward the earth is the basic factor underlying such physical phenomena as the sudden occurrence of geomagnetic storms, the singularities of the magnetic field measured by the "Pioneer," "Mariner-2," and "IMP-1" at 12 - 14 earth radii, single pulses and the existence of electrons with energy 1 - 100 keV, radiation belts, auroras, etc. [3,4]. In nuclear fusion, the possibility of generating such waves is directly connected with the problem of transforming the translational energy of plasma streams into random motion, i.e., heat, upon injection of plasmoids along the magnetic field [5].

We present here the results of preliminary experiments devoted to this problem. A column of preliminary plasma was produced in a quasistationary magnetic field $H_0 = 0 - 3$ kOe by discharging capacitor C_1 into coil 2 in a glass vacuum chamber (length ~400 cm and diameter $2R \approx 20$ cm) filled with hydrogen ($p \simeq 10^{-3} - 5 \times 10^{-4}$ mm Hg). The longitudinal electron-density distribution is shown in Fig. 1. Some 50 - 70 μsec later, capacitor C_2 was discharged into conical coil 3 to produce a fast plasmoid with density $n_1 \simeq (5 - 7) \times 10^{13}$ cm^{-3} and velocity $u_{\parallel} > v_a = H_0/\sqrt{4\pi n_0 M}$. We note that in this case we deal with a plasma having a clearly pronounced pressure anisotropy

$$p_{\parallel} > p_{\perp} = H_0^2/4\pi \qquad (1)$$

In a weak magnetic field, it should be unstable against excitation of perturbations of the "Alfven type" (the so-called hose instability [2,5]). The kinetic energy of the plasmoid should become transformed into the energy of the alternating magnetic field $\tilde{H}_{\perp}$ and the transverse particle motion in the plasma within a time on the order of $\tau \gtrsim 1/\omega_{ci} = cM/eH$. At present there is still no theory allowing a detailed description of the sequence and significance of the physical processes occurring during supersonic motion of plasmoids under conditions where there are no collisions. We therefore proceed to report the experimental results, con-