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RADIATION PRESSURE ON AN OBJECT WITH VARYING POLARIZABILITY CHANGES. DEFORMATION ABSORPTION OF A WAVE BY VARIABLE INHOMOGENEITIES

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In the calculation of the absorption of a wave and its pressure on a small piece of matter (plasmoid, macroparticle, etc.) it is usually assumed that its volume, shape, or properties remain unchanged, and that the pressure is connected with scattering or ordinary absorption of the radiation inside the medium.

We shall consider absorption of radiation and the radiation-pressure force of a wave incident on an object whose polarizability changes as a result of changes in its volume, shape, orientation, or properties. These processes, which change the dipole energy in an external field, lead to a change in the wave energy as the result of the work performed by the object on the field or by the field on the object, and can greatly change (increase or decrease) the radiation pressure on the object.

1. Pressure of Electromagnetic Wave on a Particle of Varying Polarizability

The average pressure force on a particle that is small compared with the wavelength

$$f_{av} = \frac{1}{c} < [\dot{\mathbf{P}}\mathbf{H}]>_{av} \simeq \frac{1}{c} w_{diss} n$$

is determined by the dissipation of the wave energy in scattering ($w_{scat} \approx \ddot{P}^2/c^3$) and internal absorption ($w_{abs} \approx <\dot{P}E>_{av} \approx P\omega E_0 \sin\phi$, where ϕ is the loss angle). If the dipole moment is $P \approx \alpha E_0 \sin\omega t$, then the corresponding radiation reaction forces are $f_{scat} \approx \alpha E_0^2/\lambda\!\!\!^-$ and $f_{abs} \approx \alpha E_0^2 \sin\phi/\lambda\!\!\!^-$.

Let us estimate the force connected with the change of the polarizability $\alpha(t)$ (for a simplicity, we assume that its characteristic variation time is $T >> 1/\omega$). Assuming $\alpha \approx \alpha_0 + \dot{\alpha}t$, we obtain the force

$$f_\alpha \approx \frac{1}{c} \dot{\alpha} E_0^2,$$

which can be obtained also from the expression for the average energy of a dipole in an external field

$$\mathcal{E} \simeq \frac{1}{2} \alpha E_0^2; \quad (f \simeq \frac{1}{c} \dot{\mathcal{E}}).$$

We note that the deformation force f_α can have different directions, depending on the sign of $\dot{\alpha}$. For example, when the polarizability increases the direction of the force coincides with the direction of the ordinary light pressure, and when α decreases the force is directed against the wave. The latter circumstance allows us, in particular, to choose conditions under which the "deformation" force cancels out the ordinary light pressure. Let us estimate the conditions under which the radiation reaction forces are commensurate.

Neglecting the internal absorption, the ratio of the deformation force to the force due to the scattering is $f_{def}/f_{scat} \approx \dot{\alpha}\lambda\!\!\!^{-4}/c\alpha^2$; putting $\dot{\alpha} \approx \alpha/T$ we get $f_{def}/f_{scat} \approx \lambda\!\!\!^{-4}/c\alpha T \sim u/c \times (\lambda\!\!\!^{-}/a)^4$, where $u \sim a/T$ is the characteristic rate of change of the object.

In the general case, the change of α can be connected with the change of the shape, volume, or properties of the particle material. For example, for a spheroidal dielectric particle (elongated along the electric field of the wave) we have $\alpha = V(\varepsilon - 1)/4\pi[1 + (\varepsilon - 1) \times n_x]$, where V is the volume of the particle, ε the dielectric constant of the medium, and n_x the so-called demagnetization factor (for a nearly spherical shape $n_x \approx (1/3) - (4/15) \times [(a - b)/a]$, see, for example, [1]. The changes of n_x, V, and ε can result in quite appreciable changes of the polarizability. For example, if ε depends only on the density (say a plasma) and the total amount of matter is given, i.e., $V(\varepsilon - 1) = \text{const}$, then

$$\dot{\alpha} \cdot = \{\alpha/[1 + (\varepsilon - 1)n_x]\} \frac{\partial}{\partial t}(\varepsilon - 1)\, n_x \; .$$

If the main change is deformation, then $(\partial/\partial t)(\varepsilon - 1)n_x \approx (\varepsilon - 1)(\partial n_x/\partial t) \approx (\varepsilon - 1)\, 4\dot{a}/15a$ (if the initial shape is close to spherical) and $\dot{\alpha} \approx \alpha 4\,(\varepsilon - 1)u/15a$ (usually $(\varepsilon - 1)n_{x0} << 1$). If the shape remains constant upon expansion, then

$$\dot{\alpha} - \alpha n_x (\partial/\partial t)(\varepsilon - 1) \simeq \alpha\dot{V}(\varepsilon - 1)/3V \simeq \alpha(\varepsilon - 1)u/a.$$

therefore in both cases we have

$$f_{def}/f_{scat} \simeq \frac{u}{c}(\lambda\!\!\!^{-}/a)^4 \text{ i.e., } f_{def} > f_{scat}$$

when $u/c > (a/\lambda)^4$. For example, for plasma spreading at a rate $u \geq 3 \times 10^6$ cm/sec, it is necessary to have $\lambda > 10\, \alpha$. Large rates of spreading or deformation of the plasmoid may result not only from thermal pressure, velocity scatter, or external fields, but also under from the radiation field itself (for example, from the anisotropy of the pressure of the wave field on the surface of the plasmoid). In this case at first the spreading rate is $u(t) \sim E_0^2 t/4\pi\rho\, a$, and after a time $t \sim a\sqrt{4\pi\rho}/E_0$ it reaches a value on the order of $u_m \sim E_0/\sqrt{4\pi\rho}$.

In the submacroscopic region, the condition $\lambda >> a$ is always satisfied in the optical range ($\lambda\!\!\!^{-} \sim 10^3$ Å), and following reorientation, deformation, bending, or twisting of a long molecule the light pressure can therefore exceed by many times the light pressure due to scattering. The orientation of anisotropic molecules in a particle as a result of heating or application of an external field can also cause a change of α.

In the case of small particles in radio waves, the ratio $\lambda\!\!\!^{-}/a$ can be larger, but in many cases the deformation force should be compared with the force of the reaction due to the absorption (which exceeds the scattering when $\phi > (a/\lambda\!\!\!^{-})^3$, and

$$f_{def}/f_{abs} \simeq \dot{\alpha}\lambda\!\!\!^{-}/\alpha c \sin\phi \simeq \lambda\!\!\!^{-}/Tc \sin\phi \simeq \frac{u}{c}\left(\frac{\lambda\!\!\!^{-}}{a}\right)\frac{1}{\sin\phi},$$

i.e., at large $\lambda\!\!\!^{-}/a$ small expansion rates suffice to overcome the deformation force.

2. Deformation Absorption and Amplification of the Wave.

The foregoing shows that a predominant role is played under certain conditions by absorption or amplification of the wave by small material clusters with variable dimensions or shapes. We shall call this "deformation absorption." Let us estimate the magnitude and the contribution of the deformation absorption in the case of plasmoids.

If the frequency of the wave exceeds the plasma frequency ($\omega > \omega_p$) the power lost to deformation is

$$w \simeq N\dot{a}E_0^2 \simeq Na\left(\frac{\omega_p}{\omega}\right)^2 \frac{u}{a} E_0^2 ,$$

where N is the plasmoid concentration, a the plasmoid radius, and u the spreading rate. Comparison with dissipation due to collision $w_{col} \approx N(\omega_p/\omega)^2 a^3 (E_0^2/4\pi)\nu_s$ yields the condition under which the deformation absorption exceeds the collision absorption: the collision frequency is

$$\nu_s < \left(\frac{\omega_p}{\omega}\right)^2 \frac{u}{a} .$$

In this case the absorption coefficient is

$$\kappa \simeq 4\pi Na\left(\frac{\omega_p}{\omega}\right)^2 \frac{u}{ac} \simeq 4\pi a^2 N\left(\frac{\omega_p}{\omega}\right)^4 \frac{u}{c}$$

for $\omega > \omega_p$ and $\kappa \approx 4\pi a^2 Nu/c$ for dense plasmoids ($\omega_p > \omega$). At large powers $u = u(E_0^2 t)$ and the absorption becomes nonlinear. Rapidly expanding plasma inhomogeneities can be produced, for example, with the aid of lasers, whose flashes transform small particles of matter arrosols, etc into plasma.

Observation of the considered effect is possible in a wide range of conditions, from laboratory to astrophysical.

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ANOMALOUS ABSORPTION OF A POWERFUL ELECTROMAGNETIC WAVE IN A COLLISIONLESS PLASMA

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We have previously performed experiments [1 - 3] on the interaction of a powerful lineearly polarized H_{11} wave in a round waveguide with a cylindrical dense plasma beam injected along the radius of the waveguide normally to the direction of the electric field. The plasma was collisionless ($\omega_{Le} \geq \omega \gg \nu_{ei}$, where ω_{Le} is the electron plasma frequency, ω the microwave generator frequency, and ν_{ei} the electron collision frequency). In all the experiments, $\lambda_g \gg a$, where λ_g is the length of the wave in the waveguide and a is the radius of the beam. The maximum electric field intensity E at the waveguide center changed from 100 V/cm to 6 kV/cm. At E > 1 kV/cm, a change was observed in the character of the motion of the plasma beam, and accelerated ions appeared [1, 3], indicating effective transfer of the wave