MEETINGS AND CONFERENCES

Anniversary Scientific Session of the Division of General Physics and Astronomy, USSR Academy of Sciences (22 November 1972)

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A scientific session of the Division of General Physics and Astronomy of the USSR Academy of Sciences with dedication to the 50th anniversary of the formation of the Union of Soviet Socialist Republics, was held on November 22, 1972 at the conference hall of the P. N. Lebedev Physics Institute. The following papers were delivered:

1. R. Z. Sagdeev, Laser Thermonuclear Fusion and Parametric Instabilities.

2. Ya. B. Zel'dovich, Neutron Stars and "Black Holes."

3. F. I. Fedorov, The Development of Physics in Belorussia.

We publish below brief contents of the papers that were heard.

R. Z. Sagdeev. Laser Thermonuclear Fusion and Parametric Instabilities.

The possibility of initiating thermonuclear fusion in a drop of deuterium-tritium mixture by means of powerful laser radiation with a special time profile has recently been under intensive investigation[1]. The absorption of this radiation by the plasma corona of the drop should result in a rapid rise in the temperature and pressure of the plasma, ejection of the corona, and, as a result, compression of the interior of the drop. Computer fluid-dynamic calculations and estimates indicate that the efficiency of the scheme under consideration depends critically on the efficiency of absorption of the electromagnetic wave by the envelope of the drop. Hence the mechanisms of interaction of the radiation with the plasma corona of the drop become highly important. Propagating in the direction of increasing density, the electromagnetic wave reaches a reflection point ($\omega_0 = \omega_p$) and doubles back. At plasma corona temperatures of a few kiloelectron volts and with reasonable assumptions as to the dimensions of the ejected envelope ($\sim$1 mm), the absorption of the wave on this path, which is related to the imaginary part of the refractive index

$$\operatorname{Im}\sqrt{\varepsilon(\omega)} = \operatorname{Im}\sqrt{1-\frac{\omega_p^2}{\omega(\omega+i\nu_e)}}$$

(ν_e is the frequency of electron-ion collisions) is small. For oblique incidence, there is additional absorption due to transformation of some of the energy of the electromagnetic wave into longitudinal plasma oscillations in the neighborhood of the point $\epsilon(\omega, x) = 0$[2]. Generally speaking, however, this absorption is proportional to a small multiplier that describes the subbarrier attenuation of the electromagnetic wave on its path from the reflection point to the transformation point.

The possibility of strong interaction of the electromagnetic wave with the plasma is associated with nonlinear effects. The basic process of this type is three-wave decay. In it, the initial state, in which a wave of sufficient amplitude with frequency ω_0 and wave vector $\mathbf{k}_0$ (pumping wave) is excited, is unstable with respect to small perturbations in the form of wave pairs with frequencies and wave vectors ω_1, $\mathbf{k}_1$ and ω_2, $\mathbf{k}_2$ that satisfy the so-called decay conditions $\mathbf{k}_0 = \mathbf{k}_1 + \mathbf{k}_2$, $\omega_0 = \omega_1 + \omega_2$, $|\omega_0| > |\omega_1|, |\omega_2|$. The increment γ of this instability is simply expressed in terms of the matrix elements of three-wave interaction $V_{\mathbf{k}_0,\mathbf{k}_1,\mathbf{k}_2}$, a quantity that has been thoroughly studied in the theory of plasma turbulence[3]:

$$\gamma=\sqrt{\gamma_d^2-\frac{\delta^2}{4}},$$

where $\gamma_d = |V_{\mathbf{k}_0,\mathbf{k}_1,\mathbf{k}_2}||C_0|$, $\delta = \omega_0 - \omega_1 - \omega_2$ is the frequency deviation, and C_0 is the amplitude of the pumping wave, which has been normalized so that $|\omega_0||C_0|^2$ represents the energy of this wave.

The prime example of decay instability in plasma was the "plasmon" → "plasmon" + "sound" decay[4,5]. The "photon" → "plasmon" + "sound" ($t \to l + s$) decay proceeds in the same fashion[6,7] and the increment is exactly the same, since it is unimportant whether the pumping electric field $E_0 \cos(\omega_0 t - \mathbf{k}_0\mathbf{r})$, is that of a "plasmon" or a "photon." As applied to the interaction of laser radiation with a plasma corona, the instability $t \to l + s$ implies transformation of laser energy into plasma natural-vibration energy. But both are ultimately absorbed by plasma particles. The concrete mechanism of this absorption is far from trivial, and the particle velocity distribution that appears as a result of heating may differ strongly from Maxwellian. For example, there is the danger that a group of accelerated particles may appear. This phenomenon does not yet have a quantitative theoretical basis.

Another type of laser-radiation instability that results in additional heating is the decay $t \to l + l'$ [8,9], which proceeds at plasma densities approximately one-quarter as large.

All processes of this kind are of parametric nature and can be interpreted as parametric instabilities in a system of two coupled oscillators (the pair of waves that arise from the instability). The coupling between these oscillators results from the nonlinear properties of the medium (for example, the nonlinearity of its dielectric properties) via the pumping wave ω_0, $\mathbf{k}_0$. Upon increase in pumping-wave amplitude, it is eventually necessary to take account of increasingly large numbers of participating oscillators (waves). However, this occurs only at very large amplitudes, when $\Delta\omega$, the width of the corresponding Mathieu fundamental band, becomes of the order of ω. If the frequency of one of the waves, for example ω_2, is very small: $\omega_{1,0} \gg \omega_2$ then when $\omega_1 \gg \Delta\omega \sim \gamma \gg \omega_2$ it is still sufficient to consider only the two coupled oscillators. However, the wave (ω_2, $\mathbf{k}_2$) is strongly modified. In this case, the instability increment ($\gamma_d \gg \omega_2$) is found to be $\gamma = (\sqrt{3}/2)\sqrt[3]{2\gamma_d^2\omega_2}$ [10,11]. This limiting case is sometimes referred to as modified decay. Decay instability occurs at pumping-wave amplitudes above a certain critical amplitude (above the threshold). In a homogeneous plasma, this threshold $\gamma_d^2 \geq 2\nu_1\nu_2$[12] depends on the damping decrements of the waves $(\omega_1, \mathbf{k}_1)(\omega_2, \mathbf{k}_2)$.

For the problem at hand, the laser pulse powers are practically always above the threshold calculated for a homogeneous plasma. Under these conditions, the inhomogeneities of the plasma in the corona become much more important. In the simplest case of laminar ejection, they are the density inhomogeneity $n = n(r)$ and the velocity inhomogeneity of gasdynamic ejection $U = U(r)$. The temperature in the rarefied envelope can usually be regarded as homogeneous because of the high electronic thermal conductivity. In this case, the conditions of decay resonance can be satisfied only in a limited spatial region. Moving at their own group velocities, the perturbation waves $(\omega_1, \mathbf{k}_1)$, $(\omega_2, \mathbf{k}_2)$ will ultimately pass out of the unstable zone[9,13]. Whether decay instability will develop during the finite growth time depends on whether the original fluctuations have time to increase to the nonlinear level. For equilibrium thermal noise, this implies amplification by a factor of approximately $e^{\mathscr{L}}$, where $\mathscr{L}$ is the so-called Coulomb logarithm, $\mathscr{L} = \ln(n\lambda_D^3)$ (λ_D is the Debye radius and $\mathscr{L}$ is numerically of the order of 15–20). Actual instances of the various decays indicate that as the power of the laser radiation is increased, the threshold for the $t \to l + s$ instability is reached first, and then that for $t \to l + l'$. But as the power of the incident radiation is further increased, the parasitic decay instabilities[13] $t \to t' + s$ and $t \to t' + l$ come into play and lead to the appearance of parametrically scattered electromagnetic radiation and ultimately to additional nonlinear reflection. This problem may turn out to be an extremely acute one for laser initiation of the D-T drop. It therefore requires special investigation, which should include the use of numerical experiments.

The simpler part of the problem—the linear theory of parametric instability—should be singled out first. In applications to the problem of the inhomogeneous plasma corona, we are interested in calculating not the growth increments in time, but the spatial amplification of the perturbations. This problem has been considered by Galeev, Laval, O'Neil, Rosenbluth, and the speaker for all basic parametric-decay processes of laser radiation. Scattering at a ~90° angle (in the plane problem) is found to be most important. The results of a simplified analysis are set forth in[14]. A more rigorous approach based on investigation of details of the behavior of the scattered radiation in the resonance range (using the method developed in[9]) yields results of the same order of magnitude (see Tables I—II, which summarize the calculations of the five authors[14]). Amplification coefficients for induced scattering (conversion) by ions are given in the last lines of the tables. This process can be regarded as decay when the low-frequency partner (the sound) is strongly damped, as, for example, in an isothermal plasma with $T_i \gtrsim T_e$.

The linear theory indicates that substantial growth of the perturbations should occur in the case of a plasma corona of sufficient extent L (it is necessary that $L \gtrsim 10$–20). If this condition is satisfied, the perturbations reach amplitudes at which nonlinear effects are substantial. Systematic consideration of these effects is an exceedingly complex problem. Moreover, one-dimensional models are devoid of sense, since the phase volume of the scattered waves is too small in such models. Further, and as we have already noted, the radiation scattered at an angle $\sim\pi/2$ increases more strongly. As a result, the "plateau-type" saturation of the velocity distribution function is also lacking as a purely one-dimensional effect.

Certain approximate models were constructed in[14]. We shall devote a more detailed discussion to one of them. A plasma corona with hot ions ($T_i \gtrsim T_e$), in which there is no sound, would be most likely to have the lowest reflecting properties. Instead of the decay $t \to t' + s$, it is necessary in this case to consider induced scattering on ions, $t \to t' + i$. An approximate nonlinear model of this process can be constructed as follows. Let the exponential stage in the buildup of the instability from the thermal-noise level be followed immediately by a range in which the nonlinear interac-

TABLE I. Parametric back scattering at ~90°

Process	Maximum increment	Maximum gain e
$t \to t' + s$	$\gamma_d^2 = \frac{\omega_p^4}{4\sqrt{2}} \frac{k_0 l_s}{\omega_0^3} \sqrt{1-\cos\theta} \frac{E_0}{8\pi \cap T_e}$	$\nu = \frac{4\pi\gamma_d^2\omega_0 L}{\omega_p^2 U}$ $\nu = \left(\frac{4\gamma_d^2}{\omega_p k_0 U}\right)^{4/5} \left(\frac{U}{LU'}\right)^{3/5} k_0 L$
$t \to t' + l$	$\gamma_d^2 = \frac{\omega_p^3}{4\omega_0}(1-\cos\theta)\frac{E_0}{8\pi nmc^2}$	$\nu = \left(\frac{8\gamma_d^2}{\omega_p^2}\right)^{4/5} \frac{k_0 L}{\sqrt[5]{6k_0^2\lambda_D^2}}$
$t \to t' + i$	$\gamma = \frac{\omega_p^4}{\omega_0^3} \frac{E_0^2}{8\pi n T_e}$	$\nu = \frac{\gamma}{\omega_p} \sqrt{\frac{c_s}{U'L}} k_0 L$

TABLE II. Parametric heating of plasma.

Process	Increment	Gain e
$t \to l + s$	$\gamma_d^2 = \frac{\omega_s(\mathbf{k})\,\omega_p(\mathbf{k})}{8} \frac{E_0^2}{8\pi n T_e}$	$\nu = \left(\frac{\gamma_d^2}{\omega_p\omega_s}\right)^{3/4} (k\lambda_D)^{1/2} kL$
$t \to l + l'$	$\gamma_d^2 = \frac{\omega_p^2}{4} \frac{k_0^2 E_0^2}{8\pi nm\omega_0^2} \sin^2 2\theta \cos^2\phi$	$\nu = \frac{\pi k_0 L}{6} \frac{E_0^2}{8\pi n T_e}$
$i \to l + i$	$\gamma \sim \omega_p \frac{E_0^2}{8\pi n T}$	$\nu \sim \frac{\gamma}{\omega_p} k_0 L$

tion is substantial and the incident wave is effectively attenuated (over a certain length Δx):

$$C\frac{T_0}{\Delta x}\approx\frac{\omega_p^4}{\omega_0^3}\frac{I_0}{nT}J_1kv_{Ti},\qquad I_0\equiv\frac{E_0^2}{8\pi},\tag{1}$$

where J_1 is the spectral density (on the frequency interval) of the scattered radiation. We assume that the pumping wave interacts directly with the scattered radiation in an interval of width $\sim kv_{Ti}$. The subsequent evolution of J_1 is determined on the one hand by relay pumping in a range of steadily lower frequencies (due to secondary induced scattering) and, on the other, by escape of radiation from the instability band:

$$C\frac{\omega_p}{\omega_0}\sqrt{\frac{\Delta x}{L}}\frac{J_1}{\Delta x}\sim\frac{\omega_p^4}{\omega_1^3}\frac{kv_{Ti}^2}{nT}J_1\frac{dJ_1}{d\omega_1}.\tag{2}$$

We approximate relay pumping of photons across the spectrum by a differential form, in analogy with the problem of plasmon pumping, while the angular spread of the scattered radiation around 90° is taken with consideration of refraction (rotation of the wave vector) in the inhomogeneous plasma:

$$\Delta\Theta\sim\frac{\omega_p}{\omega_0}\sqrt{\frac{\Delta x}{L}}.$$

Then the scattered-radiation spectrum drops off linearly to zero from $\omega = \omega_0$ to $\omega = \omega_r$:

$$J_1\sim\frac{I_0}{kv_{Ti}}\left(1-(\omega_0-\omega_1)\frac{\omega_0}{\omega_{pk}v_{Ti}}\sqrt{\frac{I_0}{nT}\frac{1}{k_0L}}\right).\tag{3}$$

We found the constant of integration by examining the "input-output" balance due to induced scattering near the upper end point of the scattered-radiation spectrum ($\omega_0 > \omega \gtrsim \omega_0 - kv_{Ti}$). As a result, the thickness of the nonlinear-scattering region is found to be on the order of

$$\Delta x\approx\frac{C}{\omega_0}\left(\frac{\omega_0}{\omega_p}\right)^4\frac{nT}{I_0}.\tag{4}$$

The fraction of laser-wave energy absorbed by ions can be estimated as

$$\frac{\omega_0-\omega_r}{\omega_0}\approx kv_{Ti}\frac{\omega_p}{\omega_0}\sqrt{k_0L\frac{nT}{I_0}}.\tag{5}$$

The range of validity of this model may have an upper limit at high incident-radiation intensities, when induced scattering is transformed into what is known as "modified decay." Still higher intensities $I_0/nT \gtrsim 1$ require a totally different analysis of the interaction of the radiation with the corona, since the radiation forces become basic in the gasdynamics of the corona.

Let us apply the formulas obtained above to the most frequently discussed case of the neodymium-glass laser. At $\omega_0 \sim 2 \approx 10^{15}$ sec^{-1}, $\omega_0/\omega_p \sim 2$, $I_0/nT \sim 0.1$, the penetration depth at which the laser radiation is effectively reflected is of the order of 10^{-2} cm $> \Delta x > 10^{-3}$ cm. This value is much smaller than the initial size of the D-T drop and, as we might expect, much smaller than the thickness of the plasma corona at the time of critical compression. Hence the processes considered here may play an important part in the physics of the interaction of a powerful electromagnetic wave with a plasma, and their investigation acquires great applied importance. In view of the complexities in the way of an analytical approach to the problem, it would be most desirable to perform numerical experiments. However, one-dimensional numerical models are hardly conceivable, since they lack the (basic) scattering through the 90° angle and the phase volume of the unstable waves is too small.

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Ya. B. Zel'dovich, Neutron Stars and "Black Holes."

The orbiting of satellites outside of the atmosphere has created a foundation for the development of x-ray astronomy. Discrete x-ray sources (including x-ray pulsars) with luminosities 1000 times that of the sun and even higher have recently been discovered within the limits of our Galaxy. In a number of cases, these sources form (together with ordinary stars that emit light in the optical band) binary systems or, more precisely, close pairs. It has become possible as a result to determine the mass of the x-ray star. The aggregate of data indicates that the x-ray source is in some cases a neutron star and in others a star in a state of relativistic collapse, i.e., a cooled star or, to use the current term, a "black hole."

Let us examine the observational material with the source Hercules X-1 as our example. This source has a period of 1.7 days (about 40 hours), of which about 8 hours are spent in eclipse, with the ordinary star between the source and the observer on the earth. The period of the velocity variation of the ordinary star coincides with the period of the eclipses, and this confirms duplicity.

The x-radiation has a short period of 1.24 sec, i.e., a period in the pulsar range. The 1.24-second period indicates that the source is a rotating neutron star (its mass according to orbital observations is suitable, $\sim 0.8\ M_\odot$, where $M_\odot$ is the sun's mass, 2×10^{33} g), with a magnetic field that controls the directivity of the x-radiation.

This radiation is linked to the incidence and impingement of gas flowing across from the ordinary star onto the surface of the neutron star.