SOVIET PHYSICS JETP VOLUME 31, NUMBER 6 DECEMBER, 1970

OBSERVATION OF PLASMA SATELLITES NEAR FORBIDDEN LINES OF He I *IN A TURBULENTLY HEATED PLASMA*

G. V. ZELENIN, A. A. KUTSYN, M. E. MAZNICHENKO, O. S. PAVLICHENKO, and V. A. SUPRUNENKO

Physico-technical Institute, Ukrainian Academy of Sciences

Submitted August 18, 1969

Zh. Eksp. Teor. Fiz. 58, 1879–1883 (June, 1970)

In the turbulent plasma of a high-current linear gas discharge (z pinch) satellites near three forbidden lines of He I were observed and investigated. These satellites were predicted by Baranger and Moser. Time measurements of the positions and intensities of the satellites yielded the time dependence of the electron density and of the level of plasma oscillations. Observation of satellites is a new contactless method of investigating a turbulent plasma.

In different variants of the turbulent heating of plasmas the directed energy of charged particles is transferred to collective degrees of freedom of the plasma: turbulent pulsations are excited, which are dissipated very rapidly, with resultant effective heating of the plasma. A basic parameter of the turbulent plasma state is the energy level of the plasma pulsations. Knowledge of this level enables us to compute the efficiency with which the energy of directed motion is transferred to plasma oscillations, and also, in conjunction with the pulsation spectrum, to make a comparison with the theory.

Since the peak of the spectrum of oscillations excited by turbulent heating lies near the characteristic plasma frequencies (electron plasma oscillations), measurements of microwave noise and incoherent microwave scattering are widely used to investigate high-frequency turbulent pulsations.[1,2] A disadvantage of these methods is the great difficulty of measuring the emission and scattering spectra. When the turbulent pulsation level is calculated on the basis of the microwave radiation the efficiency of the transformation of various plasma oscillation waves into electromagnetic radiation remains indeterminate. Any contactless methods of measuring the spectrum and level of high-frequency plasma turbulence without encountering the same difficulties is therefore of interest.

In 1961 Baranger and Moser suggested that forbidden helium lines could be used to measure plasma oscillation energies. It is their idea that in sufficiently high plasma fields the Stark effect could induce partial lifting of forbiddenness and that lines corresponding to forbidden dipole transitions ($\Delta l = 0, \pm 2$) would become observable. In the electric field of plasma oscillations an atom receives the energy $\pm \hbar\omega_p$, where ω_p is the plasma oscillation frequency; therefore the spectrum should reveal two lines differing by ω_p from the forbidden line. Second-order perturbation theory enables us to calculate the intensities of plasma satellites near a forbidden line relative to the intensity of an allowed line[3]:

$$S = \frac{\hbar^2 \langle E_p{}^2 \rangle R_{ll'}}{6m^2e^2(\Delta \pm \Omega_p)^2} \quad (1)$$

where m and e are the electron mass and charge, Δ is the separation between the forbidden and allowed lines, $\langle E_p^2 \rangle$ is the mean square plasma electric field, $R_{ll'}$ is the dimensionless radial integral

$$R_{ll'} = \frac{\max(l, l')}{2l+1} \left\{ \frac{1}{a_0} \int_0 R_l(r) R_{l'}(r) r^3 \, dr \right\}^2, \quad (2)$$

and $a_0 = \hbar^2/me^2$ is the Bohr radius.

Satellites of the aforementioned kind were observed for the first time in experiments on electrodeless induction discharge (θ pinch) at the moment of compression of a low-density plasma.[4] Near the two He I lines at 4471.5 Å and 4921.9 Å pairs of satellites were observed, which were displaced 0.3–0.6 Å from the forbidden lines. However, the report contains no additional data that would be evidence of the excitation of plasma oscillations.

In the present work we observed and investigated satellites near three forbidden lines of He I in the turbulent plasma of a high-current linear gas discharge (z pinch). Our apparatus was completely similar to that described in[5], with 10^{-3}–1 Torr initial helium pressure, up to 30 kV ($E \lesssim 600$ V/cm) voltage of the charged capacitor bank ($C = 15\ \mu F$), maximum discharge current up to 200 kA, and a longitudinal magnetic field up to 15 kOe. The following parameters were measured: the plasma conductivity according to current measurements and the voltage across the discharge tube, the diamagnetism of the plasma, the electron concentration determined by microwave probing, and the microwave radiation of the plasma.

It has previously been shown that when a very high electric field is applied to a fully ionized hydrogen plasma strong electrostatic instability is excited, which leads to epithermal microwave emission in a broad range of frequencies ($\omega_{0i} \lesssim \omega \lesssim \omega_{0e}$),[5] anomalously low plasma conductivity,[6] and different electron[7] and ion[8] heating.

These properties of the plasma discharge suggested that the given plasma could be a suitable medium for observing plasma satellites. Photographs of the plasma radiation spectrum in the direction of the discharge axis, using a spectrograph with 8-Å/mm dispersion, revealed satellites near the following He I lines: 4026.19 Å ($2p^3P^0 - 5d^3D$), 4471.48 Å ($2p^3P^0 - 4d^3D$), and 4921.93 Å ($2pP^0 - 4d'D$). Figure 1 is a photograph of the spectrum near the 4471.48-Å line; a satellite is

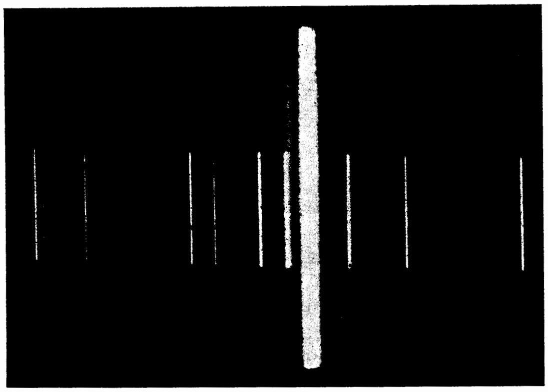

FIG. 1. Spectrum of plasma discharge radiation near the 4471.48-Å line of He I and the spectrum of iron (p = 5 × 10^{-1} Torr, U_b = 10 kV, H = 3 kOe).

clearly visible. All the observed satellites were associated with $\Delta l = 2(nP \rightarrow mF)$ transitions. Calculations of the satellite displacements relative to allowed lines showed that "far" satellites displaced 0.3–0.7 Å from forbidden lines were being observed. To verify that the allowed lines had not shifted, the spectrum of the high-current discharge was compared with that of a low-pressure glow discharge in the same discharge tube; in these experiments the sensitivity for determining a shift was enhanced by the use of a Fabry-Perot interferometer. The intensity ratio of the satellites and allowed lines was 5×10^{-2}–10^{-1}.

The spectral regions near the aforementioned lines were subsequently scanned photoelectrically using a monochromator with 25 Å/mm dispersion. Figure 2 shows the result of one such measurement at 5×10^{-1} Torr helium pressure. During the first half-period of the discharge current the "far" satellite shifted 0.7 Å. If it is assumed that the observed satellites are created by the electric fields of the plasma oscillations the maximum displacement corresponds to $\sim 10^{14}$ cm^{-3} electron concentration.

Under the given conditions it is most probable that the plasma was practically fully ionized ($n_e \approx 10^{16}$ electrons/cm^3) and that the observed "satellite" was not associated with plasma oscillations. The authors of[4] remark that the forbidden lines of He I can result from a partial lifting of forbiddenness in the quasi-static fields of plasma electrons and ions when the electron density is increased. These forbidden lines are shifted toward shorter waves (by 0.4 Å at densities $\sim 10^{15}$ electrons/cm^3). These calculations suggest that our observed satellites at high pressures are simply displaced forbidden lines of He I. It is of interest to study the radiation spectrum of a turbulent plasma near forbidden lines under conditions that induce the current instabilities previously studied in[5-8].

Figure 3 shows oscillograms of plasma parameters measured in this regime (at 2×10^{-2} Torr helium pressure), which is distinguished by the appearance of epithermal microwave radiation having 0.8–100-cm wavelengths. Simultaneously with the appearance of the microwave radiation one observes a sharply reduced intensity of the He I lines; this is evidence that the electron component of the plasma has been heated rapidly. Effective heating of the electrons is confirmed in this case by plasma diamagnetism measurements revealing that $n(T_e + T_i)$ increases sharply at the moment when the microwave radiation appears.

The low intensities of the He I lines at the given reduced pressures prevented us from photographing the spectrum. The poor reproducibility of the plasma radiation-intensity oscillograms near He I lines of a highly turbulent plasma made it necessary to average the signals from several discharges at each wavelength. The time dependence of the spectrum near λ = 4471 Å was obtained by averaging over 10 discharges, as shown in Fig. 4. Near the forbidden line we observe radiation occupying a broad spectral interval with several characteristic peaks disposed symmetrically about the forbidden line (1 – 1′, 2 – 2′,

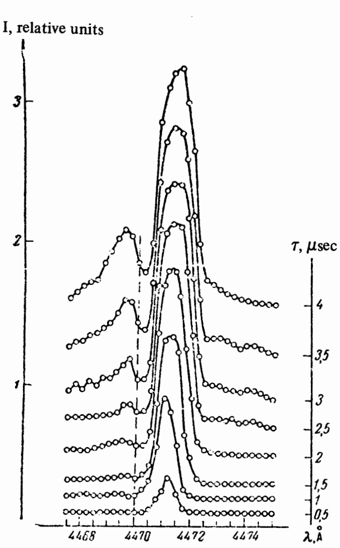

FIG. 2. Time dependence of the discharge radiation spectrum near the 4471.48Å line of He I (p = 5 × 10^{-1} Torr, U_b = 10 kV, H = 3 kOe). The position of the forbidden line is shown by the dashed vertical line.

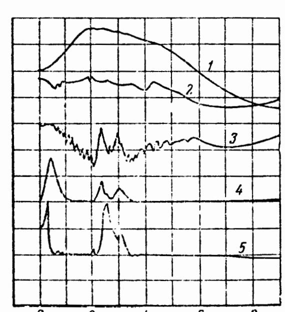

FIG. 3

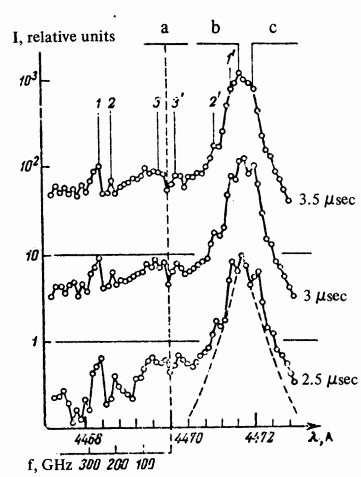

FIG. 4

FIG. 3. Oscillograms illustrating the time dependence of the parameters: 1—discharge current (I_p); 2—voltage across electrodes (U_p); 3—intensity of plasma radiation near the 4471.48Å line of He I; 4—λ = 3 cm signal from detector; 5—λ = 0.8 cm signal from detector when the plasma was simultaneously probed at this frequency (p = 2 × 10^{-2} Torr, U_b = 15 kV, H = 3 kOe).

FIG. 4. Time dependence of the discharge spectrum near the 4471.48Å line of He I (p = 2 × 10^{-2} Torr, U_b = 15 kV, H = 3 kOe). A—forbidden line; B—He I 4471.48Å; C—He I 4471.68Å.

3 – 3′), and with a dip near the position of the forbidden He I line 4470.03 Å ($2p^3P^0 - 4f^3F$).

We can assume that the observed satellite pairs correspond to characteristic plasma frequencies. In consideration of the fact that under the given conditions the plasma was practically fully ionized and that the electron density was $\sim 5 \times 10^{14}$ electrons/cm^3, the positions of the satellites 1 – 1′ about the forbidden line corresponds to the electron plasma frequency: $\Delta\omega_{1-1'} \approx 2\omega_{0e}$. The frequency displacement of the broad "near" satellites 3 – 3′ is about 0.2 ω_{0e}, while that of the satellites 2 – 2′ is about 0.8 ω_{0e}.

By measuring the intensity ratio between the satellites and the allowed line we can measure the energy density $\langle E_p^2 \rangle / 8\pi$ of the turbulent plasma pulsations that lead to the appearance of the satellites. It was shown in[4] that when we introduce the parameter $\epsilon = \langle E_p^2 \rangle / 8\pi (3/2 n_e kT)$ to characterize the level of the turbulent plasma pulsations, Eq. (1) can be written as

$$S_{\pm} = \varepsilon \frac{kT_e}{4E_H} \left[\frac{\Omega}{\Delta \pm \Omega} \right]^2 R_{ll'},$$

where E_H is the hydrogen ionization energy and $R_{ll'} = 151$ (for He I 4471 Å). The maximum measured value of S_+ was ~0.1, which at $T_e \approx 10^3$ eV yields $\epsilon \sim 10^{-4}$. At the thermal level of plasma waves ϵ is calculated to be $\epsilon_{therm} \approx \frac{1}{18}\pi^2 n_e \rho_D^3$,[4] where ρ_D is the Debye radius. In our case, $\epsilon_{therm} \sim 10^{-8}$ and the turbulent pulsation level exceeds the thermal level of plasma waves by four orders of magnitude.

The authors are indebted to V. F. Solodovnikov and N. S. Konovalov for experimental assistance.

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Translated by I. Emin
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