Flash of emission from multiply charged ions in a current sheet

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Flashes of emission in the spectral lines of multiply charged ions have been detected from the plasma of a current sheet for the first time. The excitation of nonequilibrium electric fields has been observed. The electron and ion temperatures of the plasma of the current sheet have been determined.

1. Determining the properties of the plasma in various stages of the evolution of current sheets is one of the important problems associated with research on magnetic reconnection. For example, Syrovatskiĭ[1] has shown that the thermal regime of a current sheet which develops in the solar atmosphere may determine the disruption of the metastable stage and the transition to an explosive destruction of the sheet; i.e., it may initiate the pulsed phase of a solar flare.

In experiments with plane current sheets in which magnetic reconnection has been studied,[2] emphasis has been placed on the structure of the magnetic fields and the distributions of the electric current and the plasma density in the final stages of the evolution of the current sheets. The temperatures $T_e + T_i/Z_i$ has been estimated from the pressure balance in the quasisteady stage.[3] It has been shown that the ion temperature increases gradually,[4] with the result that the pressure balance is disrupted during the pulsed phase of magnetic reconnection. A decrease in the plasma conductivity[5] has indicated a possible excitation of turbulent electric fields in the plasma of the sheet.

In this letter we report a spectroscopic study of the evolution of the electron and ion temperatures. We have observed a sharp increase in both temperatures and the excitation of nonequilibrium electric fields just before the pulsed phase of magnetic reconnection.

2. A plane current sheet was formed by a direct discharge whose current was directed along the null line of the quasisteady two-dimensional magnetic field.[2,5] The gradient of the quadrupole magnetic field has $h = 540$ G/cm; an initial plasma with a density $N_0 \sim 10^{15}$ cm^{-3} was produced in helium at a pressure $p_0 = 5 \times 10^{-2}$ Torr. The current reached a maximum value $J_m \approx 50$ kA at $t_m = 1.4$ μs.

A two-channel optical arrangement was used for spectral analysis of the emission from the plasma of the sheet. A beam splitter split the emission from the plasma into two identical channels, in each of which a fast achromatic objective imaged a central region of the vacuum chamber, ~2 cm in diameter and 40 cm long, onto a bundle of quartz optical fibers. A reduced image of the central part of the sheet was sent to the input slits of monochromators; the emission was then detected with photomultipliers and an oscilloscope. In the experiments on the time evolution of the intensities of the spectral lines, the monochromator slits were 3–7 Å; during a recording of lineshapes, the slits were 0.4–0.9 Å.

The time evolution of the optical characteristics of the plasma was compared with signals from a magnetic probe near the surface of the sheet, at its center. This probe detected the field component tangent to the sheet, $B_x(t)$. The beginning of the pulsed phase of magnetic reconnection was identified from the slope change on the curve of $B_x(t)$ ($t \approx 1.6$ μs). This feature corresponds to a decrease in the field component tangent to the surface of the sheet.[2,5]

3. It can be seen from Figs. 1 and 2 that the emission from the central part of the sheet in the lines of singly charged impurity ions (CII,NII,OII) appears 0.4–0.5 μs after the current J begins to flow in the plasma. During the first microsecond, the lines of doubly charged ions (CIII,NIII,OIII) appears. In the interval 1.0–1.5 μs, the CIV, NIV, and OIV spectral lines slowly intensify; then, at $t = 1.3$–1.8 μs, there are brief flashes in the emission in NV, OV, and OVI lines, with a typical rise time of 0.2–0.1 μs and a duration of 0.4–0.2 μs. The spectral lines of lower degrees of ionization fade to some extent, and the intensity maxima of the emission in the NV, OV, and OVI lines correlate with a rapid decay of both the intensity of the emission in the HeII line at 4685.7 Å and the tangential component of the magnetic field, $B_x(t)$.

The emission flashes in the lines of multiply charged ions are evidence of a sharp increase in the electron temperature in the current sheet. To estimate $T_e(t)$, we com-

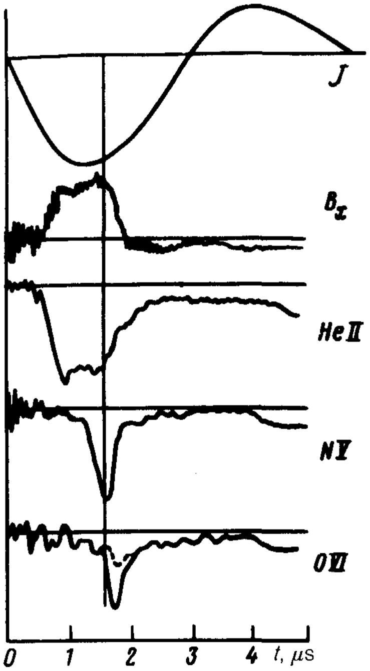

FIG. 1. Evolution of the emission from the plasma of a current sheet in various spectral lines. Here J is the plasma current, and $B_x(t)$ is the magnetic field component tangent to the surface of the sheet. HeII 4685.7, NV 4619.98, OVI 5290.6 Å.

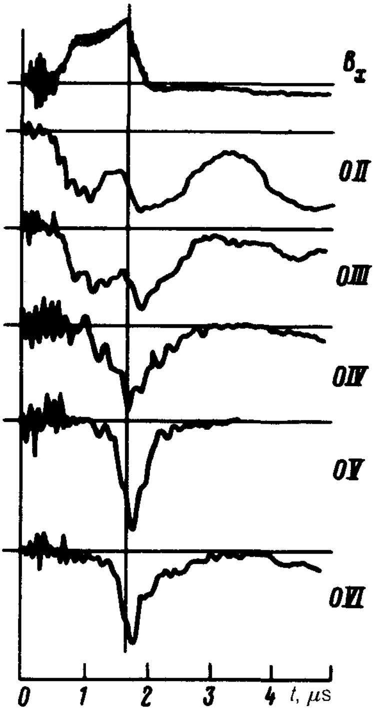

FIG. 2. Evolution of the plasma emission in the spectral lines of the oxygen series: OII 4649.14, OIII 5592.37, OIV 4798.24, OV 5597.91, OVI 5290.6 Å

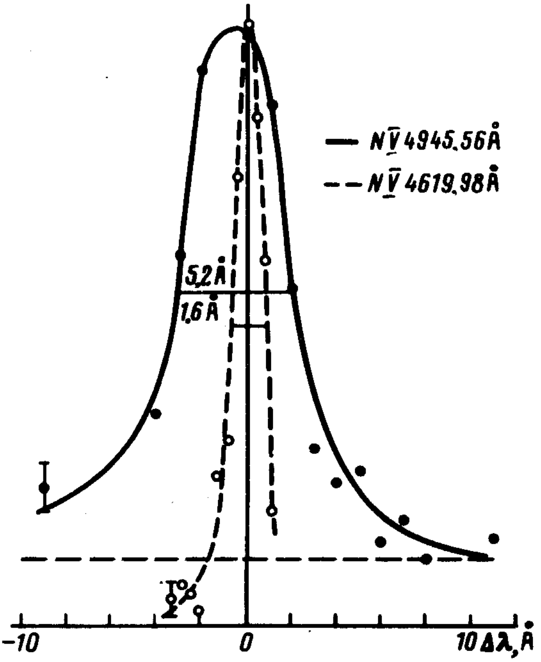

FIG. 3. Profiles of spectral lines of the quadruply charged nitrogen ion, NV 4619.98 and NV 4944.56 Å, at $t = 1.7$ μs.

pare the typical intensification times of the various spectral lines with the calculated ionization times (or excitation times) of the corresponding ions: $\tau_i = [N_e \langle \sigma_i v_e \rangle]^{-1}$. In the interval 1.0–2.0 μs, the electron density varies slowly and has values[2,3] $(1.0\text{–}2.0) \times 10^{16}$ cm^{-3}. The rates of ionization (and excitation) were calculated from data given in Refs. 6 and 7. At $t \approx 1.3$ μs, for example, when there is a slow intensification of the OIV lines, we find $T_e \leqslant 20$ eV. From corresponding estimates based on the typical intensification times of the OV and OVI lines we find $T_e = 50 \pm 20$ eV at $t = 1.5$ μs and $T_e = 100 \pm 30$ eV at $t = 1.6$ μs.

4. Figure 3 shows the shapes of two spectral lines of the quadruply charged nitrogen ion: NV4619.98 Å $(3s^2S - 3p^2P^0)$ and NV4944.56 Å$(6fgh - 7ghi)$. The first line, whose broadening is caused primarily by the Doppler effect, has a half-width of 1.6 Å, which corresponds to an ion temperature $T_i \approx 220 \pm 30$ eV. The half-width of the second line, which is sensitive to both Doppler and Stark effects, is larger by a factor of 3.3: 5.2 Å. The observed difference cannot be explained in terms of a contribution of equilibrium interparticle fields[8] to the broadening of the NV line at 4944.56 Å; this difference is evidence that nonequilibrium electric fields play an important role in that stage of the evolution of the current sheet in which there are flashes in the lines of multiply charged ions. We wish to stress that similar tendencies are seen in a comparison of the shapes of the spectral lines of other multiply charged lithium-like ions: OVI 3811.35 Å and OVI 5290.6 Å and also CIV 5801.33 Å and CIV 4658.30 Å.

5. In summary, flashes of emission in the spectral lines of multiply charged ions have been detected from the plasma of a current sheet for the first time. These flashes are evidence of a pulsed heating of the electrons to temperatures $T_e \sim 100$ eV. The electron and ion temperatures reach their maximum values essentially simultaneously; the ion temperature in the hottest parts of the plasma is $T_i \sim 200$ eV. It has been established that the pulsed phase of magnetic reconnection sets in after, and apparently because of, the rapid heating of the plasma. The excitation of nonequilibrium electric fields has been observed in the plasma of a current sheet for the first time. These fields cause a significant broadening of the spectral lines of multiply charged ions which are sensitive to electric fields.

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[1] S. I. Syrovatskiĭ, Pis'ma Astron. Zh. **2**, 35 (1976) [Sov. Astron. Lett. **2**, 13 (1976)].
[2] A. G. Frank, in: Proceedings of the Lebedev Physics Institute, Vol. 160, 1985, p. 93.
[3] G. V. Dreĭden, N. P. Kiriĭ, V. S. Markov *et al.*, Fiz. Plazmy **3**, 45 (1977) [Sov. J. Plasma Phys. **3**, 26 (1977)].
[4] N. P. Kiriĭ, V. S. Markov, M. M. Savchenko, and A. G. Frank, Preprint No. 193, Institute of General Physics, Academy of Sciences of the USSR, 1984.
[5] S. Yu. Bogdanov, V. S. Markov, and A. G. Frank, Pis'ma Zh. Eksp. Teor. Fiz. **35**, 232 (1982) [JETP Lett. **35**, 290 (1982)].
[6] H. J. Kunze, Phys. Rev. **A3**, 937 (1971).
[7] L. A. Vaĭnshteĭn, I. I. Sobel'man, and E. A. Yukov, Excitation of Atoms and Spectral-Line Broadening, Nauka, Moscow, 1979.
[8] S. A. Gulyaev and G. V. Sholin, Akust. Zh. **58**, 1057 (1981) (sic).

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