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HIGH-FREQUENCY AND MICROWAVE EXCITATION OF A DISCHARGE IN SULFUR VAPORS

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The authors study luminosity spectra of a discharge excited by high-frequency and microwave sources in mixtures of field-evaporated sulfur with argon and neon buffer. Characteristic spectra transformation stages are distinguished during the discharge development.

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1. Introduction

Electrodeless gas discharge was excited by an external electromagnetic field much later than in the classical scheme with an external current source (see [1]). Nevertheless, the former method already has a variety of applications. First, the use of microwaves is very fruitful due to preceding development of powerful and low-consumption microwave sources. Second, the conversion of microwave energy into kinetic energy of ionized gas particles and then into their emission is experimentally found as highly efficient.

Basic principles and promising applications of the gas discharge excited by microwaves are reliably developed on the basis of general concepts of plasma physics. Currently, the most advanced application seems to be a powerful and efficient light source with high-quality spectrum (very close to natural solar spectrum, see [2]). This source is described in [3] in detail.

The source includes a magnetron with the resonator containing a sealed quartz flask filled by sulfur (and/or selenium) powder and low-pressure buffer gas (argon). The discharge excitation mechanisms are in general established in [4,5]. A microwave field induces initially a glow discharge in the buffer gas that has a rather low breakdown threshold at low initial pressure. Simultaneously, the field heats the sulfur pow-

der up to evaporation. In the formed (already high-pressure) gas mixture the microwave field transits sulfur atoms (and dimers etc.) into excited states. Both a channel of direct atomic and molecular absorption and a collisional mechanism act there. Finally, re-emission from the excited states produces the observed luminosity spectrum.

Energy balance of this new light source was experimentally measured in detail in [6,7]. However, even this data array (related to the developed stationary discharge) is insufficient to formulate a quantitative model. The theory is necessary not only for obvious optimization (the source is undoubtedly a promising prototype of a new class of devices), but also from the fundamental viewpoint. The processes controlling the microwave discharge efficiency in studied mixtures are characteristic both of low-pressure glow discharge and of high-pressure breakdown. This intermediate position complicates the problem (it is hard to point to all the parameters, small during the whole process). However, this expands a variety of possible applications.

The next evident step in solving the problem is to study the microwave discharge development. Contributing elementary processes have in general different establishment rates and intensities. Therefore, separating these processes in time would allow one to estimate at least relatively these parameters.

The present work is aimed to observe a nonstationary luminosity pattern of the discharge excited by microwaves in sulfur mixtures with noble gases. In this line of inquiry several discharge spectral types (changing each other in time) are distinguished.

2. Luminosity spectra of the microwave and high-frequency discharge in sulfur vapors with a noble gas buffer

The first measuring series was carried out using a sulfur + neon mixture at high microwave excitation power to maintain conditions close to those of a light source [2]. Neon was chosen as a buffer because its characteristic lines are substantially spaced from the sulfur lines.

A spherical quartz flask 30 mm in dia filled with neon at pressure of 4 Torr with 30 mg of powder sulfur is placed into a resonator of waveguide system excited by an M-155 magnetron. The emission power of the latter is 800 W at a frequency of 2.45 GHz. The spectral measurements are carried out using an SP40 spectrograph with the operating range of 3600 to 12500 Å and nonuniform sensitivity 70–10 % from 3600 to 11000 Å, respectively.

The outer flask surface temperature plays the role of kinetic time parameter. Its relation to real time is nonlinear, although unambiguous when heating the mixture by microwaves. This technique is employed because the time scales of luminosity are significantly different at various stages of the discharge development, characterized as smooth (of order 100 s) and leapwise (shorter than a tenth of second) variations.

The outer flask temperature is measured by a remote "Kelvin" pyrometer with a laser sight and an operating range from 50 to 1000°C. The error of temperature measuring does not exceed ±1°C under the experimental conditions when the thermal flux is picked off an area no less than 20 mm. The relative error depends on sizes of that area and on the measured emittance. At high temperatures this error reaches ±(3–5) %.

The first measurements have shown these powerful excitation conditions to allow recording only three final stages of luminosity development (described in Sec. 3). At the same time, there exist other fast-proceeding stages difficult for recording.

For detailed observation the second measuring series was carried out. The discharge was excited by a generator–inductor of lower frequency (100 MHz) and power (100 W) as compared to the magnetron.

In the third series, the gas mixture composition was changed. The discharge was excited in a cylindrical quartz flask 10 mm dia and 50 mm long, filled with argon at pressure of 20 Torr with 30 mg of sulfur powder.

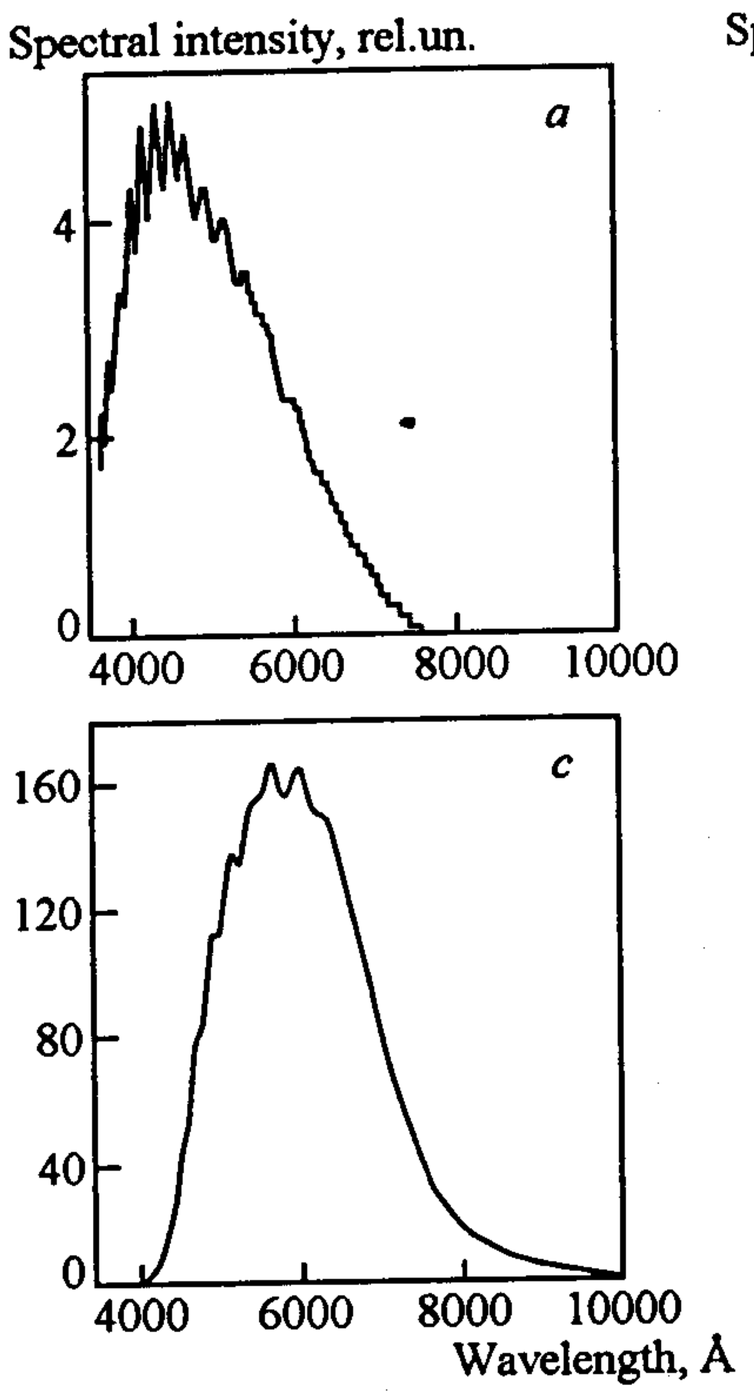

Figure 1. Luminosity spectra of the discharge excited by powerful (800 W) microwaves (2.45 GHz) in the sulfur + neon mixture. The flask outer temperature is 450 (*a*), 580 (*b*), and 640°C (*c*).

3. Spectra development in the microwave and high-frequency discharges

3.1. In the series with a powerful exciting microwave field sulfur + neon luminosity exhibits three stages (Fig. 1)

(i) Virtually from the time of microwaves switching on, a relatively low-intensity luminosity arises in the gas mixture. The spectral intensity maximum lies near 4500 Å (see Fig. 1*a*) and the spectrum extends (by half level) from 3700 to 5900 Å.

(ii) When the flask outer temperature reaches approximately 500°C, the maximum emission intensity increases seven–ninefold. The spectrum maximum simultaneously shifts to 4700 Å and the spectrum occupies the range from 3900 to 6500 Å (Fig. 1*b*).

(iii) The second leap at the surface temperature of about 600°C forms a quasisolar spectrum (Fig. 1*c*). The maximum intensity grows further three–fivefold. The spectrum blurred maximum lies now near 5800 Å and its halfwidth is 2400 Å.

3.2. Decreasing the excitation frequency and power retards the discharge development in the same mixture. Then a more detailed pattern of the luminosity spectrum change includes additional stages with lifetimes not exceeding a few fractions of second in the powerful field.

(i) A cold (below 35–40°C) flask yields a typical set of neon lines with the most intense line at 6400 Å (cf. [8]). The lamp emits red–orange light of high intensity (Fig. 2*a*).

(ii) The buffer neon discharge heats the flask above 45°C simultaneously producing an appreciable sulfur vapor concentration. The neon lines weaken relative to a drastically growing line 9200 Å of atomic sulfur (see Fig. 2*b*).

(iii) The latter line weakens from the time when the flask temperature reaches approximately 65°C. The visible band from 4500 to 6500 Å and sulfur line 4690 Å [8] simultaneously grow (see Fig. 2*c*). A blue halo appears, transiting into stable white–blue luminosity.

(iv) Simultaneously with the flask temperature growth to 120–130°C the white–blue luminosity abruptly attenuates. The spectrum

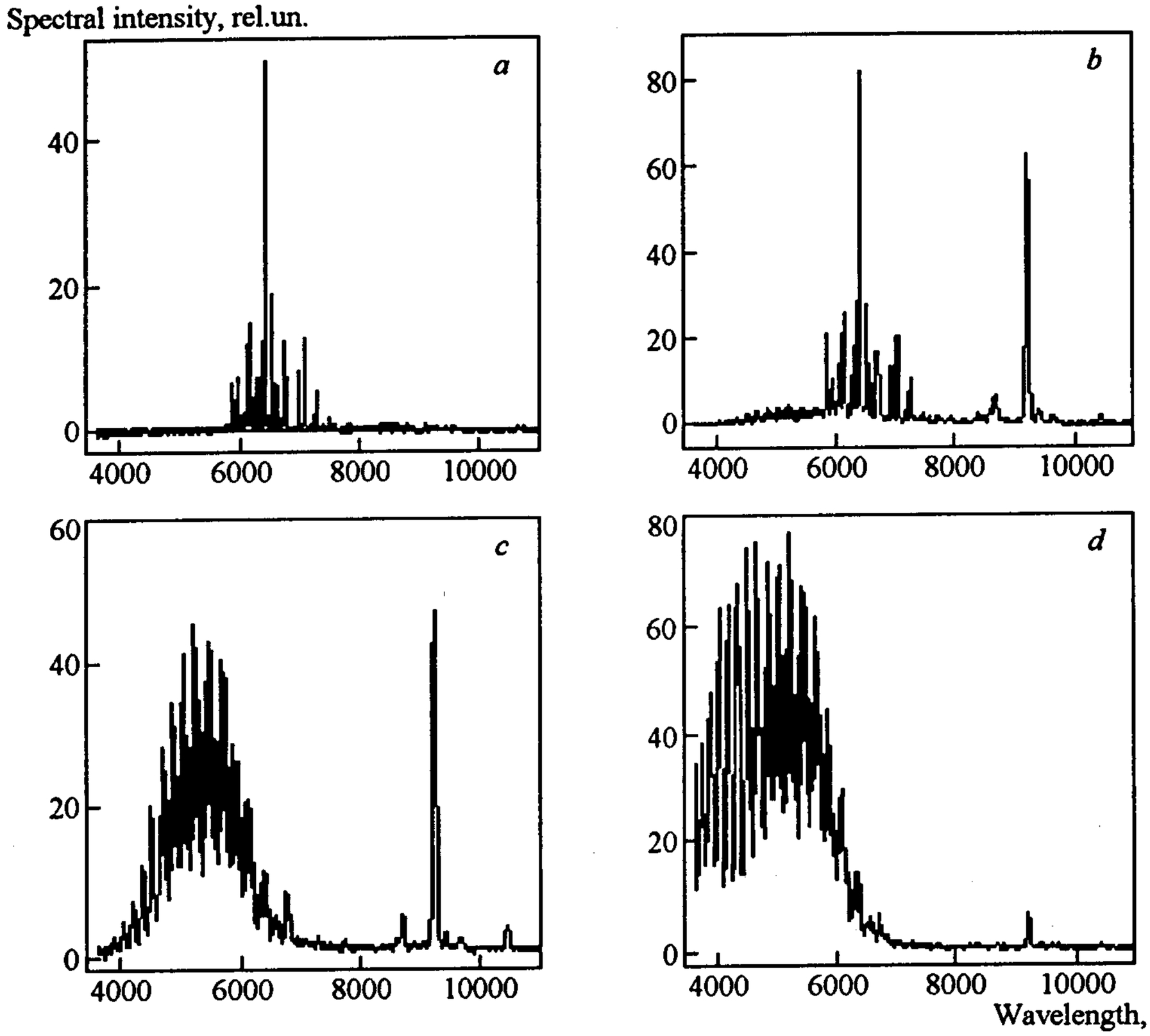

Figure 2. Luminosity spectra of the discharge in a high-frequency (100 MHz) field of relatively low (100 W) power in the sulfur + neon mixture. The flask outer temperature is 34 (*a*), 55 (*b*), 78 (*c*), and 145°C (*d*).

(Fig. 2*d*) shifts into blue and ultraviolet regions (a characteristic ozone smell is felt). The line 9200 Å virtually disappears, while the line 4690 Å remains noticeable against the molecular spectrum background.

(v) At a temperature of about 160°C the discharge is quenched. Its maintenance requires that the generator power be increased. The discharge quenching temperature depends on the power as well as the flask size. At constant power this temperature grows as the flask volume decreases.

3.3. The luminosity development in the sulfur + argon mixture excited by a low-intensity high-frequency field is basically the same as for the discharge with neon buffer. However, there are some informative distinctions.

(i) At the flask temperatures below 60°C, first of all the known argon lines 7630, 8100, and 8400 Å manifest themselves (cf. [8]). Simultaneously, an atomic spectrum of sulfur is also observed with the most intense line 9200 Å (Fig. 3*a*). This quantitative difference from the initial discharge stage in neon (where brightening the buffer and sulfur lines are separated in time) points to higher efficiency of argon as a buffer.

(ii) As temperature grows, the argon lines weaken, while molecular sulfur spectra become brighter in the ultraviolet. This indicates that argon promotes not only more efficient (than in neon) sulfur evaporation (early emission of the line 9200 Å), but also sulfur excitation in the short-wave spectral region. Only this process

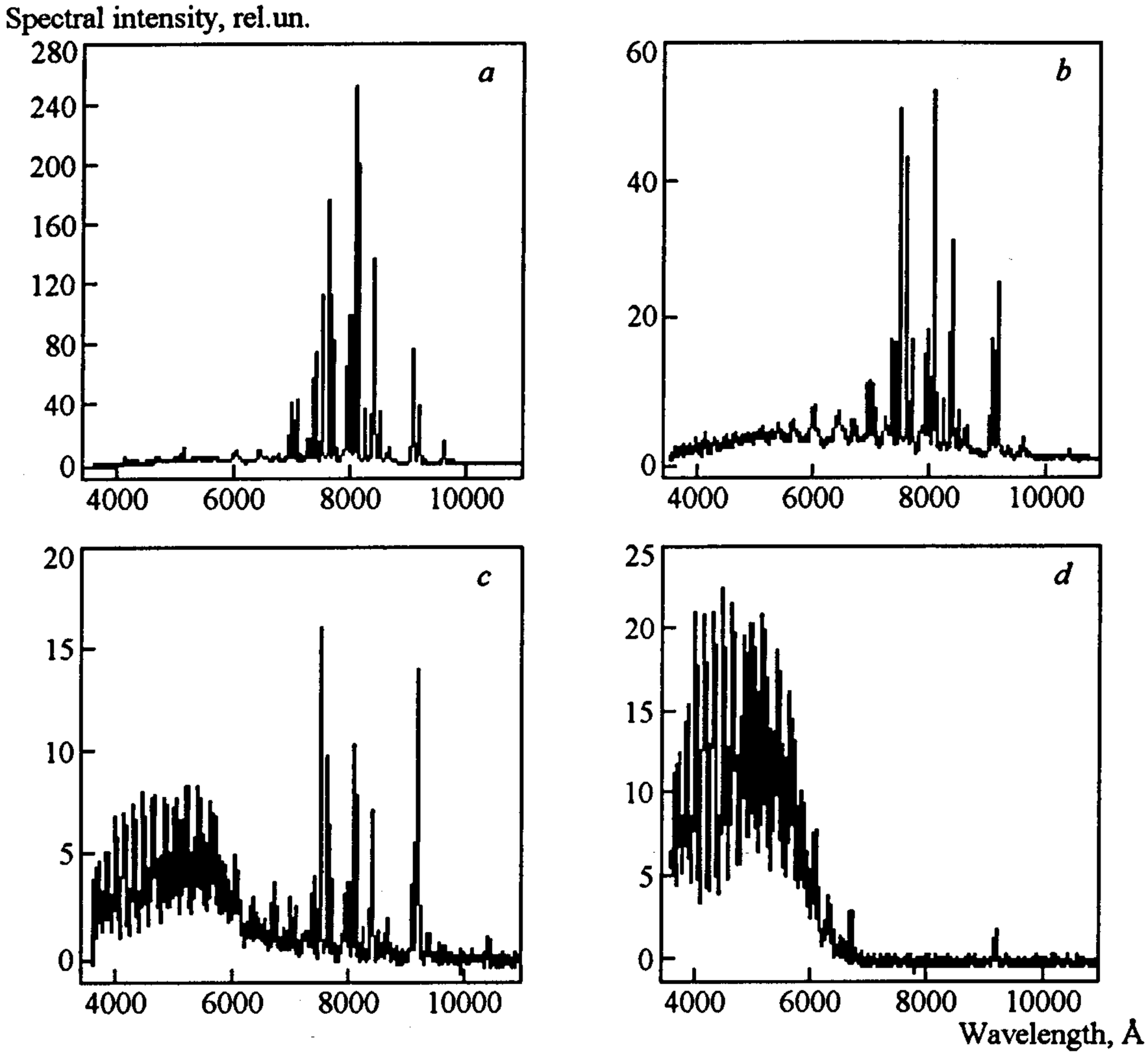

Figure 3. Luminosity spectra of the discharge in a high-frequency field of relatively low power in the sulfur + argon mixture. The flask outer surface temperature is 59 (*a*), 90 (*b*), 116 (*c*), and 180°C (*d*).

seems to be responsible for the sulfur quasisolar spectrum at high levels of microwave excitation (Fig. 3*b*).

(iii) At this stage the sulfur line 9200 Å becomes stronger than argon lines, that is the sulfur vapor concentration substantially increases. Simultaneously, the visible band intensity drastically grows due to the same cause (Fig. 3*c*).

(iv) At about 120°C the visible band intensity grows steeply, shifting to the dark blue, compared to the weak low-temperature line. The atomic line 9200 Å is weak there (see Fig. 3*d*).

4. Discussion

In our opinion the data of Secs. 2 and 3 substantially expand an array of experimental data necessary for constructing a quantitative model of the discharge excited by an electromagnetic field of frequency 0.1–10 GHz in the mixture of low-pressure buffer gas with an evaporated component having rich spectrum in the visible band.

Since the system is evidently complex, it seems unproductive to pose the problem based on exact kinetic equations. On the other hand, known data on the stationary discharge parameters are insufficient even to optimize the electromagnetic source by frequency, gas space geometry, and mixture composition. Even the problem of optimum frequency, scheduled in [9], was not posed up to now. The frequency choice in the works started by [2] is based only on low power consumption.

With our data, one can distinguish the energy transfer channels most efficient at each discharge stage and estimate the energy transfer rate and corresponding saturation level. Certainly, these data should be recalculated taking into account (see Sec. 2) the nonlinear time dependence of the flask temperatures. Then the corresponding theoretical problem can be formulated.

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