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PHOTOELECTRIC OZONOMETERS

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-USSR-

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PHOTOELECTRIC OZONOMETERS

[Following is a translation of an article by Sh. A. Bezverkhniy, A. L. Osherovich and S. F. Rodionov entitled "Fotoelektricheskiye ozonometry" (English version above), in Mezhdunarodnyy Geofizicheskiy God, Sbornik statey i materialov, Izadatel'stvo Leningradskogo Universiteta, Leningrad, 1960, pp. 81-104.]

The investigation of atmospheric ozone is one of the basic problems of atmospheric optics. This is especially true of the investigations made according to the program of the International Geophysical Year and being continued at the present time. This is explained by the role which ozone occupies in the physical processes of the stratosphere and its value as an effective means of study of the macrocirculation processes at great heights. The slow development of ozonometric observations corresponds neither to the importance of the problem nor to the general development of work on investigation of the upper layers of the atmosphere. About 100 ozonometric stations have been put in operation with the start of the Third IGY on all the continents, including Antarctica. Nine stations were organized in the Soviet Union in 1957, six of which have been included in the international exchange of ozonometric data.

The task of the Soviet stations is the measurement of the total ozone content of the atmosphere over a given station and obtaining data which will enable calculation of its vertical distribution. Various instruments are being used by us and abroad for this purpose, based on electrophotometric methods of measuring more or less broad segments of the spectrum of extraterrestrial light source.

In this paper we will consider the basic (from our point of view) systems of ozonometers and some new variants of the instruments which make it possible to proceed to a higher level of precision and, especially, of simplicity of measurement. In addition, certain questions of method which are of practical interest for modern ozonometry are considered in this article.

The principle of the indirect determination of ozone content in the atmosphere,

$$x = \int_0^\infty x_h dh$$

where x_h is the ozone content per unit of height h , consists in measuring the spectral intensity I_λ of radiation of any extraterrestrial light source with emission within the Hartley (I) (2150-3260Å), Huygens (II) (3200-3600Å), Shannon (III) (4500-6500Å) and the infrared band of O_3 absorption.

As is known,

$$I_\lambda = I_{0\lambda} \cdot 10^{-(\alpha x \mu + \beta m + \gamma m + \Delta M)}. \qquad (1)$$

Here $I_{0\lambda}$ is the intensity of monochromatic radiation at the boundary of the atmosphere; α is the decimal absorption coefficient of ozone; β is the relay dispersion coefficient; γ is the absorption coefficient of O_2, H_2O, CO_2 and other gases contained in the atmosphere; Δ is the coefficient of dispersion in aerosols; μ, m and M are the so-called relative masses of ozone, the atmosphere and aerosols respectively in the direction of the sun (moon or star).

Measurements in bands (II) and (III) have usually been made with spectral optical systems of double resolution. (The possibility has recently been shown of measuring the density of the ozone layer with thermoelectric devices [actinometers in the Shannon bands (1)]). Because of weak absorption within band (III) ($\alpha \simeq 10^{-2}$ cm^{-1}) and the dependence of the value of α on the temperature in bands (II), the long wave region (I) of the band, where α is in the order of 1 cm^{-1}, is usually used for measurement of I_λ. The values of μ, m and M are normalized so that they equal unity at the zenith distance $Z = 0$ of extraterrestrial light sources.

Measurements of ultraviolet radiation of extraterrestrial light sources (in particular, of the sun) in region (I) of the band encounters a number of difficulties caused, basically, by the following factors.

a) in the long wave region of the Hartley band the intensity of the measurable radiation falls rapidly with decrease in λ;

b) the intensity of radiation in the region 2850-3200 Å during measurements on the surface of the earth is sharply reduced (approximately by half) during transition from small to large zenith distances of the sun;

c) during measurement of a narrow segment of the spectrum with an optical system there is always danger of admixture of light of large wavelength dispersed in the system;

d) the relatively rapid motion of the sun (especially at the horizon) calls for rapid registration of change in radiation;

Taking into consideration that in the wavelengths corresponding to the edge of band (I) there is rapid increase in absorption (for example, $\alpha_{2808.0} / \alpha_{3037.5} = 16.4$) with decrease in λ and, on the other hand, there is an equally rapid decrease in intensity of radiation in the solar spectrum, it becomes evident that in using photographic photometry the exposure for this region of the spectrum should be calculated in some tens of minutes. The spectrophotometric method, in which the intensity I_λ is measured with different photoelectric indicators, is more complete and accurate for determining the value of x.

Photoelectric ozonometers can be provisionally classified into two groups: instruments of the observatory type (usually a complex system of double spectral resolution) and instruments of a broad network of stations (with a simpler optical system, for example, with a light filter).

The first group includes a spectrometer with photon counter [2], the Dobson spectrophotometer [3] and its improved variant [4, 5], as well as other spectrophotometers [6]. In the second group are instruments of the type described in [7-11], ozonometers [12-13] and an ozonograph [14].

At the present time the most widely distributed laboratory type of instrument is the Dobson spectrophotometer with a photomultiplier [4, 5]. The Dobson type of instrument has the following merits: a comparatively high monochromatization of the radiation measured; the possibility of measuring, with a single instrument, by the known method of "blinking" [15], the ratio of the intensities of two luminous fluxes.

The equipment is efficient if its light characteristics are linear and the sharpness of its amplitude characteristics in the region of small signals is great enough. Both in the Dobson instrument and in the variant of the instrument improved by two of the authors [4] a mechanical synchronous detector was used to narrow the band f the transmitted frequencies. In it the amplitude and light characteristics of the instrument were linear. When alternating current is present at the point of observation of the network it is efficient to strengthen the signal of the photomultiplier with a selective amplifier (a double "T" filter on RC in the negative feedback) and use an electronic synchronous detector. The power supply of the synchronous motor for the light modulator and synchronous detector is from a single generator (for example, in the simplest case from an alternating current network). A block diagram of such an arrangement is given in Figure 1. (M. M. Sushinskiy used a similar amplifying instrument in investigating the combined dispersion of light [16] and one of the authors [17] in investigating the luminescence of the night sky in the region of 1-3.4 mc.)

Certain shortcomings are characteristic of the Dobson type of spectrophotometer:

a) an optical quartz wedge with a given logarithmic principle of weakening is used in the instrument to weaken one of the luminous fluxes. Making such a wedge presents considerable difficulty. In addition, the presence of the wedge itself hampers the possibility of automatic recording of the results of observations of direct solar radiation,

b) in avoiding the parasitic effects of dispersion of light in the optics, high-quality quartz must be used in the manufacture of the spectrophotometer, and this is not always available.

It is necessary to recall also the comparatively large cost of the Dobson spectrophotometer. It therefore became an urgent task to develop ozonometers of both the observatory type and instruments suitable for a broad

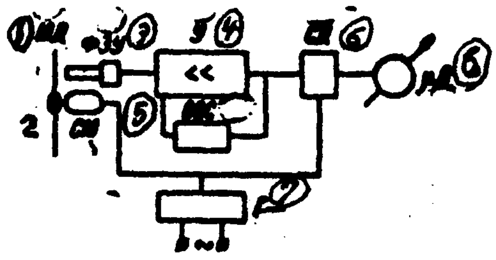

Fig. 1. Block diagram of the photoelectric part of the Dobson spectrophotometer with photomultiplier, selective amplifier and electronic synchronous detector.
1) Modulation disk; 2) Synchronous motor; 3) Photomultiplier; 4) Amplifier; 5) Negative feedback; 6) Synchronous detector; 7) Generator; 8) Microammeter.

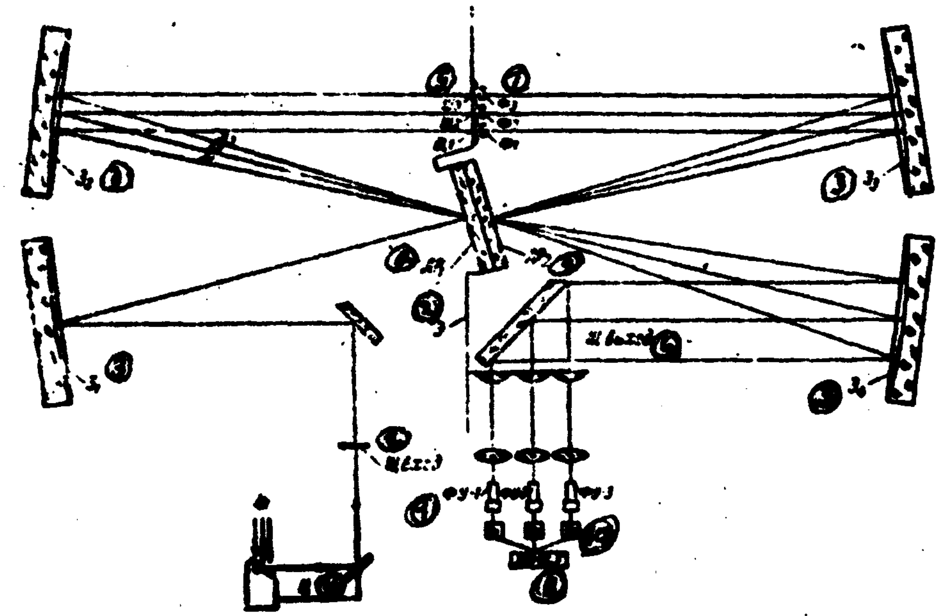

Fig. 2. Optical and principal system of ozonograph with diffraction gratings. 1) coelostat; 2) input slit; 3) spherical mirrors; 4) diffraction gratings; 5) center slits; 6) discharge slits; 7) light filters; 8) screen; 9) photomultipliers; 10) amplifiers; 11) three-point automatic recorder.

ozonometric network.

The following requirements should be set forth for a laboratory type of ozonometer:

1) automatic pointing at the light source and recording of the results of observations;

2) the possibility of narrowing the spectral band of measured radiation to 5-6 A, taking into consideration the complex structure of the Hartley band system;

3) simplicity of design and, if possible, the absence of optical methods of compensation.

One of the authors (A. L. Osherovich) has suggested, and jointly with B. A. Kiselev has accomplished the design of an ozonograph which satisfies these requirements. The instrument uses a system of a double monochromator with diffraction gratings according to B. A. Kiselev [8]. Just as in the Dobson spectrophotometer, the optical system separates three segments of the spectrum with wavelengths $\lambda_1 = 3100$, $\lambda_2 = 3300$ and $\lambda_3 = 4358$ Å. The instrument is designed for diffraction gratings with 600 lines per mm (with a lined space 62 X 51 mm). The linear dispersion on the discharge slit of the instrument for the operating sections of the spectrum is as follows:

At $\lambda_1 = 3100$ Å, $d\lambda/dl = 12.3$ Å/mm; order I;

At $\lambda_2 = 3300$ Å, $d\lambda/dl = 7.8$ Å/mm; order II;

At λ_3 = 4358 Å, $d\lambda/dl$ = 7.3 Å/mm; order II;

There is provision in the instrument for mixing the operating segments by spectrum at ± 50 Å. The focal distance of the collimator mirror is 300 mm.

The image of the sun is projected on the input slit of the spectrophotometer by means of a coelostat. A thick frosted sheet of quartz is placed in front of the slit to assure more uniform illumination.

Various automatic guiding devices can be used for observation of the moon and stars.

In order to reduce the effect of scattered and reflected light within the instrument the first phase of the spectral resolution is separated from the second by an opaque screen and the central slits are shielded by corresponding light filters.

The intensity of the separable monochromator of the three luminous fluxes is measured by three photomultipliers. The photocurrents of the multipliers are amplified by direct current amplifiers [19, 20] and recorded by a three-point recorder, type EPP-09. Switching in the output of two amplifiers (out of three) on a somewhat modified single-current EPP-09 recorder permits registering the relationship of the intensities of the two luminous fluxes [21]. In order not to depart in doing this from a linear segment of the range of the measured relationships, calibrating devices are installed in the grid circuits of the photocurrent boosters.

Use can also be made of a two-filament photoelectric device with modulation of the luminous fluxes [22] for measurement of the relationship of the intensities of the luminous fluxes. In our case the modulator is set in front of the input slit of the ozonograph.

Figure 2 shows the optical scheme and principle of an ozonograph with diffraction gratings. (The development of working drawings of the instrument was done by designer I. G. Brusilovskiy. The instrument was built by the experimental workshops of the Scientific Research Institute of Physics of Leningrad State University.) A photograph of such an ozonograph is presented in Figure 3. Without dwelling on other attempts to create a simple and inexpensive ozonometer we will examine the OFET-3 ozonograph (with light filters) which we have developed [14]. (The development of working drawings of the instrument was done by designer A. Gol'dfel'd. A series of OFET-3 instruments has been made by the experimental workshops of the Scientific Research Institute of Physics of Leningrad State University.) Instruments of type OFET-3 were supplied to the first network of ozonometric stations of the USSR, working according to the IGY program.

The OFET-3 is intended for automatic registration of ultraviolet radiation of the sun, sky and moon, data about which is needed for determination of the reduced thickness of the atmospheric ozone.

The parallactic arrangement of the instrument provides precise guiding of the receiving part behind the sun without leading the image of the disk beyond the limits of the solid angle of the instrument. The OFET-3 consists (Figure 4) of three antimony-cesium photoelements (STsV-6 or STsV-9), three independent direct current amplifiers for 6F5 tubes and a three-point electronic potentiometer of type EPP-09, shunted by a resistance of 100 ohms. The electrical circuit of the instrument is given in Figure 5.

The microammeter in the output circuit of the amplifiers can be used as a voltmeter for control of the constancy of the filament and anode voltage of the amplifiers and the operating voltage of the photoelements.

The amplification factor can be changed according to the power within the limits of from $\cong 10^2 \cong 10^4$ times.

Table 1 presents the values of the amplification factors of the amplifiers of Instrument No. 3, installed

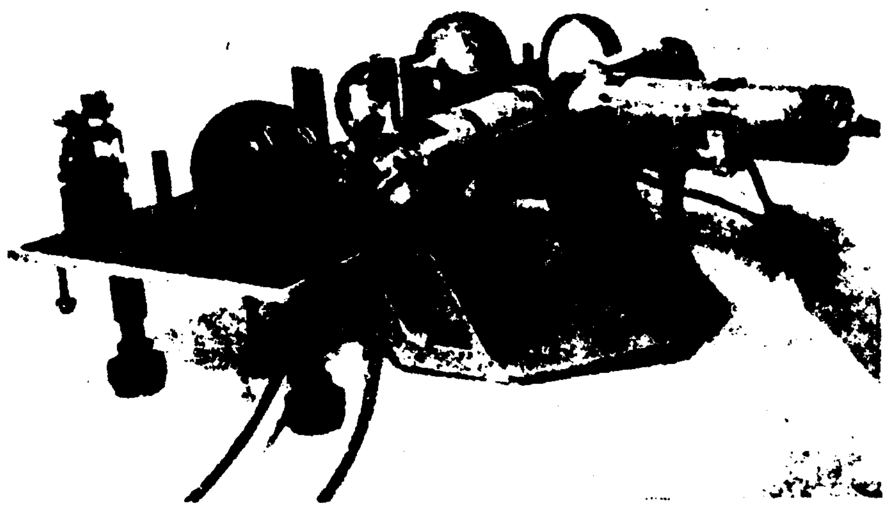

Fig. 3. Ozonograph with diffraction gratings.

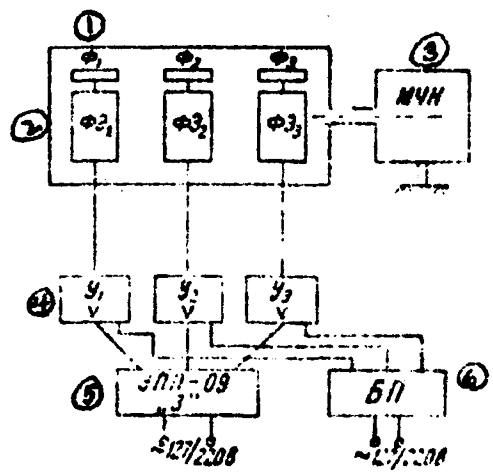

Fig. 4. Block diagram of OFET-3 ozonograph with light filter. 1) light filters; 2) photoelements; 3) power clock mechanism of parallactic equipment; 4) photocurrent amplifiers; 5) three-point automatic recording instrument; 6) power supply block of ozonometer.

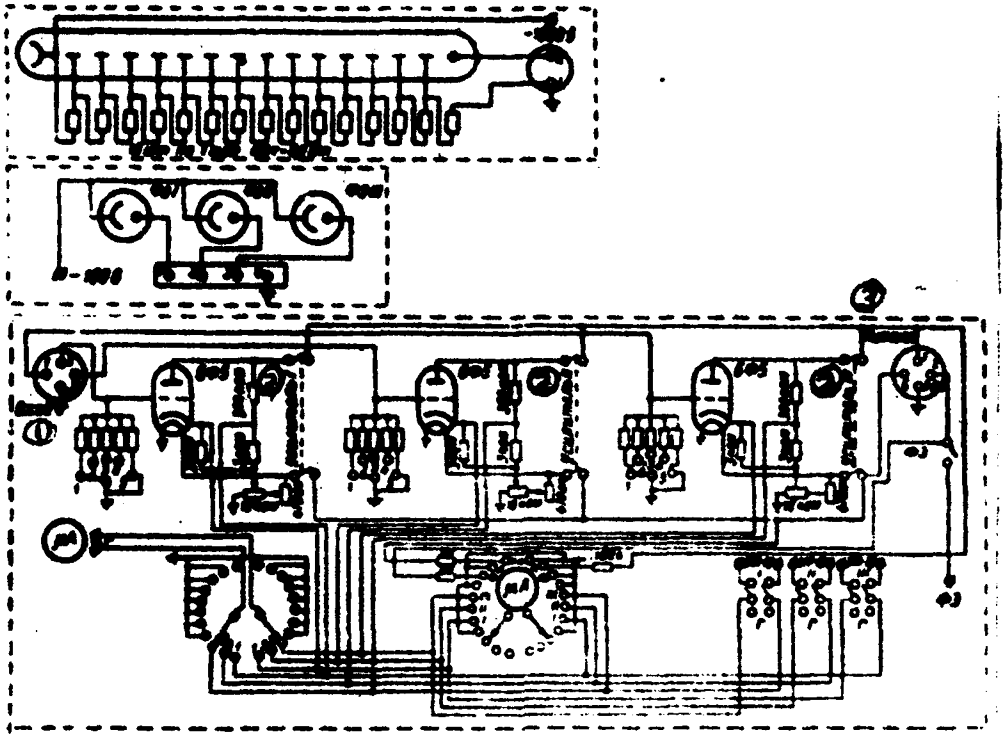

Fig. 5. Electrical circuit of OФЕТ-3 ozonograph.
1) input 2) amplifier 3) power supply

at the Abastuman laboratory, for various values of input resistance in the amplifier tube grid circuit, obtained by us at T = + 18°C. The power supply of the instrument is standard: U_{anode} = 160 V, U_{fil} = 6.3 V and U_{F-E} = 60 to 90 V.

№ канала (2)	(1) Величины входного сопротивления (в мом)				
	0,84	8,25	20,9	41,8	82,5
I	$1{,}63 \cdot 10^{2}$	$1{,}38 \cdot 10^{3}$	$4{,}92 \cdot 10^{3}$	$8{,}73 \cdot 10^{3}$	$1{,}55 \cdot 10^{4}$
II	$1{,}67 \cdot 10^{2}$	$1{,}67 \cdot 10^{3}$	$5{,}25 \cdot 10^{3}$	$7{,}94 \cdot 10^{3}$	$1{,}58 \cdot 10^{4}$
III	$1{,}47 \cdot 10^{2}$	$1{,}52 \cdot 10^{3}$	$5{,}55 \cdot 10^{3}$	$7{,}65 \cdot 10^{3}$	$1{,}53 \cdot 10^{4}$

Table 1. Amplification coefficients of the amplifiers of No. 3 OFET-3. 1) Values of input resistance (in milliohms; 2) Channel No.

For expansion of the dynamic range in the instrument it is possible to have a neutral weakening of the measured light by means of an oxidized or blackened brass grating with a cell area of ~ 0.66 mm^2. The maximum amplification of the photocurrent by $\sim 10^4$ times is sufficient both for a daytime device with photoelements and for a lunar with a photomultiplier.

The spectral characteristics of the radiation receivers are given in Figure 6. The ozonograph was designed in such a way that the radiation receiver is apart from the amplifier. The block of photoelements, along with the so-called "arc of declination" to which it was firmly attached, was seated on the axis of a power clock mechanism. Miniature MChN clocks (from the Gidrometpribor" factory at Riga), improved at the G. Ya Aksel'rod Institute of Hydrometeorological Instrument Building, provide a precision in guiding of 0.5' of arc per day at an angle of coverage of the instrument of 2-2.5°. The clock mechanism here weighs up to 2.5 kg. The precision of installation of the block of photoelements according to the declination of the sun on a given day of observation is about 40" of arc.

Automatic closing of the photoshutters for 5-10 minutes during a set period of time (1.5-2.0 hours) for registration of zero readings can be accomplished by means of a special circuit breaker [25], using the same clock device.

A photograph of the parallactic arrangement of the OFET-3 is shown as Figure 7. Under field conditions we need a block of anode batteries and six-volt battery with a capacity of 60-100 a/hr. When there is a supply of alternating current at the point of observation, a rectifier -ith electronic stabilization (types VS-11, VS-13 or VS-16) can be used for the power supply of the instrument.

We have already pointed out that the output signal was registered with a three-point electronic potentiometer, type EPP-09 (10 mV scale; time of passage of the carriage, 2.5 sec.). The small inertia and the stability of the basic parameters of EPP-09 provide a smooth registration and clear reproducibility of results of

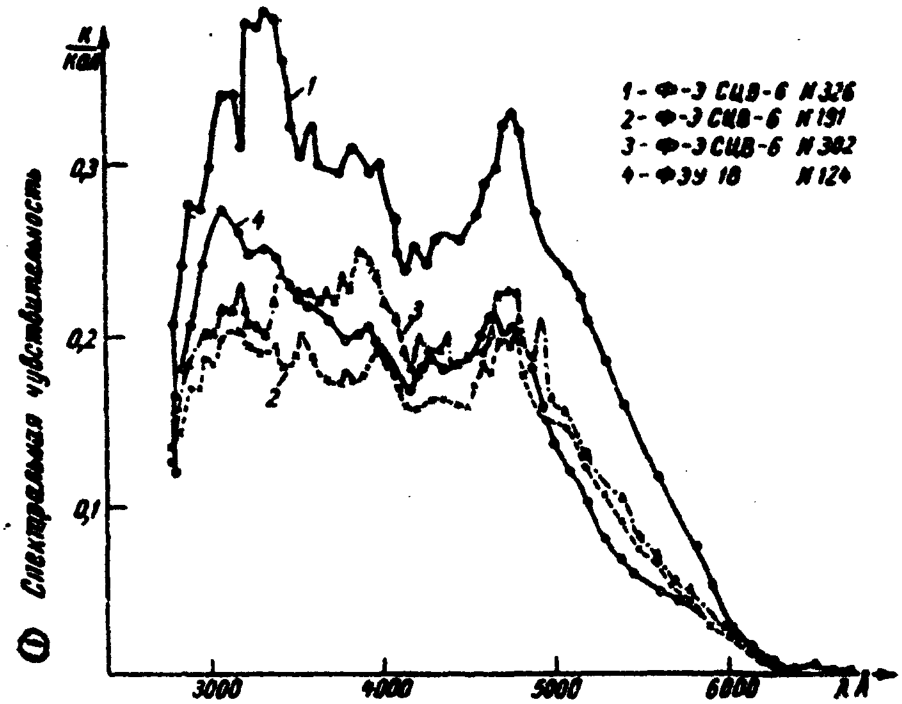

Fig. 6. Spectral characteristics of the cathodes of antimony-cesium photoelements STsV-6 (STsV-9) and the FEU-18 photomultiplier.
1) Spectral sensitivity.

Fig. 7. Parallactic (solar) arrangement of FET-3 ozonograph.

observations. Figure 8 presents a photograph of an EPP-09 strip with a registration of the intensity of ultraviolet radiation of the sun at Alma-Ata at ten-second intervals of time for $\lambda_1 = 3140\text{Å}$, $\lambda_2 = 3600\text{Å}$ and $\lambda_3 = 4100\text{Å}$. This frequency of registration makes it possible to average out with confidence the results of observations in order to calculate the reduced density of the ozone and investigate in detail the structure of variations in ozone in the course of a day. The results of processing the EPP-09 strip of Figure 8 are presented in Figure 9.

Just as in an ozonograph with diffraction gratings, a standard light source (tungsten lamp with an ultra-violet-transmitting bulb) should be used in work with the OFET-3 for controlling the constancy of its parameters.

Control measurements have been made in connection with the effect of temperature on the spectral sensitivity of antimony-cesium photocathodes [26], the filtration of light filters [27], the amount of resistance in the amplifier tube grid circuit, etc. Our investigations show that when antimony-cesium cathodes are cooled to -71° they change their absolute spectral sensitivity in the region of 3000-3300 Å by 1.5-2.0%. The temperature coefficient of the grid resistances should be determined

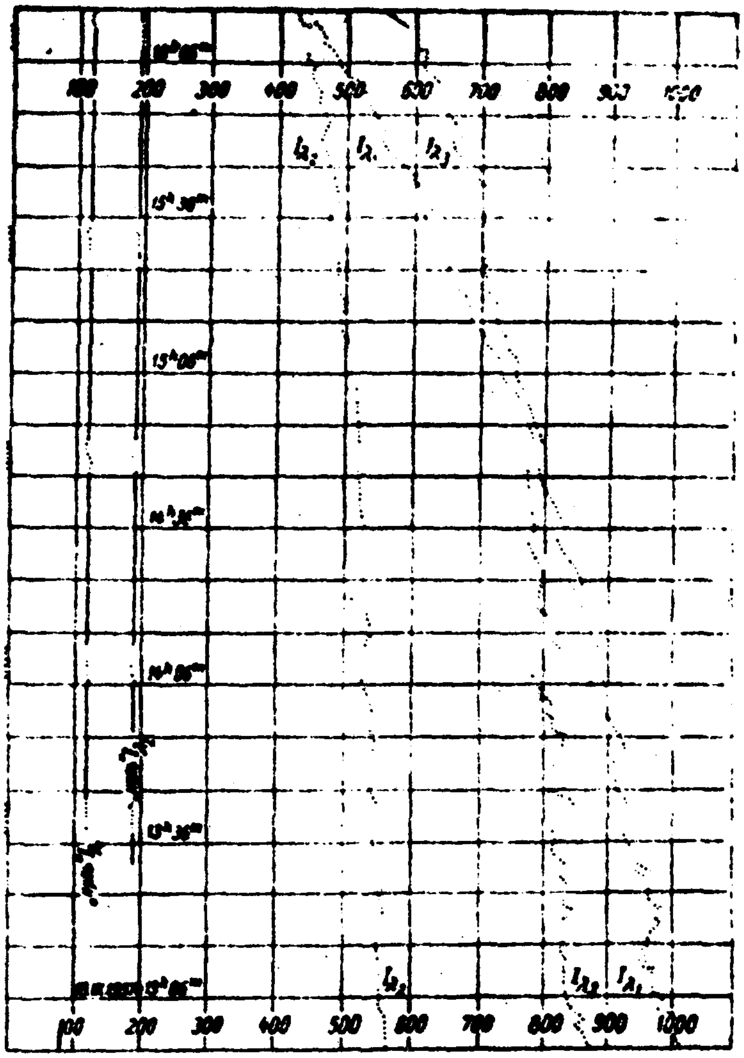

Fig. 8. Specimen of registration of the results of measurement of the ultraviolet radiation of the sun 18 September 1957 at Alma-Ata.

I_{λ_1}, I_{λ_2} and I_{λ_3} are the intensities of radiation in relative units using light filters ϕ_1, ϕ_2 and ϕ_3 respectively.

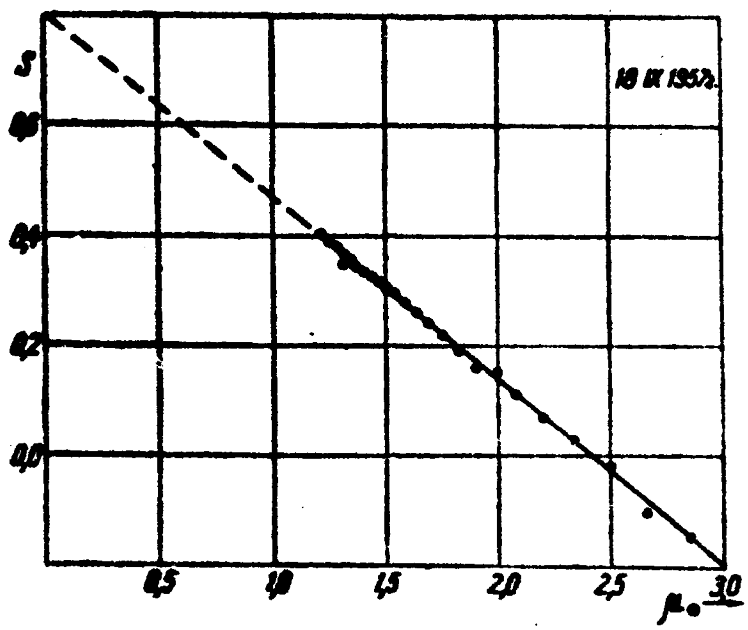

Fig. 9. Dependence of $S = \log \frac{I_{\lambda_1}}{I_{\lambda_2}} = \Phi(\mu)$,

calculated according to the data of Figure 8.

for each instrument separately.

The exponential law (1) is fulfilled with great exactness if:

1) the measurable radiation I_λ does not include emission of the absorbing medium in the same wavelength λ;

2) the life period of the excited molecules is not great;

3) measurement is made of practically monochromatic light or light limited to a small enough spectral interval, within which it is possible to assume the decimal absorption coefficient of ozone, the spectral intensity of the light source and the parameters of the measuring system to be adequately constant.

Investigations by S. I. Vavilov [28] have shown that the Bouguer-Lambert law withstands the most vigorous experimental tests. Apart from the conditions indicated this law has no limitations.

According to existing ideas, atmospheric ozone in the region of the Hartley band does not give fluorescence and absorption of solar radiation in this region leads to immediate dissociation of the ozone molecules. But serious difficulties are set in applying (1) in ozonometry by the need to measure heterochromous emission, especially in the making photographic measurement of solar light with the light filters which make up an important part of the OFET-3. It would be useless to seek precise proof by an analytical method of the applicability of the Bouguer-Lambert law for the type of instrument under consideration. It can be examined graphically, however; for this purpose we present (1) in logarithmic form:

$$\log I_\lambda = \log I_{0\lambda} - A, \qquad (2)$$

where A is the exponent of (1). It follows from (2) that obtaining a straight line on the coordinates ($\log I_\lambda$, μ) is a necessary and sufficient criterion of the applicability of the method of (1) to ozonometry. The problem has a limitation: linear dependence can be disturbed at large $z_\odot$ when the Forbes effect occurs (for mixed rays), or the effect of anomalous atmospheric transparency for narrow spectral intervals [29, 30], and also at other values of $z_\odot$ depending on the corresponding weather conditions. Work has been done with the ozonometer under various climatic conditions [31]. Measurements have revealed excellent reproducibility of the linear analysis independently of the meteorological situation (but at corresponding atmospheric-optical conditions), and this is clearly visible in Figure 10. The corresponding dependence for the instrument with relative units

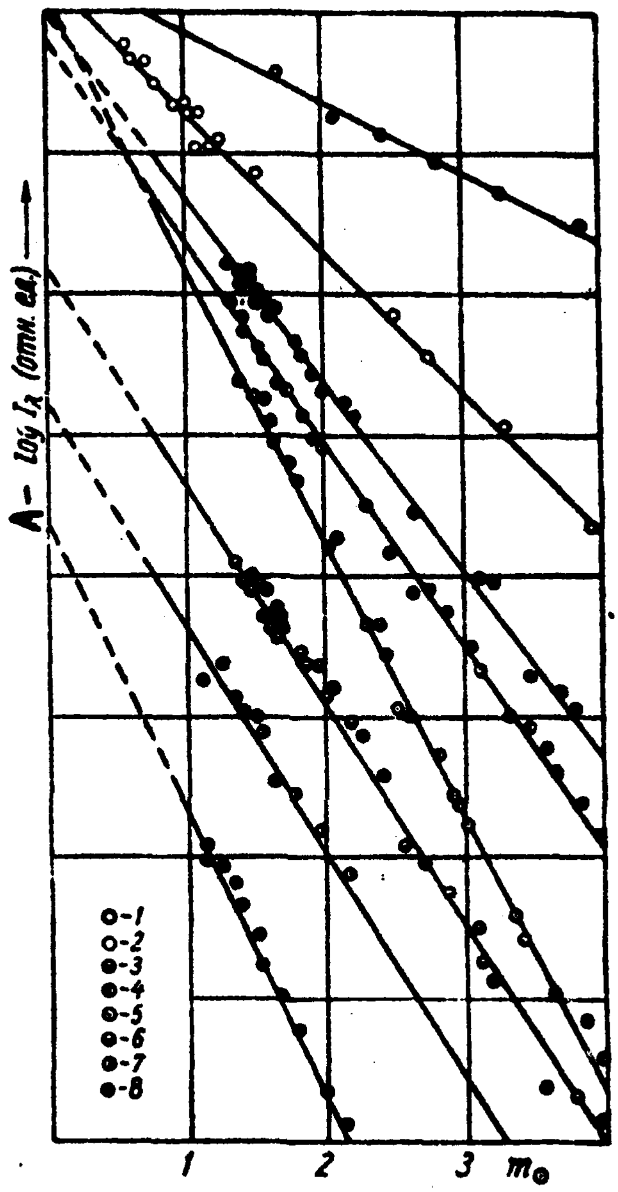

Fig. 10. Linear analysis of observations.

A – log I_λ (rel. units)

1) El'brus, λ = 4000 Å; 2) El'brus, λ = 3200 Å; 3) Chinli, λ = 3600 Å; 4) Tashkent, λ = 3600 Å; 5) Tashkent, λ = = 3200 Å; 6) Chinli, λ = 3200 Å; 7) Alma-Ata, λ = 3300 Å; 8) Alma-Ata, λ = 3200 Å.

FEU-18 is given in Figure 11. The observations are evidence of satisfactory stability of the basic operating characteristics of the instrument, that is, of the value of $I_{\lambda_1}/I_{\lambda_2}$. It must be kept in mind, however, that calculation of the total ozone content in the atmosphere according to (1) in the form of

$$x = A_1 \frac{\log I_\lambda - \log I_{0\lambda} - m(\beta_\lambda + \gamma_\lambda) - M\Delta}{\mu\alpha_\lambda} \qquad (3)$$

can involve a large error, in view of the extreme complexity of determining the value of Δ from direct measurements. In general the Bouguer straight line is only an indicator of the average atmospheric transparency during the period of observation. Therefore, in determining x we have applied a two wavelength method when

$$x = A_2 \times \frac{S_0 - S - m(\beta_1 - \beta_2) - M(\Delta_1 - \Delta_2)}{\mu(\alpha_1 - \alpha_2)}, \qquad (4)$$

or a three wavelength method when

$$x = A_3 \times \frac{S_0 - S + L - L_0}{\mu(\alpha_1 - \alpha_3)} - \frac{m(\beta_1 - \beta_3) - M(\Delta_1 - \Delta_3)}{\mu(\alpha_1 - \alpha_3)}. \qquad (5)$$

(In deriving formulas (4) and (5) it was assumed that $\gamma_\lambda = 0$, since in the 2900-4500 Å region of the spectrum

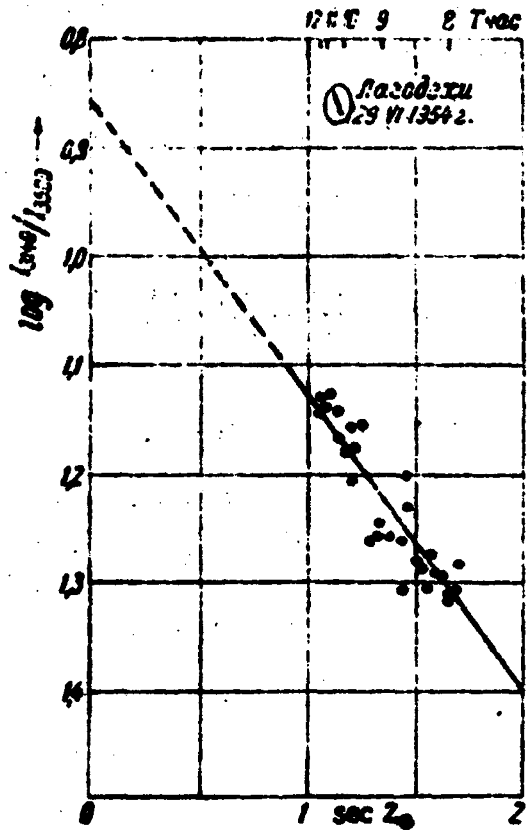

Fig. 11. Dependence of $\log \frac{I_{\lambda_1}}{I_{\lambda_2}} = Z_\odot$ for the FEU-18 photomultiplier.

1)(Lagodekhi, Georgian SSR, 29 June 1954) the basic constituents of air-oxygen and nitrogen are free of absorption, as are other atmospheric gases). Here and henceforth

$$S = \log \frac{I_{\lambda_1}}{I_{\lambda_2}} \qquad L = \log \frac{I_{\lambda_3}}{I_{\lambda_2}}$$

$$S_o = \log \frac{I_{o\lambda_1}}{I_{o\lambda_2}} \qquad L_o = \log \frac{I_{o\lambda_3}}{I_{o\lambda_2}}$$

The "masses" in the usual symbols have the expression:

$$m = \frac{1}{H_0}\int_R^\infty \rho_h dr / \rho_0 \sqrt{1-(Rn_0/rn_h)^2 \sin^2\varepsilon}\,; \qquad (6)$$

$$\mu = \frac{1}{x}\int_R^\infty x'_h dr / \sqrt{1-(Rn_0/rn_h)^2 \sin^2\varepsilon}\,, \qquad (7)$$

where x'_h is the ozone concentration in cm/km; $\varepsilon = z_\odot - \omega$; ω is the angle of astronomical refraction.

By assuming in the given spectral interval the presence of only normal dispersion one can consider the masses of (6) and (7) not to be a function of wavelength. It is therefore possible to use prepared tables to determine m (see [32] to $z_\odot \leq 86^\circ$ and [33] to $z_\odot = 89^\circ$), which have been compiled according to the argument ε. To determine the density of the ozone by the three wavelength method it is expedient to use a modified formula (5)

$$x = A_4 \frac{S_0 - S - K(s - a_0)}{\mu\,[a_1 - a_2(1 + K)]} - \frac{\mu\,[(\lambda_1 - \lambda_2(1 + K) + K\lambda_3]}{\mu\,[a_1 - a_2(1 + K)]}. \qquad (5')$$

Here A_1, A_2, A_3 and A_4 are experimentally determinable coefficients of the "linking" the results of OFET-3 measurements to the indications of a precision ozonometric instrument, and K is a parameter of the instrument which will be explained later.

One of the advantages of formula (5') is that when it is used there is no need to consider changes in the amount of relay dispersion between measurements. The molecular dispersion of light is considered constant for a given instrument with a value

$$K = \frac{(n_{\lambda_1} - 1)^2 \lambda_1^{-4} - (n_{\lambda_2} - 1)^2 \lambda_2^{-4}}{(n_{\lambda_1} - 1)^2 \lambda_2^{-4} - (n_{\lambda_3} - 1)^2 \lambda_3^{-4}},$$

where n is the refractive index of air for wavelengths λ_1, λ_2 and λ_3; λ_1, λ_2 and λ_3 are the effective values of the wavelengths of the spectral segments separable by any optical ozonometer. These values are determined from the expression.

$$\lambda_{eff} = \frac{\int_{\lambda_1}^{\lambda_2} \Phi(\lambda)\,\lambda\, d\lambda}{\int_{\lambda_1}^{\lambda_2} \Phi(\lambda)\, d\lambda}.$$

In this $\phi(\lambda)$ is the effective spectral sensitivity of the instrument (see below). For ozonometer No. 9 (Alma-Ata) K = 1.785 [34]. Calculation of the values of $z_{\odot}$ in measurements with the OFET-3 instrument is done according to time in the usual form by means of the equation

$$\cos z_{\odot} = \sin \varphi \sin \delta + \cos \varphi \cos \delta \cos t,$$

where ϕ is the latitude of the place of observation, δ is the declination of the sun, t the hour angle of the sun. The values of $z_{\odot}$ must be corrected for the value of ω (see above).

Determining x is facilitated only when $\Delta_1 = \Delta_2$ can be assumed, or for the three wavelength method

$$\Delta_1 = \Delta_2 = \Delta_3, \tag{8}$$

then

$$x = \frac{S_0 - S - m(\beta_1 - \beta_2)}{\mu(\alpha_1 - \alpha_2)}. \tag{9}$$

Let us note that the ratio Δ_1/Δ_2 does not depend on the absolute value of the density of the aerosol layer. Thus the measurements made at Alma-Ata [35] revealed in a number of cases the possibility of approximating x by expression (9); meanwhile 60% of the atmosphere over Alma-Ata consists of dry aerosols. On the contrary, under high-mountain conditions, where condition (8) is usually considered observable, investigations [37] have shown deviations from (8), namely $\Delta_1 < \Delta_2$, where $\lambda_1 < \lambda_2$. Calculations according to (9), that is, when the layer of selectively absorbing aerosols is not taken into consideration, must lead to incorrect results. It is sufficient to observe at $\Delta_{3200} = 0.2$ cm^{-1} to obtain an error (it is not less than $\Delta/\alpha x$ at $x = 0.22$ cm) of 21%. The method of the effect of anomalous atmospheric [40] transparency was utilized to evaluate the applicability of condition (8); with this method one can select observations suitable for calculation of x without taking aerosol constituents into consideration. The anomalous atmospheric transparency effect consists in that in the spectral region 2950-3200 Å at large zenith distances of the sun an increase in relative transparency of the atmosphere is observed for short wavelengths. Analysis of (4) shows that, in the case of anomalous transparency the value $n<0$ in the expression $\Delta \sim \lambda^{-n}$. If $(\Delta_{3250} - \Delta_{3125})\alpha_{\lambda\, mean} = 0.166$, $x = 0.22$ cm and $\alpha_{3125} = 1\ cm^{-1}$, the relative error reaches 52%. In the same cases, when the extinction for aerosols depends little on λ (for example, according to the data [38] for Delhi $\Delta_{3300} - \Delta_{4450} = 10^{-3}$), the relative error in determining x does not exceed 5%.

Unfortunately, in a number of works on this question the dispersion is assumed to be neutral in aerosols, which is not always true. Mention should be made of a number of attempts at a more precise (quantitative) calculation of the aerosol constituents (both constant and variable) in ozonometric measurements. Gowan and Leppars [39] suggest combining the correction for aerosol absorption $\frac{\Delta_1 - \Delta_2}{\alpha_{\lambda 1} - \alpha_{\lambda 2}}$ with the distance of horizontal visibility (see Table 2).

Table 2 Correction for aerosol weakening

Distance of horizontal visibility (in km)	$\frac{\Delta_1 - \Delta_2}{\alpha_{\lambda_1} - \alpha_{\lambda_2}}$
19.3	0
9-6-17.7	0.005
4.8-'8.0	0.015
<4.8	0.028

R. Karandikar [38] also combines the correction for aerosol absorption with the distance of horizontal visibility. One of the authors [40] has approached this very difficult problem in a somewhat different way. Applying objective photometric methods of measuring atmospheric transparency in the 3100-3300 Å region of the spectrum, he obtained absolute values of Δ. A very approximate estimate of the aerosol constituents was given later [41], using the method explained in [40].

Apart from the influence of the Δ coefficient the precision of calculation of x according to (4) and (5) is determined by the following values: the light dispersion within the instrument and the so-called "filter error"; the latter is brought about by change in α within the effective band of sensitivity of the photometer.

Our calculations show that a single dispersion of light within the solid angle of the OFET-3 for mean heights of the sun gives a correction not exceeding 0.3% of the value of x. It has been found experimentally [40] that at $Z_{\odot} = 75^{o}$ the intensity of light dispersion (λ = 3260 Å) in direct proximity to the sun ($-50' \leq \phi_1 \leq + 50'$; $\phi_1 = 0$ corresponds to the center of the disk) is 2.5 orders less than the direct light of the sun (El'brus). For Alma-Ata (with great dustiness) the maximum ratio of brightness of the sky near the sun and brightness of the disk reaches not more than 4-4.5% [35] (see also Optik, [2, 4] 1947). Thus the light dispersion within the solid angle of the OFET-3 (3-4°) can be neglected in calculating the value of x.

A more precise processing of the observations made with any ozonometric instrument, and particularly with the OFET-3, requires taking into consideration the effect of the temperature on the absorption coefficient of ozone. The basic difficulty in doing this is in correctly calculating the dependence of α_{λ} on temperature and choosing the calculated temperature itself. At the present time the most reliable laboratory data appear to be those of Vigoroux [42], based on investigation of the absorption coefficient of ozone at various temperatures.

The temperature of the ozone layer, which differs, generally speaking, from the temperature of the stratosphere, depends, apart from other factors, in the concentration of the gas. It has been shown [43, 44, 45] that in the middle latitudes the temperature of ozone fluctuates within the limits of -25 to -50°C. At the same time the annual course of the average temperature of the stratosphere in the region of maximum concentration of ozone (20-30 km) and at heights (12-18 km) which evidently are responsible for nonperiodic changes in the density of the ozone [46] is such that in the summer it varies from -65°C at a height of 13-15 km to -40°C at 30 km; in winter the temperature in the 15-30 km layer is approximately the same (about -55° C) [47]. An incorrect selection of the value of α_λ, all other conditions being equal, leads to an error in the order of 10^{-3} cm in the temperature range from -40 to -60°C and in the order of 10^{-2} cm in the density of the ozone within the limits of + 18 to -60°C [34]. (The tables of Ny and Chin [48] were compiled for t = 18°C. They have ordinarily been used by them for calculations of x. The estimates of error are given for the values of α at extreme temperatures, taken from Vigroux, after comparison with the calculation using α at t = 18°C).

Recent measurements in West Germany [49] testify that the mean temperature of the layer of ozone is closer in all to the temperature of air at a height of 30 km. It appears that the error in the calculation of x in the final processing of the IGY materials can be reduced considerably if values of α, corresponding to a temperature of -44° C and given in [42], are used.

We have already pointed out that in ozonometers destined for a large network of stations the complex optical system can be replaced by a set of light filters. The advantage of light filters is the possibility of excluding long wavelength dispersed light, comparative cheapness and adequate simplicity in handling.

Light filters for ozonometers should satisfy the following requirements:

1) separate comparatively narrow spectral intervals in the regions of 3100, 3300 and 4000-4500Å. The transmission bands should have sharp enough limits;

2) the transmission coefficient τ_λ at the maximum of the transmission curve should be not less than 0.1-0.2%;

3) the filters should not develop changes in spectral properties which depend on external influences such as temperature and humidity or on the length of time they

they are used.

In laboratory practice various liquid light filters are widely used to separate relatively narrow segments of the ultraviolet spectrum [50, 51]. The properties of liquid light filters depend strongly on temperature, which hampers their use in ozonometry. Some solid light filters of colored glass, for the ultraviolet [51, 52] have wide transmission bands (~1000 Å), which makes them also unsuitable for ozonometers. Use has been made of a combination of colored glass the borate glass of S. N. Andreev [53] and metallic films in ozonometers with light filters for separation of spectral intervals in the region of 3100 and 3300 Å. An interference light filter has been used for the separation of bands in the region 4000-4500 Å.

The S. N. Andreev filter for the region of 3100 Å has been made according to the following recipe: Na_2O - 30.7%; Bo_2O_3 - 69.1%; $K_2C_2O_4$ - 0.2%. To exclude transmission of the filter in the visible region of the spectrum, borate glass was combined with UFS-1 glass. Since borate glasses are very hygroscopic they have been covered with UFS-1 glass and a film of molten quartz in order to protect them from moisture.

Figure 12 presents transmission curves of the light filters used in the OFET-3 ozonograph. The measurements were made at t = + 18°C.

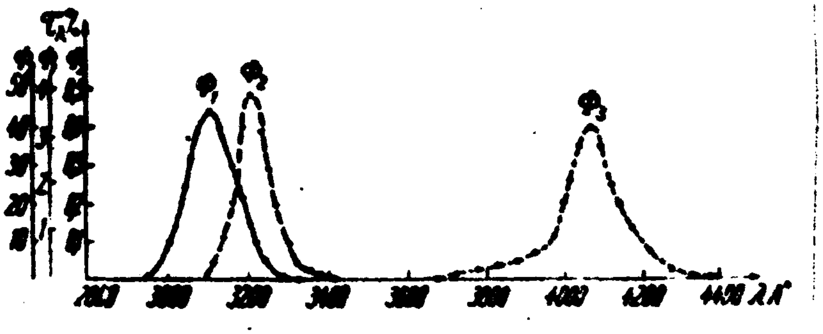

Fig. 12. Transmission curves of the light filters of the OFET-3 ozonograph

Investigations [27] have shown that when the temperature changes from +20° to -40° the transmission coefficient τ of UFS-1 colored glass for the 3100 Å wavelength changes on the side of increase during cooling by 2-2.5%. It is therefore necessary to take into consideration the temperature dependence of the spectral transmission and to introduce corresponding corrections into the results of the measurements. Since the transmission bands of the OFET-3 ozonograph are comparatively broad, it is impossible to consider α_λ sufficiently constant as a function of the wavelength in the region of the effective spectral sensitivity of the photometer. The latter circumstances makes it necessary, in calculating x, to use some averaged value of α_λ. The task of determining $\alpha_{\lambda mean}$ is complicated somewhat if the filter transmits emissions registered by the photometer outside the operating band (for example, outside the region of 3100 A or 3300 Å).

Let us consider briefly the method of determing $\alpha_{\lambda mean}$ for the case of the OFET-3 ozonograph.

Let $F_\lambda = \phi_1(\lambda)$, the distribution of energy in the spectrum of an extraterrestrial light source (for example, the sun); $\varepsilon_\lambda = \phi_2(\lambda)$, the spectral characteristics of the receiver (the photoelement or photomultiplier); $\tau_\lambda = \phi_3(\lambda)$, the spectral transmission of the filter, and $\alpha_\lambda = \phi_4(\lambda)$, the decimal absorption coefficient of ozone. In a more general case $\phi_1(\lambda)$ is the distribution of energy in the spectrum of any light source and $\phi_4(\lambda)$ is the absorption coefficient (or transmission coefficient) of the investigated medium. In work with filter electrophotometers and in the presence of sensitivity of the system only in the transmission band of the filter, the solution of several optical problems is possible. Thus, for example, if the optical density of the investigated medium is known then, having an assembly of narrow-band filters, it is possible to determine with known approximation the form of the function $\Phi_4(\lambda)$. The effect of the value of the half-width of the transmission band of the filters on the precision of such determinations has been examined in [54, 55].

In the case of an ozonometer with light filters, where $\Phi_1(\lambda)$, $\Phi_2(\lambda)$, $\Phi_3(\lambda)$ and $\Phi_4(\lambda)$ are known, a somewhat different problem arises. Here it is necessary to determine the mean value $\alpha_{\lambda\,mean}$ for a given quasi-monochromatic system.

Figure 13 presents curves of the effective spectral sensitivity of a system with the Φ_1 and Φ_2 OFET-3 filters.

$$\varphi_1(\lambda) = F_\lambda \varepsilon_\lambda \tau_{1_\lambda}$$

ε_λ represents the spectral characteristics of the STsV-6 photoelement. The data for the sun were taken by us from a monograph [56]. It should be noted that the value F_λ for the sun cannot be considered known precisely enough, since in the region up to $\lambda < 3800$ Å the data of individual rocket probes [57, 58], as well as the reduced

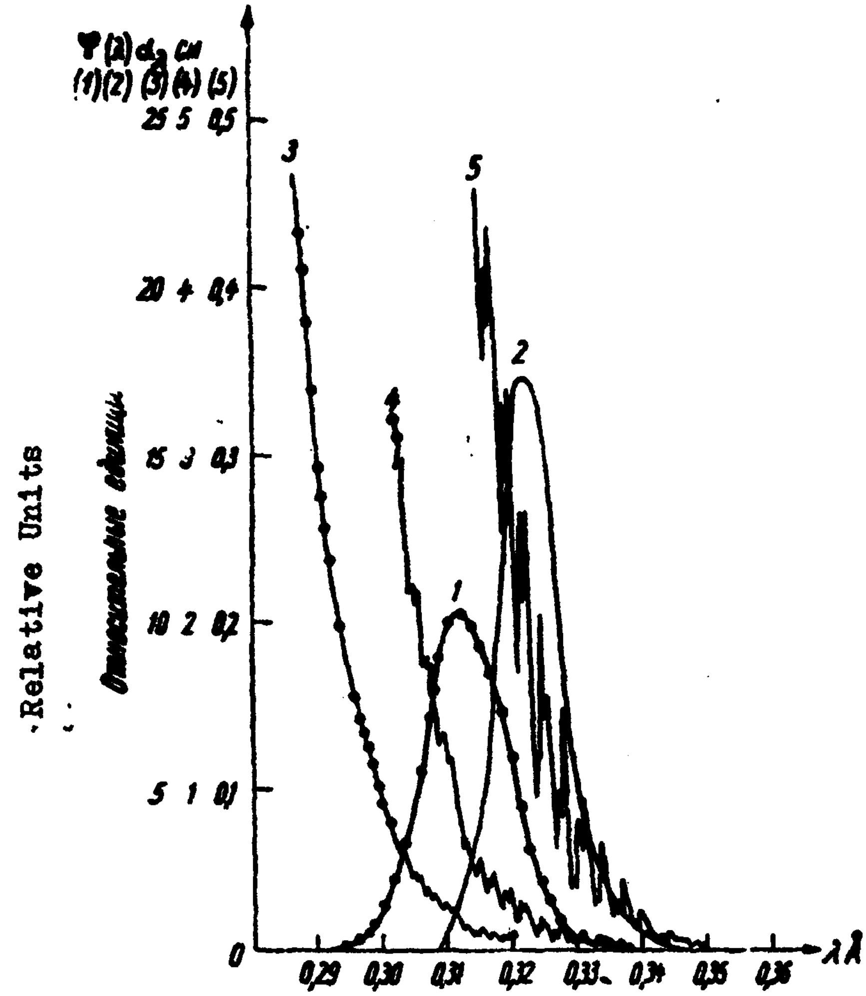

Fig. 13. Determination of the mean value of the decimal absorption of ozone, $\alpha_{\lambda mean}$. 1) effective spectral sensitivity of the system using filter Φ; 2) effective spectral sensitivity of the system using filter Φ_2; 3), 4) and 5) decimal absorption coefficient of ozone $\alpha_\lambda = \Phi_4(\lambda)$.

calculations, do not agree with one another.

Figure 13 also presents the course of the function $\Phi_4(\lambda) = \alpha_\lambda$ for ozone (according to Vigroux [42] for the temperature -44°C).

Graphic integration enables us to determine the mean value $\alpha_{\lambda\,mean}$ for filters Φ_1 and Φ_2:

$$\alpha_{\lambda_{mean}\Phi_1} = \frac{\int_{\lambda_1}^{\lambda_2} \varphi_1(\lambda)\,\alpha_\lambda\,d\lambda}{\int_{\lambda_1}^{\lambda_2} \varphi_1(\lambda)\,d\lambda}$$

and

$$\alpha_{\lambda_{mean}\Phi_2} = \frac{\int_{\lambda_1}^{\lambda_2} \varphi_2(\lambda)\,\alpha_\lambda\,d\lambda}{\int_{\lambda_1}^{\lambda_2} \varphi_2(\lambda)\,d\lambda}.$$

1 - mean

For OFET-3, according to our calculations, $\alpha_{\lambda\,mean\,\Phi_1} = 1.09\ cm^{-1}$ and $\alpha_{\lambda\,mean\,\Phi_2} = 0.20\,cm^{-1}$.

The described method of processing the data obtained by means of filter ozonometers and amounting to the determination of $\alpha_{\lambda\,mean}$ and subsequent calculation of x cannot be used with light filters of too broad bands. In the latter case, thanks to the narrow course of the energy distribution curve in the solar spectrum measurable on the surface of the earth, the changes in intensity of the solar radiations can be erroneously taken for the variation in the atmospheric ozone. We recommend investigation of light filters with a band width not exceeding 100-150 Å.

A somewhat different method of processing can be accomplished by substitution of α_{λ_M} for $\alpha_{\lambda\,mean}$, representing the absorption coefficient of ozone corresponding to the maximum of the curve of the effective spectral sensitivity of the system $\phi(\lambda)$ (A. L. Osherovicu, L. G. Bol'shakova and I. V. Peisakhson. Report to the Second conference on Atmospheric Ozone [In Russian], Moscow, 1959).

The validity of using a filter electrophotometer for ozonometric purposes has been checked by direct measurements. These were made [13] at $80^\circ \geqslant Z_\odot \geqslant 50^\circ$ with a filter photometer ($\lambda_{MAX} = 3200$ Å) and in parallel with a spectrophotometer with a photomultiplier. A quartz monochromator with double resolution was used in the spectrophotometer; this permitted separating the spectral interval $\Delta\lambda = 15$ Å in the region of 3200 Å.

The results of single measurements are given in Figure 14. Testing of the correctness of the values obtained for J in the region where $\alpha_\lambda = 0$ has been done [31] with a glass monochromator, model MS-3. The disk of the sun was projected with a lens on the input slit of the monochromator. Measurements were made at a wavelength of 4000 Å (for a filter with λ_{max} of 4000 Å). The data of the comparative observations for $11^{\circ} < z_{\odot} < 38^{\circ}$ are presented in Figure 15. Control measurements have also been made with the Dobson spectrophotometer. (The measurements were made by the A. I. Voyeikov Main Geophysical Observatory for "linkages" of the OFET-3 ozonograph distributed to the network of ozonometric stations of the USSR to the Dobson instrument acting as a control, since a more precise instrument had not been built at that time). It constituted a generalized experiment capable to a certain extent of evaluating the absolute characteristics of the OFET-3.

The results of comparative measurements with the Dobson GGO spectrophotometer and OFET-3 instrument No. 9 are given in Table 3, calculated with values of α_{λ} according to Vigroux [42].

It should be noted that the data of the table do not take into consideration probable errors in the readings of the Dobson GGO spectrophotometer, especially at small heights of the sun.

The transmission of filters Φ_1 and Φ_2 in the region of 6800-7600 Å also can be the reason for a certain observable deviation between the readings of the Dobson

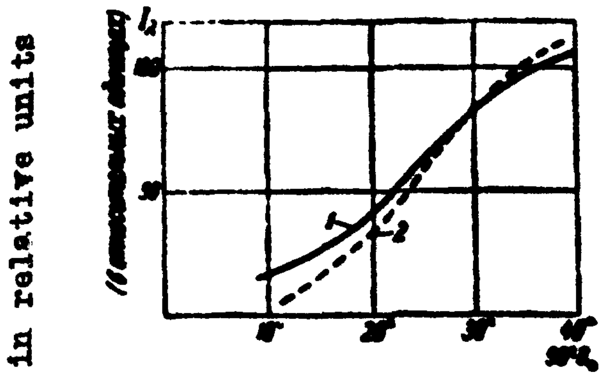

Fig. 14. Comparison of the quartz spectrophotometer (1) with the filter ozonometer (2).

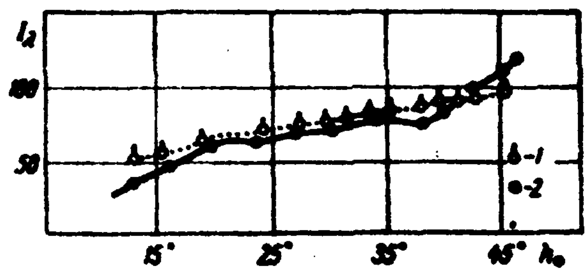

Fig. 15. Comparison of the filter ozonometer (1) with a glass spectrophotometer (2) in the region λ_{max} = 4000 Å.

1 Время		4 Высота солнца	m	μ	x·10³ см		7 Расхождение (в %)
2 час.	3 мин.				5 спектрофотометр Добсона	6 ОФЭТ-3	
6	40	18°06′	3,19	3, 2	338	324	−16,5
	50	19 12	3,02	2,95	339	326	− 3,8
7	00	20 18	2,86	2,81	349	328	− 6,0
	10	21 36	2,70	2,66	349	334	− 4,3
	20	22 42	2,58	2,54	344	341	− 0,9
	30	24 30	2,45	2,41	355	352	− 0,8
	40	25 24	2,32	2,29	378	356	− 5,8
	50	26 30	2,23	2,21	349	359	− 2,8
8	00	27 48	2,14	2,12	336	363	+ 8,0
	10	29 06	2,05	2,03	382	363	− 5,0
	20	30 18	1,98	1,96	348	362	+ 4,0
	30	31 30	1,91	1,90	352	363	+ 3,1
	40	32 48	1,84	1,83	370	368	− 0,5
	50	34 00	1,78	1,77	369	359	− 2,7
9	00	35 15	1,73	1,72	370	371	+ 0,3
	10	36 27	1,68	1,67	356	367	+ 3,1
	20	37 36	1,63	1,63	356	363	+ 2,3
	30	38 42	1,60	1,59	359	363	+ 1,1
	40	39 50	1,56	1,55	354	358	+ 1,1
	50	41 06	1,52	1,51	358	366	+ 2,3
10	00	42 18	1,48	1,48	362	369	+ 1,9
	10	43 18	1,46	1,45	374	355	− 5,1
	20	44 24	1,43	1,42	360	354	− 1,7
	30	45 06	1,41	1,41	363	352	− 3,0
	40	46°18	1,38	1,38	363	351	− 3,4
	50	47 06	1,36	1,36	366	351	− 4,1
11	00	48 00	1,34	1,34	363	354	− 2,5
	10	48 48	1,33	1,32	381	370	− 2,9
	20	49 30	1,31	1,31	366	360	− 1,6
	30	50 18	1,30	1,30	367	373	+ 1,6
	40	51 00	1,28	1,28	377	341	− 9,5
	50	51 30	1,27	1,27	385	348	− 9,6
12	00	52 00	1,27	1,27	383	347	− 9,4
	10	52 24	1,26	1, 6	367	349	− 5,8
	20	52 54	1,26	1,25	388	350	− 9,8
	30	53 06	1,25	1,25	371	354	− 4,8

Table 3. Results of the comparison of ozonometers. 1) time; 2) hours; 3) minutes; 4) height of sun; 5) Dobson spectrophotometer; 6) OFET-3; 7) Divergence (in %).

spectrophotometer and OFET-3. Although the spectral sensivity of the antimony-cesium photoelement in the region of 6800-7600 Å is rather small (see Figure 6), nevertheless the following measurements were made for a more careful checking. Glass of type ZhS-17 [52] was coated on filter Φ_1. A registration of solar emission was made both with filter Φ_1 and with filter Φ_2 + ZhS-17 glass. A sample of the record is given in Figure 16.

The recording in Fig. 16 shows that the effective sensitivity of the ozonograph with filter Φ_1 in the region of 6800-7600 Å is practically equal to zero.

An analogous method (measurements with an additional filter) can be used if the need arises to take into consideration the transmission of the basic filter outside its operating band.

The precision of the determination of x with the use of filter photometers can be increased considerably on account of the improved spectral characteristics of the receivers and filters. The design of the OFET-3 permits replacement of the photomultipliers, photoelements and filters when necessary.

The dielectric/interference light filters developed by T. N. Krylova and R. S. Sokolova [59] can be used successfully for purposes of ozonometry, and also the narrow-

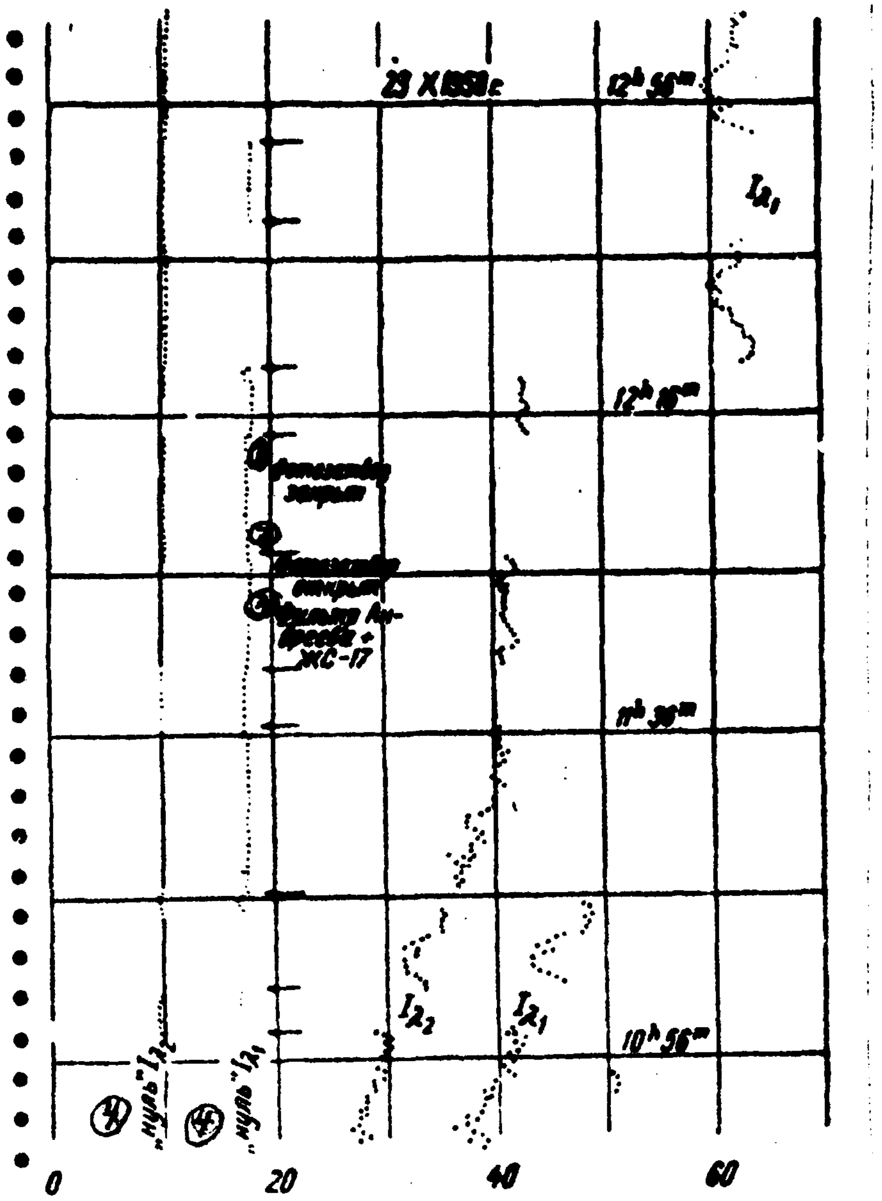

Fig. 16. Specimen of recording of the effective sensitivity of the OFET-3 ozonograph using filter No. 1 (Andreev) and filter No. 1 + ZhS-17 glass. I_{λ_1}, I_{λ_2}, I_{λ_3} are the intensities of radiation in relative units with the use of light filters Φ_1, Φ_2 and Φ_3 respectively.

1) Camera shutter closed 2) Camera shutter open 3) Andreev filter 4) Zero

band light filters of F. A. Korolev [60]. In combination with colored glass such light filters enable one to separate comparatively narrow segments of the spectrum in the ultraviolet. Figure 17 presents the transmission curves of two combined filters [59] for the region of 3080 Å and 3300 Å, intended for ozonographs.

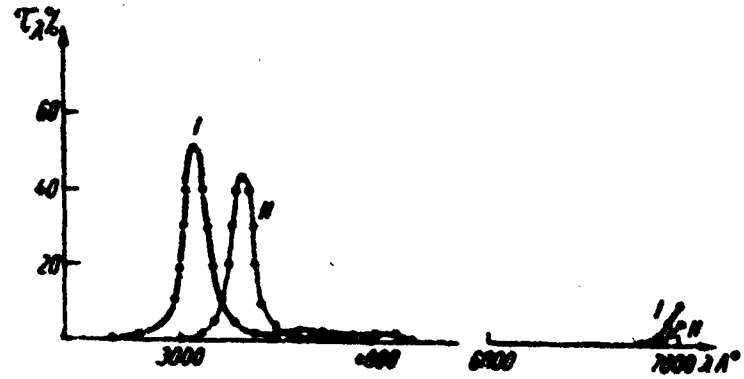

Fig. 17. Transmission curves of dielectric interference light filters for the regions 3080 and 3300 Å. I) No. 905 + UFS-2 (2 mm) with light separator; II) No. 937 + UFS-1 (5 mm) + light separator + SS-6 (2 mm).

The development of film polarizers for the ultraviolet [61] permits making a polarization filter [62] for the region 3080 Å and 3300 Å. These filters, with a transmission band of 15-20 Å and a maximum transmission coefficient of 3-4% can also be successfully used for purposes of ozonometry and of certain problems in the investigation of ultraviolet emission of the sun. According to the calculations of S. B. Ioffe, made at our request, polarization filters with a diameter of 20 mm and density of 30 mm and of the required parameters are technically feasible.

We have used photoelements and photomultipliers with antimony-cesium photocathodes [4, 12, 13, 14]. The use of photocathodes in which the red limit of the photoeffect lies in a shorter wave region of the spectrum than in antimony-cesium photocathodes does simplify, however, the problem of selecting the light filters needed for ozonometers. In this the ratio of signal noise for these receivers in the operating region of the spectrum should be comparable with the same parameter of the antimony-cesium photoelement. For registration of emissions in the region of 3100 A it is possible to use photoelectric receivers with magnesium photocathodes [63, 64] in which the red limit is in the region of 3250-3300 A. The advantage of these photocathodes is the low thermoemission ($\simeq 10 \frac{\text{electron}}{\text{sec. cm}^2}$). Titanium photoelements are also suitable for this region of the spectrum [10].

We have successfully used photomultipliers and photoelements with K-Na-Li photocathodes, in which the red limit of the photoeffect is in the region of 5500 A, for measurement of radiation in the region of 3000-5000 Å.

Figure 18 presents the spectral characteristics of a magnesium photocathode borrowed from [63] and of a K-Na-Li cathode, measured by us.

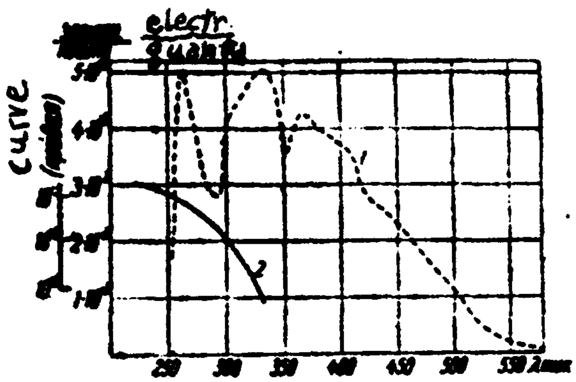

Fig. 18. Spectral characteristics of the radiation receivers with Mg and K-Na-Li photocathodes. 1) K-Na-Li photocathode; 2) Mg photocathode.

Conclusion

1. The electrophotometric ozonometers and ozonographs described above have been used successfully for a number of years for the purpose of ozonometric research.

2. Ways of improving ozonometric apparatus have been planned: a) the creation of narrower-band light filters; b) the use of more selective photoelectric receivers in the ultraviolet region of the spectrum; c)

the development of an ozonograph of an observatory type with a double monochromator with diffraction gratings and an electrophotometer on the output.

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