Spectral Measurements of Direct Solar Radiation and of Sun's Aureole (I)

— Instrumentation and the Measurements in Visible Region —

by

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Abstract

A spectro-pyrheliometer, which is composed of a telescope, a double monochrometer, an amplifier and a recorder, is designed for the measurement of the solar and the sky radiation. The opening angle of the telescope is so small that the sky radiation from the small sky area whose angular distance is one degree from the center of the sun, is measured without any intervention of direct solar radiation. The monochrometer used is the one with two quartz prisms. The photomultiplier EMI 9526-B is used to detect the light in the range from 0.3 to 0.8μ of wavelengths, and the PbS cell is used in the range from 0.65 to 2.0μ .

The intensities of solar and sky radiation coming from the small area whose angular distances are 1, 2, 3, 5, 7, 10 and 15 degrees from the center of the sun and from the zenith, are measured.

By the measurements of direct solar radiation, we obtained the optical thickness at each wavelength and inferred the content and the size distribution of the aerosol particles in the atmosphere. The spectral value of the photocurrent corresponding to the extraterrestrial value of solar radiation at each wavelength is deduced with the Bouguer-Langley method. This is the calibration constant of the instrument which is used as the unit of any measured value, and then the absolute values can be obtained. The spectral intensities of the sun's aureole in units of the extraterrestrial values have the order of 10^{-4} to 10^{-6} .

The optical thickness and aureole intensity at each wavelength obtained from the measurements are compared with those obtained by FORTZIK, VOLZ, BULLRICH and others.

1. Introduction

The size distribution of aerosol particles in the atmosphere have been investigated by many authors with various methods. One of them is the optical method, that is, the investigation of the light scattered by small particles in the atmosphere based upon Mie's theory of scattering.

Since Lord Rayleigh explained why the sky is blue, investigations have been accumulated in this field and in 1950, CHANDRASEKHAR completely solved the problem of the radiation transfer in a molecular atmosphere. The numerical information on this problem has been obtained by COULSON, DAVE and SEKERA (1960) and others.

The aerosol particles in the atmosphere, however, play important roles in optical phenomena in the atmosphere. The scattering by aerosol particles is characterized by the forward scattering intensified very much in the small scattering angles. The sun's aureole is the one of the most representative phenomena in the atmosphere.

The scattering by a particle larger than a molecule is explained by Mie, and the various treatments of this phenomena are represented by Van de HULST in his book (1957). But the problem of the radiation transfer in the turbid atmosphere is not completely solved, because the phase function for turbid air is complicated. In the U.S.A., SEKERA, DEIRMENDJIAN and DAVE *et al.* investigated this problem theoretically. In the U.S.S.R., there are many investigators who developed this problem in theoretical or observational investigations. FEIGELSON *et al.* (1960) published an important paper in which they obtained numerical solutions assuming that the phase function is expanded into a finite series of Legendre polynomials.

In Germany VOLZ published numerous results in theoretical or observational studies. Recently BULLRICH and de BARY *et al.*, the group of Mainz, prepared some practical tables on the light scattering in the turbid atmosphere. In Japan, KANO (1964) solved the problem of the polarization of sky light, especially the shift of neutral points in the turbid atmosphere. YAMAMOTO and TANAKA treated this problem theoretically expanding the scattering and transmission function into a series.

On the observational side, the technical advances in modern electronics have made the measurements easier and more precise. Since 1950, VOLZ continues the measurements of the sky light with filters and selenium and germanium cells in the spectral range from ultra violet to near infrared. He classified the atmospheric turbidity in three types according to the atmospheric scattering functions corresponding to the size distribution of aerosol particles. Recently, he discussed the difference of the chemical composition of particles between the larger particles and the smaller.

On the other hand, direct measurements of aerosol particles by the sampling of the air are performed by many investigators and the power-law size distribution in the region considered is generally recognized. The optical thickness at each wavelength is closely related to the size distribution, and FORTZIK calculated the spectral extinction coefficients assuming the size distribution composed of some Gaussian groups in the region from 0.1 to 1.8μ in the particle radii, as well as the power-law distribution. FENN, TWOMEY and HOWELL calculated the back-scattering intensities by the aerosol particles which are distributed in the form of Gaussian or of Poisson function. These distributions are the modified models of the power-law distribution based upon the measurements of FENN.

Since 1959, SEKIHARA and MURAI have continued the measurements to obtain the absolute value of insolation, and improved the instrument so as to ensure precise

measurements of spectral solar and aureole intensities. In this paper, the results of the measurements of direct solar spectral radiation and of the sun's aureole at Karuizawa (1000 m s.l.) and at Tokyo, are reported and the aerosol size distributions corresponding to these results are inferred.

2. Instrumentation and calibration

The instrument is designed so as to measure the spectral intensities of direct solar and diffuse sky radiation, in the wavelength region from 0.3 to 1.6μ . The opening angle of the telescope is made so small that sky radiation coming from the small area whose angular distance from the sun is one degree is measured without any intervention of direct solar radiation.

The double monochrometer with quartz prisms is used to eliminate the stray light in the monochrometer and these two prisms are fixed on the same shaft so that inaccuracies due to the irregular rotation of the prisms are eliminated.

As the ratio of the maximum intensity measured to the minimum amounts to the order of 10^5 , the sensitivity of the instrument is varied with the following operations:

1) Electric regulation

The value of high tension source supplied to the photomultiplier is divided into ten steps in the range from 300 V to 700 V and any step is selected manually according to the intensity of incident radiation. The voltage at each step is stabilized by the careful design of the circuit. The relative sensitivity is regulated from 1 to 10^3 by this operation.

2) Optical adjustments

The optical adjustments of the sensitivity are performed by (i) the diaphragm set on the top of the telescope, (ii) the width of the entrance and the center slit, (iii) the length of the entrance slit and (iv) the semitransparent quartz diffuser plate. The ratios of the sensitivity regulated by each of them are about (i) 10, (ii) 5×10 , (iii) 3×10 and (iv) 3×10 respectively.

To facilitate measurements at any station we prepared a portable instrument which differs only in some details. The photograph and the block diagram are represented in Fig. 1.

2.1 Telescope and sun follower

The telescope is indicated by T in Fig. 1. It is designed so as to have its opening angle about $50'$. A concave mirror, which reflects stray light towards the dark box at the side of the telescope, is set in the middle of the body. The desired light beam is transmitted through the small hole at the center of the mirror. The incident beam is focused on the entrance slit after being reflected by the two mirrors.

The sun follower, indicated by F in Fig. 1, is set at the side of the telescope and follows the direction of the solar beam. At the time of measurement, the telescope is maintained in parallel or at any angle with the sun follower. The sun follower is the simple telescope which focuses the image of the sun on the slit of two

(a)

(b)

Fig. 1. Photograph (a) and block diagram (b) of the spectro-pyrheliometer.

photocells placed in parallel, and the difference of the output voltage of the two cells is supplied, after the amplification, to the motor which drives the telescope system, so that the voltage difference becomes zero. The sun follower has sufficiently high sensitivity and the small part of the solar beam is put in the entrance slit of the monochrometer, then errors due to the movement of the image of the focused beam are negligibly small.

Fig. 2. Spectral conversion factor of diaphragm.

At the top of the telescope, a diaphragm is put to adjust the incident beam of light. The spectral conversion factors to the standard condition, determined after several experimental measurements, are represented in Fig. 2. These factors indicate the ratio of the response current in the case of a plain telescope to that in the case of one equipped with a diaphragm.

Fig. 3. Degree of dispersion of the double monochrometer.

2.2 Double monochrometer

The double monochrometer with two quartz prisms is used and the degree of dispersion is shown in Fig. 3. As described above, these two prisms are fixed on the same shaft so as to eliminate errors in wavelength due to its irregular rotations.

The width of the entrance and the center slits are changed manually from 0.07 to 0.3 mm. The length of the entrance slit is adjusted by the exchange of the plates of the slit whose values are 0.1, 0.3, 0.9 and 3.0 mm., at the place of the slit. The conversion factors of the slit width and of its length to those of the standard condition are shown in Figs. 4 and 5 respectively. The reproducibility of the slit width is worse than the other operations of the adjustments, because the slit width is varied continuously with a screw. As the width of the exit slit is fixed at 0.5 mm., the illuminated place and the area of the cathode of the detector are not changed, so that the errors caused by the irregularities of the cathode surface do not intervene.

Fig. 4. Conversion factor of slit width.

Fig. 5. Conversion factor of slit length.

In order to diminish the incident light, a semi-transparent plate of quartz is inserted in front of the entrance slit of the monochromator. Its conversion factor is represented in Fig. 6. One can see the wavelength dependency of the factor.

Fig. 6. Conversion factor of the quartz diffuser plate.

2.3 Detectors and high tension source

The detector for UV and visible light is the photomultiplier EMI 9526-B (head-on type) and PbS cell for near infrared radiation.

The fatigue of the cathode surface is considerable during the 30 minutes after the first supply of high tension to the photomultiplier and after that it is to be neglected.

Fig. 7. Characteristics of the photomultiplier for the high tension supplied.

The circuit of the high tension source is very carefully designed so as to obtain stable output voltages at each of ten steps whose value is determined by ten divisions of the voltage range from 300 to 700 volts. It is confirmed experimentally that the variation of the output values is less than 0.2%. The photocurrent curve for high tension is shown in Fig. 7. The dark current of the photomultiplier is negligibly small in the range from 300 to 700 V.

2.4 Amplifier and recorder

The incident beam of light is chopped by the sector rotating in front of the entrance slit and the alternating photoelectric current is amplified by the AC amplifier tuned at the frequency of the sector, which is about 400 cps. The output voltage is recorded on the 10 mV. range recorder. The response time of the instrument is described as follows: The time required to slide the recording pen in the range from 2 to 8 mV. caused by instantaneous illumination is about 1 second. It is the same for the instantaneous shield of light.

2.5 Standard lamp and wavelength calibration

A tungsten lamp is used as a reference light source for the comparison of the measured light intensities. The color temperature of the lamp is 2850°K at 88.3 volts supply.

The intensities of the incident radiation are all represented by the ratio $r(\lambda) = i(\lambda)/i_s(\lambda)$, where $i(\lambda)$ is the photoelectric current corresponding to the incident light and $i_s(\lambda)$ is that of the standard lamp. The lamp is switched on for 30 minutes before the measurement, for the stabilization of the filament temperature.

The measurable limit of the short wavelength side is about 0.33μ , because the lamp is covered by ordinary glass. The long wavelength limit is about 0.84μ , which is determined by the sensitivity of the photomultiplier, and the measurable wavelength range of PbS cell is from 0.65 to 1.6μ . The time required for one scanning of the total range is about 4 minutes. The speed of rotation of the prism is controlled by a cam so as to make the speed of wavelength variation constant, and the wavelength marks are recorded at 0.05μ intervals. The wavelength is calibrated by the emission lines of the mercury lamp.

2.6 Calibration errors

The errors caused by the adjustment of the slit width is the largest of the measurement errors as described above. The spectral conversion factor is shown in Fig. 4 of 2.2, the ordinate represents the response relative to that at the slit width 0.05 mm. For the determination of the conversion factor, direct solar or sky radiation is employed as the light source and the mean curves of six experiments are shown in Fig. 4. The mean deviation of the individual points of measurements in the UV region is larger than the other regions. It is about 10% of the mean value. The mean deviation in the region from 0.4 to 0.6μ is the smallest, being smaller than 5%. In the region larger than 0.7μ , as the sensitivity of the photomultiplier is very near the cut-off value, the mean deviation becomes again larger, reaching about 8%.

The errors due to the semitransparent quartz plate inserted in front of the entrance slit for the diminution of the incident light, are rather large. Its calibration curves are shown in Fig. 6 and they are the mean curve of five experimental measurements of solar radiation. The mean deviation in the UV region is about 6%. We can neglect the deviation in the visible region.

It must be considered that errors due to the instability of the high tension supplied to the photomultiplier are important. In practice, however, the fluctuations of the high tension values at each step are smaller than 0.2% of the mean values. The fluctuation of the photoelectric currents is larger at higher values of the high tension source and the mean deviation is 3% at maximum.

Errors due to the other processes of the optical adjustment, namely of the diaphragm on the telescope, of the following of the sun follower, are all very small.

Errors caused by the combined processes of the above-mentioned adjustments are about 8% in the UV region, less than 5% in the region between 0.4 and 0.6 μ and about 7% in the region larger than 0.7 μ .

3. Observations and results

The stations and dates of the observations are as follows:

- 1) Karuizawa, October 15 and 16, 1965.
- 2) Tokyo, October 28, November 1 and 12, December 13 and 25, 1965.

Karuizawa station whose distance from Tokyo is about 150 km NW is placed on a plateau 1000 m above sea level. The site of the observing station for Tokyo is about 20 km west of the center of the city.

The measurements were performed under conditions of cloudiness less than 2 and of the solar altitude between about 12 degrees and that of the southing.

3.1 Procedure of the measurements

The procedure of the measurements is as follows; the spectral intensities of direct solar and diffuse sky radiation are recorded on the chart of the recording millivolt meter, by the scanning of the wavelength from 0.3 to 0.8 μ with the rotation of the prisms driven by the motor. The time required for the scanning of this wavelength interval is about 2 minutes. The high tension values supplied to the photomultiplier are changed stepwisely during one scanning so as to the output current is contained in the range from 2 to 8 mV. The conditions of the optical adjustments are the same during one scanning.

3.1.1 Measurements of direct solar radiation

The measurements of direct solar radiation are made in the time intervals chosen so that the interval of the optical air mass may be nearly constant. There are no measurements at the time for the solar altitude lower than 12 degrees, because the effect of the earth's curvature becomes very large.

The optical adjustments for the measurements of direct solar radiation are as

follows: the width of the entrance and the center slit are between 0.07 and 0.1 mm., the length of the entrance slit is 0.1 mm., the diaphragm and neutral filter (or quartz diffuser plate) are put on the top (or in front of the entrance slit) of the telescope. In this condition, the instrument has the lowest sensitivity.

The measurement of the standard lamp is made just before each measurement of direct solar radiation, to calibrate the sensitivity of the instrument. The optical path in the instrument is changed by the rotation of the mirrors. Since the intensity of the radiation is represented by the ratio, $r(\lambda) = i(\lambda)/i_l(\lambda)$, where $i(\lambda)$ is photocurrent due to the incident radiation and $i_l(\lambda)$ due to the radiation of lamp, the effect of the fluctuation of the sensitivity of the instrument is eliminated.

The values of $r(\lambda)$ are plotted in logarithmic scale against the optical air mass M , at which $r(\lambda)$ is obtained, in linear scale, and the value $r_0(\lambda)$, corresponding to $M=0$, is obtained by the extrapolation of the $\log r(\lambda)$ vs. M curve. The mean gradient of the curve represents the value of the optical thickness of the atmosphere whose state is assumed not to change during the measurement in a day. In Fig. 8, the spectral values of $r_0(\lambda)$ are shown. These values have special meaning as the con-

Fig. 8. Spectral distribution of the photocurrent corresponding to the extraterrestrial value of solar radiation.

stants of the instrument for absolute measurements. We can, therefore, represent the measured value at any time as the ratio $R(\lambda, M) = r(\lambda)/r_0(\lambda)$, and if we know the spectral extraterrestrial values of solar radiation $I_0(\lambda)$, the absolute values will be obtained as $I_0(\lambda) \times R(\lambda, M)$. The value of the air mass M , is calculated at each time of measurement, and is corrected according to Bemporad's table.

3.1.2 Measurements of the sun's aureole

The measurements of the sun's aureole are made in the sun's vertical plane. The angle at which the measurements are made are 1, 2, 3, 5, 7, 10 and 15 degrees from the center of the sun toward the zenith and the radiation from the zenith is measured at each time. The conditions of the optical system of the instrument are somewhat different from those in the case of direct solar radiation; that is, the slit width is 0.3 mm. and the slit length is 3 mm. More than 20 minutes is needed for this survey.

The measured intensities are represented, as described before, by the ratio $R(\lambda, \theta) = r(\lambda, \theta)/r_0(\lambda)$, and one can obtain the absolute values of the aureole intensities using the existing tables of spectral solar energy outside the atmosphere.

3.2 The results of the measurements

3.2.1 The Value $r_0(\lambda)$ corresponding to the extraterrestrial solar radiation

In Fig. 8, the curves of $r_0(\lambda)$ are represented. In judging the steadiness of the atmospheric state for the determination of $r_0(\lambda)$, we can fortunately use the continuous records of the Eppley pyrheliometer of the Japan Meteorological Agency as an auxiliary datum in the case of the measurements in Tokyo. The spectral values of $r_0(\lambda)$ were determined by the mean lines in $\log r(\lambda)$ vs. M diagram, which is obtained on the day on which the atmospheric state was rather stable throughout the day.

3.2.2 The Spectral distribution of optical thickness $\tau(\lambda)$

Since $r_0(\lambda)$ is determined as described above, the optical thickness of the atmosphere is obtained at any time of the day from a single measurement of direct solar radiation. If we denote the optical thickness by $\tau(\lambda)$, the intensity of direct solar radiation, $I(\lambda)$, reaching the receiver after its passage through the air mass M , is represented by the equation

$$I(\lambda, M) = I_0(\lambda) \cdot \exp[-\tau(\lambda) \cdot M]$$

or,

$$\tau(\lambda) = \frac{1}{M} \log \frac{I_0(\lambda)}{I(\lambda, M)}$$

$I_0(\lambda)/I(\lambda, M)$ is obtained from the measurements and M is calculated from the time of the measurements. The measured values of $\tau(\lambda)$ are shown by the curves in Figs. 9a-21a.

The optical thickness $\tau(\lambda)$ is considered as the sum of several components, that is,

$$\tau(\lambda) = \tau_R(\lambda) + \tau_M(\lambda) + \tau_{O_3}(\lambda)$$

where $\tau_R(\lambda)$: Optical thickness of the molecular atmosphere (Rayleigh scattering)

$\tau_M(\lambda)$: Optical thickness of the aerosol particles (Mie scattering)

$\tau_{O_3}(\lambda)$: Optical thickness of the atmospheric ozone

The curves B in Figs. 9a-21a represent

$$\tau_M(\lambda) = \tau(\lambda) - \tau_R(\lambda) - \tau_{O_3}(\lambda).$$

Fig. 9a. Spectral distribution of optical thickness (Type I) for 15:00–16:00 on Oct. 15 1965, Karuizawa. Solid points represent observed values of optical thickness $\tau(\lambda)$, open dots those of aerosol particles $\tau_M(\lambda)$. Line R shows the spectral distribution of $\tau_R(\lambda)$.

Fig. 10a. Same as Fig. 9a but for 14:00–16:00 on Oct. 28, Tokyo.

Fig. 11a. Same as Fig. 9a but for 08:30-10:00 on Nov. 12, Tokyo.

Fig. 12a. Spectral distribution of optical thickness (Type II), for 10:33 on Nov. 1, Tokyo.

Fig. 14a. Spectral distribution of optical thickness (Type III), for 07:30—09:00 on Oct. 28, Tokyo.

Fig. 15a. Same as Fig. 14a but for 07:30—08:30 on Nov. 1, Tokyo.

Fig. 16a. Same as Fig. 14a but for 11:15 on Dec. 13, Tokyo.

Fig. 17a. Same as Fig. 14a but for 09:50 on Dec. 25, Tokyo.

Fig. 18a. Spectral distribution of optical thickness (Type IV), for 11:00 on Oct. 15, Karuizawa.

Fig. 19a. Same as Fig. 18a but for 07:30—10:00 on Oct. 16, Karuizawa.

Fig. 20a. Same as Fig. 18a but for 14:00—16:00 on Oct. 16, Karuizawa.

Fig. 21a. Same as Fig. 18a but for 13:30 on Dec. 13, Tokyo.

For the optical thickness of the molecular atmosphere, the values calculated by DEIRMENDJIAN (1953, 1955) were used, and are represented by the line R in Fig. 9a. $\tau_{0z}(\lambda)$ is represented by the product of the absorption coefficient $k(\lambda)$ and the total amount of ozone in the atmosphere Q . The values of $k(\lambda)$ used here are those obtained rather recently by INN and TANAKA (1953), and the values of Q are the results of the observation with DOBSON's spectrometer at TATENO (about 20 km. east of Tokyo). $\tau_{0z}(\lambda)$ values are shown in Table 1.

The values of $\tau_M(\lambda)$ represented by the curves B in Figs. 9a-21a vary with atmospheric conditions and have the variance of one order of the magnitude. The general feature of the distribution of $\tau_M(\lambda)$ is as follows: first, the gradient of $\tau_M(\lambda)$ curve in the UV region is rather large, and secondly, the curve in the visible region is flat.

The feature of the spectral distribution of $\tau_M(\lambda)$ obtained (Figs. 9a-21a) are classified into the following four types;

- I) Almost linear
- II) nearly linear curve with gradually diminishing gradient with the increasing wavelength.

Table 1. The values of $\tau_{0z}(\lambda)$
 $(\tau_{0z}(\lambda) = k(\lambda) \times Q)$

Date $\lambda(\text{\AA})$	Oct. 15	Oct. 16	Oct. 28	Nov. 1	Nov. 12	Dec. 13	Dec. 25
3375	0.015	0.014	0.015	0.014	0.016	0.017	0.019
3510	0.001	0.001	0.001	0.001	0.001	0.002	0.002
3750	0.001	0.001	0.001	0.001	0.001	0.001	0.001
4615	0.001	0.001	0.001	0.001	0.001	0.001	0.001
5000	0.005	0.005	0.005	0.005	0.005	0.006	0.006
5500	0.011	0.010	0.011	0.011	0.011	0.012	0.014
5800	0.016	0.015	0.016	0.016	0.017	0.018	0.021
6150	0.014	0.013	0.014	0.014	0.015	0.016	0.018
6540	0.008	0.007	0.008	0.007	0.008	0.009	0.010
7020	0.003	0.003	0.003	0.003	0.003	0.003	0.003
7600	0.001	0.001	0.001	0.001	0.001	0.001	0.001

III) concave curve

IV) nearly the same as (III), but decreases again in the region longer than 0.7μ .

The list of measurements is shown in Table 2.

Table 2. List of the measurements

Fig.	Date	Time of Obs.	Air mass M	Solar altitude	Visibility
Type (I)					
9	Oct. 15	1500—1600	2.7—4.5	21.7°—12.8°	50 km.
10	Oct. 28	1400—1600	2.3—5.3	25.4—10.5	10
11	Nov. 12	0830—1000	3.1—1.9	18.9—32.5	10
Type (II)					
12	Nov. 1	1033	1.6	38.7	10
13	Nov. 12	1430—1530	2.8—5.3	20.8—10.5	20
Type (III)					
14	Oct. 28	0730—0900	3.5—2.0	16.6—30.0	<10
15	Nov. 1	0730—0800	3.5—2.5	16.5—24.0	20
16	Dec. 13	1115	1.94	31.0	10
17	Dec. 25	0950	2.31	25.6	>20
Type (IV)					
18	Oct. 15	1100	1.43	44.5	50
19	Oct. 16	0730—1000	3.0—2.0	19.5—30.0	60
20	Oct. 16	1400—1600	2.0—5.0	30.0—11.5	60
21	Dec. 13	1330	2.34	25.4	>20

Fig. 9b. Spectral distribution of aureole intensities corresponding to Fig. 9a. $T_{\lambda} = \tau(\lambda) / \tau_R(\lambda)$, $\lambda = 0.40, 0.55$ and 0.70μ .

Fig. 10b. Same as Fig. 9b but corresponding to Fig. 10a.

Fig. 11b. Same as Fig. 9b but corresponding to Fig. 11a.

Fig. 12b. Same as Fig. 9b but corresponding to Fig. 12b.

Fig. 16b. Same as Fig. 9b but corresponding to Fig. 16a.

Fig. 17b. Same as Fig. 9b but corresponding to Fig. 17a.

Fig. 18b. Same as Fig. 9b but corresponding to Fig. 18a.

Fig. 19b. Same as Fig. 9b but corresponding to Fig. 19a.

Fig. 20b. Same as Fig. 9b but corresponding to Fig. 20a.

Fig. 21b. Same as Fig. 9b but corresponding to Fig. 21a.

Fig. 10c. Same as Fig. 9c but corresponding to Fig. 10a.

Fig. 9c. Angular distribution of aureole intensities corresponding to Fig. 9a.

Fig. 11c. Same as Fig. 9c but corresponding to Fig. 11a.

Fig. 12c. Same as Fig. 9c but corresponding to Fig. 12a.

Fig. 17c. Same as Fig. 9c but corresponding to Fig. 17a.

Fig. 16c. Same as Fig. 9c but corresponding to Fig. 16a.

Fig. 19c. Same as Fig. 9c but corresponding to Fig. 19a.

Fig. 18c. Same as Fig. 9c but corresponding to Fig. 18a.

Fig. 21c. Same as Fig. 9c but corresponding to Fig. 21a.

Fig. 20c. Same as Fig. 9c but corresponding to Fig. 20a.

3.2.2 The Angular and spectral distribution of the aureole intensities

Corresponding to the distribution of $\tau_M(\lambda)$ represented in the previous section, the spectral and angular distributions of aureole intensities are shown in Figs. 9b-21b and Figs. 9c-21c. (There is no measurement of aureole intensities corresponding to Figs. 13a, 14a and 15a). In case of the measurement of the aureole intensities, it takes more than 20 minutes to measure them for specified angular distances. Then the variation of optical path length due to the appreciable change of solar altitude during the measurement in the case of the low sun will introduce some errors into the measurements.

In Figs. 9b-21b, we can see that the order of $R(\lambda, \theta) = r(\lambda, \theta)/r_0(\lambda)$, namely, of the ratio of aureole intensities to extraterrestrial intensities are between 10^{-4} and 10^{-6} and, in general, the red intensities have relatively large values. These values are one or two orders larger than those of the molecular atmosphere.

As the aureole intensities measured are represented by their ratios to the extraterrestrial values, we can obtain their absolute values if we know the values of the solar energy outside the atmosphere. A few examples of the spectral energy distribution of aureole are shown in Fig. 22, in which JOHNSON's extraterrestrial values are used.

Fig. 22a. Energy distributions of aureole intensities ($\theta=2^\circ$).
 θ : Angular distance from the center of the sun towards zenith.

Fig. 22b. Energy distribution of aureole intensities ($\theta=10^\circ$).

The smooth curves in Figs. 9b-21b are re-plotted in the diagram of the angular distribution (Figs. 9c-21c), taking the wavelength as parameter. The general feature of the angular distribution is represented nearly by a line in logarithmic scale diagram for the visible region, that is, $R(\lambda, \theta) \sim \theta^{-b(\lambda)}$, and the deviation from this is larger in the curve of shorter wavelengths. Although the number of measurements is very small, the features of the angular distributions may be classified in some types:

- I) All curves are nearly parallel and separate from each other,
- II) All curves are nearly parallel, as in I), but are close to each other,
- III) The gradients of the curves are very different from each other.

The samples of each of the types are as follows:

- I) Oct. 28 and Nov. 12, 1965 (Figs. 10c and 13c)
- II) Dec. 13, 1965 (Fig. 16c)
- III) Oct. 16, Nov. 1 and Dec. 13, 1965 (Figs. 19c, 12c and 21c)

It is very difficult to classify the other examples into any types. The angular distributions of the aureole intensities show, therefore, large variety in their behaviors and the correlation to the distribution of the optical thickness also is not so clear.

4. Discussion of results

4.1 Meteorological conditions

All of the measurements were performed on clear days, after the passage of the cold front. In the case of Karuizawa, the fog appeared very often in the early morning. The meteorological conditions of Tokyo are represented by the records of the Eppley pyrliometer shown in Fig. 23. From this figure, the radiative conditions of the atmosphere fluctuate appreciably around the noon. The list of the meteorological condition is shown in Table 3. The measurement on the 1st of November at Tokyo is an interesting case where cirrus appeared at about 11h a.m. and after 30 minutes the sky was completely covered by it.

Table 3 List of meteorological conditions

Karuizawa						
Date	Time of observation	Wea.	Cloud	Wind (m/s)	Humidity	Visibility
Oct. 15	0900	○	—	WSW 7.5	62%	50 km.
	1500	○	—	SW 6.3	41	50
Oct. 16	0900	○	—	SW 2.2	79	60
	1500	○	—	SSW 2.3	41	60
Tokyo						
Oct. 28	0900	○	—	NNW 2.2	50	4.2
	1200	○	—	NW 2.5	31	8.0
	1500	○	—	ESE 3.5	38	10.0
Nov. 1	0900	○	0, Cu	NNW 7.8	46	80
	1200	⊖	10, Ci, Ac	N 7.3	35	70
	1500	⊙	10, Ci, Sc	NNW 3.3	39	50
Nov. 12	0900	○	0, Cu	N 3.7	48	6.0
	1200	○	0, Cu	NW 5.0	37	20.0
	1500	○	0, Cu	N 5.5	35	18.0
Dec. 13	0900	○	0, Ci	NNW 6.5	39	15.0
	1200	○	0, Ci	NW 5.8	36	25.0
	1500	①	6, Ci	NNW 5.3	35	15.0
Dec. 25	0900	○	0, Sc	WNW 3.2	39	9.0
	1200	○	0, Sc	NNW 2.2	32	9.0
	1500	○	0, Sc	NNW 4.8	30	15.0

4.2 The distribution of the aerosol particles and the optical thickness

As described above, the optical thickness $\tau(\lambda)$ is represented by the sum of the three components, $\tau_R(\lambda)$, $\tau_M(\lambda)$ and $\tau_{O_3}(\lambda)$. Of these components, $\tau_R(\lambda)$, the component due to the RAYLEIGH scattering, is considered constant. $\tau_{O_3}(\lambda)$, the component due to the absorption of ozone in the atmosphere, is not so large as compared to $\tau(\lambda)$ and its variation can be neglected.

Fig. 23. Records of the Eppley pyrheliometer.

The variation of $\tau(\lambda)$ comes mainly from that of $\tau_M(\lambda)$ because of the variation of concentration and size distribution of aerosol particles. $\tau_M(\lambda)$ is represented by the equation

$$\tau_M(\lambda) = H \cdot \int_0^\infty \pi r^2 K(\alpha, n) dN(r), \quad (1)$$

where, $K(\alpha, n)$ is the efficiency factor for Mie scattering, α the size parameter $2\pi r/\lambda$, H the effective height of the aerosol atmosphere, r the radius of a particle, n the index of refraction of the particle, $dN(r)$ represents the number of the particles with logarithms of radius between $\log r$ and $\log r + d(\log r)$, in a unit volume. The values of $K(\alpha, n)$ are available in the existing tables prepared by several authors (R. PENNDORF, 1956; K. BULLRICH, 1962).

For the size distribution of aerosol particles, JUNG (1952, 1955, 1961) gives the following expression:

$$dN(r)/d(\log r) = cr^{-\beta} \quad (2)$$

In this case, $\tau_M(\lambda)$ is represented by

$$\tau_M(\lambda) = 0.434 \cdot H \cdot c\pi \left(\frac{2\pi}{\lambda} \right)^{\beta-2} \int_{\alpha_0}^{\alpha_1} \frac{Kd\alpha}{\alpha^{\beta-1}} \quad (3)$$

the interval of the integration (α_0, α_1) corresponds to (r_0, r_1) , the range of the radius of the particle existing in the atmosphere. On the other hand, it is shown by Ångström that $\tau_M(\lambda)$ is represented by the form of $\tau_M(\lambda) = \text{const} \cdot \lambda^\gamma$ and the mean value of γ is -1.3 . Thus, the spectral dependency of $\tau_M(\lambda)$ is rather simple in the case of power-law size distribution as represented by eq. (2). The relation between γ and β is, by JUNG, represented strictly by

Fig. 24a.

Fig. 24b.

Fig. 24. Size distributions of aerosol particles measured by FENN (1963).

$$\gamma = 2 - \beta - \delta$$

(4)

where, δ is an integral containing $K(\alpha, n)$ and is negligible in the region $\beta > 2.5$.

In the results shown in Figs. 9a-21a, we can find three examples of the distribution which are approximately represented by $\sim \lambda^\gamma$ (Figs. 9a, 10a and 11a). The values of γ and β in the above three examples are, -0.668 , -2.15 , -2.76 ; 2.64 , 4.15 , 4.76 respectively. Examples of the simple form ($\sim \lambda^\gamma$) are rather few and the others have more complicated forms of distribution.

Among recent investigations, FORTZIK (1965) calculated the spectral extinction coefficient based upon the measurements on the distributions of the aerosol particles which were made by FENN (1964) with the sampling method. The most important behavior of the results is the defect of the particles in some regions in the range of the particle radius between 0.1 and 2.0μ . The samples are represented in Fig. 24. FORTZIK represents them with the groups of Gaussian distributions separated at the

Fig. 25a. Gaussian model of the size distributions of aerosol particles assumed by FORTZIK (1965).

radius corresponding to the defect of particles, and represents each group by the formula

$$dN(r) = N_{r_0} \exp \left[-A \left(\log \frac{r}{r_0} \right)^2 \right] d(\log r) \quad (6)$$

where, N is the number of particles per unit volume, r_0 the radius corresponding to the maximum number of particles, A the steepness parameter of the Gaussian group.

Substituting eq. (6) in eq. (1), we obtain the equation of optical thickness in the form

$$\tau_M(\lambda) = 0.434 \cdot H \cdot N_{r_0} \frac{\lambda^2}{4\pi} \int_0^\infty \alpha \cdot K(\alpha, n) \exp \left[-A \left(\log \frac{\alpha}{\alpha_0} \right)^2 \right] d\alpha \quad (7)$$

In Figs. 25 and 26 is shown the spectral optical thickness calculated by (7) for the distributions of aerosol particles assumed by FORZIK. One can see that some of the

Fig. 25b. Gaussian model of the size distributions of aerosol particles assumed by FORZIK (1965).

Fig. 26a.

Fig. 26b.

Fig. 26. Spectral distributions of the extinction coefficient assuming size distributions of particles shown in Fig. 25a and b (calculated by FOITZIK, 1965).

Fig. 27a. Model of Gaussian groups assumed by Fortzik.

Fig. 27b. Spectral distributions of extinction coefficients calculated with the model of Fig. 27a (after Fortzik, 1965).

curves of Figs. 9a-21a show the characteristics of the curves of Fig. 26, and can recognize the possibility of the Gaussian groups size distribution of the particles. In Fig. 27a are shown the model of the Gaussian group distribution selected by FORTZIK and the curves of $\tau_M(\lambda)/H$ calculated on the basis of the combination of the Gaussian groups described above. In these figures, we can estimate the contribution of each group. In Fig. 27b, we can recognize that the Gaussian group of the larger particles contributes to making the values of $\tau_M(\lambda)$ larger in the longer wavelength side of the region. From this feature, it can be shown that the result obtained from the measurements will be reproduced by the combination of the steep power-law distribution in the smaller size region and the Gaussian group distribution in the larger size region of particles. For example, the curves classified in Type (II) in the preceding section represent the decrease of gradient with wavelength and this decrease can be considered the contribution of the group of larger particles in Fig. 27a.

For the Types (III) and (IV), the curves are not completely reproduced by the combination of the groups, but it can be shown that the contribution due to particles with a radius of about 1.0μ is important to reproduce the observed curve, as the component of the combination of the groups of the size distribution of the aerosol particles.

Thus, the results of the measurements show that there are rather few cases where the spectral optical thickness has the power functions of wavelength (Type I) and that most of them (Type II, III and IV) deviates from the power function of wavelength, especially in longer wavelength region. From this, one might see that most of the size distribution of the aerosol particles contributing to the observed optical thickness deviates from the simple power-law distribution, especially in the region of larger particle sizes. It is necessary to do these measurements in a wide wavelength range extending to the infrared region in order to obtain more precise information about the size distribution of the aerosol particles. For this, the results of the measurements in the range between 0.3 and 1.6μ will be discussed in Part (II) of this paper.

4.3 Intensities of the sun's aureole

4.3.1 Comparison with earlier investigations

Since the phenomenon of aureole is related to the size distribution, chemical component and content of aerosol particles, many authors measured aureole intensities to get information about the atmospheric aerosol particles. However, the photometry of sky radiation in the vicinity of the sun involves some technical difficulties. ANTHONY (1953) measured spectral sky radiation using a spectrometer with a glass prism and a PbS cell, in the spectral range between 0.56 and 2.2μ and in the region of angles larger than 4 degrees from the sun. His results are shown in Fig. 28. As the results of ANTHONY are represented by the ratio of sky radiation to solar radiation reaching the ground, the author's results are shown by the ratios of the aureole intensities to the intensities of solar radiation at the ground for comparison in Fig. 29.

Since 1954, VOLZ published some results of investigations on sky radiation in the atmosphere and he classified the atmospheric turbidity into the following three types according to the form of the angular distribution of sky radiation (1961).

Fig. 28a.

Fig. 28b.

Fig. 28. Spectral distributions of sky radiation measured by ANTHONY (1953).

Fig. 29a.

Fig. 29b.

Fig. 29c.

Fig. 29d.

Fig. 29a, b, c, d. Spectral distributions of aureole intensities measured at Karuizawa and Tokyo, in a unit of solar radiation reaching the ground.

Turbidity type 1—This is characterized by a very steady increase of sky brightness and decreases of bluishness in the vicinity of the sun.

Turbidity type 2—The sun is surrounded by a uniform white disk of nearly constant brightness of about 20 degrees radius.

Turbidity type 3—This is the case of the Bishop's ring; the outer border of the disk is brownish and the inner part is bluish.

VOLZ asserts that the power-law size distribution of aerosol particles ($N \sim r^{-3}$ or r^{-4}) corresponds to turbidity type 2, a deficiency of small particles relative to the power-law distribution leads to turbidity type 1 and turbidity type 3 is caused by an excess of particles with very small radii such as about 0.2μ . The results obtained by VOLZ are represented in Fig. 30. In comparison with these figures, the results obtained by the author show that the angular distribution curves are always steeper than those of VOLZ, especially in the longer wavelength side of the range. Almost all of the author's results show characteristics of turbidity type 1 and a few of them type 2. There is no case of type 3 in the author's results.

In Fig. 30b are shown the results of measurements at FRANKFURT. These curves rather resemble those of the author and show wide variances of the gradient with wavelength. For comparison, the results of VOLZ are shown in Figs. 30c and d, some of them showing the same characteristics of distribution as the author's, but in the region of scattering angle 1 to 2 degrees the curves of the author are steeper than those of VOLZ.

Fig. 30a. Angular distributions of aureole intensities measured by VOLZ.

Fig. 30b. Angular distributions of aureole intensities measured by VOLZ.

Fig. 30c. Angular distributions of aureole intensities measured by VOLZ; in various conditions of the atmospheric turbidity.

Fig. 30d. Spectral distributions of aureole intensities, corresponding to Fig. 30c. (after Volz).

Fig. 31a. Angular distributions of aureole intensities measured by BULLRICH at MAINZ, for the conditions; $Z_{\odot} = 50^{\circ}$, $T = 2.4$ and $V = 10 \text{ km}$, where $Z_{\odot}$: zenith angle of the sun, T : turbidity factor of Linke and V : visibility.

Fig. 31b. Same as Fig. 31a but for $Z_0 = 62^\circ$, $T = 2.45$ and $V = 40 \text{ km}$.

Fig. 31c. Same as Fig. 31a but for $Z_0 = 55.5$, $T = 3.0$ and $V = 10 \text{ km}$.

BULLRICH investigates this problem together with VOLZ and in a recent investigation (1965), he presented the results of measurements of scattered sky radiation. In Fig. 31, his results are shown in the range of scattering angle 1 to 10 degrees and the results of the author are compared with them. The angular distribution curves resemble each other in this case; for example, the curve of Fig. 9c which was obtained at Karuizawa, has a similar feature to that of Fig. 31b. The others also show general similarity to the results of BULLRICH, but the results at Karuizawa have a slightly larger gradient of curves. This fact suggests that the forward scattering effect of the larger particles predominates in the measurements at Karuizawa. In comparing the measurements in Tokyo with that of BULLRICH, one might see that the distribution curves of Tokyo have a larger gradient than BULLRICH's, especially in the longer wavelength side and in the very small scattering angle region. As the result of the comparisons described above, it will be seen that the measurements in Tokyo and Karuizawa have a steeper distribution of the aureole than in Germany, and that the forward scattering due to the relatively large size of particles is predominant in Japan than in Germany. JAENICKE (1964), measuring at Mainz, found that the upper limit of the size of aerosol particles is in the region 50 to 100 μ and BULLRICH calculated that the aureole intensities increase 30 to 50% as the upper limit of size in power-law distribution increases from 3 to 10 μ in radius.

4.3.2 Comparison with recent theoretical investigations

Scattered sky radiation consists of two components: the radiation scattered by the molecular atmosphere, namely, Rayleigh scattering component, and the scattered radiation by aerosol particles, namely, Mie scattering component. The transfer problem in the molecular atmosphere is solved by CHANDRASEKHAR (1950), and the results of numerical solutions are published by many authors (CHANDRASEKHAR and ELBERT 1954; COULSON, SEKERA and DAVE, 1960).

Theoretical treatment of the transfer problem containing the Mie scattering process is very difficult because of the complexity of its scattering function, and the method of approximation is the principal problem. In the case of the sky radiation in the vicinity of the sun (aureole), the forward scattering intensity is very large and the effect of higher order scattering is relatively small, but it has not been confirmed in the case of a very hazy atmosphere whether it can be neglected or not.

DEIRMENDJIAN (1956) calculated the spectral aureole intensities with the expansion of the scattering matrix under a condition in which the scattering angle is very small. The results of calculation are given in Fig. 32, and the spectral distribution of aureole intensities calculated is widely different from that of measurements. The calculated angular distributions are represented by the curves with smaller gradient than that measured by the author. In these calculations, DEIRMENDJIAN applied the following aerosol size distribution:

$$N(r) = c_1 r^{-3/2} \quad \mu^{-1} \quad \text{for} \quad 0.1 \leq r \leq 0.35 \mu,$$

$$= c_2 r^{-4} \quad \mu^{-1} \quad \text{for} \quad r \geq 0.35 \mu.$$

In the previous section, the author emphasized that the proportion of larger sizes of aerosol particles inferred from the present measurements of spectral optical thickness

Fig. 32a, b. Spectral and angular distributions of aureole intensities calculated by DEIRMENDJIAN (in unit solid angle).

is richer than that of the power-law size distribution of aerosol particles. These distributions are very different from that assumed by DEIRMENDJIAN and may produce such intense forward scattering effect as is shown in the results of the measurements.

Recently, BULLRICH, de BARY *et al.* (1963, 1964, 1965) published the results of theoretical investigations of scattered sky radiation. According to their method, the intensity of scattered sky radiation is represented as follows, considering higher-order scattering:

$$I(\lambda, \theta) = \frac{I_0(\lambda) \cdot M[e^{-\tau(\lambda)M} - e^{-\tau(\lambda)M_0}] \cdot f(\lambda, \theta)}{(M_0 - M) \cdot \tau(\lambda)},$$

where, $I_0(\lambda)$ is the extraterrestrial value of solar radiation. $\tau(\lambda) = \tau_R(\lambda) + \tau_M(\lambda)$ and $M_0 = \sec Z_\odot$. $Z_\odot$: zenith angle of the sun, $f(\lambda, \theta)$: scattering function of aerosol particles. De BARY estimated the effect of higher order scattering on sky radiation in the region of angles larger than 10 degrees by the method described above. It must be noted that the number of the parameters on which the intensity of sky radiation depends is so large that comparison of the results of measurements with those of calculation is not simple. The parameters considered are wavelength, sun's altitude, scattering angle, turbidity factor, size distribution of aerosol particles and effective height of the turbid atmosphere. According to the calculation of de BARY, the relative effect of higher order scattering increases as the turbidity factor increases, and the larger the wavelength, the more intense the effect. She also estimated the dependency of the intensities on the size distribution, that is, computed the ratio of the sky radiation $I(\beta=3)$ to $I(\beta=4)$, assuming the power-law distribution, $dN(r)/d(\log r) \sim r^{-\beta}$. From Fig. 3 of the paper of de BARY, we can see the following values of the ratios in Table 4.

In general, the relative increase of the number of larger particles increases the forward scattering intensities in the long wavelength side in the visible region.

Table 4. The ratio of $I(\beta=3)$ to $I(\beta=4)$ after de BARY

$\lambda(\mu)$	$Z_0=23^\circ$		53°		78°	
	$T=2$	4	2	4	2	4
0.40	1.05	1.00	1.00	1.30	1.00	1.30
0.55	1.21	1.25	1.25	1.20	1.12	1.22
0.65	1.40	1.43	1.43	1.12	1.32	1.20

De BARY and BULLRICH (1963, 1964) calculated the effect of the relatively large particles on the angular distributions of aureole intensities in the case of power-law size distribution of aerosol particles, taking the ratio of sky radiation for the distribution with maximum radius of particles of 3μ to that of 10μ radius. Fig. 33 shows the effect of the relatively large particles. The values of scattered sky radiation calculated by them are rewritten in the figures so that the several cases may be compared with each other. In these figures, one might see that an increase of the relatively large particles causes an increase of forward scattering intensities, especially in the region of scattering angles smaller than 5 degrees.

The results of observations in Tokyo and Karuizawa will be compared with these features shown in Figs. 33a, b and c. The results of Karuizawa are shown in Figs. 9, 18, 19 and 20 (October 15 and 16, 1965). In the early morning a dense fog was observed each day and the results obtained before noon will be considered to contain local effects. Since the synoptic weather maps of these two days show that the anticyclone following the cold front which passed at the midnight of the 14th, covered the Japan Islands for three days, October 15, 16 and 17, the results obtained in the afternoon will be considered to contain no local effects.

The values of optical thickness obtained on these two days show that the values in the morning are rather large on both days, and their spectral distributions are both very flat. This may be due to the local effects, such as the fog. The percentage of the larger particles will be considered rather large relative to that of power-law distribution. In the afternoon, the spectral distribution of optical thickness seems to be free from local effect.

The angular distribution of the aureole intensities obtained on the morning of Oct. 15 is steeper than that on the afternoon (Figs. 18c and 9c). One might see, considering the results of Fig. 33a, b and c, that the effect of larger particles is more predominant in the morning than in the afternoon. The results of 16th (19c and 20c) show the same features of angular distributions as those of 15th. The angular distribution of the morning of 16th contains remarkable variance of the gradient of the curve with wavelength, and it shows considerable departure from the features of turbidity type 2 of VOLZ.

The meteorological conditions on the days of observation are described in Table 3 and in this table, one can see that the visibilities at the station remained constant around 50 km. throughout the two days, but the relative humidity considerably changed, the values observed in the morning being relatively high. From this, it will be suggested that the water vapor content in the atmosphere should be considered in optical determination of the size distribution of aerosol particles.

Fig. 33a.

Fig. 33b.

Fig. 33a and b. Effect of relatively large particles on the angular distributions of aureole intensities (after de BARY and BULLRICH).

Fig. 33c.

Fig. 33d.

Fig. 33 c and d. Effect of relatively large particles on the angular distributions of aureole intensities (after de BARY and BULLRICH).

In the results of Tokyo, the measurements in October and November were performed in the migratory anticyclones after the passage of rather strong depressions, and the measurements in December were performed in the continental air mass immediately after the passage of the cold front with strong northwest winds. The values of visibility are shown in Table 3. The artificial air pollution at the station is smaller than that at the center of the city, but the time variation of the quantity of aerosol particles caused by the wind is rather large, and especially the southeast wind makes measurement difficult because of the large fluctuations of turbidity during the measurement. On November 1 and December 13, the fluctuations were smaller than on other days. The results obtained on these two days (Figs. 12, 16 and 21) show that the aureole intensities are larger than those of Karuizawa; especially in the data of Nov. 1, they are very large in the long wavelength side. On Nov. 1, the weather was very stable until about 10h a.m., but at 11h a.m. the sky was covered with thin cirrus. From the synoptic weather map, we can see that the measurement was performed under the condition in which the warm front was approaching the station.

On Dec. 13 the sky of Tokyo was in a typical winter condition of this city: the weather conditions showed no remarkable variation the whole day, with a visibility of more than 10 km, the atmosphere being clear in the morning, increasing turbidity toward noon, and becoming clearness later. Figs. 16a, b and c represent the distribution corresponding to the state at morning and Figs. 21a, b and c represent the distribution corresponding to the state at noon at which the atmospheric turbidity has increased. The variation of the form of the angular distribution curves with wavelength obtained in the morning is smaller than that at the noon. It is seen in Fig. 21c that the forward scattering by larger particles is stressed in the smaller scattering angle region as the atmospheric turbidity increased.

The spectral distributions of optical thickness measured in Tokyo on October 28 and November 12 (Figs. 10a and 11a) show the linear functions of wavelength which correspond to the power-law size distribution of the particles. The angular distributions of the aureole intensities on both days represent very small variations with wavelength, but these curves are all steeper than that of turbidity type 2 of VOLZ.

The results of measurements on Dec. 25 (Fig. 17a, b and c) were obtained under sky conditions in which, as on Dec. 13, the anticyclone covered the Japan Islands after the passage of the cold front, but the visual range from the station was smaller than 10 km., and the fluctuation of atmospheric turbidity was very large. The most remarkable difference of this result from that of Dec. 13 appeared in the spectral distribution of aureole intensities, and the distribution of Dec. 25 shows very small values in the UV region.

Thus, the results of our measurements show that the aureole intensities are intensified in the longer wavelength side and its angular distributions represent a strong forward scattering in the vicinity of the sun. From this, it can be suggested that the percentage of larger particles is predominant in the size distribution of aerosol particles. The number of measurements, however, is not large enough for us to draw a conclusion on the behaviour of the size distribution of aerosol particles. It will be necessary to make measurements in the infrared region in order to dis-

cuss these problems in more detail.

In the investigation published in 1961, VOLZ discussed the nature of aerosol particles. The angular distributions of the aureole intensities obtained at MAINZ in 1958 (Fig. 30), which are classified in turbidity type 2, show that the form of angular distributions does not vary appreciably with wavelength in the UV and the visible region but the form in the near infrared region is quite different from the former. It is difficult to explain this phenomena only by the size distribution of aerosol particles. VOLZ estimated the values of the index of refraction of the particles for these results on angular distributions as follows: $n \sim 1.33$ for the visible region and $n \sim 1.56$ for the near infrared region. From this, he asserted that the values of the index of refraction of the particles vary with the size of particles. It is necessary to study how the variation of refractive index of particles with radius affects the form of angular distribution of aureole intensities.

Together with continuing the present measurements, we will extend the measurements into the near infrared region in order to get the size distribution of particles more precisely and reasonable explanation of the form of angular distribution.

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太陽直射光および周辺光の分光測定 (I)

— 装置及び紫外可視領域の測定 —

村 井 潔 三

太陽の直射光および周辺光を波長別に測定する目的で分光日射計を設計した。装置は集光用望遠鏡を石英プリズムの複式分光計に取付け、入射光を交流化して二次電子増倍管あるいは PbS セルで検出して増巾記録させるものである。望遠鏡の開口角は極力小さくし、太陽の中心から1度外れた方向からの天空光を直射光に影響されることなく測定し得る様に設計されている。測定波長域は 0.35μ より 1.6μ の間で、 $0.35\sim 0.75\mu$ を二次電子増倍管により、 $0.65\mu\sim 1.6\mu$ の間を PbS セルで検出する。

測定は快晴時に行ない、種々の太陽高度に対応する直射光および周辺光の強度を測定する。周辺光の測定は、太陽の中心から天頂の方向に $1^\circ\sim 15^\circ$ の間の領域について、太陽鉛直面内で行なう。

直射光の測定を用い、Bouguer-Langley の方法により、大気外の日射強度に対応する値を求め、測定値

は凡てこの値を単位として表わす。したがって、現在得られる大気外日射強度の値を用いてエネルギーの絶対値が得られる。

直射光の測定から得られる大気の光学的厚さの波長分布の形から大気中の aerosol 粒子の粒径分布を推定する目的で、FOITZIK の計算結果との比較を行ない粒径分布についての推論を行った。

周辺光の測定結果は、VOLZ および BULLRICH の測定結果との比較を行ない、de BARY および BULLRICH の計算結果との比較を行った。測定によって得られた周辺光強度は、大気外値に対し、 $10^{-4} \sim 10^{-6}$ 程度の値を示し、VOLZ, BULLRICH の測定結果と比較すると、角度分布の形は、forward scattering が強調された傾向を示している。

以上の比較の結果として、測定結果から推定される粒径分布としては、いわゆる、power-law 分布から外れるものが多く認められ、粒子の半径の大きい領域において、power-law 分布よりも大きくなっている事が推論される。