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OBSERVATIONS OF THE TOTAL SOLAR ECLIPSE OF 7 MARCH, 1970

BY

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ABSTRACT

Observations of the flash spectrum of the chromosphere, the slit spectrum of the inner corona, and the direct photograph of the corona were made at the 7 March, 1970 eclipse at Puerto Escondido, Mexico. The flash spectrograms in the visual region covered the wavelength range of 4650 to 6800 Å in an average plate dispersion of 19 Å/mm. They contained the coronal lines FeXIV λ 5303 and FeX λ 6374 in chromospheric heights below 10,000 km to which a special interest was attached in our observations. The height resolution of the flash spectrograms was about 220 km in heights below 2000 km, and about 760 km in greater heights. The slit spectrograms in the same wavelength range were suitably exposed for the coronal lines NiXIII λ 5116, FeXIV λ 5303, FeX λ 6374, and NiXV λ 6702 and the continuum. The direct photographs of the corona were obtained in the light of the wavelength range from 5500 to 6700 Å.

A detailed description is presented on the instruments, the observations, and the photometric calibration procedures. A discussion is also included of the acquisition in the eclipse observations.

1. Introduction

The Kwasan and Hida Observatories Group consisting of the present authors observed the total solar eclipes of 7 March, 1970 at Puerto Escondido, Mexico. It was the first aim of our observations to obtain the flash spectrograms which permit to measure the intensities of coronal lines against chromospheric heights below 10,000 km. This experiment was attempted from the suggestion by one of the authors (Kanno 1966) on purpose to determine the temperature and density structures in the interspicular medium and to find the height above the Sun's limb where the transition region between the chromosphere and corona is located. Our observations of the flsah spectrum were focused on FeXIV λ 5303 and FeX λ 6374 in the visual region and FeXI λ 7892 in IR region. The remaining light in UV region was used to observe CaII H and K lines as supplementary data of the chromosphere itself.

A similar measurement was made by Athay and Roberts (1955) on the slitless spectrograms at the 1952 eclipse. Although they obtained the integrated intensity of FeXI λ

7892 as a function of height between 3000 and 46,000 km, the data were not accurate enough to give the detailed shape of the intensity vs. height curve. Accordingly, we intended to obtain the data of the coronal lines to the lowest possible height with a greater height resolution. At the 1966 eclipse Weart (1968) made the photoelectric observations of FeXIV λ 5303 and FeX λ 6374 in heights below 10,000 km at the second and third contact points. He inferred the physical property of the interspicular medium from the data.

The second aim of our observations was to obtain the slit spectrograms and the direct photographs of the inner corona. This experiment was made on purpose to study fine structures in the inner corona by analyzing the two simultaneously. At the 1952 eclipse a series of slit spectrograms of the inner corona were obtained at all position angles by Lyot and Aly (Aly, Evans, and Orrall 1962). Orrall et al. carried out a similar observation at the 1965 eclipse (Jefferies, Orrall, and Zirker 1971). In order to increase the spatial resolution, we adopted an optical system which produced a solar image of a greater size.

Our purpose in this paper is to describe in detail the observing instruments, the program and results of the observations, and the procedures of photometric calibration. A brief discussion will be also given of features in the spectrograms and the direct photographs we obtained.

2. Instrumentation

In the eclipse observations we used an optical system illustrated in Figure 1. A coelostat M_1 and a secondary mirror M_2 with a 30-cm aperture were arranged so that the Moon's motion relative to the Sun was in a horizontal direction along the dispersion of the spectrograph. An objective L_1, which was an achromatic lens with a 30-cm aperture and

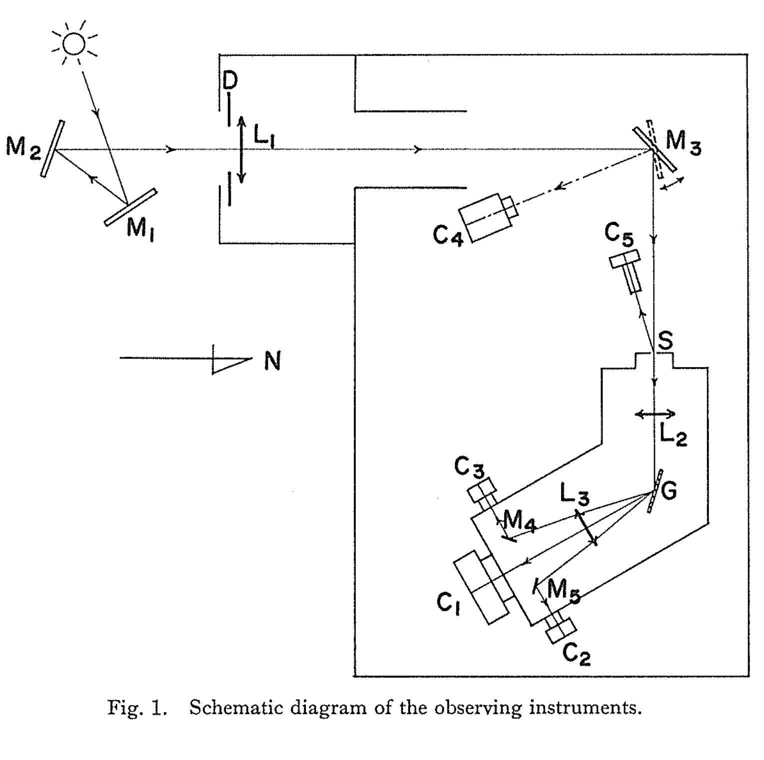


Fig. 1. Schematic diagram of the observing instruments.

a 459.3-cm focal length at the effective wavelength of 6100 Å, produced a solar image of 43.1 mm in diameter. The apertures of M_1 and M_2 were not so large that L_1 was fully illuminated. The light was thrown only onto an elliptical zone in the central part of L_1. Accordingly, an elliptical diaphragm being fully illuminated was always placed in front of L_1 in order to increase accuracy in absolute photometry. The aperture of the diaphragm was equivalent to a circular one of 205.6 mm in diameter. In addition to the elliptical diaphragm we prepared other two circular diaphragms with a 149.3-mm and a 15.19-mm aperture to reduce the light intensity. The former was used for the direct photographs of the corona and the latter for the spectrograms of the partial Sun and a series of calibration exposures on the Sun's disk made both before and after the eclipse.

A plane mirror M_3 of 25 cm in diameter was rotatable round a vertical axis by a given angle to lead the light to the spectrograph or the camera for direct photograph. For the flash spectra a wide curved slot was placed at the entrance focal plane S of the spectrograph to transmit the light from one limb and occult the other. For the slit spectra the slot was replaced by a slit of 0.34 mm in width and 20.2 mm in height. One D2 and two D1 neutral filters were able to be put before and behind S, respectively. Combinations of the filters permitted to reduce the light intensity by a factor of 10, 10^3, or 10^4. These filters were used for the spectrograms of the partial Sun and the calibration exposures. Both a collimator L_2 and an imaging lens L_3 were a wide-angle triplet with a 14-cm aperture and a 70-cm focal length. Bausch & Lomb plane replica reflection grating G, which was ruled with 600 grooves/mm over a 212×127 mm^2 surface and had a blaze wavelength of 1 μ at the first order, produced a spectrum of the first order from 3700 to 8100 Å with an average plate dispersion of 19 Å/mm. Small plane mirrors M_4 and M_5 were to direct the light to cameras C_3 and C_2, respectively.

We used five cameras for performing the observations. The visual spectrum from 4650 to 6800 Å was covered by a camera C_1 which was an aerial survey camera with a frame size of 125×125 mm^2 modified to meet our purpose. Nikon motor-driving 35-mm cameras C_2 and C_3 were used for the UV (4100 ± 200 Å) and IR (7850 ± 200 Å) spectra, respectively. Appropriate filters were placed directly in front of C_1, C_2, and C_3 to block spectra of the higher orders. The direct photographs of the corona were taken by a camera C_4 which was a box camera of cabinet size (119×164 mm^2) having a large Thornton shutter of 13.5 $\times$ 18.0 cm^2. Kodak Wratten No. 21 filter was placed close to the final focal surface of C_4. The combination of this filter and the emulsion we used enabled us to make the direct photographs in the light between 5500 and 6700 Å. This allowed to exclude the intense light of FeXIV λ 5303 and to obtain an image of good quality being virtually unaffected by chromatic aberration. Another Nikon motor-driving 35-mm camera C_5, which was provided with a telephoto lens of a 135-mm focal length, was used for photographing the slit surface during exposure of the slit spectra to monitor the slit position on the solar image. The times of opening and closing of the shutters of all the cameras were recorded in a 6-channel pen-writing recorder together with the time marks from the chronometer. The cameras C_1, C_2, and C_3 of the spectrograph were semi-automatically operated in sequent exposures by a single control system according to the observing program described in Section 3.

3. Observations

Puerto Escondido is a small village on the Pacific coast which is situated about 400 km south-east of Acapulco along Route 200. The Japanese expedition, being composed of three groups from the Tokyo Astronomical Observatory, the Hydrographic Department, and the Kwasan and Hida Observatories, selected the observing site in the flat grounds of the power plant (Comision Federal de Electricidad) in this village. According to the equal altitude observations by the group of the Hydrographic Department (Mori and Kubo 1971), the astronomical longitude and latitude of the site are 97° 04' 26" W and 15° 51' 54" N. This location is 93 m above the mean sea level and 28 km north of the eclipse central line. The predicted times of second and third contacts at the site, computed by the Hydrographic Department, were 17h 27 m 16.27s UT and 17h 30m 32.85s UT, respectively, and the altitude of the Sun was approximately 62 degrees. A more detailed description of preparations and arrangements for the Japanese expedition has been given by Saito, Makita, Hata, and Tojo (1970).

Climatic conditions were excellent during the eclipse. The sky was completely cloudless, the wind velocity moderate, and the atmospheric transparency extreme. The observations were carried out according to the instructions tape-recorded in advance. The observing program is summarized as follows, in which the origin of time is at the predicted time of second contact.

(i) −10 m∼−9 m: Exposures for absolute calibration of the direct photographs of the corona (four frames in C_4).

(ii) −70 s∼−60 s: Exposures for absolute calibration of the flash spectra (sequent exposures of 0.2 s in C_1 and 4 s in C_2 and C_3).

(iii) −20 s∼40 s: Flash spectra of the extreme limb and the chromosphere (sequent exposures of 0.2 and 2 s in C_1, 0.2, 1, and 4 s in C_2, and 1 and 4 s in C_3).

(iv) 45 s∼1 m 40 s: Direct photographs of the corona (four frames of 1, 2, 5, and 10 s exposures in C_4).

(v) 1 m 45 s∼2 m 25 s: Slit spectra of the inner corona (three frames of 1, 5, and 25 s exposures in C_1, C_2, and C_3 and monitoring pictures of the slit surface in C_5).

(vi) 2 m 35 s∼3 m 35 s: Flash spectra of the chromosphere and the extreme limb (sequent exposures of 2 and 0.2 s in C_1 and 4 and 1 s in C_2 and C_3).

(vii) 4 m 20 s∼4 m 30 s: Exposures for absolute calibration of the flash spectra (sequent exposures of 0.2 s in C_1 and 4 s in C_2 and C_3).

(viii) 15 m∼16 m: Exposures for absolute calibration of the slit spectra of the inner corona (several exposures in C_1, C_2, and C_3 and monitoring pictures of the slit surface in C_5).

When taking the flash spectra, we switched the exposure time of each camera and selected an appropriate combination of the diaphragms and the filters as the eclipse was progressing in order to attain a suitable exposure in each frame. The interval between the end of one exposure and the beginning of the next was less than 0.6 s in C_1 and 0.3 s in C_2 and C_3. In the following we list the materials obtained in the observations.

(i) Flash spectrograms of the chromosphere and the extreme limb

a) visual region
wavelength range: $\lambda\lambda$ 4650–6800
emulsion: Kodak Tri-X Aerocon (Type 8403)
height resolution: 220 km ($h \lesssim 2000$ km) and 760 km ($2000 \lesssim h \lesssim 10{,}000$ km)
number of frames: 33 at second contact and 32 at third contact
development: 8, 12, and 20 min in D-76 at 20°C for the second contact frames

and 27 min in D-76 at 20°C for the third contact frames.

b) IR region
wavelength range: $\lambda\lambda$ 7650–8050
emulsion: Kodak Infrared (IR 135)
number of frames: none at second contact and 5 at third contact
development: 20 min in D-19 at 20°C.

c) UV region
wavelength range: $\lambda\lambda$ 3900–4300
emulsion: Kodak Tri-X Pan (TX 402)
number of frames: 39 at second contact and 17 at third contact
development: 20 min in D-19 at 20°C.

(ii) Slit spectrograms of the inner corona in the visual region
wavelength range: $\lambda\lambda$ 4650–6800
emulsion: Kodak Tri-X Aerocon (Type 8403)
development: 27 min in D-76 at 20°C
exposures: three frames of 0.49, 3.91, and 21.86 s.

(iii) Direct photographs of the corona
effective wavelength: λ 6100 ($\lambda\lambda$ 5500–6700)
emulsion: Oriental Hyperpan
development: 8.5 min in D-76 at 20°C
exposures: four frames of 0.64, 1.64, 4.51, and 9.12 s.

(iv) Monitoring pictures
emulsion: Fuji SS
development: 12 min in D-76 at 20°C
exposures: thirteen frames of 1.8 s during exposure of the slit spectra and three frames of 1/500 s during exposure of the calibration slit spectra.

The flash and slit spectrograms in the visual region and the direct photographs were of fine quality. During the sequent exposures of the flash spectra, however, there occured an incomplete operation of the IR camera. Owing to the accident we were unable to obtain the desired data on FeXI λ 7892 in chromospheric heights. The slit spectra in the UV region contained CaII H and K lines of prominences, but those in the IR region were underexposed for FeXI λ 7892. It was found from the records of the pen-writing recorder that the slit spectrograms and the direct photographs, which were manually exposed, had shorter durations of exposure than those in the observing program.

4. Photometric Calibration

4-1 Characteristic Curves

To serve for the determination of characteristic curves, a number of calibration exposures of the Sun's disk were made on the day before the eclipse and after third contact. The exposure times of the flash spectra of the visual region were 0.2 and 2 s. It was found that the characteristic curves derived from the short and long exposures of the calibration spectra run practically parallel, so that they were combined into a single curve. On the other hand, they were somewhat dependent on wavelength in the observed wavelength range of 4650 to 6800 Å (the longer the wavelength, the larger "gamma" becomes). Therefore, we constructed the characteristic curves at four wavelengths 4700, 5300, 6374, and 6700 Å for the second and third contact spectra. It was found that the characteristic curves for the slit spectra were almost identical in shape with those for the flash spectra at third contact, so that we adopted the latter in reduction of the slit spectra.

The characteristic curves for the direct photographs were constructed for each of the eclipse exposures. Since the reduction factor of light intensity in the calibration exposures is known, they may serve also for absolute calibration if it is assumed the transparency of the sky to be identical between the eclipse day and the day before the eclipse when the calibration exposures were taken. It turns out that the results are in agreement within the accuracy of photometry with those derived from the exposures for absolute calibration made before second contact.

4-2 Absolute Calibration

The standardization of absolute intensity in the flash spectra was done by using the available data of the limb darkening and the absolute intensity of the continuum at the disk center of the Sun. This method has already been used at earlier eclipses (Suemoto and Hiei 1962; Kurokawa, Tominaga, Kubota, and Kawaguchi 1969) and thus is briefly described here. As mentioned in Section 3, the slitless spectrograms were obtained in the partial phases of the eclipse from 70 s prior to second contact and till 70 s after third contact.

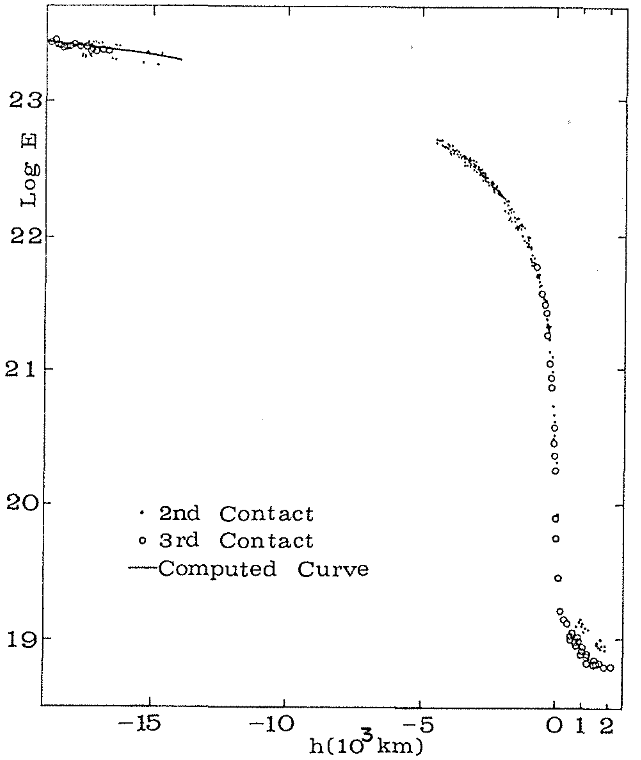


Fig. 2. Eclipse curve of the continuum at 6690 Å. The integrated intensity E is in units of erg cm^{-1} s^{-1} sterad^{-1} Å^{-1}. The dots and the open circles show the measurements at second and third contact, respectively. The full line is computed from the empirical formula of the limb darkening by Pierce and Waddell (1961) being standardized by the absolute intensity at the disk center tabulated by Allen (1963).

The observed range corresponded to the Sun's disk with $\cos\theta \lesssim 0.23$. First, we plotted the integrated intensities of the continuum at several beads above the Moon's limb against distance on the Sun's disk with an arbitrary zero point. Shifting the plots of each bead along the distance scale so that all of the plots form a single smooth curve, we got the eclipse curve of the continuum. As an example, the eclipse curve at 6690 Å is illustrated in Figure 2. Finally, we fitted the eclipse curve to the curve of the integrated intensity of the continuum computed from the available data of the limb darkening and the absolute intensity of the continuum at the disk center of the Sun. These data have been well established for the wavelength range we observed and for the Sun's disk with $\cos\theta \gtrsim 0.2$. We adopted the empirical formula derived by Pierce and Waddell (1961) for the limb darkening and Allen's (1963) table for the absolute intensity at the disk center. As seen in Figure 2, the fitting was done at the points on the Sun's disk with $\cos\theta \gtrsim 0.2$, so that we were able to obtain the absolute scale of intensity with a probable error less than 0.1 in logarithm. The whole procedure was carried out for six wavelengths 4700, 4895, 5303, 5903, 6375, and 6690 Å.

The exponent p of Schwarzschild for the flash spectrograms of the visual region was determined from comparison of the continuum intensities in successive exposures of the flash spectra. We found $p=0.83$ at 5303 Å and 0.85 at 6374 Å. They were in reasonable agreement with those derived from shifting of the characteristic curves of the calibration spectra with different exposure times. The zero point for the height scale was chosen in the usual way to be the inflection point in the plots of continuum specific intensity against height. From measurements for the six wavelengths the zero point was determined in accuracy within ± 30 km.

The standardization of absolute intensity in the slit spectra was performed by using the calibration spectra of the Sun's disk at $\cos\theta=0.2$ which were exposed on the eclipse film roll after third contact. Since only the calibration spectrogram of 3.96-s exposure had a suitable density for photometry, we had to determine the exponent p of Schwarzschild for the slit spectrograms. This was done by comparing the intensity of the continuum at 6100 Å on the slit spectra with that on the direct photographs at the position where the slit was located. Thus we obtained $p=0.85$ at 6100 Å which is in close agreement with that for the flash spectrograms. The p-factors at other wavelengths were determined by assuming the intensity distribution of the coronal continuum to be identical with that of the solar spectrum at the disk center with spectral lines smoothed.

In order to serve for the standardization of absolute intensity in the direct photographs, we impressed the partial Sun on other plates in the same package as used for the eclipse observation before second contact. Since the sky conditions were very stable through the eclipse, it was possible to perform the absolute photometry with satisfactory accuracy. For example, there was no discrepancy larger than 10% between the absolute intensities derived from the direct photographs of the 0.64-s and 4.51-s exposures.

5. Discussion

As stated in Section 1, the primary purpose of our observations was to measure the intensities of coronal lines in the flash spectra as a function of height in the chromosphere. Since coronal lines show weak and broad features in a slitless spectrum, we adopted the spectrograph with a rather low dispersion to make a brighter spectrum. Meanwhile, the angle of incidence on the grating was made much larger than the angle of diffraction. This caused a decrease in the image size along the dispersion by a factor of about 2.5 and an increase in the central intensities of the spectral lines. These were greatly convenient for photometry of the coronal lines in the flash spectrograms.

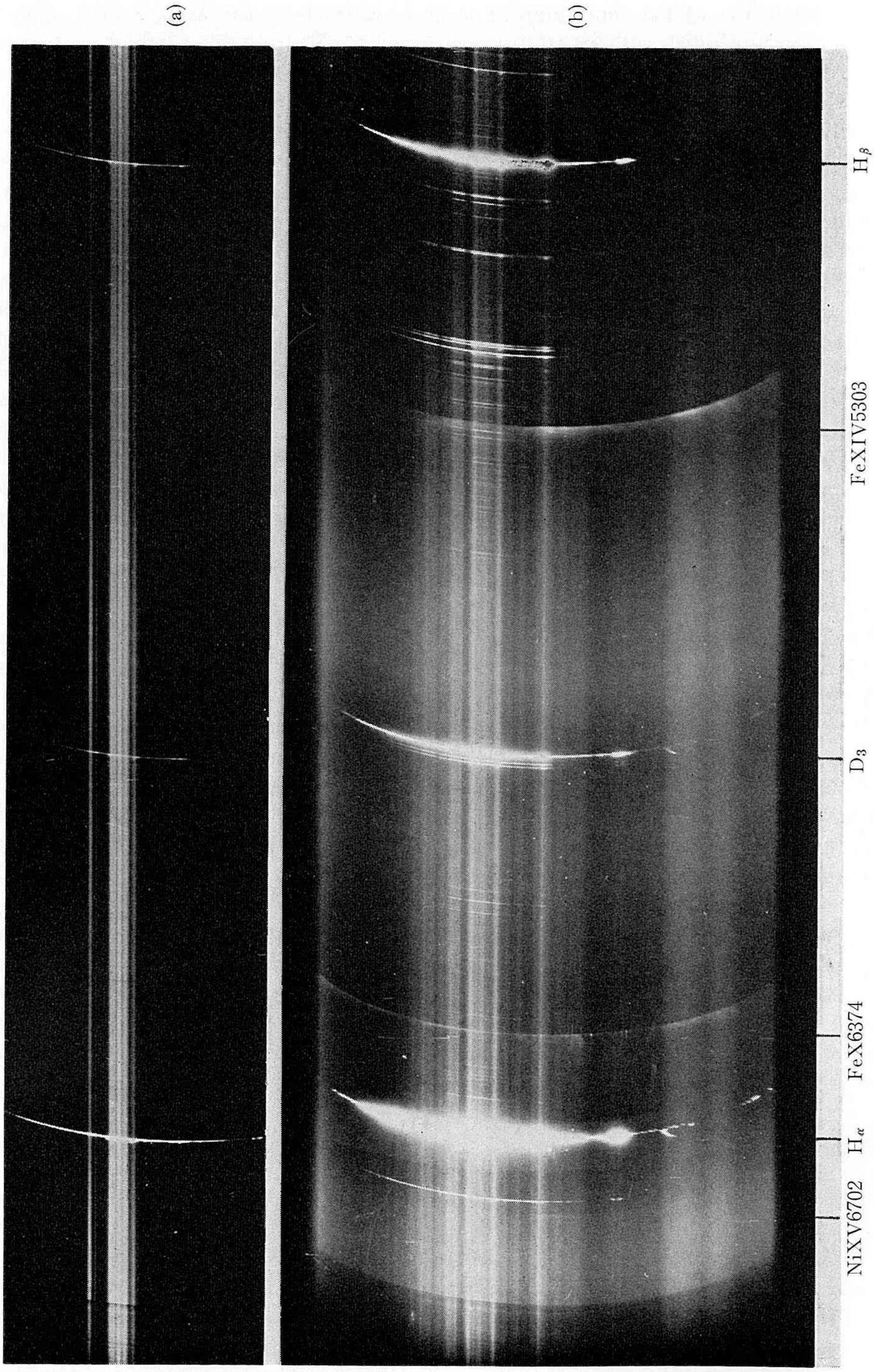


Fig. 3 (a). Flash spectrum of the visual region at 2.4 s prior to second contact.
Fig. 3 (b). Flash spectrum of the visual region at 1.6 s after second contact.

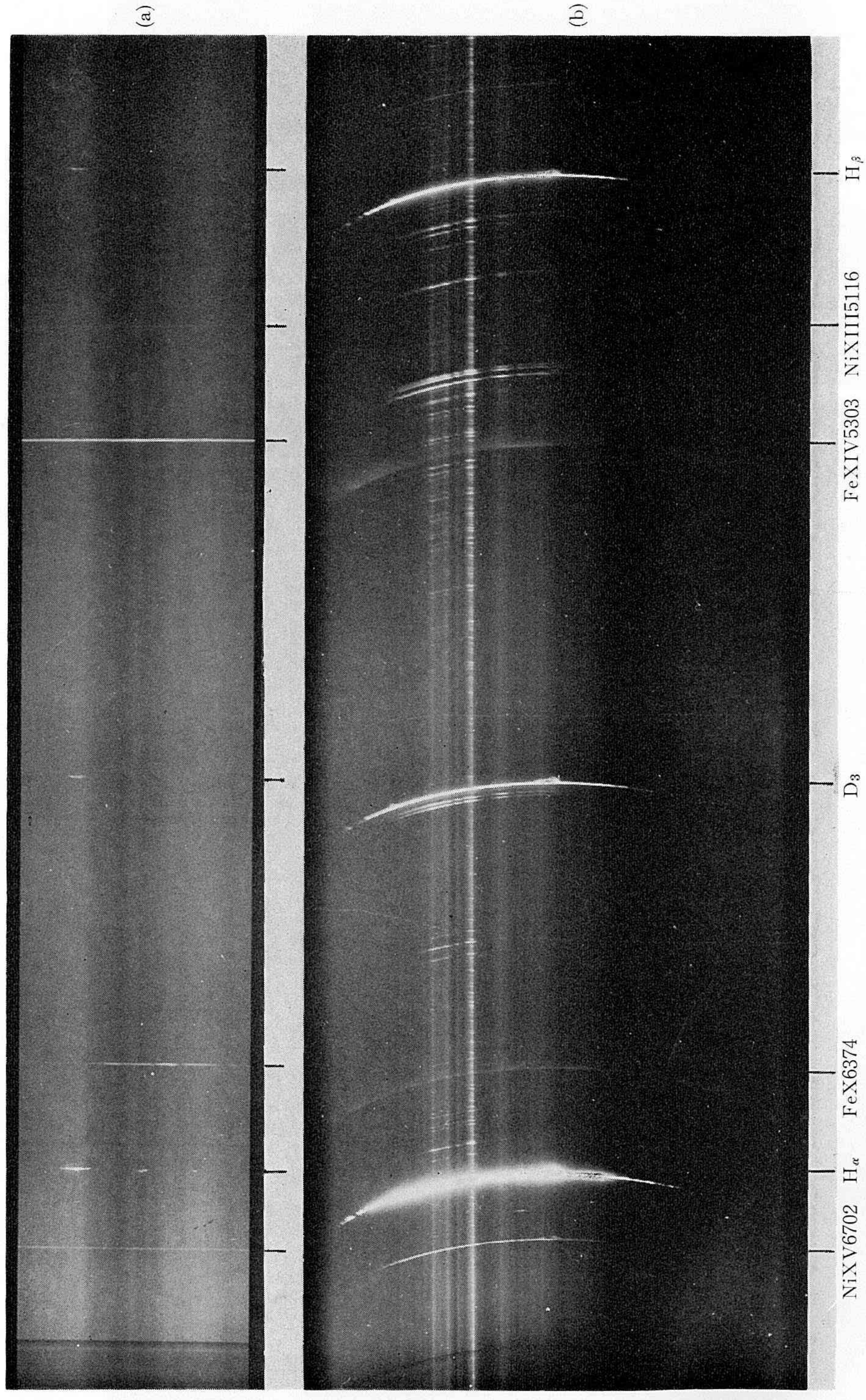
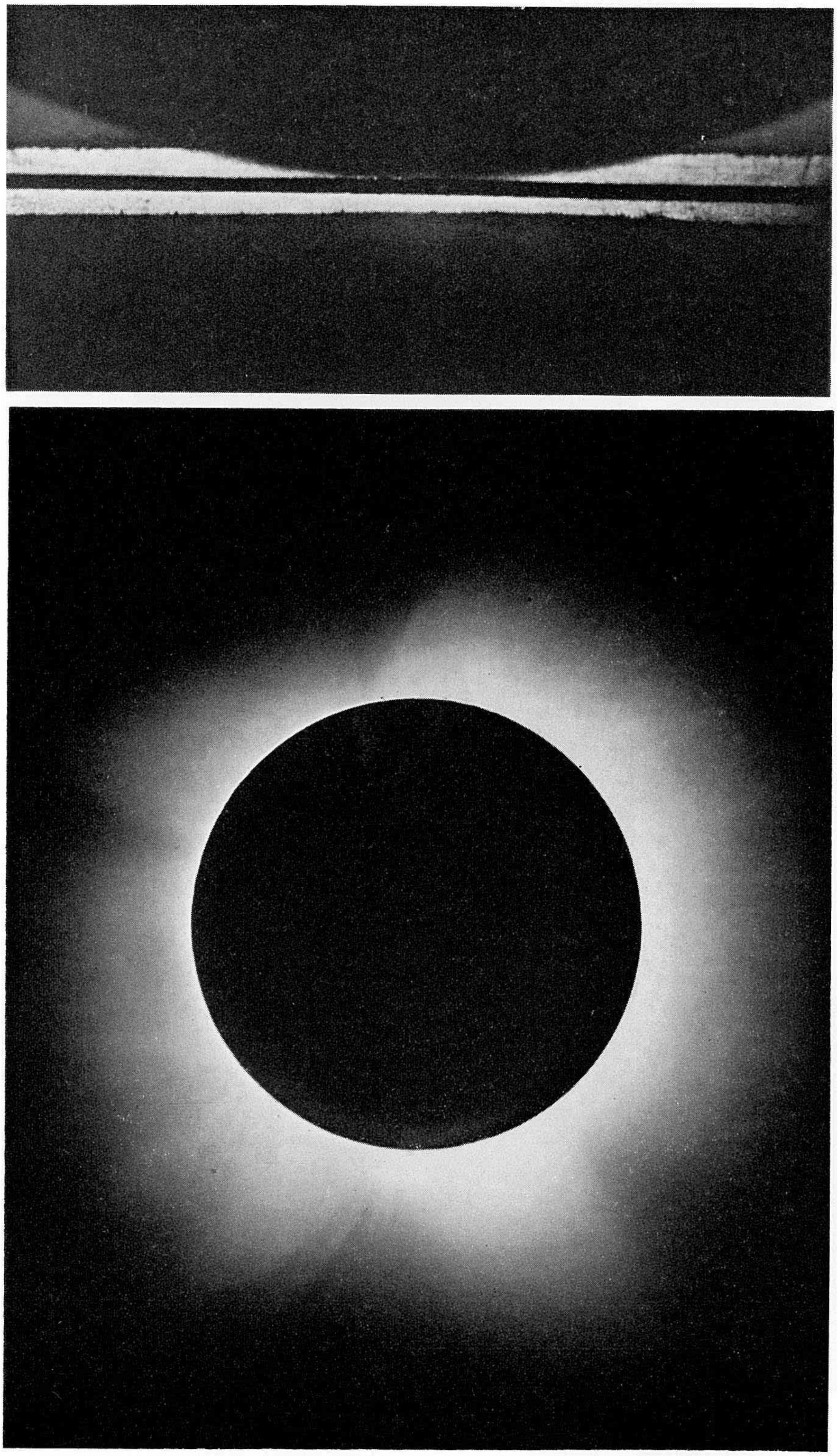


Fig. 4 (a). Slit spectrum of the inner corona of 21.86-s exposure.
Fig. 4 (b). Flash spectrum of the visual region at 0.8 s prior to third contact.



(b)

(a)

Fig. 5 (a). Direct photograph of the corona of 9.12-s exposure. North is lower left and east is upper left.
Fig. 5 (b). Monitoring picture of the slit surface during exposure of the slit spectra of the inner corona.

As seen in Figures 3 (b) and 4 (b), in the flash spectrograms of the visual region the coronal lines FeXIV λ 5303 and FeX λ 6374 appear with a measurable photographic density in spite of rather short exposure times. The good success will be attributed to the use of the low-dispersion spectrograph and the grazing incidence method. Both the coronal lines and the continuum at four regions on the west limb, which were selected for the lack of active features, were analyzed by Kanno, Tsubaki, and Kurokawa (1971) to deduce the temperature and density distributions in the interspicular region down to 1000 km.

The flash spectra at low heights contain many emission lines of the chromosphere and prominences besides the coronal lines. It is expected strong lines of a prominence to reveal its monochromatic images in the flash spectra due to the low spectral dispersion. Using one of them at third contact, Kubota, Tamenaga, and Yoshikawa (1972) carried out an analysis how the intensity ratios of D_3 to H_β and D_3 to HeI λ 6678 vary in different parts of a large quiescent prominence.

We began a continuous run of exposures of the flash spectrum at 20 s prior to second contact. At third contact we continued it till 20 s after the contact. Owing to particular care devoted to proper exposure in each frame, we were able to obtain a number of slitless spectrograms of the shrinking crescent of the Sun's limb, such as Figure 3 (a), which were suitably exposed for the continuum. An analysis of the continuum of the extreme limb has been carried out using these spectrograms to study the physical conditions in the photosphere-chromosphere transition region. The results will be published elsewhere.*

Figure 4 (a) shows the slit spectrum of the visual region with the longest exposure time. The coronal lines NiXIII λ 5116, FeXIV λ 5303, FeX λ 6374, and NiXV λ 6702 and the continuum, together with H_α, H_β, and D_3 of prominences, were suitably exposed. The intensity of the coronal lines may be assumed to represent the surface brightness because of the low spectral dispersion and the wide slit width. It is seen in Figure 4 (a) that FeX λ 6374 shows a peculiar distribution of the surface brightness compared with those of other coronal lines and the continuum. The measurements of the intensity distribution of the four coronal lines and the continuum as a function of distance along the slit were carried out by Tsubaki, Kurokawa, and Kanno (1971). One of the monitoring pictures is reproduced in Figure 5 (b). They provided valuable information as to the position of the slit relative to the Moon's disk and finally to the Sun's disk.

During totality the direct photographs of the corona were made with four different exposure times. Figure 5 (a) shows the longest one which clearly displays fibrous fine structures in the corona as far as about $2R_\odot$. The shortest one also shows such fine structures in the innermost corona together with the images of prominences. In order to study the density structure of the corona, an analysis of the direct photographs is now being carried out. By combining the data from the direct photographs and the slit spectra, we expect to clarify the physical conditions in the inner corona, especially around two large streamers seen in the north-east hemisphere where the slit was placed.

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* Kurokawa, Nakayama, Tsubaki, and Kanno (1974).

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