PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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High resolution interferometric studies of the solar magnesium II doublet spectral region

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[Plate 3]

INTRODUCTION

The resonance lines of Mg II (λ = 279.55 and 280.27 nm) are just beyond the extinction limit of the Earth's atmosphere. Because of the high cosmic abundance of magnesium, these lines are particularly important in ultraviolet astronomy and with the extension of interference spectroscopy into the far ultraviolet (Bradley 1968), sophisticated optical techniques can now be employed at these wavelengths. On the Sun, the Mg II resonance lines consist of a broad absorption with a pronounced emission core similar to the H and K lines of Ca II, but with more prominent emission and absorption features, so that the Mg II H and K lines are much more sensitive indicators of chromospheric phenomena. The discovery (Kachalov & Yakovleva, 1962) of structure in the emission core, giving a doubly reversed profile, confirmed the similarity with Ca II.

The structure of the emission core was well resolved in high resolution (*ca.* 3 pm) echelle spectrograms obtained with a Sun-pointed rocket (Purcell, Garrett & Tousey 1963). These echelle line profiles were, however, composite ones averaged over one third of the solar disk, so that it was not possible to distinguish between profiles from quiet and active regions, or to determine centre-to-limb variations.

High resolution (4.5 pm) stigmatic spectra, with spatial details of 10″ resolved along the spectrograph slit, were obtained with balloon-borne echelle spectrographs (Lemaire & Blamont 1967; Lemaire 1969) and gave for the first time information on the centre-to-limb variations of the line profiles. About the same time a Fabry–Perot interferometer, internally mounted in an echelle spectrograph, was flown on a stabilized Skylark rocket to obtain spatially resolved profiles of the Mg II doublet spectral region, with a resolution limit of 3 pm (Bates *et al.* 1969). A second echelle-interferometer spectrograph with an improved design which more fully exploited the advantages of the interferometer, was successfully flown in November 1969. The resolution limit was improved to 1.6 pm and the number of fringes, and hence line profiles, simultaneously recorded for each spectral line was increased from 10 to 20. We wish to report preliminary results obtained from the data recorded during this recent flight.

THE ROCKET SPECTROGRAPH

Figure 1 shows the optical arrangement of the spectrograph and indicates its location in the head section of the rocket. The entrance slit width of 98 μm is equivalent to 22″ on the solar disk, and the slit extended across about 90 % of the solar diameter, including one limb. Spectral filtering of the solar radiation is achieved with a thin Spectrosil prism and the resulting dispersed spectrum is focused on to the slit of a Czerny–Turner echelle (300 grooves/mm) spectrograph. The echelle isolates a spectral range of 8 nm centred near $\lambda = 280$ nm. Prism and echelle dispersions are parallel and produce an overall resolution of 13 pm, with a linear dispersion of 0.217 nm mm^{-1} at the film plane.

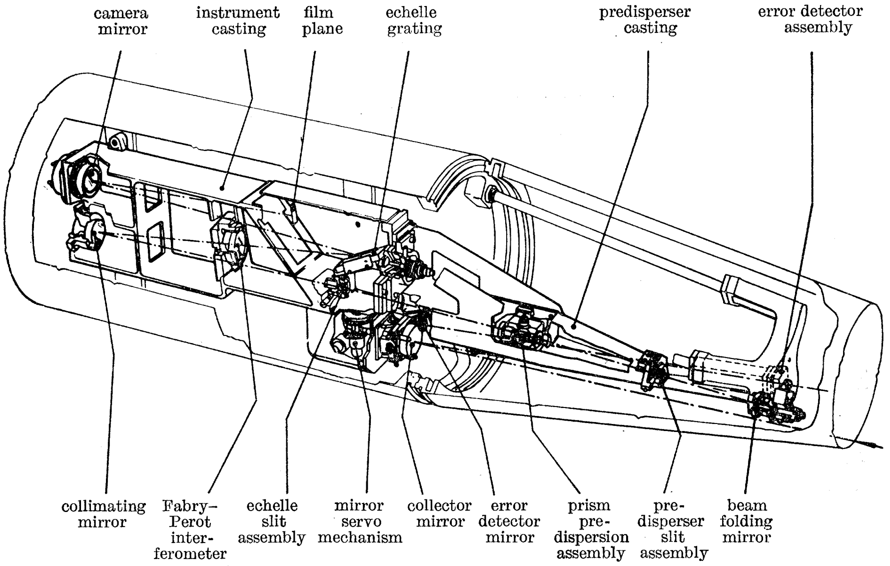

FIGURE 1. Rocket echelle–interferometer spectrograph.

An optically contacted Fabry–Perot interferometer (Bates, Bradley, Kohno & Yates 1966), with high reflectivity multilayer coatings, is internally mounted in the collimated beam before the echelle grating. With a separation of the etalon plates of 0.89 mm the corresponding free spectral range at $\lambda = 280$ nm is 44 pm. The etalon finesse for the aperture of 1 cm employed was 28 giving a spectral resolution of 1.6 pm in the fringes. The interferometer axis was tilted through an angle of 8° to the incident beam to produce 22 fringes across a solar diameter. Post-flight calibration of the recovered instrument showed that no changes had occurred in the performance of the spectrograph or interferometer.

THE ROCKET FLIGHT

Skylark SL 603 was launched at 00 h 03 U.T. 27 November 1969 from the Woomera Range, South Australia, and the rocket platform was stabilized by an Elliott Brothers attitude control unit. After the vehicle had been stabilized along the solar vector, an optical alinement system orientated the telescope collector mirror in order to maintain the final spatial resolution and also to provide the necessary programme settings of the solar disk relative to the slit (Black & Shenton 1966). Image displacements perpendicular to the entrance slit were made in ten steps of 10″ followed by a shift of 1.5′ along the slit. The sequence was repeated twice, to give a raster scan with a total of thirty different settings of the disk image relative to the slit during the flight. Both image stabilization and displacement were continuously monitored by an auxiliary camera unit. The pointing noise varied during the flight with the maximum excursions occurring during a period of some 25 s after acquisition of the attitude control unit. The measured noise varied between 5 and 15″ (peak-to-peak) along the slit and between 2 and 10″ in the perpendicular direction.

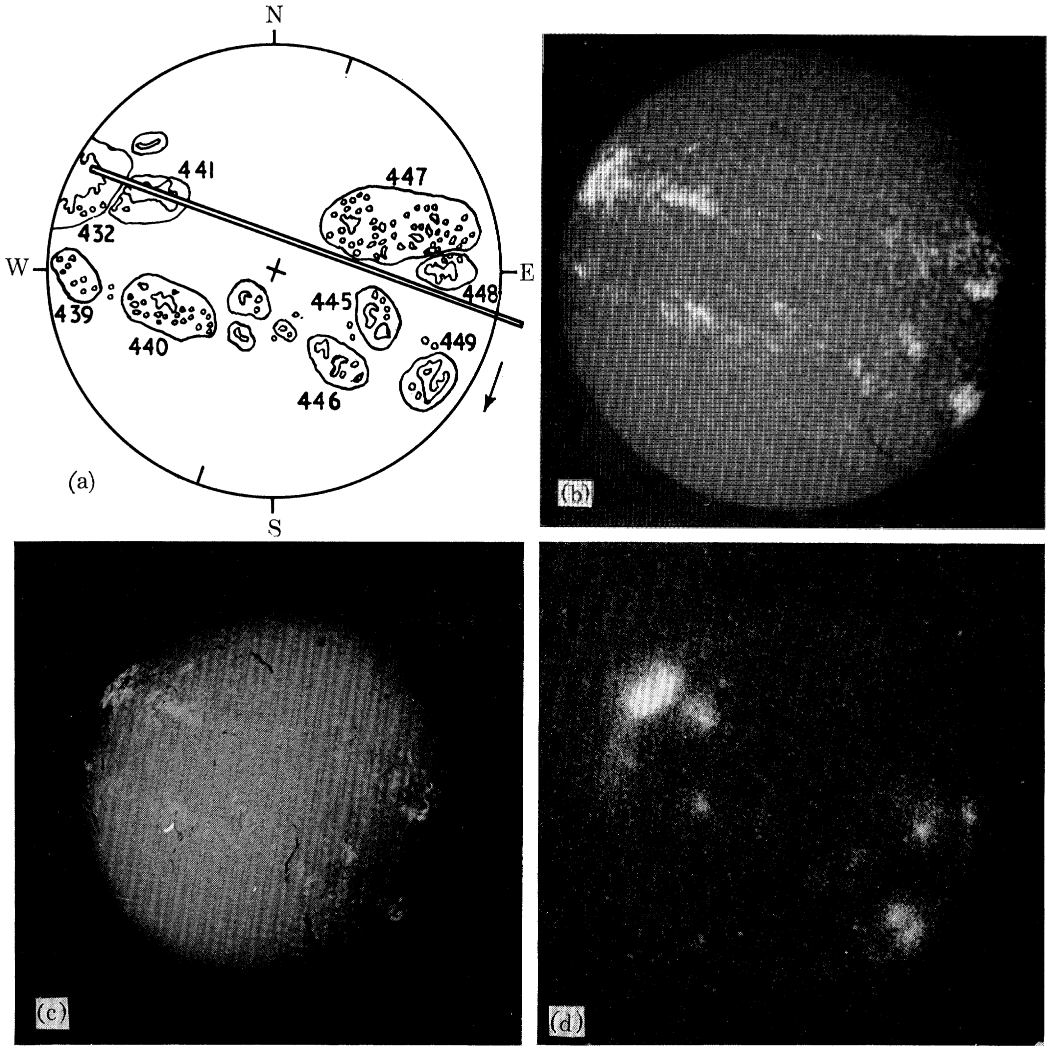

FIGURE 2. Solar activity map and images of the sun recorded on 23 and 27 November 1969. (*a*) Initial position of the spectrograph slit relative to the main regions of solar activity. The arrow shows the direction of the programmed fine scale image shifts. (*b*) Ca II K spectroheliogram 14 h 15 U.T. 26 November (courtesy McMath-Hulbert Observatory, University of Michigan). (*c*) Hα filter heliogram 00 h 03 U.T. 27 November (courtesy Carnarvon Tracking Station, Western Australia). (*d*) Pinhole camera extreme u.v. image (instrument resolution 1′).

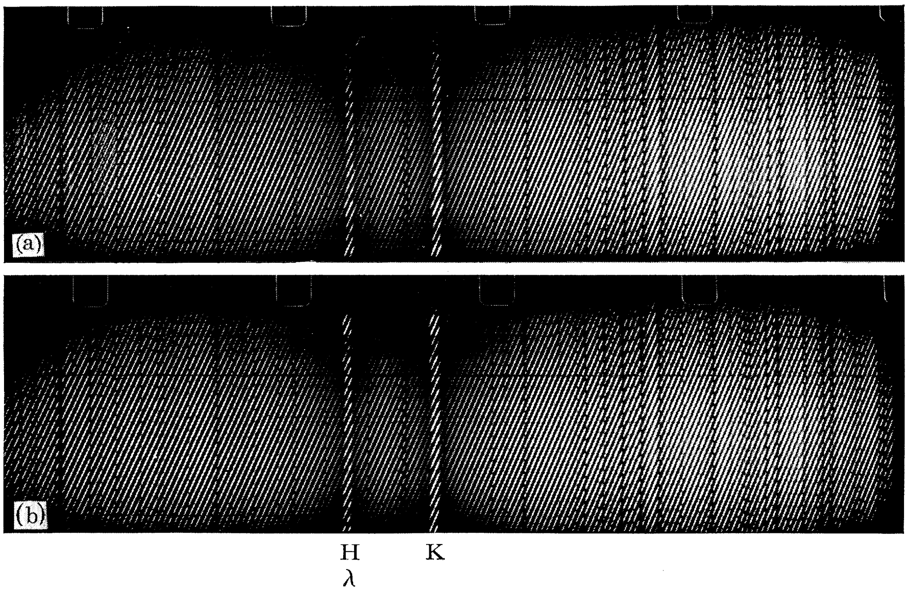

FIGURE 3. Two solar interferograms covering a range of about 7.5 nm embracing the Mg II H and K lines at 280.27 and 279.55 nm. The upper bound of the fringes is determined by the solar east limb.

For each of the thirty different solar image settings, exposures of 0.02, 0.1, 0.5 and 2 s were recorded on Kodak 103–0 emulsion. Apart from the shortest exposures of 0.02 s, successful interferogram recordings were obtained giving some 1800 useful profiles for each of the H and K resonance lines, and for the solar absorption lines extending from 275 to 283 nm.

The rocket payload included a pinhole camera unit to record solar images in the extreme ultraviolet. Four pinhole apertures of different diameters recorded separate images on Kodak 101-01 photographic film during a single exposure period of 228 s above 130 km altitude and over the 180 km apogee. Each pinhole aperture was covered by an aluminium film of 110 nm thickness which gave effective wavebands in the region 2 to 6 nm and 17 to 22 nm where the emission is particularly sensitive to solar activity.

Figure 2*a*, plate 3, shows the initial position of the spectrograph entrance slit relative to the main regions of activity on the solar disk. The slit is orientated approximately in the solar E–W direction and the arrow shows the direction of the 10″ shifts of the image. Figure 2 also shows (*b*) a Ca II K_{232} spectroheliogram taken 10 h before the flight (supplied by the McMath–Hulbert Observatory, Michigan, U.S.A.) and (*c*) an Hα filtergram (Carnarvon Tracking Station, Western Australia) taken at the time of flight. Figure 2*c* shows one of the extreme u.v. solar images recorded by the pinhole camera unit.

All the bright emission regions observed in the extreme u.v. image can be seen in both the Ca II and Hα photographs. The analysis of the Mg II profiles requires a knowledge of the distribution of activity over the solar disk, so that profile variations can be correlated with activity for each slit setting.

Analysis of Mg II interferograms

Figure 3, plate 3, shows two representative interferograms recorded at different positions of the slit on the solar disk. With an 8° angle of tilt of the interferometer, the resulting parabolic channels (Fabry & Buisson 1910) are linear to a very good approximation and their horizontal width is determined (Treanor 1949) by the spectral width of the echelle slit. In figure 3*a*, one end of the slit passes through two active regions (McMath 441 and 432) and the other end crosses the solar limb. The interferogram of figure 3*b* contains three active regions (McMath 432 ,441 and 448) and the corresponding areas of enhanced emission in the Mg II H and K fringes are clearly recorded, with the K line appearing to be more strongly affected. The fringes cover the spectrum from 275 to 283 nm and the Fraunhofer absorption lines show up as breaks in each of the channels.

The densitometer traces of one set of Mg II profiles shown in figure 4 were obtained by scanning along successive channels. Along each heterochromatic channel there is a positional as well as a wavelength variation which must be considered in the interpretation of the line profiles. While a spectral resolution element of 1.6 pm corresponds to ~ 3.5″ on the disk, the full line profile width of 0.1 nm extends spatially over 3.5′. The traces in figure 4 illustrate the changes in the H and K profiles from the solar centre to the east limb. Although these profiles were chosen as representative of quiet solar conditions, several are affected by active regions.

In general the profiles are similar to those reported by Lemaire (1969) and Bates *et al.* (1969). From 18 interferograms and 340 profiles for each line the relative intensities of the emission peaks may be classified as follows:

	$K_2v > K_2r$	$K_2v < K_2r$	$K_2v \approx K_2r$
K line (%)	70	19	11
H line (%)	72	16	12

where v and r indicate violet and red intensities respectively. Of the 340 profiles some 42 % were obviously influenced by activity and are not included in the classification.

Solar centre to east limb variation of the separation of the pairs of K_2 and H_2 emission peaks is shown in figure 5 for values obtained from four interferograms. While the intensities of these emission peaks decrease from centre to limb, their separation increases. Near the centre of the disk the separation is 30 pm. This is slightly greater than the value of 28 pm obtained by Lemaire (1939) and on our first flight (Bates *et al.* 1969). The 3.5′ spatial extension of the fringes could affect the measured separation of the peaks and this spatial spread also limits measurements near to the limb.

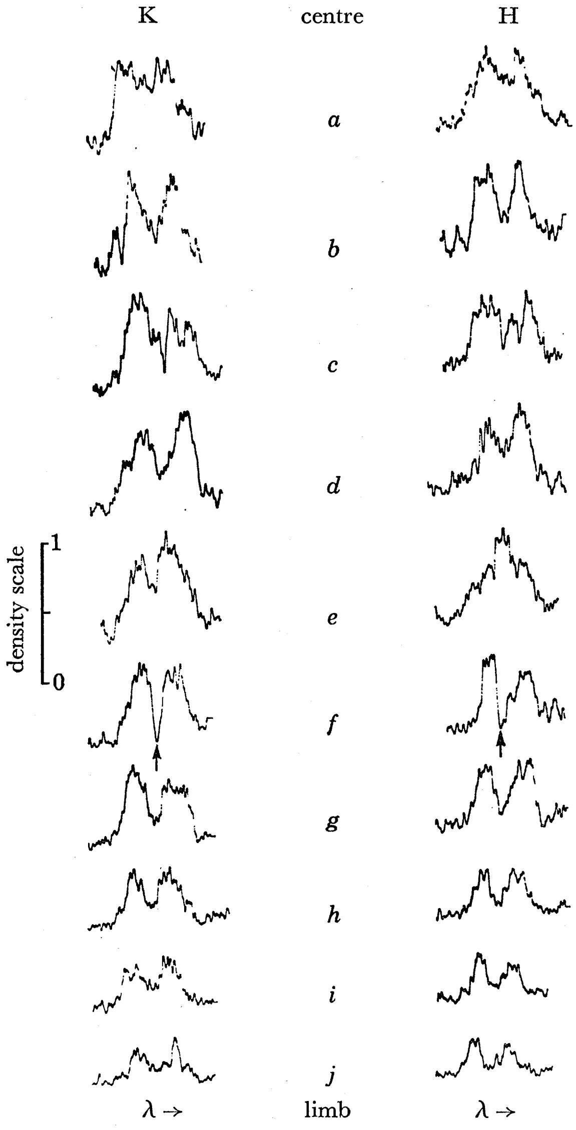

FIGURE 4. Densitometer tracings of the Mg II H and K profiles obtained from one recorded interferogram (profiles (*f*) are affected at the position indicated by the arrows by a suspected dust particle on the spectrograph slit).

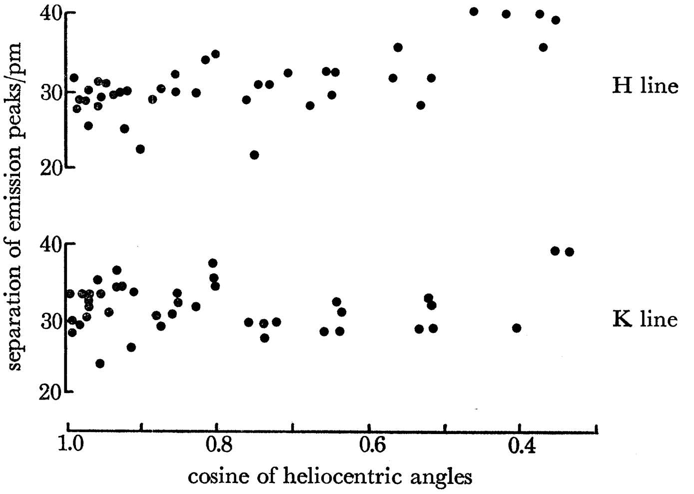

Figure 5. Centre-to-limb variation of the separation of the emission peaks of the Mg II H and K lines obtained from four recorded interferograms.

THE INFLUENCE OF SOLAR ACTIVITY ON THE Mg K LINE PROFILE

The interferograms and the line profiles described above clearly show that regions of solar activity have a marked influence on the recorded Mg II emission lines. There are sudden changes in the line shape where the fringes cross from quiet to active regions. We have made a preliminary study of these effects. The profile in figure 6*a* corresponds to the quiet disk and was recorded just outside the active region (McMath 448). Figure 6*b* shows the situation where part of the fringe is on the quiet disk and the longer wavelength part of the profile, which is greatly enhanced in intensity, falls on the active region.

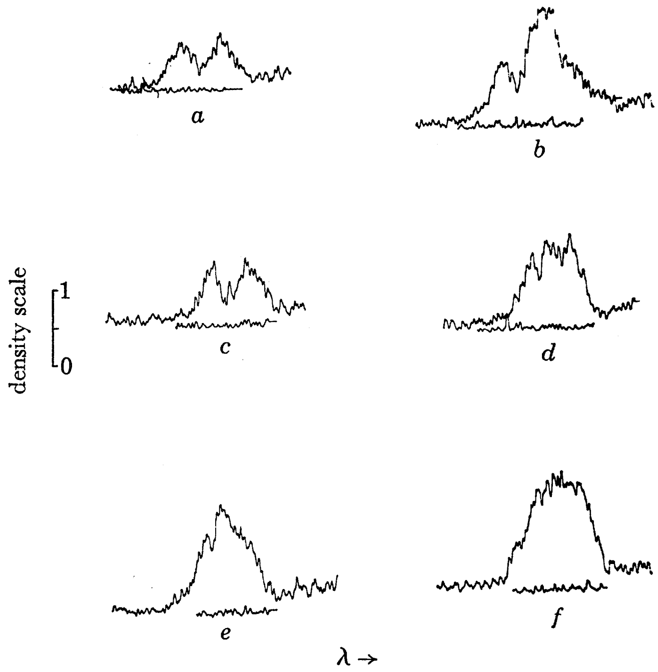

Figure 6. Profiles of the Mg II K line recorded with increasing overlap of an active region.

Records were obtained as the solar image was moved in eight steps, each of 10″ relative to the slit, from the quiet disk into the same active region. Figures 6*c* to *e* illustrate the effect on the complete profile as the spectrograph slit moves into the active region. For 6*c* the slit was just outside and for 6*f* at the centre of the active region. The first effect is that the intensity within the central reversed component (K_3) increases until it is stronger than both of the K_2 peaks. The intensities of these peaks then increase also and the profile steadily fills in to give an almost flat top with the intensity at the line centre increased by a factor of 10 to 15 compared with the quiet disk line. This pattern of overall increase both in intensity and in linewidth is similar to that reported from Ca II observations of plages by Smith (1960) and Engvold (1966). While our data are preliminary, these results clearly demonstrate, however, the sensitivity of the Mg II lines to changes in chromospheric activity.

WAVELENGTH IDENTIFICATION AND SOLAR ATLAS

The very high resolution and the excellent stray light characteristics of the interferometer spectrograph have produced the most detailed solar spectrum between $\lambda = 275$ nm and $\lambda = 283$ nm. A detailed spectral analysis is being carried out for each of the recorded channels of each interferogram to establish accurate wavelengths (to 2 pm) for subsequent identification.

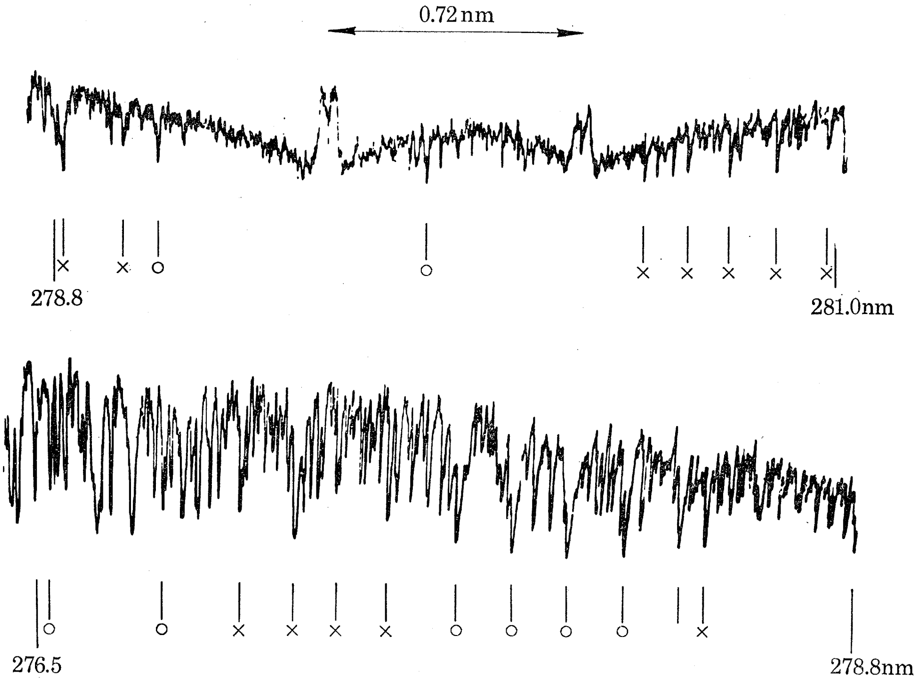

FIGURE 7. The solar spectrum between 276.5 and 281.0 nm obtained for a central region of the disk (see text). ○, Mg; ×, Fe.

This involves substantial data reduction and to illustrate the quality of these spectra a section covering the range $\lambda = 276.6$ to 281 nm is shown in figure 7. This is the spectrum of a single spatial element covering 1.6′ in the centre of the solar disk, equivalent to one free spectral range of the interferometer (44 pm). The corresponding sections of the fringe channels were microdensitometered to build up the composite spectrum. From interferograms obtained in the first rocket flight 400 lines in the same spectral range have been listed, of which some 70 % have been identified. An additional 100 spectral features occur on only two of the ten channels and some of these may possibly be faint lines. Wavelengths have been determined to an accuracy of 2 pm. The interferograms show more lines than previously reported spectra (Kachalov & Yakovleva 1962). The weaker absorption lines recorded in the first flight interferograms are well resolved with the improved spectral resolution of the second flight, and additional features are revealed.

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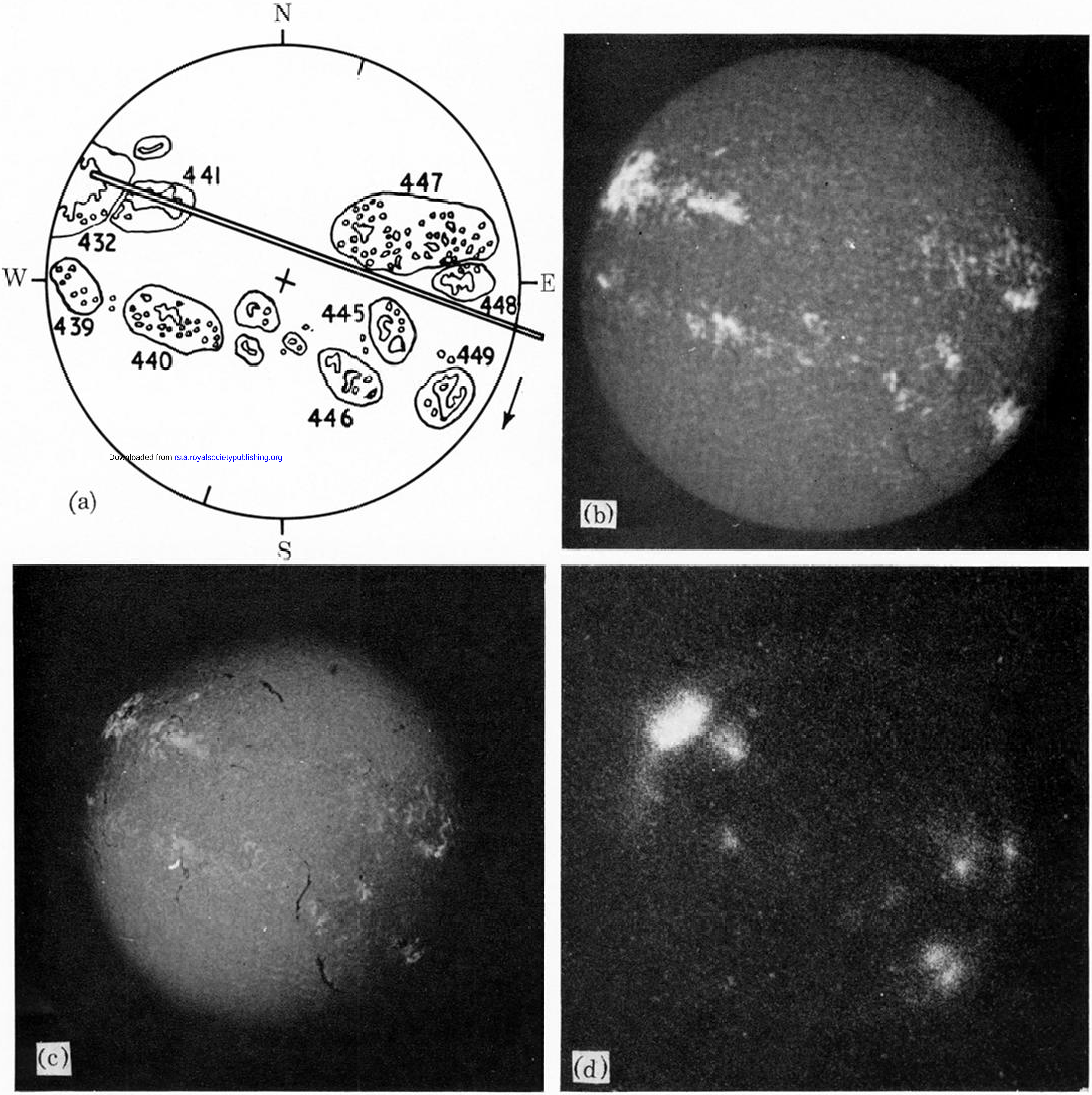

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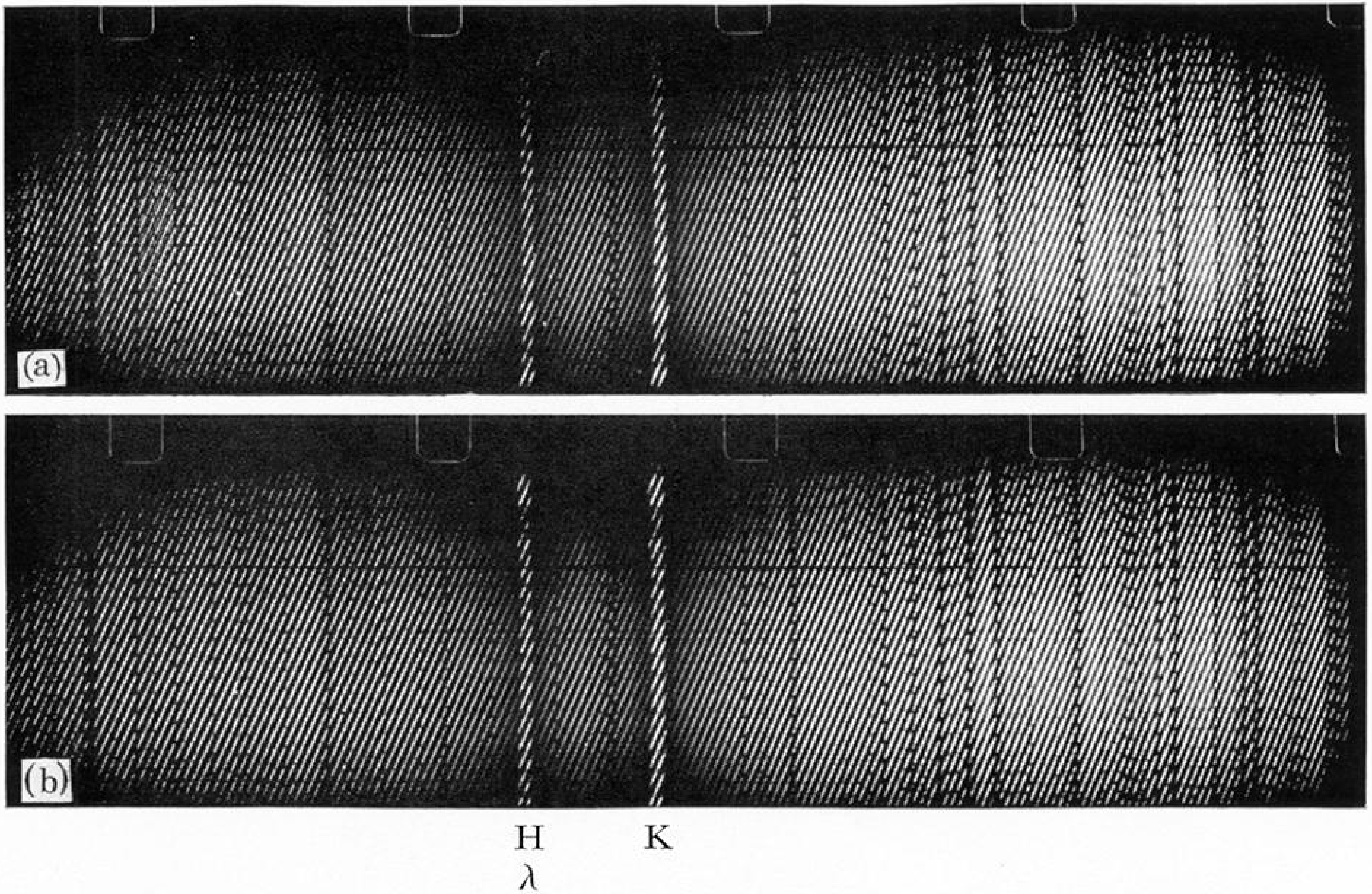

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