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The Quiet Sun in the Extreme Ultraviolet

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The quiet Sun in the extreme ultraviolet

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[Plates 4–7]

Observations of the quiet Sun with the Harvard extreme ultraviolet spectrometer on the Skylab mission are reported for the chromosphere, transition region, and corona. The changing structure of the network is examined over the temperature range from 10^4 to 1.5×10^6 K, and the distribution of intensities in the cell interiors and the network examined from the standpoint of creating characteristic models. Observations of traces of periodic oscillations at 300 s in the cells for $T \leqslant 2 \times 10^4$ is reported together with the absence of any periodic contributions at higher temperatures or periodic effects at any height in the network elements. Frequent non-periodic brightenings are observed, however, and their characteristics discussed. Observations of the increased thickness of the transition region in coronal holes, as well as other properties are discussed in limited detail. Observations of the centre-to-limb behaviour of transition region and coronal lines are used to construct coronal models, and the assumptions of spherical symmetry evaluated from the intensity data. The effects of spicules on the limb and disk data are discussed in relation to the observations.

1. Introduction

The Skylab Earth-orbiting laboratory was launched on 14 May 1973, and the scientific operation of the solar instruments in the Apollo telescope mount (A.t.m.) began shortly after the launch of the first crew on 25 May. Observations of the Sun were obtained with the A.t.m. solar experiment array and a large number of supporting ground-based observatories (Reeves, Noyes & Withbroe 1972) during three periods of manned operation, and also during the unmanned intervals, for the entire period of the Skylab mission ending in February 1974. The photoelectric spectrometer of the Harvard College Observatory operated in the extreme ultraviolet region from 28.0 to 135.0 nm with a spatial resolution of 5″ and a limiting spectral resolution of 0.12 nm. The spectrometer contained seven separate channel electron multipliers to simultaneously observe the wavelengths shown in table 1. The lines of the first polychromatic position are formed over a range of temperatures in the solar atmosphere from the 10 000 K in the chromosphere to 1.4×10^6 K in the corona. The characteristic temperatures of table 1 represent the calculated temperature of maximum concentration for the particular species. A second polychromatic position for the spectrometer permitted the simultaneous observation of Lyman α, β, γ, and the Lyman continuum, while additional polychromatic positions arose from the large number of coincidences between the fixed-slit positions and the various lines of the solar spectrum. Certain of the additional polychromatic positions recorded density-sensitive lines, and lines whose ratios could be used as temperature indicators, while others observed different stages of ionization of various elements. At each polychromatic grating position the telescope mirror could be commanded to scan a 5′ square field in approximately 5 min of time for the generation of spectroheliograms. Alternatively, with the telescope positioned to place a specific solar feature on the entrance slit of the spectrometer, the grating could be scanned to construct a complete spectrum of the 5″ spatial element with a resolution of 0.12 nm. All data were recovered by telemetry and a small proportion of the data were made available each day for scientific evaluation of the observing programs which could then be modified both in response to changing solar conditions and in response to the instrumental observations. The spectrometer has been described in more detail elsewhere (Reeves *et al.* 1974; Huber *et al.* 1974).

Table 1. Principal polychromatic position for the Harvard instrument

detector	wavelength / nm	species	temperature / K	spectral purity / nm
1	133.5	C II	2×10^4	0.16
2	121.6	H Lα	2×10^4	0.83
3	103.2	O VI	3×10^5	0.40
4	97.7	C III	7×10^4	0.40
5	89.6	H L_{cont}	10^4	0.83
6	62.5	Mg X	1.4×10^6	0.40
7	55.4	O IV	1.5×10^5	0.40

This review will cover several aspects of the Harvard solar observations dealing with the structure of the quiet Sun. As such it represents only one segment of the observing program covering a broad range of solar phenomena. More comprehensive descriptions of the observations including the active Sun can be found elsewhere (Noyes *et al.* 1974; Reeves *et al.* 1974*a*).

2. The chromospheric network

Figure 1, plate 4, shows a set of observations of the quiet Sun taken in the first polychromatic grating position (see table 1) approximately midway between the centre of the disk and the SW solar limb on 13 August 1973. The photographic presentations are conversions to a 64 level grey scale from the numerical data. Each spectroheliogram covers a 5′ field of view with 5″ spacing between each line. The chromospheric network extends almost unchanged, except in contrast, from temperatures characteristic of the Lyman continuum at 10^4 K through C II, C III, and O IV to O VI at 3×10^5 K. Between the temperatures of formation of O VI and that of the coronal line of Mg X there is a rather abrupt change in the observed structure. The chromospheric network is almost totally unrecognizable in the coronal line of Mg X, although there are frequently remnants of the network to be seen in coronal lines if the network is traced upwards from lower temperatures. Nevertheless, the reverse is not true and the course of the network cannot generally be recognized, in any complete sense, from observations of coronal lines such as Mg X, Si XII, and the higher stages of ionization, Fe XV and Fe XVI.

Comparisons of the observed network structure with ground-based observations in Ca II indicate that the bright network observed in the e.u.v. lines of the chromosphere and transition layer is very similar if not identical to the bright network observed in Ca II, which is formed at chromospheric temperatures (Reeves *et al.* 1974*b*). Often network features can be observed to persist for many hours, while fine details of the network evolve on time scales of 5–10 min or less in the e.u.v. lines. The Apollo Telescope Mount included a separate Hα telescope with a Fabry–Perot filter, which was used by the astronauts to point the ultraviolet instruments precisely on solar features and to record Hα images for subsequent data analysis. The profile of the Hα telescope Fabry–Perot filter is broader than the Lyot filter profile normally used for ground-

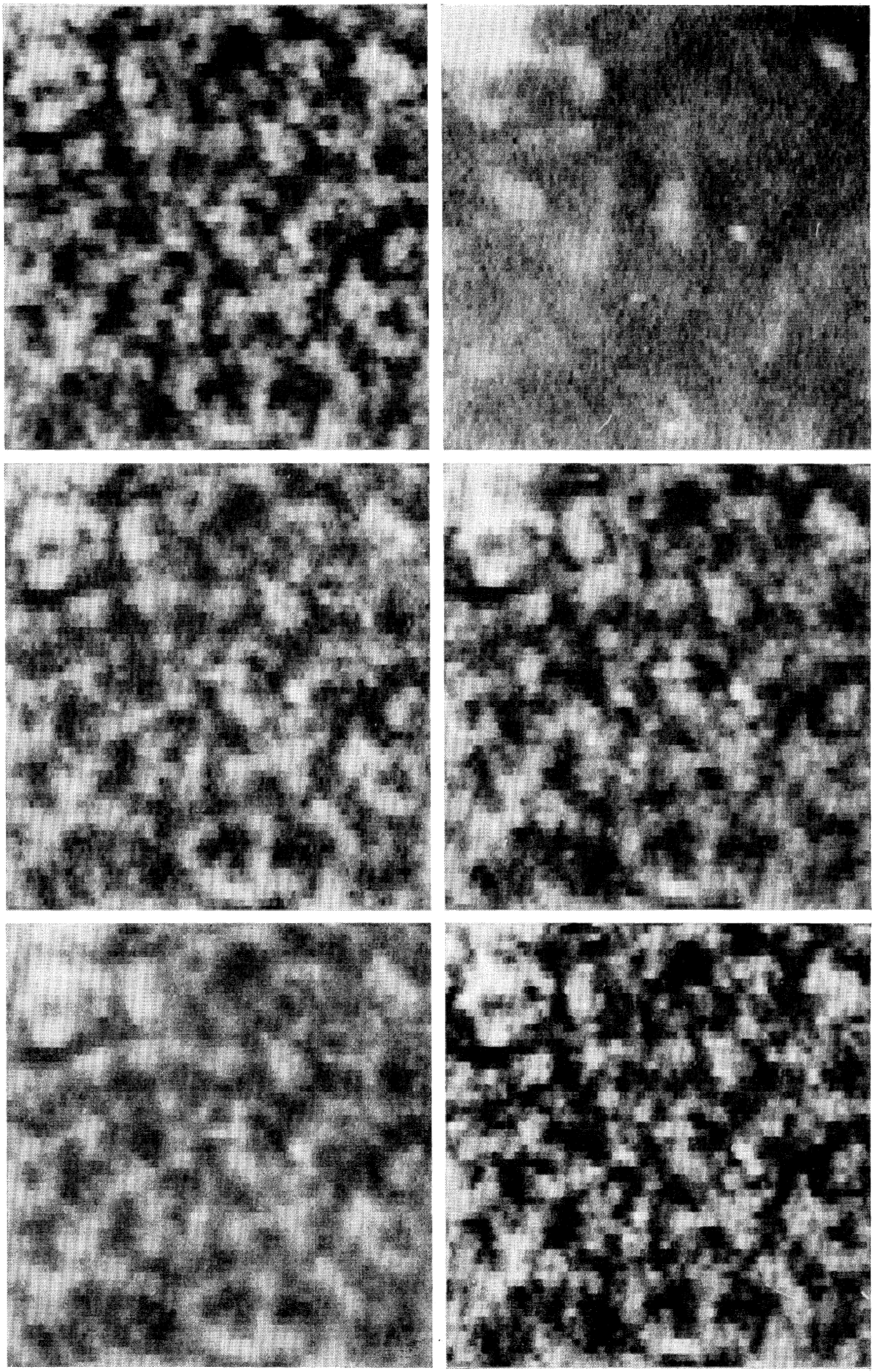

FIGURE 1. Quiet chromospheric network, 13 August 1973, 16 h 00 U.T.

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

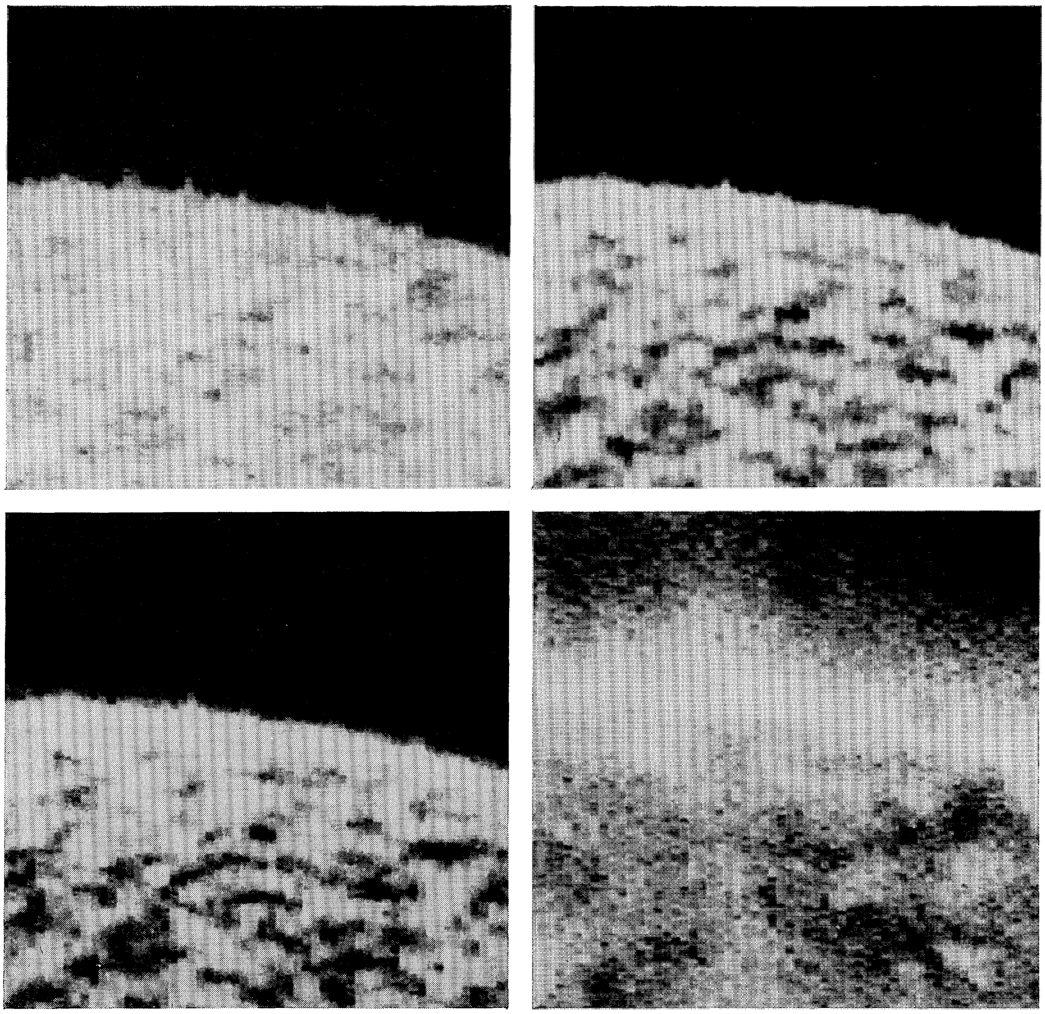

FIGURE 3. Quiet NE limb, 5 January 1974.

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

based observations. Consequently the Hα observations which were made simultaneously with the e.u.v. studies showed the dark mottles which are seen most clearly from the ground in off-band Hα (Beckers 1968). These mottles are seen to delineate the bright e.u.v. chromospheric network, although the contrast in the Hα is not high. Furthermore, the brightness of the e.u.v. network does not appear to be directly related to the visibility of the dark mottles in Hα. The coincidence of the bright e.u.v. emission with the dark Hα mottles is in accord with other observations (Brueckner & Bartoe 1974).

We made extensive observations of the structure of the quiet Sun with the A.t.m. instrument for two purposes: (1) to explore the structure of the chromospheric network, and (2) to attempt to delineate a heating mechanism for the solar chromosphere and corona. We will refer to cells as the regions bounded by the bright e.u.v. network. Studies of the spatial intensity distribution within the quiet Sun spectroheliograms indicate that the supergranulation cells are relatively large scale features (approximately 30 000 km) with a restricted and well defined range of intensities. Although a statistical analysis of the intensity distribution in cells shows that the

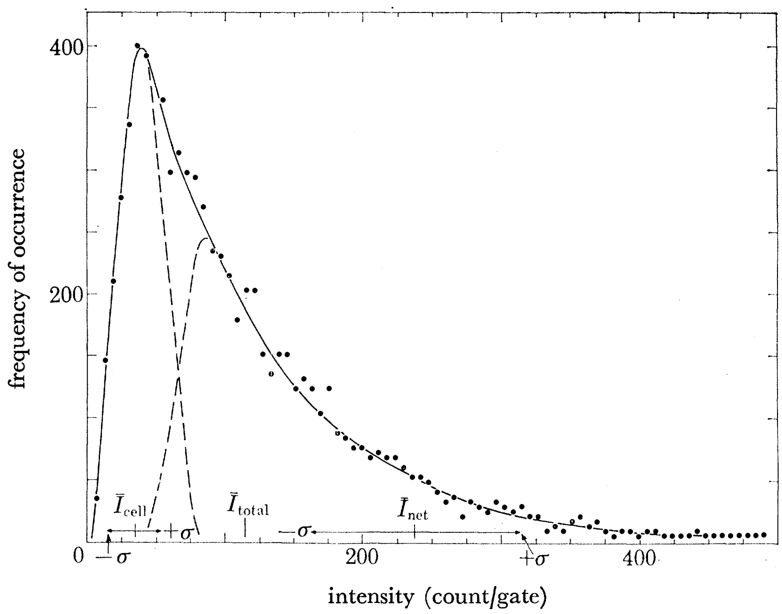

FIGURE 2. The distribution of the intensities for O IV 55.4 mm in the quiet Sun 13 August 1973, 16h 00 U.T.

standard deviation of the intensities in the cells is significantly greater than the expected distribution from statistical considerations alone (by a factor of approximately 3 for O IV, nevertheless the intensity distribution is random and restricted to a fairly narrow range. The slightly broader normal distribution probably reflects very fine scale structure within the chromospheric cell (at a spatial scale considerably smaller than the 5″ spatial resolution of the A.t.m. spectrometer). These observations indicate that, at least on a scale of 5″, the chromospheric network cells have a relatively well-defined homogeneous intensity characteristic in all e.u.v. chromospheric and transition layer lines, and can thus be considered reasonably homogeneous for the purposes of constructing theoretical models.

Figure 2 shows the distribution of intensities within the O IV spectroheliogram illustrated in figure 1. It can be seen that the distribution of intensities over the whole spectroheliogram is significantly skewed, with a tail extending to higher intensities. In spite of this continuous distribution of intensities, if the average intensity in the whole spectroheliogram was used to construct isophote contours with the numerical data, then it was readily apparent that the distribution of intensities readily separated into two distinct spatial groups. Large contiguous areas where the intensity is systematically lower than the average intensities form the cells, while the spatial association of intensities higher than the average clearly form continuous structures corresponding to the chromospheric network observed in both ground-based calcium and the on-board Hα photographs. The average intensity and standard deviation derived for the cell regions in the numerical spectroheliogram are indicated in figure 2. Separating this intensity contribution measured for the supergranulation cells, the remaining distribution of intensities can be associated with the chromospheric network, and has an asymmetrical distribution skewed to higher intensities. The network distribution also apparently shows a characteristic or threshold intensity. This same characteristic shape for the distribution of intensities is observed for all lines of the chromosphere and transition layer. For such lines as Mg x where the chromospheric network is no longer readily observed, the distribution of intensities becomes nearly Gaussian, but in this case the association of the average intensities can be attributed neither to the chromospheric network nor the supergranulation cells since the characteristic features of the quiet Sun in coronal lines are large, diffuse areas of intensity associated either with bright network remnants, residual active regions, e.u.v./X-ray bright points, or large coronal loops.

The importance of having large dynamic range even in an instrument oriented to quiet Sun studies can be emphasized by noting that the measured intensities within a single spectroheliogram in a region of the quiet Sun in O IV can extend over a range of 300 : 1, and if the small residual activity region seen in figure 1 is included, the range of intensities exceeds 1500 : 1.

Details of the intensity characteristics of the quiet chromospheric network will be described by one of us (E.M.R.) in more detail elsewhere. In particular, it is apparent that unlike the case for the cells, the network cannot be established as a simple uniform entity with regular intensity characteristics and thus amenable to a theoretical model assuming a homogeneous structure. The comparison of the data with the Hα photographs strongly suggests that the e.u.v. is coming from the same area as the spicule clumps, and possibly from the spicules themselves. The 5″ resolution of the instrument does not permit resolution of individual spicules with characteristic lateral dimensions of 1700 km (Beckers 1968). However, the spicules are not negligibly small and numerous compared to the 5″ size of the slit, and hence their spatial distribution and the subsequent observed intensity is far from regular. On a scale of 5″ the point-to-point ultraviolet intensities indicate fluctuations which are quite large (up to a factor of 10 or more), and it is therefore not meaningful to assign a regular characteristic structure to a single phenomena referred to as the 'network'. The contrast between the network and the average intensity of the cells has been investigated as a function of temperature of formation. The contrast ranges from a factor of 2 in the brighter network elements observed in Ly α and Lyman continuum up to a factor of 10 to 20 in the transition region lines such as O IV and then decreases for lines formed at temperatures corresponding to those of O VI and Ne VII, until the network is no longer recognizable in lines of coronal origin such as Mg IX and Mg X. Observations in Ne VII at temperatures of 9×10^5 K are intermediate between the transition region and the corona and show both characteristics of the chromospheric network at reduced contrast as well as characteristics predominantly associated with the large-scale corona, such as coronal holes and X-ray–e.u.v. bright points (Huber *et al* 1974*a*; Reeves *et al.* 1974*a*).

3. Centre-to-limb observations

Figure 3, plate 5, contains several spectroheliograms obtained at the limb of the Sun showing details of the quiet chromospheric network at the limb in Ly α and C III and the structure of the quiet corona above the limb in O VI and Mg X. It is readily apparent from both the numerical data and the photographic reconstructions that in many cases the quiet corona can be relatively uniform in intensity, particularly when compared with the dominant chromospheric structures which manifest themselves at lower temperatures. This coronal uniformity can also be noted from spectroheliograms in coronal lines near the centre of the disk (figure 1). The mean fluctuations in the intensity of Mg X over a quiet 5′ region near the centre of the disk is about 25–40 % of the average intensity, and since the intensities are proportional to the square of the electron density, then the electron density in the corona is uniform to approximately 10–20 %. The assumption of a uniform corona for purposes of structural modelling is therefore a reasonable assumption for quiet regions, particularly at the heights in the solar atmosphere corresponding to temperatures of formation of Mg X. Detailed examination of the spectroheliograms in a variety of lines shows noticeable irregularities along the limb, especially in Lα, C III, O IV and to a lesser degree in O VI. These irregularities can be seen in figure 3 and are probably indicative of larger spicules or clumps of spicules which begin to be resolved at our resolution of 5″.

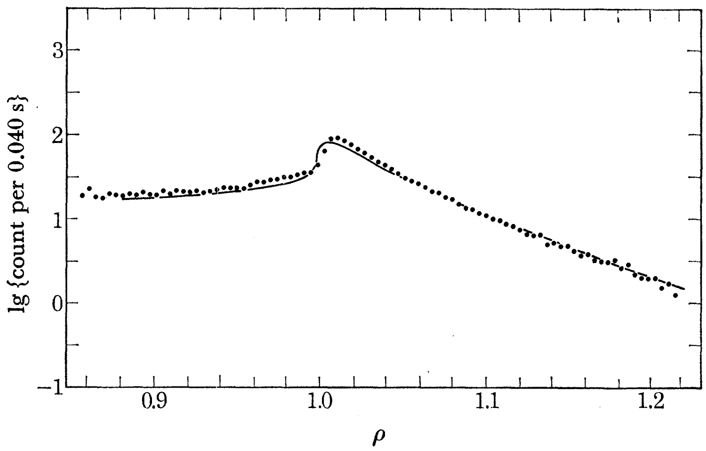

Figure 4. Centre-to-limb variation for Mg X 62.5 nm for a quiet solar region near the limb.

From the numerical data, the mean variation of the intensities for O VI and Mg X were obtained as a function of distance from disk centre. Typical data for Mg X are shown in figure 4. From the assumption of an isothermal corona in hydrostatic equilibrium, the coronal temperature can be inferred from the average height dependence of intensity. The figure shows a fit to the data obtained for a simple model a coronal temperature of 1.1×10^6 K and a scaled pressure $p = n_e T_e = 6 \times 10^{14}$. A better fit to the data for Mg X can be obtained for a mean temperature that increases slightly with height from $T = 10^6$ K at $r = 1.01 R_\odot$ (10″ above the limb) to $T = 1.1 \times 10^6$ K at $r = 1.10 R_\odot$ (2.4′ above the limb). For $r \geqslant 1.03 R_\odot$ the observed intensity ratio of O VI and Mg X is consistent with these temperatures.

For corona heights below 20 000 km ($r = 1.03 R_\odot$) the ratio of Mg X to O VI decreases substantially indicating the presence of significant amounts of material at temperatures below 10^6 K.

Since this distance above the limb corresponds to heights to which cool spicule material could extend, a uniform isothermal model is no longer adequate and the effects of spicules must be included. However, intensities of both the Mg x and O vi immediately above the limb suggest that most of the volume from 7000 km to 20 000 km is at coronal temperatures with only a small fraction of the volume occupied by cooler structures, most likely in the form of spicules. Mariska & Withbroe (1975) discuss the implications of these models in more detail, and further publications are in progress.

4. Coronal holes

Coronal holes, which appear as regions of strongly reduced coronal intensity both in the e.u.v. and X-ray regions have been observed by rocket and satellite instruments since 1968. A.t.m. provided the first opportunity to observe these large-scale features in a wide range of wavelengths and to investigate further whether the coronal holes constitute a likely source of the recurrent high velocity solar wind streams. Several such solar wind streams now have been correlated with coronal holes (Krieger, Timothy & Roeloff 1973; Krieger *et al.* 1974; Neupert & Pizzo 1974; Nolte *et al.* 1974).

Figure 5, plate 6, shows an array of spectroheliograms in excitation energies from hydrogen through Mg x, indicating a coronal hole (the large area of reduced coronal intensity), in this case near the central portion of the solar disk. The chromospheric network and its upward extension into the transition layer is still very well defined in coronal holes, although a detailed evaluation of the e.u.v. intensities indicates that the chromospheric network is systematically weakened in the coronal hole compared to intensities outside coronal holes (Huber *et al.* 1974*a*). Figure 6 shows distributions of intensities within and exterior to the coronal hole (as defined in Mg x) for lines formed in the chromosphere and transition region. The histograms of the intensities for areas within the coronal hole exhibit a much reduced contribution from higher intensity regions which arise from the network within the area of the coronal hole. The intensities of the chromospheric network in coronal holes is much more sensitive to the reduced temperature and density in the corona over a hole than are the intensities of the cell interiors. In the case of O iv negligibly small differences were observed, between the cell intensities within and exterior to the coronal hole.

The reduction of intensity in the coronal line Mg x inside the hole is about a factor of 5 whereas the average reduction in the intensity of the chromospheric network observed in transition zone and chromospheric lines is only about 25–30 %. Observations of the solar disk in the neighbourhood of coronal holes by both the Harvard instrument and the Naval Research Laboratory photographic heliograph indicate that helium lines show more striking reductions in intensities in the chromospheric network in coronal holes than other chromospheric and transition lines of comparable excitation temperature in the e.u.v.

Spectroheliograms were obtained by the A.t.m. in the density-sensitive line pair of the species C iii at 117.6 and 97.7 nm, as well as observations in several positions in the Lyman continuum capable of yielding the chromospheric colour temperature. The findings of Munro & Withbroe (1972), that the electron density inside the area covered by the hole is somewhat lower than that outside the hole were confirmed as were the results of Vernazza & Noyes (1972), that the colour temperature of the Lyman continuum is about 400 K higher within than exterior to the coronal hole.

Figure 7, plate 6, shows a series of spectroheliograms assembled into a composite image for Mg x at the pole of the Sun (Huber *et al.* 1974*a*). The upper part of the curve shows the height of

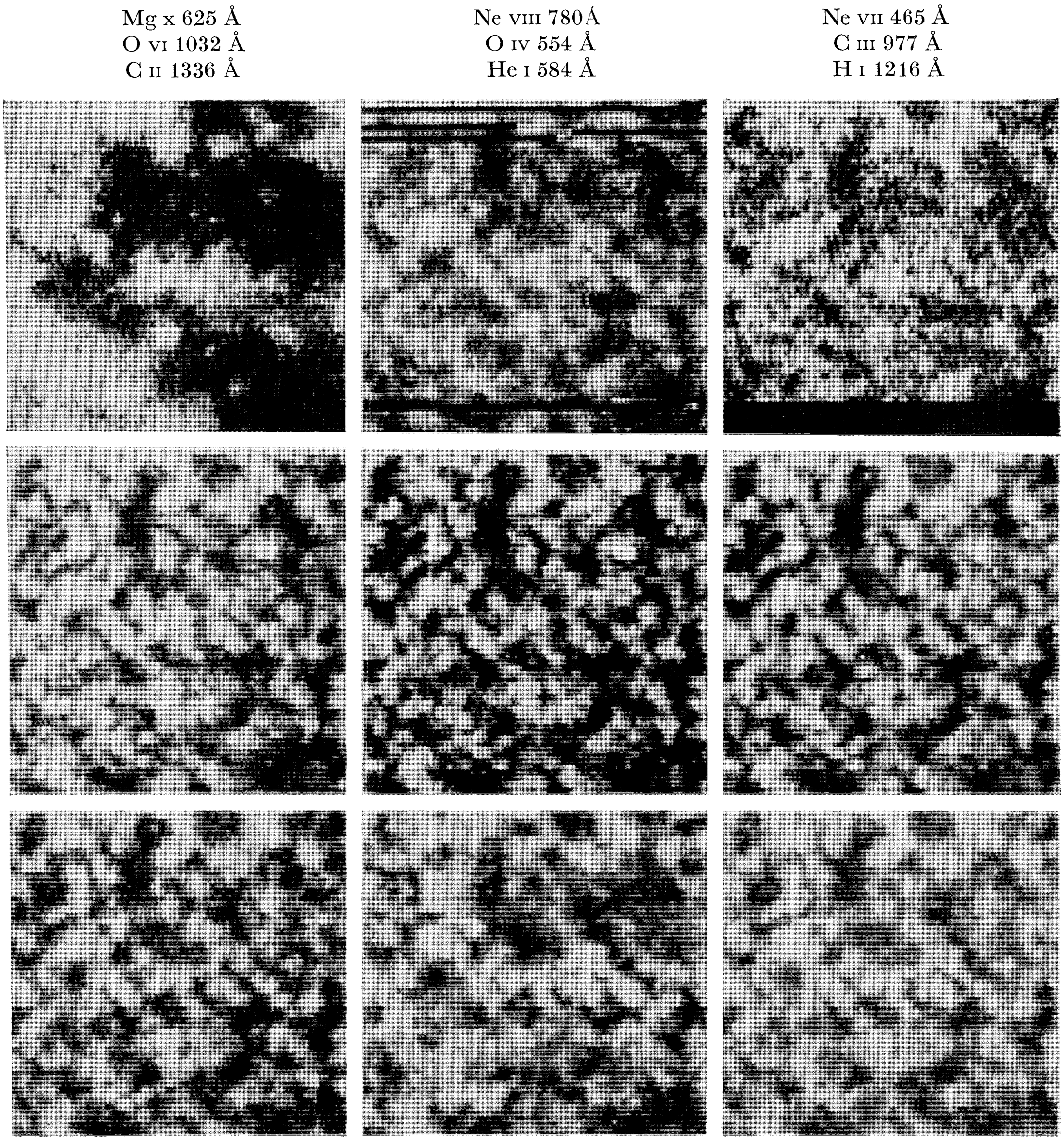

Figure 5. Spectroheliograms from hydrogen through Mg x in coronal holes.

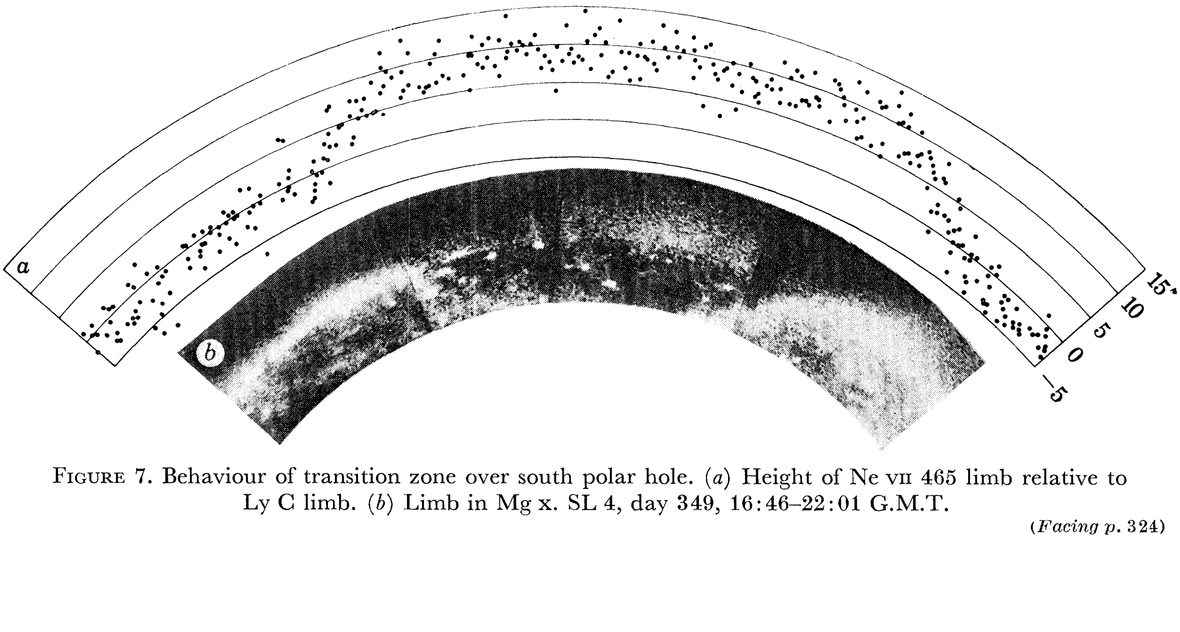

Figure 7. Behaviour of transition zone over south polar hole. (*a*) Height of Ne vii 465 limb relative to Ly C limb. (*b*) Limb in Mg x. SL 4, day 349, 16:46–22:01 G.M.T.

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

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

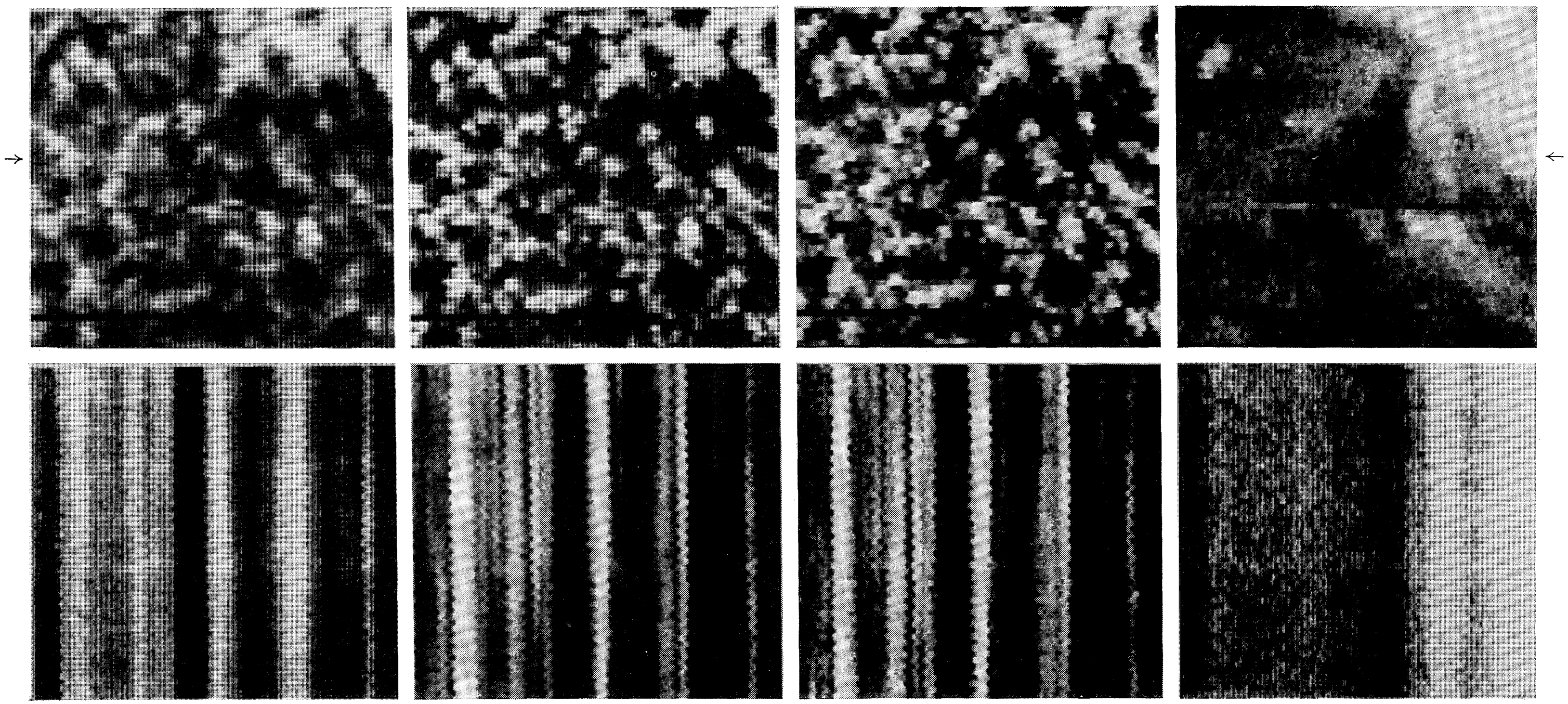

FIGURE 8. Spectroheliograms of the quiet Sun (upper portion) for selected e.u.v. lines. The lower portion shows the time development of the intensities for a single spatial line scan (arrow) in the upper portion of the figure.

the Ne VII emission relative to the limb as defined in the Lyman continuum. The heights of emission were determined as the height at which the emission drops to half its value on the disk. It can be seen that this height is systematically greater in the coronal hole than outside the hole in the case of Ne VII formed at approximately 6×10^5 K. Investigation of this height difference as a function of excitation energy indicates that the height of formation increases smoothly as a function of excitation temperature up to Ne VII beyond which the increasing scale height and the decreasing temperature gradient mask the differences between the coronal hole and the normal quiet corona.

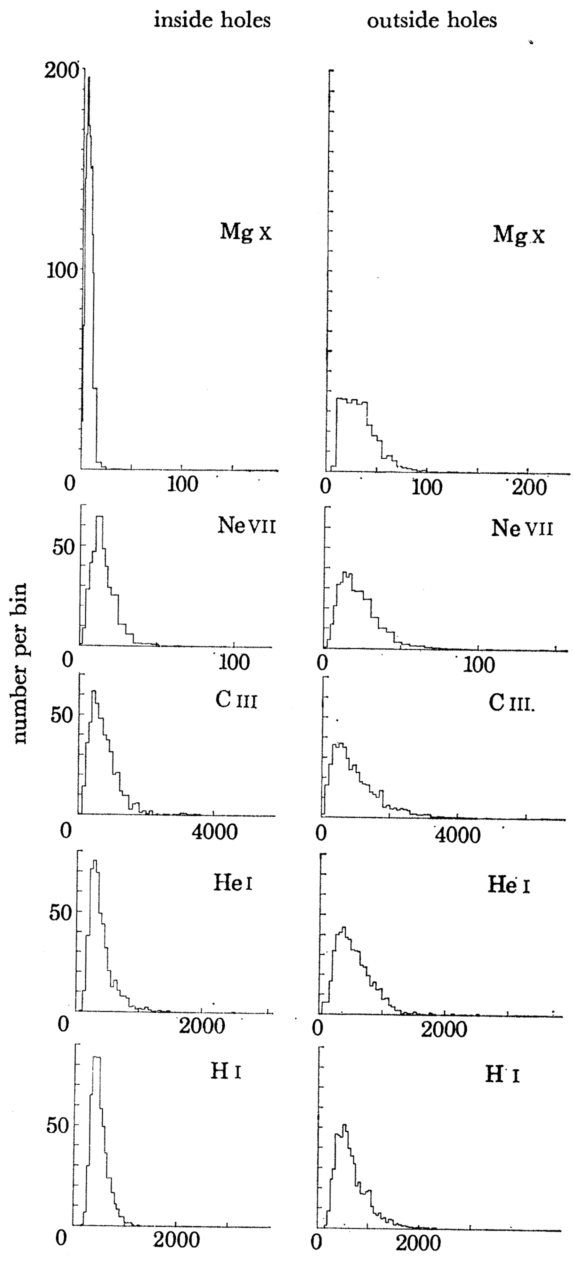

FIGURE 6. Distributions of intensities inside and outside coronal holes.

The increased thickness of the transition region indicates that the temperature gradient is significantly less in coronal holes than in the quiet Sun under the assumption of a uniform plane parallel model. These observations of polar coronal holes are in agreement with independent results reported from the Naval Research Laboratory (Bohlin *et al.* 1975), and the coronal hole models of Munro & Withbroe (1972) derived from OSO data. Clearly the complicating effects of the spicular structure along the network must be introduced to achieve more realistic models for comparison with centre-to-limb observations. Detailed analysis of the data is in progress to understand both the structure of the chromospheric network itself and the behaviour of the structure in the neighbourhood of coronal holes.

5. Oscillations

We have already referred to the importance of the problem of the heating of the corona as one of the principal objectives of the A.t.m. series of instruments. Most of the proposed mechanisms for coronal heating are based on the deposition of energy at coronal heights by shock waves, and in particular much attention has been given to the study of the well-known 5 min oscillation observed in the photosphere and low chromosphere. The 5 min oscillation has been considered as a promising candidate to provide the energy necessary for the heating of the upper chromosphere and corona (Stein & Leibacher 1974; Leibacher 1971). Figure 8, plate 7, shows spectroheliograms in several lines from the region of the quiet Sun in the upper portion of the illustration. The lower portion of the illustration contains a photographic reconstruction from the digital data of instrument operation in a single mirror line scan mode, in which the same line of the raster pattern is scanned repetitively and time progresses from the top to the bottom of the picture. The display is similar in character to a streak photograph where temporal changes of intensity appear as fluctuations in the vertical dimension, and transverse spatial changes appear in the lateral dimension. From the mirror line scan data many changes in intensity of the individual spectral lines from the same region of the sun can be seen as temporal (vertical) changes in photographic density in the illustration. Again, the range of temperature of formation of the observed lines varies from 2×10^4 K for Lα to 1.4×10^6 K for Mg x. The study of these fluctuations of intensity in chromospheric, transition layer and coronal lines constituted one of the principal observing objectives of the Harvard instrument. An analysis of these data has been performed and the results reported by Vernazza (1974; Vernazza *et al.* 1975).

Periodic recurrences of the intensity fluctuations were examined through Fourier analysis of sets of mirror line scan data of approximately 40 min in length. The data were separated into solar features corresponding to centres of cells, network, and intermediate regions. Power spectra at each point on the solar surface were averaged and normalized with the results for cells shown in figure 9. Inspection clearly indicates that there is no dominant period in the power spectra of cells (nor is there for the network) although there is a slight but significant increase in the power spectrum contribution at 300 s for lines such as Lα and C II at 133.5 nm in the cells (but not in the network). The intensity amplitude of this oscillation is of the order of 10^{-3} of the d.c. level in Lα. We conclude that periodic intensity oscillations at about 300 s are observed in chromospheric cells for lines formed below approximately 2×10^4 K, but that there is no similar contribution in the chromospheric network nor any significant systematic contribution from periodic oscillations at higher temperatures. Analysis of OSO-7 data by Chapman, Jordan, Neupert & Thomas (1972) suggested that the 300 s intensity oscillation was present not only in the chromosphere as observed in He II, but also in the corona as observed in Mg VIII and Mg IX. The current data is based on better statistics and improved spatial resolution and we feel that the observations are therefore more reliable than the OSO-7 observations.

The A.t.m. observations indicate then that the 300 s oscillation observed in the low chromosphere and temperature minimum is not manifested as a large enhancement in emergent intensity in the transition region and corona where the higher solar temperatures originate. There is certainly the possibility that the 300 s velocity oscillation observed from the ground turns into shock waves in the lower chromosphere and loses its periodic structure before ascending to higher heights and greater temperatures as suggested by Leibacher (1971). This view is at least in part supported by the observation of non-periodic intensity fluctuations in the e.u.v. which have a mean time between occurrences of approximately 330 s.

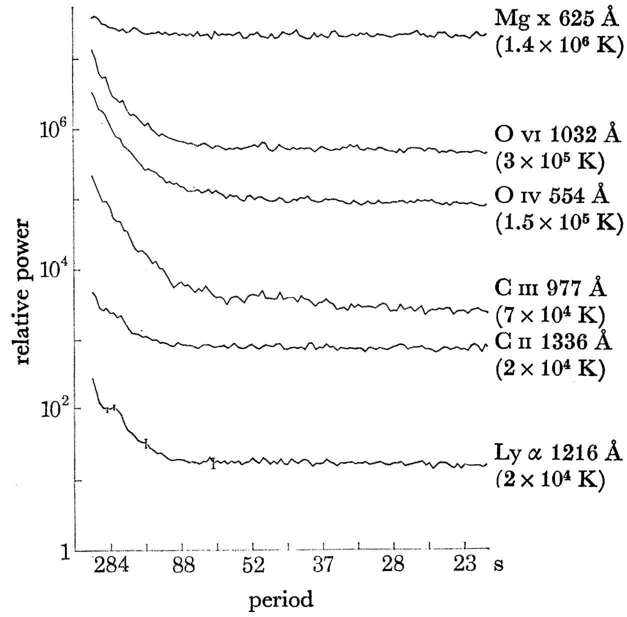

FIGURE 9. Power spectra for network cell interiors for e.u.v. lines from the chromosphere to the corona.

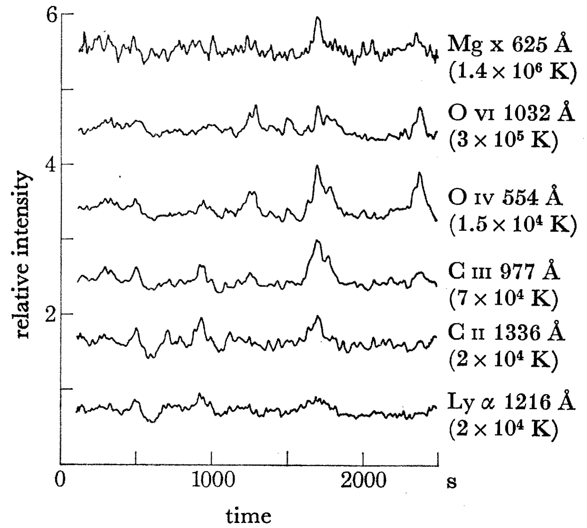

FIGURE 10. Continuous record of the intensities of certain e.u.v. lines for a single 40 min data sample.

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

Figure 10 shows the time behaviour of the intensity of lines formed between the chromosphere and corona at an arbitrarily selected point on the solar surface. Statistical noise was removed from the sample by using standard Fourier transform techniques. Many of the changes in emergent intensities occur nearly simultaneously over a range of heights in the solar atmosphere. The intensity scale for each line has been arbitrarily normalized to unity at the maximum count rate registered in the time sample and the observation in different wavelengths displaced vertically to separate them. The increase in intensity relative to the d.c. level was observed to be much less in Mg x than in lines formed at lower temperatures.

The excess in emission during the fluctuation could be associated either with an increase in density, or as a manifestation of energy deposited by some heating mechanism. In either case the observations suggest a propagating phenomenon, since the increase in intensity occurs nearly simultaneously over a variety of heights (temperatures). While the frequent brightenings occur nearly synchronously in lines throughout the chromosphere and transition region on a scale corresponding to figure 10, it appears that there is a small time delay between the occurrence of these brightenings in the transition region and the chromosphere which is the object of further investigations. The average lifetime of the fluctuations is 70 s and the mean interval between occurrences is of the order of 330 s. The energy radiated by fluctuations in the transition region lines such as O IV is approximately 20 % of the d.c. level.

The energy radiated by these observed brightenings provides a lower limit to the energy deposited at the heights corresponding to the observed ultraviolet lines but does not provide any additional information yet on how much energy is passing through or how much total energy is deposited at different heights in the solar atmosphere. R. F. Stein (1975, personal communication) has indicated that the amplitude of the intensity oscillation seems sufficient to be associated with a principal heating mechanism of the transition region and corona. The results of the oscillations observed in the e.u.v. are discussed in more detail in a separate paper (Vernazza *et al.* 1975).

6. Conclusions

The recent observations of the A.t.m. instruments are finding wide application for a variety of solar problems. Only a few aspects of the quiet Sun are discussed here, and these as well as others are still under intensive analysis. It would appear that for heights between 20 000 and 140 000 km above the photosphere the assumption of a uniform, symmetric, nearly isothermal corona in hydrostatic equilibrium is still a reasonable assumption for constructing models of the quiet solar atmosphere in the absence of specifically observed structures in the field, such as bright points or structures associated with centres of activity. Below 20 000 km inhomogeneities such as spicules, associated with the chromospheric network, play an important role. The effects of these inhomogeneities must be incorporated into more realistic models. While the centres of supergranulation cells appear to be relatively uniform in structure in the chromosphere and transition region lines, the network is decidedly non-uniform, yet it contributes much of the intensity to the average quiet Sun.

In the area of coronal holes, much is being learned about the structure of the atmosphere over a wide range of heights, but physical mechanisms establishing those regions as the source of the high velocity wind streams are as yet not discernible.

Finally the 300 s oscillations observed from the ground through heights corresponding to the temperature minimum, can be traced to heights corresponding to $T = 2 \times 10^4$ K in the ultraviolet data, but the intensity power spectra show no significant contribution from periodic oscillations for lines arising from the transition region and corona. There are, however, a significant number of aperiodic brightenings observed nearly simultaneously over a range of temperatures from the chromosphere to the corona, and very preliminary calculations suggest these pulses as a possible contender for the elusive mechanism for coronal heating.

The authors would like to extend their appreciation to the other scientists of the Harvard solar group for participation in the Skylab mission operations and many stimulating discussions on the analysis of the data. Continued appreciation is due to the scientists, engineers and support personnel at Harvard and Ball Brothers Research Corporation who built and operated the instrument over a period of many years, and to the astronauts and personnel of N.A.S.A. for their many contributions to the success of the Skylab program. This research was supported by the National Aeronautics and Space Administration under the contract NAS 5-3949.

References (Reeves *et al.*)

Beckers, J. M. 1968 *Solar Phys.* **3**, 367.
Bohlin, J. D., Sheeley, N. R. & Tousey, R. 1975 *Space Res. XV.* (In the Press.)
Brueckner, G. E. & Bartoe, J-D. 1974 *Solar Phys.* **38**, 133.
Chapman, R., Jordan, S., Neupert, W. & Thomas, R. 1972 *Astrophys. J. Lett.* **174**, L 97.
Huber, M. C. E., Reeves, E. M. & Timothy, J. G. 1974 *Proc. 9th Int. Commission for Optics*, National Academy of Science.
Huber, M. C. E., Foukal, P. V., Noyes, R. W., Reeves, E. M., Schmahl, E. J., Timothy, J. G., Vernazza, J. E. & Withbroe, G. L. 1974*a* *Astrophys. J. Lett.* **194**, L 115.
Krieger, A. S., Timothy, A. F. & Roeloff, E. C. 1973 *Solar Phys.* **29**, 505.
Krieger, A. S., Timothy, A. F., Vaiana, G. S., Lazarus, A. J. & Sullivan, J. D. 1974 *Solar Wind Three* (Inst. Geophys. Planet. Phys., Univ. Calif., Los Angeles) 132.
Leibacher, J. 1971 Ph.D. Thesis, Harvard University, Cambridge, Mass., U.S.A.
Mariska, J. T. & Withbroe, G. L. 1975 *Bull. Am. Astron. Soc.* **7**, 354.
Munro, R. H. & Withbroe, G. L. 1972 *Astrophys. J.* **176**, 511.
Neupert, W. M. & Pizzo, V. 1974 *J. Geophys. Res.* **79**, 3701.
Nolte, J., Krieger, A. S., Webb, D., Vaiana, G. S., Lazarus, A. J., Sullivan, J. & Timothy, A. F. 1975 *Bull. Am. Astron. Soc.* **7**, 358.
Noyes, R. W., Foukal, P. V., Huber, M. C. E., Reeves, E. M., Timothy, J. G., Vernazza, J. E. & Withbroe, G. L. 1974 *Proc. I.A.U. Symposium* no. 68. (In the Press.)
Reeves, E. M., Noyes, R. W. & Withbroe, G. L. 1972 *Solar Phys.* **27**, 251.
Reeves, E. M., Timothy, J. G. & Huber, M. C. E. 1974 *Proc. S.P.I.E.* **44**, 159.
Reeves, E. M., Timothy, J. G., Foukal, P. V., Huber, M. C. E., Noyes, R. W., Schmahl, E. J., Vernazza, J. E. & Withbroe, G. L. 1974*a* *Proc. AIAA/AGU Conference on the Scientific Experiments on Skylab.* (In the Press.)
Reeves, E. M., Foukal, P. V., Huber, M. C. E., Noyes, R. W., Schmahl, E. J., Timothy, J. G., Vernazza, J. E. & Withbroe, G. L. 1974*b* *Astrophys. J. Lett.* **188**, L 27.
Stein, R. F. & Leibacher, J. 1974 *Ann. Rev. Astron. and Astrophys.* **12**, 407.
Vernazza, J. E. & Noyes, R. W. 1972 *Solar Phys.* **26**, 325.
Vernazza, J. E. 1974 *Bull. Am. Astron. Soc.* **6**, 296.
Vernazza, J. E., Foukal, P. V., Huber, M. C. E., Noyes, R. W., Reeves, E. M., Schmahl, E. J., Timothy, J. G. & Withbroe, G. L. 1975 *Astrophys. J. Lett.* **199**, L123.
Withbroe, G. L. 1970 *Solar Phys.* **11**, 42 and 208.

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

FIGURE 1. Quiet chromospheric network, 13 August 1973, 16 h 00 U.T.

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

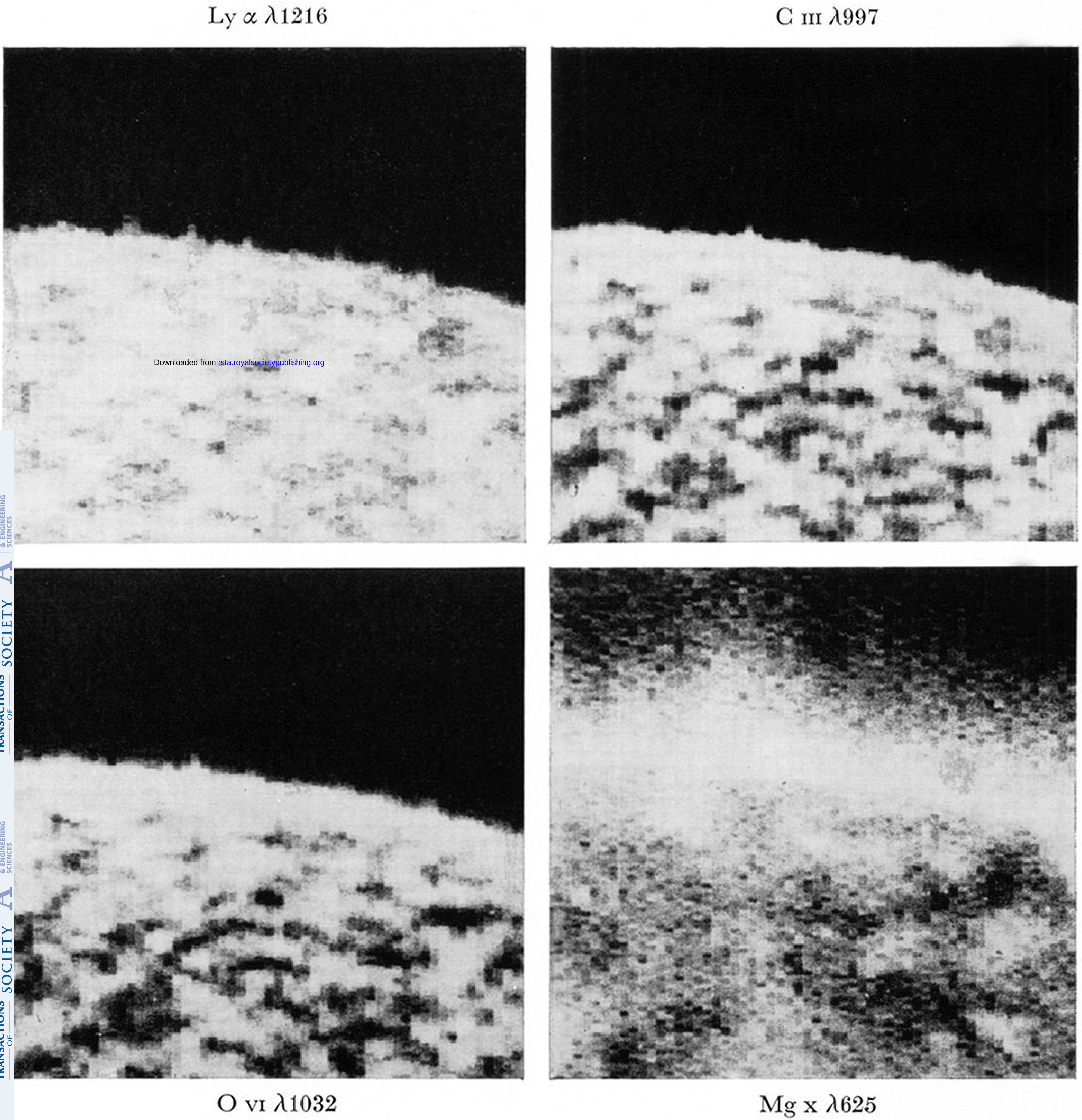

FIGURE 3. Quiet NE limb, 5 January 1974.

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

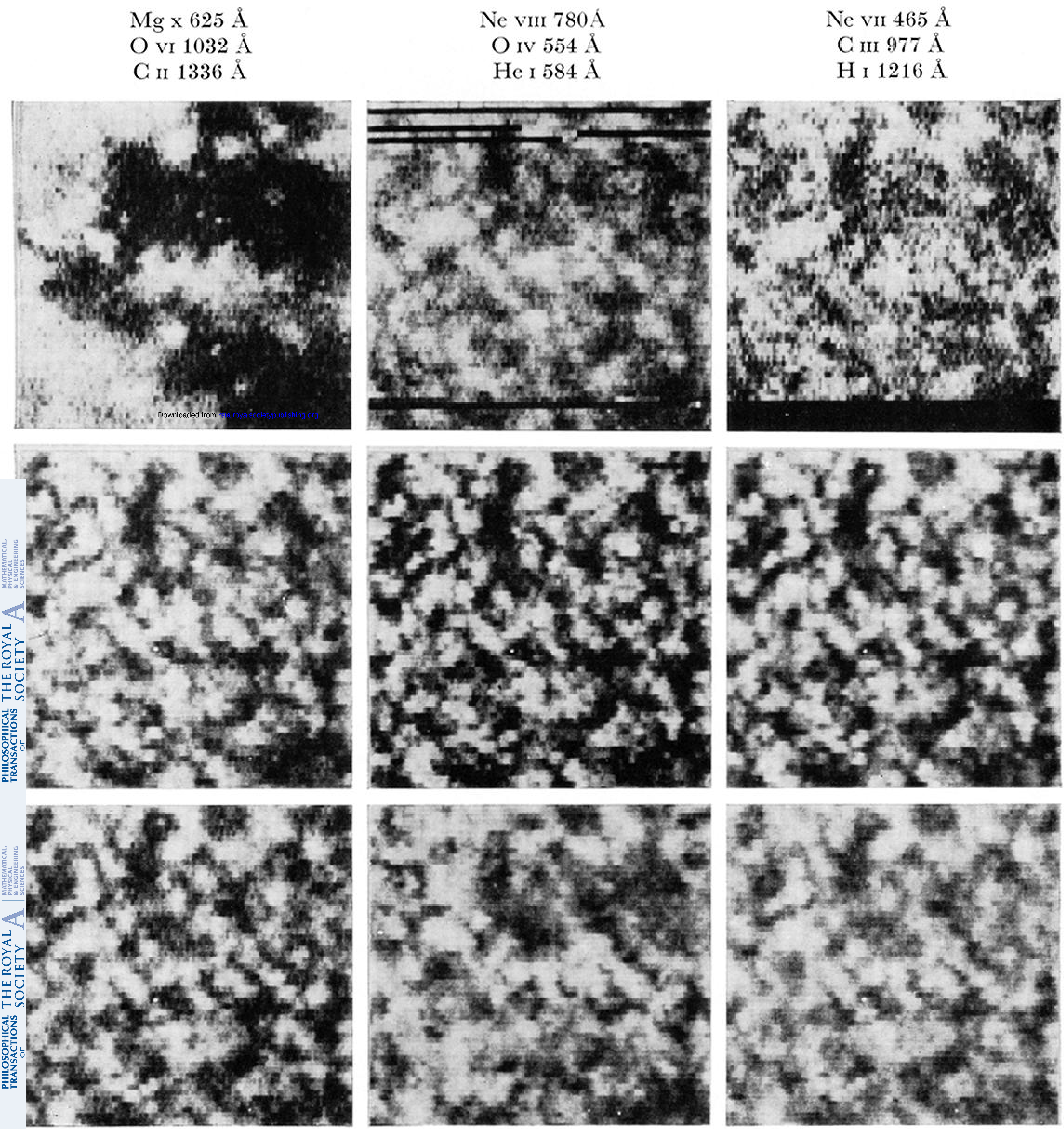

Figure 5. Spectroheliograms from hydrogen through Mg x in coronal holes.

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

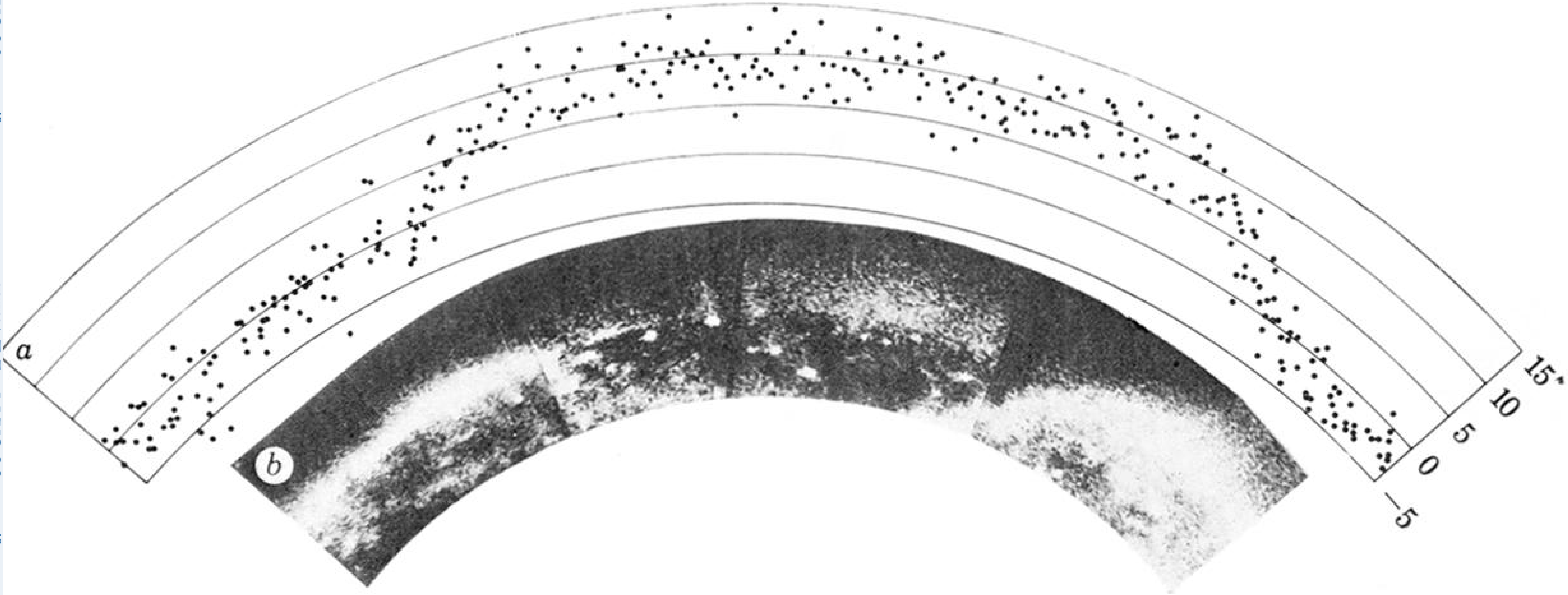

FIGURE 7. Behaviour of transition zone over south polar hole. (*a*) Height of Ne VII 465 limb relative to Ly C limb. (*b*) Limb in Mg X. SL 4, day 349, 16:46–22:01 G.M.T.

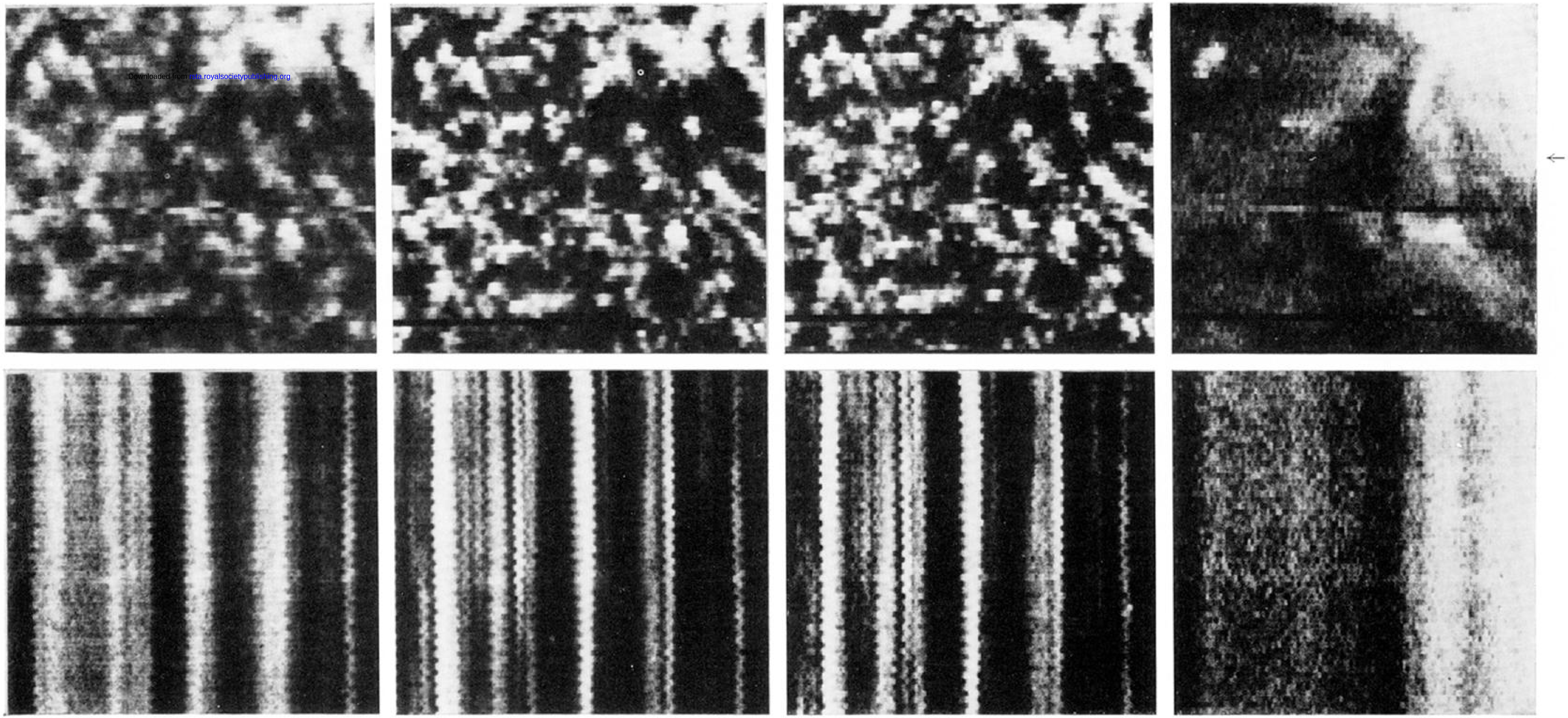

FIGURE 8. Spectroheliograms of the quiet Sun (upper portion) for selected e.u.v. lines. The lower portion shows the time development of the intensities for a single spatial line scan (arrow) in the upper portion of the figure.