12. RADIATION AND STRUCTURE OF THE SOLAR ATMOSPHERE (RADIATION ET STRUCTURE DE L'ATMOSPHÈRE SOLAIRE)

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1. INSTRUMENT DEVELOPMENT

L. Delbouille

The solar research previously carried on at the Dominion Observatory (Canada) has been transferred to the newly-formed Astrophysics Branch of the National Research Council of Canada, and a solar observatory has been installed on a new site, called the Ottawa River Solar Observatory. Its principal instrument is a multiple photoheliograph, using a 25-cm objective and a Zeiss 0·25 Å Hα birefringent filter in a folded configuration which produces a monochromatic solar image with a diameter of 100 mm.

The High Altitude Observatory (Boulder, Colorado, U.S.A.) has now ceased operation of its Climax Station after 30 years of continuous service in observational solar astronomy. HAO observational work will of course continue in the form of new projects at Sacramento Peak Observatory, at the Mauna Loa site (Hawaii, U.S.A.), and on instrumented aircraft operated by the National Center for Atmospheric Research, as well as on the Skylab and OSO-I spacecrafts.

No major general-purpose solar telescope or spectroscopic installation for the visible region has been built during the last three years. However, the new large vacuum solar telescope at Sacramento Peak Observatory (Sunspot, New Mexico, U.S.A.) and most of its associated equipment are now fully operational. Image quality is excellent.

At Locarno (Switzerland), the Göttingen group has completely reconstructed its 45-cm Gregorian coudé telescope to make it a computer-controlled vacuum telescope. At the Rome observatory (Italy), the solar tower and spectrograph have also been modernized to work under computer control, making possible very quick recordings of spectral lines as well as observations of very faint absorption features of the solar spectrum.

The infrared region of the solar spectrum is receiving more attention, and this has led to the development of special instruments. At Kitt Peak National Observatory (Tucson, Arizona, U.S.A.) the 20-m infrared spectrometer is now in general use (D. N. Hall). This instrument has been designed specially for very high resolution solar spectroscopy in the 1–15 μm region. It uses at present a 350 × 450 mm grating, ruled on the MIT 'C' engine, blazed at 44° (11·4 μm in the first order), and achieves, in double pass, a resolution of the order of 0·01 cm^{-1}. InSb detectors are used in the 1–5·5 μm region and permit spectra with signal-to-noise ratios in excess of 1000 to be obtained routinely. A Cu:Ge detector system is being developed for the 8–14 μm window.

A new infrared solar spectrometer has also been built and installed at the Jungfraujoch (Switzerland) by the Liège group, at the coudé focus of the 76-cm reflector which will be used as the light collector. Strong restrictions in the available floor space have limited its focal length to 2·5 m, and the grating is still a 10-in. Bausch and Lomb replica; used in double-pass, it gives a resolution of the order of 0·02 cm^{-1}. The main purpose of this effort is to take advantage of the very dry conditions above the Jungfraujoch to observe the solar spectrum as far as possible into the wings of the water bands, complementing the balloon program of the same group (R. Zander, L. Delbouille and G. Roland). This balloon program is now in its exploitation stage. The specially-built gondola, equipped with a 40-cm Ritchey-Chétien telescope and a 2·5 m double-pass spectrometer using an

https://doi.org/10.1017/S0251107X00024445 Published online by Cambridge University Press

8-in. Bausch and Lomb replica grating and providing a resolution of the order of 0·04 cm^{-1}, is flown twice a year with the help of the National Center for Atmospheric Research. The regions of the solar spectrum corresponding to the most intense absorption by water vapour around 1.8 and 2·7 μm have been recorded.

The ultraviolet domain, below 2950 Å, is amongst the topics more specifically discussed by Commission 44. However we must mention here the efforts of the Astrophysics Research Unit, Culham Laboratory (England), where various groups have developed and flown in rockets a series of instruments to photograph the solar sectrum from the X-ray region up to 3000 Å. A resolution of the order of 10^5 has been achieved between 1000 and 3000 Å (Boland *et al.*, 1971a, b).

At least for regions accessible from the ground, our knowledge of the photospheric spectrum, integrated both in time and over a large surface of the solar disk, is now approaching a definitive stage. Further increase in resolution, or in signal-to-noise ratio, will probably not give much additional information. It is clear that most of the instrumental effort, for the next decade, will be devoted to various approaches for obtaining spectral, spatial and temporal resolution simultaneously. More efficient ways of making use of all available photons have already been explored by various solar spectroscopists.

At Sacramento Peak, R. Dunn is developing a multiple-detector spectroscopic arrangement for recording spectra at various points at the surface of the Sun simultaneously.

A subtractive double-pass spectrograph has been installed in the Meudon Solar Tower. Developed by P. Mein and M. Blondel, this instrument works like a very flexible, highly accurate filter. Nearly-monochromatic pictures are recorded photographically.

In Poulkovo (U.S.S.R.) two different approaches have been chosen. The solar differential spectrophotometer of A. A. Kalinjak has been rebuilt. It measures differences between the spectrum of selected (but still relatively large-scale) solar features and the integral solar spectrum, and is especially valuable for the study of large-scale motions on the Sun with high accuracy. On the other hand, a four-camera isothermic spectrograph has been designed to yield the data needed for applying the escalation method for obtaining three-dimensional information (two space coordinates and the wavelength). This method is used for studying simultaneously magnetic fields, radial velocities and various physical characteristics derived from the line profiles.

Work on very narrow filters is also progressing. J. Beckers (Sacramento Peak), in collaboration with Zeiss (Germany), is developing a universal birefringent filter. When completely built, it will give access to any line in the 4300–7000 Å range, with a bandwidth ranging from 40 mÅ at 4300 Å to 125 mÅ at 7000 Å, and will be used for intensity, velocity and magnetic field observations of solar fine structure. A computer-controlled tunable filter of 1/8 Å around Hα has been developed by R. J. Bray (CSIRO, Sydney, Australia) (Bray and Winter, 1970).

A project is under way at Sacramento Peak to obtain the best possible set of high-resolution simultaneous spectra in the K, H, D1, D2, Hα, λ8498 and λ8542 lines.

The most promising work seems however to be the construction at Kitt Peak National Observatory (J. W. Brault) of a sophisticated doublebeam interferometer especially designed to obtain, in a very short time, high-resolution spectra at various points in a given field through Fourier transform spectroscopy. It is out of doubt that Fourier transform spectroscopy is, theoretically at least, the best possible way of obtaining both spatial and spectral information in the shortest time (Brault, 1972). Most of the mechanical and optical parts of the new instrument are approaching completion, and work is progressing on the electronics as well as computer programming.

2. THE PHOTOSPHERE

G. Elste

2.1. *Photospheric models*

The homogeneous model for the solar atmosphere, based on limb-darkening and energy distribution at disk centre, has been discussed in articles by Lambert (1971) and Gingerich *et al.* (1971). The latter propose an up-to-date reference model, the Harvard-Smithsonian Reference Atmosphere (HSRA), as a working hypothesis. A remark may be in order here, that the wings of the Balmer lines Hα to Hδ and their centre-to-limb variations, known as sensitive temperature indicators, point toward a higher temperature.

In the construction of the reference model, however, the main weight is given to the wavelength dependence of the absolute intensities of the quasi continuum. In the visible and near UV the values obtained by Labs and Neckel (1970) can be taken with high confidence. In the infrared high altitude measurements by several research groups must be considered. There is indication that the brightness temperature at disk centre as a function of wavelength reaches its minimum between 100 μm and 200 μm. Recent measurements by Léna (1970), Baluteau (1971), Koutchmy and Peyturaux (1970), as well as Clark *et al.* (1971), agree well with previous results. While these investigations favour an extended temperature plateau towards shorter wavelengths, Gay (1970a, b) observed a decrease of the brightness temperature with increasing wavelength towards this minimum. He has attempted to interpret the higher values near 30 μm by the presence of an unknown absorber, as in the UV. It would be desirable to repeat the observations in this spectral region with even greater resolution and accuracy and combine them with precision measurements of limb-darkening, taking into account the instrumental scattered light as done by Johnson (1971). E. A. Müller reports that new energy measurements in the range 10 μm to 1 mm from balloon-borne interferometers are being carried out by Stettler and Kneubühl (Obs. de Genève). First results between 110 μm and 500 μm agree with the model predictions of the HSRA.

In the UV, knowledge of the continuous absorption coefficients due to the metals becomes essential. Calculations and laboratory measurements seem to have converged to a narrow range, in particular since the measured Mg($^3P^\circ$) cross section has been corrected from 34 mB to 25 mB. (A useful collection of data by Hudson and Kieffer can be found in *Atomic Data* **2**, 205, 1972). Since the work of Travis and Matsushima (1968), no further progress has been made for Fe, for which the multitude of continuum edges can only be taken into account in hydrogenic approximation. Concerning other absorbing agents Vardya (1972) reports that the diatomic molecules CO, SiO, OH and CH may contribute to the missing opacity in the range between 2500 and 3000 Å, while H_2 is a significant source between 912 and 1900 Å. Inclusion of this opacity in the solar model may reduce the temperature in the low chromosphere and improve agreement between observed and calculated UV and microwave intensities. Below 2100 Å, new measurements by Widing *et al.* (1970) are in good agreement with those by Parkinson and Reeves (1969). For the wavelength range λ2000–3000Å, in which the discrepancy between model predictions and observations is increasing towards shorter wavelengths, the extensive measurements by Bonnet (1968) and Bonnet and Blamont (1968) could possibly be improved.

Generally these discrepancies are attributed to the effect of lines. The effects of line haze have been estimated by Holweger (1970), but line wings of strong and intermediate lines may not be negligible. Labs and Neckel (1972) find that the line haze may be already noticeable for $\lambda < 6000$ Å.

However we should not forget the inhomogeneous structure of the photosphere as a possible reason for the behaviour of the energy distribution in the UV, which is much more sensitive to temperature differences than the infrared. Efforts in this direction have not yet been made.

2.2. *Polarization*

In addition to the absolute intensities and their centre-to-limb variations, precision measurements of polarization constitute a sensitive parameter for judging the trustworthiness of our models and the degree to which we understand the physical processes. New measurements by Leroy (1972a) confirm the magnitude, centre-to-limb variation and the steep wavelength dependence of the polarization found previously. Part of it can be understood (Pecker, 1970; Debarbat *et al.*, 1970a, b; Dumont and Pecker, 1971) by a wavelength dependence of the collisional depolarization in spectral lines. However an additional polarization of unknown instrumental or solar origin seems to be present.

2.3. *Pole-Equator effects*

Differences in the temperature stratification between polar and equatorial regions are still under investigation, because of their importance for the internal structure of the Sun. Plaskett (1970) has measured consistently 5% brighter poles from photographic observations at 6263 Å with a Cassegrain system tower telescope. These results have not been confirmed by the photoelectric observations of Altrock and Canfield (1972a), using the Sacramento Peak Coronagraph refractor system. However they detected a much smaller variation of the temperature in the higher layers having the same trend with latitude, this being associated with active regions (1972b).

Caccin *et al.* (1970) have found a temperature difference of less than one per cent from equivalent widths of temperature-sensitive lines. From their discussion of all previous measurements they concluded that a variation with the solar cycle is not detectable. For this problem a long-term observing program should be undertaken by photoelectric techniques and with the one instrument. Recent measurements at 2.3 μm of molecular lines of CO, which are formed near optical depth $\tau_{0.5} = 0.01$, indicate a slight equatorial excess of 7 °K (Noyes *et al.*, 1972). In this connection it should be mentioned that Livingston (1970) found differential rotation of the photosphere to be independent of depth.

2.4. *Granulation and Doppler motions*

A major step forward in the investigation of granulation has been made by the work of Parvey and Musman (1971), proving objectively that the solar granulation consists of bright features, separated by dark lanes. Much greater difficulties are encountered in the measurements of the rms intensity fluctuations. Choosing moments of best seeing by high-speed photography at broad bands, Kerimbekov (1970, 1971) and Karpinsky and Kostjukevich (1971) resolved 0"18, but have not yet determined rms intensities. With interferometric techniques Harvey has obtained even higher resolution. The analysis of partial eclipse observations by Levy (1971) has the advantage that seeing effects can be measured from the sharpness of the lunar limb profile. The resulting rms value of the intensity fluctuations is the highest ever reported from photographic analysis: 17.5%; this compares well with visual estimates made by Thiessen in 1955 (recall that Edmonds (1962) obtained 13.5% from corrected stratoscope observations). The corrected power spectrum shows two maxima at 3600 and 3000 km. The only attempt to observe the photospheric granulation pattern in a quite different spectral region (1.7 μm) has been made by Arroyo and Torrecilla (1971).

Though of lower angular resolution due to the longer exposure times required, additional information is obtainable from spectroscopic or narrow bandpass observations. Beckers and Morrison (1970) succeeded in showing for the first time that the flow pattern in granules resembles that of convection cells with an upward motion at the bright centre, surrounded by outward streaming toward the intergranular lanes. Due to the necessary steps of symmetrization in this procedure the resulting absolute values for the velocities cannot carry much weight. Occasionally the velocity pattern is so strong that one may speak of exploding granules.

Mapping velocity fields and magnetic fields in an area of 60" × 300", Musman and Rust (1970) found a large-scale phase coherence of the 5-min oscillation with horizontal phase velocities of about 100 km s^{-1} starting from centres as large as 10" and extending over a distance of 50000 km. The centre-to-limb variation of the oscillations and of the supergranulation shows, according to Deubner (1971), that vertical motions increase with height, while the horizontal motions hardly change.

The short-period (1–5 s) oscillations found previously are evidently not of solar origin, as shown by Harvey and Howard (1972) from new observations in two dimensions.

A large number of investigations using high dispersion spectrograms have concentrated on intensity fluctuations in the continuum or in the wings of strong lines and their correlations with Doppler shifts measured along the slit. Although the time series of such spectra contain the maximum amount of information, valuable results may also be obtained from single spectrograms of high quality. Mehltretter (1971a, b) derived rms intensity fluctuations of 9.5%, while the rms velocity spread was

https://doi.org/10.1017/S0251107X00024445 Published online by Cambridge University Press

1 km s^{-1}. In a power spectrum analysis Reiling (1971) demonstrated that correction for seeing increases the rms velocity from 0.36 km s^{-1} to 1.0 km s^{-1}.

The most complete power spectrum analysis of time series of spectra have been carried out by Edmonds *et al.* (1971, 1972), who used lines of differing excitation as well as the wings of the Mg b lines to investigate variations of the fluctuations with height. The difficulties in the intepretation of the results lie in the separation of the effects of the oscillating velocity fields from those of the granulation. Sheeley and Bhatnagar (1971) managed to decompose these two kinds of velocity fields by photographic processes using spectroheliograms in Fe λ5434 and Fe^{+} λ4924.

Simulation experiments like that of J. H. Thomas (1972) can be helpful in attempts to understand the quite different results of various investigators. It seems that seeing shifts the power of small-scale motions (2000 km) to larger wavelengths rather than filtering out this power.

There does not seem to be general agreement between the various investigations concerned with the height variation of these velocity fields. Some complications arise from the overlap of layers contributing to line formation, in particular when combining centre-to-limb variations with disk centre observations of lines formed at different depths. Intensity-correlated granule velocities have generally been of the order of 0.6 to 0.9 km s^{-1} amplitude, the oscillatory motions of the definitely larger geometrical scale being of 0.5 km s^{-1} amplitude. We must consider these values as still affected by finite resolution due to seeing, since line profile calculations indicate that larger values are needed in order to explain the observed half-widths as well as the line asymmetries and the limb effect of wavelengths.

At the present time we would therefore arrive at the following general picture:

The granulation consists of bright regions surrounded by narrow dark lanes in a polygonal pattern of about 1000 km average diameter. The intensity fluctuations at 5300 Å increase first with approach to the limb from a value between 10 and 18% at disk centre, but decrease after reaching a maximum near $\cos\nu = 0.5$. Correlated with this intensity fluctuation is a velocity field resembling that of cellular convection, the rms velocity fluctuation being close to 1.2 km s^{-1}. Superimposed is a 5-min oscillation, apparently not correlated with the granule pattern and of smaller amplitude, 0.5 km s^{-1}, but with large horizontal phase velocities. This phenomenon seems to have connections with the supergranulation and its extension into the chromosphere. Difficulties arise in separating the oscillatory velocity component from the intensity-correlated convection velocities. In viewing the disk centre, both must be treated as macroturbulent velocities. In addition to these velocities we know from curve-of-growth analyses with improved oscillator strengths of the spectral lines that there exist microturbulent motions of less than 1 km s^{-1}, with eddy size smaller than 50 km in diameter.

For the interpretation of the centre-to-limb variation of the rms intensity fluctuations in terms of inhomogeneous model atmospheres, more observations at different wavelengths would be desirable. Preliminary studies show that, with the approach to the limb, it is necessary in the calculations to follow various lines of sight through the inhomogeneities and to take into account the changes in the optical depth. For spectral lines we must be aware that the line of sight passes through several regions of not only differing tempertaures but also a great variety of radial velocities. All of these regions contribute to the absorption at a wavelength in the flank of a spectral line, thus requiring to be treated as microturbulence.

2.5. *Line profiles*

While the structure of the granular velocity field can well be investigated by direct observations, seeing perturbations hardly permit the absolute values of the velocities to be determined reliably. For this purpose average spectra, taken with a sufficiently long slit, provide a more secure evaluation independent of the seeing. Precision measurements of half-widths and central intensities, and more complete line shapes, with their asymmetries and shifts and their variations from centre-to-limb, contain sufficient information to permit the evaluation of the physical parameters of the inhomogeneities.

The separation of the influence of macro-motions (motions of the whole line-forming regions) from that of micro-motions (the residual velocity differences inside these regions) can only be obtained from weak or mediumstrong lines. In this connection the classical method of the half-width v, equivalent-width correlation by Huang and Struve (1952) might be mentioned and its modern version by Elste (1967). If the line is too strong, the attenuation factor broadens the line core so much that the distinction of the two effects becomes impossible. This is unfortunately the case for the Mg line λ4571.1, which is expected to be unaffected by departures from LTE (White *et al.*, 1972 and recent work by Altrock and Cannon). For the investigation of the velocity fields alone, one must choose lines which are less sensitive to temperature and pressure, such as high excitation lines of neutral atoms. While the rms value for the macroturbulent motions at disk centre can be considered to be close to 1.2 km s^{-1}, an anisotropy of the velocity field with larger horizontal components seems to be present (E. A. Müller, as well as Slaughter and Wilson, 1972) in accordance with several previous investigations. However a non-LTE analysis of the cores of the Na D lines by Worrall (1971) results in almost negligible turbulence broadening but with a strongly frequency-dependent source function.

For weak lines formed much deeper, one can interpret the more rounded appearance of the line core near the limb in contrast to the quite sharp appearance at disk centre as a result of the penetration of the lines of sight through various regions of different velocities; it might be called microturbulence.

For investigating the variation of physical parameters with depth using different lines, experience tells us that the depth of line formation depends more on the strength of the line than on its excitation potential. The study of the wavelength variation of the continuous absorption coefficient is possible with lines for which the line absorption coefficient hardly varies with depth. Studies of this sort are being undertaken by E. A. Müller *et al.* at Geneva.

The most sensitive temperature indicators such as the infrared oxygen triplet may be used for the improvement of inhomogeneous models. The asymmetries of these and other lines as well as the centre-to-limb shift of the line centres along a polar diameter have not been investigated recently despite the importance for the structure of the inhomogeneities.

For a small number of lines the atomic beam resonance scattering technique has led to more reliable values of the wavelength shift (Snider, 1972). At disk centre, O'Brien (1971) has remeasured the wavelengths of a large number of lines interferometrically relative to the Hg 198 standard. An extended program of wavelength measurements relative to thorium standards is in progress at Kitt Peak National Observatory.

In almost all of the above studies, the depth variation of the damping plays an important role. Although the interaction constants contain considerable uncertainties, the neglect of damping, as well as treating damping throughout the atmosphere as a depth-independent constant, leads to erroneous conclusions. Even for medium-strong lines, damping changes the depth-dependence of the line absorption coefficient in a significant way. A striking result of the improved oscillator strength scale for Fe lines is the branching of the damping part of the curve-of-growth (Foy, 1972), confirming the dependence of damping on the transition as predicted at least in part by the theory of Van der Waals broadening. Holweger (1971) determined empirical damping constants, quite useful for stellar abundance work. In the theory of line-broadening by light atoms, hydrogen and helium, progress can be reported by Roueff (1970), Fullerton and Cowley (1971), and K. A. Brueckner (1971).

Molecular lines have been used for the investigation of the radiation temperature (Sitnik *et al.*, 1970; Porfirjeva and Sitnik, 1971; Sarychev, 1970, 1971) and of turbulent velocities (Porfirjeva, 1971) in the higher photospheric layers. Important for the interpretation of the measurements of the violet system of CN is that these lines are formed, according to Khlystov (1970), by a completely incoherent scattering mechanism together with an interaction between electronic and rotational levels, due to collisions with hydrogen atoms.

Among the methods of line profile analyses, the Goldberg-Unno method is known for demanding very few assumptions. Therefore it has been used widely, although its applicability for the solar atmosphere has been questioned. Now de Jager and Neven (1972) have shown clearly that it leads to a misinterpretation of the data if macroturbulent motions are present. However, it would seem possible to apply the method for a differential analysis of the active and quiescent photosphere as done by Badalyan and Livshitz (1971, 1972).

Schmieder (1972) and Orrall (1972) have developed methods for deriving the depth dependence of temperature and density or pressure fluctuations from measured intensity fluctuations in continuum and lines. While Orrall uses the centre-to-limb variation of the fluctuations at several points in the wings of the K-line, Schmieder analyses two disk centre spectrograms of a time series, and eliminates the influence of the 5-min oscillation. The depth dependence of the fluctuations is then derived from combining measurements at 0·58 Å from the centre of the Mg b_1 line with those at the centre of two high excitation ion lines and in the continuum. The resulting model predicts a centre-to-limb variation of the rms intensity fluctuations in the continuum which agrees fairly well with the stratoscope observations (Edmonds, 1962) for $\cos \nu > 0.5$.

Our knowledge about the deeper photospheric layers can be improved by the analysis of the temperature-sensitive wings of the Balmer lines Hα to Hδ. Precision measurements of the centre-to-limb variations are available from David (1961). Recent calculations by Elste and Hartoog (1972) show that the continuum reference model, HSRA, predicts line depths which are several per cent smaller than observed. The exact amount of the discrepancy depends on the Stark broadening theory applied. But even for the most recent and probably best founded unified theory of Cooper *et al.* (1971) the difference persists, and even increases for large distances from the line centre. A correction of the solar model toward higher temperatures seems unavoidable, so that contradictions with the energy measurements by Labs and Neckel are likely.

While the work and methods discussed so far generally assume LTE, but might incorporate the inhomogeneities, we will now turn to those investigations which concentrate mainly on the departures from LTE.

Wijbenga and Zwaan (1971) have pursued a non-LTE analysis of observations aimed at the determination of departure coefficients for both the occupation numbers and the frequency-independent source function. Inclusion of the behaviour of the lines in the flash spectrum (van Dessel, 1970; Houtgast *et al.*, 1971), in addition to their centre-to-limb variation, provides sufficient information for the solution. Fairly strong lines and the characteristic shapes of very strong lines of Fe and Mg have been used by Athay *et al.* (1972) for a very general first-order analysis of the profiles and their centre-to-limb variations. Linear approximations for the source function and the ratios of optical depths within the line-forming region serve in deriving the dependence of the physical parameters with depth. The use of a frequency-independent source function appears justified, but attention is called to the fact that in principle this function could as well depend on all the parameters, depth, direction, and frequency within the line. Canfield (1971) studied the mechanism of interlocking by photoprocesses, which can account for the characteristic behaviour of the solar lines of rare-earth ions in the wings of the H and K lines.

Investigations of the wings and cores of the H and K lines have concentrated mainly on securing a reliable absolute intensity calibration (Linsky and Avrett, 1970; Pasachoff, 1971, and current work at the McMath-Hulbert Observatory). Model calculations by Matsushima and Kawabata (1972), using the blending of various lines in the vicinity of H and K, predict a 10 to 15% higher position of the continuum than indicated by the newest empirical determinations. An excellent check on the wavelength and depth variation of the continuous absorption coefficient can be provided by the comparison of the wings of the infrared triplet lines with those of H and K (Linsky *et al.*, 1970).

2.6. *Photospheric magnetic fields*

The theory of absorption line formation under the presence of nonuniform magnetic fields has been investigated further by Lamb (1970) and by Rees (1971).

A very complete discussion of the magnetic field structure in the photosphere can be found in the *IAU Symposium* No. 43 (1971), in which the observational aspects are reviewed by Beckers (1971). The photospheric network observed photographically in the violet part of the spectrum

(Jayanthan, 1970; Chapman, 1970; Grigorjev and Kuklin, 1971) is known to be associated with photospheric magnetic fields. In particular Sheeley (1971) has shown that the intensity in the CN band head at λ3883 is well correlated with fields of the order of 300 G, and that this correlation can be extended to much weaker fields by averaging of time sequences of spectroheliograms. The extended filamentary nature of the fields has been deduced from a careful analysis of pairs of magnetograms in λ5250 and λ5233 Å (Howard and Stenflo, 1972). The narrow lanes of concentrated magnetic flux coincide with the boundaries of the supergranule cells, which extend into the chromosphere. New observations have been reported by Krat (1971). It is puzzling that these boundaries appear brighter and show dominating downward motions relative to their surrounding, while we generally associate bright granule centres with upward motion, and stronger magnetic fields with dark pores. Further observations of the supergranule boundaries are necessary before we can hope to understand the physics of this phenomenon.

Semel (1970a, c) and Harvey and Livingston (1970) have attacked the calibration problem of precision measurement of magnetic fields with magnetographs. Different lines tend to give different results, depending on the way a particular line changes in the unresolved inhomogeneities. The use of lines of different behaviour can therefore help in studying the unresolved solar fine structure (Semel, 1970b). Observations by Stellmacher and Wiehr (1971) as well as by Harvey *et al.* show indeed very little change in the Doppler broadening of non-splitting lines in gap regions, which means that we must intepret the broadening of the 5250 Å line in these regions as due entirely to the Zeeman effect.

In the theory of magnetic fields, reviewed by Parker (1970) and Deinzer (1971), we notice that the field origin must be associated with processes in the hydrogen convection zone and with differential rotation.

Confirming Severny's discovery, Scherrer *et al.* (1972) found that large scale averages of photospheric magnetic fields correlate over a 2½-year interval with the interplanetary magnetic field and its sector structure, showing a 4½-day delay.

2.7. *Abundances of the elements*

Improvements in the abundance determinations of metals have been due mainly to revised oscillator strengths provided by various laboratories. Special mention should be made of the work by Baschek *et al.* (1970), Miller *et al.* (1970), Bridges and Wiese (1970), Wolink *et al.* (1970, 1971), Garz (1971), and Garz *et al.* (1971).

Grevesse and Swings (1970, 1972) have used the advantage of forbidden lines. Common problems in abundance determinations are the uncertain values of the microturbulence and the damping (discussed in §2.5). Frequently the use of blends cannot be avoided, and a spectrum synthesis is carried out. For greater accuracy the centre-to-limb variation of the spectrum must be studied. Such analyses, based on Kitt Peak observations, are in progress by E. A. Müller and co-workers for lithium, beryllium and various other elements.

Differences between abundance values derived from atoms and ions are often found. This must call our attention to further problems: since atomic lines of almost completely-singly-ionized metals are more sensitive to the ionization conditions than ion lines, the latter would lead to a safer abundance if the oscillator strengths could be trusted. The ionization conditions depend critically on the absorption cross sections and the radiation field in the UV. Both of these are still not well known. The presence of inhomogeneities and departures from LTE in the photosphere can be expected to influence the result for atomic lines. Therefore more independent laboratory measurements of absolute oscillator strengths for ion lines would be desirable.

The iron abundance has been discussed in great detail by Unsöld (1971) and by Garstang (1971). New results for other elements have been derived by various authors:

Si (Grevesse and Swings, 1972)
Ni (Grevesse and Swings, 1970)
Cr, Ni, Ag, Er, Yb, Lu, Th (Boyle, 1972)

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Mn (Blackwell *et al.*, 1972)
Ag (Ross and Aller, 1972)
Au (Mullan, 1972)
Ga (Ross and Aller, 1970)
Cl (Lambert *et al.*, 1971a; Hall and Noyes, 1972)
Hg (Kandel and Keil, 1971).

Of special interest are the new determinations of isotopic abundance ratios. Kumar (1971), Boyer (1971), and Lambert *et al.* (1971b) have investigated magnesium, Hauge (1970, 1971) analysed europium and copper, and Fay and Wyller (1970) are searching for a new way to determine the C^{12}/C^{13} ratio. Hall *et al.* (1972) have shown this ratio to be terrestrial to within 15%.

3. THE CHROMOSPHERE

R. G. Giovannelli

3.1. *Spicules at the limb*

Beckers, Dunn and Lynch (in press) have used the Sacramento Peak tower telescope to obtain the highest-resolution observations made on spicules. They find mean diameters of 900 km which are constant to within 200 km with wavelength, height and time. The expansion reported by Mouradian (1967) is not confirmed. On the other hand, Papushev, Polyakov and Stepanov (unpublished) have found Doppler widths increasing with height; they report a time correlation between the change in Doppler width and the radial velocity which they believe is evidence for an impulsive propagation of gases in spicules.

Krat and Krat (1971) have observed spicule line profiles simultaneously in Hα, Hβ, D_3, H and K at heights from 5000 to 9000 km, finding various peaks within the one profile. They conclude that spicules often occur in narrow bundles not resolved in their spectra, individual spicules having different Doppler widths, a result also confirmed by Nikolsky (1970). In D_3, spicules appeared more diffuse than in the other lines, with faint interspicular emission. This is compatible with unpublished conclusions of Giovanelli, Hall and Harvey who found, in addition to a strong network, that there is weak 10830 Å absorption at every point on the disk, so that there seems to be a background of helium absorption outside the supergranule regions where spicules originate (this suggests that the chromosphere consists of more than spicules alone). Krat and Krat argue that the different lines originate in different parts of a spicule with different turbulent velocities, but this seems far from definite.

Considerable interest has centred on the bright mottles at the limb and the dark band immediately above the photospheric limb described by Loughhead (1969). The latter has been classed as of instrumental origin by White and Bhavilai (1970), but confirmed by Nikolsky (1970), who attributes it to self-absorption by spicules, and by Alissandrakis and Macris (1971) who incline to the view that it is due merely to the presence of bright mottles some 2″ or higher above the photospheric limb. Loughhead and Tappere (1971) have pointed out that the band does not occur at the Hα line centre, but only around H$\alpha \pm 0.75$ Å, and this makes one think, contrary to Nikolsky, that it may be due to the *absence* of spicules in such regions. However, the origin is still quite indefinite.

The relationship of dark and bright mottles to spicules is also still unsettled. Alissandrakis and Macris, finding most bright mottles at the limb extending beyond as spicules, incline to the view that bright and dark mottles are the lower and upper parts of the same features, the dark mottles being the disk representations of spicules (see also Banos and Macris, 1970). This is in contradiction with the earlier conclusion of Bray (1969) that bright and dark mottles cannot be the same structures. Loughhead and Tappere have looked for conjunctions of spicules which cross the limb with bright or dark features, and while they found some examples of each type there were numerous cases where no link occurred; they concluded that direct observations have not solved the identification problem. Later, Bray and Loughhead (in press) have argued that bright mottles at the limb are quite distinct from spicules, which are fainter and project much higher into the chromosphere. If one accepts

https://doi.org/10.1017/S0251107X00024445 Published online by Cambridge University Press

Bray and Loughhead's identification of bright mottles at the limb with bright mottles on the disk, it would seem from the discreteness of bright and dark mottles on the disk (as Alissandrakis and Macris (1972) have confirmed) that the two cannot be lower and upper parts of the same structure. A somewhat different line of argument arises from Giovanelli *et al.*'s (1971) simultaneous disk spectro-heliograms in He 10830 Å and Hα, which showed that strong 10830 Å absorption can be associated with both bright and dark Hα mottles on the disk. Since at the limb D_3, and presumably 10830 Å, is concentrated in spicules, perhaps both bright and dark Hα mottles correspond to limb spicules. A similar conclusion has been reached by Grossman-Doerth and von Uexküll (unpublished), based on a discussion of their analysis of Hα profiles in SGBs (see §3.3.2(ii)). In an attempt to leapfrog the problem, Dunn and Zirker (1972) have sought for the origin of spicules at photospheric levels, but so far without success.

There is still some uncertainty about spicule temperatures. Whereas the presence of the He D_3 and 10830 Å lines was earlier thought to be due to high temperatures above 20000 K, it is now clear that excitation is due to ionization by coronal radiation, $\lambda < 504$ Å, and the need for such high temperatures has vanished. Gulyaev (1972) has shown that Dupree and Reeves' (1971) He I intensities (465–504 Å) lead to $T \sim 12000$ K in the emitting regions, but this is some form of average over all emitting regions. Unpublished work by Giovanelli, Hall and Harvey on spicule line profiles in optically-thin I.R. lines suggests that $T < 7500$ K.

Further discussion related more indirectly to spicule temperatures is given in §3.3.2(iv). It seems clear that the wide range in 'spicule' temperatures required to satisfy all these observations must originate from a spread of temperatures through and along spicules, and between one spicule and another. It also appears inevitable that we shall have to find some way of taking this into account before all the different types of spicule observations can be reconciled.

A comprehensive spicule review has been presented recently by Beckers (1972).

3.2. *Supergranulation*

A unique study of the network for a continuous period of 62 h has led Janssens (1970) and Rogers (1970) to a description of the development of a typical supergranule (SG) and assessments of the typical mean life, 21–25 h, in good agreement with previous estimates. Several groups, Frazier (1970), Musman and Rust (1970), Giovanelli and Ramsey (1971), Giovanelli (1970), have confirmed Beckers and Schröter's (1968) observation that magnetic fields at supergranule boundaries (SGBs) are associated with downward velocities at photosperic level, and Ribes and Unno (1971) have attempted to explain this. Frazier (1971) has studied the effect of magnetic field strength on SG structure, finding that the network contrast increases with increase in field up to 500 G; at disk centre the white-light faculae increase in brightness up to ~ 200 G, but for higher field strengths the faculae become darker until pores or sunspots are produced. The differing appearances of the faculae in different lines suggest that the faculae are composed of a set of ropes of more-or-less uniform thickness, close together at photospheric levels but fanning out into the chromosphere. White (in press) estimates the angle of separation to be about 50°.

3.3. *Physical conditions*

3.3.1. *The photosphere-chromosphere transition region and the low chromosphere*

A review of empirical and theoretical models of the transition region has been made by Lambert (1971), and he has found $T_{min} = 4300$ K at log $\tau_0 \approx -4$ from new observations in the UV and far IR. Cuny (1971) has examined the UV solar spectrum in the range 600–1700 Å, assuming an atmosphere varying only in depth and in hydrostatic equilibrium. Her preferred model has $T_{min} \approx 4200$ K at 550 km, T rising to 6000 K at about 1100 km.

Hiei and Hirayama (1970), Tanaka (1971), and Tanaka and Hiei (1972) have reported on and analysed spectra of the 12 November 1966 eclipse, finding $T_{ex} > T_e$ near the temperature minimum, this arising apparently from resonance scattering of photospheric radiation. Up to 1000 km they

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find good agreement with Noyes and Kalkofen's (1970) model for neutral hydrogen densities, the electron densities being intermediate between those of Noyes and Kalkofen and of Athay and Canfield (1970). Their derived temperatures rise from $T_{\min} = 4460$ K at 100–200 km to 6040 K at 1000 km.

3.3.2. *The middle chromosphere*

(i) *K-line profiles and their interpretation*

Pasachoff's (1970) claim that violet and red K_2 peaks are present simultaneously in only about 10% of individual profiles has stimulated investigations into the asymmetry of the K-line profile by Bappu and Sivaraman (1971), Krat and Krat (1971), Krat and Stojanova (1971), Pasachoff and Zirin (1971), Wilson and Evans (1971), Liu and Elske Smith (1971), Liu *et al.* (1972), and Wilson *et al.* (1972). It turns out that in SGBs most profiles are double-peaked, whereas in supergranule centres (SGCs) profiles can have double or single K_2 peaks (in either wing) or none at all. In SGCs, the bright points usually have short lives of the order of 50–100 s, but in some cases they may exhibit brightness oscillations with periods of about 200 s, for up to 7 or 8 cycles. No line-of-sight or transverse velocities have been reported in these features. Some double-peak profiles have changed to single red and blue peak profiles in 15 s or so, and vice versa. In some cases features appear to have split into parts which separate at velocities of 50–100 km s, but the cause is uncertain. Athay (1970) and Cram (1972) have attempted to interpret K profiles, and it seems that with suitable relative vertical velocities between the lower K_2 emitting regions and the higher K_3 absorbing regions of up to 10 km s^{-1} up or down, detailed profiles and the average centre-limb variation can be reproduced.

It is interesting to compare a study of the Mg II H_2 and K_2 emission peaks by Greve (1971), who finds the optical thickness of the emitting region to be about 300, and turbulent velocities 6–8 km s. Again, Jones and Rense (1970) have obtained rocket spectra of O I 1305 Å which is formed higher than Ca II K, and has a nearly flat-top profile whereas a homogeneous spherically symmetrical chromosphere should have a rather deep reversal. They explain this by a gaussian distribution of up and down velocities with rms velocity ± 7 km s^{-1}.

(ii) *Hα*

Above heights of 1000 km all evidence points to the need to take account of inhomogeneities. In Hα, Grössman-Doerth and von Uexküll (1971, and in unpublished work) have studied line profiles and have provided evidence that at SGBs the fine structures appear as clouds of differing source function, opacity τ, Doppler width $\Delta\lambda$ and vertical velocity V superimposed on a lower uniform layer at rest. For some 88% of all fine structures, $0.5 \leqslant \tau \leqslant 2$, $0.4\ \text{Å} \leqslant \Delta\lambda \leqslant 0.6\ \text{Å}$, and $|V| \leqslant 8$ km s^{-1}. For most structures there is no strong correlation between one parameter and another. They believe that little emphasis should be put on the distinction between bright and dark mottles, though the bright features at the centres of rosettes and chains tend to be of lower opacity, broader $\Delta\lambda$ and somewhat greater source function than elsewhere. In SGCs the profiles are more irregular and most cannot be interpreted either as due to clouds above a lower uniform layer, or on Athay's (1970) velocity model. From indirect evidence they suggest that spicules may be identical with the structures, both bright and dark, of the SGBs; though spectra having spatial resolutions $\sim 0.3''$ will be needed to provide more direct evidence of this.

Schoolman (1972) has attempted a one-dimensional non-LTE study of Hα profiles, finding that unit optical depth at line centre occurs where $N_H \approx 10^{13}$ cm^{-3}. For a reasonable fit, T is required to rise to 20000 K by 1000 km. The temperature minimum is found quite transparent to Hα, and takes no part in line formation.

(iii) *Fine structures and magnetic fields*

It is now fairly well established that the pattern of the chromosphere is established by the magnetic field configuration. Several observational studies (Veeder and Zirin, 1970; Foukal, 1971; Prata, 1971; Zirin, 1972) have shown that dark fibrils and threads always join regions of opposite magnetic polarity, the fibrils lying in regions of weak longitudinal field, whereas vertical field is marked by bright plage. Active region filaments consist of threads almost parallel to the filament axis, whereas quiescent prominences consist of threads joining nearby regions of opposite polarity and lying at appreciable angles to the filament axis. Frazier (1972) warns that almost every proposed rule relating magnetic field to fine structure is invalid or unproven, except that $H\alpha$ plage invariably has an associated clump of magnetic field. We should also bear in mind that simultaneous studies of chromosphere and magnetic field are still lacking at 1″ resolution, and these could change our concepts appreciably on the relation of field to fine structure in the network and in active regions.

Theoretical studies by Raadu and Nakagawa (1971), Nakagawa and Raadu (in press), and Nakagawa, Raadu and Harvey (in press) have shown that it is possible to predict from a force-free approximation the shapes of chromospheric structures around simple or bipolar sunspots with fair success, despite some disagreements. One feels that the latter are due rather to the breakdown of the force-free approximation or our imperfect knowledge of the boundary conditions than to a lack of a one-to-one correlation between the patterns of field and chromosphere.

(iv) *The chromosphere-corona transition region*

Many studies of this region have led to somewhat conflicting results due probably to inadequate recognition of its intricate structure.

An eclipse study of the 5303 Å and 6374 Å coronal lines by Kanno *et al.* (1971) has revealed increases in emission down to 1000 km above the limb, and they have concluded that the region below 10000 km consists solely of 'spicules' (undefined) and corona. The coronal temperature in this region ranges from $1{\cdot}2$ to $1{\cdot}6 \times 10^6$ K, with $Ne \sim 10^9$ cm^{-3}.

Makita (1971) finds it impossible to fit eclipse continuum observations at 6900 Å with other types of observation without introducing inhomogeneities, while M. Simon (1971) and Hagen *et al.* (1971) have made eclipse observations in the mm and cm range showing substantial roughness on the disk. In Simon's case these were of SG size and extended out at least to 10000 km beyond the limb. Kundu (1971) and Lantos and Kundu (1972) also report on centre-limb observations at 1·2, 3·5 and 9 mm, explaining their results by emission from a hot region beginning just above 2000 km, together with absorption and emission in cool spicules, $T < 5000$K, up to 2000 km. The fraction of the area which is covered by spicules, negligible below 1000 km, is about 0·4 up to 1800 km and 0·3 about 2500 km, and then follows Beckers' (1968) distribution.

G. W. Simon and Noyes (1971) have found a positive correlation between the K network and that observed in EUV coronal and chromospheric lines. Tousey (1971) has published a rocket spectroheliogram showing the network very prominently in He II 304 Å. Since earlier work had shown the network present in O V but not in Ne VII, it appears to be present up to 2×10^5K but not at 5×10^5K. Many spicules or clumps of spicules are resolved in λ304.

Withbroe (1970a) has found that limb brightening in EUV lines can be explained by a model in which cool, absorbing spicules extend well above the thin transition zone where such lines are mainly formed. From Lyman continuum observations, Vernazza and Noyes (1972) have deduced a model consisting of a plane-parallel component rising to 10000K by 1770 km, superimposed on which are optically-thick absorbing inhomogeneities (spicules?) of low temperature (< 6500K) and high density. Their model also reproduces observed temperatures in the 0·1 to 10 mm range. Studies of rocket spectra by Burton, C. Jordan, Ridgeley and P. Wilson (1971 and also unpublished work) support not only a steep rise in T in the transition region but also cool material 8–16 $\times 10^3$K extending some 10^4 km in the corona, presumably as spicules.

All the above studies agree in needing a mixture of hot material and cool 'spicules', and it seems likely that a model can be produced consistent with all of them. Dubov (1971) has attempted an investigation of this type based on eclipse density data, radio emission at various wavelengths, and the coarse brightness distribution over the disk in visible and UV spectroheliograms. Over SGBs, T rises rapidly from about 5900 to 13000K at 2000 km, and abruptly from about 40000 to 10^6 K at 9000 km. Over SGCs, T rises abruptly from 10500 to 25000 K at 6000 km, and then slowly to coronal values around 15000 km. It is surprising that his coolest regions lie above SGCs, whereas the spicules (which appear to be cool) are believed to be at the SGBs. Further, the low-level corona does not enter into his model. It seems that we still need a more definitive model than any produced so far.

3.4. *Oscillations and waves*

Bhattacharyya (1972) has conducted an extensive investigation of velocity oscillations in photospheric and low chromospheric lines, and Hβ, over periods of 2–4 h; though no pair of lines was observed simultaneously nor was there any close restriction as to the type of region observed, conditions that would seem to be desirable.

Oscillations in the network have been investigated by Liu and Sheeley (1971) at low (CN 3883 Å) and high (K_{2V}) levels simultaneously. In these lines there is close coincidence between the bright network points, though the 3883 Å intensity there undergoes small irregular fluctuations whereas in K_{2V} there are well-developed 300-s oscillations. Over SGCs, K_{2V} shows only irregular fluctuations, with a period close to 200 s. In Hα $-0{\cdot}5$ Å, Bhatnagar and Tanaka (1972) have found intensity oscillations with periods of 170 ± 44 s in SGCs, 312 ± 56 s in rosette centres, 282 ± 49 s in plages, and 190 ± 66 s in sunspot umbras. At the Hα lines centre they report intensity oscillations of much reduced amplitude in plages, and intensity oscillations in the centres of rosettes also. They have been unable to separate the effects of any Doppler shifts and intrinsic intensity fluctuations. By observing simultaneously in opposite wings of Hα, Giovanelli (in press) was able to identify velocity oscillations in sunspot umbras and associated transverse waves propagating outwards over the penumbra, presumably basically in an Alfvén mode. In unpublished work he has established that any associated intrinsic intensity oscillations are relatively weak.

3.5. *Chromospheric heating*

Milkey (1970) has studied energy transport by weak fast-mode hydromagnetic shock waves in inhomogeneous anisotropic media, and has shown that, in the absence of magnetic fields, acoustic heating falls off rapidly with height. In the presence of magnetic fields, as at SGBs, the fast mode flux through the lower chromosphere is increased and there is increased heating above 750 km. Durrant and Michalitsanos (1971) have also studied heating in magnetic regions due to the dissipation of weak acoustic shock waves. Both investigations would predict hotter regions above SGBs, as inferred by Dubov.

Boland *et al.* (1971a, b and in press) report that rocket UV echelle spectrograms show $T_i > T_e$ in the region between 10^4 and 10^5 K. Since ion-electron relaxation times are very short, this would require the continual presence of non-thermal mechanical energy, which they suggest is propagated as an acoustic wave.

Moore and Fung (1972), using Cox and Tucker's (1969) radiation rates, have shown that, above $T = 10^5$ K, they can produce transition-region models which agree with the conductive heat inflow and the structure derived from XUV observations. However, as has long been known, at lower temperatures a static planar model is unable to radiate away the conducted heat. They have suggested that there may be sufficient agitation by mechanical waves to increase the volume of the radiating region, so overcoming the difficulty; further, funnelling the inflow into SGBs and plages by magnetic fields causes additional heat flux per unit area, requiring higher densities to radiate it away, and so lowers the temperature profile. In this way they believe that they can explain qualitatively Noyes *et al.*'s (1970) deductions from EUV observations of active regions that the pressure and temperature gradient in plages are about $5\times$ as large as in quiet regions (see also Linsky, 1970). However, Zirin (in press) has shown that, except in the very greatest flares, there is no heating by flares of the upper photosphere as seen in the 3835 Å line, and he infers that, in general, heat coming down from high in the chromosphere has negligible effect on the low network. A simple solution has been put forward independently by Lantos (1972) and Piddington (in press):

https://doi.org/10.1017/S0251107X00024445 Published online by Cambridge University Press

the conductive inflow is balanced by an outward convected flux, transported by an upward wind. Lantos finds T rising from 10^4 K to 3×10^5 K in just over 100 km, by when the upward velocity is 43 km s^{-1}. There is no direct observation of such velocities, which involve a flux of matter very much greater than in the solar wind, and Lantos suggests that a material balance is achieved by a downflow through quiescent prominences. Piddington's velocities are an order of magnitude lower. However there still seems to be an unresolved problem in that conductive inflow from the corona should lead to $T_e > T_i$ in the transition region, and an independent confirmation of Boland *et al.*'s contrary finding is highly desirable.

4. THE CORONA

F. Q. Orrall

The period covered by this report has been a vigorous one for coronal physics, being stimulated by an especially well observed total solar eclipse (7 March, 1970) and two major solar spacecraft (OSO 6 and 7), as well as by a number of other new observations from the ground and from above the Earth's atmosphere. Symposium volumes have appeared on the physics of the solar corona (Macris, 1971), the solar wind (Sonett *et al.*, 1972) and the chomospheric-corona transition region (High Altitude Observatory, 1969), as well as other symposium proceedings devoted in part to coronal science (Howard, 1971; Dyer, 1972; *Third Symposium on Ultraviolet and X-Ray Spectroscopy of Astrophysical and Laboratory Plasmas;* High Altitude Observatory, 1972). Several collections of papers dealing specifically with the 7 March 1970 solar eclipse have been published (National Science Foundation 1970; *Applied Optics* **9**, 1970; *Nature* **226**, 1970; *Solar Phys.* **21**, 1971; *J. Atmos. & Terres. Phys.* **34**, 1972). Only preliminary reports of the 10 July 1972 total eclipse have appeared (*Sky and Telescope* **44**, 1972), but a number of experiments are planned for the forthcoming long African eclipse of 30 June 1973 (National Science Foundation, 1972). The manned Skylab Spacecraft, due to be launched on 30 April 1973, will contain an elaborate package of solar instruments (the ATM), all of which can observe the corona (Reeves *et al.*, 1972).

4.1. *The large-scale coronal density structure and its evolution*

4.1.1. *Eclipse studies*

Considerable progress has been made on the density structure of the corona, especially its large-scale inhomogeneous structure. Photometric observation of the white light corona at eclipse remains the fundamental way of deriving coronal density models. Photometric and polarimetric studies (variously detailed) have been published for the eclipses of 12 November 1966 (Arnquist, 1970; Newkirk *et al.*, 1970; Saito and Hata, 1970; Pepin, 1970); 22 September 1968 (Khetsuriana *et al.*, 1971; Koutchmy, 1971); and 7 March 1970 (Hata and Tojo, 1972; Saito, 1972; Waldmeier and Weber, 1971; Gulyaev, 1971; McDougal, 1971; Keller, 1971; Koutchmy and Schatten, 1971; Billings and Oh, 1971: Koutchmy, 1972a; Bohlin *et al.*, 1971). Stanek (1971) has described an improved method for the photometric interpretation of eclipse photographs. Under the direction of Eddy at the High Altitude Observatory (Eddy and Goff, 1971) an atlas of the white light corona is being prepared by copying original plates obtained at most of the major accessible eclipses back to 1869. Saito (1970) has derived a model of the minimum corona based on a critical study of a number of eclipses. A consistent model of the density gradient and zero point in the inner and intermediate corona appears to be emerging (Saito, 1970; Saito and Hata, 1970; Hata and Tojo, 1972; Bohlin *et al.*, 1971), although increased attention is being given to coronal structures.

4.1.2. *Studies outside of eclipse*

Increasingly, coronagraph observations from the ground and observations from above the Earth's atmosphere are providing the more frequent observations needed for an understanding of coronal structure and evolution. Improved K-coronameters are in operation at Mauna Loa

https://doi.org/10.1017/S0251107X00024445 Published online by Cambridge University Press

and Pic-du-Midi, which give rather low resolution but regular observations of the inner corona out to $\sim 2R_{\odot}$ and a number of studies based on their data have appeared (R. T. Hansen *et al.*, 1969a, b; 1970, 1971; S. F. Hansen, R. T. Hansen and Garcia, 1972; Leblanc *et al.*, 1970). Leroy *et al.* (1972) have made a detailed study of sky polarization near the sun and its effect on K-coronameter observations. Altschuler and Perry (1972) have devised a method of unfolding 14 days of K coronameter limb observations to derive a three-dimensional electron density model of the inner corona. The method assumes that the corona is unchanging over half a solar rotation, but comparison with other techniques described below shows that it recovers the basic coronal large-scale structure.

Monochromatic photography of the inner corona in the light of λ5303 (Fe XIV) is regularly carried out from Mt Haleakala, Pic-du-Midi and Sacramento Peak using the coronagraph with Lyot filters, interference filters, or solid Fabry-Perot etalons. These filtergrams show the internal structure of enhancements and occasionally rapidly evolving events (Bruzek and DeMastus, 1970). Dollfus (1971) has observed four lines covering a wide range in ionization energy (λ6374, λ5303, λ6702, λ5694) as well as the K-corona. Leroy and Rosch (1970) have outlined a proposed international cooperative program of coronal filter photography. A Lallemand electronic camera has been used to study faint coronal emission, both with the coronagraph (Rozelot, 1972b) and at eclipse (Fort *et al.*, 1972). A multi-channel coronal photometer designed to obtain raster-scanned images of the corona in many emission lines simultaneously is being constructed for use at Mt Haleakala.

Raster-scanned spectroheliograms (or maps) have been obtained in a number of emissions in the UV and the soft X-ray region which show the large-scale coronal structure, both at the limb and against the disk. Reeves and Parkinson (1970) have published a large collection of spectroheliograms obtained on OSO-IV (1′ resolution) in a number of coronal and chromospheric lines between 300 and 1400 Å. Similar spectroheliograms with 25″ resolution have been obtained on OSO-VI, and have been used to derive density maps of the inner corona (Withbroe *et al.*, 1971) using intensities of λ625 Mg X and a method devised by Withbroe (1971a).

The American Science and Engineering (AS & E) group have obtained maps at 2·5–12 Å with 1′ and 4′ resolution from OSO-IV (Krieger, Lolini *et al.*, 1972), and a University College-Leicester experiment on OSO-V has yielded maps of 2′ resolution at 8·4–9·6 and 9·6–11 Å (Parkinson and Pounds, 1971). The Goddard Space Flight Center (GSFC) has flown an EUV-X-ray (400 Å–1·8 Å) spectroheliograph on OSO-VII and has obtained maps in a number of coronal lines (Neupert *et al.*, 1972; Underwood and Neupert, 1972). Maps in the line λ284 Fe XV are presently being published in *Solar-Geophysical Data.*

In a series of rocket experiments the AS & E group has obtained high-resolution ($\sim 5''$) photographs of the corona against the disk and over the limb (Van Speybroeck *et al.*, 1970; Krieger, Barrett *et al.*, 1972; Timothy *et al.*, 1972) using filters and grazing incidence telescopes in the range 3–60 Å. These show remarkable details of coronal structure not only in active regions but almost everywhere on the disk.

Observations of the white light corona outside of eclipse using an externally occulted (Evans) coronagraph have recently been obtained from above the Earth's atmosphere: from balloons by groups at the Observatoire de Paris and the High Altitude Observatory (R. T. Hansen *et al.*, 1972), and from rockets (Koomen *et al.*, 1970; Tousey and Koomen, 1971a; Bohlin *et al.*, 1971) and the OSO-VII spacecraft (Tousey and Koomen, 1971b) by the Naval Research Laboratory (NRL).

Observations of the white light corona from the Moon made on Surveyor 6 and 7 have been studied by Bohlin (1971) and on Apollo 15 by MacQueen *et al.* (1972). The Moon is clearly an ideal place to study the corona, especially the region between the intermediate corona and the zodiacal light.

4.1.3. *Structure and evolution*

At present, no complete model has been established for the form and evolution of the inner and intermediate corona, although much progress has been made. There is no consistent terminology used in the literature for the large-scale, slowly-varying, coronal structures. This confusion is partly the result of real uncertainties. For the purpose of this discussion, the following simplified taxonomy that recognizes seven structures is useful: (1) active region enhancements, (2) active region streamers, (3) coronal cavities, (4) helmet streamers, (5) coronal holes, (6) the background or 'undisturbed' corona, and (7) polar plumes.

Active Region Enhancements are the regions of enhanced temperature and density that are invariably observed in the inner corona above sunspot groups, and are the coronal extension of the chromospheric active regions. (The more compact and dense enhancements are the permanent condensations of Waldmeier.) Since they emit much of the quiet Sun X-rays, EUV, forbidden lines, metric and decimetric radio waves, they have been most extensively studied (R. T. Hansen *et al.*, 1971; Leblanc *et al.*, 1970; Batstone *et al.*, 1970; Brauninger *et al.*, 1971; Gibson and Van Allen, 1970; Landini and Fossi, 1971; Sengupta, 1971; Burger and Dijkstra, 1972; Chambe, 1971; Drago, 1970; Hall and Hinteregger, 1970; Noyes *et al.*, 1970; Fisher and Pope, 1971; Fisher, 1972; Gurtovenko and Alekayeva, 1971; Zirin, 1970; Billings, 1970; Catura *et al.*, 1972; Eddy, 1972; Walker and Rugge, 1972). *Active Region Streamers* are the extended streamers sometimes observed above active region enhancements. *Coronal Cavities* are the regions of low density that lie above quiescent prominences (filaments) usually in high latitudes. These form within the base of *Helmet Streamers*. It is generally believed that active region enhancements and active region streamers tend to evolve into helmet streamers with the evolution of the underlying BMRs into UMRs (Bohlin, 1970b). Indirect evidence for this appealing picture is strong from the poleward migration of coronal emission and prominences, but direct evidence has been difficult to obtain. Bohlin (1970a, b), in a coordinated white light study from an eclipse, from a balloon' and with the K-coronameter, has located the chromospheric base points of several coronal streamers. His work strongly supports the above picture. S. F. Hansen, R. T. Hansen and Garcia (1972) have been able to follow the K-coronal emission from its first appearance over an active region, through its evolution to a helmet streamer above the polar crown of prominences. Coronal cavities have been studied in the green line by Waldmeier (1970) and detected on X-ray photographs by Timothy *et al.* (1972). Studies of coronal streamers based on white light photometry include those of Saito (1972), Bohlin *et al.*, 1971, 1972), Newkirk *et al.* (1970), Koutchmy (1971, 1972b) and Stanek (1972). Interferometric studies of streamers have been made at 169 MHz by Leblanc (1970) and by Axisa *et al.* (1971). Fainberg and Stone (1971) have compared observations of radio storms at very low frequency (from satellite) with their metric and decimetric counterparts to study streamers between 10 and 40 $R_\odot$. Very considerable advances have been made on the theory of helmet- and active-region streamers. These include those of Pneuman and Kopp (1970, 1971), Pneuman (1969, 1972a, b, c), and Stanek (1972).

Coronal Holes are regions of very low electron density observed in the inner corona. Although they are often observed in low latitudes their densities are often less than that at the poles (Altschuler and Perry, 1972). They appear to be newly recognized as a distinct coronal phenomenon and have been observed on the density maps derived from the OSO-VI observations of Mg x λ625 (Withbroe *et al.*, 1971), on the K-corona density maps of Altschuler and Perry (1972), on white light eclipse pictures (Saito, 1972), and on the X-ray photographs of Krieger, Barrett *et al.* (1972). Altschuler *et al.* (1972) find that the chromosphere underlying the holes is extremely quiet, being free of plages and filaments and the magnetic fields in them seem to be weak and divergent. They point out the importance of the existence of these holes for energy balance in the transition region and the solar wind. Munro and Withbroe (1972) have studied the holes from EUV data, and in a study of the energy balance in coronal holes Noci (1972–3) suggests that they should be the source of strong solar wind. The structure of the *Background or 'Undisturbed Corona'* is not known. Bohlin (1970a, b) suggests that some of the apparent streamers observed at eclipse may not be distinct structures but rather the corona above quiet unipolar regions. No detailed study of the *Polar Plumes* appears to have been made since that of Newkirk and Harvey (1968). Models of the physical conditions in the low quiet corona have been constructed from EUV data, especially

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by the Harvard group, and contrasted with conditions in active regions and holes (Withbroe, 1970a, b, 1971a; Noyes *et al.*, 1970; Munro *et al.*, 1971; Munro and Withbroe, 1972; Simon and Noyes, 1972; Dupree, 1972).

4.2. *The coronal spectrum*

4.2.1. *Line identifications*

A number of new forbidden lines have been observed and many identified since Jefferies' (1969) critical review of three years ago. C. Jordan (1971) identified 20 of 28 lines observed on slitless spectra obtained by a rocket at the 1970 eclipse in the range λ977–λ2200 (Speer *et al.*, 1971; Gabriel *et al.*, 1971; Jones *et al.*, 1971). Olsen *et al.* (1971) have observed and tentatively identified 9 lines in the 1–3 μm range and Mouradian (1972) and Nikolsky *et al.* (1971) have reported new lines in the visible. De Boer *et al.* (1972) have compiled a critical list of observed and predicted lines above λ3000 and suggested the identification of two lines. Edlén (1972) has published level intervals in the configurations $2s^2\, 2p^k (k=2, 3, 4)$; Svensson (1971) has predicted wavelengths for $3s^2\, 3p^k (k=2, 3, 4)$; and Wagner and House (1971) have studied $3p^5\, 3d$ and suggest 6 identifications. Much fundamental work on the permitted spectrum of the corona in the EUV, XUV and X-ray region has been done during this period, but a systematic discussion of this work is beyond the scope of this review. The reader is referred to the report of Commission 44 and to the following references: *Third Symposium on Ultraviolet and X-Ray Spectroscopy of Astrophysical and Laboratory Plasmas*, Burton and Ridgeley (1970), Cowan and Widing (1972), Dupree and Reeves (1971), Flower and Jordan (1971), Freeman and Jones (1970), Greve (1970), Widing *et al.* (1971).

4.2.2. *Diagnostics*

Considerable attention has been given to the problem of interpreting total intensities of coronal emission lines. This has stimulated a number of studies of the excitation of coronal ions. Zirker (1970) has studied the ions of Fe, Ni, and Ca, giving rise to the visible forbidden lines. Finn (1972) has considered all of the ions in the isoelectronic sequences from Al I to Ar I. Studies of visible forbidden lines include those of Lexa (1969, 1971) (argon), Chevalier and Lambert (1970) (Ca XV), Ratier and Rozelot (1972), Byard and Kissell (1971) (Fe XIII), and Rozelot (1972a) (Fe X to XV). It is now recognized that proton collisions may be of importance equal to or greater than electron collisions (e.g. Landman, 1972). Studies of line ratios to determine coronal density include those of Gabriel and Jordan (1969), Blaha (1971), Blumenthal *et al.* (1972), Heroux *et al.* (1972), Munro *et al.* (1971), Neupert (1971), and Rugge and Walker (1971). Jefferies *et al.* (1972) have considered the general problem of interpreting line intensities from an optically thin gas in terms of a bivariate distribution function in temperature and density, and have applied it to observations of the forbidden lines. Calculations of the coronal X-ray spectrum have been made by Mewe (1972), Tucker and Koren (1971), and Culhane *et al.* (1970). Jefferies *et al.* (1971) studied the spectrum of the inner corona at the 1965 eclipse at all position angles around the limb and measured the intensity of 34 forbidden lines. Tsubaki *et al.* (1971) recorded the intensities of four forbidden lines and the continuum with high spatial resolution at the 1970 eclipse. Their observations add evidence that there is an inhomogeneous temperature structure in the inner corona. Studies of the profiles of λ5303 and λ6374 have been made at the coronagraph by Makarova *et al.* (1971). Other diagnostic studies of the emission corona from eclipse include those of Gurtovenko and Alikayeva (1972) (λ5303 and λ4231), and Alikayeva and Bekchantayeva (1972) (λ3986 and λ4566).

We have already referred to a number of studies of the temperature density structure of the active and quiet corona based on EUV and X-ray data. Excellent reviews have been given by Athay (1971), Noyes (1971), and Noyes and Withbroe (1972).

4.2.3. *Abundances*

Withbroe (1971b) finds that there is no longer any evidence for differences in the chemical compositions of the photosphere and of the corona and transition region as determined from the

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EUV data. However, De Boer *et al.* (1972) find that the forbidden lines still appear to yield higher coronal abundances for Fe, Ni, Cr, Mn, and Co. The calcium abundance has been discussed by Fisher (1971c) and DeBoer and Pottasch (1972).

4.2.4. *Line polarization*

House (1972) has developed the theory for calculating the coronal emission line polarization for magnetic dipole transitions. Using the coronal magnetic field models derived from potential continuation of the photospheric fields by Altschuler and Newkirk, he is able to calculate predicted emission-line polarization as a function of height and position angle. His technique may prove to be an important diagnostic for coronal magnetic fields. Beckers and Wagner (1971) looked for polarization in 17 lines at the 1970 eclipse but found none above the probable error of a few per cent. Emission line polarimeters specifically designed for coronal work are now in operation at Mt Haleakala and in the final stages of testing at Sacramento Peak.

4.2.5. *Low excitation emissions in the corona*

A bright image of the inner corona shows clearly in Ly-α on the slitless spectra observed by Speer *et al.* (1971) at the 1970 eclipse. Gabriel (1971) has shown that this is due to scattering of chromospheric Ly-α by the few remaining neutral hydrogen atoms (1 in $\sim 10^7$) remaining in the corona. Frequent reports of other diffuse, low-excitation line emission (Hα, D_3, H and K) in the corona have been made, but whether this of is instrumental, atmospheric, or coronal origin has been uncertain. Recent eclipse studies of this phenomenon have been made by Evans (1970), Bappu *et al.* (1972) and Caccin *et al.* (1971), and at the coronagraph by Leroy (1972b).

4.2.6. *The T-corona*

Kaiser (1970) has constructed a model for the interplanetary dust cloud close to the Sun to account for the thermal emission (the T-corona) observed at 2.2 μm by Peterson and by MacQueen at the 1966 eclipse. Observations of the T-corona in the 8–12 μm range by Lee, MacQueen, and Mankin (1970) at the 1970 eclipse are roughly consistent with Kaiser's model and support his suggestion that the particles are silicates (NCAR 1970).

4.3. *Magnetic fields in the inner and intermediate corona*

Most of our knowledge of the large-scale magnetic fields in the inner and intermediate corona have been derived by potential continuation of the observed photospheric fields using methods developed by the High Altitude Observatory group (Newkirk *et al.*, 1968; Altschuler and Newkirk, 1969; Newkirk, 1971a). In models of coronal streamers (Pneumann and Kopp, 1970, 1971; Pneuman, 1969, 1972a, b, c), this current-free assumption has been relaxed to include thermal effects and the dynamic effects of the solar wind. Shatten *et al.* (1968) have used the current-free approximation in the inner corona and then approximated the effect of the solar wind by forcing the field lines to become radial at the height ($\sim 2R_\odot$) where the solar wind velocity exceeds the Alfvén value. Shatten (1972) has improved this approximation by introducing current sheets above the boundaries of regions of opposite photospheric polarity. Newkirk and Altschuler (1970) have compared their magnetic field maps with the density structure observed at the 1966 eclipse (Newkirk *et al.*, 1970) and with other solar data for that rotation, and find general agreement. An atlas of coronal magnetic field maps has been calculated by Newkirk *et al.* (1972), using the current-free approximation and Mt Wilson photospheric field measurements. The period August 1959 to June 1970 is covered on 11000 maps for 1 to $3R_\odot$. Rust and Roy (1971) have computed the field above active regions using high-resolution observations of the photospheric fields. These fields were compared with Hα and λ5303 monochromatic photographs of the inner corona made when the active region was at the limb. The agreement in form is good, and the field strengths are in the range observed in prominences.

Lantos-Jarry (1970) has used radio interferometer observations of a noise storm to infer the

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coronal magnetic field structure on the assumption that the exciters of the noise storm are channelled by the field. Trotter and Newkirk (1971) have verified this interpretation from their calculated magnetic maps. Studies of moving type IV bursts observed at 80 MHz with the Culgoora radioheliograph, and their relation to the field, have been made by Smerd and Dulk (1971) and Dulk and Altschuler (1971). Dulk, Altschuler and Smerd (1971) find that many type II radio disturbances travel parallel to the field, rather than perpendicular to it as had been previously supposed. Stelzried *et al.* (1970) have inferred the field between 4 and $10R_{\odot}$ using Faraday rotation observations from Pioneer VI and a density model. Radio polarization measurements at 9.5 mm (Kundu and McCullough, 1972) and at 10.7 and 2.2 cm (Bell, 1972) have been used to give some information on magnetic fields in the low corona over active regions. Rosenberg (1972) has devised a theory for regular patterns occasionally observed on radio sweep spectrograms and points out that such observations can give accurate direct measurements of the coronal field in the emitting region.

Sawyer and Hansen (1972–3) have discovered (on K-coronameter data) evidence for coronal arches that cross the equator and connect the leading polarities of active regions in the two hemispheres. The evolution of the corona over the eleven-year cycle has been studied observationally by Waldmeier (1971a, b, c) based on white light and emission-line observations. Sýkora (1971) has studied the longitudinal distribution of the green coronal line and finds only a slight dependence of rotational period on latitude. Uchida (1970) has studied the propagation of Moreton waves from explosive flares through the coronal magnetic field and compared observed wave fronts with calculated field structures. Theoretical studies of coronal magnetic fields, their evolution, and effect on coronal rotation have been made by Pneuman (1971), Raadu (1972) and Pneuman and Raadu (1972).

Newkirk has given comprehensive reviews of the coronal magnetic field, the large-scale field, and the relation of coronal fields to the solar wind (Newkirk, 1971a, b, 1972).

4.4. *Observations of the structure and dynamics of the low corona*

Observations of the small scale structure and dynamics of the low corona are difficult at the limb because of projection, scattered light, and seeing. Resolution in the EUV is not yet high enough to permit its direct observation against the disk, although the ATM should provide this. Reeves and Parkinson (1972) and Simon and Lynch (1972) using OSO-VI data find indirect evidence that the chromospheric network extends into the transition region and low corona. Smith and Suffolk (1972) find evidence that the same spatial frequencies are present in the eclipse corona and in the network. As mentioned in § 2.3.2 (iv), Kanno *et al.* (1971) find that $\lambda 5303$ and $\lambda 6374$ increase to within 1000 km of the limb with a marked increase below 3000 km. They conclude that the interspicular region (below 10^4 km) emits these lines strongly. Schmidt *et al.* (1972) were unable to find evidence for compressional waves in the inner corona after an intensive search on white light eclipse pictures. Quasi-periodic fluctuations have been reported in the intensity at 3.3 cm (Durasova *et al.*, 1971) and in the displacement of $\lambda 5303$ (Curtis *et al.*, 1971). James (1970) has interpreted the moving radar echoes that he observed at 38.2 MHz as evidence for compressional waves associated with coronal heating; however, the interpretation of these important radar observations is difficult (see, e.g., Gordon *et al.*, 1971).

4.5. *The extended corona and the solar wind*

The Sun's corona and the solar wind is of course a continuous, dynamic whole. Nevertheless, because the techniques used to study the extended corona are different, current work in this area is described in other Commissions: both theory and observations in Commissions 43 and 44; the zodiacal light and the heliocentric dust cloud (F-corona) in Commission 21; solar wind disturbances and solar-terrestrial relations in Commission 10. We also call the reader's attention to an excellent volume *Proceedings of the Solar Wind Conference*, ed. by C. P. Sonett, J. M. Wilcox and P. J. Coleman Jr (1972).

Major reasons for studying the inner corona (apart from its intrinsic astrophysical interest) are that it probably holds the key to a detailed understanding of the solar (and stellar) winds, and because it controls the immediate environment of the Earth in space. It is therefore pertinent to review here briefly what is needed. First, we want to know in more detail the temperature structure of the inner corona. We have seen that an average model for the low corona in active regions, quiet regions and holes is emerging from the EUV data. However, the height in the corona where the temperature reaches a maximum is not known and is difficult to determine. Further it is now clear that the temperature of the inner corona is not homogeneous. We have seen that there is indirect evidence that the corona varies from SGCs to SGBs. The ATM experiment has the resolution to throw much light on this problem. Finally, we require the deposition of energy by waves, as a function of height in the inner corona. Here we have to rely heavily on theory, but much progress has been made on the problem of the energy balance – at least in the transition region and low corona (Athay, 1971).

WORKING GROUP ON THE HIGH-RESOLUTION ATLAS OF THE PHOTOSPHERIC SPECTRUM

Tables of wavelengths and identifications covering the domain λ7498–λ12016 have been published recently (Swensson *et al.*, 1970). Based on the Atlas published in 1963 by L. Delbouille and G. Roland, this work lists 10840 lines, and gives identifications for a large fraction of them. A high-resolution, low-noise atlas of the photospheric spectrum between 3000 and 10000 Å has been announced by Delbouille, Roland and Neven. The observations have been made from the high-altitude station of the Jungfraujoch (Switzerland), to minimize the water-vapour absorption. The section λ4300–λ6200 will be distributed first, and the subscribers will receive shorter and longer wavelength tracings with the work progressing.

A preliminary atlas, designed to supplement the above-mentioned work, is also in preparation at Kitt Peak National Observatory. The complete spectrum has been run for $\cos \nu = 1.0$, and about 40% has been completed for $\cos \nu = 0.2$. At the request of stellar observers, selected portions of the integrated solar spectrum have been observed.

The photographic wavelength program (λ2950–λ10000), started by A. K. Pierce in 1967, is nearly complete; it should be finished by the end of 1973. The necessary standard wavelengths, against which the solar values are measured, are given by a thorium source, in overlapping orders. Unblended lines are measured by hand on the plates and reduced by computer. Approximately 10 spectra are combined into each wavelength measurement, and the internal accuracy is about 0.5 mÅ for many lines. The photoelectric part of the same program, with computer simulation of the blended profiles to resolve them, has just started.

L. DELBOUILLE
Chairman of the Working Group

WORKING GROUP ON SUNSPOT SPECTRA

Several sets of observational data on sunspots exist:

(1) the photographic observations of R. Michard at Pic-du-Midi and Meudon on three spots covering the total range $\lambda\lambda$4900–6450;

(2) the photoelectric tracings of H. Wöhl $\lambda\lambda$4000–8000 obtained at Locarno for three large umbras;

(3) a photographic map with Babinet compensator of one large spot covering the interval $\lambda\lambda$3800–9200 by J. Harvey at Kitt Peak;

(4) the thesis work of D. Hall giving photoelectric tracings from Kitt Peak in the atmospheric windows between 1 and 5.5 μm;

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