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

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1. INTRODUCTION

The study of the solar atmosphere has witnessed a major expansion in recent years. A considerable improvement in spatial and temporal aspects of solar research from both ground based telescopes and space vehicles together with progress in theoretical interpretation have provided us with a much improved understanding of phenomena associated with the star closest to us. To report on these numerous contributions would be a near-impossible task even if space restrictions did not exist; this report, therefore, treats in some detail only a few subjects of topical interest. They are (1) Large scale circulations on the Sun (Dr. Gilman); (2) Five-minute oscillations on the Sun (Dr. Deubner); (3) Small scale solar magnetic fields (Drs. Livingston and Stenflo); (4) Alfvén waves in the solar atmosphere (Dr. Uchida); (5) Energy flow in the chromosphere and corona (Dr. Athay); (6) Coronal holes (Dr. Zirker); (7) Fine structure of the corona and the origin of the solar wind (Dr. Brueckner).

2. LARGE SCALE CIRCULATION ON THE SUN

(P. Gilman)

Introduction

In this review the author will comment from his own perspective on progress in observing, modelling, and understanding the global circulation of the sun. As implied in the title he will restrict himself to global features, and not, for example, attempt to discuss supergranulation. Howard (Rev. Geophys. and Space Phys. 1978, in press) has recently completed a broad review of the solar rotation problem. The most recent meeting on this problem is the Catania Workshop on Solar Rotation held in September 1978.

Observations

The effort to measure global velocities on the sun has risen dramatically in the last few years. At least four observatories in the United States (Hale, Kitt Peak, Sacramento Peak, Stanford) now make regular Doppler velocity measurements over the entire solar disk. Extensive measurements are also made at Locarno, Switzerland, and the Astronomical Observatory, Belgrade. Several other groups both in the United States and Europe, and the Soviet Union are active in analyzing a great variety of tracers of global circulation. There is renewed interest in sunspots as tracers, but the calcium network, coronal features, X-ray bright points, photospheric magnetic field patterns have also been used. It is becoming increasingly feasible to compare observations using the same techniques from different observatories, as well as different kinds of measures of global circulation for the same time period. Some of these comparisons are beginning to illustrate disquieting but potentially exciting differences.

From Doppler measurements, Howard (18.081.051) has reported long term changes in solar rotation, including a speeding up of the rotation at all latitudes from 1967 to 1976 of 3-4% as well as small changes in the amount of differential rotation between low and high latitudes. The 1976 rotation rate is within 1-2% of the classical long term average rate from long lived spots reported by Newton and Nunn. Howard also sees large short term (∿1 week) fluctuations in the rotation rate of up to ten percent, which are highly correlated in latitude from about 50°N to 50°S, as pointed out by Gilman (Coronal Holes and High Speed Wind Streams Chapter 8, University of Colorado Press, 1977). These intriguing features, which might be interpreted as evidence of global east west convective motions, have unfortunately not been seen in the Stanford measurements for the same time period. Duvall at Stanford reports fluctuations of only 1-2 percent which are not nearly as well correlated in latitude. The relatively coarse resolution used at Stanford might account for some of the differences, but certainly not all.

Beckers (Sac Peak), Duvall (Stanford), and Howard (Hale) are all independently reporting evidence of axisymmetric meridional flow toward the poles in each hemisphere of magnitude 10-40 meters/sec. A suggestion of this feature is also seen in recent Belgrade data of Karabin and Dubicela (1978 preprint). Because of the lack of an absolute wavelength reference for the Doppler shift, and possible confusion of a meridional flow with various limb shifts, caution is urged in the interpretation of these measurements. Beckers (Ap. J.224, L143) has looked carefully at the rotation rate of the poles, and found no evidence of a polar vortex there, contrary to theoretical inferences from a spherical shell convection model made earlier by Gilman (Geophys. and Astrophys. Fluid Dyn., 8,93). It has so far proved extremely difficult to find Doppler shift evidence of other global circulation, such as giant cell patterns, probably because of obscuration by smaller scale motions, as well as instrumental and limb shift effects. In addition, some previously reported evidence of anticorrelation of mid and high latitude rotation rates has now been shown by Stenflo (20.080.053) and by Duvall and Svalgaard (Solar Phys.56,463) to be an artifact of the curve fitting used.

Virtually all tracers of global circulation are connected in important ways to the magnetic field. A variety of new measurements have been made recently, but the various results still present a rather complex picture. Foukal (17.071.004) has determined that the local Doppler rotation rate in the quiet photosphere increases with increasing magnetic field strength, such that regions with the strongest flux (> 10 gauss, for a 5 x 5 arc sec aperture) rotate more than 40m/sec or about 2%, faster than the regions of weakest neighbouring fields. Thus the strong field regions are moving through the weak field areas. Beckers (19.072.012) has shown that the Doppler and tracer rotation rates of sunspots agree within 1%. Since the plasma rotation outside sunspots is a few percent slower, this represents additional evidence that the field and plasma inside the spot are moving through the surrounding medium. Related evidence for rotation differences among magnetic structures come from compact X-ray emission features found in the low corona. Golub and Vaiana (Ap.J.219, L55) have found that the smallest features, lasting two days or less, rotate at about the rate of the photospheric gas, while the largest, longest lived features rotate up to 5% faster, a rate consistent with sunspots. They postulate this is further evidence of rotation increasing with depth, since the magnetic field of the longer lived features is thought to be rooted more deeply in the convection zone. Changes in differential rotation in latitude have been seen by Stenflo (20.080.053). He showed that photospheric magnetic field patterns show regions of larger than average differential rotation on the poleward side of the sunspot zones. These regions migrate toward the equator in pace with the migration of the sunspots zones.

Several groups have looked for evidence of giant convective cells in tracer velocity patterns. Schröter and Wöhl (18.080.103) report a four cell pattern in Ca^+ network seen in the summer of 1975, with rms velocities of 80 m/sec and substantial flow across the equator. However, they were unable to find corresponding patterns in the Doppler measurements for the same period from Mt. Wilson. Two new estimates of the latitudinal transport of angular momentum by global velocities have also been made by Schröter and Wöhl (18.080.103), and by Belvedere, et al. (18.080.021) using faculae. They both find transport toward the equator (the correct sense to maintain the equatorial acceleration), which is several times larger than previously reported. The data sample is apparently too small to estimate the variation of this transport with latitude, but these results do give some observational support to the theoretical prediction that Reynolds stresses in giant convective cells are responsible for maintaining the solar differential rotation.

Interest has been renewed in using past records of sunspots to deduce changes in solar rotation. Motivated by the rediscovery of the Maunder minimum by Eddy (17.072.049), Eddy, Gilman and Trotter (18.080.019; 20.080.055) have reconstructed rotation rates for two periods before the Maunder minimum in the 17th century. They find the equatorial rotation just before the Maunder minimum onset (1642-44) was faster by 3-5%, while the differential rotation between the equator and 20^0N was enhanced by a factor of 3. In contrast, the period twenty years earlier, when there were more spots, was much more like the modern average. Eddy et al (Bull. Am.Astron.Soc.10,400) have since reanalyzed the Greenwich sunspot record for the period 1888-1964 and found a long term decline in the average rotation of about 1%. This drop occurred through a period when successive sunspot cycles were rising in amplitude, and so is consistent with the 17th century results.

Promising new techniques for measuring global circulation are currently being developed and tested. Rhodes, Deubner and Ulrich are using frequency shifts of power bands in the K- ω diagram for 5 minute oscillations to deduce angular velocity changes with depth. Early results show an increase with depth of several percent in the first $15x10^3$ km, consistent with the larger reported differences between sunspot and Doppler surface rotation values. Beckers and Brown are currently developing a Fourier tachometer at Sacramento Peak, which uses a Michelson interferometer to measure the Doppler shift. Some progress is also being made on development of spectral wavelength references against which to measure the Doppler shift. The influence of scattered light on the Doppler differential rotation signal is also receiving renewed emphasis.

Theory

During 1976-1978, development of theory for global circulation of the sun has proceeded on at least 3 fronts; compressible convection models in which symmetry about the axis of rotation is assumed; Boussinesq convection models which include departures from axisymmetry; and applications of turbulence theory.

The most highly developed compressible axisymmetric model is that of Belvedere and Paterno (20.080.068). Starting from the assumption that a weak influence of rotation upon convection leads to a small variation in latitude of the rate of radial heat transport, the model generates a pattern of meridional circulation consisting of three cells extending from pole to equator, with typical flow velocities of 20cm/sec. The variation of radial heat flux is fixed by fitting the model to the observed surface differential rotation. There results a differential rotation which increases weakly with depth, and a surface heat flux variation with latitude as small as 10^{-4}, consistent with observations. This model has attractive features, but also problems. In particular, it depends critically on the assumption of weak influence of rotation upon convection. However, most estimates of convective turn-over times for the deep convection zone imply that the rotational influence is rather strong there. Furthermore, the form of the heat transport variation with latitude is ad hoc (though not unreasonable). If compressible convection in a deep slowly rotating spherical shell were allowed to develop in its own way, (including departures from axisymmetry) would the result be the same ? The author's own experience with Boussinesq spherical shell convection models suggests that something quite different would happen, namely that an equatorial deceleration would form when the rotational influence is weak. This possibility remains to be tested in the compressible case.

Boussinesq spherical shell convection calculations have been carried out primarily by the author. He has found (Gilman, Geophys. Astrophys. Fluid Dyn.8,93) that in this model, equatorial acceleration is generated only if the influence of rotation upon the convection is strong. As this influence is weakened, by increasing the thermal driving, the profile changes over to equatorial deceleration and high latitude acceleration. The model also generates large heat flux differences in latitude at the surface which have no counterpart on the sun. These are reduced but not eliminated if the model is constrained to have constant radial heat flux at the bottom (Gilman, Geophys. Astrophys. Fluid Dyn.10, in press). As a secondary effect, the model also generates an axisymmetric meridional circulation, at least an order of magnitude larger than seen in axisymmetric models of Belvedere and Paterno and earlier workers. Near the outer boundary, the flow is toward the poles, consistent with observational results described above. Large as it is, however, this circulation is not primarily responsible for the model differential rotation, contrary to the axisymmetric models, since Reynolds stresses still overpower it to drive the equatorial acceleration.

The Boussinesq model has proved useful in adressing other questions concerning the sun's circulation. Gilman and Foukal (1978 preprint) have calculated models of convection in a thin shell weakly influenced by rotation, to simulate the momentum transport effects in supergranules. They found that in such a shell the angular velocity decreased outwards at close to the rate expected if radially moving fluid particles conserve their angular momentum. This effect has been previously postulated by Foukal and Jokipii (14.080.002) as being responsible for the difference in rotational velocity traced by sunspots as compared to the Doppler values. Based on this and earlier model calculations, Gilman and Foukal have suggested that the sun's latitude gradient of angular velocity is formed deep in the convection zone where the rotational influence is strong and where there is also a strong tendency for the angular velocity to be constant on cylinders. The latitudinal gradient is transmitted to the photosphere by supergranulation, which also changes the sign of the radial gradient near the surface.

Gilman has also shown with the model that the polar vortex, characteristic of convecting layers of depth 20% of the radius, disappears when layers as deep as 40% are adopted. This result favours a deep solar convection zone, and is consistent with the observations of Beckers (Ap.J.224, L143).

Clearly all conclusion concerning the sun drawn from Boussinesq models must be tested again with a compressible model. In the future modelling efforts are expected to focus on the problem of compressible, nonaxisymmetric convection in a deep rotating spherical shell. Basic advances in the theory of compressible convection in cartesian geometry without rotation, recently made by many workers in several countries, suggest that the time is ripe for this. Greater sophistication in the parameterization of small scale turbulent transports will be needed.

3. FIVE MINUTE OSCILLATIONS ON THE SUN

(F. L. Deubner)

The 5-min oscillations made their first appearance in solar physics through the well known work of Leighton et al and have ever since been studied by many authors, both observationally and theoretically. Beckers' and Canfield's review (18.080.066) of 1975 gives an extensive account of what had become accepted wisdom about the 5-min oscillations at the beginning of the period to be covered by this report.

By that time, the display of the observed data in the format of diagnostic (k, ω) diagrams had become common practice. This display technique gives conveniently insight into the dispersion relations governing the observed fluid motions, and is therefore ideally suited for comparison with the relevant theoretical models.

The rapid progress which was achieved in 1975 with the analysis of several new sets of observations obtained by Deubner (14.071.042) marked a kind of renaissance in the study of solar oscillations. The new observations, soon after being confirmed by Rhodes et al.(20.080.050), clearly identified the 5-min.oscillations as solar "p-modes", as first predicted by Ulrich (04.071.060). The observed p-modes are standing acoustic waves, modified by the stratification of the atmosphere, trapped in a subphotospheric cavity formed by the temperature and density structure of the solar convection zone. Through the photosphere and the temperature minimum where the acoustic cut-off frequency is too high to permit running waves at the observed frequencies, the p-modes leak in the form of evanescent waves, wave energy decreasing rapidly with height. Beyond this layer, they couple eventually to a second cavity in the chromosphere when the temperature has risen enough to permit propagation of acoustic waves in this frequency range again.

Simultaneously with the observational progress, Ando and Osaki (14.080.058) have studied the stability of the solar convection zone against these modes, and found that these modes were all overstable or just marginally stable in the range of frequencies occupied by the photospheric 5-min. oscillations. Ando and Osaki predicted as a result of their spherical, nonradial, nonadiabatic calculations an extensive list of eigenfrequencies as function of radial mode number and horizontal wave number, which could easily be compared with the observations. Deubner has demonstrated with such a comparison, not only the p-mode nature of the oscillations, but also the very close agreement of the predicted and the observed eigenfrequencies.

Further observational progress, leading to an increasingly better definition of the p-mode ridges in the k,ω diagram within a very short time, was made possible by extended scans across a substantial fraction of the solar disk (enhancing the resolution in spatial wavenumber k), very long observing runs making use of most of the available daylight time (thereby enhancing frequency resolution), application of the "long slit" technique (introduced by Rhodes et al. which permits to observe (k_x,ω) spectra in any preselected direction with respect to the solar axis, e.g. parallel to the equator), and extremely careful tune-ups of the existing observing equipment.

As a result, it became possible to resolve observationally an increasing number of p-mode ridges in the k,ω plane (>10), and at the same time, by independent observations (20,080.050) and by Deubner, Ulrich and Rhodes, to establish a small but significant difference between the observed eigenfrequencies, and those derived from standard solar models. This difference which increases with both horizontal wavenumber and radial wavenumber, is established well enough to warrant theoretical work aimed at an improvement of standard solar models. Such work is already in progress, and first results have been published. Gough (IAU Coll.36,3,1976), and Ulrich and Rhodes (20.080.035) show that better agreement can be reached by increasing the fractional thickness of the shell occupied by the convection zone, which is equivalent to increasing the mixing length parameter l/H. However, these authors have also shown that a perfect agreement may not quite be reached in this way due to the fact that other problems become aggravated by the existence of an extended convection zone (like the neutrino problem and the Lithium abundance). Ulrich (pr.comm.) suggests to study corrections to the equation of state for further improvement of the theory. Clearly, there is still a need for a more detailed modelling of the solar convection zone.

By virtue of the rapidly improving resolution in the observed k, ω plane it has become possible to study the coherence of the p-modes in space and/or time. The width of the p-mode ridges was investigated by Deubner et al. who found that it could barely be distinguished from the "instrumental profile" determined by the data window and the numerical techniques applied. In particular, Deubner (Catania Workshop on Solar Rotation, 1978, in press) found that Q (i.e.the ratio between the decay time and the period of a given mode) rises from about 80 for high wavenumber surface modes to infinity for low wavenumber modes penetrating more deeply into the convection zone. Whether the finite number observed at high k is a consequence of the perturbing influence of random surface velocity fields (such as supergranules or granules) disrupting the coherence of the p-mode velocity field, of atmospheric seeing, imperfect guiding, or of any other instrumental or solar effects, still remains to be shown.

Most sunspots seem to participate in the p-mode oscillations (Giovanelli, Livingston and Harvey, Solar Phys., in press). At any rate, the spatial/temporal coherence was found large enough to introduce the p-modes as a new kind of tracer of large scale horizontal flows in, or below the photosphere (Rhodes, Deubner and Ulrich (Ap.J., in press) and Deubner, Ulrich and Rhodes, Astron. Astrophys., in press). Normal modes of the sun, running in opposite senses parallel to the direction of the flow, may be separated in the Fourier plane according to their direction of propagation. A non-zero flow velocity then causes a frequency shift among each pair of eigenfunctions which is proportional to the flow velocity. This method seems ideally suited for large scale flows and solar rotation in particular, because it suffers only very little from spectrographic drift, atmospheric seeing or stray light as most of the spectrographic methods do which are being used to determine large scale velocities. Neither are the results derived from the observed "splitting" of the modes sensitive to "random walk" and evolutionary effects typical for small scale tracers.

Since the radial dependence of the p-mode eigenfunction depends on the geometry of the actual observed mode (Wolff 10.080.035 and Ulrich et al., Ap.J., in press) filtering the results of a mode-splitting analysis with respect to radial and horizontal wavenumber allows a probing of horizontal velocities in a given range of depths in the convection zone. A preliminary result of such an analysis concerned with radial differential rotation (Deubner et al., Astron. Astrophys., in press) has revealed a negative gradient dω/ dr with the average velocity at a geometric depth of 15 Mm below $\tau(5000) = 1$ being about 80 ms^{-1} faster than the surface rotational velocity. The implications of such a finding with respect to solar cycle models call for corroborative measurements and serious efforts to study the inversion problems connected with a non- uniform and potentially non-monotonic law of differential rotation as a function of depth (Gough, Catania Workshop on Solar Rotation, 1978, in press).

The excitation mechanism for the photospheric p-modes is not yet fully understood. The χ - mechanism (Ando and Osaki 14.080.058) could well be responsible for most of the observed power in these modes. The very low amplitude of the oscillation ($\Delta r/r$ equals a few 10^{-5}) seems to contradict self excitation, whereas the very low noise level found in the "valleys" in between the p-mode ridges on top of the instrumental noise appears to be an argument in favour of it. Careful studies of the dissipation of the p-modes in the higher layers of the solar atmosphere in comparison with the predicted growth rates are needed for an understanding of these observed facts.

Observational efforts as well as theoretical work has already been aimed at a better coverage of the resonant eigenmodes in the chromosphere/transition region (Ando and Osaki 20.080.006, Ulrich and Rhodes 20.080.035). Theory predicts that the leakage of p-mode energy into the chromosphere and corona should not seriously change the stability of the modes. The power of the photospheric ridges would be shifted further towards higher frequencies corresponding to wave modes becoming progressive already further down in the atmosphere. The chromospheric cavity would produce additional trapped modes of which the two lowest ones appear in the k, ω diagram at frequencies of about $0.027 s^{-1}$ and $0.036 s^{-1}$, nearly independent of the horizontal wavenumber.

The observational picture of this region of the solar atmosphere looks very complex, and still rather confusing, although a lot of effort has been put into these studies.

The existence of the new chromospheric p-mode ridges has been looked for, but they have not been found in the relevant k, ω diagrams (Rhodes et al. Proc. OSO-8 Workshop, 1977, Deubner et al, Astron. Astrophys. in press). However, the periods near 240s and 180s are well known from earlier high resolution spectroscopic work to stand out as resonances in the frequency power spectra of motions observed in chromospheric lines such as CaII K or H (Orrall, Ap.J., 143, 917, 1966, Deubner, 12.071.026). Possibly, these resonances can build up only in the interior of supergranulation cells, where the structure of the atmosphere is sufficiently homogeneous and comparatively little disturbed by the presence of magnetic fields, spicules, etc., but do not develop any kind of large scale coherence like the photospheric modes.

The continuing interest in chromospheric p-modes is of course related to the question of how much energy is carried by this wave field into the higher layers of the atmosphere. Until today, of the many processes which have been suggested as being capable of heating the upper part of the solar atmosphere, not a single one has yet been proven by observation to be of considerable importance.

With the p-modes and related oscillations the difficulty comes mainly from the fact that we happen to observe these motions in a layer of the atmosphere, where they change from evanescent to progressive waves. Very accurate phase measurements between velocity and intensity fluctuations in spectral lines, and between velocity flucturations at several wavelength intervals corresponding to various levels in the atmosphere are needed to determine the character of the observed wave phenomenon. An important prerequisite of such observations is high statistical stability of the data which gradually seems to become available (Lites and Chipman, preprint). For the interpretation of the relative phase relations it is vital to assess very carefully the height of formation in the atmosphere of the spectral quantities being observed. One dimensional weighting functions may not be adequate, as pointed out recently by Keil (preprint). High spatial resolution may well be important to detect the energy flux, one is looking for, (e.g. see Cram et al. 19.073.033, Deubner 18.080.015), and it appears advisable then to take advantage of the technique of separating the various wave modes with different propagation characteristics in the k, ω plane, rather than deduce the phase and amplitude relations from frequency spectra alone.

It may be because in none of the existing observations of chromospheric wave motions all of these requirements have been met at the same time, that a consistent picture of the wave field has not yet emerged. There is agreement among observers that in the photosphere the low frequency waves (3 to 5 mHz) are evanescent (Schmieder 18.071.52), with some dissipation. In chromospheric lines (MgI 5172.7Å. CaII K), where higher frequencies (5 to 8 mHz) become more prominent, some authors (Schmieder, preprint. Mein 20.073.066) maintain that there is little energy propagation detectable, perhaps from narrow isolated structures only (Mein, Solar Phys., in press, Carm et al. 19.073.033; a dynamic nonLTE model for bright K grains was proposed by Carm 18.073.001). On the other hand there is evidence in recent observations by Lites and Chipman (preprint), supported by an analysis by Musman (preprint), for preferentially upward propagating acoustic waves at about 6mHz. These authors point out, however, that the energy flux at a height of about 900 km above $\tau = 1$ is too low by nearly two orders of magnitude to explain the heating of the middle chromosphere to corona. The same conclusion was reached by Athay and White (preprints) who have in a series of papers analysed extensive data obtained with the OSO-8 satellite in SiII and CIV lines in the upper chromosphere to lower transition region.

The important role of radiation relaxation varying considerably with height throughout the upper atmosphere was recognized and studied in detail (see e.g. Schmieder 18.071.052, Giovanelli, Solar Phys., in press). A minimum of the relaxation time ($\sim$ 1.5 min.) in the lower chromosphere due to cooling by emission in spectral lines may enhance wave dissipation of the p-modes in this region.

A feature of the chromospheric p-modes which is not easily anticipated from the model analysis must also be considered in the analysis of observational data, according to Leibacher (OSO-8 Workshop, 1977). The response at high chromospheric levels (> 1000 km) to a low amplitude pulse in the sub-photosphere is far from linear, producing steep pulses at regular intervals of nearly 200 seconds (corresponding to the acoustic cut-off frequency at the temperature minimum), with pressure variations of > 50% and particle excurions, at a height of 1800 km, of the order of 600 km. Thus, the following part of the wave train will interact with an atmosphere which deviates strongly from a mean static equilibrium chromosphere.

Radio emission flucttutations have been observed at cm wavelengths, corresponding to the upper chromosphere. The presence of brightness fluctuations of solar origin in the frequency range of the p-modes has been clearly demonstrated (among many others by Kundu and Alissandrakis 14.077.008, Graf et al, Ap. J., in press). However, the power spectra exhibit the rather smooth character of a power law with a frequency index of -2, rather than significant peaks in the frequency range of 3 to 5 mHz. This is in accordance with earlier EUV measurements by Vernazza et al. (14.074.005).

Graf et al. have recently obtained the first k, ω spectrum of solar radio brightness fluctuations. One is tempted to look for the signature of the photospheric p-modes in this diagram although it is clear from the foregoing discussion that the ridge structure must have disappeared at this level of the atmosphere, and the instrumental resolution in frequency and wave-number would not be sufficient to detect the photospheric mode structure. Yet, the degree of redistribution of power among other frequencies and spatial scales, compared with the photospheric input, should contain important information on the processes of wave propagation and dissipation in the upper chromosphere.

4. SMALL SCALE SOLAR MAGNETIC FIELDS: NEW OBSERVATIONS AND PHYSICAL INTERPRETATIONS

(W. C. Livingston and J. O. Stenflo)

Introduction

During the last decade, observations have revealed remarkable and previously unsuspected properties of solar magnetic fields. We now believe that most of the photospheric magnetic flux observed with a spatial resolution of a few arc-sec, or larger, actually resides in discrete flux patches at field strengths of 0.1 - 0.2T (1000 - 2000 G). The physical conditions in these flux elements appear to be very much the same whether we examine quiet regions such as the "network", where the large-scale average field is below 1mT, or active regions (excluding sunspots and pores), where the flux concentration may be two orders of magnitude larger. These unique properties of fluxtubes over all the sun allow us to treat solar magnetic fields in a unified way. Fluxtube models should apply to a large variety of situations on the sun. The main parameter that distinguishes large sunspots from tiny network elements is then the fluxtube diameter. In this report we cover observational and theoretical programs within 1976-1978. For earlier work see the reviews of Stenflo (18.080.076; Rep. Prog. Phys. 41.865) and Harvey (20.071.014).

New techniques and instruments

To better exploit the line-ratio method for the indirect deduction of field strengths, a 3-line magnetograph was installed at the Locarno station of the University of Göttingen. The results for the temperature insensitive lines of Fe 6302, 6337, and 6408Å lays to rest any questions arising from the usually employed ground state Fe 5250/5247 pair. Field strengths in the range 0.12 to 0.22 T were found.

Giovanelli, Livingston and Harvey were able to measure the true oscillatory velocities within fluxtubes by a novel technique using the Kitt Peak multi-channel magnetograph. The cross-over point of the V-Stokes parameter was tracked, using the output of the lock-in amplifier as the error signal for a tipping glass-plate Doppler servo. Oscillations within the fluxtubes turned out to be similar in amplitude and phase to the surrounding non-magnetic region, setting new model constraints.

The possibility that large amounts of "hidden" flux exists, i.e. flux so tangled that opposite-polarities cancel, has been explored along several avenues. Harvey and Stenflo made line profile surveys of large spectral regions using the 1-m FTS to look for a correlation between line width and Lande g (see also Stenflo and Lindegren, 20.071.002). An even more sensitive test employs the Hanle effect, according to which polarization caused by coherent scattering in Fraunhofer lines is destroyed by the presence of magnetic fields. From near limb Hanle effect observations, Stenflo proposes an upper limit of 0.1 mT to the field strength in any hidden flux.

The direct measurement of sub-arc-sec fields appears best attempted by narrow-band birefringent filters (18.080.123; 19.080.044). Observations by Trabell et al. with a 0.13 Å passband on Fe 6302, using the Sacramento Peak Vacuum Tower, attain a flux limit of 2 (10^9) Wb for 0.5 arc-sec seeing. Yet they fail to detect the "inner-network" fields regularly seen at lower resolution, but with enhanced signal to noise ratio at the McMath Telescope with the 512-magnetograph. As the inner-network flux limit is ∿ 5(10^8) Wb, they suggest that if this flux is more concentrated, they should see it; and therefore, these flux patches may be intrinsically diffuse.

Finally, it is of interest that a high resolution magnetograph experiment has been accepted for Spacelab Mission 2 of the U.S. Shuttle program. A 30 cm Cassegrain telescope will feed a 60mA filter and CID array camera. Magnetograms having, hopefully, 0.5 arc-sec resolution will be acquired in such lines as Fe 5250, 6302, etc. While this resolution remains insufficient, it should be constant with time and thus allow the accurate study of how magnetic fields emerge, evolve, and dissipate. Space lab 2 is scheduled to be launched in April 1981.

Other Observations

Koutchmy and Stellmacher (Astron.Astrophys.67, 93) have obtained spectra of magnetic elements under exceptional seeing with the SPO Vacuum Tower, They confirm the existence of high field strengths in the network and show that the fields extend beyond the filigree structures. Elste and Teske show that the hyperfine structure of Mn 5394 makes this line insensitive to microturbulent and magnetic broadening (in the outer wings), and hence can be used for temperature studies of the properties of fluxtubes. A number of facular model constraints follow from their work.

Kotov (19.080.048) demonstrated that the network fields are the principal source of the solar mean field ("the sun as a star"). Duvall and Scherrer from Stanford mean field observations, support this conclusion by showing that the line ratio given by Fe 5250/5247 agrees with the value observed on the disk at high resolution. Since Livingston, Harvey and Heasley have found that the discrepancy factor 5250/5247 varies somewhat from region to region, approaching unity for what is apparently aged flux, it will be of interest to see if the mean field 5250/5247 ratio varies with the solar cycle indicating the periodic magnetic refreshment of the sun.

The topological arrangement of fluxes and polarities in the photosphere determines much of the physics in the atmosphere above. Although most of the flux that makes up the supergranulation network seems to occur in largely unipolar regions, it is also very common with flux patches of opposite polarity in close proximity of each other, corresponding to closed bipolar configurations. These so-called ephemeral active regions have a median life-time of about 12 hr. and are closely correlated with X-ray bright points (20.076.013). They are not confined to the usual zones of solar activity although they probably represent the small-scale portion of the size spectrum of bipolar magnetic regions. Larger bipolar regions are then the normal active regions with sunspots. This size spectrum shows large variations with the solar cycle (19.076.010).

Interpretative problems

The interpretation of the observations is complicated by the circumstance that the basic magnetic elements are far from resolved. While their inferred diameters may be of the order of 100 km, the magnetic-field recordings can rarely resolve structures below 1000 km. The physical conditions in fluxtubes are drastically different from the surrounding conditions. Thus the gas in a fluxtube should be partially evacuated to allow field confinement (see below), there is heating in the higher layers and a downflow of matter that increases with depth. Due to the partial evacuation, there is a depression of the isodensity surfaces (Wilson depression) in the fluxtube. When the fluxtube is viewed at an angle, we will see more of the hot walls of the depression as compared when viewing from the vertical direction. This may explain some of the center-to-limb variation of the facular contrast (18.071.100). Caccin and Severino have studied the effect of geometry on the continuum diagnostics of faculae. The detailed fluxtube geometry, however, also affects the interpretation of disk-center observations in spectral lines. Photons from the hot walls may be scattered in the vertical direction and thus add to the core intensity of spectral lines in the interior of the fluxtubes. This contribution to the 'line-gap' effect is decoupled from the local temperature enhancement in the fluxtube unless a proper multi-dimensional transfer treatment of the radiative-transfer problem is performed. The methods of treating this type of multi-dimensional transfer of the full stokes vector of polarized light have been developed by Stenholm and Stenflo (Astron. Astrophys.58,273; 67,33) and applied to the case of idealized cylindrically-shaped fluxtubes. The relative magnitudes of the effects of radiation channelling and heating depend however, on the details of the fluxtube model, how much the fluxtube interior is shielded from the hot-wall radiation, the magnitude of the Wilson depression, and the height divergence of the field. A realistic quantitative study of these effects has still to be made.

The principal method to avoid these problems and still be able to deduce information on the unresolved properties of the magnetic elements has been the 'line-ratio' method (18.080.076). By making simultaneous magnetograph recordings in two or more spectral lines, which belong to the same multiplet and are formed in the same way apart from the difference in Landé factor, it has been possible to isolate the magnetic-field effects from all the other coupled physical parameters and deduce the true field strengths. The interpretation of the results depends however, on the assumed shape of the magnetic cross section of the fluxtube. The smallest field strength, 0.1 T, is deduced assuming a rectangular (single-valued) cross section. Any other cross section gives higher values for the peak field strength in the element. Thus a Gaussian shape gives about 0.2 T or slightly more.

Fluxtube models

Various attempts to construct empirical models of the temperature and density stratification in fluxtubes from continuum and line-profile data (facular models) have been made. The most detailed LTE model of this kind is that of Chapman (19.072.013). It is based on line-profile data at disk center and shows a temperature enhancement that increases steeply with height. As noted above, however, part of the derived temperature enhancement may be an artifact of the LTE treatment, since multi-dimensional transfer effects will tend to modify the line profiles in the same direction as an increased temperature. Elste and Teske find a less steep gradient than Chapman. Further, as pointed out by Frazier (20.072.032; Astron. Astrophys. 64,351), there is nothing like a unique facular model. But we should rather have a one-parameter family of models, the varying parameter being the fluxtube diameter. The line profiles and thus also the temperature-density stratification vary continuously with fluxtube size. Small fluxtubes (network elements) are brighter in both the continuum and the lines, whereas larger elements (small sunspots) are darker in the continuum but brighter in the line cores. Facular models based on some average or typical observed facular contrasts may thus be severely contaminated by observational selection.

The continuous variation of fluxtube properties from the smallest bright elements in the quiet network to plage elements, pores and large sunspots, has been discussed by Spruit (18.071.100; 19.080.011) and Stenflo (I.A.U. Colloquium 36.143). Spruit, Beckers and Zwaan have tried to determine the relative size distribution of fluxtubes in an active region by measuring the bright points on high resolution Mg b_1 pictures. Unfortunately, much of the interesting portion of the distribution occurs at or below the spatial resolution. The distribution is also expected to vary greatly from one region to the next on the sun (enhancement of the small-scale end when we go from active to quiet regions).

Spruit (18.071.100; 19.080.011) has investigated the pressure balance and energy transport in fluxtubes and calculated a family of theoretical magnetostatic fluxtube models characterized by flux-tube radius, Wilson depression and heat flux. A major effect of the magnetic field is to inhibit convective energy transport across the field lines. For small fluxtubes the lateral inflow of radiation can cause the structures to appear bright. The effect of this inward flux is reduced in larger fluxtubes due to the increased lateral optical depth. Spruit's family of models seems to account for the major observed characteristics of fluxtubes at least qualitatively, but a detailed quantitative comparison with observed spectral features has still to be done.

The concentrated photospheric fields have important implications for the structure and energy balance of the chromosphere and corona. A model for the extension of the fluxtubes into the corona has been worked out by Gabriel (18.073.076) including the effects of the magnetic field on the temperature and density structure.

Formation, confinement and decay

The explanation of the concentration of most of the photospheric magnetic flux into 0.1 - 0.2 T fields is a major plasma physics problem. Parker has treated the basic physics of this problem in a series of papers in the Astrophysical Journal. He concludes (17.080.015) that the confinement of the field cannot be accomplished by the dynamic forces of the plasma motions nor by twisting (electromagnetic confinement, force-free fields). The only possible way to achieve confinement is by having a larger external gas pressure that balances the magnetic pressure in the tube. The gas pressure must then be reduced by evacuation or cooling. In sunspots, Parker believes that most of the cooling is achieved by the convective generation of Alfvén waves emitted preferentially downwards. In the case of the small fluxtubes in the network and faculae, Parker (Astrophys.J. 221,368) suggests that the main cooling mechanism is the adiabaticity of the downdrafts within the fluxtubes. As the magnetic field inhibits convective energy exchange between fluxtube interior and exterior, the interior is efficiently insulated from the surroundings, with the consequence that the downdrafts will be adiabatic within the fluxtube. Due to the superadiabaticity of the exterior convection zone, the fluxtubes will be cooler than their surroundings. The cooling tends to enhance the downdrafts further leading to a partial evacuation of the fluxtubes and the establishment of a Wilson depression. This effect was originally proposed by Nordlund. Unno and Ando have treated this downdraft effect as a convective instability. Spruit has gone a step further to explain the formation of the fluxtubes. Using the equations for the 'thin tube approximation' (Roberts and Webb , Solar Phys.56,6) he finds that fluxtubes with field strengths above about 0.13 T are stable against this convective instability. If the field strength is smaller, the instability will spontaneously concentrate the tube through a downdraft until the field strength reaches 0.13 T, or an updraft will dilute the field and try to make it infinitely weak. This may explain the unique properties of the observed fluxtubes.

In Spruit's model the downdrafts occur only during the stage of formation. Observations (Giovanelli and Slaughter, Solar Phys. 56,255; 20.071.014) and those made recently by Frazier and Stenflo show however, that downdrafts do occur inside the fluxtubes during most of their life time. Thus, unless the fluxtube decays as soon as it has been formed, the downdraft material has to be supplied from the exterior, through field line crossing. Giovanelli (20.071.033) has proposed that this is accomplished by an inflow of neutral gas near the temperature minimum. Unno and Ribes propose a steady state polytropic model, although their calculated downflows are somewhat higher than observed.

For alternative mechanisms of flux concentration, see Galloway et al.(19.080.014) and the review by Weiss (20.080.032).

Once formed, the fluxtubes may be subject to the flute or interchange instability and decay by fragmentation into smaller elements. Observations indicate that such fragmentation occurs at the surprisingly fast rate of 10^7 Wb s^{-1}(Stenflo, 18.080.076), although it is not clear whether this also applies to the sub-arc-sec fluxtubes. Meyer et al.(19.072.086) have shown that the buoyancy force has a stabilizing effect on the flute instability in the upper portions of the fluxtubes, where the field diverges rapidly with height. Deeper down, however, the flute instability may take over; this has lead Parker (1978b) to propose a sunspot model, in which the sunspot flux splits up into many separate fluxtubes somewhere within 1000 km below the visible surface. Piddington (18.080.064; Astrophys. Space Sci.55,401) has argued that the fluxtubes are stable against the flute instability because they are strongly twisted. In a series of papers in the journal Astrophysics and Space Science he has presented a flux-rope-fiber model of solar magnetic fields. He concludes that the fields cannot be concentrated at the surface but must emerge in the form of intense, twisted fluxropes. Gokhale (Kodaikanal Obs.Bull.Ser.A.2,10; 2,19)from a similar viewpoint has attempted to explain the creation of thin intense flux tubes in the deep convection zone and their subsequent upward motion. The stability of twisted flux tubes has been studied by Wilson (19.062.047; 20.062.073). Nakagawa and Stenflo find that pure rotational twisting motions in the photosphere or below can lead to a concentration of magnetic flux to the axis of the tube in the force-free region, accompanied by a density enhancement in the chromosphere and corona.

Some outstanding observational problems

As the fluxtubes in the network or in plages have not been spatially resolved, their properties have been inferred using more or less indirect methods, which are generally statistical in nature. We know almost nothing about the morphology and evolution of the basic magnetic elements. We do not know in what form the flux elements emerge, what are their life-times as cohesive entities, or how they decay. The necessary spatial resolution cannot be obtained by groundbased observations; so space magnetographs such as provided by Shuttle facilities are urgently needed. We need to be able to follow the interrelated evolutions of the magnetic elements, downdrafts, vorticity and azimuthal fields, oscillations, brightness enhancements, and the granulation pattern with much better resolution than has so far been achieved, in order to learn about the basic fluxtube physics. We need to determine the size distribution of fluxtubes in various active and quiet regions on the sun, in particular the latitude and time (solar-cycle) variation of the spectrum of bipolar magnetic regions. More stringent limits on the uniqueness of fluxtube properties are needed, i.e., we want to know how uniquely the fluxtube structure is determined by the fluxtube diameter.

It is also important to study the non-network weak-field fluxes with high spatial resolution, to learn about the evolution of their morphology and their relation to the strong fields. The Hanle effect in combination with high spatial resolution seems to offer promising possibilities for the study of the weak fields.

There are presently practically no observational limits on the height gradient of the field in fluxtubes. Simultaneous observations in different spectral lines may solve the problem, but a proper derivation of the height gradient requires the use of proper fluxtube models. The construction of empirical models is complicated when the observations do not resolve the structures, and the choice of fluxtube geometry affects the interpretation. However, the present rapid progress in instrumental and interpretative techniques provides hope that many of these problems may be solved during the next decade. An understanding of the basic physics of the magnetic elements in the solar atmosphere appears essential for understanding the mechanisms of the solar cycle.

Finally, since small scale magnetic structure is the dominant source of the sun's mean field, observations of the temporal variation of the fields of stars of spectral types similar to the sun may provide magnified, or clarifying, examples of solar cycle effects. Particularly if we could apply the line-ratio technique, observe stars pole-on, or simply monitor solar sector analogs on other stars, the underlying mechanism of the magnetic cycle might be deduced from models of stellar evolution.

5. ALFVEN WAVES IN THE SOLAR ATMOSPHERE

(Y. Uchide)

Introduction

In the last three years, the problem of Alfvén waves (here we do not confine ourselves to the pure Alfvén mode waves in the strict sense of MHD mode analysis in an infinite medium) has attracted attention in several aspects of solar physics. We confine this discussion to the following four major aspects among them. These are (i) the role of the Alfvén waves in the sunspot cooling mechanism whereby the cooling is effected by the escape of the excited overstable Alfvén waves rather than by the inhibition of the convective energy transport in the presence of the magnetic field, (ii) the problem of oscillations in sunspot umbrae and small magnetic knots, and of running penumbral waves, all attributed directly or indirectly to Alfvén waves, (iii) the Alfvén wave as a heating agent of the coronal loop structure observed in soft X-rays which allows us to envisage the magnetic field pattern in the corona, and (iv) the possible role of Alfvén waves in providing additional momenta to the solar wind, in order to explain the observation that the solar wind fast stream originates from the coronal hole. We attempt herein to review briefly these different aspects.

The cooling of sunspots by Alfvén waves

A series of papers was devoted to the problem of whether the Alfvén wave can play the role of the cooling agency in sunspots when it is excited through the overstability and propagates out of the region. This idea of Alfvén wave cooling was first proposed by Parker to replace the mechanism of inhibition of convective energy transport by the magnetic field as proposed many years ago by Biermann. According to Parker, the excitation and escape of Alfvén waves caused by the thermal overstable convection in the magnetized atmosphere serve as a cooling device, and the gas pressure lowered by the cooling may in turn facilitate the concentration of magnetic fluxtubes. The formation of sunspots itself may eventually be caused in its nonlinear regime. This concept has received support from some researchers (19.072.003; 19.072.085; 17.072.010) but Cowling (18.072.034) claims that Parker's mechanism is not acceptable both from thermodynamical and hydrodynamagnetic points of view. There would also be the difficulty with the eventual deposition of the missing flux. Beckers (19.072.012; 19.074.077) tried unsuccessfully to find observationally whether any appreciable part of this missing flux was found escaping into the corona. This result, or the smallness of the amount of escaping Alfvén wave flux into the corona, had been predicted theoretically by Uchida and his collaborators (11.074.052; 13.072.058) and confirmed by Thomas (Astrophys.J.225,275) in the context of coronal loop heating and of the resonant trapping of Alfvén waves in sunspots in the form of the umbral oscillation (we come back to these problems later). Parker's hypothesis may still be able to rely upon the energy leaking downwards into the deep layer, or possibly also upon the observed penumbral wave (08.072.053), but even in such cases the problem of the eventual disposal of the missing flux without any observable trace seems to pose serious difficulty (18.072.034). Spruit (19.080.011), however, has claimed that the problem of the missing flux can be resolved in a different way. According to him, all that is necessary is reduced heat conduction near the solar surface.

If this is true the bright ring expected both in Biermann's picture and in Parker's down-propagating case may become rather diffuse. Therefore, it may be said that the debate itself has also become rather "diffuse" without a definite conclusion being reached.

The oscillation in sunspot umbra, in magnetic knots, and the running penumbral waves

The problem of the oscillation of sunspot umbrae of non-300 sec period found by Giovanelli, Beckers and Schultz, and of magnetic knots (Giovanelli, Livingston and Harvey) has called for much discussion (Solar Phys.56,5). The mechanism of the excitation of the selected eigen-periods has been attributed to the overstability of the convection layer having a magnetic field with the resonant trappings of Alfvén waves in the region (13.072.058; 12.072.004), the observed oscillation being the secondarily induced compression. The running penumbral waves (08.072.053; 17.071.032) were considered to be waves leaking out of the overstable region (10.072.010) guided along the magnetic field of the penumbra (17.072.011). The observation that the umbral oscillation has a period different from the general 300 sec period oscillation may be taken to provide evidence against the hypothesis that 300 sec oscillation is a global one (Publ.Astron.Soc.Japan. 27,581; 14.071.042). Because if it is, the magnetic fluxtube of sunspots whose roots are imbedded in the denser interior should be affected by the oscillation there and may not be able to have other periods of oscillation.

The heating of the coronal loops

One of the problems related to Alfvén waves and provided with much new evidence by X-ray and EUV observations from space, is the problem of coronal heating. The Skylab observations showed that the hot corona around the active regions is directly related to the magnetic field, copying the field pattern of active regions. The background cooler corona is also related to other weaker background magnetic regions. The long-believed acoustic wave theory of coronal heating was considered inapplicable, at least as the predominant source. That the Alfvén wave was the possible agency for coronal heating was suggested by Uchida and Kaburaki (11.074.052) and by Piddington. In the above-mentioned search for evidence of sunspot cooling by Alfvén waves, Beckers (19.074.077) also examined the velocity amplitude of the loops above active regions, and found an unexpectedly low oscillatory velocity (19.074.045). Uchida and Kaburaki's proposal was to consider the non-linear wave-mode coupling which produces the decayable slow mode waves out of the energy-carrying Alfvén waves. Such waves are difficult to be dissipated in the coronal condition, and need a considerable wave amplitude (Beckers pointed out in this connection that the estimate they made for the wave-amplitude by using the WKB treatment left out the factor of area change, and accordingly, their estimate was an overestimate). Therefore, these observations of low oscillatory velocity indicated that Uchida-Kaburaki type mechanism might not operate too efficiently. Wentzel (18.074.140; 20.074.048) considered wave-mode coupling through the interaction in the chromosphere, producing short wavelength Alfvén waves with periods of 10 sec or less. He, also, pointed out that the Alfvén wave with a source of a finite (small) extent has the character of a MHD fast-mode wave rather than that of the usual Alfvén waves with an infinite wavefront extension. Wilson (Astrophys. J.225, 1058) also noted that the waves show a considerably different behaviour in a confined domain, and considered surface waves on the boundary between two media or in the skin of the loop structure. Ionson has proposed that the resonantly absorbed energy of such a surface wave may be deposited in the loop-skin and may heat up the coronal loops. Wentzel has also advanced this idea and considers that it might be the way out of the dilemma that the loops are intensely heated while they have rather low oscillatory velocity. No definite statement, however, can be made at the present stage that the Alfvén wave heating hypothesis is better than other hypotheses such as heating by the dissipation of electric currents which may be flowing along the loop (Astrophys. J.222, 317). The hypothesis of the heating of the loops by intermittent plasma injection from the heated footpoints seems inadequate to explain the majority of the loops except for some special ones, because the soft X-ray observation indicates a continual heating of the loops (Solar Phys. 57,103).

Acceleration of solar wind stream in the coronal holes

The fourth aspect is the possible role of Alfvén waves as the agent of the momentum addition to the solar wind fast stream. Frustrating enough, however, the solar wind fast stream comes from the coronal hole (09.074.083) where we can see rather little of what is occurring in the corona, but indirect evidence suggests that it is at least not an exceptionally high temperature region. On the contrary, it is likely that not only density but also the temperature is lower in the coronal hole than in the surroundings (20.074.009). We should therefore consider some additional device of acceleration other than the standard mechanism of thermal expansion wind if we want to explain the fast stream which is difficult to explain as even the thermal expansion wind from the warmer normal corona. There are several ways proposed to solve the difficulty but we here confine ourselves to the possibility of the direct momentum addition by Alfvén waves in the context of our present theme. The idea of acceleration was also motivated by the detection of the Alfvén wave in the solar wind at 1 A.U. by Belcher and Davis, although there is a possibility that it is expected insitu by instabilities involving Alfvén waves (20.062.045; Solar Phys. 57,445). Hollweg, in a series of papers (07.073.024; Solar Phys. 56,305), pursued the possibility of finding the wave source on the sun, and suggested the motion of the supergranule boundary as the source. Both he and Jacques (20.074.003) have considered the effect of the Alfvén waves as a source of momentum to the solar wind flow. Rosner and Vaiana (20.074.008) claim that this type of acceleration should take place in the coronal hole beyond the temperature maximum. It should be remarked here that other mechanisms, such as the formation of the additional de Laval point, besides the Parker critical point due to the configurational effect (18.074.110), offer little hope in explaining the fast stream, though no final preference can be made at this stage.

6. ENERGY FLOW IN THE CHROMOSPHERE AND CORONA

(R. Grant Athay)

Overview

This brief review of energy flow in the chromosphere and corona is intended to summarize our current level of understanding and to mention the major highlights of the 1976-1978 period. Because of the imposed brevity of the report, many relevant contributions must be omitted. Also,emphasis is on the quiet sun, which bypasses work related to flares and active regions.

The steady-state energy balance in the solar atmosphere may be expressed in the form

$$\nabla \cdot F_{in} = \nabla \cdot F_{out}$$

where F_{in} and F_{out} represent incoming and outgoing energy fluxes within a volume element. The problem of determining flux gradients is complicated by our inability to observe them directly.Instead, we observe only the net fluxes of radiation and mass flow reaching the vicinity of earth, and from these restrictive observations we attempt to derive all the relevant energy gradients. Such derivations, of necessity, require accurate modelling of the temperature, density, velocity and magnetic structure of the solar atmosphere.

The past few years have brought several important conceptual changes, some of which are still just emerging. Two important changes in modelling concepts are: (1) that the magnetic geometry deviates radically from a radial geometry even on a small scale, and (2) that even in the quiet sun systematic flows are important. The first concept has radically modified our evaluation of heat conduction and solar wind flow: the second has made us more aware of the importance of enthalpy transport and of work done against gravity. A change of perhaps more consequence is reflected in a notable shift in favour of magnetic heating of the corona as opposed to shock wave heating.

Measured Energy Fluxes

The only cases for which we observe energy fluxes that can be ascribed unambiguously to the chromosphere and corona are for the solar wind flow and for the emission in the EUV, X-ray and radio regions of the spectrum. Near the sun, the solar wind energy is carried mainly by thermal conduction and arises almost entirely outside the temperature maximum. We know very little about temperature gradients in the outer corona, and, as a result, we know very little about radial gradients in the solar wind flux.

The source of the high speed solar wind streams has been identified with coronal Holes, including some high latitude holes of polar origin (Hundhausen, Coronal Holes and High Speed Wind Streams, ed. Zirker, 1977, 225). Thus we must now conceive of the solar wind as emerging mainly from "nozzles" covering but a fraction of the solar surface rather than as a general expansion of the entire corona. Within the coronal holes, the solar wind flux appears to be the primary energy loss from the corona (Withbroe, ibid. 145).

EUV and X-ray fluxes from the sun at wavelengths shorter than λ 1700 arise in the chromosphere and corona. Approximately half of the flux is in Lyman alpha, which is of chromospheric origin. The remaining half comes mainly from the transition region and inner corona below the temperature maximum. The average EUV and X-ray flux exceeds the average solar wind flux by an order of magnitude. Energy flux in the radio portions of the spectrum is of little consequence.

Approximately 40 percent of the solar surface, as seen at temperatures from 2×10^4 to 10^6K, is covered by bright network. The network accounts for 75 percent of the observed flux at temperatures near 3×10^5K and for 60 percent at temperatures near 5×10^4 and 10^6K (Reeves. 18.073.034). There is little apparent difference in the network underlying coronal holes from the average network.

Network regions are characterized by a general downflow of material, but they are also the seat of spicule eruptions. Also, the network outlines the regions where the magnetic fields are strongest and where the field lines are most nearly vertical.

X-ray observations of the corona have provided convincing evidence that the soft X-ray flux is unusually large in regions where the magnetic field lines are closed, as in active regions and newly emerging dipole regions. It seems clear that the soft X-rays are of thermal origin and that high X-ray flux is a direct measure of high thermal energy content. The high energy content of the corona in closed field regions and the relatively high radiation losses from the network imply a high rate of energy input to these regions. Thus, in the corona the energy input is closely coupled, to regions of closed magnetic field lines, and in the chromosphere it appears that the energy input is highest in regions where the magnetic fields are vertical and strong.

Studies of photospheric and chromospheric oscillations with periods of 3 to 5 minutes strongly support the concept that considerable wave energy is present in the lower atmosphere and that at least some fraction of it propagates into the chromosphere and corona.

These brief preceding statements represent about the limit of what we have extracted from observations concerning the energy flow in the solar atmosphere without imposing some form of restrictive modelling of the phenomena observed.

Inferred Energy Fluxes

Models serve the dual purpose of allowing us to convert integrated fluxes into flux gradients and of identifying energy fluxes that are intrinsic to the models. By modelling the oscillations, for example we can infer the energy flux in the waves. By modelling the temperature and magnetic field structure of the corona and transition region we discover that thermal conduction plays a major role in the energy balance, and by modelling the chromosphere we discover that radiation losses from the low chromosphere exceed the combined losses from the high chromosphere, transition region and corona. It must be emphasized, however, that all such conclusions are model dependent.

Since the energy balance depends upon differentials of energy fluxes the problems related to energy balance place severe demands upon models, i.e., even a modest accuracy in the differential requires high accuracy in the quantity being differentiated. Nevertheless, models have provided considerable insight to identifying mechanisms of possible importance.

Radiation losses from the low and middle chromosphere involve separating out the chromospheric contributions to the strongest Fraunhofer lines. Such a separation requires an accurate theory of line formation and an accurate evaluation of collisonal excitation rates within the chromosphere. The latter depend sensitively on the chromospheric temperature. Current models indicate that the emission cores of the MgII and CaII resonance doublets and most of the central intensity in Balmer alpha and the CaII infrared triplet are due to electron collisional excitations the chromosphere and therefore represent a true loss of energy. The sum total of this radiation loss exceeds the chromospheric and coronal EUV radiation losses by about a factor of four.

Near the temperature minimum H^- opacity is significant and in addition, numerous Fraunhofer lines contribute to the "effective" mean opacity. Even small departures from radiative equilibrium require important energy inputs relative to the chromosphere and corona. Neither the radiative equilibrium model nor the true model is known with sufficient accuracy to provide a reliable estimate of the nonradiative energy term. It could easily be that the upper photosphere and temperature minimum regions require more non-radiative heating than either the chromosphere or the corona (Athay 17.003.016).

Deubner's (18.071.059) estimate of the very substantial energy flux in high frequency photospheric oscillations depends upon the assumption that the high frequency waves are pressure waves propagating vertically at the sound speed and, in addition, that the true velocity amplitude is smeared to a fraction of its value by radiative transfer effects. Each of these assumptions is plausible. They are reinforced by the work of Ando and Osaki (20.080.006) and Rhodes, Ulrich and Simon (Astrophys. J.218, 901), which clearly establishes the 5-minute oscillations as high order, nonradial p-modes of the global sun, and which, in addition, predict that the higher frequency modes should be present and should propagate. The energy inferred by Deubner appears to be sufficient to heat the low chromosphere.

Several attempts to obtain energy fluxes in waves in the chromosphere and transition region have been made with conflicting results. The most recent and most extensive results have come from the OSO-8 satellite. However, no one has claimed to find energy fluxes in excess of a few times 10^4 erg cm^{-2} sec^{-1}, which is at least an order of magnitude below the heating requirements of the upper chromosphere and corona (Athay and White, Astrophys.J.,226,1135). This failure plus the observed association between X-ray flux and closed magnetic field structure have undermined confidence in the theory of wave heating for the upper chromosphere and corona.

The estimate of the conductive energy flux in the transition region by Gabriel (18.073.076), which is the most reliable so far, is dependent directly upon the magnetic field geometry. Unfortunately, the geometry is based only on plausible assumptions rather than observations. Similarly, Pneuman and Kopp's (Solar Phys., 57, 49) estimate of the importance of enthalpy flux is dependent upon the assumption that the downflow velocities are typical of the most of the network rather than of just isolated segments of network. Observations have not yet provided an answer to that question.

In the low and middle chromosphere the main energy loss is radiation. Energy input by dissipation of sound waves still appears to be promising. Within the transition region and bordering regions major radiative losses occur. However, heat conduction, enthalpy transport and changes in gravitational energy associated with vertical motions are all of major importance. Whether heat input from waves or magnetic fields is important is still an open question. In the corona, heat input is again clearly required. Thermal conduction, both inward and outward and along closed field lines is of major importance. Radiation losses are of diminishing consequence, but still of importance. Enthalpy transport and gravitational energy changes are important in the outer corona and probably, as well in the inner corona. However, the latter is largely conjecture since we know little about motions in the inner corona.

Theoretical Models

Theoretical models in which energy mechanisms are specified and which predict solar wind flux and/or XUV fluxes are useful for identifying specific deficiencies in the assumed mechanisms and for helping to eliminate unimportant mechanisms. Unfortunately, one cannot be certain, at the present time, that such models contain all of the essential physics. The heat input is usually treated as an extrinsic source i.e., independent of the resulting atmospheric structure, whereas other energy flows, such as radiation and thermal conduction are completely intrinsic. A major problem occurs in the case of mass flows since these clearly may be a result of both extrinsic and intrinsic properties. The heat input may be accompanied by momentum input, as in the case of waves. Also, the resulting temperature and density configuration may be statically unstable. Most theoretical models ignore such problems, except in the case of the outer corona where the solar wind becomes important.

Gonczi, Mangeney and Souffrin (19.064.013) have discussed in some detail the basic assumptions and limitations that normally accompany treatments of heating by shock waves, and they propose improved methods for treating this problem. Flower and Pineau de Forets (18.074.035) have considered rather carefully a model in which shock heating, conduction, radiation and solar wind expansion are included. Kopp and Orrall (18.074.102) adopt a different approach in which the heat input is described by a boundary value and an exponential scale height. The heat input is balanced against radiation, conduction and solar wind flow through a magnetic geometry that diverges faster than r^2. They then select the two parameters of the heat input that give best agreement with observations.

Each of the above approaches, as well as others of similar type, has considerable merit and more work of this type is certainly to be encouraged. The models clearly represent many of the basic elements of the observations. However, until the magnetic field geometry is properly included and until the full effects of mass flow in the upper chromosphere,transition region and inner corona are properly included we cannot trust any detailed inferences regarding the heat input.

The modelling approach by Kopp and Orrall appears to be particularly promising in view of the recent pessimism about wave heating in the transition region and corona. On the other hand, the alternative to wave energy is magnetic field dissipation, and this makes it doubly important that the magnetic field geometry be compatible with the assumed heating.

Magnetic Field Dissipation

The supposition that the solar atmosphere is heated by dissipation of magnetic field energy is gaining popularity. Past theories have focused attention on magnetic reconnection in neutral sheets between merging fields of opposite sign. Such proposals have had the general disadvantage that energy is dissipated only at unique, and therefore presumably widely scattered, field locations. The heat input, however, is a widespread phenomenon.

Parker (14.076.039) proposes a means of avoiding this difficulty by noting that strongly twisted flux tubes would develop kink instabilities, and that in an aggregate of such twisted tubes magnetic reconnection between kinks in adjacent tubes would be widespread. In a much more radical departure from the normal picture,Rosner, Golub, Coppi and Vaiana (Astrophys.J.222, 317) propose that magnetic energy is dissipated by anomalous resistivity acting on force free currents. Since force free currents can arise from virtually any deformation of the magnetic field from its potential configuration, the existence of force free currents is expected to be widespread. Thus, the expected heating by dissipation of such currents would be widespread. Also, the dissipation mechanism is self contained in that it does not rely upon interactions between adjacent flux tubes. As with all other magnetic heating models, however, there are many unanswered questions. In particular, the required twisting and contorting of the magnetic field is left to a Genie still hiding in a magic lamp beneath the photosphere.

7. CORONAL HOLES

(J. B. Zirker)

Research on coronal holes and their associated high speed wind streams has progressed rapidly during the period 1976 through 1978. Just prior to this period, holes were observed as regions of low density and temperature in the corona, were identified tentatively as the source of high speed wind streams, and were recognized to rotate rigidly. Firm correlations between holes, streams and geomagnetic disturbances were beginning to appear. A nine-month Skylab Workshop on Coronal Holes (October 1975 - August 1976) stimulated many new advances (Coronal Holes and High Speed Wind Streams, ed. J. B. Zirker, Colorado, 1977; abbreviated henceforth as CHM).

This review considers only a few highlights of coronal hole research during 1976-1978. More complete details can be found in such reviews as Bohlin ("Phys. of Solar Planetary Environments," Am. Geophys.Union, 1,114, 1976), Harvey and Sheeley (Space Sci. Rev.1978), Hollweg (Rev. Geo.Sp.Sci., 1978), Orrall (OSO-8 Workshop Proc., 1978) and Zirker CHM; 20.074.009).

Observational Characteristics

Holes lie in unipolar regions of photospheric magnetic fields. The photospheric field in coronal holes differs very little from that outside them. Only when the photospheric fields are extrapolated to the corona, using the method of potential continuation (Altschuler et.al.,19-074.053), do holes stand out as essentially open field regions.

The field lines within a hole diverge non-radially. According to Levine et al. (Ap.J.,215,636, 1977), the cross-section of Skylab coronal holes expanded 10 to 100 times faster than radially; however, the north polar hole expanded in cross-section only seven times faster than radially (Munro and Jackson, 19-074.038).

Evidence for the behaviour of holes throughout the sunspot cycle is still fragmentary. According to Broussard et al.(Solar Phys., 56, 161, 1978), the area of polar holes shrank before the maximum of cycle 20. Just at maximum, holes were located between the polar caps and the sunspot belts, or near the equator. These holes were small and lasted less than two rotations. Coronal holes are largest and most stable (i.e. 3-10 rotations) during the declining phase of the sunspot cycle. During the current rising phase of the cycle, holes are small, transient and appear at high latitudes.

The Association of Holes and Streams

The holes and wind streams that occurred during Skylab (Hundhausen, CHM) showed a strong association. Of 69 central meridian passages of coronal holes (± 30° latitude), 75% are associated with streams at 1 A.U., 9% are possibly associated and 16% are not associated. All the large holes observed during Skylab have been positively identified with streams. The polar holes are also sources of high speed wind, as Rickett and Sime (J. Geophys.Res., 1978) have shown.

Prior to 1976, several authors reported associations between coronal holes, high speed wind streams, and recurrent geomagnetic disturbances. Recent work by Rickett et al. (18.074.019), Bell and Noci (18.074.021) and Sheeley et al. (18.074.128) confirms this connection.

Physical Models

One of the objectives of coronal hole research is to construct a comprehensive model of the run of physical parameters that will predict all of the observed radiation and account for the expansion of the corona. To date, this grand objective has only been partially achieved and serious discrepancies have turned up.

Preliminary analysis of some of the data has yielded important constraints on comprehensive models. Calculations of the potential magnetic field within a hole show that the field lines diverge nonradially in the middle corona. Kopp and Holzer (18.074.110) found that a diverging field geometry tends to lower the height of the critical point and to reduce the density at low altitudes in a coronal hole. Munro and Jackson (19.074.038) used Skylab observations of the white light corona to derive an empirical model of the density between 2 and 5 $R_\odot$. They showed that the cross-section of this hole expanded 7 times more rapidly than that of a radial cone, and that, for a reasonable particle flux at 1 A.U., the critical point lay between 2.2 and 3 $R_\odot$. Thus, the primary acceleration of the wind seems to occur below $R_\odot$

The earliest studies of coronal holes (e.g. Munro and Withbroe (08.074.022) showed that the temperature gradient in the transition zone, and hence the downward heat flux, was an order of magnitude smaller than in the quiet corona. These results have been confirmed with Skylab observations by Mariska (Astrophys.J. 225, 252, 1978) and by Withbroe.

The energy flux carried in high speed streams is about twice as high (i.e. 2 erg cm^2 sec^{-1}) at 1 A.U. as in the quiet wind, and if the observed expansion factors are applied, an energy flux of 5×10^5 erg cm^{-2} s^{-1} is needed at the base of a hole. This flux is an order of magnitude larger than required for the quiet wind and sets a severe constraint on solar wind theory. The energy carried in a wind stream is the predominant loss from a hole, far exceeding the downward heat conduction.

Models of the transition zone within a hole, based on Skylab EUV observations, have been very useful in setting boundary conditions for coronal expansion models. Withbroe and Mariska derive $N_e = 1.7 \times 10^8 cm^{-3}$ and $T_e = 7.6 \times 10^5$ at 1.03 $R_\odot$ within the north polar hole. Assuming a typical particle flux for this hole, Mariska derives a flow velocity of 15 km/sec at 1.08 $R_\odot$. This value agrees with the Doppler velocity measured in another hole by Cushman and Rense (18.074.003).

Unfortunately, no measurements exist of the maximum temperature or its location in a coronal hole. X-ray, EUV and white light observations imply temperatures no higher than about 2 million degrees, but considerable interpretation is necessary for this conclusion. Independent evidence consists of the ionization equilibrium of the oxygen, nitrogen, iron and silicon ions that are "frozen" in the wind (Bame, 11.074.041). These data imply that the maximum temperature in the wind stream is probably no higher than 2.1 million degrees at about 1.5 $R_\odot$. With such a low maximum temperature, the wind stream must derive energy from some other source than heat conduction to attain the observed energy flux at 1 A.U. Extended heating by waves and radiation pressure of waves (especially Alfvén waves, as proposed by Barnes and Hollweg), have been generally accepted as plausible working hypotheses.

Recent coronal hole models fall into three categories; semi-empirical (Dulk, 20.074.050), Munro and Mariska, OSO-8 Workshop Proc., 1978), energy balance models (McWhirter and Kopp, MNRAS, 1978; Rosner and Vaiana, 20.074.009) and MHD models (Suess, 20.074.015).

White light and EUV observations give a consistent density model of the north polar coronal hole for the period June-August 1973. The model Munro and Mariska extends from 1.05 $R_\odot$ to 5 $R_\odot$.

Dulk (20.074.050) attempted to reconcile Skylab EUV observations and high resolution radio maps of a coronal hole. No one model satisfied all the observations. Models that agree with the EUV data gave radio brightness by a factor of 2 to 3 too high, while models that agree with radio data gave EUV intensities a factor of 10 too low. Dulk (OSO.8 Workshop Proc.1978) suggests that EUV and radio observations could be reconciled if thermal diffusion, mass flow and ionization non-equilibrium are taken into account, but only if the overall density of the transition zone is an order of magnitude lower than usually believed. This seems unlikely, and the problem of reconciling radio and EUV measurements remain unsolved.

McWhirter and Kopp have solved the flow equations in a diverging geometry, taking into account the gradient of the pressure of an assumed Alfvén wave flux but neglecting wave dissipation. Alfvén wave pressure is an adequate mechanism for the acceleration of the wind above 2.2 solar radii. Unfortunately, the gradient of wave pressure is so steep below this radius that no stable solution could be found. This deficiency should affect all models for the whole atmosphere and stands out as one of the major difficulties with the wave acceleration mechanism.

Rosner and Vaiana investigated the effects of flow, field geometry, wave pressure and extended heating. They were able to satisfy constraints from X-ray, EUV and radio observations, but their model is still subsonic at the coronal temperature maximum, at 1.1 $R_\odot$. Thus, they are forced to conclude most of the wind acceleration occurs beyond the temperature maximum, possibly by wave pressure gradients, in conflict with the results of Munro and Jackson. Suess et al. extended the work of Kopp and Holzer. They considered polytropic one-fluid flow in the Munro-Jackson geometry and showed that it is possible to fit the observations if the magnetic field strength decreases away from the axis of a hole, and if the base temperature is about 2×10^6 K.

Thus, in the region where observations are most plentiful, i.e. between 1 and 5 $R_\odot$, semi-empirical and energy balance models are still inadequate. If Alfvén waves heat and accelerate the wind, they also seem to disrupt the lower atmosphere.

The Origin of Coronal Holes and its Relation to the Solar Interior

Bohlin and Sheeley (Solar Phys.56,125, 1978) have proposed a phenomenological model for the origin of coronal holes. The model depends upon the appearance, within the same or opposite hemispheres, of bi-polar magnetic regions with unbalanced fluxes. If these regions are sufficiently close, field line reconnection can take place to form an extended unipolar magnetic region, which is an equatorial hole.

McIntosh (18.074.045) and Hundhausen (CHM) have stressed the systematic eastward drift of the locations of new coronal holes throughout the Skylab era. Such order suggests a sub-photospheric mechanism that operates on a global scale, such as a solar dynamo.

Gilman (CHM) has analyzed photospheric magnetic fields and differential rotation measured during the Skylab period by R. Howard in an attempt to search for several kinds of dynamo effects on the holes. His results do not support the idea that the solar dynamo ultimately controls the origins and rotation of coronal holes.

Stix (19.074.079) also analysed Mt. Wilson photospheric magnetic fields. He suggests that two symmetric modes control the position of the three most conspicuous coronal holes observed during the Skylab period and that the rigid rotation of the modes accounts for the rotation of the holes.

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Problems for the Immediate Future

To make further progress in understanding coronal holes and solar wind streams, we need additional critical observations, particularly in the region of wind acceleration, and further development of some physics.

Measurements of the temperature, density and velocity profiles in the critical regions between 2 and 20 solar radii are needed as additional constraints for models of coronal holes and wind streams. Recently, Woo (Astrophys.J.219,727, 1978) has derived a velocity profile of the mean solar wind between 2 and $20R_\odot$ from phase-scintillation measurements of satellite telemetry signals. This is an extremely promising technique and hopefully will be pursued further in the future. The profile of hydrogen Lyman α can also yield information on coronal temperatures (Beckers and Chipman, 11.074.011). Any observations of the hypothesized Alfvén wave fluxes near the sun would help greatly. Synoptic observations of holes and photospheric fields, such as those being made at Kitt Peak National Observatory, are needed for a full cycle, for evolutionary studies. Developments are needed in the theory of electron heat transport in collisionless plasmas, and for the generation, dissipation, and conversion between modes of MHD waves. How is it possible for a mechanical wave flux of 10^6 ergs cm^{-2} s^{-1} to pass through the chromosphere and transition zone without totally disrupting the atmosphere ? Transition zone and coronal models have generally assumed local ionization equilibrium by ignoring the effects of flow and diffusion. These effects should now be incorporated in more refined models. One would expect that the evolution of coronal holes relates somehow to the solar dynamo. To understand this relationship we need long term measurements of the large scale circulation in the photosphere and of the large scale magnetic field migration over the sunspot cycle. In combination with continued observations of coronal holes from the ground, these dynamical observations may stimulate further development of dynamo theory.

8. THE FINE STRUCTURE OF THE CORONA AND THE ORIGIN OF THE SOLAR WIND

(G. E. Brueckner)

Several major reviews treating different aspects of the topic have appeared during the time period covered by this report. These are: "Coronal Holes and High Speed Wind Streams", 1977, J. B. Zirker, ed., Colorado Associated University Press (R1); J. V. Hollweg, "Some Physical Processes in the Solar Wind", 1978, Reviews of Geophysics and Space Physics 16, 689 (paper 8R0531) (R2), and: W. C. Feldman, J. R. Asbridge, S. J. Bame, J. T. Gosling "Plasma and Magnetic Fields from the Sun", in "The Solar Output and Its Variation", 1977, O. R. White, ed., Colorado Associated University Press (R3). Wherever reference is made to these review papers, the numbers associated to them will be used.

The Solar Wind and Coronal Holes (CHs)

It is customary to classify the corona into two different structures: Loops, that have closed magnetic fields and the remaining areas that have "open" magnetic fields. It is also generally thought that the solar wind originates from open magnetic structures. For the purpose of this report we will discuss only open magnetic field areas. Nolte et al. (18.074.025) found, that all high velocity solar wind streams observed during the Skylab period (1973 May -1974 Feb., declining solar activity) could be associated with large, nearequatorial CHs.Sheeley et al. (18.074.128) presented a similar correlation for the period 1973-76 for CHs with $\ell < 40^0$ helio-centric latitude. Cuperman and Dryer (Astrophys.J.223,601, 1978) found a weak anticorrelation between green line intensities and high speed streams (1962 -71). The magnitude of the anticorrelation coefficient increases with helio-centric latitude to a value of 0.6 at about 30°. During Carrington rotations 1595 - 1604 (late 1972 - 1973) all high speed streams seem to originate from low latitude extension of polar CHs (Hundhausen R1). Nolte et al. (20.074.036) could not find a convincing correlation between recurring high speed wind streams and low latitude CHs at solar minimum, based on x-ray photographs of the sun (1976, Nov.). Schwenn et al. (J. Geophys. Res. 83, 1011, 1978) found a good correlation between high speed wind streams and equatorial extensions of polar CHs (March 1975) comparing the measurements at 0.31 A.U. (Helios I) and 1 A.U. (Imp 7/8). They find sharp boundaries (10° in latitude) between high speed stream and the surrounding "quiet" solar wind. This result contradicts earlier estimates of the amount of meridional flows by Munro and Jackson (19.074.038). It also is not in agreement with earlier estimates of the geometric extensions of CHs into the interplanetary space (Hundhausen, R1).

While there is no doubt about the origin of high speed streams in CHs, the results do not allow a final conclusion on which solar latitudes contribute most to the high speed streams.

During solar minimum the solar magnetic field is bent more toward the ecliptic plane and high speed streams become more visible in the ecliptic plane which is in agreement with the results by Bame et al. (18.074.077) and Gosling et al. (18.074.068) who found that high speed wind streams with velocities in excess of 700 kms^{-1} are more abundant during declining and minimum solar activity than near solar maximum. Bohlin (19.074.054) reported that during the Skylab period 20% of the solar surface was covered by CHs; the lower latitude CHs ($\ell < 60^0$) provided only 2% to 5% of total hole area. Broussard et al. (Solar Phys. 56,161, 1978) show that polar CHs as seen in x-ray and XUV photographs are absent at solar maximum, but very pronounced at minimum. However, the magnitude of the interplanetary field (Hedgecock 14.106.012) and the solar wind sector structure (Svalgaard and Wilcox 14.076.056) does not exhibit changes with the solar cycle.

Wagner (17.074.041) found a correlation between the magnetic field polarity in the "quiet" solar wind and that of high latitude CHs (1972 May- 1973 Oct.). He suggests that the "quiet" solar wind originates also from polar cap CHs. Because the average "quiet" solar wind does not show solar cycle variations while the polar caps do, the possibility, that the "quiet" solar wind originates in small or "mini" CHs scattered over the solar surface, most be left open.

Coronal Holes (CH) Models

The EUV, x-ray and radio observations may be explained by either hydrostatic or flow models of homogeneous CHs as has been demonstrated by Rosner and Vaiana (20.074.008). Munroe and Jackson (19.074.038) introduced into their model an a priori outflow which is deduced from high speed wind stream observations at 1 A.U. In this way they obtain a trans-sonic point of a homogeneous solar wind between 2.2 and 3 $R_\odot$. Energy must be deposited beyond this point for wind acceleration. Dulk et al. (20.074.050) found a discrepancy of electron density values which are derived from radio and XUV observations. Inhomogeneities within a CH could remove these differences. However, Trott and Lantos (Astron.Astrophys.70, 245, 1978)and Chambe (Astron.Astrophys.70,255, 1978) pointed out that because of uncertainties in the measurements and inversions homogeneous models can satisfy the observations. While homogeneous models of CHs cannot distinguish between hydrostatic equilibrium and flow pattern, this situation changes when inhomogeneities are taken into account.

Polar plumes are fine structures of CHs. Ahmed and Webb (Solar Phys.1978) - derived models of polar plumes from x-ray data. They showed that hydrostatic models require unacceptable low temperatures. Introducing an outward flow in polar plumes they found a convective energy flux of 2×10^6 erg cm^{-2}s^{-1} which is in agreement with energy fluxes at the solar surface estimated by Hundhausen (R1) from high speed wind streams. This result shows the importance of inhomogeneities in all modelling efforts. Using medium resolution K-corona measurements Koutchmy et al. (20.074.001) found density fluctuations of a factor of 5 in a polar cap CH.

Small Scale Fine Structure of the Corona

Very small coronal structures ($\sim$ 1") called "coronal spikes" have been observed in the quiet sun during eclipses. Reliable physical parameters of coronal spikes have been determined for the first time by Koutchmy and Stellmacher (18.073.162). They found: (i) the coronal spikes have a diameter of approximately 1" at an altitude of 20,000 km above the solar surface; (ii) because of the absence of chromospheric emission lines the spikes are not of chromospheric origin, their spectrum is characteristic of Thompson scattering; (iii) a density of $Ne = 10^{10}$cm^{-3}at 20,000 km could be derived. This density exceeds that of the homogeneous background corona by two orders of magnitude. The observations suggest, that they are open field structures which must eventually bland into a more or less homogeneous solar wind. Such structures must have very large pressure gradients which would generate high outward velocities very close to the solar surface.

Coronal Heating and the Energy Input into the Solar Wind

The plasma outflow in high speed wind streams constitutes an energy sink of 3-9x10^5 erg cm^{-2} s^{-1} at the base of the corona (Hundhausen, R1). Radiation losses of the "quiet" corona may be of the same magnitude (Kopp and Orrall, 18.074.102). A few times 10^6 erg cm^{-2} s^{-1} are required to maintain the underlying chromosphere above the temperature minimum (Withbroe, R1). Therefore, the mechanical energy transmitted through the transition zone must be similar in magnitude. We have no direct coronal observation of the nature of the coronal heating mechanism. However, a large amount of material has been accumulated bearing on the question of the transmission of mechanical energy through the transition zone. Athay and White (Astron. Phys.J.226, 1135) found only low amplitude semi-periodic fluctuations in the transition zone. They estimate the combined energy flux of periodic and aperiodic sound waves to be 1 x 10^4 erg cm^{-2} s^{-1}. However, these estimates are based on observations which have a spatial resolution of 2" x 20" only, CIV line profiles of the same spatial resolution were analysed by Bruner and McWhirter and compared with profiles (Byerley et al. 1978, J. Phys.B.11, 613) calculated with the presence of acoustic waves. Bruner and Mcwhirter concluded that there is not enough flux to heat the corona by means of acoustic waves. However, from the observed line width (ξ turb. > ξ thermal) they leave the possibility open that fast MHD waves are travelling through the transition zone. From observations of Si IV line profiles (same spatial resolution 2" x 20") Billings, Roussel-Dupré and Francis (20.076.016) ruled out sinusoidal acoustic waves, sinusoidal acoustic shocks and normally propagated MHD disturbances. Vernazza et al. (14.074.005) found non-periodic, fast (< 1 min) intensity fluctuations (up to 50%) in chromospheric, transition zone and coronal lines. They interpret these intensity fluctuations as being caused by the passage of shock waves. Their observations were made with a spatial resolution of 5" x 5". In very high resolution (1"x 0.5")spectra,Brueckner et al. found superthermal material motions in the transition zone. The events are very small in size (∿ 1") but show blue shifted Doppler motions up to 400 km s^{-1}. They occur in otherwise normal regions of the quiet Sun. They can be interpreted as strong shock waves (M = 8) and can account for the heating of the corona and the mass flow of the solar wind provided that the estimate of their abundance, which is based on a large extrapolation, is correct. While the emission of these events amounts only to about a few percent of the total transition zone emission, their kinetic energy flux is approximately a factor of 4 larger than the mechanical energy flux of the whole transition zone deduced from excess line broadening. This finding underlines once more the importance of high spatial resolution observations.

Direct Observations of Mass Flows in the Transition Zone and Corona

Francis and Roussel-Dupré (20.074.062) could not find any net mass outflow in the transition zone of CHs greater than 4.3 km s^{-1}, observed with a spatial resolution of 2" x 20". The only observations of coronal mass motions are those of Cushman and Rense (18.074.003, 19.074.901) and Brueckner et al. (1977 OSO-8 workshop, Boulder, Col.). Cushman and Rense obtain net-outflow velocities of 16 km s^{-1} in a CH by comparing Doppler velocities of coronal emission lines in a CH with those in the quiet sun. Brueckner et al. found net coronal outflows of 5-15 kms^{-1} in the quiet sun by measuring Doppler velocities of coronal lines in a framework of low chromospheric emission lines which were assumed to be at their rest wave length's. However, because in neither case a full analysis of the optically thin line profile could be performed, it is impossible to derive mass flow from the line center Doppler shifts which are small when compared with the line width.

Boundary conditions of Solar Wind Theories Near the Solar Surface

As pointed out by Hollweg (R2) solar wind theories assume a hot, homogeneous corona as boundary conditions near the solar surface. As a consequence (Hundhausen, 08.003.077) electron heat conduction is the main energy source of solar wind acceleration. Also, mass conservation of a homogeneous corona close to the solar surface results in low initial outflow velocities. All models predict solar wind values at 1 A.U. which are at variance with the observations. Specifically, the predicted proton temperature at 1 A.U. is 1 order of magnitude lower than the observed one in the quiet solar wind and the electron heat conduction flux is predicted to be 1.5 orders-of-magnitude larger than the observed values. (For details see Hollweg R2). The standard models cannot explain the high speed streams, that are assumed to originate in the cooler coronal holes, where the heat conduction is even less. Nerney and Barnes (20.074.012) alter the boundary conditions and find that coronal proton temperatures of 4-5 x 10^6 K and moderate electron temperatures (1.5 x 10^6 K) can produce a solar wind at 1 A.U. which is in reasonable agreement with the observations, except for the electron temperatures. They require low densities at the solar surface (10^6 cm^{-3}). It is obvious that these changes of boundary conditions are not in agreement with the observations of a homogeneous corona. Moreover, for high speed streams very unreasonable conditions would have to be postulated. However, the introduction of fine structures such as the coronal spikes would alter the boundary conditions significantly. The superthermal jets as observed by Brueckner et al.can inject a large amount of kinetic energy at the solar surface into the solar wind. This would overcome another basic discrepancy of contemporary wind theories, which predict a substantial amount of electron heat conduction even at 1 A.U., while the observations show that 97 % of the solar wind energy is kinetic energy (Feldman et al. R3). Hollweg (C3) concluded that an additional energy source is needed to overcome the difficulties presented by contemporary solar wind theories. He proposed solar generated MHD waves to be the source of the needed additional energy. The superthermal jets (Brueckner et al. 1978) can be interpreted as very strong shock waves (M = 8) in the transition zone. They could provide the needed energy input. However, solar wind theories would have to incorporate boundary conditions at the solar surface which unite the processes of coronal heating and solar wind acceleration in the same heights regime near the solar surface. From an observational point of view, our lack of understanding of the boundary conditions for the solar wind is a direct result of our incomplete knowledge of the very small scale fine structure of the low corona.

9. CONCLUSION

Space telescopes and balloon-borne experiments have undoubtedly opened up new vistas of observation and interpretation of details of the solar atmosphere. Ground based instruments have also played a vital role in this progress, by the use of a new generation of solar telescopes, improved detectors and the new procedures of data recording, and image evaluation. As we come to the end of a summary of selected recent highlights of attainments in solar physics, we look forward with much optimism and enthusiasm to what we can learn of the solar atmosphere in the next triennium and the years thereafter.

It gives me much pleasure to place on record the splendid cooperation I have received from the Vice-President and the members of the Organizing Committee.

M.K.V. BAPPU
President of the Commission