THE SOLAR ATMOSPHERE - FROM PHOTOSPHERE TO CORONA

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ABSTRACT

A review is given of recent developments in solar physics, with emphasis on areas where observations from space have made substantial contributions. Progress in establishing the temperature and density structure of the outer solar layers has been made through measurements of emission line fluxes in the extreme-ultraviolet and X-ray parts of the spectrum, combined with spatial information from imaging instruments. The processes by which the corona and other hot plasma is heated remain elusive. Although the source of the heating is considered to be the interaction between gas motions and the magnetic fields in the sub-photospheric convective zone the means by which energy is transported and dissipated are still not determined. The further observations required to limit the range of possible mechanisms are discussed.

Keywords: Coronal Heating, Transition Region, Magnetic Fields, EUV Spectroscopy.

1. INTRODUCTION

Over the past twenty years or so observations from rockets and satellites have allowed the outer layers of the sun to be studied in the previously unexplored ultra-violet and X-ray regions of the spectrum. This brief review will concentrate on the contribution that space observations have made to solar physics, and on those observations which will be required to resolve outstanding problems. The book by Athay (Ref.1) gives an excellent account of both the observations and physics of the quiet solar atmosphere. The energy and momentum transfer in the atmosphere has been reviewed by Withbroe and Noyes (Ref.2), and aspects of the active sun by Vaiana and Rosner (Ref.3). The IAU Colloquium on 'The Energy Balance and Hydrodynamics of the Solar Chromosphere and Corona' provides a broad perspective of work in recent years (Ref.4). The outer layers of the sun are also discussed in a recent non-specialist introductory review (Ref.5).

Following a brief summary of typical values of atmospheric parameters met in the chromosphere and corona Section 2 will outline recent studies of the quiet sun, including holes, where the magnetic field opens into the solar wind.

In Section 3 an account will be given of the active sun, characterised by regions of closed magnetic fields.

Some examples of outstanding problems, mainly concerned with the processes that heat the corona, will be given in Section 4, with suggestions of how progress could be made in their solution through future observations from space.

1.1 Summary of atmospheric conditions

We will be concerned mainly with the layers above the solar photosphere, which can be defined as the region where the continuum at 5000 Å has an optical depth of unity. There, the temperature is about 6400 K and the gas particle density is \( \sim 10^{17} \) atoms cm\(^{-3} \). Above this the temperature continues to decrease outwards until a minimum value of about 4200 K is reached, at which point the height is \( \sim 500 \) km and the density is \( \sim 10^{15} \) atoms cm\(^{-3} \). Although below this region a state of Local Thermodynamic Equilibrium exists, with the radiation temperature being equal to the kinetic temperature, in the chromosphere above the kinetic temperature rapidly rises beyond the radiation temperature.

The chromosphere extends from the region of the temperature minimum to an average height of around 2000 km where the temperature has risen slowly to \( \sim 9000 \) K and the density has dropped to \( \sim 10^{11} \) cm\(^{-3} \). Because hydrogen is substantially ionized the electrons provide about half the total gas pressure.

Above 9000 K the temperature rises rapidly to about \( 5 \times 10^5 \) K over a narrow height range of \( \sim 100 \) km, hence the description of this part of the atmosphere as the 'transition region'. The temperature gradients then slowly decrease until a coronal temperature of \( \sim 2 \times 10^6 \) K is reached by \( \sim 50,000 \) km. Because of the small scale-height involved the pressure remains approximately constant between the top of the chromosphere and the inner corona, and in the quiet atmosphere is around 0.15 dynes cm\(^{-2} \).

In active centres where concentrations of strong magnetic fields exist, the electron density may be several orders of magnitude larger, and the overlying temperature in the regions of closed
magnetic field may reach $\sim 6 \times 10^4$ k. During flares even more extreme conditions are found, with $P_e \sim 3 \times 10^{-10}$ dyne cm$^{-2}$ and $T_e \sim 2 \times 10^7$ K.

There are also regions where lower than average densities and temperatures are found; in coronal holes, where divergent magnetic fields occur, the electron density can be a factor of three lower than in the quiet sun and $T_e$ is only $\sim 10^6$ K. In magnetic flux tubes associated with sunspot umbrae the maximum temperature sometimes does not exceed $5 \times 10^6$ K.

Thus any theories of the heating of the outer atmosphere must account for a wide variety of conditions, depending on the local magnetic field strength and configuration.

2. THE QUIET SOLAR ATMOSPHERE

2.1 Spatial Structure

High resolution and high contrast images of the photosphere show the presence of the granulation-convective structures of less than 1 arc sec. ($\sim 725$ km at the sun) in extent. A larger organization into super-granulation cells is observed in strong lines (e.g. Hα, Ca II H and K lines) formed higher in the chromosphere. These are also thought to be convective in origin, and are $\sim 30,000$ km across.

Measurements of the magnetic field strength show that the strongest flux is concentrated in small elements in the boundaries of the supergranulation with only weak fields ($\sim 1$ gauss) in the cell centres. The supergranulation fields reach $\sim 2000$ gauss, and are almost certainly related to the small bright chains of emission, known as filigree, seen in the high photosphere. Although small bi-polar structures are observed within the supergranulation boundaries large areas of unipolar field occur and are thought to originate from the migration of magnetic fields from the strong centres of magnetic flux known as active regions (See Section 3).

Recent observations by the U.S. Naval Research Laboratory (NRL) with their High Resolution Telescope and Spectrograph (HRTS) have shown for the first time the presence of small ($\sim 2$ arc sec. across) bright points in the EUV continuum formed around the region of the temperature minimum. (Ref. 6). The apparent bi-polar nature of these regions suggests they are related to the supergranulation boundary structure.

The supergranulation boundaries are also the site of spicules; dynamic extensions of chromospheric material into the transition region and corona, which in their motion apparently follow the local magnetic field direction.

Figure 1 shows the supergranulation and spicules in the Hα line.

Prior to observations from space only the broad properties of structure of the inner corona and chromosphere-corona transition region could be deduced from radio emission (Ref.3) and from observations made during solar eclipses. (e.g. Ref. 8). Measurements of scattering of visible light electrons in the corona showed both a systematic decrease of electron density in polar regions and also 'streamers' and 'coronal condensations' where the density was higher than average.

Although stigmatic spectra in the EUV region, obtained from rockets by NRL in the early sixties showed variations in fluxes along the spectrograph slit, the OSO satellites were the first to carry instruments designed to image the transition region in selected emission lines. The spectroheliographs designed by the Harvard College Observatory (HCO) gave, on OSO-IV, a resolution of 1 arc min. and on OSO-VI, a resolution of 30 arc sec. by 30 arc sec., just sufficient to distinguish variations on the scale of the supergranulation. (See Ref. 9 for an account of work with the OSO satellites.)

Figure 1. The chromospheric supergranulation bordered by spicules. The inset above shows spicules superposed in the line of sight at the lines. (From Athay, Ref.1.)

A spatial resolution of a few arc sec was achieved by later NRL rocket-borne spectroheliographs and these clearly showed the EUV emission to be concentrated to the supergranulation boundaries, as in the Ca II H and K emission. (Ref.10).

Extreme spectroscopic observations were made at high resolution by the NRL instruments on Skylab in 1973 and 1974. The spectroheliograph designed by HCO could resolve 5 arc sec by 5 arc sec and allowed detailed studies of the spatial distribution of lines formed at a variety of temperatures between $\lesssim 10^4$ K and $1 - 2 \times 10^6$ K. (Ref.11). The X-ray telescope designed by American Science and Engineering (ASA & E) gave 2 arc sec resolution and provided synoptic images for studies of active regions and coronal holes (Ref.12) (See Section 3).
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Figure 2 (from Ref.11) shows some of the main features of the spatial structure in the quiet atmosphere. The images are in lines of H Lyα, C II (temperature \( \sim 2 \times 10^5 \) K), C III (\( \sim 6 \times 10^5 \) K), O IV (\( \sim 10^6 \) K), and Mg X (\( \sim 10^7 \) K). The transition region emission lines are enhanced by about an order of magnitude in the supergranulation cell boundaries compared with the cell interiors. The cell boundaries have a width of less than \( \sim 5 \) arc sec. However, the supergranulation structure does not appear in the Mg X emission which is more diffuse. One view is that the magnetic fields, which are known to be concentrated in the boundaries in the low chromosphere, eventually spread out at heights above the transition region, where T \( \sim 7 \times 10^5 \) K, to form the general corona. (Ref. 13 and 14). However, the observations do not strictly exclude an atmosphere made up of closed field regions (loops) of various heights.

![Image of supergranulation structure](image18x0 to 594x792)

Figure 2. The supergranulation structure observed in transition region lines with the HCO instrument on Skylab. Each image is 5 arc min. across (from Reeves et al. Ref.11)

2.2 Density and temperature structure: quiet sun.

Early models made from radio emission and observations during eclipses showed the existence of steep temperature gradients between the chromosphere and corona but because of the dominance of cool spicular material in the line of sight at the limb the latter tended to put the interface too high.

Considerations of hydrostatic equilibrium and boundary conditions on the pressure suggested a much lower transition region and measurements of line ratios between the disk and the lines eventually confirmed the average height of the transition to be \( \sim 2000 \) km (Ref. 15).

Figure 3 (taken from Ref.1) shows an average model of the region between the temperature minimum and the steep transition to the corona. The heights over which various lines and free-bound continua are formed are indicated. Only a brief outline will be given here of how the EUV emission lines are used to determine the temperature and density variation in the atmosphere.

Each optically thin emission line has a flux which can be expressed as

\[
F = \frac{hc}{\lambda} \int N_e A_{ul} d\nu \text{ erg cm}^{-2} \text{ s}^{-1}
\]

where \( N_e \) is the population density of the excited level and \( A_{ul} \) is the spontaneous transition probability.

![Image of electron temperature as a function of height](image18x0 to 594x792)

Figure 3. The electron temperature as a function of height above the photosphere, and regions where various lines and continua are formed. (From Athay, Ref.1)

In a spherically symmetric atmosphere the integral over volume can be replaced by an integral over height.

Also if the upper level of the transition is excited by collisions with electrons, \( \frac{N_e}{N} A_{ul} \) can be replaced by \( N_e C_{1u} N \), where \( C_{1u} \) is the collisional excitation rate.

The population of the lower level \( N_l \) can be re-written in terms of other quantities, \( \frac{N_l}{N} \) the fraction of the ion in the lower level \( N_l / N \), the ion fractional abundance \( \frac{N_i}{N} \), the element abundance \( N_e / N \), and hydrogen which is fully ionized. Thus

\[
F = \text{const.} \frac{N_l}{N} \frac{N_e}{N} R \int \frac{g(T)}{T_e^{-1}} e^{-\lambda /T_e} \text{ dh}
\]

where \( g(T) = \frac{N_{1u}}{N_e} T_e^{-1} \exp(-\lambda /T_e) \)

\( W \) is the line excitation energy and \( g(T) \) contains quantities which can be calculated as a function of temperature. The strong dependence of \( g(T) \) on \( T_e \) and relatively narrow temperature range of formation of each spectral line allows the quantity \( R \frac{N_i}{N} \text{ dh} \), known as the emission measure, to be determined from each measured flux. \( R \) refers to the region where a particular line is formed. Since the lines are formed at different temperatures, a distribution of \( \frac{dN}{N} \frac{N_i}{N} \text{ dh with } T_e \) can be built up.

Figure 4 shows an averaged emission measure distribution for the quiet atmosphere.

Writing \( E_m = \int R \frac{N_i}{N} \text{ dh} \)

and re-arranging to give

\[
E_m = \int R \frac{N_i}{N} \text{ dh} \text{ dT}
\]

allows the average temperature gradient over \( \Delta T \) to be found, assuming \( P \) to be constant over the
region of line formation.

\[
\frac{\partial \ln P_e}{\partial T_e} = -\text{const.} \frac{\partial (\ln T_e)}{T_e}
\]

then, provided a boundary condition for \( P_e \) at some \( T_e \) is known the run of \( T_e \) and \( P_e \) with height can be calculated.

The electron density can be determined from suitable line ratios. The method relies on there being, within one stage of ionization, lines which have a different dependence on \( N_e \). This can occur when one line is excited from a level whose population relative to the ground state depends on \( N_e \), whilst the other is excited from the ground state. Suitable term schemes are usually those which have a low-lying metastable state, eg. as in ions of the Be I iso-electronic sequence. Several authors have recently reviewed spectroscopic methods for diagnosing plasma conditions and the subject will not be discussed further here (see Refs. 16-18).

Returning to the interpretation of the emission measure distribution, from equation (5) it can be seen that for a given value of \( N_e \) the higher the value of \( P_e \), the steeper the temperature gradient that results. This behaviour is illustrated in Figure 5.

Observations of density sensitive line ratios have also been used to show that at given \( T_e \) the electron pressure varies only a little between the supergranulation cell interiors and boundaries. (Ref.19). Since the boundary emission measures are an order of magnitude larger this immediately implies that the boundary temperature gradients are lower ie. the transition region is thicker over the boundaries than over the cell interiors.

2.3 Coronal holes

Even early eclipse observations showed regions in the corona where there was little emission and polar regions were measured to have lower than average electron densities. Around 1970 coronal holes were recognised as distinctive structures, from spectroheliograms obtained with the OCS - VI satellite. Coronal holes were studied extensively during the Skylab missions both in the EUV and X-ray images. They appear as regions of low emission in lines that are formed at the temperature of the quiet corona (e.g. MgX).

Figure 6. The supergranulation structure in a coronal hole, apparent through absence of emission in MgX. HeI is the only transition region line in which the hole is clearly apparent. (From observations with the HCO instrument on Skylab, Ref. 11)
greater height than in the quiet sun.

Figure 6. shows the behaviour of transition region and coronal lines in a coronal hole

The most significant difference between the quiet corona and a coronal hole appears to be that in

the latter the magnetic field diverges out more rapidly than expected with a radial decrease.

Coronal holes are now considered to be the origin of the high velocity streams observed in the

solar wind. This correlation can be made because the holes sometimes extend down from the poles

through the equatorial regions and plane of the ecliptic.

One aspect of coronal holes which is relevant to future space missions (see Section 4) is the

anomalous behaviour of the HeII resonance lines at 584 Å and 304 Å. (See review given

by Ref.20). The strength of these in lines depends on the local temperature gradient and

also the ion balance depends on the coronal radiation field. Lines of HeI and HeII therefore

provide a means of detecting and monitoring coronal holes with even quite low spatial

resolution.

The rotation rate shown by coronal holes is of particular interest since there appears to be

less latitude dependence than for short-lived active region phenomena. (Ref.21). This may

indicate that the underlying control of the magnetic field is deeper in the solar interior.

A full account of recent work on coronal holes in the context of the solar wind and inter-planetary

medium can be found in the proceedings of IAU

Symposium 91. (Ref.22).

2.4 Energy balance in the quiet sun and coronal holes

These two types of region are treated together on the assumption that in both the magnetic field

is open to the solar wind.

In equilibrium, the energy input into a given region of the atmosphere must be balanced by the

energy lost by radiation, with energy transferred by thermal conduction or mass motions acting as a net loss or gain. Thus the energy input is written as

\[ \frac{dP_E}{dh} = \frac{dP_F}{dh} + \frac{dF_W}{dh} \] 

where the radiation losses are given by

\[ \frac{dP_F}{dh} = 0.8 \, n_e^2 \, F_{rad} \] 

and where \( F_{rad} \) is the radiative power loss of an ionized gas of solar composition, which is

known as a function of temperature. The conductive flux is given by

\[ F_C = -kT_e^{3/2} \left( \frac{dT}{dh} \right) \] 

and \( F_W = \|ruu + 5kT_C u - \rho g \bar{u} \]

includes the terms arising from the kinetic energy flux, the enthalpy flux and the rate of
doing work against the gravitational field.

The last term in equation (7) \( dF_W/dh \) is the most difficult to estimate. To give an idea of

magnitudes, for an average quiet sun model the radiation losses from the transition regions and

corona are \( \sim 4 \times 10^6 \, \text{erg cm}^{-2} \, \text{s}^{-1} \), with a similar figure for the average solar wind. The

main energy loss from the corona is by conduction back to the low transition region, thus accounting for \( \sim 4 \times 10^6 \, \text{erg cm}^{-2} \, \text{s}^{-1} \).

The energy conducted back is small compared with total radiation loss from the chromosphere

\( (\sim 1 \times 10^9 \, \text{erg cm}^{-2} \, \text{s}^{-1}) \) but it is difficult to match the dependence of \( dF_W/dh \) with \( dF_F/dh \) in

the crucial region where the conducted energy is deposited and a static energy balance may

not be possible. It is probably no coincidence that large turbulent velocities are observed

through super-thermal line widths in this part of the transition region.

In a coronal hole, the total radiation losses are a factor of two to three lower, although the

conduction is nearly an order of magnitude lower and if the total energy input to the corona is

the same then around \( 5 \times 10^4 \, \text{erg cm}^{-2} \, \text{s}^{-1} \) must go into the solar wind. This is

indeed comparable with the kinetic energy flux of a high-speed solar wind stream, extrapolated

back to the solar surface. (Ref.23). The physical reasons why holes develop when and

where they do are not yet understood, although proposals have been made in terms of the

evolution of the magnetic field geometry.

(eg. Refs. 24-26).

3. THE ACTIVE SUN

Active regions have been studied for many years at the levels of the photosphere and chromo-

sphere and it is the description and understanding of their coronal aspects that has

advanced most dramatically in the past ten years, mainly through observations from space.

In the photosphere active regions are characterised by the presence of concentrations of

magnetic flux, particularly in the form of sunspots. In the chromosphere above, lines such as Hα and the Ca II H and K lines are

strongly enhanced. The filamentary structure present in Hα presumably outlines the magnetic

field configuration, given the high conductivity of the plasma. The development of an active

region can be observed through the emergence of Arch Filament Systems (Refs. 27 & 28). Recent

observations in the Hα line also show fine loop structures. (Ref. 29).

Prior to imaged observations in the EUV and X-ray regions, information on the structure of

active regions in the corona came from measurements at radio wavelengths and eclipse
data. Although known to be the location of higher than average temperatures and densities, the
detailed arrangement of the material into loop structures only became apparent when the
(EUV and X-ray images achieved sufficient spatial and spectral resolution. Loop-like features
were of course known to exist earlier, from visible region observations, but were regarded as
prominence or post-flare phenomena rather than the basic structure of active regions. An
account of early EUV and X-ray observations and their interpretation can be found in Ref.30;
Ref. 3 also discusses some recent developments. Radio observations are still an important means
of studying the dynamic aspects of active regions.
and flares. The high spatial resolution now available through interferometric techniques allows a more direct comparison between EUV, X-ray and radio observations, with the potential of measuring magnetic field strengths in the transition region/coronal part of active loops. The proceedings of IAU Symposium 86 (Ref. 31) should be consulted for accounts of recent work.

Essentially the same techniques as discussed in Sections 2.2 and 2.4 can be applied to the EUV and X-ray spectra of active regions, the differences lying in the application to clearly localized rather than average structures. The results show that the active region loops do have a higher density than the surrounding corona and that the maximum temperature in low lying loops exceeds that in the quiet corona. On the other hand, loops with little or no density enhancement can have maximum temperatures lower than in the surrounding corona. The general trend is for loops to emerge with high densities and temperatures, with lower values for loops which have expanded out into the corona. Although particular loops can be followed over several successive days, there is also intermittent draining or re-filling of active regions with the HCO instrument on Skylab have been particularly valuable in studying active region loop systems. (eg. Ref. 32).

A typical large loop system would reach a height of 10^4 km, and would appear to be essentially isothermal over most of its length, so that different loops show up in emission lines formed at different temperatures. Smaller loops characteristicgically show a restricted region of high temperature near their apex. These properties can be understood when the loop heights are compared with the isothermal scale heights at the temperatures present, and account is taken of the high coronal thermal conductivity.

Figure 7 shows a typical cool loop seen with the HCO instrument on Skylab.

![Figure 7. A large loop observed in the Ne VII resonance line. (From Ref.33).](image)

Modelling of the structure and energy balance of the loop systems is often carried out in terms of the physical parameters which can be most easily measured. These are \( P_0 \), the pressure in the transition region at the base of the loop, \( T_{\text{max}} \) the temperature at the top of the loop, \( L \), the loop height. The emission measure found from line fluxes can also be used to give \( dT/dh \) at the base of the loop. (See equation 5), at some \( T_0 \), and hence \( F(T_0) \), the base conductive flux (See equation 9).

This approach was adopted by Withbroe (Ref.34) and Reimers (Ref.35) in order to analyse in a systematic way, the low spatial resolution data from the GOE satellites, and has been developed by several later authors. (eg. Ref.36, 37, 38). In outline, the physical processes are as follows; the energy input per unit temperature range, is predominantly, but not entirely, at the top of a loop; thermal conduction removes energy from the loop through the local transition region to the chromosphere; radiation losses, per unit temperature range, are fairly uniform along the loop. In small, hot loops, the pressure is almost constant with height and the temperature gradients are close to those expected if there is no deposition of energy by thermal conduction. Under these circumstances, equation (9) leads to a simple scaling law between the height of a loop and the maximum temperature present, i.e.

\[
L = T_{\text{max}}^{3/2} \quad (11)
\]

Other scaling laws can be derived depending on the assumptions made and boundary conditions adopted. For example, with constant pressure, not constant conductive flux but with a fixed ratio of maximum conductive flux to total radiation losses, Rosner et al. (Ref.38) find

\[
T_{\text{max}} = P_0^{\frac{1}{3}} L^{1/3}. \quad (12)
\]

A more general relation can be based on a straight line fit to the observed emission measure, (Ref.39), i.e.

\[
E_m = a T_e^b \quad (13)
\]

from \( T_0 \sim 2 \times 10^5 \) K to the observed \( T_{\text{max}} \).

Then \( L = \frac{a}{b+1} \left( \frac{b+2}{b} \right)^{\frac{b+1}{b}} \left( \frac{T_{\text{max}}}{T_e} \right)^{\frac{b}{b+1}} \quad (14) \)

where \( T_e \) is the maximum temperature attainable in the loop, and \( \theta = T_e/T_0 \).

This reverts to equation (11) when \( b = 3/2 \) and \( P_0 = \text{const.} \) (ie. for \( P_0 = \text{const.} \)), but also successfully accounts for appearance of large cool loops where a constant conductive flux and constant pressure are not good approximations.

The temperature and density structure of active region loops may be found from analyses of their emission measure distribution provided a further boundary condition, eg. on the pressure, can be established. Then the energy input required to account for radiation losses and conduction can be calculated, as described in Section 2. Since active regions have high pressures and temperatures both the radiation losses and conductive losses are greater than in the quiet sun, and the energy input required can be as much as three orders of magnitude greater than in the quiet sun. The magnetohydrodynamic and thermal stability of loop systems have been extensively studied. A discussion of the theory involved is beyond the scope of this introductory review, and the interested reader is referred to Refs. 40 to 42 as examples of recent work.

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difficult to be conclusive at present regarding either type of stability since insufficient is known concerning the details of the magnetic field configuration and strength and because the temperature dependence of the heating function is not yet known with sufficient precision. However, it does appear that particular combinations of loop pressure and maximum temperature are excluded in a stable configuration (Ref. 42).

3.2 Flares

In many respects, flares may be considered as parts of active regions which simply have more extreme conditions of density and temperature, the latter reaching to \( \sim 2 \times 10^7 \) K. But they can also give rise to particle acceleration and ejection of material through the corona and a range of phenomena not usually observed in active regions. Most flare models being considered at present involve tapping energy associated with the magnetic field configuration. Whilst such processes probably occur in all stages of an active region, the rapid time scales involved in the development of a major flare may indicate the importance of more than one type of instability. Accounts of recent work on the analysis of flares observed with the instruments on Skylab, may be found in Ref. 43. Observations of flares over the whole electromagnetic spectrum and over a range of particle energies may be found in the book by Svetska (Ref. 44). From the Skylab observations (eg. see Fig. 8), there is evidence that at least the smaller flares occur in small loop structures emerging into an active region, and that larger flares involve the destabilizing of whole sets of pre-existing active region loops. These large flares then give rise to the two-ribbon structure observed in Hα.

Figure 8. A flare observed with the NRL's imaging instrument on Skylab. Plasma at \( \sim 2 \times 10^7 \) K emits lines of Fe XXIII and Fe XXIV and lies between material emitting in cooler ions such as He II, Si X and Fe XIV. (From Ref. 58)

Between February and December of 1980, the Solar Maximum Mission satellite observed several hundred flares. The satellite carries a visible region coronagraph and polariometer, EUV and X-ray spectrometers, polarimeters, and imaging instruments and a gamma-ray line detector. Some of the early results from the mission are given in a special issue of The Astrophysical Journal (Refs. 45-49). The aim has been to make observations of active regions and flares simultaneously in different wavelength regions, and thus at different temperatures and heights. Co-ordinated observations, eg. in H α and with magnetographs, have also been made from the ground. It is too early to assess the new contributions being made but it appears that the hard X-rays originate from the foot-points of loops rather than from the hottest thermal plasma which usually occurs near the top of a loop. Such observations will clearly limit the range of acceptable theories of how the hard X-ray emission is produced. (Ref. 46)

The spectroscopic instruments have also produced interesting and valuable new results. The EUV polarimeter has been used to measure for the first time, the magnetic field over a sunspot in the transition region. Periodic oscillations every 130 sec., were also observed over the spot. (Ref. 47)

The spectra and images obtained from the soft X-ray instruments are being used to build up emission measure distributions to determine electron temperatures and line broadening and to test current values of essential atomic data. (Refs. 48 & 49).

The SMM spectrometers, flown on a U.S. Air Force satellite have also been used over the past two years to observe X-ray spectra of flares (eg. Refs. 50 - 52). From these results, and also from the SMM X-ray spectra the following general properties of flares can be derived.

The flare shows up in X-rays as an increase in flux of over an order of magnitude in a few minutes. The electron temperature rises to \( \sim 2.2 \times 10^7 \) K, remains high before gradually decreasing and requires energy to be deposited during the decrease as well as in the impulsive phase. Large, non-thermal motions are seen during the impulsive phase, with components shifted to the blue side of spectral lines. Combining the observed upper limit to the emitting volume with the emission measure leads to electron pressures which are up to four orders of magnitude larger than those in the quiet atmosphere.

The SMM data should be able to add to our knowledge concerning the development of active regions and the systematic locations of flares within a particular region. However, the major limitations to be overcome in future missions are the low spatial resolution of the soft X-ray instruments and restricted range of simultaneous spectroscopic measurements in the longer wavelength regions.

4. THE HEATING OF THE CORONA

At present, there exists no entirely satisfactory theory of how the corona, active region loops or flares are heated to temperatures of \( \sim 10^6 - 2 \times 10^7 \) K. The energy fluxes required can be estimated from the radiation and conduction losses, as outlined in Section 2.4

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The emission measure as a function of temperature also places constraints on the functional form of the heating process.

There are two other types of observations that can be made in order to investigate the heating process. First, measurements of line widths show that the ions have random velocities which exceed that expected from the local electron temperature. Secondly, observations of line fluxes or wavelengths can show the presence of oscillations in the atmosphere which might be associated with the passage of waves.

Observations of the chromosphere do indeed show a 300 sec oscillation, but this is now considered to be a non-propagating mode and these oscillations are not observed in lines formed above $\sim 2 \times 10^5$ K. (Ref.52). So far, the only other definite oscillations observed in emission lines above the chromosphere are those recently discovered in the transition region above a sunspot (Ref.47).

The non-thermal motions in the transition region may be interpreted as due to waves in order to investigate whether or not they could carry sufficient energy to heat the corona, i.e. it is assumed that if $V_\text{w}$ is the observed r.m.s. velocity, then the energy flux propagating is

$$\Phi = \rho V_\text{w} V_\text{p}$$

where $V_\text{p}$ is the appropriate propagation velocity. If $V_\text{w}$ is taken as either the sound velocity or as the Alfvén velocity then it is clear that heating by waves would require very short periods in the transition region at $\sim 2 \times 10^5$ K; e.g. in the quiet atmosphere $T \sim 16$ sec, with even smaller values required in active regions (Ref.37). No observations have yet been made at sufficient time and simultaneous spatial and spectral resolution to test the presence or absence of such waves.

Studies of the profiles and time variation of lines formed in the chromosphere and low transition region show that insufficient flux is carried by acoustic waves to heat the corona above (Ref.53, 54). Also, interpreted as a flux, the non-thermal motions in the transition region pass through a minimum, which is not physically realistic for an upward propagating mode. (Ref.39). If one appeals to the magnetic field geometry to avoid this problem, there remains the problem that the damping of Alfvén waves under the conditions present, in the low corona or active region loops is very small according to accepted theory.

However, it is difficult to rule out a complex range of MHD waves, with the energy changing from one mode to another at different heights in the atmosphere, as suggested some time ago by Osterbrock (Ref.55).

Alternative means of heating the corona involve some form of magnetic field (or current) dissipation perhaps involving magnetic field reconnection on a small spatial scale. It is difficult to exclude such processes because the magnetic field strength, configuration and variation with time is not known.

Although studies of global properties at moderate resolution, e.g. correlation of pressure, $P_0$, and maximum temperature, $T_{\text{max}}$, with underlying photospheric magnetic field strengths may provide valuable correlations on the total energy input as a function of $P_0$ and $B$, they do not provide information on how energy is deposited as a function of $T_e$.

5. FUTURE OBSERVATIONS

Choosing the heating process, or processes, as the most significant outstanding problem is the physics of the solar atmosphere one can list the observations which are required before further progress can be made. Although the heating is apparently closely related to the magnetic field, and has its origin below the photosphere it is essential to make observations simultaneously of the photosphere/low chromosphere and of the transition region and corona above. The strong, small scale magnetic flux in the photosphere needs to be studied at very high spatial resolution over extended periods, in a way that should be possible from the proposed Solar Optical Telescope (SOT).

Although an EUV spectrograph used with SOT can simultaneously study the transition region and the potential of the region has been demonstrated by the NRL's high resolution telescope and Spectrograph (Ref.6), ideally the spectral region below 1200 Å should also be included, since it contains lines formed in the high transition region, corona and in hot active region and flare plasma.

In order to either exclude or show evidence for wave heating, the highest priority should be given to an instrument which can measure line profiles with high spatial and time resolution. This requires a large collecting area in order to obtain sufficient flux in the important emission lines. Although periods of $\lesssim 10$ sec would be required for wave heating of the transition region, the constraints from the emission measure distribution show that longer periods, up to 300 sec, would be effective higher in the atmosphere. A lines such as the resonance line of Ne VII would be ideal for such studies, since it is strong, formed over a narrow temperature range and is optically thin.

The grazing incidence telescope (GRIST) now under study by ESA has been proposed with these essential measurements in mind. The wide range of lines present below 1200 Å is required in order to simultaneously model the transition region and inner corona. Also, line ratios in this spectral region can be used to determine both the electron density and electron temperature.

The lines of He I and He II are also relevant to studies of the heating process since their excitation is sensitive to a dynamic rather than static model. As mentioned in Section 2, they are also valuable indicators of coronal holes.

Whether or not there is evidence for wave heating, a high spatial resolution is also required to study active region loops. In particular, improved observations are required.
of their radial structure, temperature and density since low spatial resolution (~5 arc sec) observations suggest that the larger loops have a cool core, surrounded by sheaths of hotter, denser material. (Ref. 56). The observed pressure profile can be used to constrain the magnetic field configuration since the observations show that large loops are rather stable features. Although high resolution images have been obtained with X-ray telescopes, it has not been possible yet to simultaneously measure accurately the plasma parameters through spectroscopic techniques.

Thus the hope of flying SOT and GRIST simultaneously on the same shuttle payload offers the strongest prospect for progress in understanding one of the most important outstanding problems in solar physics.

6. REFERENCES


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