THE SOLAR CHROMOSPHERE AND ITS TRANSITION TO THE CORONA

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Abstract. Our present knowledge on the average physical properties of the chromosphere and of the transition region between chromosphere and corona is reviewed. It is recalled that shock wave dissipation is responsible for the high temperatures observed in the chromosphere and corona and that, due to the non-linear character of the dissipation mechanism, no satisfactory explanation of the structure of the outer solar layers has yet been given. In this paper, the main emphasis is on the observations and their interpretation.

Evidence for the non-spherically symmetric structure of the atmosphere is given; the validity of interpreting the observations with the help of a fictitious spherically symmetric atmosphere is discussed.

The chromosphere and the transition region are studied separately: for each region, the energy balance is considered and recent homogeneous models derived from ultra-violet, infrared and radio observations are discussed.

It is stressed that although in the chromosphere, a study of the radiative losses may lead to the determination, as function of height, of the amount of mechanical energy dissipated as function of height, a more detailed analysis of the velocity field is necessary to find the periods and the wavelengths of the waves responsible for the heating. The methods used for wave detection and some results are presented.

Observational and theoretical evidence is given for the non-validity of the assumption of hydrostatic equilibrium which is commonly used in modeling the transition region.

We conclude that a better understanding of the heating mechanism will come through a higher spatial resolution (less than 0.2") and more accurate absolute measurements, rather than from sophisticated hydrodynamical calculations.

1. Introduction

During a total solar eclipse the naked-eye observer is given an opportunity to see the external layers of the solar atmosphere. When the bright solar surface disappears behind the Moon, an arc of pale ruby light, the chromosphere, can be seen at the Moon's limb. This arc disappears in a few seconds, leaving a faint luminous envelope, the corona, which extends over several solar radii. The solar disk emits $6 \times 10^{10}$ erg cm$^{-2}$ s$^{-1}$, the chromosphere only $2 \times 10^6$ erg cm$^{-2}$ s$^{-1}$ and the corona $4 \times 10^4$ erg cm$^{-2}$ s$^{-1}$.

The identification of the coronal lines by Grotrian and Edlen in 1943 proved that the kinetic temperature of the corona is of the order of a million degrees (see Billings, 1966, for an historical account on coronal research). This high temperature partly explains the great spatial extent of the corona. Indeed, for a temperature of a million degree, the local scale height is of the order of 50000 km.

The density at the surface of the photosphere is $10^{16}$ atoms cm$^{-3}$ and in the corona $10^8$ to $10^9$ cm$^{-3}$. The scale height at the surface of the photosphere is approximately...
100 km; this is why the transition between the photosphere and the chromosphere, though really quite smooth, looks very sharp.

The high temperature of the corona may only be explained by a non-radiative energy input. This energy input is not accessible to direct measurements. Two approaches are frequently used: on the one hand, theoretical studies are made in order to find mechanisms of energy dissipation capable of heating the corona; on the other hand, one tries to infer from the observations, both the amount of energy dissipation and the mechanism responsible for this non-radiative energy input.

It is now established that the waves created in the solar convective zone are responsible for the heating of the outer solar atmosphere (e.g. see Billings, 1966; Kuperus, 1969). Through propagation in a medium of decreasing density, the waves develop into shocks and are dissipated. This mechanism, first suggested by Schwarzschild and Biermann in 1948, was studied quantitatively by several authors (see the review article by Kuperus (1969) and Ulmschneider (1970)). These theoretical calculations still cannot correctly explain the observations because of uncertainties in the theory and in the observations.

The formation, propagation and dissipation of waves in the Sun are non-linear phenomena, hence their mathematical description presents serious difficulties. The acoustic power radiated by the turbulence in the convective zone can however be evaluated with the help of Lighthill treatment (1952); such estimates give an acoustic power of \( \approx 3 \times 10^7 \text{ erg cm}^{-2} \text{ s}^{-1} \), but the uncertainty is at least of an order of magnitude. The theory of wave propagation in an inhomogeneous medium and in the presence of magnetic fields is still rudimentary (Schatzman and Souffrin, 1967); a correct treatment should take into account the non-linear coupling between various magnetodynamics waves, wave-refraction of waves, etc.... Shock wave dissipation is essentially a non-linear problem. The growth and decay of shock strength due to dissipation and to variations in the physical parameters of the atmosphere have been studied by several authors (e.g. Kuperus, 1969; Ulmschneider, 1970); application to the heating of the solar corona requires an exact knowledge of the spectrum of the waves generated in the convective zone and of the mechanical flux present at the top of the photosphere. At the present time neither the theoretical calculations nor the observations give reliable information concerning these quantities.

The theoretical aspect of the problem of coronal heating will not be developed further here. In this paper we shall concentrate, rather, on the observations and their interpretation in terms of velocity fields, distributions of temperature and density and radiative energy losses.

As is discussed in the Section 1, the observations show that the outer layers of the Sun have a very heterogeneous structure. The present spatial resolution of the observations is not high enough to make a detailed study of the various components of the atmosphere. Our investigation, therefore, will be limited to the average physical properties of the quiet regions (with low magnetic field) of the chromosphere. The concept of a stratified atmosphere proves to be a very useful approximation to explain the observations and to investigate the problem of the energy balance in the solar atmosphere.
The observations show that the mean variations of the temperature above the limb are the following. The temperature rises from 4200 K, the temperature of the surface of the photosphere, to 9000 K over a distance of 2000 km to 2500 km; this region emits low excitation lines which are observed in absorption in the solar disk spectrum or in emission in eclipse spectra; it is called the chromosphere. Above 2000 km the temperature increases in a rather obscure way from 9000 K to 10000 K, then very rapidly to $5 \times 10^5$ K and attains a coronal value of $10^6$ K at 4000 km to 4500 km above the limb. This region of steep temperature rise between the chromosphere and the corona is called the transition region; it emits high excitation emission lines visible in ultraviolet spectra. In the corona itself the temperature increases from $10^6$ K to a maximum value of $1.5 \times 10^6$ to $2 \times 10^6$ K and then decreases slowly to interplanetary values.

In Section 2 a qualitative description of the structure of the chromosphere and the transition region is given; in Section 3 a summary of the observations concerning these layers is presented. Sections 4 and 5 are devoted to the study of the chromosphere and transition region respectively; for each region, recent models are presented and their energetic and hydrodynamic equilibria are discussed.

2. Description of the Chromosphere and Transition Region

2.1. EXTENSION OF THE CHROMOSPHERE AND TRANSITION REGION

The reddish colour of the chromosphere seen at eclipses is due to an intense Hz emission. Therefore Hz plates centered at the solar limb are a powerful tool for the understanding of the chromosphere. On such plates a bright layer, 4000 to 4500 km thick, overlies the photosphere. Its upper border looks very irregular; thin matter jets, called the spicules, are seen to rise into the corona up to 6000 to 10000 km above the limb (e.g. Lyot, 1944; Zirin, 1966; Loughhead, 1969; Nikolsky, 1970). A mean value of 4000 km for the total extension of the chromosphere and transition region agrees well with the observations of the coronal lines. Indeed, in all coronal spectra taken with the Climax coronograph (U.S.A.), the red coronal line Fex at 7892 Å appears at 5000 km above the limb (Zirin, 1966). This same line has been detected down to 3000 km during the 1952 eclipse (Athay and Roberts, 1955) and down to 4000 km during the 1966 eclipse (Weart, 1968).

There is no direct evidence for the height of the chromosphere. Eclipse measurements of the continuum intensity at 6900 Å (Makita, 1971) show that the emissivity decreases rapidly between 2000 and 3000 km above the limb, suggesting that this is the height of the chromosphere. This result is in good agreement with the interpretations of the Lyman continuum (Noyes and Kalkofen, 1970) and of the limb-brightening of ultraviolet lines (Withbroe, 1970b).

2.2. INHOMOGENEITIES

The non-spherically symmetric structure of the chromosphere and the transition region is easy to detect.
In flash spectra, if the spatial and spectral resolution are large enough, the lines may be seen to break up into a number of small sources of emission; these are the spicules. In the 1958 eclipse spectra, spicules are visible from 1500 km upwards (Suemoto and Hiei, 1962).

On Hα plates of the solar limb, taken by Nikolsky (1970) with a spatial resolution of 1″ (1″ = 750 km on the Sun), the spicules appear to extend right to the base of the chromosphere, other observations are required to confirm this observation.

On the pictures by Loughhead (1969), the spicular structure is not visible; very conspicuous, however, are bright blobs lying 1″ upwards of the limb; according to Loughhead these show a close correspondence with the bright mottles seen on the disk. This leads Loughhead to suggest that the two phenomena are identical.

Spectroheliograms in the resonance lines of Ca⁺ (the H and K lines) and in Hα show clearly the inhomogeneous structure of the chromosphere (e.g. Zirin, 1966; Banos and Macris, 1970). The interpretation of these spectroheliograms is difficult. The light emitted at a given wavelength \( \lambda \) originates in regions of optical depth \( \tau_\lambda \approx 1 \). The relation between geometrical depth and optical depth depends on the temperature and density distributions; lines emitted by moving elements are shifted by Doppler effect, thus the geometrical altitude corresponding to \( \tau_\lambda \approx 1 \) varies from one line of sight to the other. It is difficult to relate the inhomogeneities seen on the disk to those seen on the limb (e.g. Beckers, 1968; Loughhead and Tappere, 1971). Koutchmy and Macris (1971) are presently developing a method of composite photography to make such comparisons.

2.3. Contribution of the Spicules to the Chromospheric Emission

Above 4500 km, coronographs make it possible to measure the spicular emission in a few strong lines (Beckers, 1968). Below 4500 km the spatial resolution of the observations is not good enough to separate the spicular from the interspicular emission. However, the spicular contribution to the chromospheric emission can sometimes be evaluated, as for example at centimetric wavelengths. Indeed it is known that the spicules cover 3% of the solar surface at 1000 km, a proportion which decreases exponentially as the altitude increases. It is thought too, that above 2000 km the spicules are probably cooler and denser than the surrounding medium (Beckers, 1968). Thus the contribution of the spicules to the chromospheric centimetric emission may be evaluated. It is found to be negligible at the center of disk. On the limb, however, because of foreshortening effects, it cannot be neglected; it is then easily taken into account since it may be assumed that the spicules are optically thick to the centimetric emission (Lantos, 1972). For ultraviolet emission the situation is more intricate; some authors (Zirin, 1966; Suemoto and Moryama, 1963) believe that the ultraviolet emission lines originate in the spicules only (except for H and He); a spatial resolution of at least 1″ is necessary to prove such an hypothesis.

2.4. Inadequacy of Spherically Homogeneous Models

With the data presently available, only stratified, that is spherically homogeneous
models may reasonably be constructed; the plane parallel stratification assumption which neglects curvature may safely be applied for the extension of the chromosphere is only 6". However such models cannot explain all the observations obtained with low spatial resolution. For instance, the center-to-limb variation of the H and K lines cannot be reconstructed with homogeneous models (Linsky and Avrett, 1970). Let us suppose that the chromosphere is made up of two types of vertical columns, mimicking the spicules and the interspicular medium. Low resolution profiles are mean values of the profiles corresponding to the two types of structure, but because of geometrical effects, these mean values are taken differently at the center and at the limb.

Homogeneous models are, of course, non-sensical if the chromosphere is made up of spicules only. An experiment is presently under way at the 'Laboratory of Stellar and Planetary Physics, Verrières, France', to study the chromospheric emission in the strongest lines as a function of time, with a spatial resolution of 1"×1" and a spectral resolution of 0.02 Å. This experiment will be flown by the satellite OSO-EYE, whose launching is scheduled for 1973. In case of success, an enormous amount of data will be available for the study of the inhomogeneous structure of the outer solar layers.

3. Ultraviolet, Infrared and Radio Emission

The amount of observational data on the outer layers of the Sun has considerably increased since ultraviolet (UV), infrared (IR) and radio spectra of the Sun have become available. For temperature and densities typical of the solar surface, the continuous absorption coefficient is at a minimum in the visual range and increases towards the UV and the IR (Vitense, 1951). Thus, UV and IR continuous emission originate in the uppermost layers of the photosphere and in the chromosphere (Pecker, 1965). Moreover, temperatures of the chromosphere and corona are high enough to excite UV lines and to produce an important radio emission.

The terrestrial atmosphere is opaque to radiation shortward of 2900 Å and between 20 µ and 900 µ. In the UV the main absorbing elements are oxygen and ozone (Friedman, 1963); the absorption is maximum at 50 km and still notable at 200 km for wavelengths shorter than 1000 Å. Observations have, therefore, to be made from balloons, rockets or satellites. A much larger number of spectra can be obtained by satellites than from rockets or balloons, but the drawback of such experiments is their cost. In the IR, the main absorption is due to water vapor; as it is very small above 30 km, the observations are made on stratospheric balloons or airplanes.

3.1. Ultraviolet Observations

The advances in UV spectroscopy are closely tied to the development of rockets and satellites. The first UV spectrum was obtained by the American using a captured German V-2. To get good pointing accuracy, to avoid stray photospheric light which hides the UV emission and to obtain a reliable calibration are the most difficult aspects of these spatial UV techniques. The first spatial UV observations with high
spectral resolution (0.07 Å) where made by Purcell et al. (1960) in the wavelength range 1000 to 3000 Å. In the following years, spectra of the total solar radiation from 1500 Å to 3000 Å were obtained with spectral resolution up to 0.03 Å. Solar UV observations have been reviewed by Friedman (1963), Pottasch (1964), Tousey (1963, 1967, 1971), Goldberg (1967) and Noyes (1971); the reader is referred to these articles for details on the experiments and spectra. It should be noted that during the last four years major progres has been made to improve the spatial and spectral resolution of the observations as well as the accuracy of the absolute intensity measurements. For example, the Harvard College Observatory spectrometer-spectroheliometer aboard the satellite OSO 4 (Goldberg et al., 1968) was able to obtain photoelectric spectra of a 1′ × 1′ surface at the quiet-disk center in the wavelength range 300 Å to 1400 Å as well as spectroheliograms of the entire disk with a spatial resolution of about 1′ (Parkinson and Reeves, 1970). New absolute flux measurements in the wavelength region 1310–270 Å were made on the OSO 3 satellite (Hall and Hinterreger, 1970); these measurements show that the solar radiation in this wavelength range has intensity variations over the 27-day period, similar in magnitude (40%) and spectral character to variations observed over the 11-year cycle. Profiles of a few strong UV lines, such as the Mg II resonance doublet at 2802 Å (Lemaire, 1970), the O I resonance triplet at 1305 Å (Bruner et al., 1970) and the C II resonance line at 1335 Å (Berger et al., 1970) were resolved.

A detailed analysis of the UV spectrum may be found in the review articles mentioned above. Let us recall the main features of this spectrum.

Between 3000 and 2100 Å, the spectrum is mainly of photospheric origin. The absorption lines are very numerous, therefore the determination of the true continuum is difficult; a spectrum of the center of the disk, taken in the wavelength range 2000 to 2200 Å with a spectral resolution of 0.03 Å shows 660 absorption lines; the average interval between absorption lines being only 0.2 Å (Boland et al., 1971). The strongest absorption feature in this spectral range is the resonance doublet of Mg II; each line presents two emission peaks inside a wide absorption core.

Between 2100 Å and 1525 Å the radiation arises in the uppermost layers of the photosphere and low chromosphere; the absorption lines disappear progressively; none can be seen below 1525 Å; the emission lines appear around 1900 Å. The appearance of emission lines proves that shortward of 1900 Å the source function increases more rapidly with height in the lines than in the continuum.

Shortward of 1525 Å, the continuum is of the chromospheric origin. As the wavelength decreases, the degree of ionization of the elements emitting the lines increases. The strongest emission line in this spectral range is Ly-α at 1216 Å, which emits a flux of approximately \(3 \times 10^5\) erg cm\(^{-2}\) s\(^{-1}\); the profile of Ly-α, as well as the profile of Ly-β, show a central reversal characteristic of optically thick lines (Tousey, 1963).

Shortward of 1000 Å, the spectrum consists of emission lines; only the Lyman continuum at 912 Å and the neutral helium one at 504 Å can be detected. The total flux emitted below 1000 Å is of the order of \(6 \times 10^4\) erg cm\(^{-2}\) s\(^{-1}\) (Friedman, 1963).
3.2. Infrared Observations

The study of the IR emission of the Sun started around 1960. In the IR, the photon energy is much smaller than in the UV; therefore detection is a major problem and the development of IR astronomy is closely related to the improvements of the IR detectors. Nowadays, an accuracy of 1% on absolute measurements is possible.

The new technique of IR Michelson interferometry developed by Connes and Connes (1966) has made it possible to obtain IR spectra. Since at the altitude in the terrestrial atmosphere where the spectra are taken (10 km at most), the absorption spectrum is mostly atmospheric (Biraud et al., 1969), the solar spectrum is studied by comparison with the lunar one. Spectra will have to be taken aboard satellites to get completely rid of the water vapor and thus detect the true solar spectrum. In the IR, the main opacity sources in the solar atmosphere are the free-free transition of H−; thus, the true solar IR spectrum is a continuum with a few molecular bands.

More useful for the determination of chromospheric models are wide band absolute intensity measurements at the center of the disk and center-to-limb variations at various wavelengths. Shortward of 20 μ the radiation comes from the photosphere and ground-based observations are possible (e.g. Lena, 1970; Koutchmy and Peytoureux, 1968, 1970). Between 20 μ and 400 μ the radiation arises from the uppermost layers of the photosphere and low chromosphere; the observations are made from balloons or airplanes (e.g. Eddy et al., 1969; Gay, 1970). Longward of 400 μ the radiation comes from the chromosphere; there is no observation between 350 μ and 750 μ; radio-astronomical techniques allow the detection of the radiation longward of 0.75 mm. Values of the brightness temperature at the center of the disk between 4 μ and 300 μ can be found in Shimabukuro and Stacey (1968), Eddy et al. (1969), Linsky and Avrett (1970) and Gingerich et al. (1971).

3.3. Radio Observations

The study of the Sun at radio wavelengths began after 1945, for the ancestor of the radiotelescope is radar. A radio wave propagates in a plasma only if its frequency is greater than the plasma frequency; as the plasma frequency is proportional to the electron density, the radio observations have a good height resolution. Roughly, from 1 mm to 1 or 2 cm, the radiation comes from the chromosphere; from 2 cm up to 1 m, it comes from the transition region and at meter wavelengths from the corona. Let us note that the coronal contribution to the centimetric emission is not negligible; it increases with the wavelength and is, of course, greater at the limb than at the center of the disk. Brightness temperatures at the center of the disk may be be found in Linsky and Avrett (1970) and Shimabukuro and Stacey (1968) for the range 1 mm to 21 cm.

As in any other spectral range, measurements of the center-to-limb variation of the brightness temperature afford valuable data on the variation of the temperature and density in the solar atmosphere. The center-to-limb variations of the quiet Sun are obtained by drawing the lower envelope of the center-to-limb variations measured
on various days; through this procedure the contribution of active regions, which are more emissive than the quiet Sun, is eliminated. As the active regions have dimensions of a few minutes of arc, a spatial resolution of 1′ or less is required to keep the inaccuracy of this method at a reasonable level. Large telescopes, such as Nançay (France) or NRAO (U.S.A.) and interferometers provide a spatial resolution of the order of 1′. The brightness temperatures of the quiet Sun vary by approximately a factor 2 during the 11-year cycle; therefore, when choosing observations to build chromospheric models, care must be taken to use a coherent set of data.

A short summary of the height formation of the ultraviolet, infrared and radio spectra is given in Table I.

<table>
<thead>
<tr>
<th>Emissive layers</th>
<th>UV continuum</th>
<th>IR and radio continua</th>
<th>Spectral lines</th>
</tr>
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<tbody>
<tr>
<td>photosphere</td>
<td>3000–2100 Å</td>
<td>1–20 μ</td>
<td>Paschen lines</td>
</tr>
<tr>
<td>minimum of temperature</td>
<td>2100–1525 Å</td>
<td>20–400 μ</td>
<td>Hβ</td>
</tr>
<tr>
<td>chromosphere</td>
<td>1525–800 Å</td>
<td>400 μ – 1 cm</td>
<td>Hα; Ca++, Mg+ resonance lines</td>
</tr>
<tr>
<td>chromosphere-corona</td>
<td>He continuum</td>
<td>1–21 cm</td>
<td>Ly-α; UV emission lines</td>
</tr>
<tr>
<td>transition region</td>
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4. The Chromosphere

The first section is devoted to homogeneous chromospheric models; in the second section various evaluations of the amount of mechanical energy dissipated in the chromosphere are discussed.

4.1. CHROMOSPHERIC MODELS

For stars, the procedure generally adopted to determine the temperature and density distributions in the atmosphere is to build, numerically, model stellar atmospheres, taking into account the main physical processes (Mihalas, 1967; Auer and Mihalas, 1969); these theoretical models depend on parameters which are determined by fitting the spectrum computed with help of these theoretical models with the observed spectrum. Applied to the Sun, this method does not give satisfactory results, for two main physical processes are very difficult to handle. First, as was mentioned in the introduction, a correct treatment of the dissipation of mechanical energy is not possible. Second, the solar spectrum presents such a large number of absorption lines, that a complete treatment of the blanketing effect (radiative energy transfer between lines and continua) is extremely time-consuming, though recent progress has been made in this field (e.g. Carbon and Gingerich, 1969; Athay, 1970).

Another method to obtain the physical parameters of the solar atmosphere is
direct inversion of observational data; for instance, the center-to-limb variations of UV and IR continua led Bonnet (1968) and Lena (1970) to suggest improvements to the photospheric models in the region of minimum temperature. This method is very useful but may give uncertain results; a critical study of the method is given by Jefferies (1968).

At the present time the best method to build chromospheric models is to choose a variation of the temperature $T$ as function of the optical depth at a reference wavelength; the determination of a $T(\tau)$ law that leads to a good agreement between the computed spectrum and the observed one, is made by trial and error. This method can be applied to stars other than the Sun, for it does not require use of the center-to-limb variations. This method avoids all assumptions concerning the thermal equilibrium of the atmosphere. We shall now present a few chromospheric models obtained in this way, with the help of continuum and line profile measurements.

4.1.1. Chromospheric Models from Continuum Measurements

Absolute measurements of the continuum intensity shortward of 1525 Å and longward of 20 μ allow the determination of chromospheric models up to 2000 km.

In the UV, the Planck function is proportional to $\exp (-h\nu/kT)$, therefore a 10% error in the intensity measurements leads to an error of 50 K only in the temperature determination. In the IR, the Planck function is proportional to $T$, therefore a 1% precision in the measures is necessary to achieve an accuracy of 50 K in the temperature. In the UV, the continuous absorption is due mainly to metals (aluminium, magnesium), to hydrogen, silicon, carbon and sulfur; the photo-ionizations cross-sections are difficult to determine with accuracy and non-LTE effects must be taken into account in the computation of the absorption coefficient (Cuny, 1971); moreover, the spectral lines present in the spectrum hinder the determination of the continuum intensity.

In the IR, longward of 1.6 μ, the spectrum presents hardly any absorption lines, the free-free absorption coefficient of $H^-$ is well known and the non-LTE effects, which are not very important anyway, can easily be computed (Gebbie and Thomas, 1970). In order to get absolute measurements, the residual absorption by water vapor must be carefully evaluated; according to Gay (1970), this absorption is less than 0.5% above 30 km. Each spectral range thus presents its own difficulties.

Several models compatible with absolute UV and IR measurements of the continuum intensity have been proposed recently.

Cuny (1971) determined a model of the upper-most layers of the photosphere and low chromosphere from continuum observational in the range 1680 to 600 Å. This model is in hydrostatic equilibrium. Deviations from LTE are allowed for in the computation of the absorption coefficient; the determination of these deviations is made by solving the equation of radiative transfer in the continua and main spectral lines of the absorbing elements.

From the center-to-limb variations of the Lyman continuum obtained aboard OSO-4, Noyes and Kalkofen (1970) computed a model in hydrostatic equilbirum
Fig. 1. Temperature versus height in the chromosphere; the zero of the abscissae corresponds to $\tau_{5000\,\AA}=1$.

Cuny (1971)
HSRA (Gingerich et al., 1971)
Henze (1969)
Linsky and Avrett (1970)

denoted in the following as the NK model. The radiative transfer in the Lyman continuum and in H$\alpha$ has been calculated to determine the deviations from LTE in the ionization of hydrogen.

As can be seen in Figures 1 and 2, where the temperature and electron density versus height have been drawn, the NK model agrees well with the Cuny model. Various observations are well reproduced with the NK model:
- the temperature brightness in the millimeter range at the center of the disk;
- the H$\alpha$ height formation, which is found to be at 1300 km above the limb, in agreement with the observations by White and Wilson (1966);
- the 1970 eclipse measurements of the continuum intensity at 6900 $\AA$ (Makita, 1971).
Fig. 2. Logarithm of the electron density in the chromosphere; the zero of the abscissae corresponds to $\tau_{5000\,\text{Å}} = 1$.

--- Cuny (1971)
- - - - HSRA (Gingerich et al., 1971)
- - - - Henze (1969)
- - - - Linsky and Avrett (1970)

Other observations cannot be reproduced so well. Electron densities twice as high as those of the NK or Cuny models are necessary to explain the intensities of the Balmer lines and continuum measured at the 1962 eclipse (Henze, 1969). This discrepancy may be due to the inhomogeneous structure of the chromosphere or to uncertainties in the 1962 eclipse data. The NK and Cuny models predict limb-brightening for wavelengths greater than 500 $\mu$, whereas all observations show nearly constant brightness temperatures (Simon and Zirin, 1969); this discrepancy originates most probably in the assumption of a homogeneous chromosphere. One should not forget that the uncertainty in the intensity measurements is by a factor 2 to 3, which leads to uncertainties of 200 K to 500 K in the temperature, as is shown by Cuny (1971).

A model of the solar atmosphere, denoted HSRA (initials for Harvard-Smithsonian Reference Atmosphere) has been proposed by Gingerich et al. (1971). This model covers the atmosphere from $\tau_{5000\,\text{Å}} = 10^{-8}$ to $\tau_{5000\,\text{Å}} = 25$, corresponding to the chromosphere below 2000 km and the photosphere. This model is in hydrostatic
equilibrium; it combines a photospheric model that incorporates recent UV observations with the chromospheric model of Noyes and Kalkofen. In the visible wavelength region, the continuous spectrum at the center of the disk and the limb-darkening variations are well reproduced. Above the temperature minimum, the model fits a whole set of data reasonably well, but none is fit perfectly; this is due to the inhomogeneous structure of the chromosphere. In Figures 1 and 2 the temperature and electron density distribution are drawn vs. height.

4.1.2. Models from Line Profiles

The resonance lines of Ca II at 3968 Å and 3934 Å and the resonance lines of Mg II at 2882 Å and 2795 Å are formed in the chromosphere. Since numerical methods have been developed to handle non-LTE transfer in resonance lines (Cuny, 1967; Dumont, 1967a, b; Athay and Skumanich, 1967; Skumanich and Domenico, 1971; Rybicki, 1971), the low spatial resolution profiles of Ca II and Mg II lines may be used to determine the mean conditions in the chromosphere.

The H and K profiles, detected from the ground with an accuracy of 1%, have been widely used. One of the most recent models in hydrostatic equilibrium, determined empirically to fit the H and K profiles and the infrared triplet of Ca II, is the model by Linsky and Avrett (1970), denoted in the following as the LA model. As can be seen in Figures 1 and 2, where the temperature and density distributions versus height have been drawn, the LA and HSRA models agree well below 1500 km. The millimetric continuum at the center of the disk can be reproduced by the LA model, but neither the asymmetry of the emission peaks, nor the center-to-limb variations of the profiles can be accounted for by this homogeneous model devoid of macroscopic velocity fields.

Because of atmospheric absorption, the profiles of the Mg II resonance doublet cannot be measured from the ground; they have recently been obtained by Lemaire (1970, 1971) with a spatial resolution of 7" and a spectral resolution of 0.025 Å, from a stratospheric balloon. Because of residual ozone absorption, no absolute measurements could be made; a previous UV spectrum taken by Bonnet (1968) was used as reference to obtain an absolute calibration. With the LA model, Lemaire can reconstruct fairly well the Mg profiles of the quiet chromospheric regions.

Besides the temperature and density distributions, the variation of the microturbulent velocities with height may be determined from line profiles. This determination can be made directly on the observations (see Jefferies, 1968); but this method may give uncertain results. Another method is to find, by trial and error, the microturbulent velocities which lead to the best reconstruction of the observed profiles. Many lines have to be studied in order to get a unique solution for the temperature, density and microturbulent velocity distributions. The H and K profiles of Ca II and the resonance doublet of Mg II lead to a microturbulent velocity which increases almost linearly with height from 2 km s⁻¹ at the surface to 12 km s⁻¹ at 2000 km (Linsky and Avrett, 1970; Lemaire, 1971).

Other UV line profiles, such as these of the O I and C II resonance lines, have recently
been measured. Random motions of large scale bodies of gas (macroturbulence) are required to explain these profiles (Berger et al., 1970; Jones and Rense, 1970).

It was shown in this section, that below 1500 km a fairly good agreement exists between various homogeneous models based on different sets of observations; above 1500 km, the disparities are partly due to differences in the assumed microturbulent velocities. A greater precision in absolute measurements would reduce the uncertainties in these models, but a unique solution is impossible for they do not represent a real solar feature. Since high spatial resolution line profiles are available, investigations on inhomogeneous models are in progress. Let us mention a discussion on these models in Linsky and Avrett (1970) and a study of solar inhomogeneities from the Ca II infrared triplet by Mein (1971).

4.2. THERMAL EQUILIBRIUM OF THE CHROMOSPHERE

In the chromosphere, the transfer of energy through thermal conduction is negligible compared to the radiative energy transfer (Ulmschneider, 1970). Non-turbulent velocities are small enough (less than 0.4 km s$^{-1}$) for energy transfer through convection to be negligible too; the solar wind is a typical example of the opposite situation where the conductive and convective flux are of the same order of magnitude as the radiative flux. Observations of the chromosphere show it to be in a stationary state, therefore the amount of dissipated mechanical energy is everywhere equal to the net radiative losses, that is, to the difference between emitted and absorbed radiative energy. A determination of the radiative energy losses as function of height may thus lead to the dissipated mechanical energy.

These net radiative losses may be computed from simultaneous use of observations and chromospheric models; the results of such determinations are given in the first section. As will be shown in the second section, the use of theoretical models give a possible determination of the dissipation of mechanical energy.

Such indirect determinations of the non-radiative energy input, only allow the elimination of dissipation mechanisms not compatible with the observations. A direct inference of the mechanical energy dissipation is in principle possible. Indeed, the interpretation of the chromospheric line profile fluctuation, leads to the determination of period, wavelength and amplitude of the waves present in the chromosphere; these in turn allow the evaluation of the energy density of the waves and of the flux of mechanical energy. In Section 4.3 the methods used to detect these waves are briefly reviewed.

4.2.1. The Net Radiative Losses

In the chromosphere the elements responsible for the radiative energy losses are mainly the ion H$^-$, neutral hydrogen and presumably Ca$^+$ and Mg$^+$. The net radiative losses are given by

$$F = \int_{\text{chromo}}^{\infty} \chi_v (J_v - S_v) \, dv,$$

(1)
where $x_v$ is the absorption coefficient per cm at frequency $v$, $J_v$ the mean intensity and $S_v$ the source function; the integration is made over the whole chromosphere. The evaluation of this quantity requires the knowledge of the chromospheric model.

No exact calculation of these radiative losses has been made up until the present time. The first approximate evaluation of the H$^-$ radiative losses was made by Osterbrock (1961) who found a radiative flux $F = 4 \times 10^7$ erg cm$^{-2}$ s$^{-1}$. Athay (1966a) recomputed the radiative losses from the chromosphere and corona. With the same kind of approximation as Osterbrock, Athay came up with a result ten times lower, mainly because the chromospheric models have been greatly improved between 1961 and 1966; according to Praderie and Thomas (1971), Athay’s evaluation of the H$^-$ losses should be multiplied by a factor 2. In Table II are reproduced the radiative energy losses given by Athay. The radiative losses given by Athay for the UV lines, excluding Ly-$\alpha$, are twice higher than the radiative losses deduced from the flux measurements by Hall and Hinterreger (1970).

4.2.2. The Dissipation of Mechanical Energy

Another approach to the determination of the dissipation of mechanical energy is to build theoretical chromospheric models with the requirement that the total flux (radiative + mechanical) be constant. The optical thickness of the chromosphere in the visual range, where most of the energy is radiated away, is of the order of $10^{-4}$. Therefore the radiation field may be assumed to be constant and equal to the observed radiation and the temperature may be determined from the equation of thermal equilibrium. The dissipation is determined tentatively as a function of height so as to reproduce the observations. This method was used by Frisch (1967) and Gebbie and Thomas (1970); the purely radiative chromospheric temperature rise due to deviations from LTE in the ionization of H$^-$ was taken into account.

We recall that when deviations from LTE are allowed for, the temperature is a solution of the equations of statistical equilibrium and radiative equilibrium. When the density is low enough for the population of H$^-$ to be controled by photoionization and no more by collisions with the hydrogen atoms, the equilibrium temperature is equal to the color temperature $T_c$ defined by

$$J_v = \frac{W B_v(T_c)}{v^3}$$

where $J_v$ is the mean intensity, $W$ a geometrical factor and $B_v$ the Planck function. For

<table>
<thead>
<tr>
<th>altitude km</th>
<th>0–500</th>
<th>500–1000</th>
<th>1000–1500</th>
<th>1500</th>
</tr>
</thead>
<tbody>
<tr>
<td>radiator</td>
<td>H$^-$</td>
<td>Balmer series</td>
<td>Ly-$\alpha$</td>
<td>UV lines</td>
</tr>
<tr>
<td>flux erg cm$^{-2}$ s$^{-1}$</td>
<td>$4 \times 10^6$</td>
<td>$1 \times 10^6$</td>
<td>$3 \times 10^6$</td>
<td>$3 \times 10^6$</td>
</tr>
</tbody>
</table>
the visible spectrum, the color temperature is 5600 K, thus one would expect a pure
temperature rise up to 5600 K (Cayrel, 1963). If one uses the observed radiation field
instead of expression (2), the temperature rises to 5100 ± 100 K only, for the radiation
field deviates from a black-body because of the absorption lines. The figure of 5100 K
is an upper limit for the radiative temperature rise, because line absorption was not
accounted for in the equation of radiative equilibrium. Athay (1970) has confirmed
that this purely radiative temperature rise is very small. Frisch (1967) determined
empirically the mechanical energy dissipation compatible with the millimetric bright-
ness temperature at the center of the disk; it comes out that around the minimum
temperature, the dissipation given by Osterbrock (1961) is ten times too large; this
result is in agreement with Athay’s conclusion (1966, 1970). In Frisch’s work the dissipa-
tion of mechanical energy is introduced in the equation of energy conservation, but
the corresponding term in the equation of momentum conservation is not considered,
nor is the continuity equation.

At the present time a reasonable estimate for the radiative energy losses in the
chromosphere is of 3 x 10^6 erg cm^-2 s^-1, with an uncertainty factor 2. With the help
of recent chromospheric models, a more accurate determination of the net radiative
losses and thus of the dissipation of mechanical energy as a function of height could
be obtained.

4.3. WAVES IN THE PHOTOSPHERE AND THE CHROMOSPHERE

Measurements of the Doppler shifts of spectral lines allow the study of the waves
present in the solar atmosphere. Since 1960 various techniques have been developed
for this purpose.

From the superposition of negative and positive prints of spectroheliograms taken
in both wings of chromospheric lines, Leighton et al. (1962) studied the structure of
the velocity field in horizontal plane. They showed the existence of a vertical oscillation
having a period of 5 min, an amplitude of the order of 0.3 km s^-1 and an horizontal
wavelength varying between 3500 km and 7000 km, according to the line considered.
Evidence for descending movements concentrated at the chromospheric network was
obtained. We recall that on the H and K spectroheliograms, the regions of maximum
intensity form the so-called chromospheric network. These regions of enhanced in-
tensity correspond to magnetic fields greater than average; the characteristic dimen-
sion of this network, which is also referred to as the supergranulation, is of the order
of 40000 km.

With a technique similar to that of Leighton et al., Sheeley and Bhatnagar (1971a,
b) have separated the solar velocity field into a slowly varying component and an
oscillatory component of period 5 min. In agreement with Leighton et al., the wave-
length of this oscillation varies from 4000 km to 6000 km. A study of the wavelength
and time evolution of the slowly varying component leads Sheeley and Bhatnagar to
suggest that this component represents the velocity field of the photospheric granulation.

As the spectral lines are formed at various heights in the atmosphere, the vertical
propagation and horizontal wavelengths of the perturbations may be studied from
time sequences of high dispersion spectra of a solar chord. The time sequences of
spectra taken by Evans and Michard (1962) were thoroughly examined by Mein (1966).
Mein showed that the 5 min oscillation has the same evolution as evanescent waves.
A study of the Doppler shifts and intensity fluctuations of photospheric lines and
neighbouring continua was made by Frazier (1968) on sequences of high resolution
spectra, taken at the center of the disk with a spatial resolution of 1", every 20 s for
55 min. Frazier found that there is no systematic correlation between the appearence
of a convective cell and the beginning of a 5 min oscillation and that these oscillations
could be detected in the convective zone. These results show that the 5 min oscillations
build up in the convective zone itself and are not due to the excitation of the stable
photospheric layers by a convective cell acting like a piston. This last result is in agree-
ment with absolute measurements of Doppler shifts on the SrI line at 4607 Å, made
by Roddier and Gonczi (1969) who found that the life-time of the oscillation phase is
of the order of 20 min, whereas the life-time of a photospheric granule is only about
7 to 8 min.

Magnetographs, initially meant for magnetic field measurements, have been modi-
fied to give simultaneous determination of the velocity fields. Howard (1967), for
example, has shown that the amplitude of the 5 min oscillations is 25\% smaller in
regions with high magnetic fields (\(> 80\) G) than in those with low magnetic fields
(\(< 10\) G). The coincidence between the descending matter flux and the chromospheric
network found by Leighton et al. (1962), has been definitively proven by Tannenbaum
et al. (1969) by means of magnetograph.

Measurements of wave amplitudes lead to the determination of mechanical energy
density, but the knowledge of the group velocities is necessary to get the flux of
mechanical energy in the various waves; group velocity determinations are much more
difficult than amplitude determination. Ulrich (1970) gives, without details, a flux of
mechanical energy of \(7 \times 10^6\) erg cm\(^{-2}\) s\(^{-1}\) for the 5 min oscillations; this flux is of
the same order of magnitude as the net radiative loss from the chromosphere. It is to
be remembered that the origin of the 5 min oscillations is not known although various
mechanisms have been suggested (e.g. Ulrich, 1970). Another obstacle met in the
observational determination of the flux of mechanical energy is the impossibility of
obtaining the energy content of the waves with very short wavelengths, for they form
the so-called microturbulence and contribute only to line broadening.

We have seen in this part devoted to the chromosphere, that recent UV and IR
observations allow a fairly accurate description of the mean density and temperature
distributions. Much observational progress has to be made to determine the inhomoge-
nous structure of the chromosphere and the flux of mechanical energy.

5. Chromosphere-Corona Transition Region

The transition region emits a continuous spectrum on centimetric wavelengths and
UV emission lines. The UV lines are mainly resonance lines from highly ionized stages
of the most abundant elements (He, O, C, Ne, Mg, Si, Fe). The degree of ionization of the elements increases with decreasing wavelength. The origin of this correlation is that the wavelength of the resonance line of an ion is approximately proportional to the ionization potential.

In the first section various methods are presented which may be employed to construct homogeneous models of the transition region. In the second section, the thermal and hydrodynamic equilibria of this layer are discussed.

5.1. Homogeneous models of the transition region

Until 1969 the UV observations gave only the spectrum of the total solar radiation, i.e. the radiation integrated over the whole disk. The first quantitative interpretation of the UV spectrum was made by Ivanov-Kholodnyi and Nikol'skii (1961). Later Pottasch (1963) developed a similar method that has been widely used to determine abundances in the chromosphere and corona, and to build, granted some supplementary assumptions, homogeneous models of the transition region. Pottasch's method is described in Section 5.1.1 and homogenous models derived from the total solar radiation in Section 5.1.2.

Center-to-limb variations of the UV and radio spectra obtained recently offer new possibilities to study the transition region. The models derived from these observations are presented in Sections 5.1.3 and 5.1.4. In Section 5.1.5 we discuss the height above the limb of the transition layer.

5.1.1. Analysis of Total Line Intensities (Pottasch, 1970)

This analysis is valid only for optically thin lines. As it makes use only of the total line intensities, it may also be applied to stellar chromospheres.

In the chromosphere and corona, the density is too small for LTE. Because of the high temperatures, the upper levels of the transitions are populated through collisions with the electrons; depopulation occurs through spontaneous radiative de-excitation. For optically thin lines, the radiative energy emitted is equal to the energy lost by the electrons for the excitation of the upper levels; thus for any line of a particular element

$$I_{\text{line}} \propto \int n_1 n_e C_{12}(T) \, dv,$$

where $I$ is the observed intensity, $n_1$ the population of the lower level, $n_e$ the electron density, $C_{12}(T)$ the rate of excitation and $dv$ the integration element. The integration is over the whole atmosphere.

Nearly all the electrons come from the ionization of hydrogen, thus $n_e \simeq n_H$, where $n_H$ is the density of hydrogen nuclei. Ionization is due to collisions with electrons and recombinations are radiative. As both reactions have the same dependance on the density, the state of ionization depends only on the temperature. Moreover, ions are almost completely in their ground state, thus for a particular element

$$n_1/n_{\text{element}} \simeq n_{\text{ion}}/n_{\text{element}} \simeq g(T)$$
and

$$I \propto \int \frac{n_{\text{ion}}}{n_{\text{element}}} \frac{n_{\text{element}}}{n_{H}} \frac{n_{H}}{n_e} n_{e}^{2} C_{12}(T) \, dv,$$

If one assumes that the abundances of the elements are constant over the whole atmosphere, one can write

$$I \propto A \int n_{e}^{2} f(T) \, dv,$$

where $A = n_{\text{element}}/n_{H}$ is the abundance relative to hydrogen and $f(T) = g(T) C_{12}(T)$. The function $f(T)$ may be computed for each ion; it is a sharply peaked function, for the various ionization stages exist only in very limited temperature ranges (e.g. House, 1964; Jordan, 1969). If one assumes that $f(T)$ is constant between $T_1$ and $T_2$ and zero outside

$$I \propto A \int_{v(T_1)}^{v(T_2)} n_{e}^{2} \, dv.$$ 

Thus, for each ion, one gets a quantity depending only on the abundance of the element and on the structure of the atmosphere. These two quantities may be separated in the following way. For each element the observed line intensities of the various ionization stages are drawn as function of the temperature (a mean value of $T_1$ and $T_2$ is attached to each line). The curves thus obtained are similar but shifted. As the integrals

$$\int_{v(T_1)}^{v(T_2)} n_{e}^{2} \, dv$$

depend only on the structure of the atmosphere, the differences between the curves can only be explained in terms of a difference in the values of $A$, namely in the abundances. The best defined curve happens to be that of silicon, since many silicon lines are observed. The silicon curve is chosen as a reference curve all the abundances being then determined relative to silicon. The fact that the curves corresponding to the various elements may be superposed by a convenient choice of the abundances shows that the assumption of constant abundances is not unreasonable. The validity of this assumption has been questioned from a theoretical point of view. Some physical processes, such as thermal diffusion, tend to produce a variation in the abundances (Delache, 1967); others, such as turbulent diffusion, which has not yet been studied, tend on the contrary to establish constant abundances; so neither on an observational nor from a theoretical point of view, has the question been settled.

This method was used for relative abundance determinations by Pottasch (1963, 1967), Jordan (1966), Athay (1966b), Dupree and Goldberg (1967) for example. In general, the dispersion in the abundance determinations are rather large. For Fe, for instance, it attained a factor of 7. Indeed, for such an analysis to be accurate, several
conditions have to be fullfilled. A precise knowledge of oscillator forces and cross-
sections for collisional excitation and ionization of highly ionized atoms is required.
For the determination of the integrals

\[ A_{\text{element}} \int_{v(T_1)}^{v(T_2)} n_e^2 \, dv \]

many lines have to be used. And, of course, differences in the observational material
used in the various analysis react on the abundance determinations.

The above analysis is not valid for optically thick lines such as hydrogen and helium
lines. To get the abundance relative to hydrogen, other data must be used. Pottasch
(1964) and Dupree and Goldberg (1967) used a combination of UV and radio ob-
servations. The assumption of a homogeneous atmosphere is necessary for their
analysis, but the results that are obtained show that this assumption is not reason-
able. Withbroe (1970a) used coronal electron density measurements and UV limb-
brightening to construct a homogeneous model of the transition region (see Section
5.1.3); a comparison of observed UV intensities with the intensities calculated from
the model, yielded absolute abundances.

There is yet no general agreement on the abundances of the elements in the transition
region and corona and on possible variation with height.

5.1.2. Homogeneous Models from Total Line Intensities

Once the abundances relative to hydrogen have been determined (which requires the
assumption of a homogeneous atmosphere) the emission measure, that is the integral

\[ \int_{h(T_1)}^{h(T_2)} n_e^2 \, dh, \]

where \( h \) is the height in the atmosphere, is known as a function of a mean value of \( T_1 \)
and \( T_2 \). The emission measure does not carry enough information to determine the
temperature and density distributions; it shows, however, that the temperature of a
homogeneous model rises very rapidly between \( 4 \times 10^4 \) K and \( 6 \times 10^5 \) K.

Supplementary data are thus required to build models of the transition region. For
example, a knowledge of the electron density as a function of height would provide
the needed data, but at the present time the observations give insufficient accuracy
concerning this quantity. The most widely used method, therefore, is to make some
supplementary assumptions about the atmosphere. To give an example, the assump-
tions used by Burton \textit{et al.} (1971) are listed below.

The transition region is assumed to be in hydrostatic equilibrium. The justification
given for this assumption is that the chromosphere and inner corona are in hydrostatic
equilibrium. The only proof of this assertion is that observations can be reproduced
with hydrostatic models. As will be seen below, this assumption of hydrostatic equi-
librium for the transition region is questionable. The equation of hydrostatic equilibrium is then written by Burton et al.

\[
\frac{d(\log P)}{d(\log T)} = -1.7 \times 10^{-4} \frac{dh}{T \, d(\log T)},
\]

where \( P \) is the electron pressure.

The other assumptions are that for each line the electron pressure \( P \) and \( dh/d(\log T) \) be constant over the region which emits the line. With those assumptions, which are compatible with a very steep temperature gradient only, the emission measure is written

\[
\int_{h(T_1)}^{h(T_2)} n_e^2 \, dh = \int_{\log T_1}^{\log T_2} n_e^2 \frac{dh}{d(\log T)} \, d(\log T)
\]

\[
= \frac{P^2}{T_m^2} \frac{dh}{d(\log T)} \log \frac{T_2}{T_1},
\]

where \( T_m \) is a mean value of \( T_1 \) and \( T_2 \). Starting from a known pressure at an arbitrary chosen temperature, Equations (3) and (4) give the temperature and density as function of height. The zero point of the scale height is arbitrary. The variation of temperature versus height obtained by Burton et al. is drawn in Figure 3.

Fig. 3. Temperature versus height in the transition region; the origin of the abscissa is arbitrary.

--- Burton et al. (1971)

--- Lantos (1972)
Similar methods for the construction of homogeneous models have been used by Athay (1966b) and Dupree and Goldberg (1967). In all models the temperature varies from $4 \times 10^4$ K to $5 \times 10^5$ K over less than 100 km as can be seen on Figure 4. The model of Dupree and Goldberg is compatible with radio brightness temperatures at the center of the disk, but, according to Pottasch (1967), the model of Athay predicts too much radio emission.

5.1.3. **Homogeneous Models Compatible with Center-to-Limb Variations of UV Lines**

The OSO-4 satellite flown in 1967 generated spectroheliograms at any wavelength between 300 and 1400 Å. Center-to-limb curves for various resonance lines of lithium like ions ($\text{N}_\text{V}$, $\text{O}_\text{VI}$, $\text{Ne}_\text{VIII}$, $\text{Mg}_\text{X}$, $\text{Si}_{\text{XII}}$) were determined by Withbroe (1970a) from these spectroheliograms. To obtain the real center-to-limb curves of each line, the underlying continua were subtracted, taking into account their own center-to-limb variation. All the studied lines, which are formed between $2 \times 10^5$ and $2 \times 10^6$ K show limb-brightening; this is consistent with an outward temperature rise.

Assuming that the conductive flux is constant in the transition zone (see Section 5.2

![Graph](image)

**Fig. 4.** Temperature versus height in the transition region; the origin of the abscissae is arbitrary.

- Athay (1966b)
- Dupree and Goldberg (1967) and Withbroe (1970a)
for details concerning this assumption) that the corona is isothermal and that the transition layer is in hydrostatic equilibrium, Withbroe developed a model which is defined by three parameters:

(i) the electron pressure at the base of the transition zone,
(ii) a constant $C$ defined by

$$F_e = CT^{5/2} \frac{dT}{dh},$$

where $F_e$ is the conductive flux, and

(iii) the temperature $T_e$ of the isothermal corona overlying the transition region.

The temperature $T_e$, which is determined from the ratio of the line intensities above the limb, is found to be equal to $2 \times 10^6$ K. The pressure at the base of the transition region is determined from brightness measurements of the corona at $2'$ above the limb, and is found to be such that $n_e T = 7 \times 10^{14}$. Once $T_e$ has been fixed, the constant $C$ is determined from the limb-brightening curves and leads to a conductive flux $F_e = 6 \times 10^5$ erg cm$^{-2}$ s$^{-1}$. The results of Withbroe (see Figure 4) are in good agreement with Dupree and Goldberg (1967). Let us note that Withbroe's analysis relies on the assumption that the corona is spherically symmetric; no check for consistency with the radio data has been made for this model.

Another attempt to build homogeneous models from the variations of UV lines from disk to limb was made by Burton et al. (1971) on observations made by Burton et al. (1967). They confirmed a very rapid temperature rise between $4 \times 10^4$ K and $5 \times 10^5$ K. The spatial resolution of the observations was not good enough to derive a model.

As was seen in the preceding paragraphs, the UV spectrum provides invaluable data on the structure of the chromosphere and transition region, but many difficulties arise in the interpretation of the observations. An accurate knowledge of atomic constants is required; arbitrary assumptions such as hydrostatic equilibrium have to be made in order to build models. The influence of the inhomogeneities on the abundances and model determinations is difficult to evaluate though some attention has recently been given to this problem (e.g. Withbroe, 1970b, 1971). As will be apparent in the next paragraph, the radio data afford the possibility of studying the transition layer while avoiding many of these difficulties.

5.1.4. Homogeneous Models from Radio Observations

The radio emission in the wavelength range 5 to 20 cm brings information concerning the transition region or, more precisely, regarding the interspicular regions; indeed, the spicules' contribution to the radio brightness is negligible or easily taken into account (Lantos, 1972). The spectrum of the brightness temperatures at the center of the disk and the variations of the brightness from center to limb were used by Lantos, together with the hydrodynamic transport equations to build homogeneous models of the interspicular regions between $10^4$ K and $3 \times 10^5$ K.

In the equation of energy conservation, Lantos has taken into account the radiative
energy losses and the energy transferred through convection and thermal conduction. In the equations of momentum and mass conservation there appear the corresponding terms. The contribution of the sound waves to the energy and momentum transfer is neglected, as are possible magnetic effects. So little is known at the present time concerning these effects, that such simplifications are reasonable.

The Jeans approximation of the Planck function, valid at radio wavelengths, gives for the solution of the transfer equation

$$T_B(\lambda) = \int_0^{\infty} T(\tau_\lambda) \exp(-\tau_\lambda) \, d\tau_\lambda,$$

(5)

where $T_B(\lambda)$ is the brightness temperature at the wavelength $\lambda$ at the center of the disk and $\tau_\lambda$ the optical depth. The inversion of this equation leads to a relation of the form

$$n_e^2 = f(T, \, dT/dh).$$

(6)

The simultaneous resolution of Equation (6) and of the mass and energy conservation equations leads to models which depend upon two parameters, the convective velocity (or expansion) and the density at an arbitrarily given temperature. The center-to-limb variations of the brightness temperature at a given wavelength and the equation of momentum conservation allow the determination of these two parameters. The reference point has an arbitrary altitude, therefore only relative heights are derived.

The homogeneous model of the interspicular regions thus obtained presents two main features. First, the model presents a large temperature gradient (see Figure 3) in agreement with UV observations. Second, a non-zero expansion velocity is necessary to avoid incompatibilities between the equations. The expansion velocity found by Lantos is larger than 10 km s$^{-1}$. Thus the mass flux is greater than the flux of the solar wind; this raises the equation of how the matter flows down. If this expansion velocity really exists, the transition region is not in hydrostatic equilibrium and the ionization equilibrium of the ions has to be recomputed.

The greatest uncertainty in this interpretation of the radio data lies in the inversion of Equation (5); indeed the results depend on the assumed polynomial expansion chosen for $T_B(\lambda)$ (Delache, 1971).

5.1.5. Location of the Transition Layer

The models of the chromosphere (see Section 4) cover a 2000 km thick layer, overlying the photosphere, where the temperature varies from approximately 4200 K to 9000 K. The models of the transition region derived from UV and centimetric emission cover the temperature range from $10^4$ K to $10^6$ K, but in none of the models, is the altitude scale related to an absolute height above the solar limb. The limb-brightening variations of the UV lines should in principle give the location above the limb of the transition region; the accuracy of the intensity measurements made aboard OSO-4 was within factor 2 to 3, and hence insufficient to provide this information.
Therefore the models of the chromosphere and of the transition region do not overlap and the extension and physical properties of the layers located between the top of the chromosphere and the base of the transition region are very imperfectly known. In this region, denoted in the following as the upper chromosphere, where the temperature is of the order of $10^4$ K and where hydrogen is almost completely ionized (Noyes and Kalkofen, 1970), there are formed optically thick UV lines, such as the Lyman series of hydrogen and lines of singly charged ions. Pottasch's analysis is not valid for these lines. The derivation of physical parameters from these lines requires a complete treatment of radiative transfer including non-LTE effects. A preliminary analysis on the Ly-$\alpha$ and Ly-$\beta$ lines made by Cuny (1968) has shown that a temperature plateau in the upper chromosphere is necessary to explain the observed central reversal of Ly-$\beta$. A similar result has been obtained from the OSO-6 data (Thomas and Maran, 1971). This temperature plateau is not necessarily a real feature of the solar atmosphere and might be due to the neglected inhomogeneities. The high resolution profiles of Ly-$\alpha$ and Ly-$\beta$ that will be obtained with the satellite OSO-EYE will help to clarify this point.

The center-to-limb variations of the millimetric solar emission should provide useful information on the structure of the upper chromosphere. In fact, difficulties arise in the interpretation of these data (Simon and Zirin, 1969), since the spicular and non-spicular contributions cannot easily be separated.

At the present time the abrupt rise of temperature may safely be placed between 2000 and 4000 km above the limb. Improved resolution of the observations is needed to make a more accurate determination.

5.2. ENERGETIC AND HYDRODYNAMIC EQUILIBRIUM OF THE TRANSITION REGION

In Section 5.2.1 the data provided by the UV and radio spectrum on the energetic and hydrodynamic equilibrium of the transition layer are discussed. In Section 5.2.2 a theoretical work by Delache (1969) on the dissipation of waves is summarized.

5.2.1. Observational Results

(a) Velocity field. The most direct source of information on velocity fields is provided by line profiles. Among the UV lines formed at temperatures greater than $10^4$ K, only the profiles of Ly-$\alpha$, Ly-$\beta$ and CII resonance doublet are available; the spatial resolution of these profiles is low. The profiles of Ly-$\alpha$ and Ly-$\beta$ could correctly be reproduced by Cuny (1968) with a microturbulence of 10 km s$^{-1}$, but more profiles are required to confirm this result. The width of the CII lines can only be explained by broadening through random motions of large bodies of gas (Berger et al., 1970). The intensities of the other UV lines formed in the transition region are so low that the measure of their profiles is a difficult task.

The centimetric emission gives indirect evidence for an expansion velocity greater than 10 km s$^{-1}$ in the spicular regions. It would be very interesting to find a direct proof of this expansion.

To increase significantly our knowledge of the velocity field in the transition region,
a very high spatial resolution (greater than 1”) is required in order to separate the spicular from the interspicular emission. Let us note that the spicules have ascending velocities of 10 km s\(^{-1}\) to 30 km s\(^{-1}\).

(b) Energy balance. In the chromosphere, the dominant energy fluxes are the radiative energy flux and the mechanical flux. In the energy balance of the transition region the conductive and convective flux play a part too.

The radiative energy losses deduced from UV observations are of the order of \(3 \times 10^5\) erg cm\(^{-2}\) s\(^{-1}\), of which the main part, that is \(2.5 \times 10^5\) is emitted in Ly-\(\alpha\) (Friedman, 1963).

The conductive energy flux can be derived from UV observations. Athay (1966b) showed that the emission measures are consistent with a temperature structure obeying \(T^{-5/2}\) \(dT/dh\) = constant, between \(10^5\) K and \(7 \times 10^5\) K. As the coefficient of thermal conductivity of a totality ionized gas is proportional to \(T^{5/2}\), Athay's conclusion is that the conductive flux is constant in this temperature range and equal to \(3 \times 10^5\) erg cm\(^{-2}\) s\(^{-1}\). Athay's analysis depends on the assumption that the pressure is constant in the transition layer and that \(dT/dh\) is constant over any line emitting region, both of which assumptions require a very steep temperature rise. Through the same kind of analysis as Athay, Dupree and Goldberg (1967) found a constant conductive flux equal to \(6 \times 10^5\) erg cm\(^{-2}\) s\(^{-1}\) in the temperature range \(10^5\) K to \(10^6\) K. In the homogeneous model of the transition region constructed by Withbroe (1970a) to reproduce the UV limb-brightening, the conductive flux is constant and equal to \(6 \times 10^5\) erg cm\(^{-2}\) s\(^{-1}\). Thus all UV line analyses lead to a conductive flux of the same order of magnitude as the radiative energy losses of the upper chromosphere.

The convective energy flux appears only in Lantos’ analysis of centimetric emission where it represents a non-negligible part in the energy balance.

The observations of the transition layer still offer no possibility of evaluating the mechanical flux carried by the waves. However, one knows from the measurements of coronal radiative losses and from evaluations of the energy required to support the solar wind, that the flux of mechanical energy at the base of the corona must be of the order of \(10^5\) erg cm\(^{-2}\) s\(^{-1}\) (Kuperus, 1969).

Though it is reasonable to conclude that the thermal energy conducted inward from the corona to the chromosphere plays a major role in the physical properties of the transition region, the energetics of this region are still poorly known.

5.2.2. Theoretical Analysis

Various authors (see Kuperus, 1969) have built theoretically homogeneous models of the chromosphere and corona. The transformation of mechanical energy into thermal energy through shock waves, the radiative energy losses and the energy transfer through conduction and convection are taken into account. However, many unjustified assumptions have to be made in order that the problem be tractable. The results, therefore, are not very convincing. Moreover, they do not agree well with the observations.

A less ambitious, but very instructive, study of the validity of the assumption of
hydrostatic equilibrium in the transition layer was made by Delache (1969). The author considers a completely ionized plasma characterized by its temperature and gaseous pressure. Heat deposition is assumed to take place through a propagating wave, which is described by its radiation pressure and its velocity. Thermal conductivity and radiative energy losses are taken into account. To avoid the choice of a particular wave, the acoustic pressure \( P_w \), the velocity \( c \) and the dissipated energy are related by the usual relation

\[
d \{ P_w (h) c (h) \}/dh = - s (h),
\]

where \( s(h) \) is the energy dissipated in the wave and \( h \) the altitude. For the sake of simplicity \( c(h) \) is assumed to be constant and \( s(h) \) constant or a linear function of \( h \) in the transition region; outside the transition zone, there is no source nor sink of energy.

The resolution of Equation (7) together with the equation of state and the conservation equations of momentum and energy leads to a determination of the temperature and density distributions. The gaseous pressure is found to increase significantly from the base to the top of transition zone because of the transfer of momentum between the wave and the gas. This result shows that the assumption of hydrostatic equilibrium in the transition region is questionable. For the temperature distribution Delache finds that, except near the top of the transition region, the temperature gradient does not depend on the assumed dissipation of mechanical energy; it is proportional to \( T^{-5/2} \) as if the conductive flux were constant. This shows that a knowledge of the temperature gradient cannot lead to a determination of the mechanical energy dissipation.

It has been shown in Section 5, that our knowledge of the transition layer and upper chromosphere is not as good as that of the chromosphere. The main reason, of course, is that these layers emit 10 times less energy than the chromosphere. New high spatial resolution observations, as will be obtained from future satellites, will prove extremely useful for our understanding of these layers. A systematic study of the total intensity of optically thick UV lines would be very fruitful, too, and would not require such expensive technology.

6. Conclusion

Thanks to the development of IR, UV and radio observations, and thanks to the increase in the spatial and spectral resolution of the observations, our description of the chromosphere has made considerable progress in the last 10 years. The temperature and density distributions in the chromosphere are fairly well known and in the near future the upper chromosphere and transition region will be correctly described.

However, our understanding of the mechanism responsible for the existence and properties of the chromosphere and corona has not been fundamentally improved. It appears that a determination of the mechanical energy dissipation will come only through direct measurements of velocity and magnetic fields. These parameters are more difficult to determine than the temperature and density for they require very accurate techniques. The presence of inhomogeneities, closely related to the inhomogeneous structure of the magnetic field, make the problem still more intricate. New
observations of high spatial resolution (<0.2") seen necessary before the temperature of the chromosphere and corona are really explained (Kiepenheuer, 1971).

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