Chapter 1

INTRODUCTION

1.1 Introduction to the solar corona

The solar corona is the region which begins at an altitude of ~2000 km above the solar photosphere, and then extends out to many solar radii. This region becomes visible to the naked eye during a solar eclipse as seen in figure (**1.1**).

Figure (1.1). The solar corona as seen during the solar eclipse of February 26, 1998. Picture: NASA eclipse library

Accounts of solar eclipses date back to at least the fourteenth century BC. However it is not clear that the solar corona was ever mentioned. The first clear mention of the corona was from Kepler in his *Astronomiae pars Optica*, although he seemed to have attributed the corona to be a property of the moon. With the advent of photographic methods and spectroscopy in the nineteenth century experimental studies were initiated on the nature of the sun during eclipses. By then eclipse path predictions were also possible. Edmond Halley was the first to predict the path of an eclipse in 1715 using the Newton's law of gravity.

At the 1860 solar eclipse, comparisons of photographs by De la Rue and Secchi from different locations confirmed that prominences were solar in nature. Prominences are cloud-like features with a reddish color, often seen during solar eclipses off the sun's limb. This confirmation also added weight to the fact the corona too was solar in nature.

Further discoveries followed with each subsequent solar eclipse. In the solar eclipse of 1871, Janssen discovered and identified absorption features in the solar spectrum. In 1814, Fraunhofer had been the first to label certain absorption features in the spectrum of the sun, and Janssen was able to identify some of Fraunhofer's lines in the coronal spectrum. Most of the Fraunhofer features in the solar spectrum are atomic lines that are formed in the solar photosphere, although some are caused by molecules in the earth's atmosphere. Janssen's discovery of the solar absorption lines in the coronal spectrum confirmed that the corona was also solar in nature.

At the same eclipse of 1871, through spectroscopic observations Lockyer showed that the coronal gases extended ~500,000 km above the solar limb. This observation provided the first clue that the corona was also very hot. Later observations have showed that the corona extended to over thirty solar radii above the solar limb. Because of this great spatial extent, it can be inferred that the coronal gas is very hot. As to how hot the gas actually is, we look to the coronal spectrum for an answer: this is a major aim of the present work. However it was already known in 1957 (from work of E.N. Parker) that the coronal temperature is so high that it has important dynamical effects. To see this, we note that the extended nature of the solar corona is a result of a competition between gravity and gas pressure: the radial gradient of gas pressure tends to force material away from the sun, whereas gravity tends to hold the material back. In the inner corona, within one or two solar radii of the surface, these opposing tendencies balance each other almost exactly. However, beyond a few solar radii, Parker (1965) showed that gravity loses the competition, and the corona accelerates away from the sun to form the solar wind. Spacecraft measurements of the wind flux show that if the corona were not continually re-supplied with material, the wind would empty the corona in a time-scale of a few days.

With the dawn of the spectroscopic age it was now possible to identify the elements present in hot gases through spectrum analyses. Hot gases emit photons at wavelengths, which are precisely characteristic of the elements present in the gases. However the coronal spectrum posed a great problem because most of the wavelengths could not be identified with known elements on Earth. Edlen (1937) identified some of the emission lines as originating in **forbidden transitions** of the element iron in highly stripped stages of ionization, FeX and FeXIV. Forbidden transitions are those which are not allowed by electric dipole selection rules: the transitions must be induced by magnetic dipole or electric quadrupole interactions. For iron to be in the ionization stages FeX or FeXIV requires that the electron temperature in the coronal gas be at least 1.0 MK. For the forbidden transitions to occur, the ambient gas must have densities that are lower than a certain value. The upper limit of the density depends on the details of the transition. Golub and Pasachoff (1997) give a very detailed account of the history that led to the discovery of the solar corona and its properties.

Figure (**1.1**) shows the solar corona during an eclipse. It is also evident from this picture that the coronal intensity peaks around the solar equator and gradually diminishes as it approaches the solar poles. Due to the reduced coronal intensity around the solar poles, these regions are called **coronal holes**. Although the coronal light intensity is small in these holes compared to the equatorial region, the holes are also the region for the **fast solar wind**. Figure (**1.1**) also shows solar plumes that radiate out from the north pole and south pole of the sun tracing its magnetic field.

In the solar wind, material consisting of protons, electrons and a mixture of heavy elements flow out from the sun into interplanetary space. This ionized flow is so highly conducting that it drags along the magnetic field from the sun. The spatial extent of the solar wind is unknown: eventually, the wind runs into the interstellar medium and is terminated at a shock. Spacecraft has not yet located the termination shock of the solar wind, but estimates put it at a distance of order 100 AU from the sun.

In essence the solar corona is an extremely hot (> million Kelvin), highly ionized gas surrounding the sun. This is visible only during a total solar eclipse as a white light region extending to several solar radii, displaying streamers, plumes and loops. Its appearance changes during the solar cycle. At solar maximum it consists of many structures around the disk, but at the solar minimum it is dominated by large coronal holes at each pole and sheet-like structure near the equator.

The brightness of the solar corona surrounding the solar disk is composed of three main components, namely;

a. **K- (*Kontinuierlich*) corona:** The K-corona is due to the scattering of the photospheric light incident on the rapidly moving free electrons in the solar corona. The free electrons are a result of the electrons stripped off the coronal gas elements due to extremely hot temperature in the corona. Due to the high thermal velocity of these electrons they tend to broaden the photospheric spectrum, which consists of narrow lines, giving rise to a continuous spectrum. This scattering process is commonly known as Thomson scattering.

b. **E- (*Emission*) corona:** The E-corona is due to the emission from coronal ions, especially in highly ionized states. These emission lines are in many cases forbidden transitions resulting from atomic transitions from the highly ionized ions in the corona. Although these transitions are difficult to replicate in laboratories, however, they are not over ruled by selection rules for atomic transitions.

c. **F- (*Fraunhofer*) corona:** The F-corona is due to photospheric light being scattered by dust particles in interplanetary space. Dust particles which are refractory enough to be able to survive at radial distances of a few solar radii also emit radiation in the near and mid-infrared wavelength regimes. The F-corona dominates the visible coronal brightness from about three solar radii distance from the center of the sun and has an increasing contribution to the total coronal brightness at longer wavelength.

Figure (**1.2**) shows the radial brightness distribution of the F-corona, the K-corona and the E-corona. From figure (**1.2**) it is evident that the K-corona dominates in the coronal brightness to a height of ~ 2.0 solar radii above the limb and the F-corona begins to dominate beyond that height.

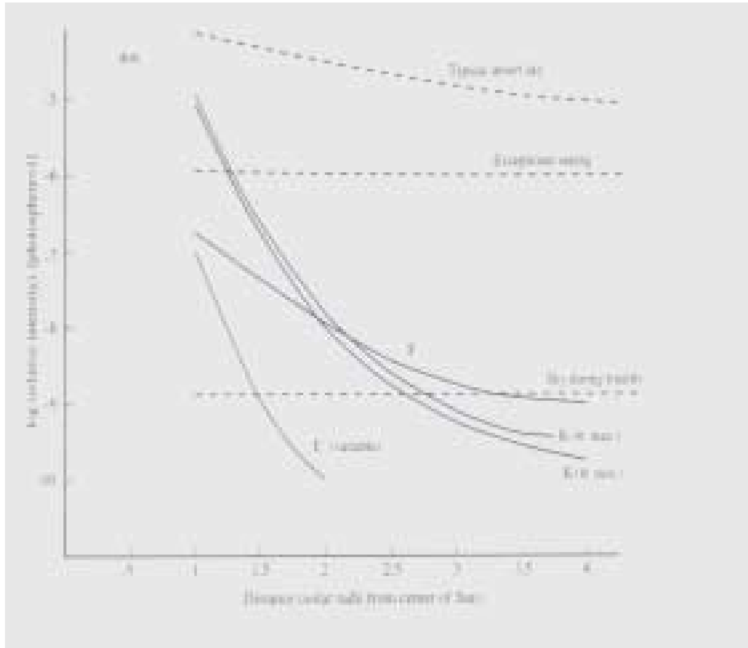

Figure (1.2). This plot shows the variation of the E, K and F components of the solar coronal brightness with height above the solar limb.

As for the reason for the existence of the solar corona there does not exist a firm answer. Observations of other stars have revealed that many stars have coronae and many others do not. Empirically, the solar corona is densest and hottest in regions of closed magnetic fields (“loops”), and is coolest and fastest moving in regions of open fields (“coronal holes”). These results indicate that magnetic fields play an important role in the coronal heating process.

Figure (**1.3**) shows a cross section of the sun with some of its prominent features and the temperature scales between the core, photosphere and the corona. The **core** is the innermost part of the sun where energy is generated by nuclear reactions and its temperature is ~15,000,000 K. The **photosphere** is the visible surface of the sun and also the layer which emits the light the human eye sees. Its temperature is ~ 6,000 K. The **corona** is the outer most layer in the solar atmosphere and consists of highly rarefied gas. This layer begins at altitudes of about ~ 2000 km above the photosphere and its temperature is ~1,000,000 K. The corona is visible to the naked eye only during a solar eclipse. The region between the photosphere and the corona is the **chromosphere**. The region demarcating the chromosphere and the corona is the **transition region** that features a sharp temperature rise from ~10^4 K to ~10^6 K within a range of ~ 500 km. The coronal **streamers** are large-scale magnetic structures in the corona.

From the point of view of physics, the most interesting aspect of the corona is the huge increase in temperature that occurs as we move from the photosphere (~ 6000 K) up into the corona (~1.0 MK). Now, coronal material must be replenished every few days (due to the solar wind): the only source of this material is the photospheric gas. Therefore, the creation of the corona is a continual process that involves heating the 6000 K gas to several million K. It is impossible for a thermal process, i.e. one based on solely on exchange of internal energy, to do this. Therefore, a variety of non-thermal processes have been considered in the literature (Narain and Ulmschneider, 1996). The energy budget of the corona is not very demanding. Of the total energy flow through the solar surface, one part in 10^5 suffices to heat the corona (Tsuneta, 1996).

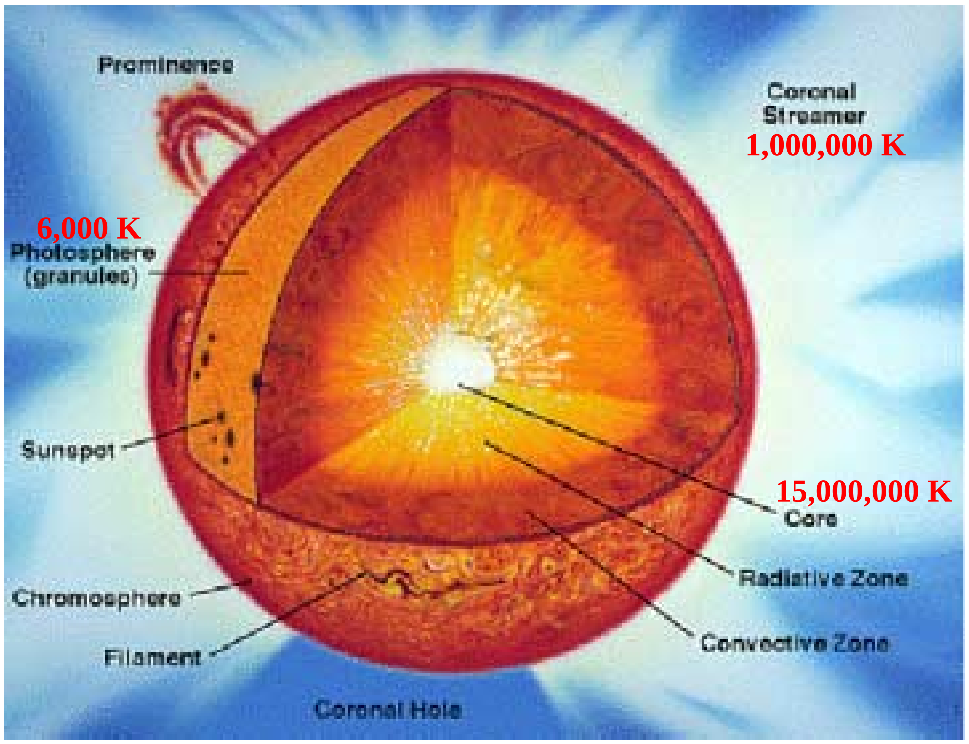

Figure (1.3). A cross section of the sun to highlight the prominent parts of it and the temperature scales between the core, photosphere and the corona.
Picture: SOHO pictures library

The most likely source of non-thermal energy input to the solar corona is associated with disturbances generated in the solar convective layers, as shown in figure (**1.3**). These disturbances in the solar interior are manifested as supergranulations, granulations, magnetic flux tubes, and wave motions on the solar photosphere and acoustic energy above the photosphere. Now the question is to determine, which of these energy forms can propagate upwards and then dissipate in the solar corona. However this process is further compounded by the need for the widely differing power requirements for the different coronal structures. The following are some of the popular method of non-thermal energy deposition in the solar corona.

The most favored candidates are the Ohmic dissipation of the coronal electric currents and the viscous dissipation of magnetohydrodynamic (MHD) waves and turbulence (Narain and Ulmschneider 1990). The coronal electric currents are believed to be generated by the twisting of the magnetic flux tubes and, depending on the resistivity of the coronal plasma, dissipate through Joule heating in the coronal plasma. The MHD disturbances are believed to propagate along the magnetic fields protruding from the solar surface into the solar corona and dissipate their energy. These MHD waves can be visualized as a combination of the longitudinal sound waves and the transverse Alfven waves. Alfven waves are waves generated by the disturbance of the magnetic field lines and the sound waves could be produced by pressure perturbation. See Zirker (1993) for a survey of coronal heating theories, and conditions a successful theory must satisfy.

The sun is also occasionally the site of transient releases of energy in the form of flares. These events emit high-energy particles and shock waves that may create aurorae on the earth. Although the reason for the solar wind is well understood to be driven by gas pressure due to the high temperature of the gas, however, the driving mechanism that causes the solar wind flow velocity to change from subsonic velocities to supersonic velocities during its flow in the solar corona is yet to be established. The first analytical treatment of the solar wind model is due to Parker (1965). It was based on a thermally driven wind model. However the large velocities predicted at 1.0 AU do not seem to match the physical parameters at the coronal base. Here again the treatment of the solar wind as a purely thermally driven wind cannot produce the experimentally observed high velocities for the solar wind and some form of other non-thermal energy deposition mechanisms are needed to describe its transformation into supersonic velocities. Solar Wind Nine (1998) and the references therein give a summary of the present situation.

Since the corona itself does not contain any heat sources that could possibly heat the corona to above million degrees or drive the solar wind flow to supersonic velocities the possibilities need to be linked to various phenomena on the solar surface itself. And, as a natural consequence to link various solar surface phenomena with the properties of the solar corona it is important to measure the coronal properties as accurately as possible. In this regard two of the most important physical parameters on the solar corona are the temperature and the solar wind velocity at different latitudes and radii in the solar corona. Therefore measurement of the coronal temperature and the solar wind velocity, simultaneously and globally on the solar corona, would help in gaining further insight into the state of the matter and its dynamics in the solar corona and its association with the solar surface phenomena.

The focus of this research is on the measurement of the coronal temperature and the solar wind velocity, simultaneously and globally, on the solar corona from the measurement of a single observable quantity. In section (**1.2**) some of the methods used by other researchers for the determination of the coronal temperature and the solar wind velocity are discussed.

1.2 Other methods to measure the solar wind velocity and the coronal temperature

The following are some of the techniques adopted in the measurement of the coronal temperature and the solar wind velocity.

(a) Measurements of the radial intensity distribution of the white light corona (Saito 1965, Koutchmy 1971, Guhathakurta et al. 1992) allow one to derive the scale-height of electron density. This can be converted to an equivalent electron temperature if one assumes hydrostatic equilibrium.

(b) Emission line intensities of various lines have been used to determine the temperature of coronal electrons (Gabriel 1971, Nakada et al. 1975, Tsubaki 1975, Guhathakurta et al. 1992). These emission line theories rely on the ionization balances, various excitation mechanisms and atomic constants. Some of these quantities are subject to major changes owing to new discoveries in atomic physics. Ionization balance occurs when the rate at which an ion loses electrons per second (as a result of collisional ionization by free electrons) is balanced by the rate at which the ion gains electrons per second (as a result of recombination). The excitation mechanism that is assumed to be predominant is collisional excitation. This model is a simple two-level atom consisting of the ground level *m* and an excited state *n*. The population of the upper state is set by a balance between collisional excitation from *m* to *n* due to electron-atom collisions, and by spontaneous radiative decay from *n* to *m* via an allowed atomic transition. For the coronal conditions the induced emission from *n* to *m*, the photoexcitation from *m* to *n* and the collisional de-excitation from impacts with electrons are considered negligible. The atomic constants that are inherent in this model are the Einstein coefficients for spontaneous emission, statistical weights of the various atomic levels, collisional excitation coefficient and the collision strength factor. The latter is a slowly varying function of the incident electron energy and involves difficult quantum mechanical calculations. In this regard we have preliminary evidence to suggest that Thomson scattering could be partly responsible for the emission lines in the EUV region using the Thomson scattering code developed as part of this dissertation work.

(c) Hara et al. (1994) used the ratio of the soft X-ray intensities in different energy bands to determine the coronal ‘color temperature’. They used the X-ray analysis filters onboard Yohkoh to formulate a filter ratio method to determine the temperature of the quiet corona and have reported a value of 2.7 MK (Hara et al. 1992). Here photon energy ratios are determined for different filters. These are again functions of the wavelength and temperature dependent emissivities and the response characteristics of the filters. Hara et al. (1994) and Withbroe (1988) contains reviews of coronal temperature measurements by various other groups.

(d) Withbroe et al. (1985) measured the temperature of coronal ions using the Doppler widths of emission lines. The Doppler width measures the wavelength shift due to motion of the gas responsible for the observed emission line, which could be determined by comparison with a calibration lamp for the same emission line. Here the motion is attributed to the kinetic temperature, which includes both thermal and non-thermal motions. However to isolate the thermal effect on the motion the non-thermal effects on the motion, such as motions due to turbulence and waves, have to be eliminated.

(e) Radio observational techniques have also been used to infer the temperature of coronal electrons (Zirin 1966). This method involves the radio observation of the quiet sun in determining the coronal temperature. From each level of the solar atmosphere only emission at frequencies higher than the plasma frequency may escape. Therefore, by tuning on to different frequencies the radio emission down to the region where the plasma frequency matches to the tuned frequency could be measured. This will include levels on the solar atmosphere with different temperatures too. If these temperatures are irregular the hotter regions are heavily weighted. For low optical depth the radio emission intensity is a product of the source function and the optical depth where optical depth is a measure of how far the radiation will travel before being absorbed or scattered, which is also a function of the frequency. The radiation in the radio region is assumed to be due to free-free emission neglecting other non-thermal processes where the free-free emission is due to deceleration of an unbound electron during its passage close to an ionized atom. In addition the Planck function is assumed to represent the source function. Here again these are beset with uncertainties associated with the optical depth effects, refraction and the emission mechanisms. Furthermore, the presence of magnetic fields could produce other cut-off-frequencies associated with gyroresonance, which complicates the propagation. This reversal of the above procedure is also possible where radar signals are directed at the corona and are bounced off the layer where the plasma frequency is greater than the frequency of the incoming signal.

(f) Doppler dimming technique has been used to measure solar wind velocity. In this technique (Strachan et al. 1993) the aim is to measure the intensity of a chromospheric line which has been resonantly scattered off coronal material. If the coronal material were to be at rest relative to the chromosphere, then the resonant scattering would be optimized, and the intensity of the scattered line would be maximized. However in the event that the coronal material has a non-zero velocity relative to the chromosphere, there is more or less significant reduction in the overlap of the line profiles in the chromosphere and corona. As a result of this mis-match between chromospheric and coronal line profiles, the efficiency of the resonant scattering is reduced. The scattered line becomes dimmer, the larger the velocity difference between corona and chromosphere. Quantitative interpretation of an observed dimming in terms of wind velocity is subject to a number of uncertainties: among these are the emission mechanism of the line, and the associated atomic constants.

(g) Solar wind velocities have also been measured using remote sensing techniques. Here a known radio signal is made to propagate through the solar corona and through the detection of fluctuations in various properties of the radio signal is utilized to determine the motions of density inhomogeneities in the solar corona. For these remote sensing techniques, a variety of methods are available, depending on whether the distant source is a natural source (broadband) or artificial (narrow-band). The fluctuations which the solar corona creates in intensity or in phase or in frequency or in line-width contain information on coronal density inhomogeneities on a broad variety of length scales, from a few kilometers up to tens of thousands of kilometers (Yakovlev and Mullan 1996). Observations can also be made from widely spaced ground stations or from single stations (Coles et al. 1986, Watanabe & Schwenn 1989, Efimov 1994). Here the results are acknowledged to be substantially lower than the Doppler dimming techniques (Strachan et al. 1993). These too could be beset with problems owing to solar radio interference, carrier signal broadening and the sensitivity to variations in the density of the ionosphere. In addition they also detect the motions of density inhomogeneities that include not only the bulk outflow of the solar wind, but may also include wave motions if the latter have a compressive component. A review on this subject is found in Bird (1982).

In all of the techniques summarized above, the aim is to measure the temperature of the coronal electrons or ions, or the solar wind speed. The techniques depend in different ways on a number of parameters, each of which is subject to uncertainty. However the theoretical idea utilized in this dissertation work is based on an well-understood simple physical principle, which is based on Thomson scattering of the photospheric radiation by the coronal free electrons, which is responsible for the formation of the K-corona. Here the quantity measured, which is the intensity, is dispersed over a wavelength region. The scattered intensity over this wavelength region is dependent on both the coronal temperature and the solar wind velocity with certain regions in the wavelength spread being sensitive to either the temperature or the wind velocity. This feature of selective sensitivity is exploited to formulate temperature and velocity diagnostics. In chapter-**2** the physical overview for the formation of the K-corona is explained, together with a methodology to derive the thermal electron temperature and the solar wind velocity from the K-coronal spectrum.