HIGH RESOLUTION INTERFEROMETRIC STUDIES OF THE
SOLAR CORONA
CHAPTER I

INTRODUCTION

1.1 CORONAL SCIENCE: STATUS AND PROSPECTS

The science of the mysterious, tenuous, outer envelope of the solar atmosphere called the Corona has come a long way since the days of Plutarch, who two thousand years ago noticed its presence during a total eclipse as "some light that does not permit total darkness".

The recognition of the high temperature of the corona following the identification of several lines of highly ionised atoms in the coronal spectrum by Edlen in 1942 revitalised Solar physics. It posed new and fundamental problems which in turn stimulated the development of theoretical and observational techniques needed for their solution.

The most important unsolved mystery surrounding the quiet Sun is still the explanation of how the temperature increases outward from 4500 K just above the photosphere to over $2 \times 10^6$ K in the corona without violating the first law of thermodynamics. If today we are any closer to solving this puzzle than ever before, it is largely because we have access to
measurements made over 36 octaves of the solar spectrum, from gamma rays to long radio waves - measurements that are being made with solar instruments on the ground, in balloons, airplanes and rockets, and in orbiting solar observatories. Extended observations made at high spatial and spectral resolutions in hitherto in-accessible parts of the spectrum like EUV and X rays from satellite platforms like Orbiting Solar Observatories (OSO) and Skylab have radically changed our views of the corona. These studies have emphasised the role of magnetic fields in defining coronal structures like active region arches and loops while discounting the old concept of a homogeneous corona.

However much remains to be done. A complete quantitative analysis of the state of the solar plasma and of energy transport mechanisms responsible for the observed dynamic phenomena has not yet proved possible. The reason is that observational data has been inadequate for diagnostic purposes because of incomplete spectral coverage, absence of simultaneous high spatial and spectral resolution or lack of accurate photometric calibration. Consequently our knowledge of physical properties of the corona does not yet permit us to
discriminate completely among existing theories concerning heating and energy balance of the solar atmosphere as well as sources of energy needed to drive the solar wind.

The 1980s provide exciting possibilities for resolving many of these outstanding problems through the Space-lab flights of sophisticated instruments like NASA's Solar Optical Telescope (SOT) and ESA's Grazing Incidence Solar Telescope (GRIST). The last few years have seen the identification of a new frontier - the study of stellar coronae. This subject is an excellent example of a field in which observations have generally led and dictated theoretical developments. The recent measurements from International Ultra Violet Explorer (IUE) and Einstein Observatory satellites have precipitated a major change in our understanding of stellar coronae. This infant field is certain to mature during this decade and provide refreshing inputs for better understanding of the outer envelope of our own average star.

1.2 THE SOLAR CORONA – A HISTORICAL INTRODUCTION

1.2.1 The early years:

The first observations of the Solar corona are probably lost to antiquity. However little was known
about the corona till about the middle of the 19th Century. The eclipse of 1842 whose path of totality crossed Southern Europe was viewed and discussed by a wide body of scientists and marked the real beginning of coronal science. By 1875 eight eclipses had led scientific expeditions to various parts of North and South America, Europe and Asia. Many sketches of coronal structure had been made. Photography had been tried out. The green line had been isolated by Young and Harkness in 1869 with the use of a spectroscope. The tenuous nature of the atmosphere was noted from observations of sun grazing comets which did not suffer any appreciable drag in their orbits.

By 1900 several good photographs of the corona were available which enabled Young (1896) to deduce the Sunspot maximum and minimum structures. It was recognised by this time that brightness of the corona was more or less comparable with that of the full moon and varied considerably with sunspot cycle. Coronal polarisation was also known and recognised as evidence of reflection of photospheric light in the corona by small particles (Schuster, 1879).

A number of characteristics of the green line had been investigated in the hope of determining the nature
of the elusive element "Coronium" to which it was attributed. It was noted that the green line extended much further beyond the limb than Hα. It was also known that the green line emission was much stronger at the time of sun spot maximum than at minimum and that its distribution varied over the limb in a manner different from that of white light.

The early years of this century saw the perfection of optical techniques for coronal studies. Large cameras with focal lengths of a hundred feet and more were put to use to obtain several outstanding eclipse photographs. Many improvements in eclipse spectroscopy, especially slitless spectrophotography led to improved spectrograms and a clear distinction of coronal lines from prominence and chromospheric lines. 18 coronal lines were isolated. By 1930 the continuum corona was distinguished from Fraunhofer corona, the latter being attributed to scattering by interplanetary dust along or close to the line of sight.

1.2:2 1930-1942
1.2:2.1 Lyot's contributions

The twelve years 1930-1942 saw an explosive growth of coronal science. This activity was triggered by two
important developments, both of which can be traced to the genius of Bernard Lyot. These developments were

a) The perfection of a working coronagraph

b) The recognition of a corona much hotter than the underlying photosphere.

The Coronagraph permitted astronomers to view the corona for the first time outside of total eclipses though over a much smaller extent. Lyot further demonstrated that the instrument could be used either in narrow spectral intervals (using the special filters he had himself devised) or with polarimetric equipment for a much more effective discrimination of the white light corona.

The first hint about the high temperature of the corona came in 1931 when Grotrian while analysing the spectrograms taken during the 1929 eclipse noted that in the spectrum of the inner corona, the H and K lines were replaced by shallow depressions in the continuum extending from below 3900 Å to above 4100 Å. He also pointed out that the broadening indicated a velocity in coronal electrons of $7.5 \times 10^8$ cm sec$^{-1}$ compared to the average thermal velocity of electrons at 6000K of $5 \times 10^7$ cm sec$^{-1}$. Then Coronal temperature $T_c \simeq 6000 \left(\frac{7.5 \times 10^8}{5 \times 10^7}\right)^2 \simeq 1.3 \times 10^6$K.
In 1932 Lyot made a decisive measurement which was to pave the way for the acceptance of a million degree corona. Using a high dispersion spectrograph he measured the width of the green coronal line and obtained a value of 0.9 Å. A few years later he suggested that the broadening was thermal. He was however unable to compute the temperature as the green line was yet to be identified as an emission from highly ionised iron (Fe XIV) atoms.

1.2.2.2 Identification of Coronal emission lines.

The identification of coronal line emissions came as the culmination of a series of events which began with the puzzles present in the spectrum of Nova Pictoris 1925. This spectra had attracted a lot of attention in the thirties as it contained a number of lines which defied identification. Finally in 1935 Bowen of California Institute of Technology identified some of the lines as Forbidden transitions of Fe VI. Later with Edlen in 1939 he identified the remaining lines as transitions in Fe VII. Meanwhile Adams and Jcy discovered unambiguously five coronal lines in the spectrum of Nova RS Ophiuchi during its 1933 brightening. These two discoveries suggested to Grotrian that other coronal lines might also be
forbidden transitions of highly ionised atoms. Edlen, meanwhile had studied the spectra of ions in the iso-electronic sequence beginning with $\text{C}^8$ I upto Co XI and had identified some levels and terms in Fe X. Grotrian noticed that one of the transitions in Fe X corresponded closely to the red coronal line ($\lambda 6374 \AA$) and the first identification was made. Following Grotrian's lead, Edlen studied other coronal lines in detail and by 1942 had identified nineteen of them as forbidden transitions in highly ionised atoms, mainly of Iron, Nickel and Calcium.

1.2.3 High temperature of the Corona: Acceptance and Implications.

The general acceptance of a million degree corona by 1945 following the identification of highly ionised atoms by their emission lines changed the corona from one of the most mysterious to one of the better understood of all astronomical objects. The density gradients in the corona could now be maintained in hydrostatic equilibrium. At the high temperature of $(1-2) \times 10^6$K the heavy atoms could be ionised to produce the observed emission lines; the complete ionisation of Hydrogen and Helium provided the electrons to scatter the photospheric light and also accounted for the absence of H, He lines. The
concept of high coronal temperature was also in accordance with observed brightness of the sun at metre wavelengths, the absence of Fraunhofer lines in the scattered light spectrum and the width of coronal lines. In short the corona was reduced to a reasonable physical object though basic questions about its precise temperature and its origin remained unanswered.

1.2:4 The extent of the Corona

Radio measurements of the Crab nebula by Viktevich and Hewish during its close (angular separation) passage to the sun indicated that the tenuous outer atmosphere of the sun extended at least up to 50 solar radii. Chapman (1957) greatly enhanced the picture by suggesting that the corona extends to the earth’s orbit and beyond, being supported hydrostatically. Parker (1960) on the other hand argued that since the pressure of interstellar gas was not adequate to maintain the corona in hydrostatic equilibrium it must be in a state of constant expansion merging gradually with interstellar medium. The resultant flow called the solar wind would reach the earth with a supersonic velocity of \( \sim 400 \ \text{km sec}^{-1} \), a density of a few particles per cubic cm and a temperature of \( \sim 10^5 \text{K} \). In situ measurements of the solar wind parameters have largely confirmed Parker’s hypothesis.
1.2.5 Early temperature measurements.

The recognition of the corona as a high temperature object immediately raised two questions

a) What is the precise value of the temperature?

b) What is the heating mechanism?

The first problem was taken up by Biermann (1947); Woolley and Allen (1948); Miyamoto (1949); Shklovskii (1965); Hill (1951) and Elwert (1952) who all determined the coronal ionisation temperature (i.e.) the temperature that would lead to the degree of ionisation indicated by coronal line emission. Their temperatures ranged from 500,000K to 11,00,000K. On the other hand temperatures obtained from linewidths by Pecker et al. (1954); Billings (1957) and Zirin (1959) were all greater than $1.8 \times 10^6 K$ and sometimes as great as several millions of degrees. Radial density gradients in the corona that vary strongly both spatially and temporally gave intermediate values of temperature. The same was true of radio measurements.

The discrepancy between coronal temperatures computed from various types of observations was one of the outstanding astrophysical problems of the early
sixties. The problem was largely solved by Burgess and Seaton (1964) who pointed out the importance of a hitherto over looked process - di electronic recombination. As a result of this work ionisation temperatures were raised and the small discrepancy between linewidth and ionisation temperature could be explained by a reasonable amount of microturbulence.

1.2.6 Coronal heating theories - A few historical remarks

The problem of heating the corona was taken up within a year of the acceptance of its high temperature. During the next three decades a number of plausible theories have been proposed but none is considered adequate in detail. The accretion hypothesis by Hoyle (1949) envisaged coronal heating by the release of gravitational potential energy of interstellar particles captured by the sun in its motion through the galaxy. Theories by Biermann (1946); Schwarzschild (1948); Schwartzman (1949); Alfven (1950); Piddington (1956); Osterbrock (1961) and Uchida (1963) have all considered coronal heating by nonthermal notions originating in the hydrogen convective sub photospheric layer of the sun. According to this approach, acoustic waves propagate
upwards from the deep photosphere and steepen into shocks in the outer atmosphere as a consequence of rapid decrease in density with height (Leibacher and Stein, 1974). The role of photosphere in this picture is to filter out the short period waves by radiative damping but to permit waves with periods larger than 300 seconds to shock and dissipate their mechanical energy as heat higher up in the atmosphere. The acoustic theory was generally accepted until recently because of considerable corroborative empirical evidence. The existence of convective cells (granulation), photospheric motions and 300 second oscillatory patterns confirmed the existence of a turbulent medium in which acoustic waves could be generated. In addition, time series spectra of Ca II K line and others obtained by Liu (1974) and Cram (1978) provided evidence for upward propagation of heating pulses into the low chromosphere. The current status of coronal heating theories is reviewed by Kuperus et al. (1981).

1.2.7 Recent developments.

The last 15-20 years have witnessed rapid development of space craft borne instrumentation for X ray and Extreme Ultra Violet (EUV) measurements of the solar atmosphere. The region to benefit most from these new
techniques has been the chromosphere - corona interface or the so called transition region which lies in the temperature regime $10^4 K - 10^6 K$ and emits inefficiently in the visible. The Sky lab and Orbiting Solar Observatories (OSO) have provided a wealth of coronal data which still remains to be properly understood. One of the significant contributions made by the high resolution X ray imaging instrument on Skylab was the clear identification of strong X ray emission with extended loop structures presumably defined by the coronal magnetic field (Vaiana and Rosner, 1978). These observations support the view that the radiative emission of the corona comes predominantly from plasma confined by topologically closed magnetic field structures (Pneuman, 1973). The loop structure is seen in emission lines with ionisation temperature ranging from $2 \times 10^4 K$ (He II) to $2.5 \times 10^6 K$ (Fe X VI) (Cheng, 1980). There is no evidence for a more homogeneous corona with gas density lower than in the loops.

Another major result is the association of regions of low X ray surface brightness with open magnetic field configuration (coronal holes) (Withbroe and Noyes, 1977). Significantly coronal holes are the origin of high speed
solar wind streams which are the dominant cooling mechanism in the region.

In addition to its passive role in shaping coronal features, magnetic field is now being viewed as actively providing the mechanism for transmission and dissipation of energy in the corona. The acoustic wave heating theories are currently encountering difficulties following the OSO-8 UV Spectrometer observations (Athay and White, 1978, 1979) on the acoustic flux passing through the transition region. The low value of the flux observed, compared to what is needed to balance the measured, coronal radiative, conductive and wind losses has cast some doubt on wave heating theories and spurred efforts on magnetic heating. A new class of heating theories which especially focus on closed loop structures have evolved (Rosner et al. 1978; Ipson, 1978). Alfvén mode dissipation and localised current heating are the two main theoretical forms of heating consistent with the loop model. A third alternative is the steady field annihilation driven by twisting of field lines caused by convective motions in the photosphere.

The evolution of the correct heating mechanism from the alternatives available is the major problem confronting solar physicists in the 1980s.
1.3 METHODS OF MEASURING CORONAL TEMPERATURES:

There are basically four methods of determining coronal temperatures.

i) Temperatures by degree of ionisation.

ii) Temperatures from electron density distribution.

iii) Temperatures from Radio measurements.

iv) Temperatures from line profiles.

1.3.1 Temperatures by Degree of Ionisation.

We postulate that the corona is in a steady state, (i.e.) the rate of atoms changing from a lower to a higher degree of ionisation is equal to the rate at which they return to the state. If we consider, in a simple case, collisional ionisation (with a rate coefficient $C$) balanced by radiative recombination (with a rate coefficient $R$) then the populations of ions per unit volume in the $i$th and $(i+1)$th state of ionisation are related by

$$N_e N_i C = N_{i+1} N_e R$$

where $N_e$ is the electron density.
The ratio $\frac{N_{i+1}}{N_i} = \frac{C}{R}$ as pointed out by Woolley and Allen (1948) for a single step ionisation process is independent of electron density but a strong increasing function of temperature. If $C$ and $R$ are known as functions of temperature then an observational determination of the relative number of ions in two successive ionisation stages of an element provides a sharp evaluation of ionisation temperature. The most useful representation of ionisation computations is a plot against temperature of the fraction of atoms of an element that are in each of several successive stages of ionisation.

The simple theory when applied to coronal ions gave temperatures between 500,000K and 1100,000K as seen in Section 1.2.5. Dielectronic recombination, in which a recombining electron having its kinetic energy equal to the sum of the exciting energies of two bound states excites a bound electron to one excited state while itself getting excited to the other excited state, is an important process at high temperatures. For the Fe XV to Fe XIV recombination this process is $\sim 20$ times as great as ordinary radiative recombination. Inclusion of this process consequently raises the ionisation temperatures.
In recent years EUV observations have become available for obtaining transition zone ionisation temperatures. The importance of the observations arises from the fact that any given ion exists only in a comparatively narrow temperature range which is also a narrow height range in the atmosphere.

The flux emitted by a collisionally excited EUV line is given by

\[ E = \text{Const.} \ A \ \frac{\alpha Q}{N_e} \int G(T) \, dh \ (\text{Noyes and Withbroe 1972}) \]

where \( A \) is abundance of element producing the line and \( G(T) \) the temperature dependent function which depends upon ionisation and excitation properties of the atom emitting the line.

Assuming geometrical thickness of transition zone is far less than pressure (\( P \)) scale height and a constant temperature gradient over the relatively narrow temperature regime of the ion we have

\[ E = \text{Const.} \ P^2 \ \left< \left( \frac{dN}{dh} \right)^{-1} \right> \int \frac{G(T)}{T^2} \, dT \]
The integral can be evaluated independent of any atmospheric model. Using a number of lines formed at different temperatures one can obtain $dT/dh$ as a function of temperature. One can then evaluate the run of temperature with height from a subsequent integration.

In the upper transition zone Athay (1966) found temperature gradients proportional to $T^{-5/2}$. Reeves et al. (1976) have shown from Skylab's ATM measurements that $H\alpha$ and CII are formed at $10^4K$, CII at $\sim 6 \times 10^4K$, O IV at $\sim 10^5K$, O VI at $\sim 3 \times 10^5K$ and Mg X at $\sim 10^6K$. EUV measurements have also provided some constraints on the temperature distribution in the corona. Nakada et al. (1976) from a study of brightness gradients find that negative temperature gradients may extend to as low as $1.2\ R_\odot$ measured from the centre of the sun. Mariska and Withbroe (1978) from a similar study using Skylab data find evidence for a positive temperature gradient from $1.03\ R_\odot$ to $1.23\ R_\odot$.

1.3:2 Temperatures from electron density distribution.

Upper and lower limits for an average coronal temperature can be obtained from electron density measurements. The derivation of both limits assume LTE for
both electrons and ions. The lower limit is based on a model of the corona in hydrostatic equilibrium where pressure gradient \( \frac{dP}{dR} \) exactly balances the acceleration due to gravity at any point.

We write

\[
\frac{dP}{dR} = -\rho \frac{g_o}{R^2}
\]

where \( g_o \) is the acceleration due to gravity on the solar surface, \( R \) is distance from the centre of the sun in units of \( R_o \), \( \rho \) is the mass density at \( R \).

For an isothermal corona assuming perfect gas law we can write

\[
\frac{dn}{n} = \frac{m_H g_o}{kT} \frac{dR}{R^2}
\]

\[
\log_e \left( \frac{n}{n_o} \right) = \frac{m_H g_o}{kT} \left( \frac{1}{R} - \frac{1}{R_o} \right)
\]

where \( n, n_o \) refer to number densities of electrons at \( R \) and \( R_o \) respectively and \( m_H \) the mass of a hydrogen atom (we are assuming a pure hydrogen plasma).

Consequently a plot of \( \log_e n \) obtained from observations against \( 1/R \) must be a straight line. The temperature can be deduced from the slope. Departures from linearity
would signify different scale height temperatures. Actual observations yield a straight line for $R \leq 2 \ R_\odot$ with temperatures in the range $(1.4 - 1.6) \times 10^6 \ K$. Hydrostatic temperatures are useful as lower limits of average coronal temperature. For an expanding corona following Parker (1960) we can write

$$\frac{dP}{dR} = \frac{- \rho g R^2}{R^2} - \int V \frac{dv}{dR} = kT \frac{dn}{dR} + kn \frac{dT}{dR}$$

$$= - \int \left( g + \sqrt{\frac{dv}{dR}} \right)$$

$V$ is the expansion velocity at $R$. As $\frac{dv}{dR} > 0$ the effect of expansion is to increase effective acceleration due to gravity and hence the temperature. The effect is however small.

Assuming a constant average solar wind mass flux from measured values of $V$ and $n$ near the earth, we can extrapolate to obtain $V(R)$ and $\frac{dv}{dR}$ at the corona. The above equation can then be used to deduce temperature gradient $\frac{dT}{dR}$, knowing the electron density distribution. The variation of coronal temperature with radial distance can then be studied.
Waldmeier (1945) was one of the first to obtain coronal temperature from density gradients. He obtained a value of $1.3 \times 10^6$ K. Van de Hulst (1953) using empirical formulae he had presented for electron density in 1950 obtained a sunspot maximum temperature of $1.62 \times 10^6$ K and a sunspot minimum temperature of $1.15 \times 10^6$ K. Hepburn (1955) obtained temperatures of $1.73 \times 10^6$ K at the equator, $1.44 \times 10^6$ K at the poles and $2.3 \times 10^6$ K in a great streamer. She found the temperatures to drop off sharply beyond $2 R_\odot$. Evidence of a similar abrupt decrease in temperature with height was found by Baturova et al. (1960). He obtained temperatures of 3 to 5 million degrees below $1.5 R_\odot$ and only 2 million degrees between $1.5$ and $2 R_\odot$. The Pottasch density model (1960) leads to a temperature distribution in which temperature increases steadily up to $1.43 \times 10^6$ K at $1.3 R_\odot$ then drops off to $\sim 10^5$ K at the outer limits. Von Kluber (1961) from a careful study of coronal brightness on a 1927 solar minimum eclipse photograph obtained temperatures in the range $(1.4 - 2.1) \times 10^6$ K. Ney et al. (1961) after a careful separation of K and F coronae, in their photoelectric measurements, obtained, in the solar equatorial plane a temperature of $1.22 \times 10^6$ K at $1.3 R_\odot$ and $0.91 \times 10^6$ K at $1.8 R_\odot$. They also found evidence of increasing
temperatures below 1.3 R⊙. Billings and Cooper (1957) studied intensity gradients in \( \lambda 5303 \text{ Å} \) and \( \lambda 6374 \text{ Å} \) in regions of bright line emission. On the assumption that the emission was proportional to the square of the electron density, they obtained temperatures in the range \((1.8 - 2.2) \times 10^6 \text{K}\). A great deal of scatter in their data gave evidence of thermal and magnetic structures causing brightness and temperature fluctuation about the mean values. The Skylab electron density data interpreted through a model incorporating coronal expansion yields a temperature over a coronal hole rising steeply to a value of \(3.5 \times 10^6 \text{K}\) at \(\sim 3 \text{R}⊙\) (Keller and Billings, 1980).

1.3.3 Temperatures from radio measurements.

Thermal Bremsstrahlung is the major contributor to quiet radio emission from the corona. For radio wavelengths below 2 metres the corona is optically thick and the emitted radiant intensity can be approximated by Rayleigh Jean's relation

\[
B(\lambda) = \frac{2 c k T_e}{\lambda^4}
\]

where \(T_e\) is the electron temperature.

It is customary in Radio Astronomy even if source is not optically thick to define a brightness temperature
$T_b$ such that the measured intensity $I_{\lambda}$ is given by

$$I_{\lambda} = B_{\lambda} (T_b)$$

where

$$T_b = \frac{\lambda^4}{2c \lambda} I_{\lambda}$$

$$T_b \ll T_e$$

For a finite optical depth $\tau$ we have

$$T_b(\lambda) = \int_{\tau}^{T_e(h)} \exp[-\tau(\lambda, h)] \, d\tau$$

where $h$ refers to the height above the limb.

The basic problem is in inverting the above equation to get $T_e(h)$. The problem of theoretical prediction of the radio spectrum and of its brightness temperature distribution have been considered since the early days of solar radio astronomy (Martyn, 1946; Shklovskii, 1946; Ginzburg, 1946). A remarkable characteristic of the radio sun has been the increase in brightness temperature as the wavelength increased from the centimetre to metre range. This was correctly deduced to be due to increasing contribution from the corona at longer wavelengths (Smerd, 1950).

Now-a-days taking into account the inhomogeneous structure of the solar corona two component models are
considered where cool dense spicules, radially oriented are interspersed with hot radially symmetric interspicular gas. Radio observations by Le blanc Le Squeren (1969) gave a solar minimum temperature of \((1.1 \pm 0.2) \times 10^6 \text{K}\) and a solar maximum temperature of \(1.9 \times 10^6 \text{K}\) at 169 MHz. Since the corona is optically thick at this frequency the measured brightness temperature is also the coronal temperature.

Till 1970 the radio picture of a quiet corona has been that of a single region with density and temperature varying with the cycle of activity. Since the discovery of coronal holes there has been a revision of classical ideas. It is believed that the systematic choice of low brightness regions to separate quiet from slowly varying component might have resulted in radio astronomy, at metric wavelengths, observing the coronal hole regions only in the last 30 years. Lantos (1980) reports that Pallagi, P. and Patriarchi, P. have obtained a 2-dimensional brightness temperature distribution of the sun at 408 MHz. They find previous brightness temperatures in hole and arch regions to be underestimated. Their results are in accordance with EUV measurements of Mariska and Withbroe (1978) whose temperatures for a quiet region are in the range \((1.1 - 1.7) \times 10^6 \text{K}\).
1.3.4 Temperature from line width measurements.

In this method we are confronted directly with the meaning of temperature in a non uniform, non equilibrium medium like the corona. Consider a region of space small enough for the properties of the corona to be considered homogeneous. If \( N_i \) is the number density of particles of \( i^{th} \) kind, \( \vec{v}_{x,i} \) the rate of drift of this species through wind or diffusion, then relative to this drift each particle will have a thermal velocity.

\[
\vec{v}_{x,i} = (\vec{v}_{x,i} - \vec{v}_{x,i})
\]

If \( X \) axis also defines the line of sight then this is also the line of sight thermal velocity. The momentum transferred per unit time to a surface of unit area normal to the line of sight moving with the drift velocity is \( N_i m_i \vec{v}_{x,i}^2 \). This can be equated to the partial pressure of the species \( N_i k T \) to get from a very fundamental point of view the kinetic temperature given by

\[
T = \frac{m_i \vec{v}_{x,i}^2}{k} = \frac{m_i \sigma^2}{k} \left(\frac{\Delta \lambda}{\lambda}\right)^2
\]

where \( \Delta \lambda \) is Doppler shift measured from the mean
position. The above relation is applicable to any profile whether Gaussian or not and indicates that line profile measurements will give temperatures consistent with gas laws even though Maxwell-Boltzmann distribution may not hold for the gas.

In a Maxwell-Boltzmann gas line intensity \( I(\lambda) \) at wavelength \( \lambda \) can be written as

\[
I(\lambda) = I(\lambda_0) \exp \left[ - \frac{MC^2}{2kT_D} \left( \frac{\lambda - \lambda_0}{\lambda_0} \right)^2 \right]
\]

where \( \lambda_0 \) is the rest wavelength
\( T_D \), the line width Doppler temperature
\( M \), the Mass of the atom emitting the line

Defining a full width at half maximum (FWHM, \( \Delta \lambda_D \)) \( 2(\lambda - \lambda_0) \) when \( I(\lambda) = I(\lambda_0)/2 \) we get

\[
T_D = \frac{MC^2}{8k \log e^2} \left( \frac{\Delta \lambda_D}{\lambda_0} \right)^2
\]

or

\[
\frac{\Delta \lambda_D}{\lambda_0} = 7.16 \times 10^{-7} \sqrt{\frac{T_D}{m}} \quad \text{where} \quad m = \frac{M}{M_H}
\]

Determining \( \Delta \lambda_D \) from line profile measurements one can readily calculate \( T_D \). Unlike the ionisation method this
method is a direct one where only one atomic parameter and that too a well determined one - the atomic weight needs to be used. However there is some uncertainty in attributing line widths completely to temperatures as some broadening can also result due to microturbulence according to the equation:

\[
\frac{2k T_0}{M} = \frac{2k T_D}{M} + \nu_t^2
\]

where \( T_0 \) is the observed line width temperature and \( \nu_t \) the non thermal velocity characterising microturbulence.

Historically the use of line profiles is one of the oldest schemes for the determination of coronal temperature. We have already noted Iyot's pioneering spectrographic measurement of the width of the green coronal line (Iyot, 1937). In 1941 Waldmeier reported a green line width of 0.65 Å and concluded that it corresponded to a high turbulence in the corona with velocities of \( \sim 37 \text{ km sec}^{-1} \). Pecker et al. (1954); Billings (1957) and Zirin (1959) measured the widths of \( \lambda \) 5694 Å (Ca XV) line and obtained temperatures in the range \( (3.5 - 4.5) \times 10^6 \text{K} \). Boardman and Billings reported even higher temperatures Billings (1966). Dollfus (1953) studied the widths of
the red coronal line $\lambda 6374$ Å (Fe X) and found temperatures of $(1.7 - 1.8) \times 10^6$ K. Billings (1959) reported a temperature of $2.4 \times 10^6$ K from green line observations valid for both sunspot latitudes and polar regions. He suggested higher temperatures in active regions.

Following the successful observations of Jarrett and Von Klüber (1955, 1961) there have been several attempts to determine coronal temperatures from line widths using interferometric methods rather than traditional spectrographic methods during total eclipses. These observations are discussed in the next section. More recently Gurtovenko and Alikayeva (1971) have studied the variation of green line widths with height in the region $1.05 - 1.15$ R during the eclipse of March 7, 1970. Their spectrographic methods yield temperatures in the range $(4.5 - 3.0) \times 10^6$ K which decrease with height.

1.4 INTERFEROMETRIC OBSERVATIONS OF THE SOLAR CORONA

The large Luminosity - Resolution product of a Fabry-Perot interferometer makes it an ideal instrument for observing relatively isolated emission lines from an extended source like the corona. In combination with
photographic techniques it can be a very valuable tool for probing the corona with good spatial and spectral resolution even during the few minutes of totality of an eclipse. The development of narrow band interference filters and multilayer dielectric coatings have enhanced the efficacy of the technique resulting in its increasing use in eclipse coronal studies. In this section we review the development of the method as applied to the study of forbidden line emissions in the corona.

Before the first successful observations of Jarrett and Von Klüber (1955) there had been several attempts to use Fabry-Perot interferometers at eclipses. In the 1920s and 1930s Wright and Curtis made no less than four eclipse attempts with specially coated Fabry-Perot etalons. In 1941 Kaliniak (1949) used a slit spectrograph in conjunction with a Fabry-Perot interferometer. As the resolving power was $\sim 5000$ the green line profile could not be properly resolved. After correcting for the large instrumental width he reported a width of $\sim 1.4$ Å which is rather large. J.A. Carrol (1947) made three unsuccessful attempts, the last being frustrated by an aeroplane accident.
The successful observations of Jarrett and Von Klüber on the green line were obtained at the solar minimum eclipse of June 30, 1954 off the West Coast of Sweden. Their success can be traced to the use of a narrow band interference filter and low absorption dielectric coatings on the interferometer. The √/40 optical flats had a seven layer coating of Zinc sulphide and Cryolite and a spacing of 350 µm. Instrumental resolution was 0.1 Å. A Hilger interference filter with a peak transmission of 25% and a half width (FWHM) of 15 Å was used to isolate the green line. The interference pattern was recorded on a specially prepared Kodak emulsion similar to Kodak II a-J plate. The observations covered a region 1.05 - 1.3 R⊙ in the corona and yielded green line temperatures in the range (2.2 - 5) x 10⁶K with most values around 2.5 x 10⁶K. The mean error in the measurement was ~ 800,000 K. The authors reported that the measurements seemed "to indicate decrease of line widths with increasing distance from the sun as indicated earlier by coronagraphic measurements of Waldmeier".

At the solar maximum eclipse of October 12, 1958 Jarrett and Von Klüber were again successful. This
time they observed both the red and green coronal lines with a resolving power of $\sim 10^4$. To accommodate the two wavelengths, the Fabry-Perot flats were aluminised and plates (Kodak Code V 1008 for green, Kodak IIa E for red) rather than films were used. The line to continuum ratio for the green line was 1.6 times that of the 1954 eclipse. Along a streamer (position Angle $120^\circ$) green line emission could be seen up to $1.8\ R_\odot$ and red line up to $1.7\ R_\odot$. Analysis of line profiles yielded for the green line, temperatures in the range $(1.6 - 3.2) \times 10^6\,\text{K}$ and for the red line temperatures in the range $(2 - 3.5) \times 10^6\,\text{K}$. The differences in green and red line temperatures were not considered statistically significant. There was also no evidence of any change in linewidths with distance from the limb.

Increasing sophistication of the Fabry-Perot instrumentation was evident at the total eclipses of May 30, 1965 and November 12, 1966. Liebenberg (1975) during these eclipses used an aircraft borne Fabry-Perot photographic interferometer with a resolution of 0.08 Å to obtain line profiles of $\lambda 5303\,\text{Å}$ (Fe XIV); $\lambda 6374\,\text{Å}$ (Fe X) and $\lambda 5694\,\text{Å}$ (Ca XV). The aircraft platform (a modified NC 135 military version of
Boeing 707) provided complete freedom from cloud cover, reduction by a factor of two of the scattered sky light intensity and improvement in the reliability of logistical support for the equipment. However methods of accurate telescope pointing had to be developed to maintain tracking control of the corona for times long compared to photographic exposure times. In addition to the main photographic interferometer, a pressure scanned photoelectric interferometer was also operated, on axis, for integrated line and continuum intensity in selected wavelengths at several locations in the corona. Scan rates of 1 order per 2 seconds were obtained using Freon 12 as a pressurant compatible with instrumental resolution and amplifier response. Emission line profiles recorded up to 1.8 R⊙ indicated that coronal conditions are neither quiet nor homogeneous. The photographic interferometer employed \( \lambda / 100 \) flats with dielectric coatings (Reflectivity \( \sim 0.97 \)) spaced 382 \( \mu \text{m} \) apart along with temperature controlled filters each of bandwidth 12 \( \text{Å} \) for the three emission lines. Instrumental resolution was \( \sim 0.08 \text{Å} \). Photographic plate Kodak 103aG was used for the exposures. This interferometer provided data on Fe XIV emission line profiles, absolute line intensities, Doppler line shifts and interfringe continuum coronal intensities as a
function of latitude on west limb (Liebenberg et al. 1975). An elaborate deconvolution procedure yielded actual line profiles which were mainly Gaussian except for a few notable exceptions. The west limb coronal enhancement was determined to have a temperature $\lesssim 3 \times 10^6$ K and turbulent velocities ($\sim 25$ km sec$^{-1}$) were found decreasing with distance from the limb. Their results were also consistent with the X-ray emission line measurements giving a turbulent velocity of 34 km sec$^{-1}$ observed at presumably a lower altitude (Feldman and Behring, 1974). Temperature gradients provided evidence of marginal solar wind flow from this enhancement. Doppler shifts were found to be negligibly small in sharp contrast with the results of Delone and Makarova (1969) who obtained for the same eclipse velocities up to 149 km sec$^{-1}$.

Delone and Makarova studied both the red and green lines during the eclipse of May 30, 1965 using separate temperature controlled interferometers. Five fringes could be traced up to $1.35 R_\odot$ in the red line and one in the green line. Nearly two-thirds of the profiles showed a non-Gaussian character. The observed half widths for the red line ranged from 0.32 to 2.12 Å with
a mean value of 1.2 Å which corresponds to a temperature of $3.9 \times 10^6 K$. The large spread of line widths have been reconciled by authors by the suggestion of non-thermal mass motion with velocities exceeding 20 km sec$^{-1}$.

At the eclipse of September 22, 1968 Delone and Makarova (1975) obtained an interferogram of the green line in polarised light with a spectral resolution of 0.1 Å. From the eclipse frame they studied $\sim$ 700 profiles in the region 1.02 to 1.39 R$^\odot$. In at least 10% of the profiles studied they obtained large line of sight velocities ( $> 100$ km sec$^{-1}$).

Hirschberg et al. (1970) found evidence for a corona in violent motion as indicated by definite spectral shifts and differences in Doppler temperature during the eclipse of March 7, 1970. Using classical fringe photographic techniques they could go upto 1.85 R$^\odot$ with a spectral resolution of $\sim$ 0.2 Å on the green line. The results showed Doppler widths mainly in the range 0.8-1.1 Å. In an active area there was evidence of a cooler fan system rotating slowly around a hotter less dense corona. They also found a larger Doppler temperature in the core of a streamer ( $\sim 6 \times 10^6 K$) than in the periphery ( $\sim 2.5 \times 10^6 K$). The authors also attempted but were
unsuccessful in the use of a pressure scanned Fabry-Perot interferometer.

Marshall and Henderson (1973) used successfully, a single fringe, single etalon air spaced with photoelectric detection for studying the green and red lines during the 1970 eclipse. Their earlier attempts are chronicled in Henderson (1970). The etalon (λ/100 flats) had an air gap of 400 μm and an instrumental width of ∼ 0.2 Å. Two 5 Å bandwidth filters were used for isolating the green and red lines. A unique feature of this set up was the use of piezoelectric scanning which eliminated misalignment problems caused by rapid pressure (and hence temperature) changes and also greatly increased the speed of the scan. An oscilloscope for on line display and high speed UV chart recorders were used in data acquisition. Spectral scans were made at ∼ 1.05 R° (position Angle 180°) and at ∼ 1.1 R° (P.A. 270°). The line profiles were analysed by generating synthetic profiles for different Doppler temperatures obtaining by a least square analysis the best fit temperature (Hays and Roble, 1971). The analysis gave green line temperature of ∼ 4 x 10^6 K and a red line temperature of ∼ 3.5 x 10^6 K. The estimated error in the temperature measurement was
The authors interpret the high temperature as a consequence of the maximum phase of the solar cycle.

Apart from the 1970 eclipse the same equipment was also used in conjunction with the Pic-du-Midi coronograph where observations were possible up to 1.5 R☉. A mean green line temperature of 3.7 x 10⁶ K much higher than the mean red line temperature of 2.8 x 10⁶ K was deduced in agreement with Billings and Lehman (1962). No variation of line width temperature either with increasing radial distance or with position angle was observed. However, the authors found evidence for a temporal variation of line widths to the extent of ~ 1 x 10⁶ K in 10 minutes. The coronagraphic observations employing λ5302.3 Å Fraunhofer line as a fiducial marker also yielded line of sight velocities < 1.16 km sec⁻¹ with a standard deviation of 3.49 km sec⁻¹.

Kim and Nikolsky (1975) observed the eclipse of July 10, 1972 in three spectral lines λ5303 Å, λ6374 Å and λ5876 Å (He I). The instrumental resolution was 0.31 Å at λ5303 Å. Red line observations were consistent with a temperature of 2.7 x 10⁶ K while green line observations indicated a halfwidth increasing through the region (1.2 – 1.7 R☉). The
<table>
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<tr>
<th>Sr. No.</th>
<th>Eclipse date</th>
<th>Author(s) and Year of Publication</th>
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<tr>
<td>1</td>
<td>June 30, 1954</td>
<td>Jarrett and Von Klüber (1955)</td>
<td>5303</td>
<td>Pressure scanned photoelectric interferometer</td>
<td>0.21 (10^6 \text{K}) for red line, large spread in linewidth suggested non-thermal velocities greater than 20 km sec(^{-1}).</td>
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<td>2</td>
<td>Oct 12, 1958</td>
<td>Jarrett and Von Klüber (1961)</td>
<td>6374</td>
<td>Photoelectric interferometer</td>
<td>0.5 ((1.6 - 3.2) \times 10^6 \text{K}) for green line, ((2.0 - 3.5) \times 10^6 \text{K}) for red line.</td>
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<tr>
<td>3</td>
<td>May 30, 1965</td>
<td>Delone and Makarova (1969)</td>
<td>6374</td>
<td>Photoelectric interferometer</td>
<td>0.21 (3.9 \times 10^6 \text{K}) for the red line. Large spread in the linewidths suggested non-thermal velocities greater than 20 km sec(^{-1}).</td>
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<td>4</td>
<td>May 30, 1965</td>
<td>Liesenberg (1965)</td>
<td>5303</td>
<td>Pressure scanned photoelectric interferometer</td>
<td>0.08 ((1.6 - 4.2) \times 10^6 \text{K}) for green line, Turbulent velocity (\sim 25) km sec(^{-1}) Decreasing with altitude.</td>
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<td>Date</td>
<td>Authors</td>
<td>RA</td>
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<tr>
<td>Sept 22, 1968</td>
<td>Delone and Makarova (1975)</td>
<td>5303</td>
<td>0.21</td>
<td>Interferogram obtained in polarised light. Large line of sight velocities (&gt;100 km sec(^{-1})) noted in 10% of the profiles. Spatial coverage 1.02-1.39 R(_{\odot}). Uncorrected temperature (\approx 4.5 \times 10^6) K.</td>
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<tr>
<td>March 7, 1970</td>
<td>Hirschberg et al. (1970)</td>
<td>5303</td>
<td>0.2</td>
<td>(2.5-4.8) (\times 10^6) K Doppler shifts indicate a vortex velocity of (\approx 6) km sec(^{-1}).</td>
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<tr>
<td>March 7, 1970</td>
<td>Marshall and Henderson (1973)</td>
<td>5303</td>
<td>0.2</td>
<td>(\approx 4 \times 10^6) K for green line; (\approx 3.5 \times 10^6) K for red line. Photoelectric detection and piezoelectric scanning employed.</td>
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<tr>
<td>July 10, 1972</td>
<td>Kim and Nikolsky (1975)</td>
<td>5303</td>
<td>0.3</td>
<td>2.7 (\times 10^6) K for red line. Non thermal velocities found to increase with a gradient 1-2 km sec(^{-1}) per 0.1 R(_{\odot}) from green line analysis.</td>
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increase interpreted as due to increasing non thermal velocities implies velocity gradients of $1-2 \text{ km sec}^{-1}$ per $0.1 \ R_\odot$. The non thermal velocities are found to increase from $24 \text{ km sec}^{-1}$ at $1.2 \ R_\odot$ to $34 \text{ km sec}^{-1}$ at $1.7 \ R_\odot$.

The salient features of interferometric observations of the corona are summarised in Table 1.

1.5 **MOTIVATION FOR THE PRESENT STUDY**

1.5.1 Temperature structure of the corona

Unlike the rather well known electron-density distribution the temperature structure of the quiet, undisturbed inner corona remains only crudely known inspite of the increased understanding of the chromosphere-corona interface that has emerged from the recent EUV studies. Yet the inner corona is of fundamental importance for both solar physics and the physics of the interplanetary medium. Mechanical energy is deposited there as heat which flows inward to maintain the transition region and upper chromosphere and outward to maintain the solar wind and extended corona.

As seen in Sections 1.3 and 1.4 various temperature measurements of the corona do exist but they
have not succeeded in delineating any temperature structure. Some constraints have been placed on the possible structure by EUV measurements leading to estimates of temperature gradients – Nakada et al. (1976); Mariska and Withbroe (1978); Kohl et al. (1980). Kuperus (1969) on the other hand has reviewed theoretical coronal studies and finds some agreement for the maximum temperature to be located near $1.1 \, R_\odot$. Keller and Leibenberg (1980) further point out that acoustic wave theory of coronal heating would place the temperature maximum at $1.1 \, R_\odot$; while magnetic heating could push the maximum beyond $2 \, R_\odot$. It is also not clear how the temperature distribution would be affected by centres of activity like loops and arches. In fact the determination of temperature density structure of an individual loop is an essential first step towards construction of a realistic model of an active region consisting of numerous discrete loops often unresolved in X ray photographs. A direct method of determining the temperature at various points in the corona nearly simultaneously would therefore be invaluable in constraining coronal heating theories.

1.5.2 Non-thermal broadening:

The amount of excess broadening (due to microturbulence) over and above that due to thermal broadening
has so far eluded all attempts for a clear cut solution. While Kim and Nikolsky (1975) inferred increasing non-thermal velocities with gradients of 1-2 km sec$^{-1}$ per 0.1 R$_{\odot}$ in the region 1.2 - 1.7 R$_{\odot}$, Liebenberg (1975) present evidence for a decrease in these velocities from 25 km sec$^{-1}$ at 1.25 R$_{\odot}$ to 5 km sec$^{-1}$ at 1.53 R$_{\odot}$. There has been no consensus as to whether non-thermal motion is constant, increasing or decreasing with altitude in the corona. Its link, if any with gross mass motion as evidenced by Doppler shifts of lines is also far from being established.

1.5:3 Mass flows:

Coronal heating is the key to the understanding of solar wind expansion. Rosner and Vaiana (1975) suggest that most significant portion of flow acceleration occurs beyond the temperature maximum. In this context velocity measurements in the corona together with more sensitive temperature and density determinations are essential in understanding the role of energy transfer from mechanical flux to the wind. Further as pointed out by Jordan (1981) if temperature-density structure can be determined with sufficient accuracy, it is possible to deduce static terms in the energy balance relation - radiation loss
and conductive flux. Careful Doppler shift measurements are required to investigate terms associated with mass flows.

From the above considerations it is clear that there is a strong case for making observations with a view to

a) Determine the temperature structure of the corona and to establish exactly the location of the maximum temperature.

b) Study whether this temperature maximum depends on underlying structures.

c) Determine the magnitude and distribution of the microturbulent velocity distribution in the corona.

d) Determine Doppler shifts if any and investigate the connection of gross mass motion with microturbulence.

This thesis addresses itself to some of the above stated problems of coronal physics through a study of line profiles of the green coronal line $\lambda 5303 \, \text{Å}$ [Fe XIV, $3 \, ^2P_{3/2} - 2 \, ^2P_{3/2}$ Forbidden Magnetic dipole transition].
obtained using a Fabry-Perot interferometer during the total solar eclipse of February 16, 1980.

Chapter II deals with the details of the instrumentation used—Concepts, planning, fabrication and testing prior to the eclipse.

Chapter III records the details of the observations carried out on eclipse day.

Chapter IV describes the method of analysis used in the reduction of the data.

Chapter V discusses the results obtained from the observations and areas of agreement/disagreement with other results both theoretical and experimental.

Chapter VI is a deviant from the main topic of the thesis. It describes a new technique of stabilising the frequency of a Helium-Neon laser and outlines its possible use as an extremely accurate wavelength calibration source for solar velocity field measurements in the red region.