Line-of-sight velocities observed in the inner solar corona during the total solar eclipses of 1980 and 1983

K. P. Raju, J. N. Desai, T. Chandrasekhar and N. M. Ashok
Physical Research Laboratory, Ahmedabad – 380009, India

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ABSTRACT
Line-of-sight velocities in the inner solar corona are calculated from the coronal green-line profiles obtained from Fabry–Perot interferometric observations of the solar corona during the total solar eclipses of 1980 and 1983. The main features of the line-of-sight velocities seen in the Fabry–Perot fringes are reported here. Line profiles obtained from the 1980 observations show strong signatures of multiple components. The line profiles, in general, are found to contain one main component and a few subsidiary components. A large excess of components on the blue side of the main component is found. Line profiles belonging to the coronal active regions often show line splitting. The derived velocities associated with the 1980 coronal line profiles in general show an outward increase with respect to the innermost regions. This increase is found to be dependent on the coronal position angle and hence related to the activity of the underlying coronal region. The dispersion in velocities is found to be smaller in the closed magnetic field regions than that in the open regions, indicative of a more ordered flow in the former regions. The majority of the line profiles obtained from the 1983 observations show single components. The derived velocities associated with the fringes are small in comparison to 1980 values. The trend of increasing velocity with increasing coronal height is seen only in one case out of three. The line-of-sight velocities in the line profiles are interpreted as due to the discrete moving plasma components in the line of sight, which arise as a result of the motion of plasma inside the coronal loops. It is suggested that coronal loop motions were stronger in 1980 than in 1983.

Key words: line: profiles – Sun: corona – Sun: magnetic fields.

1 INTRODUCTION
The coronal heating mechanism has been a topic of active research ever since the wide acceptance of the existence of a 10⁶-K solar corona in about 1940 (Edlén 1942). It was generally believed that shock-wave dissipation could heat the solar atmosphere; however, space-borne measurements in recent years have convincingly shown that the shock-wave flux cannot provide the required heating (Athay & White 1977). It is now generally known that coronal heating is a magnetic field related phenomenon. Observations in recent years point out that the temperature of the active regions, where the magnetic field is strong and predominantly closed, is higher than that of quiet regions, where the magnetic field is weak and open (Roberts 1987). Magnetic heating may be expected as a result of the dissipation of magnetohydrodynamic waves and the different current mechanisms in the regions of large electric current density. The velocity spectrum in relation to the magnetic field is the most important deciding factor in the acceptance or rejection of a particular heating mechanism (Kuperus, Ionson & Spicer 1981). With the advent of space observations, a good data base is now available on the chromosphere–corona transition region (Athay, Gurman & Henze 1983b). This is also true for the outer solar atmosphere, as a result of solar wind observations. There have been only a few attempts, however, at observations of the inner solar corona. One of the inherent difficulties in this regard is the faintness of the visible coronal emission lines.

It has been generally accepted that the inner solar corona is static, with no macroscopic motions greater than a few km s⁻¹ (Newkirk 1967). However, there have been many observations which have reported large-scale motions in the corona (Delone & Makarova 1969, 1975; Harvey & Liv-
2 OBSERVATIONS AND DATA REDUCTION

The observations of the solar corona were carried out by the Physical Research Laboratory group during the total solar eclipses of 1980 and 1983, using Fabry–Perot techniques. Details of the observations are given elsewhere (Chandrasekhar 1982; Chandrasekhar et al. 1984). The interferograms were later digitized by a Perkin–Elmer photodigitizing system (PDS). The pixel size chosen for digitization depended on the grain size of the film: it was 10 μm square for the film that was used for the 1980 observations (Kodak Tri-X panchromatic, 400 ASA) and 5 μm square for the 1983 observations (Kodak 2415). The PDS recorded the x, y positions and the photographic density of every pixel which were later used for the analysis on a magnetic tape. The centre of the fringe system and the solar centre do not coincide in interferograms, because of the off-axis mode of operation of the interferometer. This mode of operation was pre-decided, to obtain a good coverage of different coronal regions.

For the present analysis, we have used two interferograms of the solar corona obtained during the 1980 observations (10- and 30-s exposure), which recorded the eastern and western active regions, and one interferogram of the solar corona obtained during the 1983 observations (exposure time 3 min 30 s). The position angle coverage used for the present analysis for the two 1980 interferograms together is about 210°, while that for the 1983 interferogram is only 30°. The centre of the fringe system for the interferograms was decided in order to obtain intensity profiles for a particular direction. This was done by noting the coordinates of the fringe maxima and then fitting a circle to them by least-squares. During the 1980 observations, one of the interferograms recorded the third contact position very clearly. Knowing the coordinates of the third contact position, all of the frames were then transformed into solar coordinates. The intensity profiles in a particular direction may be obtained by selecting the intensity values of all of the pixels lying in that particular direction. A computer program was developed for this purpose. Given the coordinates of the reference point, the angle and the scanning interval, the program calculates the coordinates of the pixels defining a particular direction and then selects the density values from them. Averaging of the densities in the nearby pixels was found to be necessary, to reduce the noise. The photographic density was converted into relative intensity in the film using the photographic characteristic curve. The intensity profiles in a typical scan direction are shown in Fig. 1. Note the repeated appearance of a weak component on the short-wavelength side of most of the line profiles.

3 RESULTS AND DISCUSSION

From the constructive interference condition in a Fabry–Perot etalon,

\[ 2\mu \cos \theta = n\lambda. \]

(1)

For small \( \theta \), we may write

\[ 2\mu \left(1 - \frac{\theta^2}{2}\right) = n\lambda. \]

(2)

In addition, \( \theta = \tan \theta = R/F \), where \( R \) is the radius of the fringe maxima and \( F \) is the focal length of the imaging lens used in the interferometer:

\[ R^2 = 2F^2 - \frac{F^2}{\mu} \frac{n\lambda}{\lambda} \]

(3)

For two adjacent fringes, the difference of the squares of the radii of any two adjacent fringes,

\[ R_{i+1}^2 - R_i^2 = \frac{F^2}{\mu} \lambda, \]

(4)

will be a constant for a given wavelength. The expected value of \( R_{i+1}^2 - R_i^2 \) for the observed wavelength \( \Delta R^2 \), as well as the error involved in the measurement, may be obtained from the calibration interferogram, which was obtained in the mercury green line at 5461 Å. This was done by scanning the calibration interferogram in different directions and calculating the average value for all of the fringes. Both the 1980 and 1983 calibration interferograms were scanned in five different directions at an interval of 20°, measuring nine fringes in each of them. The \( \Delta R^2 \) values for the 5302.86-Å line were found to be \( (52.928 \pm 426) \times 10^2 \) and \( (53.109 \pm 362) \times 10^2 \) μm² in the 1980 and 1983 interferograms respectively. In terms of the velocity, the standard deviations correspond to 2.11 and 1.79 km s⁻¹ respectively. The grain size of the photographic film for the 1980 interferogram is about 20 μm, while that for the 1983 interferogram is about a few microns. Hence the accuracy with which the fringe peaks are located is limited by the large grain size in the case of the 1980 observations and by the large sampling interval in the case of the 1983 data. The variation of \( \Delta R^2 \) in different directions is only a minor fraction of this error, thus ruling out the possibility of directional variation.

It is also possible that the changes in atmospheric temperature and pressure between the time of eclipse and the
Line-of-sight velocities in the solar corona

Table 1. The values of $\Delta R^2$ obtained from the calibration and the actual interferograms (columns 4 and 5). The difference between these two in terms of velocity is given in the last column.

<table>
<thead>
<tr>
<th>No</th>
<th>Identification</th>
<th>No. of Calib</th>
<th>Actual</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Scan</td>
</tr>
<tr>
<td>1</td>
<td>30 sec exp 1980</td>
<td>91</td>
<td>52928±426</td>
<td>53398±990</td>
</tr>
<tr>
<td>2</td>
<td>10 sec exp 1980</td>
<td>40</td>
<td></td>
<td>53471±710</td>
</tr>
<tr>
<td>3</td>
<td>3min 30sec exp 1983</td>
<td>13</td>
<td>53109±362</td>
<td>52927±428</td>
</tr>
</tbody>
</table>

One can then compute, from the measured values,

\[ \Delta R_i = (R_i)^{obs} - (R_i)^{calc}, \]

and hence

\[ \frac{R_i \Delta R_i}{R_i^2} = \frac{\Delta \lambda}{\lambda} = \frac{v}{c}. \]

The derived velocity $v_i$ at the $i$th fringe is related to the actual line-of-sight velocity $V_i$ as follows:

\[ v_i = V_i - V_{i-1} - i(V_{i+1} - V_i), \]

where $V_i$ and $V_{i+1}$ are the line-of-sight velocities at about 1.03 and 1.06 R$_\odot$. Since the velocities at the first two fringe points may not be appreciably different, we may take $V_2 = V_1$. Then $v_i = V_i - V_{i-1}$ and hence the measured velocities are approximately the line-of-sight velocities at each fringe with respect to that at the first fringe. Local velocity fields will have little effect, since the averaging is carried out over all of the observed position angles. If the velocity difference between the first two fringes is appreciable, however, the derived velocities will be underestimated and hence they may be taken as the lower limit to the absolute velocities.

The solar coordinate corresponding to a particular fringe maximum point has been determined by a coordinate transformation from the interferogram coordinates to the solar coordinates. The values of velocity and radial and azimuthal coordinates have been found for 850 points from the three interferograms. The observed points have then been sorted into 10° position angle intervals in solar coordinates to study the possible position angle variation.

The uncertainty in the fringe peaks resulting from the coarse grain size and large sampling interval could be minimized by dealing with fringe centroids. The fringe centroid is defined as that point $R_i$ for which the area of the line profile is divided into two equal halves. In Fig. 2 we have compared the behaviors of the fringe peaks and fringe centroids for four representative position angles from the three interferograms. It may be seen that the behaviors of the fringe peaks and fringe centroids are essentially the same, with the fringe peaks showing more scatter. Thus for the following analysis we proceed with the fringe centroids.

The other factors that may possibly affect the derivation of line-of-sight velocities from the interferograms are the spatial variations of the 5303Å line, K-continuum and F-corona. A model calculation has been performed by taking into account the spatial variations of the 5303Å line for a quiet corona with an average temperature of $2 \times 10^6$ K and...
In Fig. 3 we have plotted the observed velocities against coronal height for various position angles. The position angle and year are given in each plot. A second-degree best-fitting polynomial is plotted along with the velocities to derive the average behaviour. The goodness of the polynomial fit is given for each plot. In Fig. 4(b) we have marked the various position angles and the radial extent of our observations. This is compared with coronal pictures showing structures (Fig. 4a), such as those derived by Rusin & Rybansky (1983) and Loucif & Koutchmy (1989). A one-to-one comparison of the structures and the observed velocities for the various observed position angles is now possible.

The derived velocities in the 1980-epoch corona show a distinct increase with coronal height for most of the position angles. The increase is found to be dependent on the coronal position angle. A rough correlation between the coronal activity and the velocities may be seen from a comparison of Figs 3 and 4, if we accept a 10° positional mismatch between the coronal picture and the interferograms. It should also be noted that each position angle (PA) actually represents the results from within a 5° interval on either side. At the coronal PA of 260°-320° near the western active region, where a multitude of loops is seen, the observed velocities show a well-defined increase. The increase is maximized at PA 270°, where the activity is a maximum. At PA 250°, where the activity has reduced, the observed increase in velocity is reduced to a minimum. At PA 330°-340°, which corresponds to the open polar regions, the observed velocities are chaotic. Although activity at these azimuths is at a minimum, the observed velocities still show an increasing trend, albeit with a reduced correlation. The sharpest increase in the observed velocities is seen at PA 40°, which corresponds to the isolated loop system lying nearby. At PA 50°-110°, where the results are derived from the interferogram with 10-s exposure, a similar correlation may be seen. The PA of 50°, which corresponds to the region between the two loop systems, shows no correlation between the velocity and the coronal height. As the observed PA traverses the large loop system in the eastern active region, the rise in the observed velocity also increases and, at PA 70°, the increase in velocity reaches a maximum. Thereafter, the trend of increasing velocity dies down, and reaches a minimum at PA 100°, which again corresponds to a region where no loops are present. The PA of 110° shows signatures of loop structures nearby, and correspondingly the velocities show an increasing trend. It is also interesting to note that, for some of the position angles associated with the western active region, the observed velocities show negative values. If the average behaviour of the observed velocities is assumed, one finds a maximum of this at PA 270°, where the trend of increasing velocity also reaches a maximum.

For the 1983 epoch, we have results for only three position angle intervals. The radial coverage is also small, and hence it is difficult to make general deductions. Two of the observed PAs (240° and 260°) do not show appreciable velocities above the expected errors. However, PA 250° shows a clear trend of increasing velocity with coronal height. A comparison with the coronal picture (Loucif & Koutchmy 1989) shows some evidence of loop structures at these position angles.

It may be seen that the dispersion in the observed velocities is greater in the open magnetic field regions than in the closed field regions. In Fig. 5 we have plotted the
standard error in the observed velocities from the best-fitting polynomial, which is a measure of the dispersion in the actual velocities, against the coronal position angle. The result shows that the velocities are more ordered in the closed field regions than in the open field regions. This could be due to the fact that, in closed field regions, plasma is forced to flow along the magnetic field lines, thus reducing the scatter in the actual velocity.

In Fig. 1 we noticed the repeated appearance of a weak component on the short-wavelength side of the main peak in most of the line profiles. Intense line splitting is seen in many active-region line profiles, and is mainly on the blue side. We thought that the excess blueshifts in the derived velocities and the appearance of multiple components might be related to each other. With this in mind, about 400 line profiles belonging to the 30-s interferogram of 1980 have been examined visually to determine the nature of the multiple components. The line profiles from different coronal regions such as active, quiet and polar regions have been examined separately. For this purpose, interferograms have been compared with coronal pictures that show structures (Rusin & Rybansky 1983; Loucif & Koutchmy 1989). The multiple components seen in the line profiles have been divided into four categories according to their structure: components that are clearly blueshifted with respect to the main component in the line profile (‘blue’); components that are clearly redshifted (‘red’); components that are apparently single and hence representative of the whole line profile (‘single’); and components that are complex and hence make it difficult to judge the nature of the multiple components (‘complex’). 31 line profiles belonging to the 1983-epoch corona have been examined in a similar way. The results are shown in Table 2.

The majority of the line profiles in the 1980-epoch corona are found to contain multiple components. The blueshifted

![Figure 3](https://academic.oup.com/mnras/article-abstract/263/3/789/1206440)

Figure 3. The relative line-of-sight velocity plotted against coronal height for various position angles observed during 1980 and 1983. For each panel, filled circles denote the observed points and the solid curve denotes a second-order best-fitting polynomial. Position angle, year and correlation coefficient for the polynomial fit are given for each plot. The error involved in the measurement is 2.11 km s\(^{-1}\) for 1980 and 1.79 km s\(^{-1}\) for 1983.
components are found in greater numbers than the redshifted components. It is also found that, in general, the blueshifted components are stronger than the redshifted ones. The line profiles of the 1983 corona are of the ‘apparently single’ type. However, a detailed analysis by Chandrasekhar et al. (1991) of 53 line profiles from the same interferogram, covering two pockets of 5303 Å emission and a position angle interval of 110°, showed the presence of a single Gaussian component in 25 of them. 19 line profiles were found to be double Gaussians and two were found to be triple Gaussians, while seven were classified as ambiguous. Out of 31 line profiles obtained from the coronal red-line observations, Chandrasekhar et al. found 18 single Gaussian components, three double Gaussians and 10 ambiguous ones. Our analysis and that of Chandrasekhar et al. suggested the following:

(i) the coronal line profiles of 1980 show strong signatures of multiple components;
(ii) the coronal line profiles of 1983 show weaker signatures of multiple components, compared to the 1980-epoch data;
(iii) multiple components seen in the 1980 profiles are mainly on the blue side of the main line profile; and
(iv) the appearance of multiple components in the line profiles for the 1980 epoch is related to the activity of the underlying coronal region.

Thus, when the line-of-sight velocities associated with the fringes are large in the 1980-epoch data, we see strong multiple components in the line profiles while, when the line-of-sight velocities associated with the fringes are small in the 1983-epoch data, the signatures of multiple components are comparatively weak. These results are consistent in that the line-of-sight velocities in the 1980-epoch data mostly represent blueshifted components and the subsidiary components are mainly on the blue side of the line profile.

Although the derived velocities are the relative line-of-sight velocities with respect to that in the innermost coronal regions, the excess blueshifted components in the line profiles obtained from the above analysis lead to the conclusion that the velocities in the 1980 corona indeed represent blueshifted material. This may not be the case for the 1983 data. The derived velocities also represent a blueshift, but visual examination of the line profiles does not reveal whether they are blueshifted or redshifted. Now, as we stated above, the multiple components in the line profiles arise from the discrete motion of plasma in the line of sight (Bilitings 1966). The discrete motion of plasma, in turn, could be associated with the coronal loops. Coronal photographs reveal the ubiquitous nature of coronal loops. The 1980 solar maximum corona shows distinct evidence of the presence of coronal loops (Rusin & Rybansky 1983; Hanoaka & Kurokawa 1988; Loucif & Koutchmy 1989).

Since the loop evolution is a comparatively slow process, involving time-scales of a few days (Priest 1984), we interpret the discrete motion seen in the coronal line profiles as arising from the motion of coronal plasma along the coronal loops.

As mentioned earlier, there exists some controversy regarding the occurrence of mass motion in the inner corona. In this regard, Athay (see Delone et al. 1988) observes that the moving features in the corona are expected, as they are found everywhere else in the solar atmosphere, but that we do not have sufficiently good observations to reveal them (cf. Delone et al. 1988). Our observations provide unequivocal evidence of mass motions in the inner solar corona. A comparison of the results for the two eclipses suggests that the velocity of the mass motion is intimately linked to the phase of the solar activity cycle. The solar corona at solar maximum is in a state of violent motion, with derived line-of-sight velocities increasing to 35 km s⁻¹ and resulting in complicated emission-line profiles. On the other hand, the
Figure 4. (a) The structure of the solar corona during the 1980 total solar eclipse (Rusin & Rybansky 1983). (b) The radial/azimuthal coverage of the present observations.
The standard deviation of the polynomial fit (shown in Fig. 3), plotted against coronal position angle. It can be seen that the standard deviation is larger in the open magnetic field regions than in the closed regions.

![Coronal Position Angle Diagram](image)

**Table 2.** The nature of the multiple components in the 1980 and 1983 coronal line profiles. The percentage of each type found in the given coronal region is given in brackets. See the text for details.

<table>
<thead>
<tr>
<th>Active Region</th>
<th>Year</th>
<th>Blue</th>
<th>Red</th>
<th>Single</th>
<th>Complex</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>130</td>
<td>67</td>
<td>34</td>
<td>7</td>
<td>(54.6)</td>
</tr>
<tr>
<td>1983</td>
<td>(49.3)</td>
<td>(17.7)</td>
<td>(23.4)</td>
<td>(0.09)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quiet Region</th>
<th>Year</th>
<th>Blue</th>
<th>Red</th>
<th>Single</th>
<th>Complex</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>78</td>
<td>28</td>
<td>37</td>
<td>15</td>
<td>(49.3)</td>
</tr>
<tr>
<td>1983</td>
<td>(49.7)</td>
<td>(17.7)</td>
<td>(23.4)</td>
<td>(0.09)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Polar Region</th>
<th>Year</th>
<th>Blue</th>
<th>Red</th>
<th>Single</th>
<th>Complex</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>17</td>
<td>2</td>
<td>22</td>
<td>25</td>
<td>(25.8)</td>
</tr>
<tr>
<td>1983</td>
<td>(25.8)</td>
<td>(0.03)</td>
<td>(33)</td>
<td>(37.9)</td>
<td></td>
</tr>
</tbody>
</table>

The above analyses suggest that the deduced line-of-sight velocities associated with the line profiles in the 1980-epoch corona are a result of the excess blueshifted components in the line profiles. However, the presence of excess blueshifted components in the 1980 coronal line profiles is not properly understood. Our results imply that the preferential direction of motion of the coronal plasma in the inner regions was towards the observer during the solar maximum year of 1980. The observed velocities are smaller for the 1983 data, and it is difficult to judge whether they represent blueshifts or redshifts. In the following, we list some of the recent observational findings on the Sun that could be related to the asymmetry that we have found in the derived velocities. The solar corona displays many behavioural asymmetries. The activity of the northern hemisphere is generally found to be greater than that of the southern hemisphere for recent solar cycles, with the maximum asymmetry seen at heliographic latitudes of \( \pm 10^\circ \)– \( 20^\circ \) (Gibson 1973; Petropoulos 1988). Coronal loops are often seen to be associated with bipolar sunspot groups. The polarities of all the leading spots in one hemisphere are the same, and also represent the polar field which reverses its sense at the start of a new cycle. Thus the two epochs of 1980 and 1983 represent periods for which the sunspot polarities are reversed. It is also found that the magnetic axis of a bipolar group is inclined typically by \( 10^\circ \) in such a way that the leading spots tend to lie near the
equator. One other related observation is that the plasma in the emerging foot of a coronal loop is brighter than that in the closing foot (Priest 1981). Asymmetry is also seen in the observed velocities in the chromosphere–corona transition region. The observed UV lines are mainly redshifted, possibly as a result of the downward motions of coronal matter at these heights (Athay & White 1977; Brueckner 1980; Athay et al. 1983a). The velocities of mass flow seen in the transition-region lines show a reversal in sign at some point along the loop (Athay et al. 1983b). Our observation of the 1980-epoch corona provides marginal evidence that the velocities in the innermost coronal regions at some position angles (PAs 270°, 280° and 290°) represent redshifted material. This is probably related to the above-mentioned observations. Rocket-borne spectrograph measurements of coronal ions such as Si x (303 Å), Mg x (610 Å) and Mg ix (368 Å) showed evidence for an outward flow of plasma, with velocities of ~16 km s⁻¹. The line centres in the coronal hole regions were found to be systematically shifted to shorter wavelengths (Kushman & Pense 1976). Are the velocities predominantly representative of redshifted material in the transition region and in the innermost coronal regions, while becoming more representative of blueshifted material at greater coronal heights?

The increase in line-of-sight velocity with coronal height is of considerable interest. The possibility of coronal rotation can be easily ruled out, because the magnitude of the rotational velocity amounts to less than 2 km s⁻¹ at the observed heights, while the observed increase in velocity is up to 35 km s⁻¹. In addition, the eastern and western coronal regions show similar increases, which cannot be explained by rotation. The observed increase in the line-of-sight velocity may be a result of three distinct effects: (i) the existence of constant-velocity loop flows which are mainly directed towards the observer; (ii) the acceleration of the loop flow towards the loop summit; or (iii) wave propagation preferentially directed towards the observer. Though none of the above possibilities can be ruled out, it seems most likely that a flow of plasma along the loop, such as that arising from a siphon flow (Meyer & Schmid 1968; Cargill & Priest 1980; Priest 1984), produces the observed effect. Wave propagation is generally not seen in the inner regions of the corona (Parker 1983).

4 CONCLUSIONS

Our observations provide strong evidence of mass motions in the corona. Whereas the corona is found to be in a state of violent motion at the phase of solar maximum, it is quieter during the epoch of decline. The line-of-sight velocities show a systematic increase with coronal height during the solar maximum phase of 1980, with a position angle dependence, while such a correlation is not generally seen during the declining phase of 1983. It is clear from our 1980 and 1983 data that the corona was more structured in 1980 compared to 1983. A large excess of blueshifted components is seen in the 1980 coronal line profiles, which remains an enigma. Our observations also suggest that coronal loop motions were stronger in 1980 than in 1983.

ACKNOWLEDGMENTS

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