Density Structure of the Coronal Loops Derived from the 1991 Total Eclipse Observation

A. Takeda, H. Kurokawa, R. Kitai, and K. Ishiura

Kwasan and Hida Observatories, Kyoto University, Yamashina-ku, Kyoto, 607-8471, Japan

Abstract. High-resolution images of the corona obtained during the total solar eclipse on 11th July, 1991 were carefully analyzed to derive the electron densities along the loops of the green (530.3 nm) and red (637.4 nm) emission lines. We found no difference more than a factor of 2 between the averaged densities of the green and the red line loops at corresponding heights. Most of the analyzed loops were found to be approximately in hydrostatic equilibrium.

1. Introduction

A total eclipse of the sun provides a unique opportunity to obtain a set of high-quality images in several coronal emission lines and the continuum with ground-based equipment. We have succeeded in obtaining such data sets during the total eclipse of 11 July, 1991, and report herein the results from the analysis of high-resolution images of active region corona observed in the green (FeXIV:530.3nm) and the red (FeX:637.4nm) lines and the continuum. These two lines are good diagnostics of the plasma having temperatures of 2MK and 1MK, respectively, while the continuum intensity gives the total column density of the corona integrated along the line of sight.

The detail of the observation is described in Kurokawa et al. (1992). Results from the morphological analysis are given in Takeda et al. (1994a, b), in which we observed the following trends: (1) As reported in several earlier works, the structures in the red line appear to be thinner and of higher contrast than those at the green line. (2) Structures of the green and the red lines distribute quite exclusively. Namely, the axes of the loops in both lines do not coincide with each other. In addition, we conclude, from further analysis, that: (3) About a half of the continuum structures are found to have their counterparts in the green or the red lines. The contribution of the red-line structures to the continuum intensity is comparable to that of the green line, especially at the innermost corona.

In this paper, we introduce some results of studying the electron densities of hot(530.3 nm) and cool(637.4 nm) coronal loops. We show in Figure 1 the emission-line images of the observed corona used in the analysis.
Figure 1. Intensity images of the emission-line corona obtained on 11 July, 1991. Top two images are the green-line corona, while bottom two images show the red-line corona. Intensities are differently contrasted for the regions higher and lower than the height of 1.15R☉.
2. Data reduction

Observed images of the active region corona in the green and the red lines are digitized, carefully co-aligned, and converted to an absolute intensity scale. They are then separated from the continuum component expected to be contained within the filter-passbands. The coronal intensity at a point in a given emission line is written as

\[ I_E = \int_{-\infty}^{\infty} J_E(n_e, T)dy, \]

where the integration is along the line of sight, or y-direction, and \( J_E(n_e, T) \) is the volume emissivity of the line, which is a function of the electron density \( n_e \) and temperature \( T \). For an isolated loop, we divide the observed intensity into two components; one originating from the loop, \( I_{lp} \) and the other from the background corona, \( I_{bg} \), so as to satisfy the relation, \( I_E = I_{lp} + I_{bg} \). With the assumption that the density and temperature within a loop are constant along the line of sight, the intensity of the loop is reduced in the approximate form:

\[ I_{lp} = J_E(n_e, T)d, \]

where \( d \) is the diameter of the loop, which is assumed to be equal to that measured in the plane of the sky. We calculated the electron density of the loops with measured \( I_{lp} \) and \( d \) by using the emissivity table of Mason (1975), assuming \( T \) to be the ionization equilibrium temperature of the relevant ion.

Ideally, the loops to be analyzed should be isolated and have well-defined axes. It is not easy, however, to find such loops in the observed region, especially in the green line images. We selected four green-line loops and eight red-line loops, although some parts of them still may overlap with other structures. Their locations on the east and west limbs are surrounded by squares on the loop-enhanced images of the emission-line corona in Figure 2. The intensity profiles were measured along several lines perpendicular to the loop, whose locations are also shown in Figure 2. For each profile, the background intensity level was estimated in two ways; 10% higher and 10% lower level than that determined by connecting the nearest minima at both sides of the loop. These two background levels are chosen by taking account of the variation among the adjacent profiles and to give the lower and upper limits of the quantities derived from the intensity profiles. After the subtraction of the background level, the intensity and width (diameter) of the loop at each point were defined as the maximum intensity and the FWHM of each subtracted profile, respectively. From these quantities, the electron densities were calculated for the two different backgrounds with the procedure described above.

3. Results

The results are visualized in a series of plots in Figure 3. All the quantities are plotted as a function of the height above the solar limb for the two different background levels; the symbols + and \( \times \) show the quantities obtained with the 10% higher and lower background levels, respectively. In each pair of panels assembled for a loop, the left shows the distribution of the electron density
along a loop, while the right shows the variation of the loop width. Compared to the loop width, the electron densities at a given point differ little for the two background levels. This is because the electron density depends on the ratio \((I_{lp}/d)\) of the intensity to the width, both of which change parallel to each other for the two different backgrounds.

In terms of the distribution of the electron densities, there is little difference between the green- and red-line loops except for the innermost region. They are generally in the range of \(5 \text{ - } 20 \times 10^8 \text{ cm}^{-3}\) at the portion below \(1 \times 10^5 \text{ km}\), and around \(5 \times 10^8 \text{ cm}^{-3}\) at the portion of \(1 \text{ - } 2 \times 10^5 \text{ km}\). It should be noted, however, that in several red-line loops the densities exceed \(2.0\times10^9 \text{ cm}^{-3}\) at the innermost portion, which might be typical of the red-line loops. By assuming that the observed loops lie in the plane of the sky, the height variation of these electron densities are compared with those expected in the case of hydrostatic equilibrium:

\[
n_e(r) = n_e(r_1) \exp\left[-(r - r_1)/h_0 r_1 r\right],
\]

where \(r\) is the height in the corona, and \(r_1\) is a reference height. \(h_0\) is the density scale height at the coronal base in unit of the solar radius, \(R_\odot\):

\[
h_0 \equiv kT/mg_\odot R_\odot,
\]

where \(k\) the Boltzman constant, \(T\) the electron temperature, \(g_\odot\) the surface gravity of the sun, and \(m\) the mean particle mass which is taken to be 0.62 times the hydrogen mass. For \(n_e(r_1)\) being fit to the electron density measured at the lowest height and for \(T\) of 2MK and 1MK for the green- and red-line loops, respectively, the calculated curve \(n_e(r)\) is overplotted in a dash-dotted line on each panel of the electron density in Figure 3. Similarly, a broken line shows the curve in the case of \(n_e(r_1)\) chosen to be the electron density at the highest measured point.
Figure 3. Electron densities and widths of the green- and red-line loops, estimated for the two different backgrounds. Densities are compared with the hydrostatic equilibrium curve for the corresponding temperature. (see text)
As the result, we find no significant deviation from the hydrostatic curve in the green-line loops. By contrast, only a half of the red-line loops ($R_2$, $R_3$, $R_4$, and $R_5$) seem to be in hydrostatic equilibrium, whereas in the other loops ($R_1$, $R_6$, $R_7$, and $R_8$) the electron densities do not decrease so much as in the hydrostatic case. The result for the red-line loops is similar to that of Dere (1982) for the cool loops formed below 1MK, in which some loops are supported hydrostatically but others not. These non-hydrostatic loops are considered to exist only temporary, because such structures are hard to be thought of as stable.

The width of the green-line loops analyzed here tend to gradually broaden with increasing height, and be in the range of $0.5-1.5 \times 10^4$ km. By contrast, most red-line loops are less than $1.0 \times 10^3$ km in width, especially in the lower corona. While some loops broaden with height similarly to the green-like loops, the loops with clear tops tend to be either constant or narrowing in width.

The above results were compared with some previous work; the corona- graphic observation by Fort et al. (1974) and the total eclipse observation by Hanaoka et al. (1988). In Figure 4, our results are all overplotted on the left panels, in which each curve represents the variation of the arithmetic mean of the upper and lower limits. Our plots show that the densities of the green- and red-line loops are comparable. Plotted on the middle panels are the results by Fort et al., which were read from their maps of the electron densities. Their results yield that the green-line loops are a few times denser than the red-line loops. Unfortunately, as they noted, the atomic data they used for the red-line are less certain, so that the densities derived from the red line observations are similarly uncertain. The right panels show the results derived from the observation on February 16, 1980 presented in Hanaoka et al. (1988). In addition to their reported values derived from the continuum intensities, we show the electron densities newly calculated using their observed total intensity, the loop intensity, and the width of the emission-line loops following the procedure described in the previous section. For the red-line loops, however, we assumed the loop contrast to be 0.3 and 1.0, since neither the loop intensities nor background levels were not given in their paper. Although Hanaoka et al. concluded that the red-line loops must be much denser than the green-line loops, our new calculation finds the densities of the red-line loops as being comparable to, or slightly less, compared to those in green-line loops. This is consistent with the results of the present study.

We have presented so far the most reliable electron densities of the coronal loops observed in the green and red emission lines. As far as we treat the corona as an aggregate of loops, the study on loops like this provides basic data to solve a mystery on the coronal heating mechanism. In order to construct a realistic model of the corona, however, we need to know also the time evolution of the physical condition of the loops, which will be obtained by further observations with ground based coronagraphs or those from space.
Figure 4. Electron densities of the green-line loops (upper panels) and of the red-line loops (lower panels). Our results are overplotted in left panels, and are compared with some earlier work by Fort et al. (1973) (middle panels) and Hanaoka et al. (1988) (right panels), (see text).
References