CORONAL ENVIRONMENT OF QUIESCENT PROMINENCES

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(Received 7 May, 1993; in revised form 2 July, 1993)

Abstract. With the spectro-coronagraph and the multichannel subtractive double pass spectrograph (MSDP) at the Pic du Midi Observatory two quiescent prominences were observed simultaneously. From the spectro-coronagraph observations 2D maps of He I λ10830 Å, Fe XIII λ10798 and 10747 Å line intensities were obtained. In addition, we obtained 2D maps of the ratio \( R \) of the two iron lines. This ratio is used as a diagnostic for determining the density of the hot coronal plasma surrounding prominences. We found that the electron density is higher at the location of the prominences than in the corona, whereas small regions (∼40") of lower electron density are unevenly distributed around the prominences indicating that the surrounding corona is highly inhomogeneous. The density of the cavity is reduced by a factor 1.5 compared to the density of the prominence environment (∼5 × 10^8 cm^-3). We discuss the existence of cavities around these prominences according to the orientation of their axes relative to the line of sight and according to the velocity field inside the prominences. Constraints on models for prominence formation are derived.

1. Introduction

It has long been known from eclipse observations that quiescent prominences are embedded in a complex coronal structure of cavity, arch and streamer (Saito and Tandberg-Hanssen, 1973). At optical wavelengths quiescent prominences are seen to be associated with emission in the red and the green coronal lines, even if the structures observed in these lines and in Hα are not coincident everywhere (Fort and Martres, 1974; Smartt and Zhang, 1984). From Skylab X-ray photographs, Serio et al. (1979) determined the following characteristics of coronal cavities. (i) The cavities are situated above photospheric neutral lines. (ii) Only a fraction of the cavity contains filaments or segments of filaments. (iii) The average length is 600 Mm, the average width 60 Mm and the average height usually reach altitudes higher than 50 Mm.

Models for formation of prominences often invoke a condensation process, either directly by the condensation of coronal material or by the condensation of heated chromospheric material (Choe and Lee, 1992; Poland and Mariska, 1986; Wu et al., 1990; Antiochos and Klimchuk, 1991). If material is supposed to condense in a helical magnetic field, as in the models of Priest, Hood, and Anzer (1989) and Van Ballegooijen and Martens (1990), velocity effects can be expected to be seen (Wiik, Heinzel, and Schmieder, 1992). Thus, the relation between the velocity field and the mass depletion of the surrounding corona might give important clues on the formation mechanisms.
Estimates based on the assumption that prominences are formed by condensed coronal matter show that the missing mass in a cavity cannot account for the total mass of the prominence (Saito and Tandberg-Hanssen, 1973). As pointed out by Engvold (1989), these estimates do not take into consideration that the prominence mass is confined to thin threads inside the volume occupied by the prominence. Allowing a filling factor of 0.01−0.1 the missing mass in a cavity is sufficient to account for the mass of a prominence.

When observing and interpreting observational data of solar phenomena such as prominences, it is always important to take into account their topology. Ideally, the Sun is a sphere and we can determine exactly the meridian that corresponds to the limb. But, even in the most quiet regions the plasma forms different structures protruding from the surface to different altitudes. The projection of such structures is visible above the limb before their anchorage points (in the photosphere or the chromosphere). Even if the global form of the structure remains constant during the limb crossing, the projection of the structure often changes dramatically from one day to the next.

The projection effects are important for other properties than the exact global form and height of the structures. The generally filamentary structure of solar plasmas normally causes several fine structures to be superimposed along a line of sight. For objects like prominences, where the prominence axis is much longer than the other dimensions, the effect of such superposition is crucially dependent on the angle between the prominence axis and the line of sight.

When looking for coronal cavities, the effects of projection onto the plane of the sky must be considered. Assume now that all prominences are surrounded by cavities. When their axes are parallel to the line of sight, a large fraction (100−500 Mm) of the line of sight will be inside the cavity, and it will look dark relative to the surrounding corona. When observed with the axis normal to the line of sight, only a small fraction (<60 Mm) of the line of sight is inside the cavity, and it will be much more difficult to detect. In addition, the low solar spectral irradiance in the wavelength range 10 000−11 000 Å is weaker by a factor 3 than at optical wavelengths (Hα).

We analyse observations of two prominences observed simultaneously with the spectro-coronagraph and the multichannel subtractive double pass spectrograph (MSDP) at Pic du Midi. In Section 2 we discuss the topology of the prominences derived from Meudon spectroheliograms and synoptic maps in order to estimate the orientation of the prominence axes relative to the line of sight. In Section 3 we present 2D intensity and velocity maps derived from the MSDP Hα observations, as well as 2D intensity maps of He I and contour plots of the electron density derived from the spectro-coronagraph observations. The distribution of electron density around the prominences is discussed with respect to their topology and their velocity fields in Section 4. As stated in the conclusions (Section 5) it is clear that the topology is of importance when studying cavities and that the velocity fields might give important information concerning the formation of prominences.
Fig. 1. Meudon synoptic maps. (a) With segments A1 and A2 observed as a prominence on June 7, 1988. (b) With the segment A2 and its parts S1 and S2 observed as a prominence on June 11, 1988.

2. Topology

The topology of prominences can be deduced from the shape and orientation of their filaments as outlined on the Meudon synoptic map. Each synoptic map represents a solar rotation. A solar rotation begins when the central meridian of the visible hemisphere crosses the Carrington origin defined by the Carrington coordinate
system. Observations in several wavelengths are used to map the solar structures. The drawing of the filaments represents the position, shape and lifetime of their different segments. Segments of filaments that stayed more than two-thirds of the total visibility time are represented as black areas; the dashed areas correspond to a visibility time between one- and two-thirds, and the empty areas to a visibility time less than one-third. Small isolated filaments visible on a single observation are not drawn on the maps (Figures 1(a) and 1(b)).

The information in the synoptic maps on the position and orientation of the different segments of filaments can be used to reconstruct the topology of the corresponding prominences at the limb. In this procedure we have to assume that the positions and orientations do not change radically when the segments are displaced from the disk center to the limb. For polar crown filaments the rotation does not significantly influence the orientation of the filament axis as they are oriented more or less parallel to the equator. However, low latitude filaments are oriented at a larger angle to the direction of the rotation and the differential rotation therefore tends to shift the orientation of the filament axis. A careful study of spectroheliograms taken while the filament rotates from the disk center to the limb can give useful information on the development of the filament such as the orientation, formation and disappearance of different segments.

By plotting the positions and shapes of the different filament segments as seen on the synoptic maps onto a plane of heliographic coordinates, it is possible to study the topology of the prominence both in front of and behind the limb. This knowledge is of crucial importance to understand the observations of high-altitude objects such as prominences. For instance, a prominence with height 30 Mm is in principle visible over 60° of heliographic longitude (Figure 2). Depending on the relative orientation of the Sun’s rotation axis (the angle $\beta$, see below) the angles between the prominence axes and the line of sight might be very different for segments on the visible and the invisible disk.

3. Observations

Two large quiescent prominences, P1 and P2, were observed in June 1988. The angle $\beta$ describing the inclination of the Sun’s rotation axis relative the plane of the sky can reach values as high as $\pm 7^\circ$, and was equal to 0.2° on June 6 and 0.5° on June 11, 1988. The prominences were observed simultaneously with the 20 cm spectro-coronagraph and the MSDP at the Pic du Midi Observatory (see Mein, 1977). From the Meudon spectroheliograms we obtained information on the positions and heights of the prominences. The maximum altitudes of the prominences at the times of observation were 57 000 km and 49 000 km, respectively.

3.1. Hα Observations of P1: June 7, 1988 (45° SE)

The prominence was observed on the south–west limb on June 7, 1988, between 07:17 and 08:37 UT with the MSDP. From the synoptic map, Figure 1(a), it is
seen that the observations contain information on two different segments, labelled A1 and A2. Segment A1 has just crossed the limb, while segment A2 is just about to cross the limb. The angle of the filament segments with the equator is $\sim 10^\circ$. However, when plotted onto a plane of heliographic coordinates, taking into account the angle $\beta$ it can be seen that the segment A1 is more or less normal to the line of sight, while the segment A2 is approximately parallel to the line of sight.

Figures 3(c) and 3(d) show MSDP images of the prominence (Mein et al., 1989; Mein and Mein, 1991). The two prominence parts seem to be connected by a 'bridge'. Part A1 of the prominence which is already behind the limb looks like it stretches towards part A2. High velocity amplitudes are mostly located at the edges of the prominence.

3.2. H$\alpha$ OBSERVATIONS OF P2: JUNE 11, 1988 (55° NW)

The polar crown prominence P2 situated on the north–west limb was observed on June 11, 1988, between 07:42 and 08:46 UT. The corresponding filament consists of three segments labelled A1, A2, and A3 in Figure 1(b). It is only A2 that contributes to the prominence on June 11. From spectroheliograms obtained on June 13, the altitude of A1 is estimated to be 33,000 km. On June 11 A1 is situated 20–40° east of the limb and is therefore barely observable (Figure 2). The segment A3 is situated more than 40° behind the limb, too far to be visible. A2 is the longer segment of this filament. It consists of three smaller parts labelled S1, S2, and S3. The angle between these filament parts and the equator is negligible. When plotted in heliographic coordinates it can be seen that the axes of these parts are parallel...
Fig. 3. (a) He I image of the prominence P1 on June 7, 1988. The superimposed contour is the Hα contour in the MSDP field of view. (b) Contour plot of the coronal electron density (levels: 7000 to 10000 with steps equal to 500 in arbitrary units) with the He I contours. Dotted contours surround regions with densities lower than the mean coronal value, continuous lines surround regions of higher density values. The pixel size is 2.5″. (c) Hα observations (MSDP) of P1: intensity map; (d) velocity map. White represents blueshifts, black redshifts. At the limb there are non-computed pixels due to the saturation of the Hα profiles.
to the line of sight.

MSDP images of the prominence are shown in Figures 4(c) and 4(d). The small westernmost part corresponds to the filament segment S1, while the main part of the prominence, corresponds to the segment S2, or is a part of it. In the uppermost parts of the prominence, large shearing or twisting motions are observed with redshifted velocities up to 25 km s\(^{-1}\) in the northern part and blueshifted velocities up to 10 km s\(^{-1}\) in the western part (Wiik, Heinzel, and Schmieder, 1992).

3.3. IR LINE INTENSITIES

The time to scan the whole region of prominence and environment is longer for the IR lines than for H\(\alpha\). P1 was observed between 07:00 and 07:50 UT and P2 between 08:35 and 09:23 UT with the spectro-coronograph at Pic du Midi. A total of 22 slit pointings was obtained for P1 and 11 slit pointings for P2.

In four wavelength intervals, each of 7 Å, three infrared lines and continuum are observed simultaneously with the spectro-coronograph: (1) He I \(\lambda 10830\) Å, (2) Fe XII \(\lambda 10798\) Å, and (3) Fe XII \(\lambda 10747\) Å. For a detailed description of the instrument, see Noëns, Pageault, and Ratier (1984). The detectors, one for each wavelength interval, are linear arrays of diodes with 256 pixels of size 2.5". The slit of the spectrograph is positioned normal to the limb and is stepped azimuthally a distance equal to 0.5°. This corresponds to 15" at the limb. To get a complete scan of the region, a number of slit pointings are obtained. The exposure time for each slit pointing, \(\sim 1\) min, was chosen to give a reasonable intensity signal for the iron lines. This is too long for the He I line which is mostly saturated, but gives the outline of the cool prominence matter. Therefore, as the lines are observed simultaneously, we know exactly the position of the hot Fe XII emission relative to the cool He I emission. To obtain a 2D map of the intensity of the lines, the necessary interpolation between two successive slit pointings was done using a two-dimensional cubic spline interpolating procedure.

The ratio of the two iron lines, \(R = I(10789)/I(10747)\), is an increasing function of electron density in the \(10^7 < N_e < 5 \times 10^8\) cm\(^{-3}\) range (Flower and Pineau des Forêts, 1973). For higher values of the density, the ratio, \(R\), is constant and does not depend on electron density. Our data do not allow a quantitative determination of the electron density without severe assumptions on the geometry of the structures along the line of sight, but give information on the relative distribution in the corona. 2D maps of the ratio \(R\) were obtained for the two prominences P1 and P2.

4. Results

4.1. RELATIONSHIP BETWEEN THE CAVITY AND THE ORIENTATION OF PROMINENCES

The prominence P1 observed on June 7, 1988, consists of two parts A1 and A2. The axis of part A1 is more or less normal to the line of sight, while the axis of part
Fig. 4. (a) H$_\alpha$ image of the prominence P2 on June 11, 1988. The superimposed contours are the H$_\alpha$ contours of P2 in the MSDP field of view. (b) Contour plot of the coronal electron density (levels: 7000 to 10000 with step equal to 500 in arbitrary units) with the H$_\alpha$ contours. Dotted contours surround regions of densities lower than the mean coronal value; continuous lines surround regions of higher density values. (c) H$_\alpha$ observations (MSDP) of P2, maximum intensity map; (d) velocity map. White represents blueshifts, black redshifts.
A2 is approximately parallel to the line of sight. The prominence P2 observed on June 11, 1988, consists of the two parts, S1 and S2. Both prominence parts have their axes along the line of sight. Prominences with their axes along the line of sight are ideal for observing coronal cavities because a large fraction of the line of sight is inside the cavity. For the two prominences, P1 and P2, we present the He I intensity maps obtained together with contour maps of the density (Figures 3(a), 3(b), 4(a), and 4(b)). The regions of high electron density are not completely cospatial with regions of high intensity in He I. It seems that the electron density is slightly lower in the center of the high-intensity regions but increases rapidly towards the edges. The regions of low electron density above part A2 of P1 are larger than such regions around part A1, supporting our theory that the axis of the prominence must be oriented mainly along the line of sight for the cavity to be seen. However, according to the same theory P2 should be a good candidate for observing the cavity. Actually there is a complex region just above the prominence with inhomogeneous medium while a large low-density region is situated to the right of P2.

4.2. ELECTRON DENSITY IN THE CAVITY

A quantitative discussion is possible by combining the MSDP and coronagraph observations. The latter are not sufficient because of the poor calibration of the iron lines. Actually we have derived the electron density of the prominence P2 by comparing the observed Hα profiles with theoretical profiles derived from a NLTE radiative transfer code (Wiik, Heinzel, and Schmieder, 1992). An average value of $5 \times 10^{10}$ cm$^{-3}$ was found in the prominence at $T = 10^{4}$ K. If we assume that the coronal environment of the prominence (CP) is in pressure equilibrium with the prominence, we derive an average value of the coronal (CP) electron density equal to $5 \times 10^{8}$ cm$^{-3}$ at $T = 10^{6}$ K under the assumption of complete ionization of hydrogen. The quiet-Sun corona and the cavities may have lower electron density values which can be estimated from the ratio $R$, which is a relatively linear function in this density range. We reference all density values to the mean density value of the corona well above the prominences. Scans through the CP (scan A) and above the prominence (scan B) parallel to the limb are presented in Figure 5; the unit of the electron density is arbitrary. The average values for the quiet-Sun corona is $\sim$9000, for the CP $\sim$ 12 000 and for the cavity regions $\sim$8500. There is evidence for higher electron density at the location of the prominences by a factor 1.3. The cavity regions have lower electron density, reduced by 20% compared to the corona and are distributed unevenly around the prominences. The typical size (FWHM) of such regions is 40" (Figure 5).

Between the quiet-Sun corona and the CP the factor of increase of the density is 1.4. Therefore, we can derive an electron density of $3.5 \times 10^{8}$ cm$^{-3}$ in the cavity. This result is in good agreement with results obtained by Serio et al. (1979) with Skylab data. They found an average electron density value of $3 \times 10^{8}$ cm$^{-3}$ in
Fig. 5. Scans obtained at different altitudes parallel to the limb: (a) scan A through the prominence P1, (b) scan B above P1. The scans are indicated as A and B in Figure 3(b). The ordinate represents the electron density in arbitrary units. The pixel unit along the abscissa is $15''$. 
regions without a filament and half this value in regions where a filament was found. Radio observations lead to similar results (Kundu, 1979).

4.3. RELATIONSHIP BETWEEN THE CORONA AND THE BULK VELOCITY

In the prominence P2, large bulk flows have been detected leading to concepts of shears along the main axis of prominences, or of twisted flux ropes (Wiik, Heinzl, and Schmieder, 1992). In P1 such flows are also observed, principally in segment A1. These flows may give indications of the global motions of the condensing material along the field lines which contribute to the formation of the prominences by condensation. But the regions with high line-of-sight velocities observed with the MSDP do not correspond to regions of low electron density. Rather, the regions of low electron density seem to be found close to regions of mean values of the velocities (Figures 3(d) and 4(d)). Clearly, these phenomena occur on a smaller spatial scale, suggesting that high-resolution observations are required to observe the inhomogeneities of the environment of prominences.

5. Conclusion

Two prominences have been observed simultaneously with the MSDP and the spectro-coronograph at Pic du Midi in order to study the nature of cavities. The angle between the prominence axis and the line of sight is certainly important for the observation of cavities around prominences, even if the spatial resolution of our coronal observations is not sufficient to uniquely support this hypothesis.

The formation of prominences from condensed coronal matter might be observed in the form of a bulk flow of matter. With these observations it is difficult to decide whether such a relationship exists between the velocity fields of the prominences and regions of low density. However, the matter should be investigated further.

The observations of the two Fe XIII lines at 10747 Å and 10789 Å obtained with the spectro-coronograph give a good diagnostic to derive the electron density in the corona surrounding prominences. The electron density is actually higher at the location of the prominences by a factor 1.3, while small regions of low electron density, reduced by 20% compared with the coronal density, are distributed unevenly around them. If the small regions of lower electron density belong to a coronal cavity, it is highly inhomogeneous and can probably not account for the total mass of the prominence. The coordinated observations with the MSDP have led us to estimate the cavity electron density value, around $3.5 \times 10^8$ cm$^{-3}$. Certainly, a better calibration of the coronal data may help to quantify the electron densities. These results are nevertheless very promising and give new guidelines for coordinated observations between the MSDP, the coronagraph, and certainly with the future SOHO instruments, to understand better the relationships between the cool prominence plasma and the transition region with the corona.
Acknowledgements

We thank Drs. E. Tandberg-Hanssen and M. J. Martres for fruitful discussions, the anonymous referee for his suggestions and R. Hellier and C. Coutard for the MSDP observations at Pic du Midi. The MSDP data were digitized with the Mama microdensitometer of the Paris Observatory. One of us (J.E.W.) thanks the Pic du Midi Observatory (OPMT) for financial support during her stay at Pic du Midi and in Bagnères-de-Bigorre.

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