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Magnetic field and nonthermal velocities in different coronal formations on the Sun

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Abstract. Profiles of coronal lines are used to investigate plasma movements in the solar corona. The nonthermal velocities ξ within coronal holes are higher and near quiet prominences they are smaller than in quiet coronal regions ranging from a dozen to several dozens $km\ s^{-1}$. Comparison of ξ-velocity magnitudes and magnetic field characteristics in different coronal formations allows us to believe that changes of turbulence in coronal plasma are caused by magnetic field variability. The authors' own observations during several eclipses and literature data have been used.

Key words: Sun: corona – Sun: prominences – Sun: magnetic fields – turbulence

1 Introduction

It is well known that the observed half-widths of coronal lines are almost always wider than it follows from the temperature determined from ionization equilibrium temperature of the specific ions. This width "excess" is believed to be the consequence of the existence of nonthermal velocity ξ in coronal plasma. Up to now the physical nature of nonthermal velocity is not clear, but the most probable explanation consists in the magnetohydrodynamic turbulence.

In this paper, data on the turbulent velocities observed in quiet corona (QC), coronal holes (CH) and regions surrounding quiet prominences (QP) are analysed. The authors results obtained during the total solar eclipses in 1968, 1981 and 1999 and results from the ground-based and cosmic observations in visible and extreme ultraviolet spectral ranges (literature data) have been used. Every coronal formation is characterized by its own magnetic field features. Near sunspot minimum coronal holes are known to be generally unipolar with minority-polarity fields being weak in comparison with majority-polarity ones, and what is more, the magnetic field becomes more unipolar with height above solar surface as the greater part of the minority-polarity magnetic field lines closes down and becomes trapped inside magnetic bipoles lying at low levels of the coronal holes. The magnetic field strength within coronal holes is higher than the background magnetic strength. In long-lived quiet prominences the magnetic field is relatively stable. A relation between turbulent (nonthermal) velocities and magnetic field characteristics are considered.

2 Observations and results

The collisional ionization in the solar corona is supposed to be caused by a Maxwellian electron velocity distribution. Deviations from the Maxwellian distribution are known to exist at low densities and high temperature gradients in the transition region (Roussel-Dupre 1980; Pinfield et al. 1999) and are displayed in extreme line wings. Really the profiles of the coronal lines have been found to be fitted well enough to a single or the sum of several Gaussians. After correction for the instrumental broadening the Doppler half-width of the line is

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$$\Delta\lambda_D = \frac{\lambda}{c}\sqrt{\frac{2kT}{m} + \xi^2}, \tag{1}$$

where m is the mass of the ions, k is the Boltzmann constant, c is the velocity of light, ξ is the nonthermal velocity, λ is the standard wavelength of the emission line and T is the ionization temperature. Assuming T to be equal to the temperature corresponding to the maximum abundance of a given ion, one can estimate the turbulent velocity in different coronal structures, knowing $\Delta\lambda_D$ from the observations.

In this paper the results of our own observations during several solar eclipses are revised. The installations with Fabry-Perot interferometers for different lines together with the corresponding interference filters were employed. The interference filters with a full widths of 15 Å for the Fe XIV green line and $H\alpha$ line were used as premonochromators (Delone, Makarova 1975; Delone et al. 2002).

On the 5303 Å interferogram obtained by Makarova during the solar eclipse of 1968 (Delone, Makarova 1975) twenty six line profiles were measured around a quiet prominence. The average magnitude of $\Delta\lambda_D$ is found to be equal to 0.604 Å giving the mean turbulent velocity $\xi = 24$ km s^{-1}, if we assume T to be equal to the value 2×10^6 K usual for the green coronal line. Far from the prominence $\Delta\lambda_D = 0.720$ Å and, correspondingly, $\xi = 32$ km s^{-1}. Above the south pole at the height of $90''$ from the limb $\Delta\lambda_D = 0.94$ Å and $\xi = 50$ km s^{-1}. For the 1981 total solar eclipse the average ξ value seems to be by 25 percent smaller around the quiet prominence than in other coronal regions.

Our results agree with the results by Tsubaki (1975), who analysed the observations of the corona formation near the long-lived quiet prominence in the Fe ions lines 5303, 6374, 7059, 7892 ÅÅ on 23 March 1974. The observations were fulfilled on the Sacramento Peak coronograph. The slit of the spectrograph was parallel to the solar limb. The mean value of the turbulent velocity was 13.1 km s^{-1}, ranging from 6 km s^{-1} to 16 km s^{-1} depending on the slit cut position. The smallest values of ξ correspond to the cut nearest to the solar limb where the contribution from the QP was the highest. We can consider as a first approximation these results as a characteristic of the turbulent movements in the cavity around the quiet prominence. Really there are contributions from quiet corona. We see that in this case, as it was discussed above for the solar eclipses of 1968, 1981, the nonthermal velocities around the prominences are smaller than in the quiet corona far from the prominences, if we compare them with the mean value of ξ in the quiet corona. As it was discussed in (Delone et al. 2003), the mean value of ξ for the quiet corona ($6.0 < lgT < 6.4$) is equal to 18 km s^{-1} according to numerous investigations of the coronal line profiles.

During the August 11, 1999 eclipse two quiet prominences were observed at the solar limb, while near the eastern limb there were two small coronal holes (according to SGD). This allowed us to compare nonthermal velocities using the half-widths of the λ 5303 line profiles obtained under equal conditions in different coronal structures. Assuming T = 2×10^6 K everywhere, we found $\xi = 14 km$ s^{-1} near the quiet prominence, $\xi = 20$ km s^{-1} in the quiet corona and $\xi = 32$ km s^{-1} in the CHs. Since according to numerous investigations a coronal hole is cooler than the quiet corona, the turbulent velocity in CH must be higher than derived by us with the same temperature in different coronal structures. If we assume in CH $T = 1.3 \times 10^6$ K according to Tu (1998), then ξ will be equal to 31 km s^{-1}. Possibly, during the 1968 solar eclipse a coronal hole existed above the south pole of the Sun. That is why the Doppler half-widths in this coronal place were also higher than in the neighbouring regions. Thus, it is obvious that the turbulent velocities are lower in the coronal sites with an invariable field.

Numerous studies devoted to investigation of nonthermal velocities in CH lead to the conclusion that ξ in CH increases with height, they are higher between plumes than in plumes and higher in CH than in the quiet corona. For example, according to the results derived by Banerjee et al. (1998), on the basis of observations from SUMER SOHO in the Si VIII line (λ1445.75 Å) and the supposition that T in CH was homogeneous ($T \sim 10^6$ K), the average turbulent velocities were found to be 27 km s^{-1} at a height of $27''$ and 46 km s^{-1} at a height of $250''$ above solar limb.

Observations from SUMER SOHO during 1996–1997 in the Mg IX 706, 750 and Si VIII 1440, 1445 lines in the coronal holes near the north and south solar poles showed that the typical full velocities, being the sum of the thermal and turbulent velocities were ~ 43 km s^{-1} in plumes and ~ 55 km s^{-1} between plumes (Wilhelm et al. 1998). If we assume that T is equal to the generally accepted temperature of the line formation $lgT(MgXI)$=5.95 and $lgT(SiIX)$=5.99 (under the ionization equilibrium assumption in the CH) (Wilhelm et al. 1998), then we can calculate the values of the nonthermal velocities from the full velocities. The values of ξ change in the range from 30 to 60 km s^{-1}, with the average $\xi = 45$ km s^{-1}, which is higher than in the quiet corona.

In (Raju et al. 2000) the nonthermal velocities in a large CH near the north pole and nearby quiet regions were obtained from the observations fulfilled during $6^{\mathrm{h}}\!.3$ on November 3, 1998 at the coronograph of the Norikura Solar Observatory in the coronal red line λ 6374 Å with a CCD. The nonthermal velocities were found to be in the range from 14 to 36 $km\ s^{-1}$ in CH, and in the range from 10 to 30 $km\ s^{-1}$ in the QC, the average magnitudes are 24 $km\ s^{-1}$ and 15 $km\ s^{-1}$, correspondingly. The coronal images in the Fe IX and Fe X 171 Å and Fe XII 195 Å lines from EIT SOHO were used to make temperature maps of the corona at the time moments of the Norikura observations. The formation temperatures of the UV lines of the Fe ions and red Fe X line are the same, about 10^6 K.

Doschek and Feldman (1977) found $\xi = 18.3\ kms^{-1}$ in the quiet Sun region and $\xi = 22\ km\ s^{-1}$ in CH using the Si VIII (1446 Å) and Fe X (1463 Å), Fe XI (1467 Å) and Fe XII (1242 Å and 1349 Å) line profiles observed from Skylab. The temperatures were in the range from 9.3×10^5 K (Si VIII) to 1.7×10^6 K (Fe XII).

Hassler, Moran (1994) found that the nonthermal velocities within a coronal hole near the south pole changed in the range from 40 to 60 $km\ s^{-1}$, while the height above solar limb increased up to 1.16 $R_{\odot}$. The observations were carried out at the Sacramento Peak Observatory Coronograph with a CCD camera in the Fe X (6374) line.

So, the turbulent velocities seem to be smaller in the cavities around quiet prominences than in the quiet corona far from them and higher within coronal holes than in the quiet corona.

3 Discussion

As is seen from the results cited in the previous section the thermal velocities observed at different times in a similar coronal structures are different from each other. So in quiet corona regions ξ varies in the range from $\sim$ 10 to 32 $km\ s^{-1}$, in CH the values of ξ are between 14 and 60 $km\ s^{-1}$ and can be even higher. The statistics of this magnitudes is convincing. Unfortunately, there are not many observations of the corona nearby quiet prominences. In the cavities surrounding QP the nonthermal velocities vary in the range from 6 to 24 $km\ s^{-1}$.

No doubt the variability of ξ reflects to some extent real differences in physical conditions in definite coronal formations and their temporal behavior. However ξ-variability can be partly due to systematic errors of background corrections (specially for observations carried out during solar eclipses). However in every specific case ξ in the vicinity of a quiet prominence is always smaller than in the quiet corona regions, and on the contrary ξ in CH is higher than in the quiet corona. The results obtained by us from the observations during the eclipse in 1999 are particularly valuable. The ξ magnitudes in three different types of coronal formations were registered simultaneously in the same system, which confirms the regularity of the turbulent movements in the corona.

Coronal holes and coronal cavities surrounding quiet prominences are distinguished from the quiet corona by their low densities (Wielhelm 1998; Waldmeier 1970). A decrease in density can result in an increase in the nonthermal velocities (Banerjee 1998). But the turbulent velocity is higher in CH and smaller near the QP in comparison with surrounding quiet corona. Hence the low densities and low turbulent velocities in the vicinities of quiet prominences contradict each other and higher magnitudes of ξ in CH do not seem to be explained fully by the low density.

What else can distinguish coronal holes and coronal cavities around quiet prominences from the surrounding quiet corona? The magnetic field is known to be relatively stable in long-lived quiet prominences and continuously changeable in CHs. Harvey et al. (1982) investigated magnetic field changes in coronal holes during 1975–1980. They pointed out that the average magnetic field strength lies between 3 and 36 Gauss during the maximum of the solar activity and does not exceed 1–7 Gauss during the solar minimum. Investigating recurrent CH near the maximum of solar activity, the authors pointed out that frequent emergences of new magnetic fluxes change the boundaries of CH so strongly that they appear topologically different in subsequent solar rotations. The authors write that such activity is responsible for large changes of fluxes, sizes and average field strength that are observed for some CH from one rotation to another. Bilenko and Kononovich (1999) showed that in the period of increasing solar activity in 1996–1999 the total magnetic flux in the CH regions was 2–3 times higher than in the nearby quiet coronal regions.

Wang et al. (1997) found that darker part of coronal hole in Fe IX 171 and He II 304 occur where little flux of either polarity exists or where an isolated flux of the dominant polarity is observed. Malanushenko and Stepanyan (2001) investigated a case where during several days an emergence of weak (< 7 G) magnetic field in some separate structures inside a CH was observed. At first their total area grew slowly, then the rate of growth of the area and the magnetic field sharply increased. The authors also emphasize numerous cases where in the $\lambda 10830$ solar images the coronal holes are surrounded by a bright border, which, as they suggest, represents the increasing magnetic flux. The very existence of a CH is connected with the evolution of the magnetic flux. As pointed by Malanushenko (2002), a CH is destroyed when its internal magnetic flux approaches its boundaries.

The relation between the magnitude of turbulent velocity and the changes of magnetic field is obvious from comparison of the magnitudes of nonthermal velocities for coronal regions around a quiet prominence (QP), in a quiet corona (QC) and a coronal hole (CH):

$$\xi_{QP} < \xi_{QC} < \xi_{CH}.$$

It is not yet understood whether the increase in turbulence causes the magnetic field to grow or, on the contrary, the field variation forces plasma turbulization. The process of emergence of the magnetic flux as due to turbulence was described by Parker (1979). On the other hand, according to Parker, there is no indication that the magnetic field has an effect on turbulence. Contrary to Parker's suggestion, observations have provided such an indication as it is discused in this section.

The rotational velocity of the CH is known to differ from the rotational velocity of the background magnetic field. The change in the differential rotation with solar activity cycle is more significant in the coronal holes than in the background magnetic field (Stepanyan, Malanushenko 2001).

Only point structures and no fibrils are seen in a coronal hole in the $H\alpha$ line when observing in the centre of the solar disk. It means that the magnetic field lines in the CH are spreading radially. Suppression of the oscillations in the CH at the photospheric level (Malanushenko 2002) gives evidence that the coronal hole roots are located in subphotospheric layers. Hence, CH are connected with the magnetic fluxes the source of which is situated deeper than the source of the background magnetic field. And it is natural to suppose that ascending deep fields cause growth of turbulence in the transition region and the corona rather than turbulence of the upper atmosphere is responsible for the change in these deep magnetic fields.

Thus, comparing the nonthermal velocities near quiet prominences, in quiet coronal regions and coronal holes with the magnetic field characteristics of the formations, we can conclude that the turbulence increase is caused by magnetic field changes.

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