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Magnetic field and turbulent velocities in the solar corona

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[1] Observations conducted by the authors during total solar eclipses in 1968, 1981, and 1999 and the results of noneclipse observations in the visual, IR, and far UV regions of the solar spectrum obtained both on the ground and in the space (according to publications of other authors) are considered. The relation of nonthermal velocities to characteristics of the magnetic field is studied. The nonthermal velocities in coronal holes are found higher than in quiet corona. In quiet corona they are higher than in the coronal cavity around a quiet prominence. A conclusion is drawn that the difference in the turbulence in various structural formations in the corona is related to the magnetic field variability.

INDEX TERMS: 7509 Solar Physics, Astrophysics, and Astronomy: Corona; 7511 Solar Physics, Astrophysics, and Astronomy: Coronal holes; 7524 Solar Physics, Astrophysics, and Astronomy: Magnetic fields; *KEYWORDS:* Coronal magnetic fields; Coronal turbulence; Coronal formations.

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1. Introduction

[2] It is widely known that the observed profiles of coronal lines almost always are wider than one would expect if their widths were determined only by thermal motions of the emitting ions. This "excess" is usually explained by the presence of nonthermal velocities in the corona.

[3] *Chae et al.* [1998] studied long observations of 17 lines of various ions ($\lambda = 625 - 1551$ Å). The temperature of formation of these lines (from 10^4 K to 2×10^6 K) covers a large height range from the chromosphere to the upper layers of the transition region and coronal layers. *Chae et al.* [1998] found that the nonthermal velocities ξ increase with an increase of T reaching a maximum of ~30 km s^{-1} at $T = 3 \times 10^5$ K and decrease to ~20 km s^{-1} in the corona. *Delone et al.* [2003] collected data on 18 publications confirming this result.

[4] The increase in the nonthermal velocity ξ with an increase in the temperature in the transition region agrees with theoretical predictions. For example, it was demonstrated by *Mariska et al.* [1978] considering propagation of Alfvén or sonic waves without dissipation. However, the decrease of ξ with T in the region of coronal temperatures $\log T_e \sim (5.8 - 6.4)$ is not understandable especially taking into account that at further increase of the temperature ($\log T_e > 6.4$) an increase in ξ is observed again [*Hara and Ichimoto*, 1999; *Harra-Murnion et al.*, 1999]. Possible this increase is related to the fact that the temperature and nonthermal velocity are higher in active regions than in the quiet corona [*Delone et al.*, 2003; *Dere and Mason*, 1993].

[5] In this paper we analyze the observations of nonthermal velocities in quiet corona, in coronal holes (CH), and in the regions adjacent to quiet prominences. The results that we obtained during the total solar eclipses in 1968, 1981, and 1999, and also the results of noneclipse observations in the visual, IR, and far UV regions carried out both on the ground and in space (using publications of various authors) are used. The relation of nonthermal velocities to characteristics of the magnetic field is also considered.

2. Method of Determination of Nonthermal Velocities and the Observational Results

[6] At low-density and high-temperature gradient in the transition region and corona [*Pinfield et al.*, 1999; *Roussel-Düpre,* 1980] a deviation from the Maxwell velocity distribution is observed. However, the deviation is influencing considerably the far wings of the line. The observed profiles of coronal lines are well represented by a Gaussian even at the level of Doppler widths measurements. The Doppler half width of a line (after taking into account the instrumental

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profile) is determined by the well-known expression

$$\Delta\lambda_D = \frac{\lambda}{c}\left(\frac{2kT}{m} + \xi^2\right)^{1/2}$$

where ξ is the nonthermal velocity. Taking the temperature T equal to the temperature of the maximum abundance of the given ion and using $\Delta\lambda_D$, turbulence velocities are evaluated both in the coronal hole and in the vicinity of quiet prominences where the magnetic field is stable, the fact making it possible for the shape of such prominences to stay unchanged during several solar rotations.

[7] On 23 March 1974 a coronal formation in the vicinity of a long-living prominence was observed at the coronograph of the Sakramento Peak observatory in the Fe ion lines 5303 Å, 6374 Å, 7059 Å, and 7892 Å [*Tsubaki*, 1975]. The spectrograph slit was positioned in parallel to the solar limb. At all cuts passing the prominence, a local minimum of the intensity of the coronal lines and Doppler temperature T_D corresponding to the prominence position were observed. The value of T_D was determined from

$$\Delta\lambda = \frac{\lambda}{c}\left(\frac{2kT}{m}\right)^{1/2}$$

The electron temperature value was determined from the ratio of the intensities of the lines $\lambda 7059/\lambda 5303$. Usually, an equality of ionization and electron temperatures is taken for the coronal plasma. Using this assumption the values of ξ averaged over cuts parallel to the limb are calculated from the value of $T_D = T + \xi^2 m/2k$. The value of the nonthermal velocity varies (depending on the cut number) within the limits from 6 to 16 km s^{-1}, the mean value of ξ being 13 km s^{-1}.

[8] We can assume with some stretch that this value characterizes nonthermal velocities in the cavity surrounding the quiet prominence. Actually, these estimates are contaminated by the contribution from the quiet corona with different weight for different cuts.

[9] For the cut closest to the limb this contribution is minimal. For this cut $\xi = 6$ km s^{-1}. According to *Delone et al.* [2003] the mean value of ξ for the quiet corona in the temperature region $6.0 < \log T_e < 6.4$ is 18 km s^{-1}. We see that the nonthermal velocities in the cavity surrounding a quiet prominence are less than in the quiet corona.

[10] We reconsidered the results of our observations of solar eclipses and obtained a confirmation to the conclusions discussed above. Observations during eclipses were carried out at installations using Fabry-Perot etalons and narrow interference filters as premonochromators. Using the interferogram of the corona in the $\lambda = 5303$ Å line obtained by *Delone and Makarova* [1975] during the 1968 eclipse, we measured 26 profiles around a quiet prominence. The mean Doppler half width in this region is $\Delta\lambda_D = 0.604$ Å. At the corona temperature of 2×10^6 K the turbulent velocity in the vicinity of the quiet prominence is 24 km s^{-1}. Far from the prominence we obtained $\Delta\lambda_D = 0.720$ Å and, respectively, the mean calculated velocity $\xi = 32$ km s^{-1}. The line profiles above the southern pole at altitude $90''$ above the limb had larger Doppler half widths (averaged $\Delta\lambda_D = 0.948$ Å) and turbulent velocity ($\xi = 50$ km s^{-1}). Using the interferograms obtained in the $\lambda = 5303$ Å line during the 1981 eclipse [*Delone et al.*, [1988], we obtained the nonthermal velocity around a quiet prominence ξ by 25% less than in other coronal regions.

[11] During the 11 August 1999 eclipse, two quiet prominences were observed. In the eastern region according to the Solar Geophysical Data, there were two small coronal holes located close to the limb on the disk. This provided a chance to compare the nonthermal velocities obtained from the 5303 Å line half widths for all studied coronal structures (CH, coronal cavity around the quiet prominence, and quiet corona) in the same system. Assuming in all formations that $T = 2 \times 10^6$ K, we obtain in the vicinity of the quiet prominences $\xi = 14.4$ km s^{-1}. In quiet (undisturbed) region of the corona $\xi = 20$ km s^{-1} and in CH $\xi = 28$ km s^{-1}. It is known from a series of publications that the temperature in a coronal hole is lower than the temperature of quiet corona. Therefore the turbulent velocity in CH should have been even higher than the temperature determined with the same $T = 2 \times 10^6$ K for all regions. If one assumes the temperature in a coronal hole $T = 1.3 \times 10^6$ K [*Tu et al.*, 1998], the nonthermal velocity in the CH would be $\xi = 31$ km s^{-1}. Apparently, in 1968 [*Delone and Makarova*, 1975] a coronal hole also existed over the southern pole. That is why the Doppler half widths in this place of the corona were higher than in the adjacent regions.

[12] Observations on board Solar Ultraviolet Measurements of Emitted Radiation (SUMER) Solar and Heliospheric Observatory (SOHO) during several months in 1996–1997 in the lines: Mg IX (706 Å and 750 Å) and Si VIII (1440 Å and 1445 Å) near the southern and northern poles of the Sun over coronal holes showed that the electron temperature along plumes $T_e < 0.8 \times 10^6$ K, whereas in interplume lanes $T_e < (0.75 - 0.88) \times 10^6$ K [*Wilhelm et al.*, 1998]. Typical velocities obtained from Doppler half widths of the line were $V_D \sim 43$ km s^{-1} within the plumes and $V_D \sim 55$ km s^{-1} in the interplume regions. *Wilhelm et al.* [1998] noted that the assumption on the ionization equilibrium provided by collisions (and so the equality $T_e = T_i$) apparently is not fulfilled within a CH. This is emphasized also by some other authors on the basis of observations. On this basis, *Wilhelm et al.* [1998] did not try to separate the line half width to the thermal and turbulent components. The values presented above are the total velocities. However, if one assumes that T_i is equal to the commonly accepted temperature of formation of the lines ($\log T_i(\mathrm{Mg\,XI}) = 5.95$ and $\log T_i(\mathrm{Si\,IX}) = 5.99$), then on the basis of the data of *Wilhelm et al.* [1998] one can calculate the values of the nonthermal velocities in coronal holes. The values of ξ vary from 30 to 60 km s^{-1}. The average value $\xi = 45$ km s^{-1}, which is higher than in the ambient corona.

[13] According to numerous publications dedicated to studying of nonthermal velocities in coronal holes, the value of ξ increases with height. For example, according to the data by *Banerjee et al.* [1998] based on SUMER SOHO measurements in the line Si VIII ($\lambda = 1445.75$ Å) and the assumption on homogeneous temperature ($T \sim 10^6$ K) in CH, the turbulent velocities are $\xi = 27$ km s^{-1} at an altitude of $27''$ over the limb and $\xi = 46$ km s^{-1} at an altitude of $250''$. The nonthermal velocities are higher in the interplume regions and higher than in quiet corona.

[14] Using the observations at Norikura coronograph in the $\xi = 6374$ Å line conducted on 3 November 1998 by the CCD matrix in the vicinity of the north pole of the Sun in a large coronal hole and adjacent quiet corona during 6.3 hours, *Raju et al.* [2000] obtained that the nonthermal velocities within CH and quiet corona lie in the limits from 14 to 36 km s^{-1} and from 10 to 30 km s^{-1}, respectively. The average values of ξ are 24 km s^{-1} in CH and 15 km s^{-1} in quiet corona. The temperatures are about 1.08×10^6 K in CH and 1.2×10^6 K in quiet corona.

[15] The corona images in the lines $\lambda = 171$ Å (Fe IX, Fe X) and $\lambda = 195$ Å (Fe XII) obtained at the Extreme Ultraviolet Imaging Telescope (EUIT) SOHO were used to draw temperature charts of the corona for the moments of observations at the Norikura coronograph in the $\lambda = 6374$ Å. The temperature of formation of the UV lines of Fe ions is about 10^6 K, that is the same as the temperature of formation of the red line.

[16] Using the profiles of the lines of Si VIII (1446 Å) and Fe X, Fe XI, and Fe XII in the range of $\lambda \sim 1242 - 1467$ Å, observed on board the Skylab spacecraft (the spatial resolution $2'' \times 60''$), *Doschek and Feldman* [1977] obtained $\xi = 18.3$ and 22 km s^{-1} in the quiet region and coronal hole, respectively. The temperature was taken the same both for CH and quiet region: $T \sim 1 \times 10^6$ (Si VIII) to 1.7×10^6 (Fe XII) K.

[17] Using the observations at Sakramento Peak observatory in the 6374 Å line carried out in September 1992 in the CH near the southern pole, *Hassler and Moran* [1994] obtained that the nonthermal velocities are varying in the range from 40 to 60 km s^{-1} with an increase of the distance over the limb (up to $r = 1.16 R_\odot$). Thus the turbulent velocities in a coronal cavity around quiet prominence are lower than in the ambient quiet corona, whereas the velocities in CH are higher than in the quiet corona.

3. Discussion and Conclusions

[18] The values presented above of the nonthermal velocities for the same formations in the corona are significantly different not only according to various authors but also according to our observations carried out during different eclipses. No doubts, these results manifest in some sense real differences in physical conditions in various places in the corona and their variability with time. However, (during eclipse observations) the variability from one occasion to another probably is partly related to systematic errors in taking into account the background. However, it is important that in each particular observation the nonthermal velocity in the vicinity of a quiet prominence is always less than in the undisturbed corona, whereas in a coronal hole the velocity is always higher than in quiet corona. The result we obtained during the 1999 eclipse is especially valuable because of the scatter of the observational results obtained by different authors. We determined the values of ξ for all three different structural formations in the corona within the same system, this fact reliably confirming the obtained regularity.

[19] The CH region and the coronal cavity around a quiet prominence are characterized by the density depleted as compared to the quiet corona [*Waldmeier*, 1970; *Wilhelm et al.*, 1998]. The depleted density can lead to an increase of nonthermal velocities [*Banerjee et al.*, 1998], but this is not observed in the cavity around a quiet prominence. The observations show that ξ is increased in CH, but reduced in the cavity around a quiet prominence as compared to the ambient environment. Therefore the depleted density cannot completely explain high nonthermal velocities also in CH. Until now the physical nature of the additional nonthermal broadening of spectral lines is not fully clear. Observations show that the nonthermal velocities are isotropic and processes causing them have short timescale and small space-scale nature. The most plausible mechanism is thought to be magnetohydrodynamic turbulence [*Chae et al.*, 2000; *Delone et al.*, 2003; *Dere and Mason,* 1993; *Dmitruk and Gomez*, 1997; *Doyle et al.*, 1998; *Gomez et al.,* 2000; *Voitenko and Goossens*, 2002]. The magnetic field in coronal cavity around a quiet prominence is relatively stable, whereas in the CH that is unstable.

[20] *Harvey et al.* [1982] studied variations in the magnetic field within CH during 1975–1980. They noted that the mean magnetic field strength in the maximum of solar activity lies within the range of 3–36 G, whereas in the activity minimum it does not exceed 1–7 G. Studying recurrent CHs around solar activity maximum, *Harvey et al.* [1982] noted that frequent emergences of the new flux change the boundaries of the coronal holes so strongly, that CH look topologically different during the sequent rotations of the Sun. Such activity is responsible for strong changes in fluxes, dimensions, and average strength of the field observed in some coronal holes from one rotation to another [*Harvey et al.*, 1982]. *Bilenko and Kononovich* [1999] showed that in the epoch of rising solar activity in 1996–1999, the total magnetic flux in the region of coronal holes was by a factor of 2–3 higher than in the adjacent undisturbed coronal regions.

[21] *Wang et al.* [1997] have found that the most dark parts of a coronal hole coincide with the area in the magnetograms in the $\lambda \sim 8542$ Å (the chromospheric level) where there are small fluxes of contaminating polarity or where there are isolated spots of the main polarity. *Malanushenko and Stepanyan* [2001] studied the case when during several days an emergence of a weak magnetic field (< 7 G) was observed in the CH in the form of separated formations. At the beginning the total area of these formations grew slowly, then the rate of the growth of this area and the magnetic field strength increased sharply. The same authors note frequent cases when on the Sun image in the $\lambda \sim 10,830$ Å line the activating region within the coronal hole is surrounded by a light rim. They interpret this fact as a manifestation of a magnetic flux output. *Malanushenko* [2002] noted that CH is destroyed when the magnetic flux formed inside the hole comes to its boundaries. *Malanushenko* [2002] concludes that the coronal hole existence itself is related to changes in magnetic flux.

[22] The relation of the value of the turbulent velocity to variations in the magnetic field is obvious from the comparison of the values of nonthermal velocities for the coronal

region around a quiet prominence, in quiet (undisturbed) corona and in a coronal hole:

$$\xi\{\text{around quiet prom}\} < \xi\{\text{quiet cor}\} < \xi\{\text{coronal hole}\}$$

[23] The question is still left: What is the cause and what is the result. Does the turbulence increase lead to an increase in the magnetic field (as was shown by *Parker* [1982], or vice versa changes in the fields lead to plasma turbulization? *Parker* [1982] stated that there is no indication that the magnetic field influence turbulence in general. At the same time, the analysis of the observational data presented above demonstrates that there are such indications.

[24] It is known that the rate of the coronal hole rotation differs from the rotation rate of the background magnetic field. The change in differential rotation with solar activity of the coronal hole with an open magnetic configuration [*Stepanyan and Malanushenko*, 2001] is stronger than of the background magnetic field. While observing a coronal hole in the center of the solar disk in the H_α line only point-like structures are seen and there is no fibriles. This shows that the magnetic field in the coronal hole is radial. Observations fulfilled in the Crimean Observatory (Ukraine) in 1999 demonstrated that five minutes oscillations were suppressed at the photospheric and chromosphere levels of the CHs in comparison with quiet regions on the Sun outside CH [*Malanushenko*, 2002]. The suppression of the oscillations in the coronal hole manifests that the roots of CH are in underphotospheric layers. Therefore the CHs seem to be solar formations originating under the photospheric layer and stretching up to the chromosphere. As it was concluded by *Malanushenko* [2002] the CH are related to the fluxes of the magnetic field the source of which is located deeper than the source of the background magnetic field.

[25] So it is natural to suggest that not changes in these deep fields are caused by the turbulence of the upper atmosphere, but rising up of deep fields lead to the increase of the turbulence in the transition region and corona.

[26] Thus, comparing the nonthermal velocities in the coronal plasma around quiet prominences, in quiet (undisturbed) coronal regions, and in coronal holes to the magnetic situation, we can conclude that the turbulence difference is caused by differences of the magnetic field in the considered formations. The turbulent increase in CH with changeable (by flux, topology and strength) magnetic field with open configuration is possibly due to enhanced wave dissipation as in comparison with closed-field quiet regions of the corona or coronal cavities around quiet prominences with relatively stable magnetic configuration.

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