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Heating the magnetically open ambient background corona of the Sun by Alfvén waves

H. Peter[1] and C. Vocks[2]

[1] Kiepenheuer-Institut für Sonnenphysik, 79104 Freiburg, Germany
[2] Astrophysikalisches Institut Potsdam, 14482 Potsdam, Germany

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Abstract. Observations of UVCS/SOHO of very high emission line widths in the outer corona suggest that the open field regions there are heated by ion-cyclotron resonance absorption of Alfvén waves resulting in the ions being much hotter than the electrons. In the lower corona it is usually assumed that the effective Coulomb-interactions ensure equal temperatures of ions and electrons. However, recent models have shown that in regions of strong magnetic field gradients the ion-cyclotron absorption can be so efficient that the ion temperature overcomes the electron temperature.

In this paper we will present new observational results from SUMER/SOHO showing that the lines of O V and S VI have very large line widths just above the limb. The peak line width occurs at about 10″ above the limb and corresponds to ion temperatures of more than 3×10^6 K. We compare these observational results to new models in which plasma in coronal funnels is heated and accelerated by means of ion-cyclotron absorption of high-frequency waves. As our model is in good qualitative agreement with the observations we come to the conclusion that the open corona in coronal funnels could well be heated by an ion-cyclotron absorption mechanism, even close to the Sun in the low corona.

Key words. Sun: corona – Sun: solar wind

1. Introduction

Images of the solar corona are dominated by loop-like structures which are concentrated above active regions with strong magnetic fields. Outside these active regions, in the "quiet Sun", the emission formed in the upper atmosphere at temperatures up to 300 000 K is enhanced above lanes outlining super-granular convection cells, where the photospheric magnetic field is accumulated. At higher temperatures, i.e., into the corona, this network with a typical cell size of 20 to 30 Mm is vanishing (Reeves 1976). Rooted in the network, magnetic funnels are rapidly widening to fill the whole space in the corona (Gabriel 1976). Below these magnetically open funnels small magnetically closed loop-like structures have to exist if one is to understand the emissivity observed in emission lines formed below 100 000 K (Dowdy et al. 1986; Peter 2001).

Initially bright loop systems as seen in EUV or X-ray wavelengths by the TRACE or Yohkoh satellites seem to be the most rewarding objects representing the magnetically closed corona. However, these active regions fill only a fraction of the space available. To investigate the major part of the corona and also the acceleration of the solar wind near the solar surface we have to study the darker ambient background corona, even though this seems, but only at first glance, less exciting. Coronal holes, regions of significantly reduced emission from the corona, are mainly magnetically open and dominated by coronal funnels. When observing quiet solar regions above the limb with no high arching loops the emission some 1000 km above the limb should be dominated by open coronal funnels as well (cf. Fig. 1). In this paper we will investigate the properties of these open structures above the limb and for the first time present evidence for heating of the lowest open corona by high-frequency Alfvén waves. This conclusion is based on a comparison of spectroscopic observations with a kinetic model for coronal heating in a coronal funnel, the basic constituent of the open background corona.

Send offprint requests to: H. Peter,
e-mail: peter@kis.uni-freiburg.de

2. Line width observations across the limb

The observations presented here have been obtained on 13 June 2000 using the SUMER spectrometer (Solar Ultraviolet Measurements of Emitted Radiation; Wilhelm et al. 1995) on-board the SOHO spacecraft (Solar and Heliospheric Observatory; Fleck et al. 1996). The 0.3″ × 120″ spectrograph slit (# 7) was used to observe the south-east limb (Fig. 1) from 15:58 to 17:48 UT with detector A with exposure times of 100 s. We will concentrate on profiles of the emission lines of O V at 62.9 nm formed at about 240 000 K and of S VI at 93.3 nm formed at 190 000 K, while we have analysed a much larger number of lines from higher and lower temperatures. For each profile a single Gaussian fit was calculated

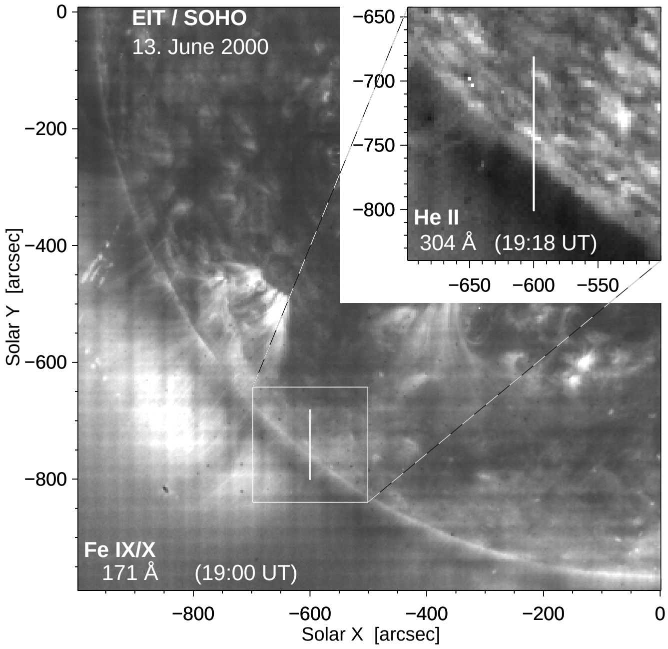

Fig. 1. The area on the Sun under study here seen in light from the million Kelvin corona (Fe IX/ X lines) and from the cool chromosphere (He II). The vertical line shows the position of the slit of the SUMER spectrograph used to acquire the emission line profiles. The slit was positioned well outside regions of coronal activity, i.e. in the ambient background corona. (Images from SOHO/EIT.)

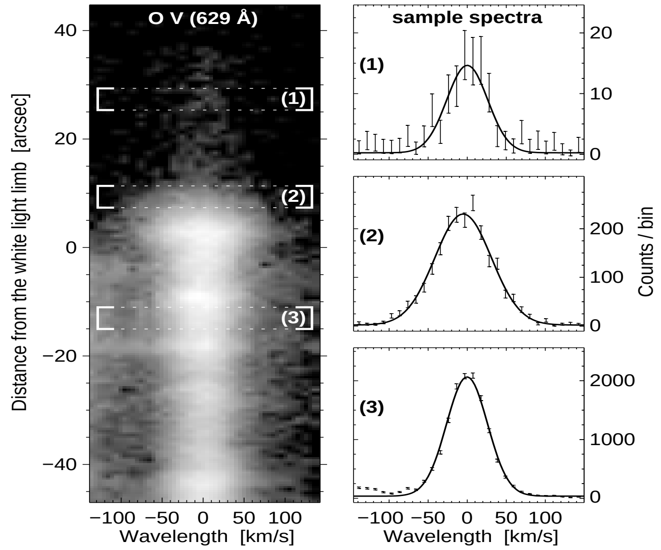

Fig. 2. Spectrum in the line of O V at 62.9 nm (left panel) at the approximate slit location shown in Fig. 1. Note that the emission of this line formed at about 240 000 K extends well above the white light limb of the Sun. The right panels show individual spectra as bars (Poisson statistics; spatially binned) at the location along the slit indicated at the left panel. The solid lines are single Gaussian fits to the line profiles.

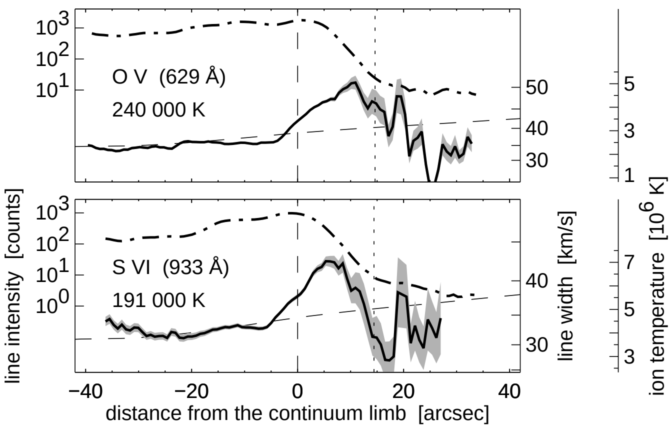

Fig. 3. Variation of line intensity (dotted-dashed, left axis) and line width (solid, right axis) as a function of distance above the limb for the lines of O V at 62.9 nm (see also Fig. 2) and S VI at 93.3 nm. The shaded areas indicate the error estimates for the line width. The dashed curves show the variation of line width for Mg X as published by Hassler et al. (1990) (scaled to match O V and S VI on disk values respectively). The vertical dashed lines show the position of the limb, the dotted lines indicate the location where the stray-light becomes important (outside about 15″). The axis to the far right shows a scale of the line width converted into an ion temperature.

using a Genetic Algorithm based optimisation method from Charbonneau (1995). To enhance the signal-to-noise ratio and to ensure better fits we applied a spatial running mean with a box width of five 1″ pixels. A sample spectral frame covering the O V line at 62.9 nm is shown in Fig. 2. The distance along the slit has been converted into a distance above the white light limb (the location of the limb was determined from the continuum near the respective line; 1″ corresponds to 720 km on the Sun). The fits to the spectra are quite good even far above the limb, where the count rates are rather low.

In Fig. 3 we plot the line intensity (dotted-dashed) and the line width (solid) of the O V and S VI lines as a function of height above the white light limb. The intensity gradually increases towards the limb, which is a simple line-of-sight effect for optically thin emission lines. It then decreases roughly exponentially reflecting the stratification of the atmosphere. For O V and S VI beyond about 15″ (dotted lines) the instrumental stray-light is dominating and thus the intensity gradient becomes more shallow.

The most interesting part is how the line width is changing across the limb. The line width (Gaussian half width at $1/e$) starts rising just at the limb reaching a maximum *well outside* the intensity maximum before it starts decreasing again. In the stray-light domain the width is close to the on-disk value again, of course. It should be stressed here that the intensity starts decreasing already well before the stray-light dominates. The line widths well exceed the thermal line widths expected for a temperature equilibrium of ions and electrons, which are about $11\,\mathrm{km\,s^{-1}}$ and $7\,\mathrm{km\,s^{-1}}$ for O V and S VI. One possibility to interpret the line width is for it to be due to a (kinetic) ion temperature well exceeding the electron temperature (this will be used in the following discussion of the Alfvén wave heating). Then the line width w is related to the *ion* temperature $T_{\rm ion}$ by $w^2 = 2\,k_{\rm B}T_{\rm ion}/m_{\rm ion}$, with the ion mass $m_{\rm ion}$ and Boltzmann's constant $k_{\rm B}$. We added these $T_{\rm ion}$-scales to Fig. 3.

The effect of an increasing width above the limb is not observable with lines formed at lower temperatures such as C II simply because of the small intensity scale height of these lines. For higher temperature lines such as Mg X we do not expect to see this effect because of the very large spatial extend of the line contribution function smearing out the effect. Ionisation equilibrium calculations from Mazzotta et al. (1998) show that O V and S VI are the *only* lines having a contribution sharply concentrated from 150 000 K to 300 000 K in electron temperature and which are suitable for this study. Emission lines from ions with similar formation temperature have also either a strong contribution from higher temperatures (e.g. N V) or are not strong enough above the limb (e.g. Ne V).

Summarising these observations we find for the first time that *exclusively* the O V and S VI lines show a strong increase of line width *above* the solar limb *outside* the maximum intensity of the respective line, with a peak line width at about 10″ or 7500 km above the limb followed by a strong decrease further outwards. Even though we concentrated on one particular observation here, we found this effect also in other data sets.

Interpreting the peak line width as an ion temperature, we find maximum values of 7 and 5 million K for S VI and O V (Fig. 3), corresponding to an ion temperature ratio of 1.4. This corresponds quite well to the ratios of the mass-to-charge ratios of the two ions, $(32/5)/(16/4) = 1.6$, i.e. the ion temperatures are proportional to mass-to-charge ratios. This outcome implies that a kinetic process of wave-particle interaction could be involved.

3. Ion-cyclotron heating

To interpret these results we turn to a discussion of heating the open corona in funnels by high-frequency Alfvén waves. One successful mechanism of coronal heating and solar wind acceleration in funnels is based on absorption of high-frequency Alfvén waves close to the ion-cyclotron frequency (Tu & Marsch 1997; Marsch & Tu 1997; Hackenberg et al. 2000). These high-frequency disturbances of the magnetic field are a natural consequence of small-scale reconnection in the chromospheric plasma (Axford & McKenzie 1997), and they can propagate up through the steep temperature gradient into the corona (Vocks 2002; Vocks & Marsch 2002). Alternatively they could be produced by a turbulent cascade in the corona (Li et al. 1999).

This ion-cyclotron heating mechanism has two major consequences for the temperature: (1) The ions are heated preferentially perpendicular to the magnetic field. This leads to non-isotropic velocity distributions of the ions that can be characterized by two ion temperatures, one parallel and one perpendicular to the magnetic field, $T_{\mathrm{ion}\|}$ and $T_{\mathrm{ion}\perp}$, with $T_{\mathrm{ion}\perp} > T_{\mathrm{ion}\|}$. (2) The other major consequence is that the ion temperatures are higher than the electron temperature T_{e}. Both consequences were observed in-situ with HELIOS in the inner heliosphere and are in good agreement with model calculations (Marsch et al. 1982; Marsch 1991).

Other than in the in-situ observations, spectroscopic investigations give directly information only on $T_{\mathrm{ion}\perp}$ when observing above the limb and assuming that the magnetic field is predominantly vertical. To derive the parallel temperature model assumptions have to be made.

In the outer corona, some solar radii above the surface, observations of UVCS indeed show extreme line broadening indicating high perpendicular ion temperatures (Kohl et al. 1998). Some evidence has been presented that the perpendicular temperature exceeds the parallel one (Cranmer et al. 1999), but as just mentioned this latter conclusion is model dependent. Nevertheless, as with the in-situ observations in the inner heliosphere, the temperature of the ions largely exceeds the one of the electrons, at least perpendicular to the magnetic field.

In the lower corona, where the densities are higher, it is usually assumed that the Coulomb interaction will ensure equal and isotropic temperatures of ions and electrons. However, using the following model we will show that it is still possible that the heating of the ions by ion-cyclotron resonances can overcome the equilibrating effect of the Coulomb collisions, even in the low corona, i.e. $T_{\mathrm{ion}} > T_{\mathrm{e}}$.

4. Model for ion-cyclotron heating in coronal funnels

We have performed new computations of ion-cyclotron absorption of high-frequency Alfvén waves in a coronal funnel in order to interpret our observations (for details of the model see Vocks 2002; Vocks & Marsch 2002). The funnel geometry is prescribed as in the analytical model of Hackenberg et al. (2000) and a simple single fluid model is used to provide the initial conditions. The model plasma consists of protons, alphas, and the ions O V, O VI, S VI, and Mg X. Electrons are treated as a neutralizing fluid only and their temperature is taken from the initial single fluid model. The velocity distribution functions of the ions are calculated self-consistently by a kinetic method (see Vocks 2002; Vocks & Marsch 2002) solving the Boltzmann-Vlasov equations in one spatial dimension along the centre of the funnel. This includes Coulomb collisions and especially resonant interaction between ion-cyclotron waves and the ions. The latter process leads to the heating of the ions and is treated self-consistently. The simulation box extends from the transition region to over 60 Mm into the corona. The ion cyclotron waves enter the box at its lower boundary with a given power-law spectrum and propagate upwards. Inside the box, the wave spectrum evolves due to the absorption by the ions and according to the plasma conditions changing with height.

Ion-cyclotron heating is most efficient if a wide range of frequencies are absorbed in a rather small volume, i.e. if the gyro-frequencies available in the given volume match a large part of the incident Alfvén wave spectrum. Therefore in regions of strong magnetic field gradients, i.e., of a wide range of gyro-frequencies over a small distance, the heating can be very efficient. Such a region can be found at the base of coronal funnels where these are rapidly expanding, i.e. some 2 to 10 Mm above the solar surface (Gabriel 1976; Hackenberg et al. 2000). In fact, this heating can be so strong there that the temperatures of the ions exceed those of the electrons and are not equilibrated by Coulomb collisions as usually assumed for high densities as found in the low corona (cf. Fig. 4).

This effect is restricted to a rather small volume, where the magnetic field gradient is large. Thus the resulting profile of the

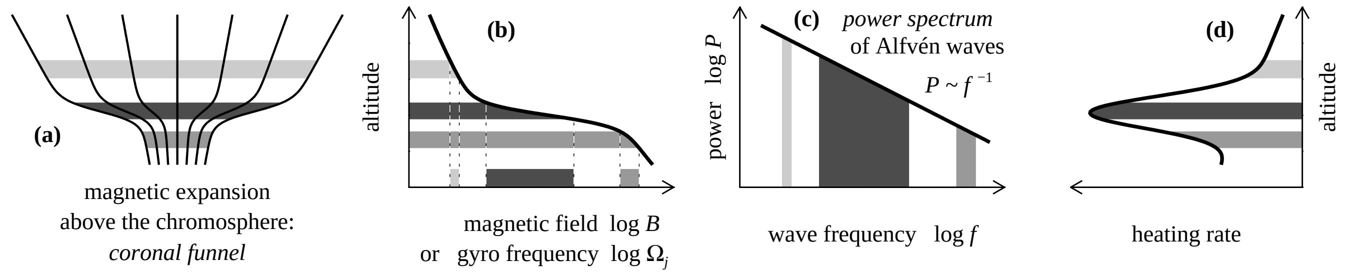

Fig. 4. Schematic representation of the ion-cyclotron heating at the base of a coronal funnel. The left panel (**a)**) indicates the magnetic field geometry of the coronal funnel. Where the funnel expands the magnetic field drops rapidly (**a)**, **b)**; dark shaded area). Thus in that region a large range of gyrofrequencies is covered (**b)**). As the incident Alfvén wave spectrum is (roughly) a power law (**c)**), the power absorbed in the small region of rapid field expansion is very large (dark shaded area). That is why the heating rate is highest in the region of strong magnetic field gradients (**d)**).

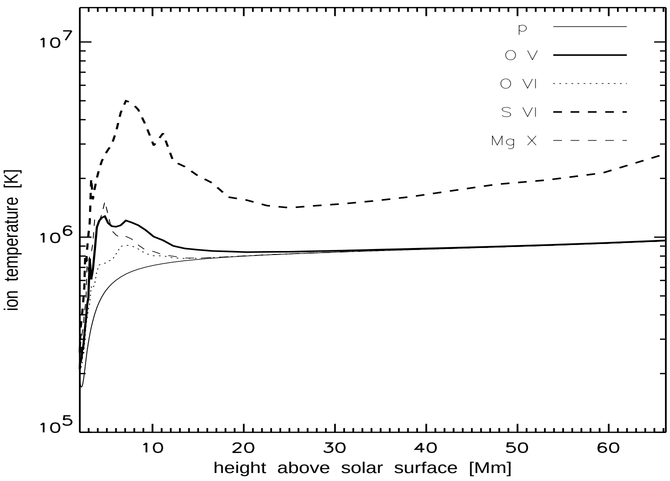

Fig. 5. Ion temperatures perpendicular to the magnetic field computed using the model of ion-cyclotron absorption of high-frequency Alfvén waves in a coronal funnel. The electron temperature is basically the same as for the protons.

ion temperatures perpendicular to the magnetic field $T_{\mathrm{ion}\perp}$ has a bump just where the magnetic field gradient is largest. This is clearly evident from Fig. 5, where $T_{\mathrm{ion}\perp}$ as following from the model is plotted as a function of altitude. $T_{\mathrm{ion}\perp}$ can reach more than 10^6 K well in excess of the electron temperature. The parallel temperatures $T_{\mathrm{ion}\|}$ are close to the electron temperature.

5. Comparing models and observations

The model shows that very high ion temperatures can be produced at the very base of the corona and so demonstrated that the large line widths we have reported in Sect. 2 could be a signature of the heating mechanism. The high $T_{\mathrm{ion}\perp}$ are expected where the magnetic field rapidly expands. As the flow will follow the magnetic field at the base of the funnel (low plasma-β), the flow will *not* be strictly vertical, but will be quite inclined especially at the edges of the funnel (cf. left panel of Fig. 4). Thus we will see not only the perpendicular temperature, but also (partly) the parallel temperature of the ions when observing above the limb – the observations will show some mixture of $T_{\mathrm{ion}\perp}$ and $T_{\mathrm{ion}\|}$. Especially, we will not be able to distinguish between $T_{\mathrm{ion}\perp}$ and $T_{\mathrm{ion}\|}$ from spectroscopic observations.

Nevertheless we can list a number of properties predicted by the model: (1) Even though we see a mixture of $T_{\mathrm{ion}\perp}$ and $T_{\mathrm{ion}\|}$ we should observe a line width of the emission lines corresponding to an ion temperature well in excess of the electron (or line formation) temperature. (2) As the effect is quite restricted in height, and consequently in electron temperature, we can expect to see this effect only in a limited number of lines, namely those that are formed in just the temperature range where the funnels expand most rapidly. According to Gabriel (1976) this is the case at about 200 000 K. (3) Furthermore the high line width should be quite restricted in geometrical height, as the effect mentioned above will occur only at the base of the funnels, i.e. some 2–10 Mm above the photosphere.

All these predictions are observed: The effect is observed only in S VI and O V formed at 190 000 and 240 000 K respectively, the widths of these lines show a sharp peak about 7 Mm above the limb reaching well above 10^6 K.

We did not fine-tune the model to match the observed ion temperatures, as this would have required specific assumptions on, e.g., the poorly known expansion of the funnel. We would still like to stress that the model and the observations nicely fit *qualitatively*. Especially the peak ion temperatures occur at roughly the same altitude as the observed line widths peak.

But as the observations cannot tell about the ratio of $T_{\mathrm{ion}\perp}/T_{\mathrm{ion}\|}$, the observations do not provide a final proof that what we see is a signature of ion-cyclotron heating. The agreement is in many other properties strongly supporting this interpretation, though.

6. Discussion

Hassler et al. (1990) studied the *coronal* lines of Mg X at 609 and 625 Å and found increasing line widths above the limb. Their increase of line width though was shallow compared to our results for the *transition region* lines O V and O VI, and can be attributed to an upward propagating wave (cf. Fig. 3). A similar result for Mg X has been found more recently by Harrison et al. (2002). We would like to stress that these Mg X results are not comparable to our results, as we see a pronounced peak in O V and S VI widths close to the Sun and decreasing width above this, while the coronal Mg X width increases much slower and does not reach a maximum line width within some 200″. A more elaborate comparison of transition region and coronal lines is on the way.

As the line broadening for O V and O VI is of the order of the sound speed or more it is hard to imagine that not resolved flows can account for the effect. It would especially demand clarification why the effect should be so restricted in line formation temperature. Opacity effects can also be excluded, as the maximum of the line width would then be expected near or inside the maximum of the intensity, which is contrary to the observations (an opacity effect can be found for other lines like C IV (Mariska 1992).

As we think the peak of the line width as presented in Sect. 2 cannot be understood in terms of the effects we have just discussed, i.e. waves, flows and opacity, we are left with concluding that this effect should be caused by direct heating of the ions. Considering these arguments and the good agreement of model predictions and observations, we conclude that the ion cyclotron absorption is a valuable candidate for the interpretation our observations.

It would be of interest to extend the model calculations presented here further out into the corona and by that to link the present observations with the UVCS results. Such a numerical effort is beyond the scope of this paper, however.

We have presented observations which reveal for the first time a strong increase of the width of emission lines from the lower solar corona just above the limb. The comparison with new model results of ion-cyclotron absorption of high-frequency Alfvén waves by six ion species showed that this effect can be attributed to an increase in ion temperature. Thus the presented investigation strongly suggests that heating by ion-cyclotron absorption of high-frequency Alfvén waves is present even in the lowermost corona and plays an important role in the heating of the low corona and the initial acceleration of the solar wind.

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