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CORONAL HEATING AND CHROMOSPHERIC ENERGY DENSITY: AN OBSERVATIONAL ASSOCIATION

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Abstract. The time-averaged equivalent width of the He I 10830 Å line is seen to be correlated with the time-averaged line width. This correlation is interpreted as evidence for the association of the chromospheric energy density with the heating of the overlying corona.

1. Introduction

The problem of coronal heating continues to interest solar physicists to this day (Scudder, 1992a, b; Heyvaerts and Priest, 1992; Ulmschneider, Priest, and Rosner, 1991; Narain and Ulmschneider, 1990; van Ballegooijen, 1986; Parker, 1983; Kuperus, Ionson, and Spicer, 1981). The observational challenge originates from the fact that the non-radiative power necessary for the heating is generated in the convection zone, while this energy is 'deposited' in the corona after transmission through the photosphere, chromosphere, and transition region. Generally, the signature of photospheric and chromospheric dynamics are available in spectral lines appearing in the visible portion of the solar spectrum, whereas coronal processes are chiefly discernible through the X-ray and XUV emission on the one hand and through radio emission on the other. One therefore generally requires multi-frequency observations to find correlations between photospheric or chromospheric dynamics and coronal heating. The difficulties associated with such observations, e.g., registration of images or spectra obtained by different instruments, are quite well known. There is one exception, viz., the He I 10830 Å line which is formed in the chromosphere and which is most likely excited by nonlocal XUV or EUV radiation originating from above the chromosphere. In principle, this line must provide an excellent link between chromospheric dynamics and the heating of the atmosphere overlying the observed chromospheric regions.

Recently, Venkatakrishnan *et al.* (1992) studied the spatio-temporal fluctuations of the He I 10830 Å line profile parameters in the context of spicule formation. They found a correlation between observed equivalent width and line width over a large number of spatial locations on the solar disc. This correlation was not commented upon in Venkatakrishnan *et al.* (1992, hereinafter called Paper I). In this paper, I will argue that the observed correlation provides the first direct association of chromospheric dynamics with coronal heating. In Section 2, the link between coronal heating and the equivalent width of the He I 10830 Å line will be

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established. In Section 3, the width of the 10830 Å line will be interpreted in terms of random velocity fluctuations. In Section 4, the implication of the correlation between equivalent width and line width will be discussed.

2. He I 10830 Å Equivalent Width and Coronal Heating

The enhanced absorption of the He I 10830 Å line associated with coronal X-ray bright points (Harvey *et al.*, 1975) and the low level of absorption in coronal holes (Harvey and Sheeley, 1977) provide broad clues that the He I absorption is indeed related to the amount of X-radiation emitted from the corona. Paper I provided more quantitative evidence for this. For example, the mean equivalent width of the He I 10830 Å line was found to be a factor of eight in strong line regions over that in weak line regions. This rules out spatial density enhancements as the cause of the equivalent width excess since empirical models of quiet-Sun features (Vernazza, Avrett, and Loeser, 1981) show only a 50% increase in the plasma density associated with the quiet network over that associated with the cell interior. The only other way of increasing the equivalent width is by increasing the excitation rate. The line width data rule out collisional excitation (Paper I) which leaves us with radiative excitation caused by photoionization of the He atom followed by recombination to the required energy levels (Zirin, 1989).

The He II 304 Å resonance line emission was seen to match the He I 10830 Å absorption very well (Harvey and Sheeley, 1977) thereby indicating that the high-energy photons from the He II emission dominate the excitation to the ^3S lower energy state of the He I transition. However, the cause of the He II excitation has remained a puzzle. Pure radiative excitation by coronal XUV radiation (Zirin, 1975) leads to the prediction of a central absorption (Milkey, 1975) which is not seen. One might explain the filling in of this absorption by Doppler broadening with a spread in velocity $\simeq$2.5 times the thermal broadening. Such a large spread was believed to be non-existent (Milkey, 1975), but the line-width data in Paper I indeed shows the required amount of broadening in the He I line. Since He I and He II are both assumed to form at similar heights (in the radiatively excited scenario), then He II would also be broadened to a similar extent. Thus one of the objections to the radiatively excited scenario can be answered.

At the other extreme, collisional excitation requires the He II line to be formed at very high temperatures in the emission region. Even after assuming such high temperatures, the predicted He II line intensities are much different from the observed intensities. Some schemes of diffusion of hot electrons have been suggested to mitigate the problem (Jordan, 1975) but these cannot fully solve it. In the present context, the hot electrons diffusing into region transition layers will reduce the coronal conductive losses and will thus contribute to an increase in the net heat gain of the corona.

Either way, an enhancement of radiative or collisional excitation of He II directly implies an enhanced level of coronal heating. A straightforward conclusion is that the He I absorption, parametrized in terms of the equivalent width, is an index of He II emission and therefore is an index of coronal heating.

3. He I 10830 Å Line Width and Chromospheric Energy Density

The He I 10830 Å line is effectively optically thin and is thus a good velocity diagnostic (Lites, 1985). In fact, other popular chromospheric lines (in the visible) are mostly resonance lines that are significantly influenced by radiative transfer effects and are therefore poor diagnostic probes of the kinematics of the chromosphere. Figure 4(a) of Paper I shows that the line depth, η, of the He I 10830 Å line varies linearly with the equivalent with q. The observed residual intensity R_λ is in the range of 0.95 (Paper I). From Figure 10-1 of Mihalas (1978), it is clear that this range of R_λ corresponds to a very low value of β_0 (the ratio of line to continuum opacity). Equation (10-38) of Mihalas (1978) reveals that for small values of β_0, the ratio $q/(\eta w)$ is a function of only the damping parameter. For a constant damping, $q/(\eta w)$ must be conserved. In the present case of constant value of q/η, w must be constant for a constant value of the damping. However, Figure 4(b) of Paper I shows that w increases with q implying that ηw increases nonlinearly with q. This gives an unambiguous evidence that there is a random velocity field present which is a function of the equivalent width. Such velocity fields are generally given the name microturbulence. The main feature of the so-called microturbulence is that the dominant length of the velocity eddies is smaller than the photon mean free path. Hydromagnetic waves could possibly inject energy at such small enough scales. In fact, Athay and White (1979) have used the line width of upper chromospheric UV lines as a measure of the energy density of mechanical waves. It is reasonable to assume, therefore, that a significant fraction of the observed width of the He I 10830 Å line represents the mechanical energy density of the chromospheric material.

4. Discussion

From the arguments presented in Sections 2 and 3, we can interpret the correlation between line width and equivalent width of the He I 10830 Å line, as a correlation between chromospheric mechanical energy density and coronal heating. The question remains as to what to make of this correlation. We could rule out coronal radiation from heating the chromosphere and causing an increase of the mechanical energy density, purely on the basis of the energy flux required to do this. For example, if $\langle \rho v^2 \rangle$ is the mechanical energy density of the chromosphere and F_c is the radiative flux of the corona, then $F_c \simeq \rho \langle v^2 \rangle V_g$, where V_g is the group velocity of the mechanical energy flux from the chromosphere required for maintaining equilibrium. If we assume $F_c \simeq 10^6$ ergs cm s^{-1} (which is a very generous upper limit), $V_g \simeq 9$ km s^{-1} (the acoustic speed at 10 000 K), and $\rho \simeq 1.6 \times 10^{-12}$ g cm^{-3}, then $\langle v^2 \rangle^{1/2}$ turns out to be $\simeq$8 km s^{-1}. The smallest and largest values of the observed line width are 0.45 and 1.00 Å. These correspond to microturbulent velocity amplitudes of 9 km s^{-1} and 24 km s^{-1} respectively for an assumed temperature of 10000 K. A 'typical' value for this velocity amplitude is more like 20 km s^{-1}. We thus see that $\langle v^2\rangle^{1/2}$ is far less than the observed microturbulence. This estimate of $\langle v^2\rangle^{1/2}$ will decrease even further if we replace the acoustic speed by the Alfvén speed corresponding to a network magnetic field strength of 10 G. Hence, it is safe to assume that the coronal back radiation is not the cause for the enhanced broadening of the He I 10830 Å line.

The other alternative is that an enhanced level of chromospheric mechanical energy density causes enhanced heating of the corona overlying the observed sites. To put things in the right perspective, Figure 4(b) of Paper I is replotted in Figure 1 of this paper after interchanging the abscissae and the ordinates. Figure 1 is thus a plot of the equivalent width of the He I 10830 Å line versus its width. The two different symbols in the plot correspond to two different data sets obtained on 20 January, 1985 separated by one hour. From Section 3, one can conclude that for a weak line like He I 10830 Å, the natural correlation between equivalent width and line width must show a vertical line of constant line width, given the tight correlation between equivalent width and central line depth (Paper I). It is reasonable to assume that all deviations from the observed minimum value of the line width (≈0.45 Å) correspond to the amplitudes of the local microturbulence.

Figure 1 shows that these deviations from a minimum value of the line width do not fall on a straight line. We can express the amount of coronal wave heating, Q, as

$$Q = \frac{\rho\langle v^2\rangle}{L} V_g \,, \tag{1}$$

where the right-hand side is an approximation to the divergence of the mechanical energy flux written as the ratio of the mean flux, $\rho\langle v^2\rangle^{1/2} V_g$, to the scale length, L, of dissipation of this flux. Assuming equivalent width, q, to be a parameter proportional to the heating Q, we have

$$q \sim \frac{\rho c^2}{L\lambda^2} V_g(\Delta\lambda^2 - \Delta\lambda_D^2) \,, \tag{2}$$

where $\Delta\lambda_D$ is the thermal Doppler width and $\Delta\lambda$ is the total line width. Thus,

$$q = \alpha(\Delta\lambda^2 - \Delta\lambda_D^2) \,, \tag{3}$$

α is the efficiency of heating which also includes the factor $\rho c^2 V_g/(L\lambda^2)$. Relations such as (3) can indeed be verified to pass through the data points reasonably well with a not too wide range of $\Delta\lambda_D$ and α. A least-squares fit is not presented here since it would be a detail that is not warranted in view of the scatter in the data.

The scatter in the data is solar in origin (Singh, Jain, and Venkatakrishnan, 1993). A remarkable fact is that there is a well-defined upper limit to the data points of

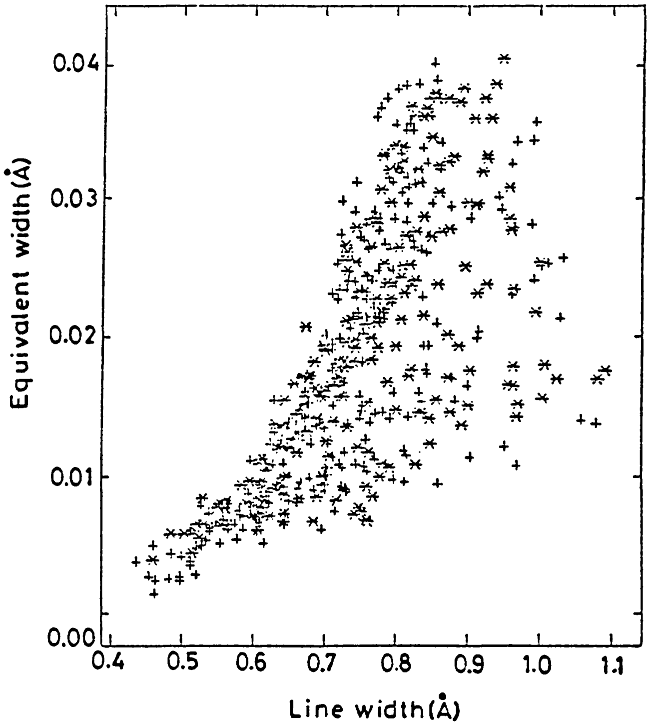

Fig. 1. The width (averaged over values for 60 spectra taken every minute) of the He I 10830 Å line is plotted against the equivalent width. The two symbols denote data for two contiguous one-hour intervals. There are 250 time-averaged data points for each set corresponding to 250 contiguous spatial locations on the solar disc, each having an effective pixel size of 1 arc sec × 2 arc sec.

Figure 1 for every value of the line width. In other words, the spread in the data points is only towards lower values of the equivalent width. One interpretation is that there is a typical value for the efficiency of heating which cannot be exceeded very much. If the efficiency depends mostly on the group velocity of the mechanical flux, then Figure 1 indicates that there is an upper limit for the magnetic field strength at the observed locations, and which is fairly ubiquitous. Figure 1 also indicates that there are locations where the velocity amplitude is large but the coronal heating is not so effective. Without supplementary information on the actual magnetic field strength at these locations it would be difficult to hazard a guess as to the reasons for such relatively inefficient heating.

We must remind ourselves of the fact that the observations were obtained for locations on the solar disc away from active regions (Paper I). What would be the nature of the correlation for active regions? The coronal back radiation is predominant along a vertical direction (since absorption is minimum along this direction) while the mechanical flux will follow the direction of the group velocity. Thus, it is difficult to predict the kind of correlation for active regions. Theoretical modelling of the energy flux for specified field geometries and the comparison with observations of the width of chromospheric lines as well as coronal X-radiation seem interesting possibilities for active region studies. What one needs to complete the picture is simultaneous magnetic data to clarify the role of the magnetic field in the generation of the mechanical energy flux. Thus, the arguments presented in this paper point the way of planning future observational studies on the problem of coronal heating.

5. Conclusions

The He I 10830 Å line is an excellent diagnostic of chromospheric dynamics as well as coronal heating. The observed correlation of its line width with the equivalent width at several hundred spatial locations on the quiet solar disc was therefore proposed as direct evidence for the correlation of the chromospheric energy density with the heating of the overlying corona. A simple-minded interpretation of this correlation is that the quiet corona is heated by mechanical waves which manifest themselves in the chromosphere as an excess broadening of the He I 10830 Å line.

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