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# TEMPERATURES OF QUIESCENT PROMINENCES MEASURED FROM HYDROGEN PASCHEN AND CaII IR LINES

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## INTRODUCTION

Prominence temperatures and non-thermal velocities are most commonly determined from emission line widths from elements of different atomic weight. It is assumed that the lines are optically thin. The average temperature for the main part of quiescent prominences is 6500 K (5000-8000 K) according to Hirayama (1985). The corresponding velocities are 3 km $s^{-1} < V < 8$ km $s^{-1}$. The lowest value recorded from the combined widths of H, He, and metallic lines is 4300 ± 200K (Hirayama 1978). A tendency of increasing temperature towards the periphery of prominences was first noticed by Hirayama (1964, 1971). The results from a number of studies give 8000 K < T < 12000 K and 8 km $s^{-1} < V < 20$ km $s^{-1}$ in the outer parts of prominences (Hirayama 1971; Engvold 1978; Landman et al. 1977).

Analysis of the hydrogen excitation-ionization equilibrium (e.g. Chultem and Yakovkin 1974) indicates that the excited levels of the hydrogen atoms in quiescent prominences are near thermodynamic equilibrium, i.e. $T_{exc} \approx T_{kin}$. The gas temperature will then be reflected in the relative intensities of hydrogen lines. Earlier measurements of hydrogen Balmer lines in prominence spectra are incomplete (Jefferies and Orrall, 1962; Nikolsky et al. 1971) and show large variations from case to case in terms of excitation temperature. Stellmacher (1969) finds $T_{exc}$ = 6000 - 6250 K from the brightness variation of the lines Hβ through $H_9$, and Morozhenko (1974) gets $T_{exc} \approx$ 7300 K using the lines from Hα to $H_{20}$.

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Measurements by Landman and Mongillo (1979) gave still a substantial scatter in the H I Balmer decrement which represented excitation temperatures ranging from 3450 K to 11000 K. This quite large variation in $T_{exc}$ was ascribed partly to measurement errors, and to the low spectral resolution in the observation which did not permit the authors to correct properly for line-blends. Very recent observations in the far infrared (10 - 20 μm) of prominence hydrogen lines have been analysed by Zirker (1985) who finds a Boltzmann distribution corresponding to $T_{exc}$ = 3800 K. The author points out that the IR hydrogen lines span a narrow range of energy and the result is therefore highly sensitive to errors in the measured line intensities. The value of $T_{exc}$ is nevertheless uncomfortably low when compared to $T_{kin} \approx$ 10 000 K which is derived from the widths of the same lines and an infrared line of He.

Observations of continuum emission near the Balmer jump at 3646 Å have been used to derive prominence temperature and density (cf. Jefferies and Orrall 1962). The results are quite uncertain since they depend on the assumed thickness of the emitting volume. The H I Lyman continuum of nine hedgerow prominences observed with the EUV spectrometer on Skylab could be represented by color temperatures between 6122 K and 8669 K with a mean of 7524 ± 739 K (Orrall and Schmahl 1980). Considering the large optical thickness of the Ly C these values presumably equal the electron temperatures.

The temperature of prominence gas is a function of the incident radiation from the corona, chromosphere and photosphere (c. Heasley and Mihalas 1976). One notices that an equilibrium temperature will also be a function of the Ly C opacity. The concept of an actual equilibrium situation may however be debated. The relatively short lifetimes of the small scale structures of quiescent prominences could suggest that the gas is subjected to rapid changes in temperature and/or density (Engvold 1980)

The noted centre-to-edge effect evidently represents a real variation in prominence temperature. But generally, the notable variations in the result quoted above may largely reflect deficiencies in the method used. Different combinations of line widths are often found to give different temperatures (Jefferies and Orrall 1962; Hirayama 1978; Landman 1979). This clearly illustrates problems with the 'line width'-method. For instance unresolved filamentary structures may affect the profiles of various lines differently and thus lead to slightly erroneous temperatures. The excitation temperature determined from hydrogen line intensities is highly sensitive to photometric errors and to effects of line opacities.

New and high quality observations of infrared prominence lines of hydrogen, calcium and other species have been obtained. We have compared temperatures derived from line widths and from hydrogen line intensities in an attempt to assess the reliability of the two methods discussed above.

## OBSERVATION, INSTRUMENTATION AND DATA REDUCTION

During 12-17 September 1983 a number of prominences were observed with the McMath solar telescope of National Solar Observatories, using the Fourier transform spectrometer with a InSb detector (Brault 1979). The present study refers to three prominences observed 13 and 14 september.

Prominence A: Large quiescent prominence at S28 E90
Prominence B: Stable prominence in weakly enhanced magnetic region at about N08 E90
Prominence C: Quiescent prominence at N30 E90

Spectra were obtained at a total of 15 different locations in the three prominences in the wavelength range λλ7740-14000 Å. The aperture covered an area of 80 arcsec$^2$ on the solar image. The light reflected off the aluminium coated aperture plate was imaged through a narrow band Hα filter. This system allowed us to select the pointing within a prominence and to maintain aperture position during a scan. The integration time for individual spectra was 17 minutes. Spectral resolution was typically $\Delta\nu = 0.005$ cm$^{-1}$ ($\lambda/\Delta\lambda = 2\ 000\ 000$).

The spectrum of the sky background is bright in comparison to all infrared prominence emission lines, with the exception of the He I λ10830Å line, and it needs to be subtracted from the data. For this purpose we made separate spectral scans of the sky background close in time to the prominence observations and at corresponding distances from the solar limb. The incident solar spectrum is modified by absorption in the terrestrial atmosphere and by the spectral responses of the beamsplitter and the detector. In order to establish an absolute intensity scale we made spectral scans of the solar disk center with the same instrument setting except for a necessary gain adjustment of the detector system.

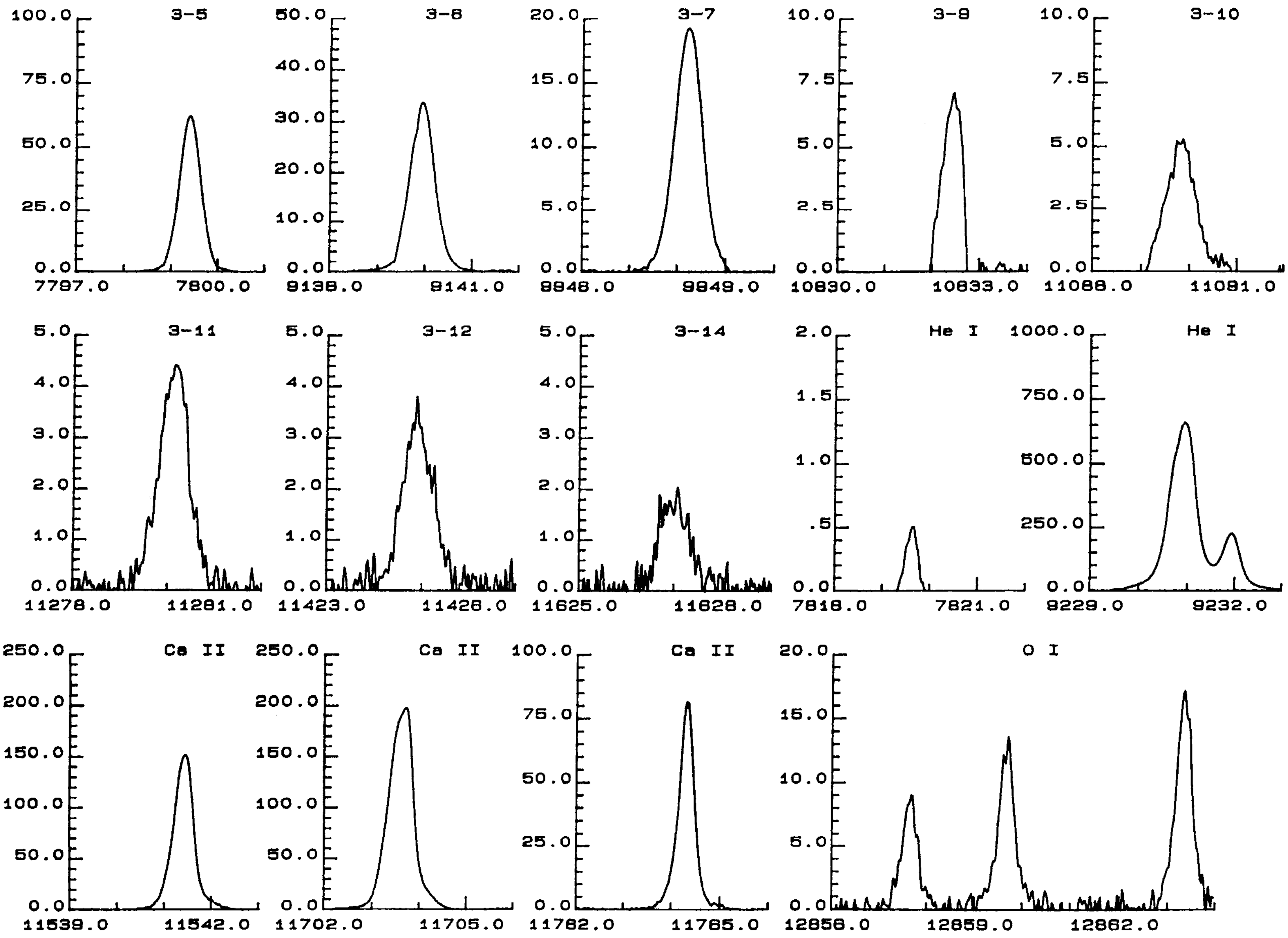

Figure 1. Emission lines from edge of Prominence A observed on 14 September 1983. The intensities x250 are in units of erg $cm^{-2}s^{-1}sr^{-1}Å^{-1}$.

The first step in the data reduction was to subtract the appropriate sky background emission from each of the prominence spectra. The intensities were then transformed to an absolute scale via the solar disk spectra and the corresponding continuum intensity values given by Labs and Neckel (1968). Further details of the data reduction procedures are given in Engvold and Brynildsen (1986).

Figure 1 shows an example of emission lines recorded in a medium bright portion of prominence A. In the spectrum of particularly bright prominence structures the hydrogen line from up to levels $n = 23$ could be observed.

## ANALYSIS

### Excitation temperature

The line intensities reflect the relative upper state populations. In the case that the population of the excited levels is determined basically by the balance of ionizing collisions and recombinations the population will obey a Boltzmann distribution. The intensity variation with level quantum number is then a function of temperature only and may be represented by the relation

$$\frac{1}{kT}(\chi_0 - \chi_i) = \ln (E\lambda/g_i\, A_{ij}) + \text{const.}$$

where the observed line emission is E, and all the other parameters have their usual meaning. The indices 0, i and j denote respectively ionization energy from ground level, the upper and lower energy level.

Figure 2 shows a plot of the right hand side of the equation versus ionization energy from level i divide by Boltzmann's constant, $\Delta\chi/k$. The slope of the best fitting yields excitation temperature, which in the present case becomes 8 000 ± 700 K. The solution is sensitive to photometric accuracies, to statistical noise in the data, and to effects of line saturation. Terrestrial line absorption disturbs the observations of $H_{3-8}$ and $H_{3-9}$ and reduce the total line emission relative to its true value. (The $H_{3-8}$ line is severely disturbed and is not measured at all.) The deviation of the line profile from a best Gaussian fit ($r^2$) is a good measure of the quality of the data in terms of signal/noise and it indicates effects of saturation in

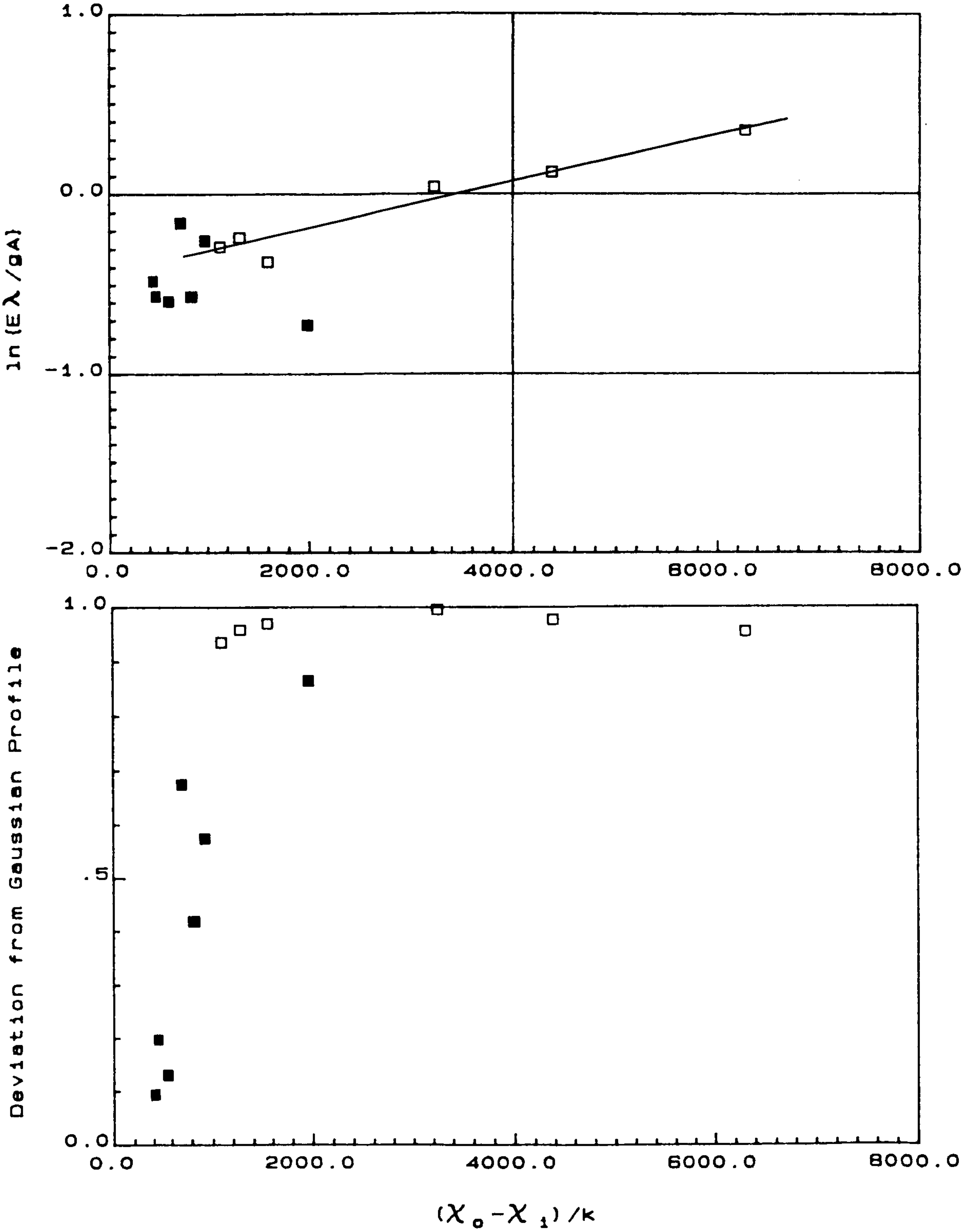

Figure 2a. The Boltzmann graph of the hydrogen Paschen lines shown in Figure 1. The slope of the distribution corresponds to $T_{exc}$ = 8000 ± 700 K.

b. The deviation of line profiles from a best Gaussian fit.

the profile of the earliest lines in the series. Figure 2a shows the deviation from Gaussian profile of the lines given in the Figure 2b. The value $r^2 = 1$ means that the profile is Gaussian. The excitation temperature is determined from the slope through lines for which $r^2 > 0.95$.

Table 1

Temperature and non-thermal velocities of three quiescent prominences. The kinetic temperatures and velocities are derived from H I and Ca II lines.

| Date | Prom.: Location | $T_{exc}$ (K) | $T_{kin}$ (K) | V (km $s^{-1}$) |
|---|---|---|---|---|
| 13 Sep-84 | A: Edge | 8000 ± 700 | 6300 | 6.3 |
| | A: Central part | 8000 ± 700 | 6850 | 5.9 |
| | A: Top part | 7000 ± 500 | 6430 | 5.3 |
| | A: Central part | 8000 ± 700 | 5540 | 5.9 |
| | B: " " | 7200 ± 500 | 12200 | 7.7 |
| | B: " " | 8000 ± 500 | 9010 | 6.8 |
| | B: " " | 6000 ± 500 | 6470 | 11.1 |
| | B: Edge | 8000 ± 500 | 5530 | 12.2 |
| 14 Sep-84 | A: Edge | 8000 ± 700 | 7270 | 6.3 |
| | A: " | 10000 ± 1000 | 5900 | 6.0 |
| | B: Central part | 10000 ± 1000 | 6340 | 4.8 |
| | C: " " | 6500 ± 500 | 7100 | 6.9 |

**Kinetic temperature.**

The line widths are determined from the best fit Gaussian profile for each line. If we assume that lines of different elements are formed in the same volume we may separate and obtain the kinetic temperature ($T_{kin}$) and the non-thermal velocity (V) according to standard procedure (cf. Zirker 1985). We may apply the 'line width'-method to various combinations of lines from the present data, such as H-Ca, H-O, H-He, and in principle even Ca-O. The tripple component He I λ10830Å is generally strongly saturated and cannot be used to determine $T_{kin}$ except in a very few cases of weak emission. The hydrogen Paschen lines are basically optically thin in the prominence spectra, and the widths are measured from the most Gaussian shaped profiles ($r^2 \approx 1$) in each case. The same profile criterion was used to derive non-saturated widths from the Ca II lines (λ8498Å, λ8542Å and λ8662Å) and from O I (λ7772Å, λ7774Å, and λ7775Å). The relative strength and width of the lines of Ca II and of O I provide additional informations on the line opacities. See Engvold and Brynildsen (1986) for further detail.

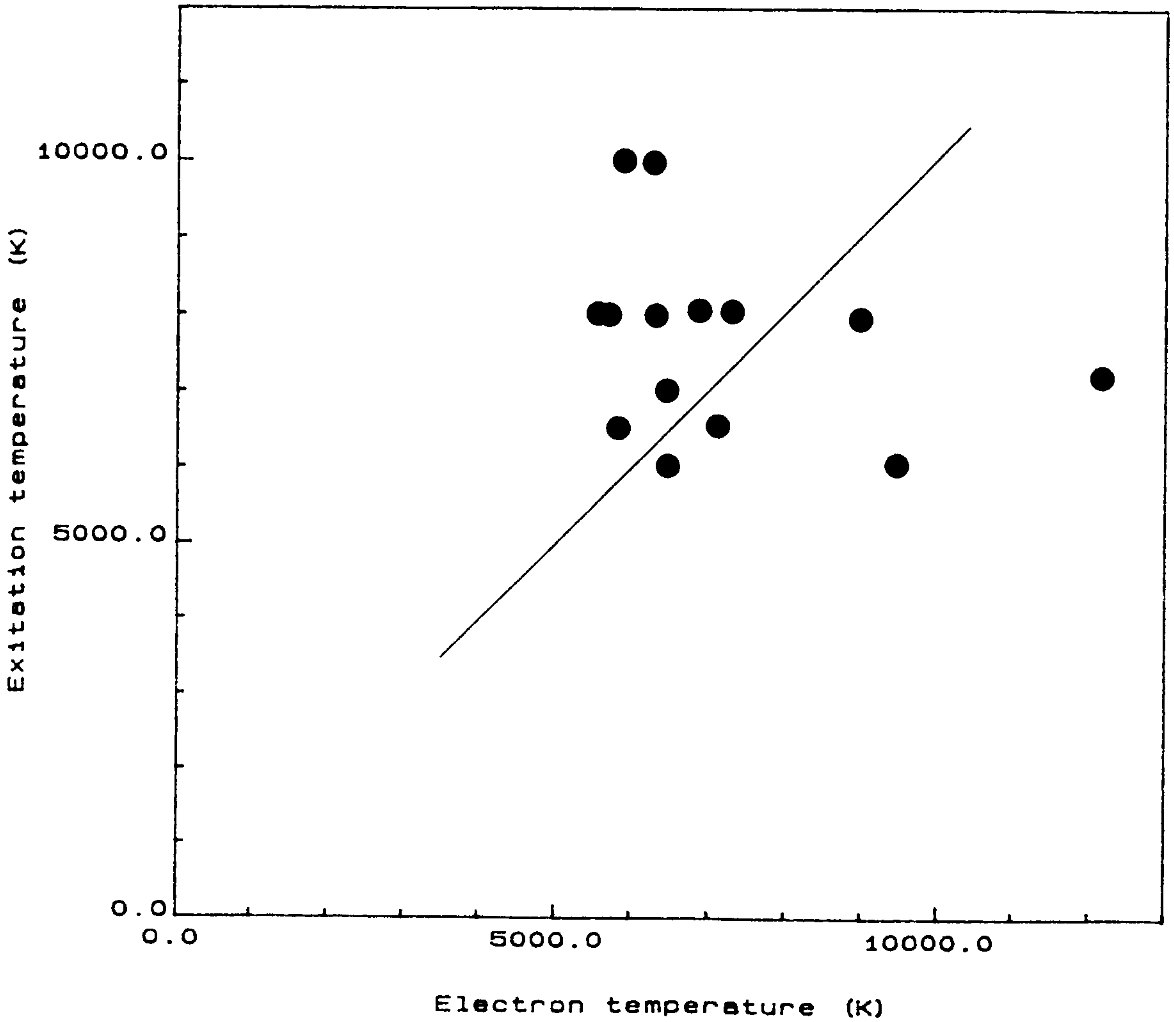

Figure 3. A plot of $T_{exc}$ versus $T_{kin}$.

Table 2

Averaged temperatures and non-thermal velocities in two quiescent prominences.

| | Prominence A | | Prominence B |
|---|---|---|---|
| | Central region | Edge and top | Central region |
| $T_{kin}$ (K) | 6200 ± 900 | 7000 ± 900 | 8500 ± 2700 |
| $T_{exc}$ (K) | 8000 ± 700 | 8250 ± 1200 | 7800 ± 1700 |
| V (km $s^{-1}$) | 5.9 | 6.0 ± 0.5 | 7.6 ± 2.6 |

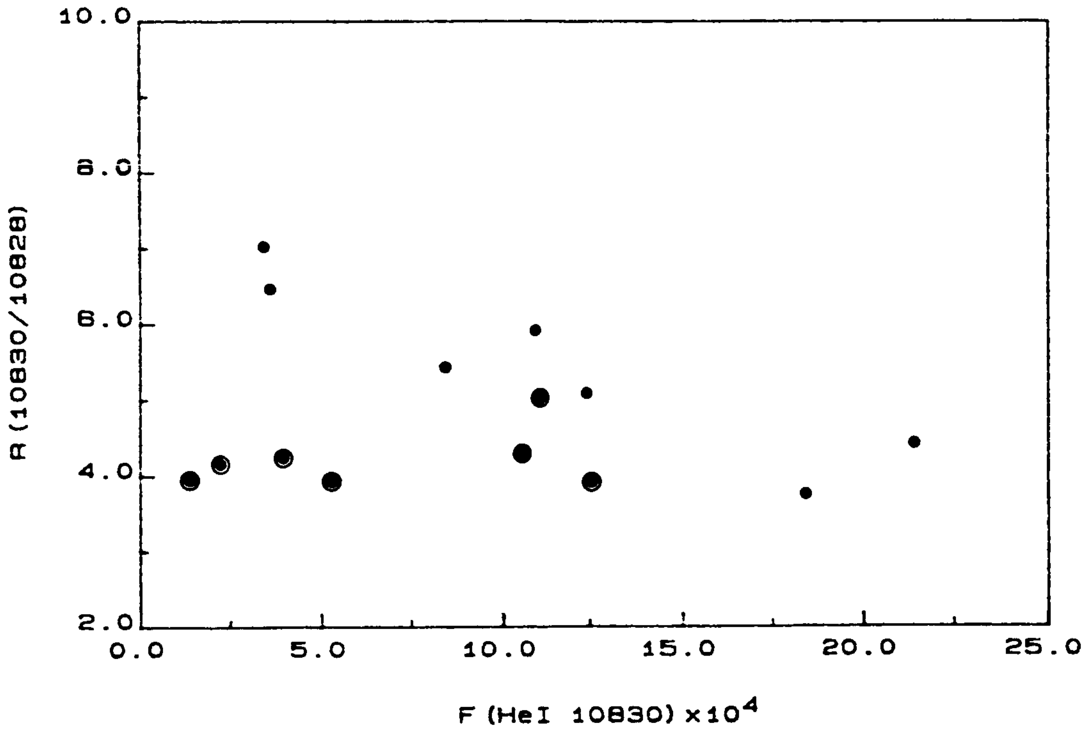

Figure 4. A plot of the He I line ratio λ10830Å/λ10828Å versus total flux of the He I line. The optical thin line ratio is 8:1. Small dots represents central parts of the prominence and circles with dots are from prominence edges.

## Comparison of $T_{exc}$ and $T_{kin}$

Table 1 gives $T_{exc}$, $T_{kin}$ and the non-thermal velocity (V) determined from 13 positions in the prominences A, B and C. (In two of the positions observed the line profiles were irregular and strongly asymmetric and were therefore not measured.) The tabulated kinetic temperatures have been derived from H I and Ca II line widths. The result from H I and O I is not substantially different from H I and Ca II. Figure 3 shows a plot of excitation temperature versus kinetic temperature ($T_e = T_{kin}$).

## CONCLUDING REMARKS

The observed differences between $T_{exc}$ and $T_{kin}$ are hardly significant and can be attributed to data noise which is partly unresolved filamentary structure, and partly measurement errors. We conclude that the two methods for temperature determination when applied to optically thin lines give reasonably consistent results, i.e. the population of the excited levels of hydrogen is collisionally controlled.

The well known increase in T and V towards the edge of quiescent prominences (Hirayama 1964) is not corroborated by the present data. One explanation for this could be that prominence A is atypical. The optical thickness of prominence emission lines tends to increase from center to edges as demonstrated by the case of He I λ10830Å in Figure 4. If line opacity plays a significant role in earlier centre to edge determinations of T and V, a smaller variation would be expected from measurements in optically thin lines, such as in the present case.

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