EQUATOR-POLE DIFFERENCES IN THE SOLAR CHROMOSPHERE FROM LYMAN-CONTINUUM DATA

J. E. VERNAZZA

Harvard College Observatory, Cambridge, Mass., U.S.A.

and

R. W. NOYES

Smithsonian Astrophysical Observatory and Harvard College Observatory, Cambridge, Mass. 02138, U.S.A.

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Abstract. From the analysis of OSO-4 Lyman-continuum spectroheliograms, differences in the brightness and the color temperature between the poles and the equator have been found. These differences are interpreted as resulting from a lower chromospheric density at the poles than at the equator. Two models, one for the poles and one for the equator, giving temperature and density as a function of height, explain the observations. The poles have a lower density and a smaller temperature gradient than the equator does. The differences begin in the middle chromosphere and increase toward the transition zone.

1. Introduction

Contradictory evidence for unequal physical conditions between the solar poles and the equator has accumulated since 1935. Differences between the residual intensity of Fraunhofer lines at the polar and equatorial limbs were first observed by Abetti and Castelli (1935). Beckers (1960) summarized most of the observations up to 1960 and suggested that the pole-to-equator temperature difference depends on the solar cycle. In Beckers' picture, the temperature difference $\Delta T_{pe}$ reaches a maximum during minimum solar activity. However, observations by Mulders and Slaughter (1965) and by Appenzeller and Schröter (1967) contradict Beckers' picture by finding $\Delta T = 0 \pm 11$ K and $\Delta T = 0 \pm 6$ K, respectively, between poles and equator. Burger and Houtgast (1969) found no change in the residual intensities of Na I D1 and D2, Mg I b1 and b2, and H$\beta$. Altrock and Canfield (1972) found an excess of about 8 K at active-region latitudes in the upper photosphere ($\tau_{5000} \sim 10^{-3}$) from analysis of the Ca II K-line wing.

In interpreting the observations, most authors assumed LTE and looked for temperature variations in the optical-depth scale. No attention has been given to density variations that may shift the temperature scale or to departures from LTE.

In the present analysis, we study pole-equator differences in the region of Lyman-continuum formation in the middle chromosphere. In previous papers (Noyes and Kalkofen, 1970; Vernazza and Noyes, 1972; hereafter called Papers I and II), a model of the solar chromosphere was derived on the basis of the Harvard OSO-4 data on the Lyman continuum. Here we extend the analysis to explain the observed differences between equator and poles, and derive comparative models of the two regions.
2. Observational Data and Method of Analysis

Figure 1a shows a Lyman-continuum intensity spectroheliogram; Figure 1b, a Lyman-continuum color-temperature spectroheliogram; and Figure 1c, a $\text{Mg x}$ electron-density spectroheliogram. These spectroheliograms were reduced from data obtained by the Harvard spectrometer aboard OSO-4 on orbits 391 (897 Å), 392 (740 Å), and 397 (Mg x) (Reeves and Parkinson, 1970). The Lyman-continuum color-temperature spectroheliogram was constructed from intensity spectroheliograms at 897 and at 740 Å, by using at each point the relation

$$\frac{I(\lambda_2)}{I(\lambda_1)} = \frac{B_{\lambda_2}(T_c)}{B_{\lambda_1}(T_c)},$$

where $T_c$ is the color temperature. The two spectroheliograms were obtained 2 h apart and were numerically rotated to a common point to correct for solar rotation during that interval. The electron-density spectroheliogram was obtained from the Mg x spectroheliogram, the intensity of which has been shown (Withbroe, 1972) to vary approximately as $N_e^2$ (corona)/$\cos \theta$. Thus, in Figure 1c, $N_e = (I_{\text{Mg x}} \cos \theta)^{1/2}$.

It is immediately obvious from Figure 1b that the color temperature increases toward the limb. The color temperature $T_c(\cos \theta)$ reflects the electron temperature at $\tau_0 \sim \cos \theta$, where $\tau_0$ is the optical depth at the head of the Lyman continuum. Thus, the center-to-limb variation of $T_c$ reveals the increase of electron temperature with height in the region of Lyman-continuum formation. (Quantitative models based on this effect are derived in Papers I and II.) Three other effects are present in the data shown in Figure 1, although they are difficult to see in the reproduction. First, the intensity of quiet regions at the limb in the Lyman continuum is larger at the equator than at the poles. Second, the color temperature of quiet regions at the limb is somewhat smaller at the equator than it is at the poles. Third, active regions in general show a lower color temperature than does the mean chromosphere (see also Noyes, 1971). Thus, in general, areas with larger Lyman-continuum intensity have a smaller color temperature, and vice versa.

Comparison of Figure 1a with 1b reveals in addition a good correlation between coronal electron density and chromospheric color temperature. Even some features of the electron-density spectroheliogram that do not show up in the Lyman-continuum intensity spectroheliogram appear well defined in the color-temperature spectroheliogram. In particular, coronal 'holes' — i.e., extended regions of lower than average coronal electron density (Munro and Withbroe, 1972) — show as areas of higher color temperature in the chromosphere. We conclude that the low density of the polar coronal regions must be reflected in the chromosphere.

For the analysis of the Lyman-continuum data, we have used the same set of data as in Paper II, namely, spectroheliograms at 897, 865, 825, 800, and 740 Å. For these data the inclination of the poles ($B$ angle) was less than 3°, and we neglected it in our analysis. We eliminated from the analysis latitudes containing active regions. From a comparison of intensity ratios between all pairs of spectroheliograms, we determined
Fig. 1. (a) Spectroheliogram obtained by OSO-4 on November 13, 1967, in the Lyman-continuum (897 Å). (b) Lyman-continuum color temperature derived from the ratio of spectroheliograms at 897 and 740 Å. (c) Coronal electron-density map derived from spectroheliogram in Mg X 625 (see Withbroe, 1972).
the color temperature at each point and then found the average quiet-region color temperature, both for equatorial and for polar regions. Details of the analysis are given in Papers I and II. Figures 2a and 2b show the resulting center-to-limb variation and the color temperature for both the equator and the poles. The curves for the equator extend to \( \cos \theta = 1 \), but, of course, polar regions cannot be observed at \( \cos \theta = 1 \) and their spectrum at \( \cos \theta \) can be obtained only by an uncertain extrapolation. The uncertainty in this extrapolation will lead to a corresponding uncertainty in the polar temperature distribution at \( \tau_0 = 1 \) as deduced from the empirical model.

![Graphs showing the variation of R(897 Å), T, and I(897 Å)/I(825 Å) with \( \rho \)](image)

Fig. 2. Top: The ratio \( R(\rho) \) of the intensity at wavelength \( \lambda \) to the intensity at 825 Å as a function of \( \rho \), the normalized distance from the disk center. Middle: The average color temperature \( T \) of the Lyman continuum. Bottom: The intensity \( I \) at 897 Å normalized to its central value as a function of \( \rho \). For all curves, the equator is indicated by lines, and the poles, by dashed lines.

Nevertheless, certain qualitative conclusions can be drawn from Figure 2. The color temperature in the polar regions is higher than that in equatorial regions for \( \cos \theta > 0.45 \) (\( \rho < 0.9 \)), and lower for \( \cos \theta < 0.45 \) (\( \rho > 0.9 \)). This suggests that the temperature at the poles is greater than at the equator for \( \tau_0 > 0.45 \), and less for \( \tau_0 < 0.45 \) - i.e., \( dT/d\tau \) is less at the poles than at the equator.
We note from Figure 2c that the intensity at the poles is less than at the equator even at positions where \( T_0(\cos \theta) \) is greater at the poles than at the equator. This is in keeping with the trend noted earlier in active regions, in coronal holes, and even in the overall limb darkening itself; namely, increased intensity is correlated with decreased color temperature.

In the case of the comparison of poles and equatorial limbs, there appear to be two possible explanations for the behavior just noted:

(1) Spicules, which decrease the observed intensity at the limb by absorbing the chromospheric Lyman-continuum emission (Paper II), might be more numerous or extend higher at the poles than at the equator. Thus they would decrease the mean polar intensity below that at the equator, even though in the absence of spicules the chromospheric polar intensity might be higher, owing to a higher temperature at \( \tau_0 = 1 \).

(2) The pressure at \( \tau_0 \sim 0.5 \) could be less at the poles than it is at the equator. This would create at the poles a greater departure coefficient \( b_1 \) of the hydrogen ground states, leading to a smaller source function \( S_i = B_i(T)/b_1 \), and hence a smaller emergent intensity.

We believe the first possibility – that the properties of polar spicules cause the effect – to be unlikely for two reasons. First, and more important, spicules cannot explain the fact that the same trend is seen in active regions and coronal holes. Second, spicules by themselves seem inadequate to cause the effect. The increase of 100 K in color temperature at the poles would translate into a 30% increase in intensity in the Lyman continuum, if the density in the chromosphere were unchanged. To reduce this intensity to the observed value of only 90% of that at the equator would require about a two-fold increase in the number of spicules at the poles as compared to the equator. There is no evidence for such a large increase (Beckers, 1968).

Therefore, we are led to consider the possibility that a decreased pressure at \( \tau_0 \sim \cos \theta \sim 0.5 \) at the poles causes the observed effect. We note that a correlation has already been established between increased pressure and increased intensity in active regions (Noyes et al., 1970) and in coronal holes (Munro and Withbroe, 1972). Thus, unlike the spicule hypothesis, the pressure hypothesis may be applicable to all these situations.

In Paper II, we determined the pressure in the Lyman-continuum chromosphere by matching the empirically determined depth variation of the Lyman-continuum source function (which was obtained from Laplace inversion of center-to-limb data and makes no assumptions on pressure) with a theoretically determined depth variation in which the pressure enters through collisional transition rates in hydrogen. In applying this treatment to the present set of data, we extrapolated the polar limb-darkening curves to disk center. We also corrected the limb-darkening curves for absorption by spicules as in Paper II, assuming the same spicule distribution at the poles and the equator. The analysis produced not only the values of pressure at equator and poles but also \( T(\tau_0) \) and \( b_1(\tau_0) \).
3. Models

As a result of the findings summarized in § 1, we assume the photospheric model to be the same for the poles and the equator, and use the HSRA model (Gingerich et al., 1971). From the temperature minimum outward we use the HSRA model as modified by Vernazza and Noyes (1972) for the equator, but at the poles we make slight adjustments in $T(\tau)$ and the surface pressure $P_0$ in order to produce the pole-to-equator differences described above. Figure 3 shows the run of $T(h)$ and $N_e(h)$ for the poles compared with the equator. The pressure at the poles that gives agreement with both the empirical and the theoretical models (corrected for spicule absorption) is $P_0 = 0.10$ dyne cm$^{-2}$, as compared with $P_0 = 0.175$ dyne cm$^{-2}$ for the equatorial regions.

Fig. 3. The temperature $T$ and the electron density $N_e$ as a function of height for the equator (solid line) and poles (dashed line).

The present models for the poles and the equator reproduce the observed Lyman-continuum limb darkening of Figure 2 as well as the absolute intensities. The models
predict almost identical millimeter limb darkening for the poles and the equator, with
differences of less than 2%. Kundu (1971a, b) did not find any significant difference
between the poles and the equator at 1.2, 3.5, and 9.5 mm, but the observations do
not have high spatial resolution.

We did not attempt to reproduce the observed Hα line profile, because our atomic
model, a three-level atom plus continuum, underestimates the third-level population
and consequently the Hα source function. As a result, the residual intensity in Hα will
be underestimated. Nevertheless, the atomic model is suited to look for differences in
Hα between different temperature models. The computed differences between poles
and equator for the Hα profile are less than 1%.

4. Conclusions

Two chromospheric models, one for the poles and one for the equator, are presented
here. They reproduce the differences between poles and equator in the Lyman-conti-
nuum and predict very small differences in brightness temperature in the millimeter
region and in the Hα line, as observed. In our models, the polar and equatorial tem-
peratures and densities are approximately equal through the photosphere and low
chromosphere. In the upper chromosphere, the effects of a decreased coronal pressure
begin to be felt at the poles, causing an increased departure coefficient in the hydrogen
ground state and a consequent decrease in emergent intensity in the Lyman-continuum.
In addition, the temperature gradient dT/dx becomes less at the poles. This model
agrees with the finding of Withbroe and Wang (1972) that the density and temperature
gradient in the chromosphere-corona transition zone are both smaller at the poles than
at the equator.

It is possible that part of the observed effect may be caused by a greater number
density or height of spicules at the poles. Furthermore, we have not evaluated the
effect of a change from equator to poles of the temperature or thickness of the ‘plateau’
at the base of the transition zone, discussed by Vernazza and Noyes (1972) and
Vernazza (1972). For these reasons, the model derived should be considered a qualita-
tive rather than a quantitative one.

The persistent correlation between color temperature and intensity in the Lyman-
continuum for equator-pole differences, coronal holes, and active regions suggests
that, in general, both the chromospheric density and the temperature gradient are low
in regions of low Lyman-continuum intensity. Thus, active regions have a higher den-
sity and temperature gradient at τ_0 ~ 1 in the chromosphere, and coronal holes, the
reverse. The situation at the poles is physically very similar to that in holes and may
well be a special case of the more general hole phenomenon.

Because non-LTE effects enter into calculations for lines such as Ca ii K and
He i λ10830 just as they do for the Lyman-continuum, attempts to infer pole-to-equa-
tor differences by using these lines should take into account the possible influence of
pressure differences.

Finally, we note that the continuous opacity in the visible is so low in the Lyman-
continuum chromosphere that the present observations have no direct bearing on the problem of the solar oblateness (Dicke, 1970).

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References