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ON THE UNIFORMITY OF THE LOWER CHROMOSPHERE

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It is appropriate at a solar session during a radio astronomy conference to report on an analysis of optical observations to infer the properties of a non-spherically-symmetric chromosphere. For the first detailed model of such a non-symmetric chromosphere was that presented by Giovanelli (1949) [1] in an attempt to reconcile apparent contradictions between radio and optical data. Here we summarize some investigations based only on optical data, obtained by the High Altitude Observatory at the 1952 eclipse. Our observations of this eclipse were obtained as part of a joint programme with the Naval Research Laboratory, which conducted radio observations. Dr Hagen reports on the radio material (papers 46 and 47). The optical data in the present paper come from hydrogen and helium alone, the metallic data being still in reduction.

I. POINTS OF CAUTION

(*a*) An analysis for the distribution of n_e and T_e under the assumption of a spherically-symmetric atmosphere is relatively straightforward. Dropping the assumption introduces a wide range of possibilities. If, for example, one adopts the Giovanelli two-component model, it is tempting to identify the two components with spicular and inter-spicular regions, as Hagen (1953) [2] and Woltjer (1954) [3] have done. In the following we adopt this concept of two kinds of regions, homogeneous within themselves at a given chromospheric height, recognizing that it can be only a first approximation.

(*b*) Our use of the data from hydrogen and helium alone reduces the information that could be used, particularly for heights < 2000 km., where the metals would contribute, and for heights > 4000 km., where the radio

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results contribute. Any final model must include all these data, not available for the present analysis.

(*c*) Comparison of results from eclipse measurements at different phases of the solar activity cycle demonstrates (Athay and Thomas, 1955) [4] an appreciable variation of chromospheric structure with phase of the cycle. The present results apply only to the 1952 phase, thus near minimum.

2. DATA

There are basically two kinds of data. Type I whose use does not involve the question of whether or not the chromosphere is in local thermodynamic equilibrium, namely, free-bound and scattered light; type II in which the equilibrium question is highly relevant, namely, all line emission. Only the first type gives direct information on T_e and n_e; the second requires an indirect approach through a treatment of the non-equilibrium factors.

Type I data give the average value of two functions of n_e and T_e along the line of sight:

$$\overline{n_e n_p T_e^{-\frac{3}{2}}} = f(h) \quad h < 2500 \text{ km.} \tag{1}$$

$$\overline{n_e + n_e^2 T_e^{-\frac{1}{2}} n_p \alpha_{\mathrm{H}^-} e^{\psi/kT_e} c_1} = g(h) \quad h \lesssim 50{,}000 \text{ km.} \tag{2}$$

These two relations are sufficient to specify $n_e(h)$ and $T_e(h)$ over a limited height range (Athay, Menzel, Pecker, Thomas, 1955) [5], if spherical symmetry be assumed.

Type II data give certain indirect information, some of which may be used to check the consistency of the above solution, assuming spherical symmetry.

The hydrogen lines provide principally data on self-absorption. Results on self-absorption obtained under the assumption of a spherically-symmetric chromosphere may be applied to a combination of line and continuum data to estimate non-equilibrium factors. These non-equilibrium factors imply T_e values much in excess of those obtained from the continuum model. (Athay and Thomas, 1955 [6].)

Lines of He I appear to be free from self-absorption, and provide for several series the possibility of extrapolating the emission to the series head. From this extrapolation, one obtains the quantity:

$$\overline{n_{\mathrm{He\,II}} n_e T_e^{-\frac{3}{2}}} = \phi(h) \quad h \gtrsim 1200 \text{ km.} \tag{3}$$

The total helium abundance obtained from (3) and the spherically-symmetric continuum model exceeds that of hydrogen by a factor 10^6.

Then, the observed helium emission cannot come only from material at greater heights lying along the line of sight because of the absence of the 'shell' effect in a plot of emission vs. height until $h \sim 1100$ km. Thus, the helium data appear to require regions of high T_e at heights above ~ 1100 km. (Athay and Menzel, 1956) [7].

3. THE TWO-COMPONENT MODEL

Tentatively, then, we assume a model of the Giovanelli type; i.e. two types of regions, each homogeneous within itself, and occupying total fractions a_1 and $a_2 = 1 - a_1$ of the distance along the line of sight, specifying region 1 to be the source of He emission.

(a) *Equations*

We have the three equations already discussed, written for the two regions.

$$a_1 n_{e1}^2 T_{e1}^{-\frac{3}{2}} + a_2 n_{e2} n_{p2} T_{e2}^{-\frac{3}{2}} = f(h), \tag{4}$$

$$a_1 n_{\mathrm{He\,II}} n_{e1} T_{e1}^{-\frac{3}{2}} = \phi(h), \tag{5}$$

$$a_1 n_{e1} + a_2 n_{e2}[1 + n_{e2} n_{p2} T_{e2}^{-\frac{1}{2}} \alpha_{\mathrm{H}} e^{\chi_0/kT_{e2}} c_1] = g(h). \tag{6}$$

There are six unknowns: a_1; n_{e1}, n_{e2}; T_{e1}, T_{e2}; R. The H/He abundance is denoted by R, which we assume satisfies $5 \leqslant R \leqslant 20$. We assume constant pressure across the horizontal boundaries between the two regions to add the equation:

$$2n_{e1} T_{e1} = (2n_{e2} + n_{\mathrm{H}2})\, T_{e2}. \tag{7}$$

While there are apparently two free parameters in this system of four equations in six parameters, the actual range of solution is relatively small. In the following summary of the solution, we have deliberately picked the widest range of solution that is at all compatible with the data, in order to emphasize the physical implication of the results.

(b) *Summary of numerical solution*

We find that a_1 increases from 0·05–0·11 at 1500 km. to 0·9–0·99 somewhere between 2500–3500 km.

Further, in the height-range 1500–3000 km., T_{e1} has a value in the range 15,000–30,000° K.; while T_{e2} lies in the range 6000–8000° K. These values represent the range in solution; the change with height is small. Equation (4) rests on direct observations only for $h < 2500$ km.; the equations (4) and (5) become inconsistent for $h \sim 5000$ km. If we are permitted to use the equations (4)–(7) up to 3500–4000–4500 km., the numerical results suggest a considerable rise in T_{e2} at the greater heights.

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(*c*) *Comment on solution*

We note first that the chromospheric line-emission becomes concentrated into spicule-like structures at ~5000 km., and that coronal line-emission begins below 10,000 km. (Athay and Roberts, 1955) [8]. It is then tempting to regard the above numerical results as giving the following properties to the two components.*

	Cold component	Hot component
Size:	> 90% at 1500 km., gradually decreasing to ~1% at 5000 km.	< 10% at 1500 km., gradually increasing to ~99% at 5000 km.
T_e	6000–8000° K. for $1500 < h < 3000$; rises to 15,000–30,000° K. between 3500–5000 km.	15,000–30,000° K. for $1500 < h < 3000$ rises to much higher value between 3500–5000 km.

4. RELATION OF THE RESULTS TO OTHER INVESTIGATIONS

(*a*) *General form of $T_e(h)$ from stability considerations*

Any solution for $T_e(h)$ should come from a balance of net radiative emission against mechanical (or other non-radiative) energy input, and should give stability against fluctuations in T_e due to variation in local energy input. The chief sources of emission appear to be H^- in the lowest chromosphere, neutral hydrogen in the next higher regions, then ionized helium, and finally either free-free or highly-ionized metals. The computed regions of stability differ for the different sources. Thus, as each source gives rise to the succeeding, there will in general occur a rather abrupt rise in T_e. We find these jumps should occur from somewhere in the interval 7000–10,000° K. to a value near 20,000° K. as neutral hydrogen becomes unstable; and from 20,000–40,000° K. to $\sim 10^5$ as ionized helium becomes unstable (Athay and Thomas, 1956) [9]. The resemblance of these values to the values found in the empirical analysis of the actual chromosphere is striking.

One would assume that the thermodynamic structure of the spicule is somehow fixed by its dynamic state, as in the jet model (Thomas, 1948 and 1950) [10]. The fact that its thermal structure falls within the range suggested by stability considerations emphasizes the need to include a coupling between radiative and kinetic degrees of freedom in treating aerodynamic models in astronomy. The above spicule model (Thomas, *loc. cit.*) is inadequate in this respect. Moreover the interpretation of $a_1(h)$ also rests,

* We note that the expressions for emission per cm.^{3}, $(f(h), \phi(h), g(h))$, come from a double differentiation of the observations under the assumption of continuity of variables along, and perpendicular to, the line of sight. Thus, a_1 and a_2 contain implicitly the differential emission gradients of our two regions, and a correction is necessary before a literal interpretation in terms of relative areas is made. In the present rough analysis we simply defer the problems, since the corrections can only be made by successive approximation.

in the actual case, on the statistics of spicule height-distribution, and the associated thermodynamic properties.

(b) General comment on the 'hot' spicule models

Woltjer has presented a two-component model, based on the interpretation that spicules are everywhere hotter than the surroundings, and occupying about 2 % of the area along the line of sight. We find (Athay and Thomas, 1956) [4] four objections to his model. First, we are unable to represent our data with such a model and we believe these data to be more extensive than those which were available to Woltjer. Secondly, there are certain difficulties in his photometric data, since he was forced to calibrate observations made with an H_α filter by means of spectroheliographic data, obtained several years apart. It is not clear that the effect of variation of the chromosphere and the effect of scattered light in the spectroheliograph are negligible. Thirdly, we believe the actual choice of the spicule as hot is arbitrary, and cold spicules in a hot medium will satisfy the observations equally well. We believe that spectra, rather than only H_α filter observations, are required to settle the point. Finally, the questions of the stability of a hot spicule against radiative dissipation and of how the spicule can avoid heating the chromosphere must, we believe, be explored before accepting this model.

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Discussion

Minnaert: Is there a possibility of distinguishing between hot jets in a cold gas and cold jets in a hot gas?

Thomas: In our model this makes no difference.