

# Structure of the atmosphere above sunspots

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A comparison of optical, radio, ultraviolet, and x-ray observations demonstrates the need for a refined model of the atmosphere above a sunspot. A new two-component model is proposed, consisting of a double system of loops. Loops connected with local fields in the neighborhood of the spot would have a temperature up to  $7 \cdot 10^5$  °K; other loops connected with large-scale fields in distant parts of the active region or with the fields of other active regions would have a temperature  $T_e \gtrsim 2 \cdot 10^6$  °K. The relative volume occupied by these two types of loops would vary with height. This model can explain the chief characteristics of the emission in all ranges of the spectrum.

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## 1. INTRODUCTION

In collaboration with Livshits and Pikel'ner, the present author proposed in 1966 a model of the solar atmosphere above sunspots<sup>1</sup> which explained the apparent conflict between the heights of radio sources above spots accepted at that time ( $\gtrsim 20,000$  km) and the concept of a magnetobremstrahlung mechanism for the slowly varying component of the radio emission. According to this model, the sharp rise in temperature to its subcoronal values would set in at only a small height above a spot, about 1500–2000 km. In fact, an abrupt rise in temperature at low heights is fundamental for our model.

At greater heights various temperature profiles are possible, not only because of the differing size and field strength of sunspots but also since the height dependence of the magnetic field gradient is uncertain. In our 1966 paper we constructed a homogeneous model atmosphere for an isolated unipolar spot  $\approx 37,000$  km in diameter, having a field strength of  $\approx 3100$  gauss at the photospheric level. The field structure above the photosphere was approximated by a dipole distribution, with the dipole taken to be at a depth of 13,000 km. At wavelength  $\lambda \approx 3$  cm the size of the radio source was then found to be  $\approx 10,000$  km. The spectrum of the radio source was calculated; it agreed satisfactorily with observations of the slowly varying component. The behavior of the temperature and spectrum with height in this model is set forth in Table I below.

Our earlier analysis<sup>1</sup> was of some importance for reaching a final judgment as to the magnetobremstrahlung character of the polarized radio sources above sunspots.

Since that time much has been learned about the physical conditions above sunspots. We summarize the new information in Sec. 2 and compare it with the homogeneous model.<sup>1</sup> On the whole, the sharp rise in temperature at small heights indicated by our model is confirmed. There are, however, a number of new facts calling for refinement of the model, especially at large heights. In Sec. 3 we propose a new inhomogeneous model which, while retaining the advantages of the old one, provides an interpretation of a variety of new results gained from ultraviolet and x-ray observations.

## 2. COMPARISON OF HOMOGENEOUS MODEL WITH OPTICAL, RADIO, ULTRAVIOLET, AND X-RAY OBSERVATIONS

Relatively little research has been done on the physical conditions in the chromosphere above spots according to the strong optical lines. Indeed, only three models have been proposed,<sup>2–4</sup> and two of them were devised by the same author.<sup>2,3</sup> But the three models differ greatly from one another. The main result inferred from all the models is that the temperature gradient above a spot is considerably higher than in the chromosphere surrounding the spot. About 1500 km above a spot the temperature is higher than above a flocculus. The temperature begins to rise abruptly at a relatively small height above the spot,  $\approx 1000$  km. In this zone the temperature gradients actually exceed those obtained on our 1966 model.<sup>1</sup> This result is not surprising, however, since our main purpose had been to explain the radio spectrum at  $\lambda \gtrsim 2$  cm, so the temperature profile in our model was to be relied on beginning at  $T \gtrsim 3 \cdot 10^4$  °K. Thus our chief finding, the sharp rise in temperature at heights of  $\approx 1500$  km, is wholly confirmed by the optical observations.

Considerably more work has been devoted to analysis of the emission of local radio sources above spots. Zlotnik<sup>5,6</sup> has made a detailed calculation of the spectrum of radio sources. According to her model, in sources whose maximum radio brightness occurs in the range  $\lambda \approx 5$ –7 cm, the temperature reaches coronal values at a height of 6000–8000 km, while in sources with a maximum at  $\lambda \approx 10$ –12 cm the corresponding height is  $\gtrsim 10,000$  km. More recently Felli et al.<sup>7</sup> have sought to explain the polarized radiation of the S emission component in higher harmonics (fourth to seventh) without invoking hypotheses that would suppress the high-temperature levels above the umbra. They postulate that magnetic fields of 1000 gauss exist  $2 \cdot 10^4$  km above an action region, but they do not discuss the question of whether such strong fields are realistic. Nevertheless, Felli et al. encounter major difficulties in explaining the polarized radiation of sources at 3-cm wavelength.

Interpreting various eclipse observations, Gel'freikh

and Korzhavin<sup>8</sup> have concluded that for at least some radio sources the region of very high temperatures ( $T \approx 4 \cdot 10^6 \text{K}$ ) sinks to a level of  $\approx 2000 \text{ km}$ . They emphasize, as have other radio astronomers of the Pulkovo school, that the atmosphere above a spot umbra is a strongly heated region. But Gel'freikh and Korzhavin's conclusion that temperatures of order  $4 \cdot 10^6 \text{K}$  occur on a homogeneous model even at a height of  $4000 \text{ km}$  is not consistent with observations in the x-ray range (see below).

Observations at ultraviolet wavelengths<sup>9-11</sup> also indicate that high-temperature regions [ $T \approx (3-8) \cdot 10^5 \text{K}$ ] are present in spot umbrae. On the Skylab flights, images of active regions were scanned in lines of the C II, C III, O IV, OVI, Ne VII, Mg VIII, Mg IX, and Mg X ions at  $\approx 5''$  resolution. Immediately above a spot umbra a source considerably smaller than the umbra is observed, at a temperature of  $(3-7) \cdot 10^4 \text{K}$ . As the temperature rises the size of the source also increases. So long as the temperature is  $\leq 10^6 \text{K}$  the source is nearly an order of magnitude brighter than the surrounding flocculi, and its diameter is 2.5-3 times as great. At  $T = 1.6 \cdot 10^6 \text{K}$  the source can hardly be discriminated at all, and it no longer exceeds the active region around the spot in brightness. The emission of the O IV, O VI, and Ne VII ions is highly variable with time. Occasionally the spot will be the brightest feature in an active region, but sometimes it will not be visible at all in the lines of these ions. Cases may occur where the loop structure preserves its main features for many hours.

According to the ideas developed by Foukal,<sup>10</sup> the entire magnetic field tube of a spot has a temperature deficiency up to the top of the loop in coronal space. The width of the zone in which  $T \leq 2 \cdot 10^5 \text{K}$  would then be  $\approx (1-2) \cdot 10^4 \text{ km}$ . Some very recent work, however, changes the situation somewhat. Brueckner et al.<sup>12</sup> have obtained spectrograms of a spot umbra with the exceptional resolution of  $\leq 1''$ . They conclude that the radiation with  $T \leq 2 \cdot 10^5 \text{K}$  is concentrated in very small cells, below the resolution limit.<sup>12</sup> Levine and Withbroe<sup>13</sup> arrive at the same conclusion regarding the small width of the tubes when  $T \leq 2 \cdot 10^5 \text{K}$ . The electron density is quite high in this zone<sup>12,13</sup>:  $n_e \geq 2 \cdot 10^{10} \text{ cm}^{-3}$ .

Brueckner et al.<sup>12</sup> have also obtained direct evidence that substantial descending streams of plasma exist. The C II, Si III, C IV, N V, and O V lines (those formed in layers where  $T_e \leq 3 \cdot 10^5 \text{K}$ ) in the spectrograms always have a red satellite line corresponding to a velocity of  $\approx 100 \text{ km/sec}$ . Such satellites are absent from the chromospheric and high-temperature lines.

The accumulated data from a large number of x-ray observations,<sup>14-18</sup> especially those carried out from the Skylab station<sup>19</sup> at the high space resolution of  $\approx 2''$ , reveal that an entire coronal condensation is composed of individual loop-shaped tubes. The hottest tubes are confined to the central part of the condensation, above or between spots. However, according to the x-ray observations the zone where temperatures  $T \geq 2 \cdot 10^6 \text{K}$  are reached lies well above the same levels inferred from radio data. Most authors quote heights above  $(1.5-2.5) \cdot 10^4 \text{ km}$ ; only Poletto et al.<sup>17</sup> and Brabban<sup>18</sup> find levels of  $\approx 1 \cdot 10^4 \text{ km}$ . Admittedly, Parkinson's estimate<sup>16</sup> of the height of an x-ray source rests on observations with low space resolution; nonetheless

an apparent contradiction with the radio-astronomy results does exist and needs to be explained.

On the whole, then, the fundamental claim of our 1966 paper<sup>1</sup> concerning the sharp rise in temperature above sunspots at heights of  $\approx (2-4) \cdot 10^3 \text{ km}$  has been confirmed. At the same time there are several new facts that do not fit directly into our model and make some improvements necessary. These include the following:

a. The radio observations suggest the presence of temperatures  $T \geq 2 \cdot 10^6 \text{K}$  at heights  $h \approx 4 \cdot 10^3 \text{ km}$ . On the other hand, in observations at the limb no x rays are observed at these heights, or at any rate they are considerably weaker than at heights  $h \geq 2 \cdot 10^4 \text{ km}$ .

b. Observations of lines in the transition zone suggest a continuing temperature deficiency in spots at heights up to  $2 \cdot 10^4 \text{ km}$ , and the presence of regions of temperature  $T \leq 2 \cdot 10^5 \text{ km}$  at heights where radio and x-ray observations yield  $T \geq 2 \cdot 10^6 \text{K}$  instead.

c. The transition-zone lines exhibit a plasma flow directed downward at velocities up to  $100 \text{ km/sec}$ . There are no such velocities in the chromospheric and coronal lines.

d. The entire space above a spot is filled with loops and arches which evidently are magnetic in nature and join fields of opposite polarity.

## 2. TWO-COMPONENT MODEL FOR A CORONAL CONDENSATION

In attempting to refine the homogeneous model for a coronal condensation, it is natural to proceed with construction of an inhomogeneous model. A special stimulus in this direction is afforded by the observed structure of the magnetic loops and arches that link up with magnetic fields in the photosphere. Over the past few years the photospheric magnetic field in active regions has itself been found to be exceedingly irregular. Part of the magnetic flux of sunspots is locked into compact elements with a strong field,  $\approx 1000-2000 \text{ gauss}$  (pores, mottles, moving magnetic structures<sup>20-27</sup>). Another part of the spot field seems to form part of the large-scale and background fields, the fields of adjacent flocculi, or the fields of other active regions.

A natural hypothesis would be that this subdivision is also reflected in the structure of the atmosphere above the spots. The coronal condensation above a spot consists of a double system of loops. The flux tubes, closing up into local compact formations in the immediate vicinity of the spot, extend only a short distance into the corona [to  $h \approx (1-4) \cdot 10^4 \text{ km}$ ]. They are denser than the hot material surrounding them [ $n_e \approx (1-3) \cdot 10^{10} \text{ cm}^{-3}$ ] and have a temperature as high as  $7 \cdot 10^5 \text{K}$ . The density in these tubes does not obey the hydrostatic law and varies little with height, due to the strong flow of plasma along the field (see below). Heating at the top of the tube through thermal instability governs the temperature distribution. The transverse size of the tube is small, comparable with the size of the compact magnetic formations into which it closes ( $\leq 1-2''$ ). Although the tube becomes hotter at its boundaries, we shall henceforth neglect this behavior to simplify the calculations. The lines of force connecting with large-scale

TABLE I. Models for Atmosphere above a Sunspot

$h$ , $10^3$ km	$H$ , gauss	$\lambda$ , cm	Homogeneous model (Ref. 1)			Two-component model				
			$T_e$ , °K	$J_\lambda \cdot 10^{-22} \frac{W}{m^2 \cdot Hz^{-1}}$	$\bar{T}_{eff}$ , °K	$\tau_1$ , °K	$\tau_2$ , °K	$\alpha$ , %	$J_\lambda \cdot 10^{-22} \frac{W}{m^2 \cdot Hz^{-1}}$	$\bar{T}_{eff}$
2-4	$2 \cdot 10^5$	2	$3 \cdot 10^4$	0.28	$5 \cdot 10^4$	$3 \cdot 10^4$	$2 \cdot 10^6$	5	1.10	$1.38 \cdot 10^5$
4-8	$1.2 \cdot 10^5$	3	$5 \cdot 10^5$	1.4	$4.5 \cdot 10^5$	$(3-5) \cdot 10^5$	$(2-3) \cdot 10^6$	10	1.68	$5.34 \cdot 10^5$
6-12	700-1000	5	$(1-1.5) \cdot 10^6$	2.2	$2 \cdot 10^6$	$(5-7) \cdot 10^5$	$(3-4) \cdot 10^6$	50	2.2	$2 \cdot 10^6$
13-22	400-500	10	$(2-3) \cdot 10^6$	1.0	$3.65 \cdot 10^6$	$(7-9) \cdot 10^5$	$(4-5) \cdot 10^6$	80	1.06	$3.9 \cdot 10^6$

fields and the fields of other active regions form a second loop system. These loops may extend much higher into the corona; their temperature  $T \geq 2 \cdot 10^6$ °K. The density in these loops is lower than in the cool ones ( $n_e \leq 5 \cdot 10^9$  cm $^{-3}$ ) but it again varies little with height, because at  $T \approx 2 \cdot 10^6$ °K the scale height of the atmosphere is comparable with the height of the loop. Thus, unlike the cool tubes, the hot loops are in hydrostatic equilibrium. The thermal regime of the hot loops is determined by dissipation of magneto-hydrodynamic waves.<sup>15</sup>

A fundamental question facing our model concerns the relative abundance of cool and hot tubes above the spot. If we introduce a filling factor  $\alpha$  as the relative proportion of the area occupied by hot tubes, then up to heights of  $\approx (2-4) \cdot 10^3$  km the cool tubes will evidently occupy a larger part of the umbra ( $1 - \alpha \approx 95-90\%$ ). Beyond, as the lines of force emerge into nearby elements of the active region, the proportion of cool loops will fall off in inverse proportion to the mean strength of the magnetic field. Generally speaking, the value of  $\alpha$  may vary strongly from spot to spot, producing the strong variability of radio, ultraviolet, and x-ray sources.

A possible two-component model of this kind for the atmosphere above a sunspot is indicated in Table I. For the cool tubes we have adopted the value  $n_e \approx 10^{10}$  cm $^{-3}$ . The range of temperatures in the tube covers the principal temperature range for the ultraviolet line emission. The particular profile of temperature with height in the tube (just as in the hot tube) may vary somewhat, weakly affecting the results. For the hot tube we have adopted the value  $n_e \approx 5 \cdot 10^9$  cm $^{-3}$ . The spectrum of the S component of radio emission for observations on the disk has been calculated for such a model atmosphere; the calculation procedure has been described previously.<sup>1</sup> The same parameters have been adopted for the magnetic field and the area of the spot.<sup>1</sup> The quantity  $1 - \alpha$  has been assumed to vary in inverse proportion to the field strength  $H$  for heights  $h > 4 \cdot 10^3$  km.

The intensity and spectrum of the S component in our present model agree perfectly with the parameters of the old model<sup>1</sup> for a radio source above an isolated, medium-sized spot, and are consistent with the observations. The ultraviolet radiation will also agree with observation, both at the limb and on the disk. Most of the x rays will come from the layers with  $T \geq 2 \cdot 10^6$ °K. In this model the x-ray source is located at heights  $h \geq 2 \cdot 10^6$ °K. In this model the source is observed to rise and set at the limb, the radiation from heights below  $10^4$  km will be sharply reduced because the temperature is somewhat lower, and also since the proportion of hot loops is diminished. Furthermore, as  $h$  decreases the total horizontal extent of the high-

temperature zone above the spot will diminish as well. Thus at heights  $h \approx 4 \cdot 10^3$  km the emission measure will be at least an order of magnitude lower than at  $h \approx 2 \cdot 10^4$  km.

We have performed control calculations, allowing for a possible variation in temperature across the cool tube. In these calculations the model of the cool tube has been assumed to coincide with the central part of Levine and Withbroe's model loop<sup>13</sup> up to  $T \approx 6 \cdot 10^5$ °K. The characteristics of the emergent radiation turn out not to be significantly changed (to within the uncertainty in the quantity  $\alpha$ ).

If the hot model tube is altered in the sense of raising the temperature at low heights,  $J_\lambda$  will naturally be increased somewhat at short wavelengths. Thus if we assume that a temperature of  $4 \cdot 10^6$ °K is already reached at  $4 \cdot 10^3$  km height in the hot tube, the maximum in the spectrum will shift to  $\lambda = 3$  cm, and the intensity of the radio source and  $T_{eff}$  will increase by 35% at this wavelength.

The plasma flows along the cool tubes can be explained by the Meyer-Schmidt syphon mechanism<sup>28</sup> (see also Pikel'ner<sup>29</sup>). In the compact formations the magnetic field is somewhat weaker than in the spot umbra, while the gas pressure at the base of the tube resting on the umbra is lower than at the same level outside the umbra. Under these conditions material should flow within the umbra.

On the basis of the equations of continuity and motion, Maltby<sup>30</sup> has derived a simple equation for the plasma velocity in the tube:

$$(v^2/c^2 - 1) \partial \ln v / \partial s = g \cos \gamma / c^2 + \partial \ln \sigma / \partial s. \quad (1)$$

Here  $v$  is the velocity of the material,  $c = \partial p / \partial \rho$  is the sound velocity,  $g$  is the gravitational acceleration,  $\gamma$  is the angle between the magnetic field and the normal,  $\sigma$  is the cross-sectional area of the tube, and  $s$  is the coordinate along the tube. Material will rise at subsonic velocity from the region of enhanced pressure. At the top of the tube the velocity will become equal to the sound velocity if the tube does not change its cross section. Because of the decrease in the tube cross section near the spot umbra, the sound velocity will be passed on the descending part of the trajectory.

Numerical calculations performed for our model of a cool tube on the basis of Eq. (1) show that velocities  $\geq 100$  km/sec should exist at heights of  $(4-8) \cdot 10^3$  km, as observed by Brueckner et al.<sup>12</sup> This result does not depend at all on the initial velocity, which might be very low ( $< 1$  km/sec). The density rises sharply with transition into the chromosphere (by a factor of 20-100), and according

to the equation of continuity ( $\rho V \sigma = \text{const}$ ) the velocity will drop abruptly to 1–4 km/sec. These values agree with the result of direct velocity measurements in the chromosphere.<sup>12,31,32</sup>

#### 4. DISCUSSION OF MODEL

We find, then, that a two-component model based on the principle described above enables us to explain the observed properties of the coronal condensation and to remove the apparent conflict between the radio, ultraviolet, and x-ray observations. This model has the advantage that it affords a perfectly natural explanation for the strong variations in the ultraviolet radiation and the fine structure of the centimeter radio spectrum [see, for example, Kobrin (Ref. 33)]. The fluctuations have an amplitude of 0.5–10% of the total flux of the local radio source<sup>34</sup> at  $\lambda = 4$  cm. This amplitude corresponds to a change in the quantity  $\alpha$  by only 0.15–3%; that is, it can be explained simply by transverse motions of one or several loops.

The model might be tested by analyzing simultaneous observations of an active region in all three parts of the spectrum. In particular, one might expect a high correlation between the x rays and the radio emission at  $\lambda \approx 7$ –10 cm. As the wavelength decreases, the correlation should weaken, and at  $\lambda \approx 2$ –3 cm it should become poor. In this range it would be more likely for there to be a correlation between the radio and ultraviolet emission of such ions as C II, C III, O IV, O VI. Foukal<sup>10</sup> has pointed out that a bright source in the EUV spectrum above a spot would be completely invisible in the Fe XV and Fe XVI x-ray lines. Good correlation has been reported<sup>35</sup> between x rays and the radio emission at  $\lambda = 10.7$  and 6 cm. The correlation deteriorates at  $\lambda = 3.5$  cm, and becomes very poor at  $\lambda = 2$  cm. This result agrees fully with our findings, but unfortunately it rests on a comparison of various sources rather than analysis of the time behavior of some particular coronal condensation.

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