Origin of bright umbral dots in sunspots

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(Submitted March 25, 1974)
Astron. Zh., 51, 1272-1276 (November-December 1974)

Bright umbral dots are interpreted as the effect of instability in the deep layers of sunspots.

Bright structures in sunspot umbrae, the bright umbral dots, were observed by Chevalier[1] as early as the beginning of the present century, although they did not receive much attention for a long time. Interest in them has risen sharply recently, on the one hand due to increased resolving power of modern solar telescopes, and on the other because of apparent difficulties in constructing homogeneous models of sunspots.

Bray and Loughhead[2] obtained good photographs of these bright umbral dots. The size of these features appeared smaller than the limiting resolution of their telescope ($\lesssim 1''$). It was shown later that these features characteristically have a diameter of 200 km, a lifetime of ~ 15 min, and a brightness comparable to that of the undisturbed photosphere. Their velocity is directed upwards at the beginning of their life at the rate of approximately 3 km/sec, and downwards at the end of their lifetime. Their magnetic field is weaker than in the ambient medium, and during their lifetime the features move toward the penumbra.[3,4] Ikhsanov[5] maintained once again, on the basis of high-quality stratospheric photographs, that these bright features have characteristic diameters of 200-300 km. Moreover, it was discovered that the luminous bridges evidently have the same origin as the bright dots. At high resolution, the bridges break down into features with characteristic diameters of ~ 200 km. The magnetic field in bright dots and bridges has a significant transverse component. A connection seems likely between the bright features and the fine structure of the magnetic field in sunspots.[6,7] Inasmuch as both indirect and direct measurements of the magnetic field in Fe II lines yielded significantly lower values than in Fe I lines, there is now no doubt that the field is considerably weaker in the hot bright features than in the ambient umbral medium of the sunspot.

There is, on the other hand, no question of a connection between the bright features in the sunspot umbra and the model of the umbra. It is necessary to obtain data on the least bright umbral dots in order to construct an adequate model of the cold component of a sunspot. In these cases, one obtains a nearly hydrostatic optically opaque model of the cold component. In attempts to construct an "average" umbral model based on observations with small spatial resolutions, we inevitably arrived at a rarefied model, which strongly deviated from hydrostatic equilibrium.[8]

What are these bright features?

Two explanations are possible. The bright feature may be a relatively shallow formation, suspended within the umbral material, and not in any way associated with the substratum beneath the sunspot. Wilson[9] tends toward this viewpoint. In this case, the energy transfer within the features and their heating should apparently be affected by some kind of nonradiative mechanism. One of the possible mechanisms, Joule dissipation in small volumes, was examined in ref. 10. However, the picture of a suspended hot and dense formation within the rarefied cold material of the sunspot seems somewhat artificial. All of the suggested heating mechanisms have their difficulties.[9] It is not understandable why nonradiative mechanisms produce a brightness in these features that is comparable to the brightness of the undisturbed photosphere. The hydrodynamic stability of these features is completely unclear. Finally, such a model explains only the fact that bright features exist and leaves unexplained the remaining characteristics mentioned above. A model in which the hot features sink down deeply and are associated with hot material at the base of the sunspot would be more attractive. As discovered in the past few years, the magnetic field both in the spot and in the undisturbed photosphere consists of knots. It is possible that the spot is merely a tighter concentration of knots. It could be conjectured that the bright formation is simply a place of less concentration of knots, and we see the nearly unchanged photosphere. Nevertheless, such a simple static model also has its difficulties. Radiative transfer is effective only to depths of several hundred kilometers. Below that, another transfer mechanism would have to exist which would be able to transfer energy within a narrow (approximately 300 km wide) tube. Ordinary convection has a low efficiency in such conditions. Furthermore this tube cannot be a feature of the regular photosphere. Another more complex dynamic model is needed.

As is known, the reduced temperature of the sunspot is explained by the magnetic field altering the convection properties and weakening the transfer of energy from the deep layers of the sun upwards into the photosphere. The usual equation of convective instability

$$\nabla > \nabla_{ad} \tag{1}$$

in the presence of a magnetic field is replaced by another:[11]

$$H^2(H^2 + 8\pi P_g) < \nabla - \nabla_{ad}. \tag{2}$$

Here ∇ is the average temperature gradient in the medium ($= d \log T/d \log P_g$), and ∇_{ad} is the adiabatic gradient. It is apparent from Eq. (2) that there cannot be convective instability in the upper layers of the sunspot, where $H^2 > 8\pi P_g$. However, the ratio between magnetic and gas pressures varies in proportion to depth. The magnetic field increases rather slowly with depth. The average gradient of the field evidently does not increase more than 1 G/km. At a depth of $\sim 2 \cdot 10^3$ km, the magnetic field increases to less than double, and its pressure rises by a factor of 4. At the same time, the gas pressure at the same depth increases by an order of 3, compared with the sunspot levels. Therefore, beginning at a certain depth, convective
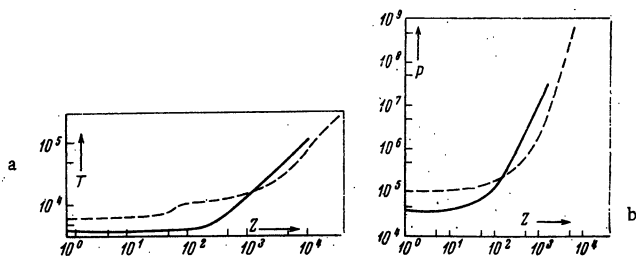
Fig. 1. Temperature (a) and pressure (b) in the sunspot (solid curve) and in the photosphere (dashed curve) as a function of geometric depth.

movements can no longer impede the magnetic field. If Zwaan's model[12] is taken as the basis and extrapolated to the convective zone model of Böhm-Vitense,[13] this critical depth corresponds to ~ 2-$2.5 \cdot 10^3$ km.

At this depth, the temperature and pressure beneath the spot and in the photosphere should balance out. In reality, this evidently proceeds even further; the temperature and pressure beneath the spot are higher than in the surrounding photosphere. Above a depth of 2-3 $\cdot 10^3$ km, convective and radiative transfer are ineffective for various reasons, and lateral transfer also cannot carry off all the energy. Consequently, local heating[14] should occur at this depth. This heating can be stabilized by the lateral transfer of energy in waves and the eruption of hot material upwards through the convective stable part of the spot.

Curves for temperature and gas pressure in the sunspot (compared with the photosphere) are shown in Fig. 1. In the upper parts the curve corresponds to the hydrostatic model of Zwaan;[12] at the base of the spot it is assumed that T beneath the spot is 1.2 times greater than below the photosphere.

For the model shown in Fig. 1, one can calculate curves for the radiative gradient ∇_{rad} and the adiabatic gradient ∇_{ad} as a function of depth, and curves for the logarithmic gradient of temperature as a function of pressure (Fig. 2). Despite some uncertainty in the calculations for the deep layers, it is evident that conditions arise to produce convective instability even starting at a depth of $1.5 \cdot 10^2$ km $\nabla > \nabla_{ad}$. A curve for entropy in the sunspot is shown in Fig. 3.

Therefore, at a depth of approximately $2 \cdot 10^3$ km (from here on we will designate this depth Z_0), a transition layer arises between the convective stable zone in the spot and the region of permissible convection beneath the spot. In this transition layer convection cells can arise that are close in size to photospheric granules (1000-2000 km). Naturally, the picture of convection in this transition layer should be nonstationary, and the cells do not fill the entire area under the spot. When a cell is formed, the magnetic field is carried by movements outward to the cell boundaries (if the field is concentrated in knots, this merely
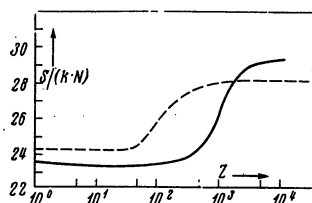
facilitates the task). Meanwhile, the magnetic field which is outside the boundaries of the cell becomes stronger, while a band with reduced intensity of the magnetic field arises above the cell. In the upper parts of the spot, where the pressure of the magnetic field is stronger than the gas pressure, the magnetic lines of force are deflected within the band, and a transverse component arises.

In the weak magnetic band beneath the transition layer, $\nabla > \nabla_{ad}$. The feature with characteristic dimensions smaller than the width of the band drops below the level Z_0 at a velocity tending toward zero. Above level Z_0 the feature moves by inertia and is, moreover, somewhat accelerated by the hydrostatic force. The divergent magnetic field creates a rarefaction in the medium, facilitating the formation of the feature above. The feature has some possibility of expanding laterally, although no farther than the walls of the cell. Besides, it can extend in height without limit.

In the lower layers of the tube the losses of the feature through radiation are insignificant, $\delta F/F = 10^{-4}$. The feature rises upwards with acceleration and arrives at the level $Z \sim 300$ km with a velocity of approximately 3 km/sec. However, at this depth it rapidly begins to brake. Losses through radiation are sharply increased: The horizontal optical thickness of the feature is $\lesssim 1$. The feature is also brought to a halt by the transverse magnetic field of the upper layers. At levels of $Z < 300$ km, the transfer is already performed by radiation.

Therefore, the general scheme of the origin, development, and decay of a bright dot in a sunspot consists of the following stages.

1. In the deep layers of the spot, where the temperature is higher than in the photosphere surrounding the spot, a convection cell may arise. The energy of the transverse motion in the cell is greater than the energy in the magnetic field. Lines of force separate, rarefaction occurs, and material rises from below, forming a weak magnetic band.

2. Energy transfer is established by convection in the weak magnetic band which forms, closely resembling the undisturbed photosphere in its physical characteristics. Convective transfer supports the brightness of the feature, close in brightness to that of the undisturbed photosphere.

3. The established convective transfer lowers the temperature gradient in the band. The temperature in the deep layers of the band becomes lower than in the surrounding spot. The energy of the movements drops; the
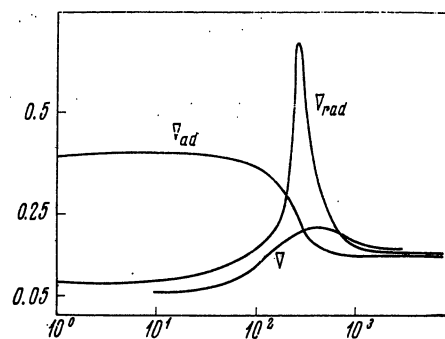

Fig. 2. Specific entropy in the sunspot (solid curve) and in the photosphere (dashed curve).

Fig. 3. Curves for gradients ∇, ∇_{rad}, and ∇_{ad} in a sunspot.

magnetic field upon expanding checks the inflow of energy from below. The bright dot, gradually dimming, ceases to exist.

The lifetime of the feature should be somewhat longer than the duration of granules in an undisturbed region, since the vertical path of the feature is larger, and for the most part it moves at low velocity. Since the entire picture is nonstationary, there should be a broad dispersion of brightnesses, lifetimes, and characteristic dimensions.

Near the penumbra, the magnetic tube is inclined toward the outside. Therefore, the bright features will move during their lifetimes toward the penumbra and increase in size.

The examined mechanism also makes it possible to explain the fine structure of the magnetic field in the sunspot. In old spots, the heating of the lower part is so high that it leads to the origination of conglomerates of bright features, namely the bridges, which is an indication of the imminent decay of a sunspot.

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