A THEORETICAL MODEL FOR THE CONVECTION OF MAGNETIC FLUX IN AND NEAR SUNSPOTS

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Abstract. In this paper we investigate the physical processes that lead to the growth and decay of magnetic flux in and near sunspots.

An initial phase of rapid growth is characterized by the emergence of magnetic flux from the deep convection zone. As the flux rope rises through the surface the magnetic field is swept to the junctions of the supergranular network where sunspots are formed. These flux concentrations follow the footpoints of the emergent flux rope as they rapidly move apart.

When all the flux has appeared and the footpoints have become stationary at their maximum extent the second phase sets in. It is characterized by a reversal of the supergranular flow around the spot. During the growth phase the converging supergranular flow descends around the sunspot and cools the region at its base. The spreading penumbral field covers part of the supergranule and reduces the area over which heat is transmitted to the photosphere. As long as the sunspot follows the footpoint of the emerging flux rope and moves rapidly through the supergranular network no steady accumulation of heat in one place occurs. Once the spot has become stationary however, the region around its base is insufficiently cooled. The gas in this region heats up and eventually rises reversing the flow pattern around the sunspot.

This reversal can break up the flux rope and destroys many sunspots within a few days. Some large sunspots however after an initial loss of flux achieve a quasistationary configuration. The reversed flow forms an annular cell (the moat) around a concentrated vertical shaft of magnetic flux at the center. Into this concentrated field region the supergranulation flow cannot penetrate. Small scale convection mainly due to the rapid rise of opacity also takes place within the concentrated vertical flux at depths below 2000 km. This provides an eddy diffusivity for the magnetic field.

The interplay between these two regions accounts for the slow decay of the sunspot and the observed motion in the moat around the spot. As the magnetic flux slowly diffuses outwards it enters into the supergranular flow and its photospheric ends are rapidly carried outwards across the surface towards the faculae region. The boundary between the supergranular flow outside and the diffusive region inside will be charac-

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terized by a critical magnetic field strength B_c for which the field can prevent penetration of the flow. We show for a cylindrically symmetric model that this leads to a linear decay law for the sunspot magnetic flux in quantitative accord with the observations.

We have tested the assumptions of the model by two-dimensional numerical computations in the Boussinesq approximation. It was found that motion is excluded from the region where the magnetic field strength exceeds some critical value B_c, that the flux decays on a time scale slow compared to the turnover time for the cell, that the decay rate is determined by diffusion throughout the flux rope, and that once fieldlines have diffused into the convecting region they are rapidly swept aside by the motion.

We discuss the implications of this model for the observations of moving magnetic field concentrations around sunspots and for evidence of small scale convective motion within the sunspot.

DISCUSSION

Athay: One aspect of your model that I don't understand is that when you reverse the supergranule flow there does not appear to be any force that holds the sunspot together. Why doesn't the field just disperse then into the surrounding medium?

Meyer: That's an interesting question. Once you have brought the flux together it does not partake further in the supergranular motion. The field is held together by the balance of magnetic pressure and the decrease of gas pressure inside the flux tube. The field just sits there quietly. In the Bussinesq approximation it is just a uniform column. In the non-Bussinesq approximation there would be some reordering of the flux tube with height but in general the column will still be rather verticle.

Athay: Wouldn't this configuration be very unstable however?

Meyer: This is an interesting point. Though there is no dynamic instability of the magnetohydrostatic configuration one might have expected an instability feeding on some thermal-convective effect. However the computations show that this is not the case, and I would like to emphasize that they of course contain the thermal and bouyant effects. The field concentration region excludes the large scale convection pattern, and only as diffusion weakens the field at the outer boundary can it be sheared off. However there will be an instability against large scale supergranular flow when the flux tube is not sufficiently vertical or branches off into different branches at depth. As soon as the flow reverses these will be pulled apart with the supergranular time scale of one or two days. We believe that this is just what happens to many sunspots.

Sturrock: You drew attention to the depression of the sunspot as tending to give it stability. It occurs to me that this might also help to explain the formation of sunspots since if there is a pore on the edge of the penumbra, it would see an inward moving force. In addition, I wish to ask whether there is any way to understand the division of a spot into an umbra and penumbra in terms of your model.

Meyer: That question has been considered by Simon and Weiss who compute what the equilibrium form of the flux tube is by neglecting the gas pressure inside and using the photospheric gas pressure outside. The gas pressure in the photosphere decreases exponentially with height. If there is very little magnetic flux, the bending over of the field lines occurs above $\tau = 1$ and at $\tau = 1$ one sees a pore. If there is enough flux however, the bending over will occur inside of $\tau = 1$. If these field lines are then horizontal and press onto the photosphere, it suggests that you have a penumbra. I am inclined to think that that is a reasonable explanation.

Wilson: I would like to reply to Athay's question. We were worried about the question of stability of a flux tube with motions occurring around the borders of it so I looked into the Kelvin-Helmholz instability in this regard. If you take just a two-dimensional model you obtain the same sort of answer that Chandrasekhar obtained in his book. If you include the cylindrical geometry you can increase the stability against this kind of dissipation quite significantly. May I just briefly show one slide which illustrates this

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question with possible ways in which the flux tubes move away from the spot. Friedrich has shown two possible cases, the first (the Harveys) is one in which the tube frays away at the top but the rope deep below the spot retains its original concentration. I think it is a fairly important feature of the second possibility that the flux rope starts to fray away from the central rope at some depth below the surface and is then carried towards the surface by the deep supergranule motion. On the first model it would be very difficult to imagine that these loops are produced in a horizontal flux tube solely by the granule motions. The supergranule motions, particularly the deep motions, must play some part in this and give rise to the succession of opposite polarities in the MMFs. However it may be possible to settle this problem by observation, in which case we'd have a much better grasp on what is going on underneath.

Zirin: How is it possible for a homogeneous plage to sit there for 10–14 days if this supergranule motion is sweeping everything to the edges. It's true that the edges of the plage show a supergranule pattern but the large plage that you want to make the sunspot out of is quite permanent and shows no such motion.

Meyer: Surely the supergranule motion exists in the plages?

Zirin: Then why don't we form sunspots all over the place. I don't see that kind of motion.

Meyer: I don't think you do because the foot points of these elements are just going in different direction. This is only a suggestion and I do not want to go into too many details because we have not worked them out. I feel very strongly that the linear decay rate is a very strong argument for the eddy viscosity that we have predicted.

McKenna-Lawlor: I have observed sunspot umbrae to disappear or reduce in size very rapidly following certain major flares. In one case an umbrae with a field of up to 2700 G disappeared in less than 5 h. What mechanism could produce this?

Meyer: I don't really know what I should say to such a case. I do know however that the unipolar flux that you have inside of a sunspot cannot just disappear. It has to either be transported away or opposite flux must move in so it can be submerged under the surface. In the spots you have observed some such effect must have happened. What is the time scale?

McKenna-Lawlor: Unfortunately the cadence of pictures was not better than 5 h. The umbra probably disappeared within a shorter time interval.

Meyer: That seems very short for such a sunspot to disappear by any of the required processes mentioned.

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