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THE SIZES OF ACTIVE REGIONS AND CONVECTIVE TRIGGERING OF THE BUOYANT LOOP INSTABILITY

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ABSTRACT The sizes of solar active regions were quantitatively studied using *Debrecen Heliographic Results 1977* data. The size-total area dependence was also examined. The size of a region was defined as the distance between the area-weighted mean positions of p- and f-polarity subgroups at the time when the total (umbral + penumbral) area of the spot group is at its maximum. Excluding the groups for which this occurred on the invisible hemisphere and other dubious cases, 68 active regions were left in the present one-year sample. Despite the smallness of this sample, the average size of the regions was found to be 58 400 km with a relatively low error of 3000 km (though the individual regions show a considerable scatter in size). It is proposed that the toroidal magnetic flux tubes lie in a sufficiently subadiabatic layer to be linearly stable and they are only destabilized by finite-amplitude convective disturbances that lift parts of them into the unstable layers. In such circumstances the typical size will be determined by the horizontal correlation length of the finite disturbances, thereby explaining the observed size.

INTRODUCTION

According to the presently most widely accepted view, active regions (AR's) are formed by a loop instability of toroidal flux tubes lying near the bottom of the convective zone. The instability is driven by buoyancy, and since the pioneering work of Spruit and van Ballegooijen (1982) linear and nonlinear stability analyses were carried out by numerous authors. A common result of these analyses is that the growth rate of the instability monotonously decreases with perturbation wavenumber, as the curvature force "pulling back" the loop becomes more and more pronounced as the curvature radius decreases. Now, if, as usually assumed, toroidal flux tubes lie in a layer where they are unstable against infinitesimally small finite-wavelength perturbations, perturbations of all wavelengths will be present and one would expect that during the evolution of the instability the low-wavenumber modes having the highest growth rate will become predominant—consequently the typical size of the loop formed should be as large as possible, i. e. comparable to the solar disk. This is in contrast with the observed size of AR's which is at least by an order of magnitude smaller than the solar disk.

If we want to understand the reasons for this discrepancy, it would be useful to have some more quantitative and detailed knowledge concerning the sizes of active regions. The main reason why such studies have rarely ever been carried out before is probably the obvious difficulty that the size of an AR changes constantly during its evolution, and it is difficult to find a basis on which to choose a particular instant of time to make the size determination. Today, however, a qualitative comparison between the results of nonlinear computations of buoyant loop emergence and observations of sunspot proper motions makes it possible to find this proper instant.

The computations serve with two important conclusions: during the emergence of the loop its footpoints stay fixed at a distance $\Delta \sim \frac{2}{3}\lambda$, λ being the wavelength of the original perturbation (e. g. Moreno-Insertis 1986), and after the top of the loop breaks through the surface, the motion of its mesh points with the surface (i. e. of sunspots and other elements of the AR) is first still governed by the buoyancy in the tilted subsurface parts, resulting in a fast expansion of the AR, then, as the "legs" of the loop become nearly vertical, buoyancy ceases and the expansion stops or slows down, driven only by the curvature force near the base of the loop (Shibata *et al.* 1991, van Ballegooijen 1982). Consequently, the instant when the legs have just become vertical and the size of the AR corresponds to Δ can be observationally identified with the time when the initial fast expansion of the sunspot group slows down, gets halted or even reversed. On the other hand, observations (Greenwich 1925, Waldmeier 1955, Dezső *et al.* 1964, Vitinsky *et al.* 1986) show that this time statistically coincides with the time when total spot area is maximal. (Our own study suggests, though, that this coincidence applies less well to spot groups with maximal total area not exceeding a critical limit.)

STATISTICAL STUDY

In accordance with what was said above we decided to determine the size of each single active region in our sample *at the time when its total (umbral+penumbral) area is at its maximal value A*. The d size was defined as the heliographic longitude difference between the area-weighted mean positions of p- and f-polarity subgroups within the AR.

Our basic data set was the Debrecen Heliographic Results 1977. Unlike the Greenwich Heliographic Results, this new series includes information about the coordinates and polarities of individual spots, and therefore it gave all necessary information for our investigation. Excluding the groups which reached their maximal development on the invisible hemisphere and some other dubious cases we were left with 68 AR's. Their distribution on the A-d plane is shown on Figure I. The zones of avoidance at the high d–low A and high A–low d parts of the diagram are apparent. Indeed, there seems to be an abrupt jump in the range of possible d sizes between small ($A < 60$) and large ($A > 60$) spot groups. Because of the smallness of the present sample this jump may be a statistical fluke but if real, it certainly suggests that two rather different populations of spot groups exist. This is independently confirmed by our study of how well the maximal area concides in time with the end of the first rapid expansion phase of the spot. The simple pattern of behaviour described in the preceding section seems to apply only to the larger groups only, while smaller groups often exhibit erratic changes in expansion velocity with little correlation to area changes. The strange behaviour of smaller groups may perhaps be explained by assuming that these spots begin decaying owing to turbulent erosion and fluting instability at an early phase of their development, well before the legs reach a vertical position.

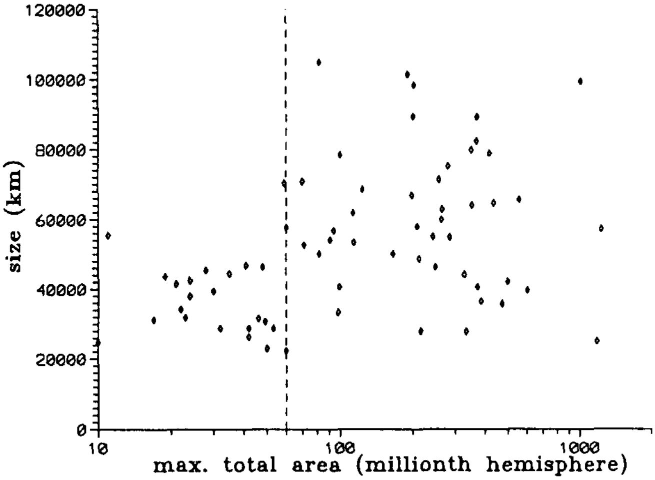

FIGURE I The distribution of sunspot groups in our sample on the maximal total area–size plane

For these reasons we decided to include in our sample the spot groups with $A > 60$ only. Thus, the final sample consisted of 46 spots. For these, the average size was found to be $d \sim 58\,400 \pm 3000$ km. Projecting this down to the bottom of the solar convective zone, taking into account the sphericity of the Sun we get $\Delta \sim 41\,700 \pm 2200$ km, i. e. $\lambda/2 \sim 30\,000 \pm 1500$ km.

DISCUSSION

The λ value found above is definitely much smaller than the size of the solar disk. As explained in the Introduction, this is hard to explain on the basis of linear instability theory. On the other hand, the above value of $\lambda/2$ is rather similar to the probable horizontal correlation length of turbulence near the bottom of the convective zone. Indeed, this l_h horizontal length scale is known from Petrovay (1992) to be related to the l vertical length scale by $l_h = (2/x)^{1/2} l$ with $x \simeq 1.55$. The vertical correlation length is close to the pressure scale height (Chan and Sofia 1989) which is $l \sim H_P \sim 4 \cdot 10^4$ km (Unno, Kondo and Xiong 1985). From this one gets $l_x \sim 0.7\, l = 29\,000$ km, in agreement with $\lambda/2$.

This coincidence of the horizontal scale of the perturbations leading to AR formation, as deduced from observations, and of the scale of turbulence leads us to suggest that *toroidal flux tubes lie in a layer which is sufficiently subadiabatic to make them linearly stable thereby suppressing the low-wavenumber modes with high growth rates. The tubes are only destabilized by finite-amplitude turbulent disturbances that lift parts of them into the higher-lying, unstable layers where*

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buoyancy can take over. In this case the typical size of the loop will be determined by the characteristic length scale of the perturbing mechanism, i. e. of turbulence.

One problem however remains: in numerical models of buoyant loop emergence the shortest unstable Δ is found to lie somewhere between $\Delta_{cr} \sim 8 \cdot 10^4$ and $2 \cdot 10^5$ km. Thus, loops with the observed small base separation could never be destabilized. The discrepancy between these lower limits and the Δ value found by us is however just a factor of 2 to 4, much better than the discrepancy with the size of the solar disk. It could be explained either by assuming that some physical mechanism not accounted for in previous emergence computations can push the limit down to about 30 Mm, or by clarifying the relation between maximal spot group area and vertical loop legs which may not be (in fact, probably *is* not) so strict as assumed in the present study.

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