AXIAL TILT ANGLES OF ACTIVE REGIONS

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(Dedicated to Cornelis de Jager)

Abstract. Separate Mount Wilson plage and sunspot group data sets are analyzed in this review to illustrate several interesting aspects of active region axial tilt angles. (1) The distribution of tilt angles differs between plages and sunspot groups in the sense that plages have slightly higher tilt angles, on average, than do spot groups. (2) The distributions of average plage total magnetic flux, or sunspot group area, with tilt angle show a consistent effect: those groups with tilt angles nearest the average values are larger (or have a greater total flux) on average than those farther from the average values. Moreover, the average tilt angles on which these size or flux distributions are centered differ for the two types of objects, and represent closely the actual different average tilt angles for these two features. (3) The polarity separation distances of plages and sunspot groups show a clear relationship to average tilt angles. In the case of each feature, smaller polarity separations are correlated with smaller tilt angles. (4) The dynamics of regions also show a clear relationship with region tilt angles. The spot groups with tilt angles nearest the average value (or perhaps 0-deg tilt angle) have on average a faster rotation rate than those groups with extreme tilt angles.

All of these tilt-angle characteristics may be assumed to be related to the physical forces that affect the magnetic flux loop that forms the region. These aspects are discussed in this brief review within the context of our current view of the formation of active region magnetic flux at the solar surface.

1. Introduction

It has been known for a long time that the axes joining the leading and following parts of active regions are tilted on average so that the leading portions lie slightly equatorward of the following portions. Perhaps the first quantitative treatment of this effect was by Hale *et al.* (1919), but the phenomenon may have been known earlier. The important contribution of Hale *et al.* was to present carefully measured average tilt angles and to point out and describe in detail the latitude dependence of this effect, which is now known as 'Joy's law'.

The earliest considerations of the average tilt angles and Joy's law simply were that they represented additional mysterious solar activity phenomena to be added to the long list compiled by observers of the Sun, starting with Galileo. The list of mysterious observed phenomena is still long, perhaps, but it can be argued now that the active-region tilt angles, and possibly Joy's law as well, belong instead on the growing list of phenomena which are beginning to tell us something about the

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nature and behavior of active-region magnetic flux loops beneath the photosphere, and, by implication, about the very nature of solar activity.

In this brief review, the tilt-angle phenomenon will be examined in some detail. Recent results indicate that various dynamic characteristics of regions may depend on the tilt angles of the regions. These results carry implications regarding the nature of the flux tubes that form the regions, their origin, field strengths, and the physical effects that shape their dynamic behavior during their rise to the surface through the convection zone. A recent review (Howard, 1996) gives a broader discussion of the tilt angle phenomenon, among other active region characteristics, without going into the detail given here on certain aspects.

The data sets used by this author in recent years for active region studies include the Mount Wilson daily full-disk magnetograms, which have been used in the 'coarse array' format to construct a data set of individual plages (on each day on which they are detected by the magnetograph). This plage data set, which now covers the interval 1967–1995, has been described (Howard, 1989). In addition, the Mount Wilson daily white-light photographs from 1917 through 1985 have been digitized to extract the positions and areas of all of the sunspots seen in this interval (Howard, Gilman, and Gilman, 1984). These sunspot data are also used in the discussion that follows. This data set also represents spots on each day on which they were observed. So for both data sets, a single plage or spot group may be represented a number of times for a single disk passage.

2. Tilt Angle Distribution

The distribution of region axial tilt angles over 2.5-deg increments of tilt angle is shown in Figure 1. Here the plage and spot group results from the data sets mentioned above are plotted separately. The solid line represents multi-spot groups, and the dashed line represents plages with areas greater than 3 resolution elements in the 'coarse array', where each of these pixels has an area of 1.68×10^{19} cm^2 (Howard, 1989). The smaller plages are omitted because with only a few pixels, the tilt angle is not well determined.

It may easily be seen in Figure 1 that the average tilt angle for spots is a small positive angle (the leading portion of the region positioned equatorward of the following portion). The average angle for all regions is close to 5 deg. This average tilt of the region axis has been explained as being due to the effect of the Coriolis force on the rising flux tube loop that forms the region and which is assumed to start its rise to the surface in the east–west orientation near the base of the convection zone (Schmidt, 1968; Wang and Sheeley, 1989; Howard and D'Silva, 1993).

A characteristic of region tilt angles that has already been noted (Howard, 1991a, b; 1996) may be seen in Figure 1, namely that plages have slightly larger tilt angles, on average, than do spot groups. The average tilt angle for the plages in Figure 1 is 6.27 ± 0.19, and for the spot groups it is 4.28 ± 0.19. If we adopt the

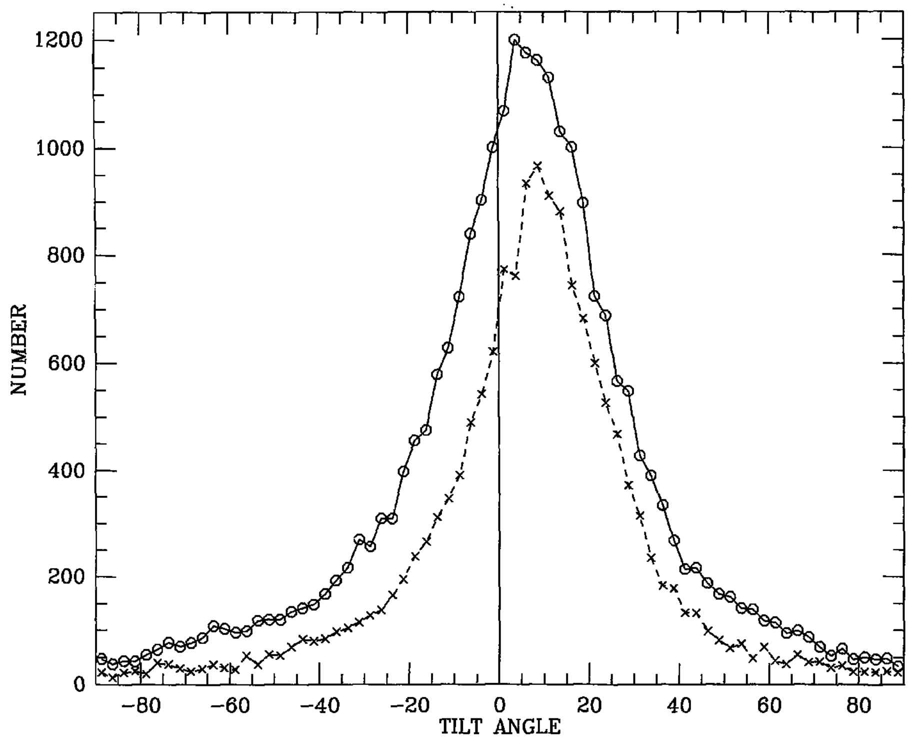

Figure 1. The distribution of axial tilt angles (in degrees) of 24308 sunspot groups from the Mount Wilson daily white-light photographs in the interval 1917 – 1985 (solid line) and 15692 plages derived from the Mount Wilson daily magnetograms in the interval 1967 – 1995 (dashed line). The angular resolution of the plages is coarse: a pixel is 1.68×10^{19} cm^2, or about 3×10^3 arc sec^2. Plages with areas <4 of these pixels have been omitted in this plot because the tilt angles of such regions are poorly determined.

explanation given above for the average tilt, i.e., that the Coriolis force on the rising flux loop twists it to result in a tilt angle that is a small positive quantity, then we may perhaps explain the difference in the tilt angles between these two features as being due to the greater field strength seen generally for sunspots than for plages. This may provide a stronger restoring force, and thus keep the tilt angle from growing as large, on average, as for the case of plages. An alternative or additional explanation is that the distances separating the polarities of plages is greater than that of spot groups, on average, and the larger polarity separation would also imply a lower magnetic tension for the plage fields, which means that the Coriolis force would counteract a weaker magnetic tension, thus leading to a larger tilt angle.

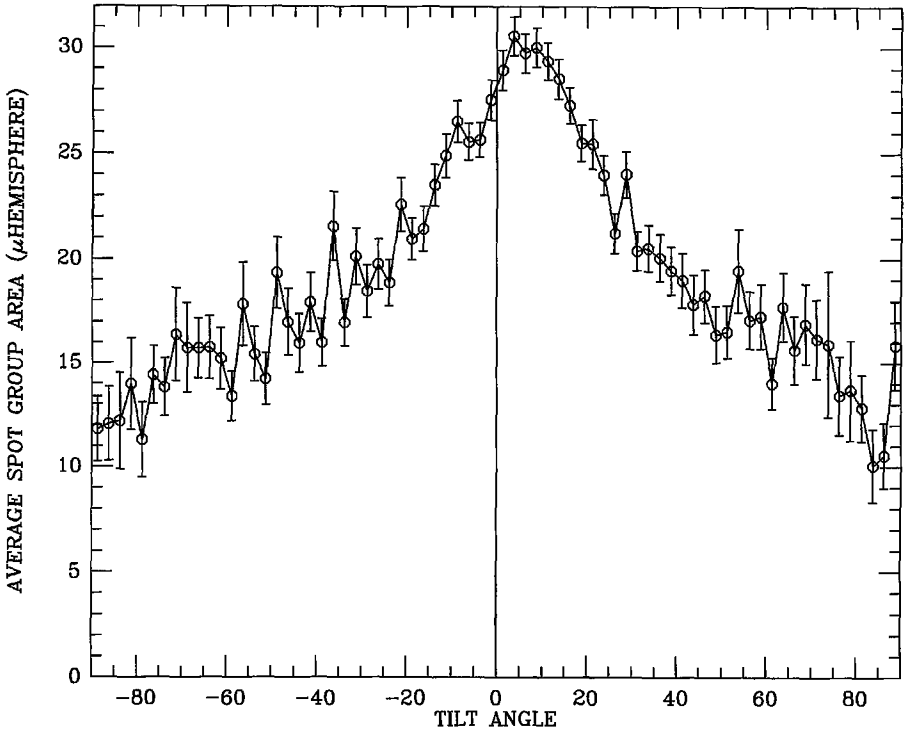

Figure 2. Average spot group areas for the sunspot group data set shown in Figure 1 for different values of axial tilt angle. Averages are taken over 2.5 deg. Full error bars shown here and in later plots represent 2 standard deviations.

3. Region Size

3.1. Region Areas and Total Fluxes

Average sunspot areas taken over 2.5-deg increments of group tilt angle are shown in Figure 2. It may easily be seen that average areas are largest for those angles closest to the average tilt angle (not to 0 deg). In the case of plages, the area is not a very useful parameter for such a study because all plages expand with age, and this tends to make a plot such as Figure 2 for plages very noisy. A better parameter for plages is total magnetic flux ($F_T = |F_+| + |F_-|$). Figure 3 shows this relationship. In this case, because of the low angular resolution of the data set, the smallest regions, consisting of less than 4 pixels, have again been omitted (as in Figure 1). Again there is a peak near the average tilt angle. Note that the curve in Figure 3 peaks at a slightly higher value of the tilt angle than that in Figure 2, corresponding to the fact, as seen in Figure 1, that plages have a slightly higher average tilt angle than spot groups.

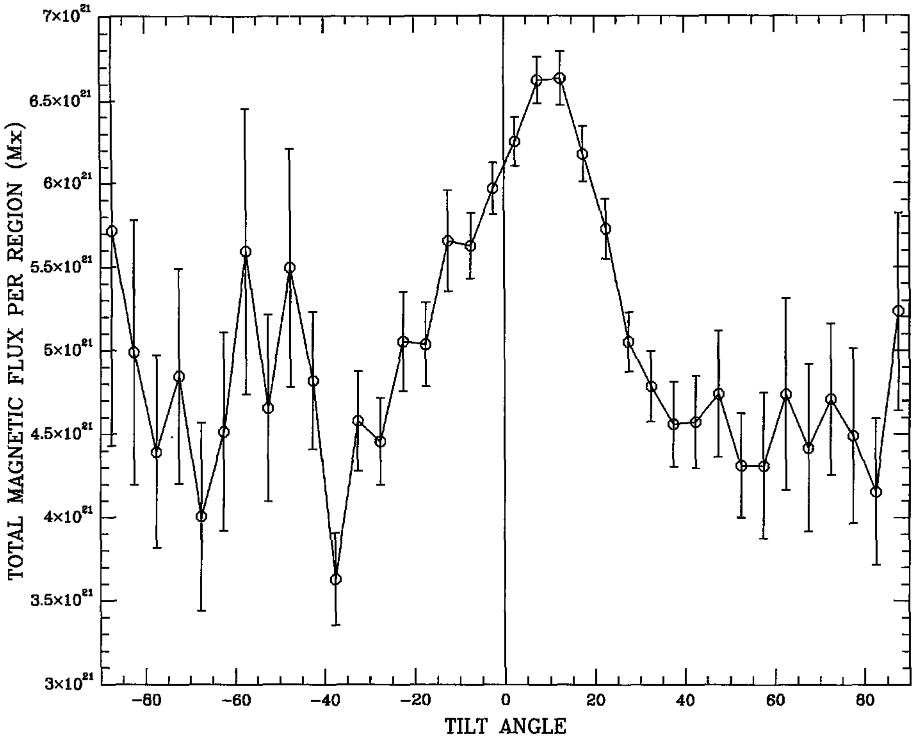

Figure 3. Average total magnetic flux ($F_T = |F_l| + |F_f|$) for plages from the same data set used in Figure 1. Fluxes are averaged over intervals of 5 deg in tilt angle.

A quite similar result concerning region size and tilt angle, illustrated in a different manner, has been found by Harvey (1993) using National Solar Observatory/Kitt Peak magnetogram data to define active regions.

It appears that the behavior of the larger plage tilt angles on this plot is different than that of the groups with larger tilt angles, seen in Figure 2. The areas for the groups show a general monotonic decline for larger (absolute) tilt angles, while for the plages, although the signal is more noisy, the effect seems to be a leveling off, or even perhaps it shows a slight increase for the largest (absolute) tilt angles.

The tendency for the average areas or total magnetic fluxes of the regions to peak near the average tilt angle may be explained in the following way. If the rise of the magnetic flux tubes through the solar convection zone of the region about to be born is affected by large-scale turbulent motions of the solar plasma, then one would expect the tilt angles of the regions with greater magnetic flux to be less altered by the turbulent convection than the tilt angles of the regions with less magnetic flux, because the stronger-field regions, with greater magnetic tension, will be less influenced by the turbulent velocity field. Thus more strong regions would be left close to the 'normal' tilt angle (determined by the Coriolis force, the rise time, and other factors) than small regions, and the result would be plots such as Figures 2 and 3.

3.2. Polarity separation

The average tilt angles of plages and sunspot groups vary with the distance separating the leading and following portions of the regions (Howard, 1993). This has been explained (Howard, 1993; D'Silva and Howard, 1993) as being the result of the increased magnetic tension for regions with smaller polarity separations. The larger magnetic tension provides more resistance to the Coriolis force on the rising flux tube, and thus regions with larger magnetic tension (smaller polarity separation distances) have been influenced less by the Coriolis force, which results in smaller tilt angles.

D'Silva and Howard (1993) used this result to derive a field strength of the region source flux tube at the base of the convection zone of 40–150 kG. This result comes from a numerical simulation of a source flux loop near the base of the convection zone. The model result reproduces not only the observed tilt angle-polarity separation relationship, but also the latitude dependence of this quantity.

Figure 4 shows an updated version of the tilt angle-polarity separation relationship for both the plage and sunspot group data sets. The plage data set used here includes only regions with normal ($|\text{tilt angle}| < 90$ deg) polarity separations. More data are included here than in the earlier plot (Howard, 1993). The points near the smallest polarity separation values for plages are likely to be influenced by the low angular resolution of this data set, and this effect may be seen by the errant points and large error bars on the left. The smallest (< 4 pixel) plages have been omitted from this data set, as mentioned above, but some residual resolution problems may still affect the smallest polarity separation regions. The slope for the plage data is 0.0382 ± 0.0047 deg Mm^{-1}. For the spot groups, the slope is 0.0600 ± 0.0047. Clearly there is a well-defined effect that is similar for both features, although the slopes show a significant difference. The tilt angle of a region depends (in part) on its polarity separation distance.

This raises the possibility that Joy's law is actually just a consequence of a possible polarity-separation dependence on solar latitude. An examination of the polarity separation distances of both plages and spot groups shows, however, that this cannot be the case. In plots of average polarity separation distance for regions as a function of latitude (not illustrated here), the slope for spot groups is -0.045 ± 0.027 deg Mm^{-1}, which is not significantly different from zero. For plages, the slope is 0.209 ± 0.023. Although this is in the right direction to explain Joy's law for plages, the magnitude of the effect is much too small. The difference in the average polarity separation between 5 and 30 deg from this plot is about 5 Mm. From the slopes seen in Figure 4, this would correspond to a tilt angle variation of about 0.15 deg. But the actual tilt angle change for these plages from Joy's law between 5 and 30 deg latitude is about 10 deg (Howard, 1991a). So

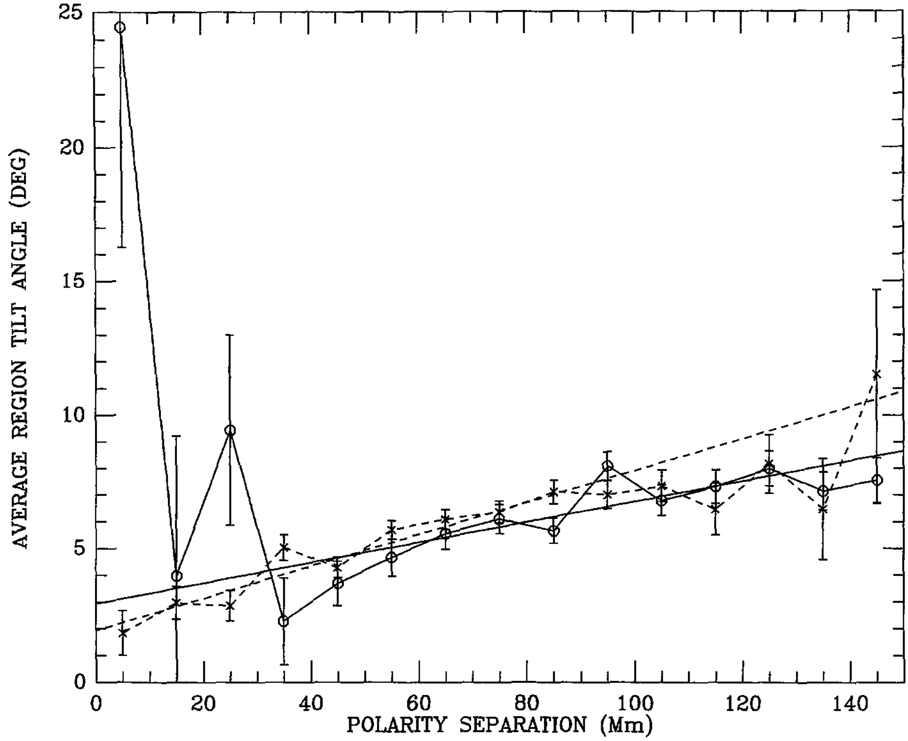

Figure 4. Average tilt angles for plages (solid lines) and spot groups (dashed lines) averaged over 10 Mm intervals in polarity separation. The data sets are those of Figure 1. The straight lines are linear least-squares fits to all the original points (not to the average points).

clearly the tilt angle-polarity separation distance effect plays an insignificant role in explaining Joy's law.

4. Region Dynamics

Within the commonly accepted view of the origin of active regions, the behavior of the rotation rates of regions in relation to their axial tilt angles presents a puzzling problem of interpretation. Figure 5 shows a plot, first described in an earlier paper (Howard, 1991b) but shown in a clearer presentation here, of average residual rotation rates for Mount Wilson multi-spot sunspot groups having different tilt angles. The residual rotation rate of each group is determined by subtracting the grand average rotation rate of all groups at that latitude from the measured rotation rate of the group. This eliminates the effects of the differential rotation of groups during the cycle from the resulting averages. Average residual rotation rates are taken over 10 deg in tilt angle. Here, as in so many plots of this sort involving tilt angles, we find a clear effect which is centered on the average tilt angle – or perhaps here it is centered on 0 deg; this difference is not very clear here, judging

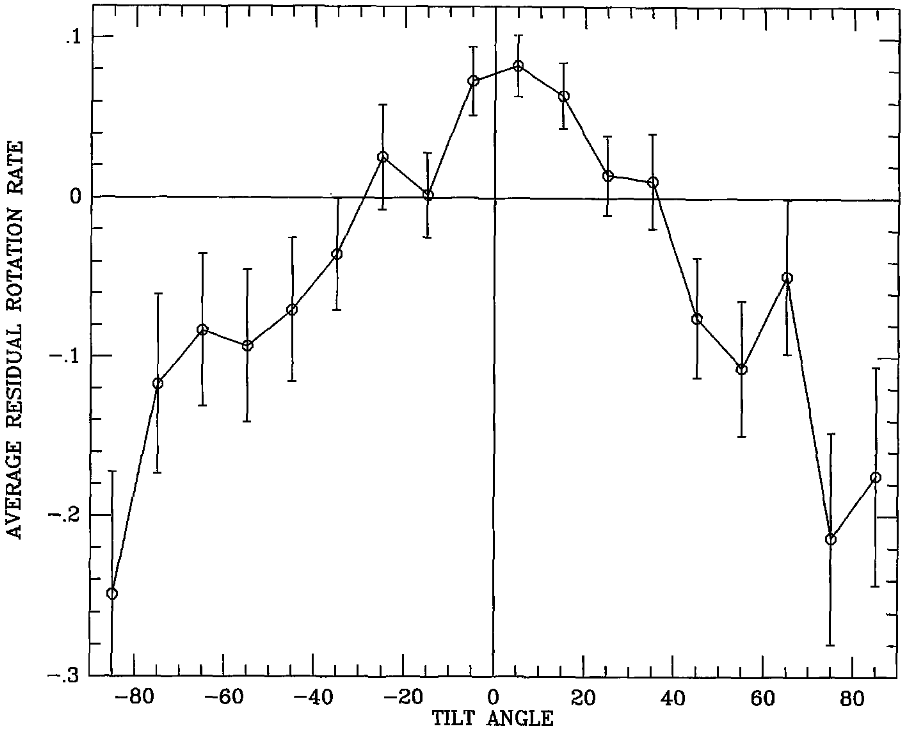

Figure 5. Average spot group residual rotations (the rotation of a group minus the average rotation rate of all groups at that latitude) over 10-deg intervals of tilt angle.

from the magnitude of the error bars. Clearly, on average, spot groups with tilt angles near the average value, or 0 deg, rotate significantly faster ($\approx$ 1% between tilt angles of 0 and 45 deg) than do groups having tilt angles far from this value.

Regions with tilt angles far from 0 deg are presumed to have greater twist in the field lines connecting them to subsurface layers than are regions with tilt angles near 0 deg. It is possible that this twist in the field lines affects the dynamic properties of the region in such a way as to alter its rotation rate. It is also possible that we see here an effect of region size, because it is known that smaller groups rotate faster than larger groups (Howard, 1996). However, from Figure 2 it can be seen that spot groups near the average tilt angle tend to be larger than spot groups far from the average tilt angle, which means that the the influence of the area-tilt angle effect should be to make the rotation rates of groups near the average tilt angle smaller than those far from that angle (or 0 deg). This is the opposite effect than what we see in Figure 5, and so this cannot be the explanation for this relationship. In fact, without the area-rotation rate effect, the peak seen in Figure 5 would have an even greater amplitude.

So the relationship seen in Figure 5 – a slowing of the rotation for spot groups with tilt angles far from the average value or 0 deg – may be related to the twist in the subsurface region field lines for groups with large absolute tilt angles. If this is the case, then the rotation rate of a region should be in part a result of an ongoing motion of the subsurface field lines during the lifetime of the region – a motion that is affected (slowed down) by the increased magnetic tension of a twisted flux loop. Note that a somewhat analogous effect is seen for region sizes. Larger regions, which also have greater magnetic tension in their subsurface flux tubes, rotate more slowly than smaller regions (Howard, 1996).

5. Discussion

These and other observational results which have been obtained over the last ten years or so (Howard, 1996) are beginning to set constraints on the nature of the subsurface flux tubes that rise to the surface to form active regions and on the physical processes that act to determine the nature and orientation of the magnetic fields of these regions. We may expect that continued studies of this sort will further our understanding of these subsurface fields, and, in conjunction with continued new results concerning subsurface features from helioseismology, will expand our knowledge of the structure of active regions and the nature of the activity cycle.

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