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Limits on magnetic fields that produce sunspots

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The solar dynamo is believed to operate in a thin stable region at the bottom of the convection zone and the bipolar magnetic regions (BMRs) that we see on the surface are produced by magnetic flux tubes generated there. These flux tubes emerge as Ω shaped loops (Parker 1955, 1979) due to magnetic buoyancy, and the regions where they intersect the surface are called BMRs. These BMRs obey Joy's law (Hale *et al.* 1919; Wang & Sheeley 1989, 1991; Howard 1992), which states that the line joining the two poles of BMR makes an angle with the latitudinal line, called the tilt, which increases with increase in latitude and the p-spot (preceding region of the BMR which is Westward) is closer to the equator. We give a theoretical model for these tilts (D'Silva & Choudhuri 1993). We also show that if the BMRs produced by flux tubes emerging from the bottom of the convection zone have to exhibit the tilts measured by observations (Wang & Sheeley 1989, 1991; Howard 1992), then the field strength at the bottom of the convection zone has to lie between 60 and 160 kG. For fields stronger than 160 kG, magnetic buoyancy dominates over Coriolis force and the tilts produced are very small compared to the observed values. Whereas, for fields weaker than 60 kG, Coriolis force dominates over buoyancy and makes them emerge at very high latitudes, well above the typical sunspot latitudes.

Fields above 60 kG are an order of magnitude stronger than the 10 kG fields that can be energy equipartition with the velocity fields at the bottom of the convection zone. Such strong fields will severely inhibit dynamo action (DeLuca & Gilman 1986). In addition, we do not know how a dynamo could produce such a strong field. We propose a couple of mechanisms (Choudhuri & D'Silva 1990; D'Silva & Choudhuri 1991; D'Silva 1993) by which equipartition fields could produce BMRs with the observed tilts : (a) Giant cells, if they exist, can dominate over Coriolis force and drag these equipartition fields in their updraughts, (b) Small scale turbulence can interact with the flux tube and exchange momentum with it, thus suppressing Coriolis force and making them emerge at the sunspot latitudes. We show that these two mechanisms can make equipartition fields emerge at the sunspot latitudes with the proper tilts, provided their sizes are smaller than a couple of hundred kilometers. We also show that special anchoring mechanisms have to be invoked in order to make equipartition fields of any size produce BMRs with the observed tilts.

Our understanding of the physical processes that produce flux tubes in the convection zone and from the BMRs is still very primitive. There could be some other mechanisms that

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are responsible in bringing large scale equipartition flux tubes to the sunspot latitudes with the observed tilts. On the other hand, it is possible that we would have to revise our current understanding about the dynamo theories so that they can produce fields stronger than the equipartition values by an order of magnitude, which we claim can reproduce the observed values of the tilts.

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