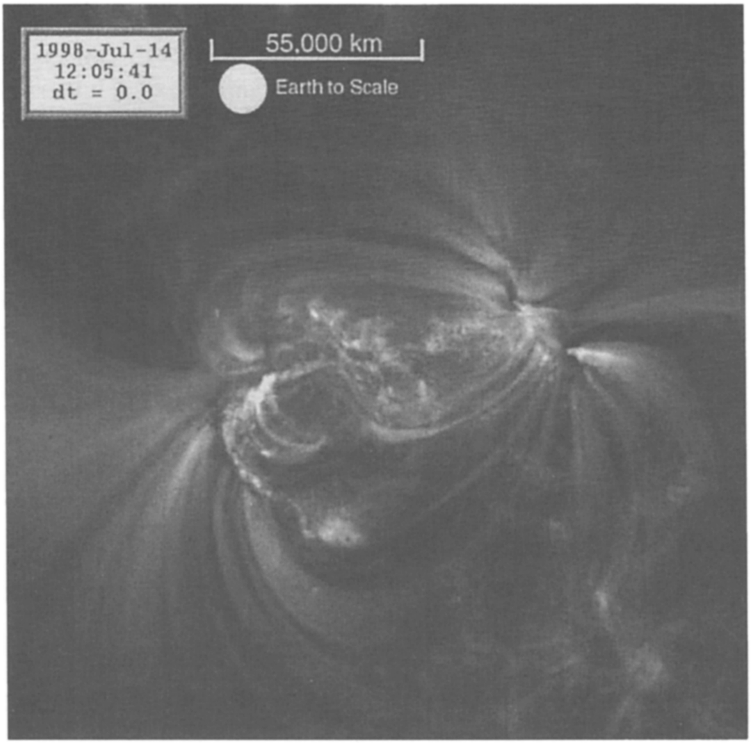
Session III

Active Region Structure and Dynamics



An EUV image of AR8270 observed by TRACE
(Adapted from Wang, p. 328)

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The Emergence of Magnetic Flux in Active Regions

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Abstract. Over the past decade, "thin flux tube" models have proven successful in explaining many properties of active regions in terms of magnetic flux tube dynamics in the solar interior. On the other hand, recent 2-D MHD simulations of the emergence of magnetic flux have shown that many of the assumptions adopted in the thin flux tube approximation are invalid. For example, unless the flux tubes exhibit a large degree of initial field line twist — and observations of emerging active regions suggest they do not — they will fragment (break apart) before they are able to emerge through the surface. We attempt to resolve this paradox using a number of 3-D MHD simulations (in the anelastic approximation) that describe the rise and fragmentation of twisted magnetic flux tubes. We find that the degree of fragmentation of an evolving Ω-loop depends strongly on the 3-D geometry of the loop, and that the Coriolis force plays a dynamically important role in the evolution and emergence of magnetic flux.

1. Introduction

Magnetic fields within active regions exhibit a bipolar structure, which suggests that they are the tops of large, Ω-shaped loops that have risen through the convection zone and emerged through the photosphere. On average, these bipoles are oriented nearly parallel to the East-West direction, which suggests that the underlying field geometry is toroidal. Since this orientation persists for many years during a solar cycle, we can infer that the toroidal flux layer must reside well below the solar surface, in a region relatively free from convective or buoyant disruption. However, if the field were embedded deep inside the stable radiative zone, it would never emerge on the time scale of a solar cycle. Thus, the magnetic field is likely stored at or near the "convective overshoot region", located at the boundary between the convective and radiative zones. In this region, the toroidal flux layer can succumb to one of several possible instabilities (eg. Caligari et al. 1995; Fan & Fisher 1996; Fan 2000; Wissink et al. 2000) that can initiate the formation of a magnetically buoyant tube. The tube then rises toward the photosphere as an Ω-shaped loop, where it will be observed as an emerging, bipolar active region.

The simplest way to model this picture is with the "thin flux tube" approximation. In this simple model, magnetic flux tubes move through a field-free plasma, pressure balance is always maintained across the tube, and the tube cross-section is always smaller than other length scales of the problem. Given these assumptions, an equation of motion can be derived for a 1-D tube that moves through a 3-D atmosphere. This model has proven very successful in explaining many observed properties of active regions (eg. Moreno-Insertis et al. 1994; Fan & Fisher 1996; Longcope et al. 1998). However, recent 2-D MHD studies have found that unless there is a significant amount of initial field line twist, the flux tube will not retain a "tube-like" identity, and will instead fragment before it is able to rise to the surface (Longcope et al. 1996; Moreno-Insertis & Emonet 1996; Emonet & Moreno-Insertis 1998; Fan et al. 1998). Recent observations of emerging active regions indicate that such a level of twist is not typically present (Pevtsov et al. 1995; Longcope et al. 1998), thus we are left with a theoretical quandary.

2. Results

We address this problem via 3-D numerical MHD simulations in the anelastic approximation (see Lantz & Fan 1999, and references therein). The effects of the Coriolis force are included by solving the non-dimensional form of the anelastic equations in the "modified local f-plane approximation" of Brummell et al. (1996). In Abbett et al. (2000), we first consider the effects of field line twist and 3-D loop geometry on an initially buoyant magnetic flux tube embedded near the base of a *non*-rotating, stratified model convection zone. We develop a quantitative means of describing the volumetric distribution of magnetic flux in terms of a single "tube" which may fragment into separate, distinct tubes during its rise toward the surface. We then use this technique to investigate the degree to which flux tube fragmentation in 3-D depends on the amount of initial field line twist, and the eventual geometry of the Ω-loop. Like previous 2-D studies of flux tube fragmentation, we find that if the initial field line twist along the tube exceeds a critical limit, then the tube will not fragment during its ascent toward the photosphere. However, if the initial field line twist is less than this critical value, then the degree of fragmentation at the loop apex depends on the curvature of the loop at that point — the greater the apex curvature of the Ω-loop, the lesser the degree of fragmentation for a given amount of initial field line twist (see Figure 1). Thus, loops that are tall and narrow show less fragmentation at their apex than loops that are short and wide.

There are two primary reasons for this behavior. The first is purely a geometric effect. In a 2-D, axially symmetric geometry, counter-rotating vortices that form during the tube's rise are effectively infinite in extent. They generate long-range flows that act to fragment the tube and prevent its buoyant rise to the surface. In a more realistic 3-D geometry, these vortex pairs form only along a short, finite section of the loop near its apex. Thus, forces due to vortex interaction are reduced, and the loop is able to rise to the surface more cohesively. The effective length scale of vortex interaction is related to the apex

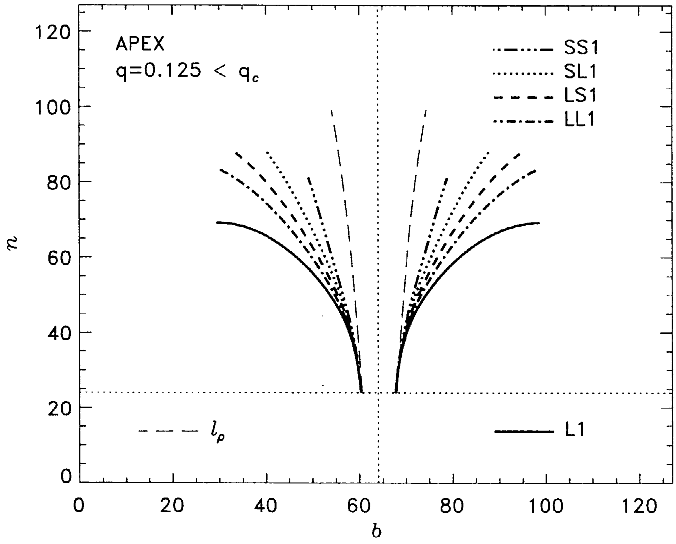

Figure 1. Fragment trajectories in the apex cross-section of a rising Ω-loop for a set of runs with gradually increasing values of apex curvature (see Abbett et al. (2000) for details).

curvature of an Ω-loop. For example, if a loop is tall and narrow, the length scale of the interacting vortices is short, and the degree of apex fragmentation is low. The second reason for this behavior stems from the differential circulation that exists between the apex and footpoint of the loop. This introduces additional magnetic twist of opposite sign in each leg of a loop fragment, which reduces the circulation of each fragment. Thus, the forces acting to separate the fragments of the flux tube are reduced.

In Abbett et al. (2001) we extend this analysis to a rotating model convection zone. We find that, even in the *absence* of initial field line twist, a buoyant flux tube that rises toward the surface in a rotating convection zone rises more slowly, and is better able to retain its cohesion than an identical flux tube that rises through a non-rotating convection zone. To better understand this behavior, we develop an approximate model that predicts the initial evolution of the circulation, and characterizes the formation and interaction of oppositely-directed vortex pairs of a fragmented Ω-loop. We find that the total circulation of tube fragments is suppressed via inertial oscillations introduced by the Coriolis force. Thus, if an initially untwisted tube is sufficiently magnetically buoyant so that it is able to rise a distance of several tube diameters before $t \approx \pi/4\Omega$ (where Ω is an estimate of the relevant solar rotation rate at a given latitude), then the tube will fragment during its rise toward the photosphere — otherwise it will retain its cohesion. The Coriolis force will also induce a retrograde flow along the loop that will manifest itself observationally as a relatively strong flow directed from the region of leading polarity to the region of trailing polarity of an emerging active region. This "LTT" flow will be present in both the magnetized and unmagnetized plasma.

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