THE EVOLUTION OF A SHEARED POTENTIAL MAGNETIC FIELD IN THE SOLAR CORONA*

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1. Introduction

Several theoretical studies have proposed that, in response to photospheric footpoint motions, current sheets can be generated in the solar corona without the presence of a null point in the initial potential magnetic field. In these analytic models, current sheets form wherever the coronal field dips down and is parallel to the photosphere. A fundamental assumption in these analyses — commonly referred to as the line-tying assumption — is that all coronal field lines are anchored to a boundary surface representing the top of the dense, gas-pressure-dominated photosphere. In theoretical arguments presented elsewhere (Karpen, Antiochos, and DeVore 1989), however, we show that line-tying is not valid for "dipped" coronal fields, and hence that the conclusions of the line-tied models are incorrect. We contend that current sheets will not form if the photosphere–corona interface is represented by a physically valid model. Here we summarize a numerical investigation of the response of a "dipped" potential magnetic field in a hydrostatic-equilibrium atmosphere to shearing motions of the footpoints. Our results show that, in the absence of artificial line-tying conditions, a current sheet indeed does not form at the location of the dip. Rather, the dipped magnetic field rises, causing upflows of photospheric and chromospheric plasma.

2. The Numerical Model

Our calculations were performed with a new, 2.5-dimensional, Cartesian finite-difference code which solves the compressible, time-dependent conservation equations of ideal Eulerian magnetohydrodynamics plus solar gravity. We assume that the plasma is fully ionized with a mean ionic charge of 1.059. The effects of momentum and magnetic field normal to the computational ($x-y$) plane are included self-consistently, assuming no gradients in this direction (z). The atmosphere begins in hydrostatic equilibrium, with temperature and density profiles typical of the photosphere–chromosphere interface. The initial magnetic configuration is a 2D potential field whose source is a pair of line quadrupoles separated by 5000 km. The initial field strength is in the range $1.3 < |\mathbf{B}| < 101\ G$. We take advantage of the inherent symmetry in this field and model only the right half. Appropriate symmetry conditions were imposed at the left boundary. The bottom boundary was assumed to be sufficiently deep in the photosphere that the normal component of velocity is negligible there. Elsewhere, we applied open conditions to allow maximum freedom for the magnetic field and plasma to adjust to the shear.

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3. Results

The initial 2D potential field was sheared by imposing a localized body force for the entire run duration of 500 s. By this time, the effects of the shear clearly extend to the left axis yet no vertical current structures are visible there. Contours of the shear-induced B_z are aligned with the planar field lines in the low-β region, indicating that this region is approximately force free. Where $\beta \gtrsim 1$, significant mass flows exist along the field. Upflows of a few km s^{-1} predominate in the upper left quadrant, where $\beta \sim 0.1$, in response to the magnetic-field uplift. The magnetic flux through the left axis, $\int_0^x B_y dx$, decreases with time at a given height for $\beta \lesssim 5$, and varies smoothly with height at each time. This verifies that the upward field-line motion increases continuously from zero at the base to finite values above, and that a vertical current sheet never develops.

4. Conclusions

We find that no discontinuity or current sheet forms when the footpoints of an initial potential magnetic field are sheared at the photosphere–chromosphere interface in a gravity-stratified atmosphere. This result contradicts the conclusions of Aly (1985), Moffatt (1987), and Low and Wolfson (1988), for the following reason. Contrary to a basic assumption of these models, the transition between the photosphere and chromosphere is continuous. The field lines are not line-tied at this level, but rather can adjust to the imposed stress as long as $\beta \lesssim 5$. Hence, the effects of solar gravity cannot be neglected in determining the coronal magnetic-field reponse to photospheric footpoint motions. In addition, the dynamic response of the photospheric and chromospheric plasma lifted by the stressed field might have interesting ramifications for solar activity such as surges and spicules (*e.g.*, Blake and Sturrock 1985). On a larger scale, this process might drive flux eruption in complex magnetic topologies.

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References

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DISCUSSION

VARMA: What role has gravity played, physically speaking, in your calculations?

KARPEN: Gravity is responsible for the stratification of the atmosphere, and hence the invalidation of treating the photosphere as an infinitely thin discontinuity (between high and low β plasmas) at which contacting field lines are line-tied.

FORBES: Are you saying that the Low & Moffatt results are not valid because a slight violation of the line-tying condition completely prevents the formation of the current sheets that occur in their model?

KARPEN: Essentially, yes.

TAKTAKISHVILI: Is your calculation relevant for spicule formation?

KARPEN: Our results - which show upward velocities of a few km s^{-1} in the vicinity of the dipped magnetic field - may have interesting ramifications for dynamic chromospheric events of this type. We plan to investigate this issue further in future numerical simulations.

PRIEST: A time of 400 secs is how many Alfvén times? Does the experiment approach an equilibrium.

KARPEN: 400s is approximately 10 Alfvén transit times in the low-β portion of the system. We have performed relaxation calculations of the asymmetric version of the Low-Wolfson model and do observe current sheets forming along the separatrices as predicted. Thus far, none of our calculations - either with or without gravity - exhibit a loss of equilibrium.

DRYER: (i) As I recall - your calculation did not have explicit resistivity included?
(ii) In your high-β case, am I correct in thinking that a small shearing velocity was sufficient to get dynamic motion? (In our calculations [Wu,Song, & Dryer,poster], for our $\beta = 15.4$ case, a peak shearing velocity of 5 km/sec was sufficient. For another case of $\beta = 0.06$, we required a higher value of 15 km/sec.)

KARPEN: (i) That is correct - we are solving the ideal MHD equations, although the finite difference technique always introduces a small "numerical" resistivity which does not affect the present results.
(ii) Our calculations employed a shearing velocity which was smaller than your smallest value; we did not see any evidence for the instability observed in your work, under those low-velocity conditions, but we do see upflows of a few km s^{-1} in the vicinity of the magnetic-field "dip".

HOLLWEG: Did your forcing actually get applied to field lines which touch the photosphere?

KARPEN: The forcing was applied to a range of field lines - those which extended deep in the photosphere as well as up to the $\beta \approx 1$ level. It is important to realize, however, that there is no *discrete* photosphere to "touch", due to the gravitational stratification of the atmosphere.

ROBERTS: Can you say how your results will change with varying g? I am wondering whether current sheets will again form if stratification is sufficiently weak (low g), as it will be in low g stars, or whether your results will show that sheets are always absent if $g \neq 0$. My guess would be that a critical strength of stratification would arise; if so, this might be important for ideas of heating of stellar atmospheres in the case of stars that are different from the Sun.

KARPEN: Our present intuition suggests that the effective width of the current structures which form in a gravity-stratified atmosphere should be roughly equal to the photospheric gravitational scale height. What actually happens when $g \rightarrow 0$ is an open but very interesting question, however. We plan to investigate this issue numerically, by repeating our calculations with successively smaller gravitational scale heights.