Best
Available
Copy

E202 1480

AD-A282 019

PAGE

Form Approved
OMB No. 0704-0188

June 17, 1994

Reprint

ON THE RELATION BETWEEN PHOTOSPHERIC FLOW FIELDS AND THE MAGNETIC FIELD DISTRIBUTION ON THE SOLAR SURFACE

PE 61102F
PR 2311
TA G3
WU 27

George W. Simon (AFGL) A.M. Title, K.P. Topka, T.D. Tarbell, R.A. Shine, S.H.Ferguson(Palo Alto Rsch Lab), H. Zirin (California Institute of Technology)& SOUP Team[2]

Phillips Lab/GPSS
29 Randolph Road
Hanscom AFB, MA 01731-3010

PL-TR-94-2173

[2] SOUP team includes L. Acton, D. Duncan, M. Finch, Z. Frank, G. Kelly, R. Lindgren, M. Morrill, N. Ogle (deceased), T. Pope, H. Ramsey, R. Reeves, R. Rehse, and R. Wallace, Lockheed Palo Alto Research Laboratory; J. Harvey, J. Leibacher, W. Livingston, and L. November, National Solar Observatory.

Reprinted from the Astrophysical Journal, 327: 964-967 , 1988 April 15

Approved for public release; distribution unlimited

Using the technique of local correlation tracking on a 28 minute time sequence of white-light images of solar granulation, we have measured the horizontal flow field on the solar surface. The time series was obtained by the Solar Optical Universal Polarimeter (SOUP) on Spacelab 2 (Space Shuttle flight 51-F) and is free from atmospheric blurring and distortion. The SOUP flow fields have been compared with carefully aligned magnetograms taken over a nine hour period at the Big Bear Solar Observatory (BBSO) before, during, and after the SOUP images. The flow field and the magnetic field agree in considerable detail: vectors which define the flow of the white-light intensity pattern (granulation) point toward magnetic field regions, magnetic fields surround flow cells, and magnetic features move along the flow arrows. The projected locations of free particles ("corks") in the measured flow field congregate at the same locations where the magnetic field is observed.

14. SUBJECT TERMS Granulation, Mesogranulation, Supergranulation, Magnetoconvection, Velocity fields, Magnetic fields	15. NUMBER OF PAGES 4
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

THE ASTROPHYSICAL JOURNAL, 327:964-967, 1988 April 15

ON THE RELATION BETWEEN PHOTOSPHERIC FLOW FIELDS AND THE MAGNETIC FIELD DISTRIBUTION ON THE SOLAR SURFACE

GEORGE W. SIMON
Air Force Geophysics Laboratory, National Solar Observatory–Sacramento Peak[1]

A. M. TITLE, K. P. TOPKA, T. D. TARBELL, R. A. SHINE, AND S. H. FERGUSON
Lockheed Palo Alto Research Laboratory

H. ZIRIN
California Institute of Technology

AND

THE SOUP TEAM[2]

Received 1987 August 31; accepted 1987 October 5

ABSTRACT

Using the technique of local correlation tracking on a 28 minute time sequence of white-light images of solar granulation, we have measured the horizontal flow field on the solar surface. The time series was obtained by the Solar Optical Universal Polarimeter (SOUP) on Spacelab 2 (Space Shuttle flight 51-F) and is free from atmospheric blurring and distortion. The SOUP flow fields have been compared with carefully aligned magnetograms taken over a nine hour period at the Big Bear Solar Observatory (BBSO) before, during, and after the SOUP images. The flow field and the magnetic field agree in considerable detail: vectors which define the flow of the white-light intensity pattern (granulation) point toward magnetic field regions, magnetic fields surround flow cells, and magnetic features move along the flow arrows. The projected locations of free particles ("corks") in the measured flow field congregate at the same locations where the magnetic field is observed.

Subject headings: Sun: atmospheric motions — Sun: granulation — Sun: magnetic fields

I. INTRODUCTION

Simon and Leighton (1964) suggested that the solar supergranulation flow field (Leighton, Noyes, and Simon 1962) carries the solar magnetic field to the flow cell boundaries to form the well-known chromospheric network pattern long seen in calcium and hydrogen images. Leighton (1964) also created a diffusion model of the solar cycle in which the interaction of the flow field and the magnetic field through a random walk process was responsible for the distribution of the magnetic field along the solar surface over the solar cycle.

Later theoretical studies of magnetoconvection (Weiss 1978; Meyer *et al.* 1979; Galloway and Weiss 1981; Parker 1982) showed how the motion of supergranules could redistribute and concentrate magnetic flux tubes in and below the solar surface. Recent papers have confirmed and extended the earlier work to include motions in granules (Schmidt *et al.* 1985) and have applied more elaborate two-dimensional and three-dimensional computational techniques (Proctor and Weiss 1982; Galloway and Proctor 1983; Nordlund 1985*a*, *b*; Cattaneo 1984; Hurlburt and Toomre 1988). The theoretical analyses suggest that the observed magnetic and intensity structures in the surface and higher layers of the solar atmosphere depend on the nature of both large-scale (supergranular, mesogranular) and small-scale (granular) subsurface flows.

On the observational side, Simon (1967) showed evidence in a statistical study of the motions of some 2300 granules during a 25 minute time series that individual granules tend to flow toward supergranule boundaries. Using much better data, Muller and Mena (1987) have recently succeeded in directly observing outflows of granules and facular points from sunspots on Pic du Midi images. There have also been many attempts to measure the motions of individual magnetic field elements (Vrabec 1971; Smithson 1973; Schröter and Wöhl 1975; Mosher 1977) in order to validate the idea that field is moved to supergranulation boundaries by subsurface flows. Good reviews of these observations may be found in Harvey (1977) and Zwaan (1978, 1987). Recent observations of the motion of intranetwork fields at BBSO (Martin 1988) have clearly shown motions of mixed polarity elements toward the boundaries of the magnetic network. Further evidence comes from Title, Tarbell and Topka (1987) who used high-resolution (0".5) data obtained at the Sacramento Peak Vacuum Tower Telescope to show that the loci of magnetic fields correlate better with velocity downdrafts and dark lanes in the granulation, than with upflows and bright regions in the continuum. Taken together, these observations suggest that not only the *large-scale supergranular flow*, but also the much smaller motion fields of individual granules help to determine the structure of magnetic field on the Sun's surface.

The above discussion suggests that the flow determines the evolution and distribution of the magnetic fields. However, at least in active regions, it is clear that the magnetic field has a significant effect on the flow field. Zwaan (1978) has shown that

[1] Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation. Partial support for the National Solar Observatory is provided by the USAF under a Memorandum of Understanding with the NSF.

[2] SOUP team includes L. Acton, D. Duncan, M. Finch, Z. Frank, G. Kelly, R. Lindgren, M. Morrill, N. Ogle (deceased), T. Pope, H. Ramsey, R. Reeves, R. Rehse, and R. Wallace, Lockheed Palo Alto Research Laboratory; J. Harvey, J. Leibacher, W. Livingston, and L. November, National Solar Observatory.

the size of the network cells in plage is significantly less than in the quiet Sun. This shows that the presence of the field modifies the flow pattern.

The high-quality granulation pictures taken in space by SOUP now provide a unique opportunity to detect large-scale surface flows by direct displacement measurements of the local intensity pattern. We have applied correlation tracking methods to make the required measurements (November *et al.* 1986). The flow field is detectable because it advects the granulation pattern. That is, granulation serves as a tracer for the flow. Since granules typically last 10–15 minutes, measurements must be made in a time short compared to this lifetime. In addition, because the 5 minute oscillation is also present in the movies (Title *et al.* 1986), measurements must be separated by considerably less than 2.5 minutes. We have used time differences between images of 10–60 s in this study. This seems adequate since velocities obtained from images up to 60 s apart do not differ significantly. Because the supergranulation flow ranges from 0.1 to 1 km s^{-1}, in a 30 s interval the local granulation pattern should move 3–30 km or 4–40 milliarcsec. The best ground-based imagery is rarely better than $\sim 1''$, and it contains distortions of magnitude comparable to the blurring. Clearly, measuring the small displacements caused by solar flows had previously been very difficult to make with confidence. No such problem hampers the seeing-free SOUP observations (with positional stability of a few milliarcsec) which we report here.

II. DATA

The white-light data were obtained by the Solar Optical Universal Polarimeter (SOUP) instrument flown on Spacelab 2 (NASA Space Shuttle mission 51-F). SOUP contained a 30 cm Cassegrain telescope and an active secondary mirror for image stabilization (Title *et al.* 1986). A white-light optical system with 35 mm film provided the data described herein. White-light images were obtained beginning in orbit 100 (1985 August 5, 04:01:22 UT) and ending in orbit 111 (1985 August 5, 21:08:24 UT). In this paper we have mainly used images from orbit 110 taken between 19:10:35 and 19:38:05 in the vicinity of active region 4682. Frames were obtained every 2 s. The field-of-view covered an area $166'' \times 250''$. The effective wavelength band of the observations is ~ 1000 Å centered on 6000 Å.

During the flight of Spacelab 2 the Big Bear Solar Observatory (BBSO) collected correlative data on the same active region. The BBSO data covered the period before, during, and after the SOUP maps. BBSO data included magnetograms (1985 August 5, 15:25:43 to August 6, 00:50:54), Hα (1985 August 5, 16:17:21 to 21:08:30), and calcium K images (1985 August 5, 16:48:30 to 21:10:25). However, only the magnetic data are discussed here.

Data reduction began with digitization of the analog data (SOUP white-light, BBSO calcium and hydrogen films). The SOUP data were digitized by a 1024 × 1024 CCD camera developed for the High Resolution Solar Observatory (HRSO). They were collected on a Hewlett-Packard 9836 minicomputer and then transferred to the Lockheed Palo Alto Research Laboratory (LPARL) VAX. The BBSO films were digitized with a commercial RCA CCD camera and transferred via the BBSO Megavision image processor to a MicroVax. These data and the BBSO digital magnetograms were then also read into the LPARL VAX 780 where they were registered frame to frame. They were then rescaled, rotated, and rectified, so that the SOUP and BBSO images could be accurately co-aligned. The registered image sets and various overlays were recorded on analog video disk to allow easy visualization of the inter-relationships. In the next section we present the results of some of these comparisons.

III. ANALYSIS

Shown in Figure 1 (Plates 10–13) are (*a*) a SOUP image, (*b*) a BBSO magnetogram at nearly the same time, (*c*) the SOUP flow field (shown as vectors) overlaid on a gray-scale map of the divergence of the flow field, and (*d*) the SOUP flow field superposed on the magnetogram. The speed and also the direction of the transverse motions are accurately measured by the correlation tracking algorithm. Values generally lie in the range 100–800 m s^{-1}, with 1 σ uncertainties of ~ 75 m s^{-1}. The velocities (shown as arrows in Fig. 1) represent the average velocity obtained by correlation tracking over the 28 minute observation time of orbit 110. The divergence of the horizontal flow vector is approximately proportional to the average vertical velocity (November *et al.* 1986) and thus identifies cell interiors (sources or upflows) and boundaries (sinks or downdrafts). We have marked with numbers in Figures 1*c* and 1*d* the centers of four strong cellular outflows in or adjacent to the active region; note that these centers are void of magnetic flux.

We see from Figure 1 that the flow field and the magnetic field are intimately related. In relatively compact magnetic features, the flow field points toward the concentrations. In cell-like regions of the magnetogram the vectors of the flow field point radially outward from the cell centers toward the boundaries (network). We also see a third type of magnetic structure, roughly linear in shape, but not obviously part of the network surrounding a cell. These are locations where the flow field converges, not to a sink point, but to a line (analogous to the flow of tributaries in a river basin).

Other large-scale flows occur in the region of the spot and pores. First, there is an ordered flow pattern into the pore region. Second, we see the well-known moat flow in which magnetic features (MMFs) flow radially out from the sunspot (Sheeley 1969, 1971; Sheeley and Bhatnagar 1971; Vrabec 1971). Because of its strong magnetic field, the spot inhibits normal convection to the surface, so one might expect that upflows would be diverted radially outward from the sunspot (Meyer *et al.* 1974). This was the first and most striking discovery in the white-light movies from SOUP: an annulus, $\sim 5''$ wide extending from the edge of the penumbra into the surrounding photosphere, composed of radially out-streaming granules (Title *et al.* 1986). This phenomenon has also been observed by Muller and Mena (1987). We observe that magnetic field motions across this annulus closely follow the flow vectors determined from the pattern of granular motions.

Additional insight into the relationship between flows and magnetic fields is gained by asking where the measured surface flow field would carry hypothetical free particles ("corks") that are originally distributed uniformly in the flow field. We calculated the cork flow by moving each cork according to the velocity of the local flow field at that cork's location. Figure 2 (Plates 14–17) shows (*a*) the initial distribution of corks on a SOUP image and (*b*) the location of the corks overlaid on a magnetogram after 4 hr, (*c*) 8 hr, and (*d*) 12 hr. The same four flow cells as in Figure 1 are identified. We started with a dense, uniform distribution to avoid any biasing assumption about the initial sites of solar tracers, such as emerging magnetic fields. Therefore, there is a cork for each tracer, and concentrations of magnetic flux should coincide with concentrations of corks, but there may not be enough flux to outline all the computed cork positions. Most of the stable magnetic structures (i.e., those which show little or no motion during the 9 hr movie) outside the sunspot are located at or near corks. And in places where we see magnetic flows, the movies show similar motions of corks and magnetic features. The 75 m s^{-1} uncertainty in the flow speeds used for Figure 2 would cause an uncertainty of less than 3" in cork positions after 8 hr. This is quite small compared to the overall scale of the final cork pattern. The calculation assumes that the flow field remains unchanged over an 8 hr period. As a check of this hypothesis, we have measured the flows using shorter (and thus noisier) data sets from orbits 108, 109, and 111, which span an interval of 4.5 hr. These measurements show little evidence for major changes in the average flow field during this time, but unfortunately they are severely limited by "solar noise" contributed by random motions of granules and by 5 minute oscillations.

The cork paths represent streamlines of the flow. Figure 3 (Plate 18) shows this streamline pattern overlaid on the magnetogram. The streamlines and corks illustrate an important feature of the flow pattern. Initially the flow carries corks to the cell boundaries, but then, as time proceeds, the corks are carried along the boundaries to sink regions. These sinks are usually vertices in the network pattern as seen in calcium, hydrogen, or magnetograms. We have made a magnetogram movie overlaid with the SOUP white-light flow field vectors. It is very clear from the movie that in the quiet Sun small magnetic field elements appear randomly near supergranule/mesogranule centers, then rapidly move first to cell boundaries and then flow slowly along the boundaries, just as the cork model suggests. In several instances we see from the magnetogram movies that a ring of surrounding magnetic network increases in diameter. This suggests that the flow cell is similarly increasing in diameter.

The magnetic (or cork) network sometimes shows a larger dominant cell size than do the flow maps. This is illustrated in Figure 4 (Plate 19) where we have superposed a divergence map of the flow in Figure 1 and a snapshot of the corks after 12 hr. It shows that two or three smaller cells of mesogranular scale (November *et al.* 1981) are often contained within one apparent "network cell." Cell sizes (center-to-center) in the flow divergence maps are often 6–12 Mm rather than the 30 Mm value usually associated with supergranulation.

IV. DISCUSSION

Through these simultaneous observations of white-light granulation and digital magnetograms, we show clearly the intimate interactions between surface motions and magnetic structures. Our movies demonstrate that the white light granular flow field is a nearly perfect descriptor of the motion and evolution of the magnetic field. The flow field determined from one 28 minute measurement is an excellent indicator of the motion of the corresponding magnetic field configuration, and is valid for at least 4 hr before and after the SOUP observations. From the cork simulations we estimate that the magnetic pattern would require ~8–10 hr to develop. This suggests that the flow field and magnetic field have a lifetime longer than 10 hr as would be expected for large-scale supergranular structures. Once the field gets to a boundary the flow velocity slows appreciably.

Especially in quiet Sun regions, both the magnetograms and the cork simulation show an incomplete network: fully outlined cells are rare, and usually there are just enough markers in the boundaries to suggest a cellular pattern. The cork simulation shows that this is an intrinsic property of the flow patterns and not only a result of insufficient magnetic flux to complete the pattern.

As mentioned in § III, Figure 1 is in excellent agreement with Simon and Leighton's (1964) idea that the flow field pushes the magnetic field into boundaries. However, observationally it is difficult to distinguish this concept from the converse hypothesis that the locus of the flow field is constrained by the prior presence of magnetic field. In fact, the moat flow pattern around the spot and the steady flow into the pores suggests that, at least in these regions, magnetic structures cause the flow pattern. In magnetic regions, the apparent outlines of "magnetic cells" seen in the magnetograms are sometimes smaller (15–20 Mm) than in quiet Sun, where they are closer to the traditional supergranulation size of 30 Mm; this observation has previously been made by Zwaan (1978). Inspection of our flow maps shows that the flow cells are somewhat smaller in magnetic regions, where cells can be identified at all. However, our very limited sample does not permit us to give this observation much weight; more data are needed to confirm this impression. Since mesogranules are ubiquitous in quiet Sun regions, the difference in apparent cell size in magnetic area may also reflect increased visibility of the smaller cells, due to a greater density of tracers.

Another remarkable new result is the existence of streams (or currents) in the flow maps. We had always tacitly thought that the Sun is covered by closely packed cellular structures of several scales (granules, mesogranules, supergranules) with old cells disappearing as new ones are formed. However, we see in Figure 1 that there are also several streams, some of which are 50–100 Mm in length and 5–10 Mm in cross section, where there exist no large scale cellular structures. The most striking of these begins at the left boundary of Figure 1 and extends halfway across the bottom part of the image.

Our observations suggest that flow along network boundaries may be an important feature in the evolution of the magnetic field pattern. This would have important implications for coronal heating and buildup of magnetic stresses in the network. First, flow along the network boundaries will tend to mix and twist the fields on very small scales. We have measured the vertical component of vorticity of the flow field and find that at some locations it reaches values of $\sim 10^{-4}$ s^{-1}. This suggests that the time scale for imparting substantial twist to the magnetic field may be only a few hours in places where the vorticity is large. The mixing and twisting will also be enhanced by local displacements of the field caused by randomly directed motions and explosions of individual granules. Since both dissipation and heating in magnetic regions depend critically on the spatial scale of the twisting of the flux tubes (van Ballegooijen 1986; Parker 1972, 1983), chromospheric and coronal heating can be enhanced by the flow along the boundaries. Mikic, Barnes, and Schneck (1988) have used three-dimensional models to show how shearing photospheric flows might build up the energy of a magnetic arcade until it becomes unstable, forms current sheets, and then reconnects with rapid release of magnetic energy in the corona. Second, flow along the boundaries concentrates fields in vertices. These vertices are probably stable points in the flow field, so that new supergranules may form with a vertex at the previous boundary. If so, the random-walk diffusion of magnetic field discussed by Leighton (1964) may be much slower than would otherwise be expected.

Just as the Doppler spectroheliogram observations of Leighton *et al.* (1962) made the phenomenon of supergranulation clearly recognizable near the limb, local correlation tracking can make horizontal flow patterns apparent at disk center. This latter geometry is much better suited to search for giant cell patterns (Simon and Weiss 1968), banana cells (Hart *et al.* 1986*a*, *b*), and circumferential rolls (Ribes, Mein, and Mangeney 1985; Wilson 1987). With this new technique we have been able to see the mesogranulation pattern discovered by November *et al.* (1981), and to characterize its effect in magnetic field evolution. We note, finally, that these new observations raise the question whether the mesogranule is really a scale of solar convection distinct from supergranulation, or whether the supergranule/mesogranule is a single entity with a wider range of sizes than previously thought, affected perhaps in part by the presence or absence of magnetic field.

The authors thank F. Meyer, H. Spruit, J. Zirker, and C. Zwaan for critical reading of the text and helpful comments to improve it. This work was supported in part by NASA contracts NAS8-32805 (SOUP) and NAS5-26813 (HRSO). Lockheed Independent Research funds provided support for the laser optical disk analysis system. Observations at Big Bear Solar Observatory are supported by NASA under grant NGL 05 002 034 and by the NSF Solar Terrestrial program under ATM-8513577.

REFERENCES

Cattaneo, F. 1984, Ph.D thesis, University of Cambridge.
Galloway D., and Proctor, M. 1983, *Geophys. Ap. Fluid Dyn.*, **24**, 109.
Galloway, D., and Weiss, N. 1981, *Ap. J.*, **243**, 945.
Hart, J., Glatzmaier, G., and Toomre, J. 1968*a*, *J. Fluid Mech.*, **173**, 519.
Hart, J. *et al.* 1986*b*, *Science*, **234**, 61.
Harvey, J. 1977, *Highlights of Astronomy*, ed. E. A. Müller Vol. 4, Part 2 (Dordrecht: Reidel), p. 223.
Hurlburt, N., and Toomre, J. 1988, *Ap. J.*, **327**, 000.
Leighton, R. 1964, *Ap. J.*, **140**, 1547.
Leighton, R., Noyes, R., and Simon, G. 1962, *Ap. J.*, **135**, 474.
Martin, S. 1988, *Solar Physics*, in press.
Meyer, F., Schmidt, H., Weiss, N., and Wilson, P. 1974, *M.N.R.A.S.*, **169**, 35.
Meyer, F., Schmidt, H., Simon, G., and Weiss, N. 1979, *Astr. Ap.*, **76**, 35.
Mikic, A., Barnes, D., and Schnack, D. 1988, *Ap. J.*, submitted.
Mosher, J. 1977, Ph.D thesis, California Institute of Technology.
Muller, R., and Mena, B. 1987, *Solar Phys.*, in press.
Nordlund, A. 1985*a*, in *Proc. 1st Workshop on Theoretical Problems in High-Resolution Solar Physics*, ed. H. Schmidt (München: Max Planck Institut für Astrophysik), Publication MPA 212, p. 101.
———. 1985*b*, in *Proc. Workshop, Small-Scale Magnetic Flux Concentrations in the Solar Photosphere*, ed. W. Deinzer, M. Knölker, and H. Voigt (Göttingen: Vandenhoeck & Ruprecht), p. 83.
November, L., Simon, G., Tarbell, T., Title, A., and Ferguson, S. in *Proc. 2d Workshop on Theoretical Problems in High-Resolution Solar Physics*, NASA Conf. Pub. 2483 (Washington, DC: NASA) ed. G. Athay, p. 121.
November, L., Toomre, J., Gebbie, K., and Simon, G. 1981, *Ap. J. (Letters)*, **245**, L123.
Parker, E. N. 1972, *Ap. J.*, **174**, 499.
———. 1982, *Ap. J.*, **256**, 292.
———. 1983, *Ap. J.*, **264**, 642.
Proctor, M., and Weiss, N. 1982, *Rept. Progr. Phys.*, **45**, 1317.
Ribes, E., Mein, P., and Mangeney, A. 1985, *Nature*, **318**, 170.
Schmidt, H., Simon, G., and Weiss, N. 1985, *Astr. Ap.*, **148**, 191.
Schröter, E., and Wöhl, H. 1975, *Solar Phys.*, **42**, 3.
Sheeley, N. 1969, *Solar Phys.*, **9**, 347.
Sheeley, N. 1971, in *IAU Symposium 43, Solar Magnetic Fields*, ed. R. Howard (Dordrecht: Reidel), p. 310.
Sheeley, N., and Bhatnagar, A. 1971, *Solar Phys.*, **19**, 338.
Simon, G. 1967, *Zs. Ap.*, **65**, 345.
Simon, G., and Leighton, R. 1964, *Ap. J.*, **140**, 1120.
Simon, G., and Weiss, N. 1968, *Zs. Ap.*, **69**, 435.
Smithson, R. 1973, *Solar Phys.*, **29**, 365.
Title, A., Tarbell, T., Simon, G., and the SOUP Team. 1986, *Adv. Space Res.*, **6**, 253.
Title, A., Tarbell, T., and Topka, K. 1987, *Ap. J.*, **317**, 892.
Van Ballegooijen, A. 1986, *Ap. J.*, **311**, 1001.
Vrabec, D. 1971, in *IAU Symposium 43, Solar Magnetic Fields*, ed. R. Howard (Dordrecht: Reidel), p. 329.
Weiss, N. 1978, *M.N.R.A.S.*, **183**, 63p.
Wilson, P. 1987, *Solar Phys.*, **110**, 59.
Zwaan, C. 1978, *Solar Phys.*, **60**, 213.
———. 1987, *Ann. Rev. Astr. Ap.*, **25**, 83.

GEORGE W. SIMON: Air Force Geophysics Laboratory, National Solar Observatory–Sacramento Peak, Sunspot, NM 88349

ALAN TITLE, KENNETH TOPKA, THEODORE TARBELL, RICHARD SHINE, and STUART FERGUSON: Lockheed Palo Alto Research Laboratory, O/91-30, B/256, 3251 Hanover Street, Palo Alto, CA 94304

H. ZIRIN: Big Bear Solar Observatory, Building 264-33, California Institute of Technology, Pasadena, CA 91125