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Magnetic Fields in the Solar Atmosphere

JACQUES MAURICE BECKERS

22 June 1976

SACRAMENTO PEAK OBSERVATORY PROJECT 7649
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FOR THE COMMANDER:

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Chief Scientist

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This paper describes the magnetic field configurations observed in the solar atmosphere including the corona and the solar wind. The techniques for observing solar magnetic fields are briefly reviewed. The significance of Alfven waves in transporting energy is stressed.

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Preface

I would like to acknowledge discussions with Drs. J. Harvey, N. Sheeley, and W.J. Wagner during the preparation of this manuscript. Mrs. C. Fisher and M. Zang as well as Mr. R. Faller helped with the typing of the paper and all the preparation of the illustrations.

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Magnetic Fields in the Solar Atmosphere

1. INTRODUCTION

Magnetic fields play a major role in the behavior of all the observable layers in the solar atmosphere and perhaps of the unobservable solar interior as well. Magnetic fields become an important parameter in the structuring of an atmosphere when the magnetic pressure $B^2/8\pi$ is comparable or exceeds the gas pressure or kinetic pressures ($\rho v^2/2$). This happens in all the observable layers of the solar atmosphere. In the photosphere the sunspots represent the clearest example of strong fields (~ 3000 gs), but there is strong evidence for concentrations of magnetic fields of ~ 1500 gs on a much smaller scale all over the sun. In the chromosphere, the entire structure is determined by the magnetic field since the magnetic field scale height is much less than the gas pressure scale height in the photosphere-chromosphere transition layers. The chromospheric network and spicules are clearly affected by the magnetic field. The structure of the corona is of course strongly influenced by magnetic fields. Extended heating of the corona by Alfven waves tends to come in vogue again. The relative importance of Alfven wave versus acoustic wave heating of the corona is still not clear, although acoustic heating is generally given preference. The solar wind velocity structure and magnetic fields are strongly related, but the magnetic fields appear to play a secondary role except for the presence of Alfven waves which result in

(Received for publication 21 June 1976)

major magnetic field and velocity fluctuations and whose pressures might affect the solar wind dynamics.

This review will give a short summary of our knowledge of solar magnetic fields and will focus on the major current questions in the topic. In doing so, I will rely strongly on the proceedings of a number of international conferences concerned with solar magnetic fields (IAU Symposia 22, 35, 43 and to a lesser extent 56 and 57) and previous review papers (Howard,[1] and Babcock[2]). The literature on the subject of solar magnetic field is extensive and it will be impossible to do justice to all of it. It will also be necessary to restrict myself to a discussion of nonflare related magnetic fields and a description of the properties and effects of the sun's magnetic fields, thus omitting the review of the literature of the origin of the field and of the theories dealing with the question of why the field behaves the way it does. This review will deal mainly with the observed properties of the fields. It will, therefore, start off with a short summary of the methods used to observe solar magnetic fields.

2. METHODS OF MEASURING SOLAR MAGNETIC FIELDS

In a previous review (Beckers[3]), I discussed the many methods of determining the magnetic fields on the sun. Table 1 summarizes these methods. I refer to this previous review for details of these techniques. Many of the techniques have serious difficulties associated with the interpretation of the observed signals in terms of actual magnetic field configuration.

The safest way of measuring solar magnetic fields may at first appear to be the Zeeman effect. Most magnetograms indeed use the Zeeman effect. There are, however, serious problems associated even with that method especially when the Zeeman splitting is insufficient to clearly separate the components of the Zeeman multiplet. That is the case for fields less than 1500 to 2000 gs for Zeeman triplets in the optical region of the spectrum with large Lande factors ($g = 3$). On the sun these difficulties, therefore, apply to virtually all magnetic regions on the solar disk except for sunspots. Problems that arise in the interpretation of the measured signals, like the variation of the 4 Stokes parameters as a function of wavelength, in terms of the solar magnetic field strength and orientation, result not so much from remaining uncertainties in the theory of line formation in the

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1. Howard, R. (1967) Magnetic field of the sun, Annual Reviews Astronomy and Astrophysics 5:1.
2. Babcock, H.W. (1963) The sun's magnetic field, Annual Reviews of Astronomy and Astrophysics 1:41.
3. Beckers, J.M. (1971) The Measurement of Solar Magnetic Fields. IAU Symposium No. 43, "Solar Magnetic Fields" (Ed., R. Howard), p. 3.

Table 1. Methods of Measuring Solar Magnetic Fields

	Measured Component of the Field*					Solar Region**			
	$\vec{H}$	$H_{//}$	$\|H\|$	$h_{\perp}$	f(H)	Photo-sphere	Chromo-sphere	Corona	Solar Wind
EM RADIATION:									
Zeeman Effect:-Visual, Near IR	X	x				X	X	(X)	
-Microwave(~700μ)	X	x						X	
-UV(100-200 nm)		x					X	X	
Hanle Effect(Hα, D_3, CIV, etc.)				X	x		X	X	
Gyro-Synchrotron Radiation					X			X	
Faraday Rotation		x						X	X
MHD EFFECTS:									
Alignments of Structures				x		(X)	X	X	X
Influence on T-P Structure					X	X	X	X	
Alfvén Velocity $V_A = \|B\|/\sqrt{4\pi\rho}$			x				X	X	X
Prominence Oscillations			x					X	
IN SITU MAGNETOMETERS	x								X
THEORY:									
Equipartition ($P_g \approx P_B$)			x			(X)			
Force Free/Potential Field Calculations	x						X	X	

*X = strong fields only; x = strong and weak fields; $\vec{H}$ = vector magnetic field; $H_{//}$ = line of sight magnetic field; $|H|$ = scalar field; $h_{\perp}$ = direction of magnetic field component at right angles to the line of sight; f(H) = some other function of the field.

**Region where applicable (in parenthesis limited or questionable application).

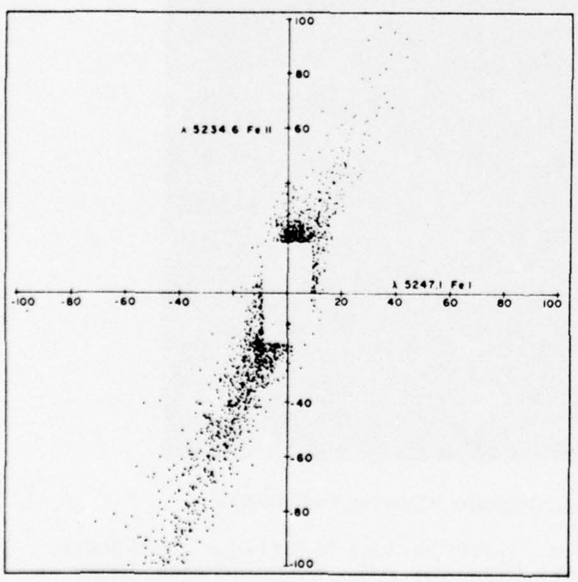

Figure 1. Relation of the Solar Line of Sight Magnetic Field as Measured in Two Different Lines With Different Temperature Sensitivity (Harvey et al) 1969

solar atmosphere in the pressure of magnetic fields, as from uncertainties introduced in the measurements by scattered light, calibration techniques and, especially, averaging over volumes on the solar atmosphere in which the magnetic field changes dramatically. Even for the very best up to date observations (~ 1 arc sec resolution), one averages over a volume of 700 x 700 km times ~ 150 km in height. There is substantial evidence, to be discussed in Section 3.2, that fields often change dramatically within such a volume. It is believed that these averaging errors are responsible for the disagreement between magnetic field strength as measured on the sun in different spatial lines (see Figure 1). Similar averaging errors are present in velocity measurements where different lines give different line of sight velocities. I, therefore, refer to another paper (Beckers and Canfield[4]) for a further discussion of these so-called averaging errors.

3. PHOTOSPHERIC MAGNETIC FIELDS

Figure 2 is a magnetrogram of the entire solar disk obtained using the Zeeman effect. In such a magnetogram are distinguished the following magnetic structures:

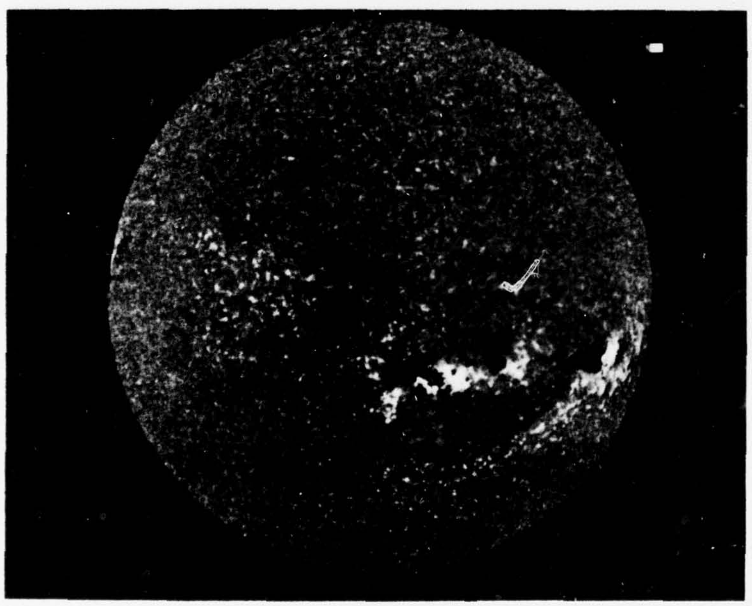

Figure 2. Full Disk Magnetogram (Courtesy of KPNO)

4. Beckers, J.M., and Canfield, R.C. (1975) Motions in the solar atmosphere, AFCRL Environmental Research Paper No. 540. (Also in Proceedings CNRS Nice Symposium on "Physics of Motions in Stellar Atmospheres").

(1) Sunspots and pores with very strong fields and notable resulting changes in the photospheric structures, (2) plage regions constituting the magnetic areas around the spot and forming together with the spot the so-called *active region*, (3) large scale magnetic patterns of the same polarity extending over distances comparable to a solar radius, (4) supergranulation magnetic fields with sizes ~30 Mm, and (5) small scale magnetic phenomena (<< 1 Mm) at the limit of the resolution of our observations.

3.1 Sunspots

Sunspot magnetic fields are large and hence easy to measure. The typical field in the center of the umbra is 3000 gs and vertical. It changes gradually to nearly horizontal fields of 1000 to 1500 gs near the boundary of the spot penumbra and the photosphere (Beckers and Schröter[5]). There is some inconclusive evidence for inhomogeneities in the umbral and penumbral magnetic fields (Beckers[6]). A major feature of sunspots is of course their low temperature. Recently, models explaining this cooling by an energy loss by Alfven waves have become popular again (Parker[7], Beckers[8, 9]). The flux of Alfven waves in these theories is comparable to the missing sunspot radiation flux (5×10^{10} ergs $cm^{-2} sec^{-1}$). For these models to be valid, most of the Alfven wave energy has to escape into the solar interior with only a small fraction (0.1 to 1 percent) escaping into the solar corona across the highly reflective chromosphere-corona transition region (Uchida and Kaburaki[10]), where it probably heats up the active region corona or perhaps escapes into the solar wind. These Alfven wave sunspot models have received support from observed velocity oscillations in sunspots with periods near 180 sec, and from the observations of large unresolved horizontal velocities at right angles to the spot magnetic field (Beckers[9]). The magnitude of these velocities corresponds

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5. Beckers, J.M., and Schröter, E.H. (1969) Properties of a unipolar sunspot, Solar Physics 10:384.
6. Beckers, J.M. (1969) The Microstructure of Sunspots. "Plasma Instabilities in Astrophysics" (Ed., Wentzel and Tidman), Gordon and Breach Publ, p. 139.
7. Parker, E.N. (1974) The nature of the sunspot phenomenon: I solutions of the heat transport equation, Solar Physics 36:249.
8. Beckers, J.M. (1975a) New views of sunspots, AFCRL Environmental Research Papers No. 499.
9. Beckers, J.M. (1976) The flux of Alfven waves in sunspots, Astrophys. J. 203:739.
10. Uchida, Y., and Kaburaki, O. (1974) Excess heating of corona and chromosphere above magnetic regions by nonlinear Alfven waves, Solar Physics 35:451.

indeed to the values predicted by the models. Horizontal scale for the Alfven wave structure is estimated to be 30 km, well below the resolution limit. It has been suggested that the Alfven waves from sunspots are responsible for the heating of the active region corona and of the plage regions surrounding the sunspots (Wentzel,[11] and Uchida and Kaburaki[10]). If indeed the sunspots are giant generators of Alfven waves, major changes in the active region corona and chromosphere resulting from wave dissipation and Alfven wave radiation pressure are to be expected.

3.2 Plages and Faculae

Surrounding the sunspots are the magnetic fields associated with the plage regions. Low resolution magnetograph observations are used to give magnetic field strengths of a few hundred gauss. In the past decade, it has become increasingly clear that these low magnetic field strength plage regions consisted of unresolved magnetic elements in which the magnetic field was in the vicinity of 1000 to 2000 gs. These magnetic elements have been called magnetic knots, micropores (Beckers and Schröter[12]) or gaps (Chapman and Sheeley[13]). These magnetic knots are closely associated with the facular network which constitutes the plage region.

This network is particularly well visible at the center of the solar disk in the green magnesium b lines. Figure 3 is a filtergram of such a plage region taken at b_1 - 0.04 nm. Figure 4 is an enlarged portion of this filtergram together with a filtergram taken at b_1 - 0.08 nm which shows the so-called photospheric filigree structure discuvered by Dunn and Zirker[14]. Each element in the filigree structure as seen at b_1 - 0.08 nm coincides with a facular element at the higher levels seen in b_1 - 0.04 nm. The facular element is larger than the filigree element and is probably the broader upward extention of the filigree element. Figure 5 shows the facular network in the wing of the b_2 line as observed simultaneously in opposite circular polarizations with a 0.016 nm filter. The striking difference between the images results from the near perfect correlation between the structure of the circular polarization introduced by the Zeeman effect, and the facular structure, so that at the higher levels seen at b_2 - 0.01 nm there is a one to one correlation between the magnetic fields and the upward extension of the filigree

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11. Wentzel, D.G. (1974) Coronal heating by Alfven waves, Solar Physics 39:129.
12. Beckers, J.M., and Schröter, E.H. (1968) Properties of magnetic knots, Solar Physics 4:142.
13. Chapman, G.A., and Sheeley, N.J. (1968) The photospheric network, Solar Physics 5:442.
14. Dunn, R.B., and Zirker, J.B. (1973) The solar filigree, Solar Physics 33:28.

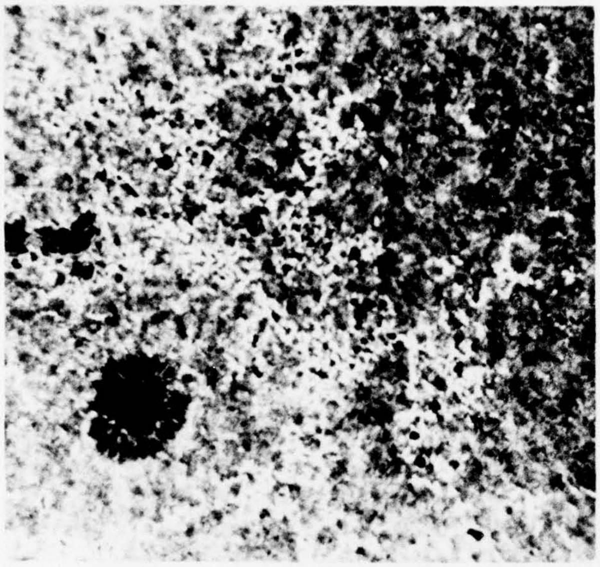

Figure 3. Filtergram Taken in the MgI b_1, Line (518.62 nm) 0.04 nm From the Line Center Showing the Facular Network Near Disk Center. Filter bandwidth was 0.016 nm (SPO Filtergram)

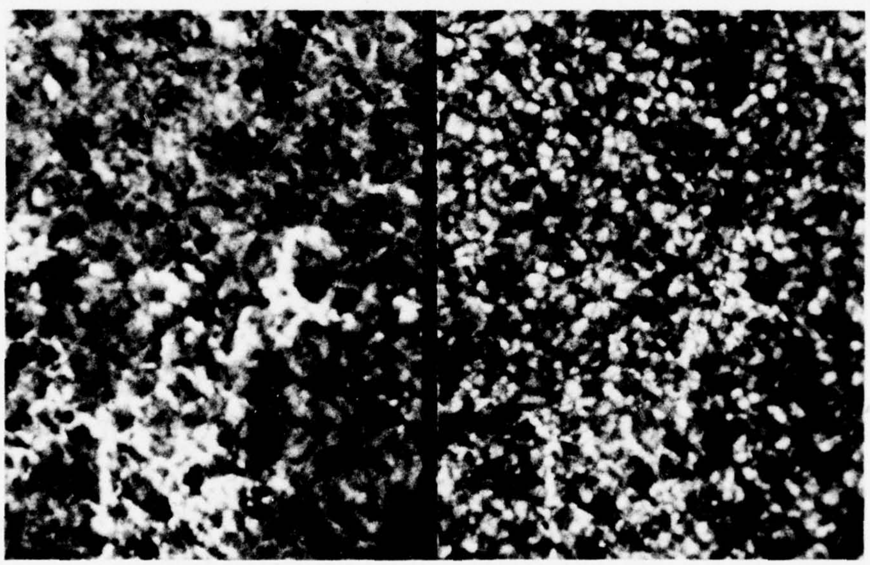

Figure 4. Magnification of a Small Region of Figure 3 (Middle, Right) in Both b_1-0.04 nm (Left) and b_1-0.08 nm (Right) Showing the Relation Between the Facular and the Filigree Structures. Filter bandwidth was 0.016 nm (SPO Filtergrams)

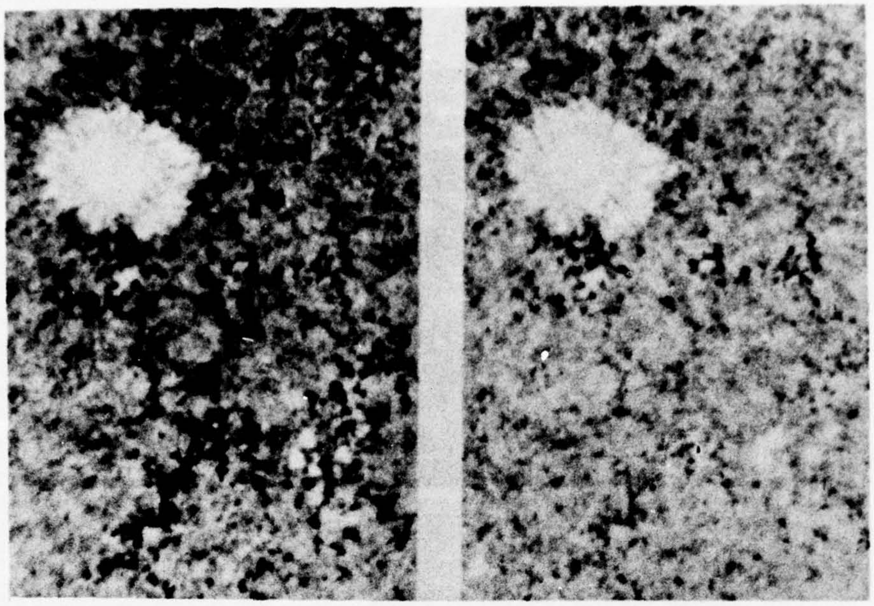

Figure 5. Simultaneous Filtergrams (Negatives) of the Facular Network Taken in Opposite Circular Polarizations 0.01 nm to the Blue of the MgI b_2 Line at 517.27 nm. The pronounced difference in network contrast is the result of the close relation between the facular brightness and magnetic field structure. Filter bandwidth was 0.016 nm (SPO Filtergrams)

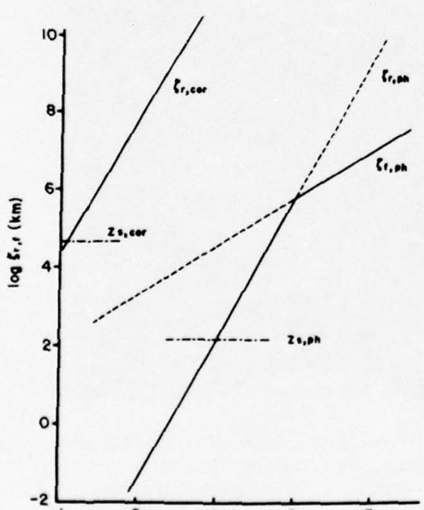

Figure 6. Joule (ζ_r) and Frictional (ζ_f) Decay Lengths as Function of the Magnetic Field Strength (H_o) Under Typical Photospheric and Coronal Conditions and for a Temporal Wave Frequency ω = 0.038 sec^{-1} (Or a Period of 165 sec). Both dissipation lengths decrease with increasing temporal frequency as ω^{-2} (Uchida) 1974. $Z_{s, ph}$ and $Z_{s, cor}$ are the photospheric and chromospheric scale heights

(Beckers[15]). This suggests a correlation also at lower levels, an opinion adhered to by many (for example, Beckers,[15] Mehltretter,[16] and Stenflo[17]). Simon and Zirker[18] contest this idea of a spatial coincidence between filigree and magnetic field but agree that the filigree occurs in regions of high magnetic field strength. The latter they believe have, however, a substantially larger scale than the filigree structures. A definite resolution of this controversy will have to wait for very high resolution magnetograms (~ 1/3 arc sec). The indirect evidence is, however, strong for the identification of the 200 km filigree elements with magnetic elements with field strength of 1500 to 2000 gs.

It is of great interest to know the size and field strength of these magnetic elements. The occurrence of these elements places high demands on the theories of magnetohydrodynamics of the solar atmosphere which have real problems explaining the phenomena (Parker[19,20], Stenflo,[17] and Deubner[21]). The clustering of magnetic fields in these strong elements make the production of coronal Alfven waves much more likely. The spatially-averaged generation of these waves may only be a weak function of magnetic field strength and clustering, but the decay length of the waves by finite conductivity and ion-neutral interaction is a strong function of magnetic field strength (see Figure 6). In weak fields the waves are, therefore, dissipated long before they can reach the corona. With the strong fields, one might expect on the other hand an enhanced emission of Alfven wave into the corona.

It is not clear what effect the sunspot and plage magnetic field, and their associated Alfven fluxes, have on the solar wind although one suspects a major influence (Section 6). An important question to be addressed in this connection relates to the fraction of the field lines in an active region which escape into the interplanetary medium. With the accuracy of measurement, it seems that positive and negative magnetic fields in an active region are pretty well balanced (for example, Beckers and Schröter[5]), but then one cannot measure fields well enough (Section 2) to say definitely that there could not be a 10 percent difference or so.

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15. Beckers, J.M. (1975b) Is the solar filigree the site of strong photospheric magnetic fields, Bull. Am. Astron. Soc. 7:346.
16. Mehltretter, J.P. (1974) Observations of photospheric faculae at the center of the solar disk, Solar Physics 38:43.
17. Stenflo, J.O. (1976) A model of the supergranulation network and of active-region plages, Solar Physics 42:79.
18. Simon, G.W., and Zirker, J.B. (1974) A search for the footpoints of solar magnetic fields, Solar Physics 35:331.
19. Parker, E.N. (1976a) Hydraulic concentration of magnetic fields in the solar atmosphere, Astrophys. J. 204:259.
20. Parker, E.N. (1976b) Preprint.
21. Deubner, F.L. (1976) Photospheric magnetic flux concentrations and the granular velocity field, Astron. and Astrophys. J., 47:475.

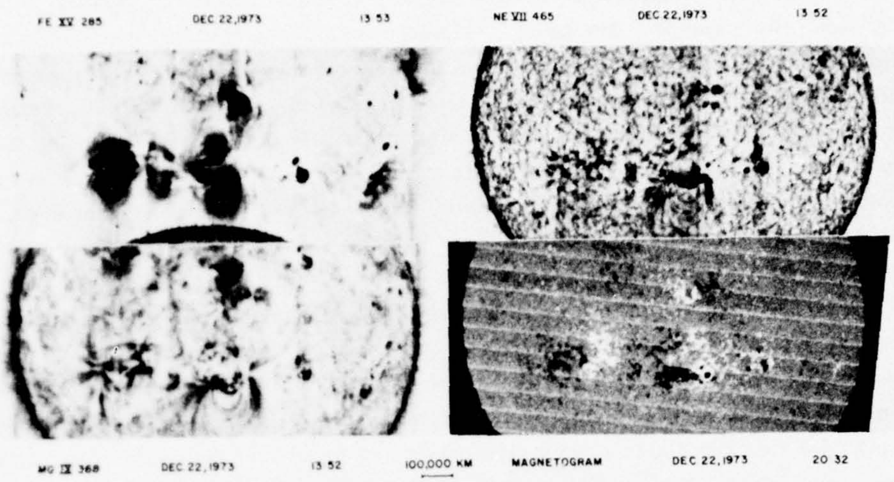

Figure 7. Slitless Spectrograms in Fe XV, Mg IX and NeVII Lines Taken With the Naval Research Laboratory Instrument Aboard Skylab Together With a KPNO Magnetogram (Sheeley et al) 1975

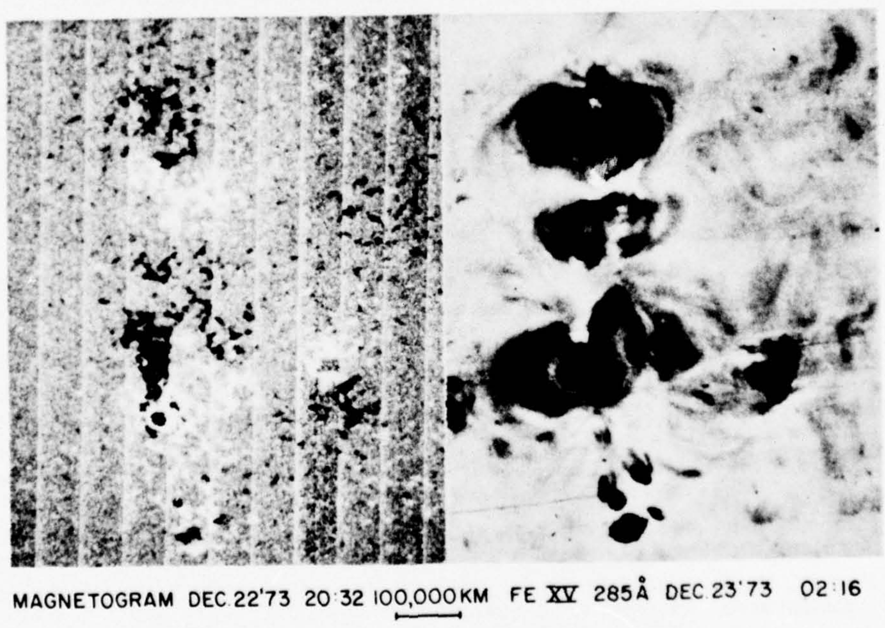

Figure 8. Magnification of a Part (Center) of Figure 7 in the Fe XV Line Image and the Magnetogram (Sheeley et al) 1975

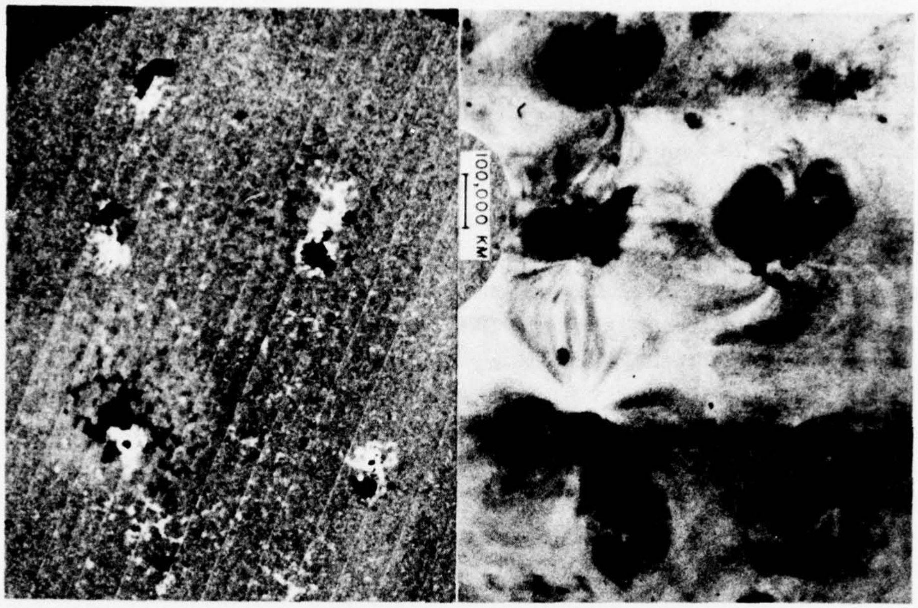

Figure 9. Same as Figure 8 But for a Different Date (Sheeley et al) 1975

Recent observations from ATM (Sheeley et al[22]) show the full outline of coronal magnetic fields in active regions (Figures 7, 8, and 9). Most or all of the field lines connect positive and negative polarities in a very direct way, mostly within the same active region but occasionally between active regions. It is very difficult to find even one coronal structure in these Fe XV spectroheliograms which seem to go out, away from the sun, into the outer solar corona. That seems to indicate that solar active regions are pretty well "closed", but again one has to be careful since it may be that the mechanism which makes these Fe XV arches visible works only for the strongly curved closed arches (Wentzel[11]) so that the outward going field lines are invisible. In fact, the type III bursts and cosmic ray emission by active regions even in the absence of solar flares suggest that a significant fraction of the sunspot region magnetic fields might be open.

3.3 Motion of Magnetic Elements near Sunspots

The magnetic elements visible in the so-called moat surrounding the sunspot (Figure 3) tend to show a motion away from the sunspot of ≈ 1 km/sec (Sheeley[23]).

22. Sheeley, N.R., Bohlin, J.D., Brueckner, G.E., Purchell, J.D., Scherrer, V., and Tousey, R. (1975) XUV observations of coronal magnetic fields, Solar Physics 40:103.

23. Sheeley, N.R. (1969) The evolution of the photospheric network, Solar Physics 9:347.

This outflow phenomena, reminiscent of the Evershed outflow in the penumbra, is most pronounced in decaying sunspots. Vrabec[24] estimates that the amount of magnetic flux transferred across the moat in about 2 days ($\sim 3 \times 10^{21}$ Maxwells) compares with the total flux of the spot, so that the outflowing elements are a critical factor in the evolution and decay of the sunspots.

Outside the moat, the magnetic elements do not show a systematic motion. The elements can be followed over quite a long time; their morphology changes, however, rapidly with a lifetime comparable with the granule lifetime. It is in fact very likely that the granular motions and the motions of the magnetic elements are coupled. The horizontal, random like motions of the magnetic elements is of the order of 1 km/sec with typical time scales of ~ 500 sec. This generates a flux of Alfven waves of $\rho v^2 V_A \approx 2 \times 10^9$ ergs cm^{-2} sec^{-1} at the location of the magnetic knots or $\approx 10^8$ ergs cm^{-2} sec^{-1} inside the plage region if the knots are taken to occupy 5 percent of the area. The area of the plage region itself is an order of magnitude larger than that of the sunspots, so that the total resolved flux of Alfven waves in plages appears to be somewhat smaller than that thought to exist in the sunspots ($\sim 2 \times 10^{10}$ ergs cm^{-2} sec^{-1}) although it is still very significant.

3.4 Large Scale Magnetic Field Configurations

Although solar magnetic fields are most pronounced in active regions, one sees magnetic fields all over the solar disk (Figure 2). Very often the weak, fragmentary magnetic fields outside active regions form very large patterns of same polarity extending over hundreds of thousands of kilometers in longitude and latitude. It has been suggested that these patterns (also called UM regions = Unipolar Magnetic Regions) may be the result of the long term diffusion of the magnetic elements left over after the disintegration of sunspots (Leighton[25]), or that they may be associated with very large convection cells (giant cells) in the solar interior (Bumba[26]). The rotation characteristics of these regions appear to be different from that of other surface features, showing less of a differential rotation (Wilcox et al,[27] and Bumba et al[28]), a characteristic shared with coronal holes and perhaps the high

24. Vrabec, D. (1974) Streaming Magnetic Features near Sunspots. IAU Symposium No. 56, "Chromospheric Fine Structure" (Ed., R.G. Athay), p. 257.
25. Leighton, R.B. (1969) A magneto-kinematic model of the solar cycle, Astrophys. J. 156:1.
26. Bumba, V. (1970) Concerning the formation of giant regular structures in the solar atmosphere, Solar Physics 14:80.
27. Wilcox, J.M., Schatten, K.H., Tanenbaum, A.S., and Howard, R. (1970) Photospheric magnetic field rotation: rigid and differential, Solar Physics 14:255.
28. Bumba, V., and Howard, R. (1969) Solar activity and recurrences in magnetic-field distribution, Solar Physics 7:28.

speed solar wind streams (Wagner[29]). This decrease or absence of differential rotation may be the result of a hypothesized rigidly rotating inner region of the sun where perhaps these large scale fields originate. Newkirk[30] has given a review of the properties of the large scale magnetic field configurations on the sun. The polar, or so-called general, magnetic field of the sun appears to be nothing but the remnant of these large scale patterns after their poleward migration.

3.5 Supergranule Magnetic Fields

Within the large scale patterns, there is an ordering of the magnetic fields by the supergranular convection cells (Simon and Leighton,[31]) which causes the magnetic field to be concentrated at the edges of the supergranule cells where they form a network pattern with a cell size of $\approx 30,000$ km. A similar network is visible in plage regions; the quiet sun network is, however, much more fragmented. The average field in irregular magnetic field patches constituting the network equals a few tens of gauss. High resolution observations show that these fields are made up of small regions of high magnetic field strength of the same character as the magnetic knots which make up the plage regions. In fact, it appears that the main thing which distinguishes the plage regions from the quiet sun magnetic field is the abundance of the magnetic knots. Harvey and Hall[32] using a very Zeeman sensitive line ($g = 3$) in the near infrared (1.565μ), actually resolved the Zeeman triplet splitting in these quiet sun magnetic knots and determined a field strength of 1700 gs (Figure 10).

It is commonly thought that the supergranule horizontal outflow of ≈ 0.5 km/sec causes the concentration of the flux at the cell boundary, and that perhaps the granules are responsible for the fragmentation into the smaller magnetic knots. There is some observational evidence to directly support the supergranular transport of magnetic fields (Worden[33], Smithson[34]). The granular fragmentation

29. Wagner, W.J. (1975) Solar rotation as marked by extreme-ultraviolet coronal holes, Astrophys. J. 198:L141.
30. Newkirk, G.A. (1971) Large Scale Magnetic Fields and Their Consequences. IAU Symposium No. 43, "Solar Magnetic Fields" (Ed., R. Howard), p. 547.
31. Simon, G.W., and Leighton, R.B. (1964) Velocity fields in the solar atmosphere. III large-scale motions, the chromospheric network, and magnetic fields, Astrophys. J. 140:1120.
32. Harvey, J.W., and Hall, D.N. (1976): Private Communication.
33. Worden, S.P. (1975) Solar Supergranulation. Thesis University of Arizona, p. 75.
34. Smithson, R.C. (1973) Magnetic field diffusion in weak plage regions, Solar Physics 29:365.

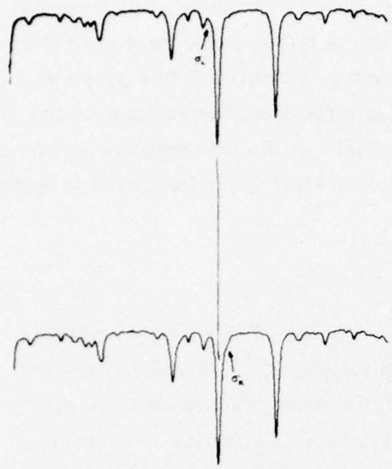

Figure 10a. Spectra of a Magnetic Element in Opposite Circular Polarizations in the Fe I Line, at 1564.8 nm. This line has a large Lande' factor (g=3) and shows a large Zeeman splitting because of this and because of the large wavelength

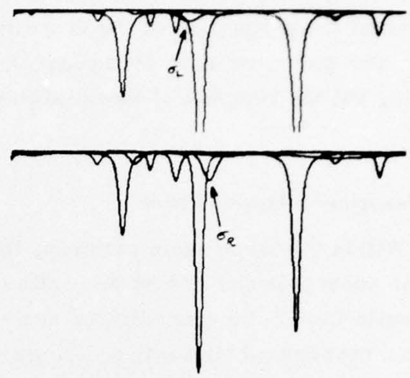

Figure 10b. Analysis of the Spectrum in Terms of the Two σ Components and π/Scattered Light Component

is supported by the fact that filigree elements/magnetic knots tend to be located in intergranular regions. That does not prove of course that the granular flow deposits the fields there; it could as well show that granular convection elements only occur in regions between the magnetic field elements.

3.6 Ephemeral Regions

Most of the magnetic structures within the large scale magnetic patterns are of the same polarity. There are, however, many small scale regions with bipolar characteristics which were studied by Harvey et al[35] and which they called Ephemeral Active Regions. Figure 11 shows a number of these regions most of which seem to occur on the boundaries between the large scale unipolar magnetic field patterns or within regions of mixed polarities. The total magnetic flux in each region amounts to $\sim 10^{20}$ Mx and there were some hundreds of these regions present on the solar surface near the maximum of the last solar cycle. Harvey et al[36] actually suggest that this number may change during the solar activity cycle

35. Harvey, K. L., Harvey, J. W., and Martin, S. F. (1975) Ephemeral active regions in 1970 and 1973, Solar Physics 40:87.
36. Harvey, J. W., and Livingston, W. (1969) Magnetograph measurements with temperature sensitive lines, Solar Physics 10:283.

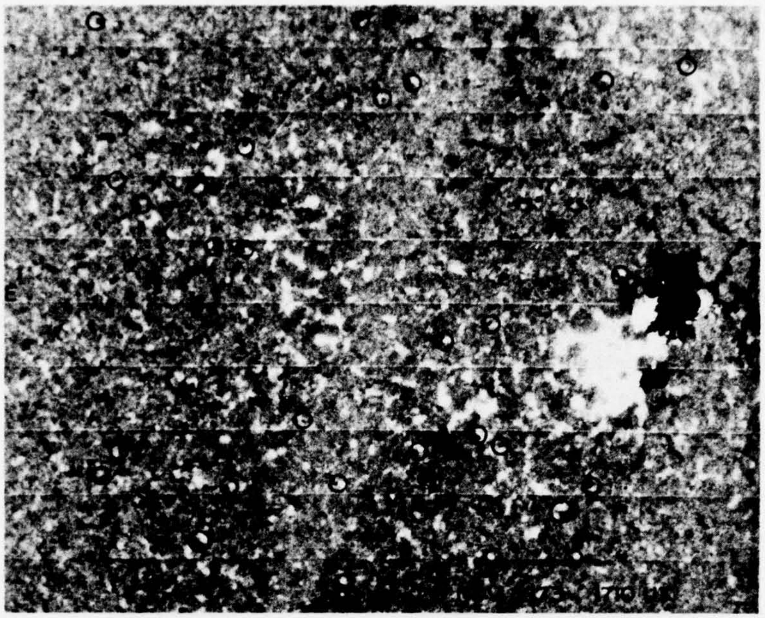

Figure 11. Kitt Peak Magnetogram Showing the So-called Ephemeral Active Regions. At the right, halfway up, there is a normal active region (Harvey et al) 1975

in the same way as sunspot regions do, and that these ephemeral regions are nothing else than the small scale end of a broad spectrum of the distribution of active region sizes. There are, however, major differences between the ephemeral regions and the normal larger scale active regions: (1) They do not show preferred latitudes to the degree that normal active regions do, (2) they live for only ~12 hours, and (3) their polarity orientation does not clearly show an E-W preference like sunspots do. Like sunspot regions the ephemeral regions show, however, strong X-ray emission but this emission is of course smaller in size (Krieger et al,[37] and Golub et al[38]). Again this may indicate the trapping and dissipations of Alfven waves in these closed field regions in the same way as might occur in active regions. Like normal active regions, it would appear that these ephemeral regions are of little interest for the structure of the outer corona and solar wind as compared to the unipolar magnetic elements which are probably the source of the interplanetary magnetic fields.

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37. Krieger, A.S., Vaiana, G.S. and Van Speybroeck, L.P. (1971) The X-Ray Corona and the Photospheric Magnetic Field, IAU Symposium No. 43, "Solar Magnetic Fields" (Ed., R. Howard), p. 397.

38. Golub, L., Krieger, A.S., Silk, J.K., Timothy, A.F., and Vaiana, G. S. (1974) Solar x-ray bright points, Astrophys. J. 189:L93.

4. EXTENSION OF THE SOLAR MAGNETIC FIELDS UPWARDS INTO THE CHROMOSPHERE AND CORONA

The determination of the magnetic fields in the corona are exceedingly difficult. There are plans to build magnetographs which will attempt to measure the Zeeman splitting of coronal emission lines in the ultraviolet region of the spectrum. The low photon flux, the small Zeeman splitting in the ultraviolet and the large width of coronal lines all make such a measurement highly inaccurate. Optical coronal lines have similar problems, and in addition present line of sight integration difficulties. Microwave emission lines from the corona (nα lines) would present a large Zeeman splitting but have not yet been detected. The principal methods used to study coronal magnetic fields are, therefore, quite different from those used in the photosphere (Table 1). They use alignments of structures like coronal streamers, polar plumes and green line structures as seen outside the solar limb and X-ray and XUV structures as seen against the solar disk (Figures 7, 8 and 9) to determine the outlines of the coronal fields. They use linear polarizations in the optical forbidden coronal lines to define the direction of the coronal field, or they use the photospheric field measurements and extrapolate these into the corona by means of theories based on assumptions of current-free or force-free magnetic field configurations above the photosphere. Figure 12 shows the results of such a calculation

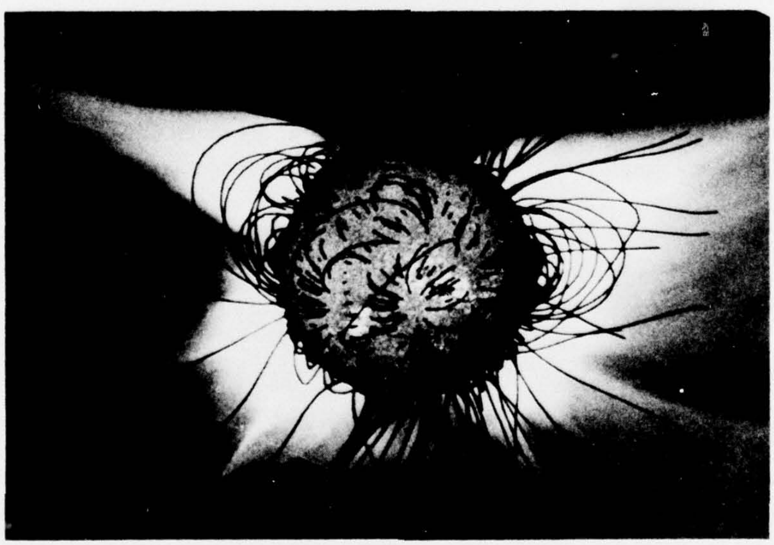
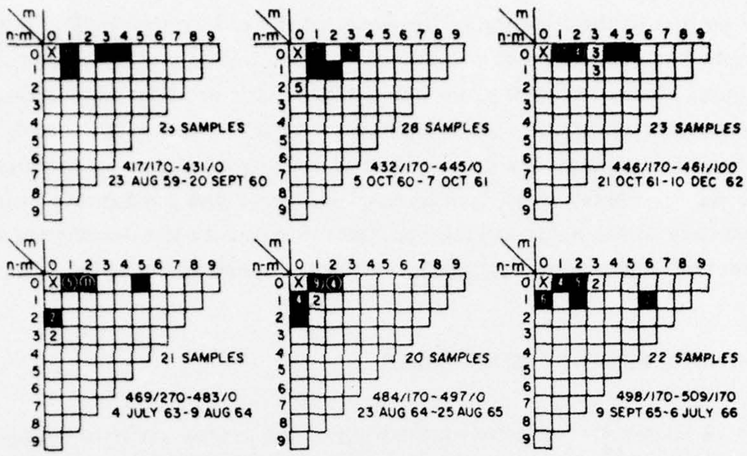


Figure 12. Superposition of Calculated Coronal Magnetic Fields With the 12 November 1966 Eclipse Observation of the Solar Corona and a Hα Disk Filtergram (Newkirk et al) 1970



SOLID - 4 HARMONICS MOST OFTEN AMONG LARGEST 5
NUMBER - NUMBER OF TIMES HARMONIC WAS DOMINANT
CIRCLE - MORE THAN 2x NEXT HIGHEST HARMONIC

DOMINANT SURFACE HARMONICS FOR SOLAR MAGNETIC FIELD 1959-1966

Figure 13. Most Significant Terms in the Legendre Polynomial Expansion of the Solar Magnetic Field (m Corresponds to the Number of Cycles in Longitude, n-m Corresponds to the Number of Zeros Along a Meridian, Excluding the Poles). Note that n-m = 0 for the dominant harmonics indicating an n sector structure (Altschuler et al 1971)

combined with a white light coronal photograph and an Hα spectroheliogram. Calculations like this, more or less agree with the structure arrangements in the white light (Newkirk and Altschuler[39]) and X and XUV corona (Poletto et al,[40] and Sheeley et al[22]), especially after some modifications are included to include the effects of the solar wind whose presence destroys the current-free assumptions at greater heights in the corona ($r/R_{\odot} \gtrsim 2$).

One characteristic of the current-free calculations is that the spatially rapidly varying fields show up only in the inner corona, whereas the large scale fluctuations show up much further out. Figure 13 shows the location of the dominant harmonics of the Legendre polynomial analysis of the surface magnetic fields by Altschuler et al.[41] The strength of the radial magnetic fields in the corona drop off like

39. Newkirk, G.A., and Altschuler, M.D. (1970) The observed connection between magnetic fields and the density structure of the corona, Solar Physics 13:131.

40. Poletto, G., Vaiana, G.S., Zombeck, M.V., Kneger, A.S., and Timothy, A.F. (1975) A comparison of coronal x-ray structures of active regions with magnetic fields computed from photospheric observations, Solar Physics 44:83.

41. Altschuler, M.D., Newkirk, G.A., and Trotter, D.E. (1971) Time Evolution of the Large Scale Solar Magnetic Field, IAU Symposium No. 43, "Solar Magnetic Fields" (Ed., R. Howard), p. 588.

$(r/R_{\odot})^{n+2}$ so that at the location of the basis of the solar wind ($r/R_{\odot} \approx 2$), the fifth harmonic has decreased by a factor of 128 versus only a factor of 8 for the first harmonic. It is, therefore, not surprising that the solar wind shows large sectors of predominantly one polarity since the smaller sector structure visible closer to the polar surface has been "filtered out" by the large spatial distance. In addition, as Altschuler et al[41] point out, the m = 1 and 2 magnetic field structure dominate already at the solar surface contributing thus to the dominance of the ~2 and 4 sector structure at $r/R_{\odot} = 2$, as is often seen in the solar wind.

5. SOLARMAGNETIC FIELDS NEAR THE EARTH

Figure 14 shows the well known drawing of the sector structure first discussed by Ness and Wilcox.[42] When short term variations in the magnetic fields are averaged out (3 hour averages), the solar wind fields are directed along the Archimedes spiral either towards the sun or away from the sun with the direction constant for typically one quarter of a solar circumference. As discussed in the previous section, this simple magnetic field configuration is due both to the presence

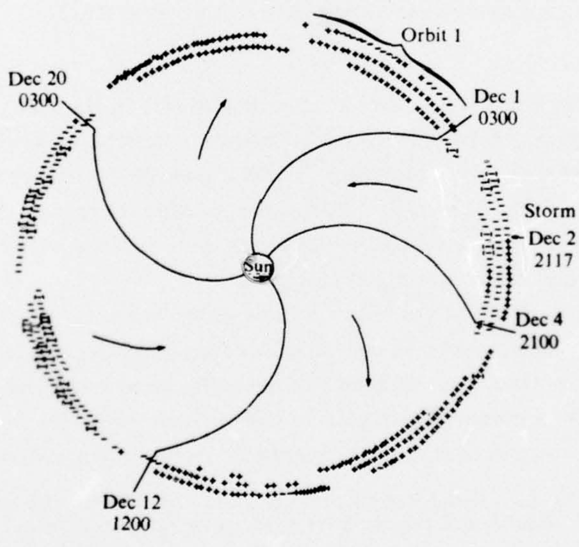


Figure 14. Sector Structure of the Interplanetary Magnetic Field (Ness et al) 1965

42. Ness, N.F., and Wilcox, J.M. (1965) Sector structure of the quiet interplanetary magnetic field, Science 148:1592.

of large scale magnetic fields patterns on the solar surface and to the filtering out of the small scale magnetic field fluctuations, including most of the magnetic fields in active regions, by the large distance from the solar surface to the source surface for the solar wind. The high speed (> 400 km/sec) solar wind streams occur in these sectors with the sector boundaries being located between the high speed velocity streams at positions of relatively low solar wind speed.

In the past few years, it has become evident that the location of high speed streams in the solar wind are also correlated with the location of coronal holes on the solar surface (Krieger et al[43]). These coronal holes are regions of very low emissivity in the corona when viewed in X-rays or other coronal radiations, and are now thought to be located at the locations on the sun where the magnetic field lines are open to the interplanetary medium (Altschuler et al[44]). It is also known (Snyder et al[45]) that recurrent geomagnetic disturbances (M-regions) are related to high speed streams in the solar wind and hence coronal holes (Neupert and Pizzo[46]) so that the coronal hole monitors have become important tools in the prediction of geomagnetic indices. Generally, a maximum of geomagnetic activity occurs ~3 days after the central meridian passage of a coronal hole. The relation: Coronal Holes ⟷ Open Magnetic Field Regions ⟷ Sectors ⟷ High Speed Solar Wind Streams ⟷ Geomagnetic Disturbances is thought to start with coronal holes located near the solar equator. Wagner,[47] however, gives evidence that at those times when there are few coronal holes at the equator (which are also times with few high speed streams) the interplanetary fields near the earth correlate well with the occurrence of coronal holes near the solar poles so that coronal holes at all latitudes seem to have an influence on the solar wind near the earth with, however, the equatorial holes dominating.

The typical sector magnetic fields near the earth are $\sim 5\gamma = 5 \times 10^{-5}$ gs. There are, however, large fluctuations ($\sim 3\gamma$) superposed on these average sector fields as shown in Figure 15 taken from Belcher and Davis.[48] Typically, these

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43. Krieger, A.S., Timothy, A.F., and Roelof, E.C. (1973) A coronal hole and its identification as the source of a high velocity solar wind stream, Solar Physics 29:505.

44. Altschuler, M.D., Trotter, D.E., and Orrall, F.Q. (1972) Coronal holes, Solar Physics, 26:354.

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48. Belcher, J.W., and Davis, L. Jr. (1971): Large amplitude Alfven waves in the interplanetary medium. J. of Geophys. Research, 76:3534.

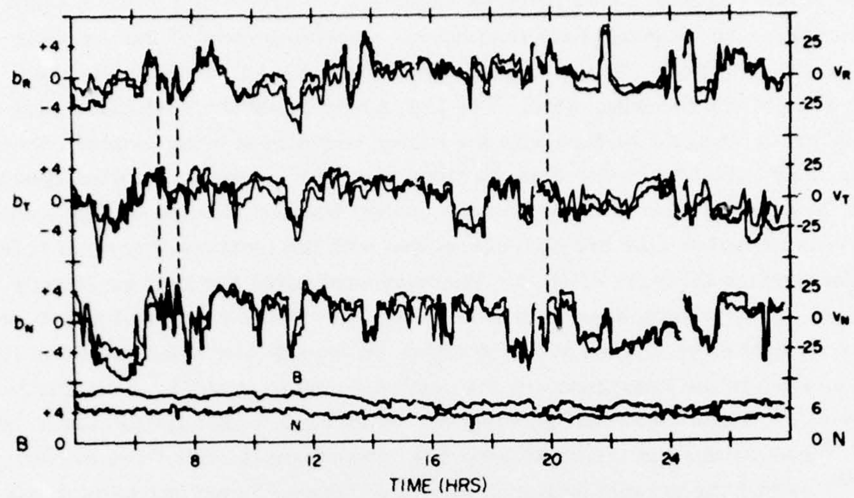

Figure 15. Fluctuation of the Interplanetary Magnetic and Velocity Field at 1 AU (R = Radial, T = Tangential, and N = Normal With Respect to the Sun Direction and Ecliptic Plane). Units in γ and km/sec. (Belcher et al) 1971

magnetic field fluctuations, present in all magnetic field components, are highly correlated with velocity fluctuations. Belcher and Davis[48] identified these variations with aperiodic outward propagating Alfven waves adhering to the relation $b \simeq (4\pi\rho)^{1/2} v$, where b and v are the magnetic field and velocity perturbations and ρ the solar wind density. These waves are visible in their purest form in the fast streams and especially at their leading edges. The outward propagation indicates that the waves are generated near the sun, perhaps at the solar surface itself. In fact, observations seem consistent with the generation at the solar surface itself (Barnes,[49] and Volk[50]). Figure 16 shows the power spectrum of the magnetic field fluctuations as measured by various spacecraft (Russell[51]) and shows the temporal frequencies associated with different solar phenomena including the solar granulation and supergranulation. As seen in Section 3, these convection cells transport magnetic fields and therefore will generate Alfven waves while doing so. Significant variations are observed in the magnetic fields at all observed frequencies. Figure 16 gives the spectrum of the

49. Barnet, A. (1972) Microscale Fluctuations in the Solar Wind. "Solar Wind" (Ed., C. Sonett), NASA publishing SP 308, p. 333.

50. Volk, H.J. (1975) Microstructure of the solar wind, Space Science Reviews 17:255.

51. Russell, C.T. (1972) Comments on the Measurement of Power Spectra of the Interplanetary Magnetic Field, "Solar Wind" (Ed., C. Sonnet) NASA publication SP 308, p. 365.

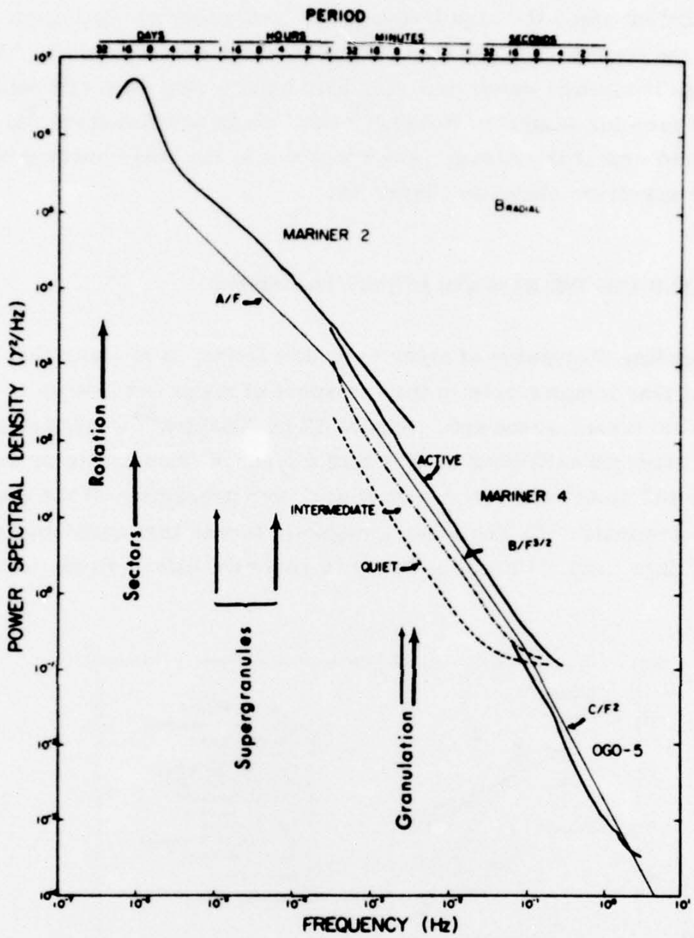

Figure 16. Temporal Power Spectrum of the Magnetic Field Fluctuations in the Solar Wind Near the Earth (Russell) 1972. The arrows indicate the time scales associated with different solar features (light arrows correspond to the lifetime of the features, heavy arrows to the time it takes for the solar synodic rotation to move from one feature to the next)

fluxes near the earth. Naturally, the fluxes near the sun have a much different spectral distribution since the high frequency Alfven waves dissipate much more rapidly during the transport to the earth than the low frequency waves. In fact, many of the high frequency waves will dissipate before they even can penetrate into the corona (see for example, Holweg[52] and Uchida and Kaburaki[10]). One, therefore, should expect the Alfven wave spectrum at the solar surface to be much flatter than the spectrum shown in Figure 16.

6. MAGNETIC FIELD AND THE MASS AND ENERGY TRANSPORT

In the preceding discussion of solar magnetic fields, it is clear that solar magnetic fields play a major role in the transport of mass and energy in at least all the observable layers of the sun. Figure 17 by Newkirk[30] summarizes the magnetic field strength estimates at different distances from the solar surface for both the active and quiet sun. On the quiet sun, two properties of the magnetic fields seem to dominate: (1) The electromagnetic forces that make matter move along the field lines, and (2) the possibility to generate Alfven waves whose energy

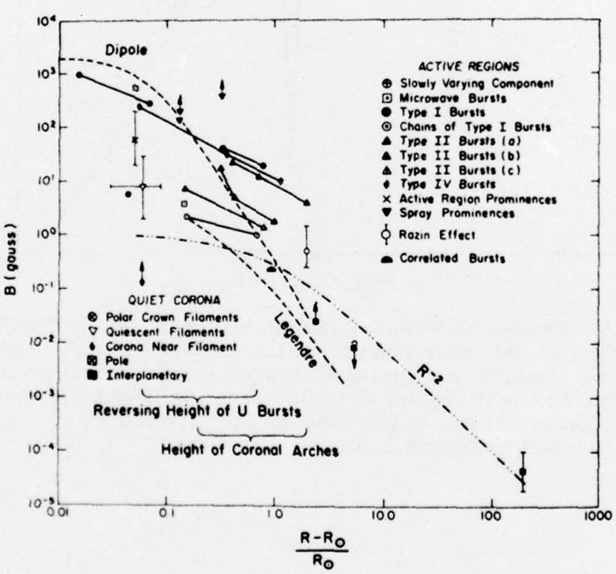

Figure 17. Summary of the Solar Magnetic Field Strengths Measured in Different Regions in the Solar Atmosphere From the Solar Surface into the Solar Wind (Newkirk) 1971

52. Hollweg, J. V. (1972) Supergranulation driven alfven waves in the solar chromosphere and related phenomena, Cosmic Electrodynamics 2:423.

propagate along field lines. In addition, one recognizes on the active sun the property of the field to store magnetic energy which can be released in the solar flares.

I have stressed in this paper the consequences of the presence of magnetic fields for the generation of Alfven waves. Table 2 gives estimates of the energy fluxes for both quiet sun and active region. The Alfven wave flux of 7×10^{26} ergs cm^{-2} for the quiet sun corona are based on the observed motion of the magnetic elements associated with the changing granular patterns (velocity ≈ 1 km/sec, field strength 1500 gs, and 0.1 percent coverage of the surface). Using the results of Uchida and Kaburaki[10], I assume a 0.3 percent penetration into the corona. Hollweg[52] estimated a similar coronal flux of Alfven waves due to supergranular motions: 4×10^3 ergs cm^{-2} sec^{-1} or 2.5×10^{26} ergs sec^{-1} for the entire sun. For sunspots, I use the flux derived by Beckers[9] together with the calculation by Uchida and Kaburaki[10]. Study of Table 2 leads to the following possible conclusions: (1) The quiet sun Alfven wave flux is comparable to the solar wind kinetic energy flux. Most of the Alfven waves have disappeared at 1 AU. Dissipation cannot occur in the inner corona where radiation losses might be important as an energy sink, so that one concludes that Alfven waves may very well dump their energy in the form of solar wind motions either by extended heating in the corona or by Alfven

Table 2. Energy Present in Different Forms at Various Layers in the Solar Atmosphere (ergs sec^{-1})

	Radiation*	Mechanical**	Alfven** Waves
Quiet Sun			
Photosphere	4×10^{33}	10^{31}	3×10^{29}
Chromosphere	10^{30}	3×10^{27}	10^{28}
Corona (inner)	10^{28}	small	7×10^{26}
Solar Wind (IAU)	small	10^{27}	3×10^{24}
Active Sun			
Sunspot	2×10^{28}	small	10^{29}
Chromosphere	--	--	10^{27}
Corona	4×10^{27}	--	10^{27}
Large Flare	10^{29}	10^{29}	--

* Partial fluxes from the different layers

** Total fluxes

wave pressure (for example, Belcher[53]). The occurrence of high speed streams within the magnetic sector and the decrease of a solar wind velocity at the sector boundaries may be the result of this.

(2) Should the solar wind come solely from coronal holes, then one should decrease the Alfven wave flux in Table 2 as well as the comparable radiative flux, by some factor depending on the relative area occupied by the coronal holes (~ 20 percent). It still leaves the previous argument but weakens the effect of Alfven waves compared to other solar wind drivers. One wonders whether the absence of high speed streams near solar maximum is the result of a decreased coronal hole area.

(3) The flux of Alfven waves in one sunspot corona is comparable to that of the total quiet sun. But so is the total coronal radiation. The big difference with the quiet sun is that most or all of the field lines are closed, so that the Alfven waves are trapped and have to dissipate eventually perhaps by radiation. The same may be the case for closed field lines on the quiet sun (noncoronal hole regions) and bipolar regions.

Effects of the forced matter motion along the field lines are again the origin of the solar wind fast streams in coronal holes because that is where the fields open to interplanetary space and the angular momentum of the sun, because of the forced outflow in the low corona along the rigid magnetic field lines.

7. CONCLUSION

This summary does not pretend to give a full review of the present solar magnetic field knowledge. I have only sketched my picture of the properties of the solar magnetic field as it extends from the solar surface. I have omitted any discussion of the all important solar flares and other transients both because of time limitations, because of my limited familiarity with that topic. From the energy numbers for flares in Table 2, that is obviously a major omission. At the time of the flare, it dominates all the mechanical fluxes in the corona and solar wind by orders of magnitude. My summary of the coronal, and even more of the solar wind field is often based on second hand knowledge and a far from complete study of the literature.

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53. Belcher, J.W. (1971) Alfvenic wave pressures and the solar wind, Astrophys. J. 168:509.

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