

LARGE-SCALE SOLAR MAGNETIC FIELDS AND H-ALPHA PATTERNS *Patrick S. McIntosh*

ABSTRACT Coronal and interplanetary magnetic fields computed from measurements of large-scale photospheric magnetic fields suffer from interruptions in day-to-day observations and the limitation of using only measurements made near the solar central meridian. Procedures have been devised for inferring the lines of polarity reversal from H-alpha solar patrol photographs that map the same large-scale features found on Mt. Wilson magnetograms. These features may be monitored without interruption by combining observations from the global network of observatories associated with NOAA's Space Environment Services Center. The patterns of inferred magnetic fields may be followed accurately as far as 60° from central meridian. Such patterns will be used to improve predictions of coronal features during the next solar eclipse.

INTRODUCTION

Careful interpretation of structures seen on H-alpha solar filtergrams allows the inference of magnetic field patterns within active regions and in areas of extended weak magnetic fields [McIntosh, 1970]. The large-scale distribution of weak magnetic fields is mapped by the dark filaments (fig. 1) and the patterns of fine fibrils which have been called filament channels or neutral bands [Rust, 1970]. These large-scale H-alpha patterns have not received much attention for two reasons: (1) the predilection of solar astronomers for high-resolution photography of small areas of the sun, and (2) the low resolution of most full-disk H-alpha patrol photographs. The limited field of view of the nonpatrol instruments prevents recognition of the large-scale organization of H-alpha structures. The adoption of new high-resolution films in recent years by many of the patrol observatories makes it possible to study the large-scale patterns mapped by fine structures formerly seldom observed on full-disk photographs. The continuity of filaments and filament channels over large areas of the sun, in and out of several active regions, implies that all these features

are physically associated. Examples of extremely long, continuous, longitudinal neutral lines are shown in the synoptic chart of inferred magnetic patterns for a single solar rotation (fig. 2). Magnetograms that display the strength and polarity of the longitudinal component in the magnetic field do not reveal the large-scale associations without ambiguity. The filament channels are apparently responses to patterns of magnetic field lines parallel to the solar surface. They often form a common boundary to many separated areas of longitudinal fields. The absence of measurable longitudinal fields on these boundaries makes the boundaries indistinguishable from areas where the total field vector goes to zero, if only the longitudinal component is recorded.

The studies of the distribution of large-scale magnetic fields have previously been limited by the low resolution of the full-disk magnetograms and the restriction to using measurements within 40° of the center of the disk [Bumba and Howard, 1965b]. The positions of inferred lines of polarity reversal are certainly accurate to better than the 23 arc-sec resolution of the synoptic magnetic charts, and it is possible to obtain usable magnetic field patterns as far as 60° from the center of the disk. It should be possible to monitor the evolution of large-scale magnetic patterns for as many as 10 consecutive

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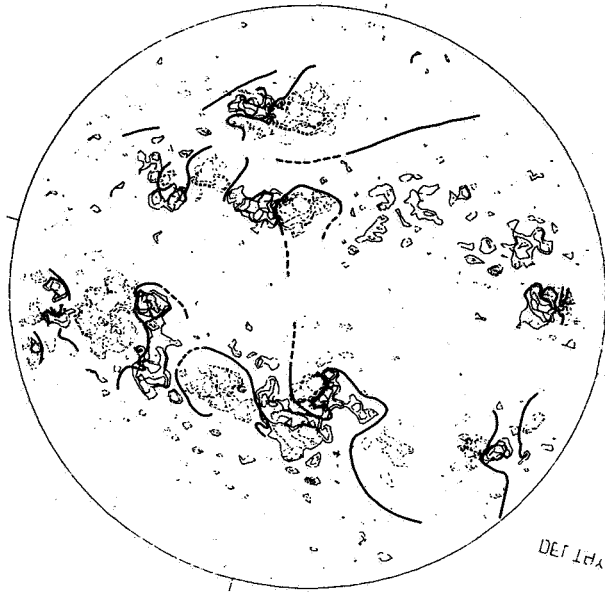


Figure 1. An H-alpha filtergram (top) for 4 June 1968 is compared with a Mt. Wilson plot of line-of-sight magnetic fields [McIntosh, 1971]. The heavy lines are the lines of polarity reversal inferred from the H-alpha structures. The dark filaments map most of the polarity reversals, with patterns of parallel fibrils (filament channels) connecting some filaments with the bright active regions. Filtergram from the NASA SPAN observatory operated by NOAA in Boulder, Colorado.

days with time resolution as good as the rate of photography on the solar flare patrol telescopes (as high as 10 sec). The many existing H-alpha telescopes assures that there will be no interruptions in the data such as now hamper studies based on magnetograph data [Altschuler, 1971]. The H-alpha data may reveal patterns of evolution that can be safely extrapolated from one solar rotation to the next, thereby allowing more accurate predictions of the large-scale magnetic fields. Such predictions could provide more accurate estimates of the coronal structures to be expected at times of total solar eclipses [Schatten, 1968]. Inferred magnetic patterns will be used for 1972 eclipse predictions.

Several maps of inferred longitudinal neutral lines have been combined to form the unforeshortened map of the entire sun in figure 2. This synoptic chart bears a strong resemblance to the *Cartes Synoptique* because both include all filaments. This chart also displays large-scale features spaced at regular intervals, mimicking the patterns revealed on synoptic charts of Mt. Wilson magnetograms [Bumba and Howard, 1965b]. Neither *Cartes Synoptique* nor the Mt. Wilson magnetic field charts reveal the continuity of longitudinal neutral lines over such large distances.

Nearly the full variety of forms exhibited by large-scale inferred magnetic patterns are shown in figure 2. A large cell of follower polarity in the northern hemisphere near 0° longitude is bounded by filaments on its

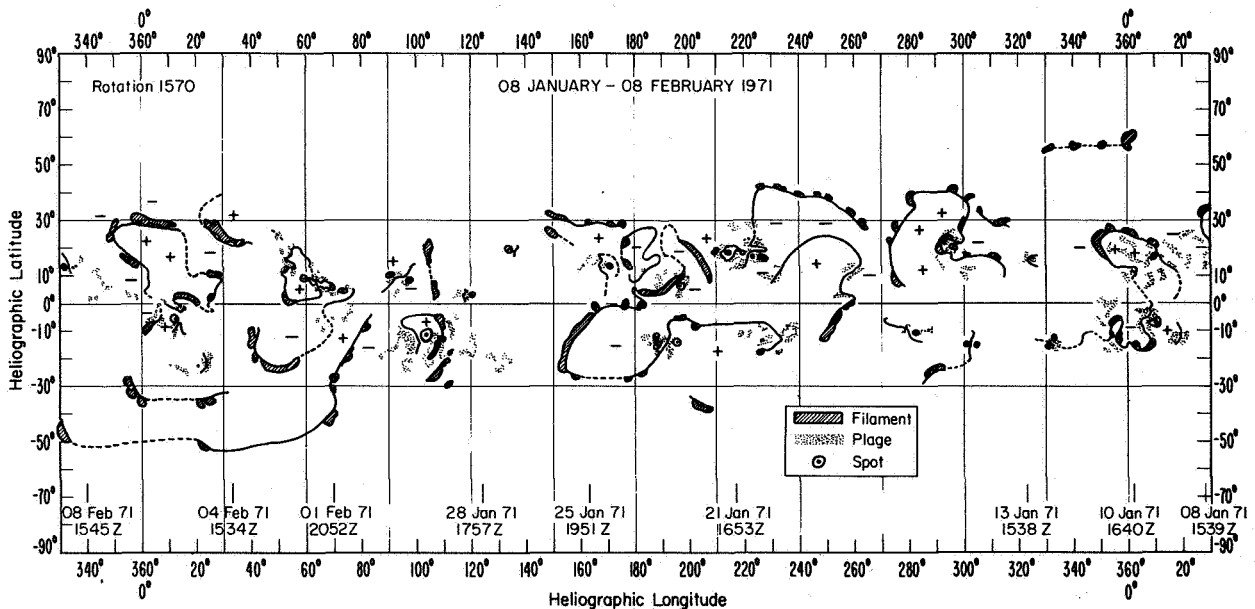


Figure 2. Daily maps of inferred lines of polarity reversal were combined to form a synoptic chart representing one solar rotation from 8 January through 8 February 1971. Dotted lines are extrapolations over areas of poorly ordered, or poorly resolved, H-alpha structures.

poleward side. This feature is typical of the areas of following polarity that evolve near areas of persistent active-region formation [Sýkora, 1969], and which have been identified with unipolar magnetic regions (UMRs); see figure 8 in *Bumba and Howard [1965b]*. The eastern, or following, side of the cell is bounded by an inferred line of polarity reversal that continues across the solar equator to form a weak mirror-image of the UMR, a pattern noted by Bumba and Howard in their discussion of UMRs seen in the magnetic field data.

The large cells of follower polarity always evolve from large active centers or complexes of activity, expanding and moving poleward and eastward after the active regions decay. *Bumba and Růžicková-Topolová [1969]* found a close relationship between positions of enhanced coronal emission and these filament-bounded areas of follower polarity. This relationship with active centers conforms to the relationship of coronal helmet streamers to active centers as discussed by *Bohlin [1970]*. *Pneuman [1969]* argues from theoretical grounds that the coronal structure associated with an active region should evolve toward a helmet-streamer form as the follower polarity fields expand into the extended areas studied by *Sýkora [1969]* and *Bumba and Růžicková-Topolová [1969]*. It appears that the coronal development must follow the development of the large, follower-polarity cells that are clearly visible on H-alpha filtergrams.

The large-scale patterns in both the inferred magnetic charts and the Mt. Wilson synoptic charts have typical diameters of about 25 heliographic degrees, in near-perfect agreement with the 300,000-km cell size predicted for the largest scale of solar convection [*Simon and Weiss, 1968*]. Study of the evolution of some of these large-scale features indicates that there are some features that undergo such rapid changes as to be unrecognizable after one solar rotation, while other patterns of similar scale remain little changed for as many as six solar rotations. Poleward migration of follower-polarity magnetic fields can be detected on a day-to-day basis (fig. 3). Note the poleward motion of filaments bounding the "cell" at 0° longitude in figure 2, comparing aspect at right to aspect at left. Proper motions of coherent features 30° in diameter have occurred that clearly exceed the motions attributable to differential rotation. Studies are planned that should determine whether these motions resemble large-scale circulatory patterns deduced by *Ward [1965]* and theorized by *Gilman [1969]*, *Kato and Nakagawa [1969]*, and others.

The study of the large-scale magnetic field patterns associated with the birth and development of an active

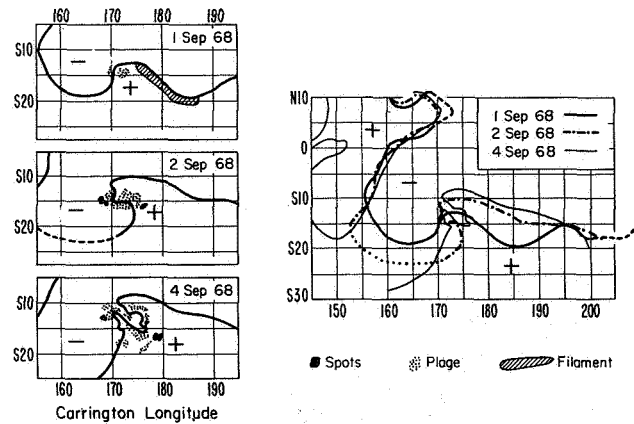


Figure 3. The patterns of inferred magnetic fields for a 4-day period near a developing active region are superposed. Large features distant from the activity repeat positions from day to day while rapid motions are evident near and within the active center.

region (fig. 3) showed some behavior that has since proven to be typical. The continuous patterns made up of filaments and filament channels extending over large distances tend to change slowly in time and repeat positions on successive days to within a fraction of a heliographic degree. Within a developing active region the pattern of the inferred polarities changes rapidly, generally becoming most complex at the time of greatest development of the active region.

The repeatability of the positions of the large-scale patterns is significant when an area near east limb is compared with its aspects at central meridian and near west limb. In no way could an eager observer influence the making of the map so that such an accuracy could be artificially produced. This repeatability of inferred patterns provides an additional proof of the validity of the techniques for inferring magnetic fields from H-alpha observations; in particular, it demonstrates the close correspondence of filament channels with the former positions of filaments.

Just as active regions first appear at the borders of supergranulation (30,000 km diameter) [*Bumba and Howard, 1965a*], the large complexes of activity [*Bumba and Howard, 1965b*] may prefer to form at the junction of two or more giant cells outlined by the filaments and filament channels [*Simon and Weiss, 1968*]. Understanding the evolution of large-scale magnetic field patterns could be important to long-range solar-activity forecasting.

The association of large, filament-bounded cells of follower polarity magnetic fields with UMRs, enhanced green-line corona, and helmet streamers implies that

proper interpretation of large-scale H-alpha patterns might lead to inference of interplanetary structures. Wilcox [1968] has shown that the interplanetary magnetic field is dominated by a sector structure corotating with the sun in which the field is predominantly away from the sun for several days (as observed near the earth) and then toward the sun for several days. This interplanetary structure and some of the coronal forms seen at times of eclipse have been successfully modelled by combining photospheric magnetic field measurements with potential theory [Schatten *et al.*, 1969]. Wilcox and Howard [1968] and Wilcox *et al.* [1969] have demonstrated a direct correlation between the interplanetary magnetic field distribution and the pattern of large-scale magnetic fields on the solar surface, finding an average delay of 4.25 days between central meridian passage of the solar source and the magnetic field reversal measured near the earth (Archimedes spiral of solar interplanetary field). Bumba and Obridko [1969] discovered that flare activity correlated closely with the interplanetary sector-boundary positions on the solar surface, with the correlation improving with increasing flare magnitude. The correlation was most striking for proton flares. The great flares and the extended areas of follower-polarity both originate from the large complexes of active centers; therefore, it appears that the follower cells, the UMRs, the coronal intensity, and the helmet streamers should also prefer positions near sector boundaries.

The UMRs were associated with the sources of recurrent geomagnetic activity by Bumba and Howard [1966] and Wilcox and Colburn [1969] demonstrated a strong correlation between geomagnetic activity and the passage of sector boundaries past the earth. The UMR was associated with the extended areas of follower polarity that were usually mirror-imaged in opposite hemispheres [Bumba and Howard, 1965b]. The enclosed cell of follower polarity near 0° longitude in figure 2 plainly has a southern hemisphere counterpart. Such conspicuous crossings of the solar equator by chromospheric markers of polarity reversal can be tentatively associated with the polarity reversals measured by spacecraft near the earth. First attempts at identifying the chromospheric marker of interplanetary sector structures indicate that equator-crossing filaments, filament-bounded cells of following polarity, and combinations of both are the most common features occurring near central meridian 4 days prior to a measurement of interplanetary polarity reversal near the earth. Attempts are being made to forecast sector structures from such features. Early results are encouraging, but there seem to be numerous features crossing the

equator without a measured reversal in the interplanetary fields. It appears that the degree of persistence of an equator-crossing filament (or filament channel) is related to whether that feature is a reliable indicator of the interplanetary structure. The longitude distribution of X-ray flares appears to follow the distribution of the filament-bounded cells of following polarity, with the most persistently active longitudes correlating with the most persistent equator-crossing inferred longitudinal neutral lines.

The prediction of recurrent geomagnetic activity from sector boundary positions depends, at present, on either interplanetary spacecraft or measurements of the solar magnetic polarity averaged over the whole solar disk [Wilcox *et al.*, 1969]. The positions and limited number of interplanetary spacecraft place limits on the reliability and lead time provided by predictions based on their measurements. The solar magnetic polarity measurements allow a 4-day advance notice of the passage of sector boundaries past the earth. If these boundaries can be inferred from the patterns of solar activity in H-alpha, then advance notice may be possible as soon as the appropriate patterns can be identified in the eastern hemisphere of the sun, increasing the lead time of prediction to as much as 8 days.

The correlation of solar activity with sector boundaries is stronger than the correlation with the active heliographic longitudes [Bumba and Obridko, 1969]. This implies that the fundamental source for flare activity is also the source of the interplanetary sectors. The detailed monitoring of large-scale solar magnetic fields through the interpretation of H-alpha patterns will contribute to a greater understanding of how flare-active regions and interplanetary sectors emerge and evolve.

ACKNOWLEDGEMENTS

John M. Wilcox has provided advice and encouragement for the pursuit of a relationship between large-scale H-alpha features and the interplanetary sector structures. Bela Scheiber, John E. Allen, and Charles Shanks prepared synoptic charts for the initial studies of the large-scale H-alpha features.

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COMMENTS

E. C. Roelof. Bob Lin and I have been interested for quite a while in trying to use quite low-energy low-rigidity particles, solar energetic particles, to get some idea of how the field lines above active regions are mapped out to the earth, as sort of a way of doing this independent of the plasma data. The particles we are talking about are 45 keV electrons and 0.3 meV protons. Now, first of all, during an analysis from 1967 to 1969 of the electron data with regard to sector boundaries, the time histories at 45 keV are quite different from what one sees at thermal energies. The electrons just don't seem to know that the sector boundaries are there. These 45 keV electron fluxes are continuous across the boundaries when they are above background.

The story is a bit different for the protons. The protons sometimes undergo a discontinuous jump in intensity, either up or down but these are discontinuous jumps in a "D.C." level. There aren't peaks and therefore one would not say that at these times there is any streaming of the protons out along the sector boundaries, but rather that the sector boundaries are in some way related to proton storage in the corona. However, the 45 keV electrons don't seem to know that the boundaries are around.

We have tried to analyze some peculiar events that we call "core-halo" events. We found one in 1966 and we have found three more in 1967, and we don't seem to be finding any more after that. These are events in which about a day or so after a flare one sees an enhanced particle density coming around as a more or less quasi-stationary structure on the field lines, on the spiral field lines from the sun. There is a narrow core of these

low-energy particles that lasts only perhaps a fraction of a day, a third of a day, and a more extended halo, which can last several days. And harking back to the last solar wind conference, what we have done is take the technique of extrapolating solar wind streams back to the sun using the observed plasma velocity that was originally suggested by Neugebauer and Snyder. Figure 1 shows a mapping in an r - ϕ plot where r is the radial

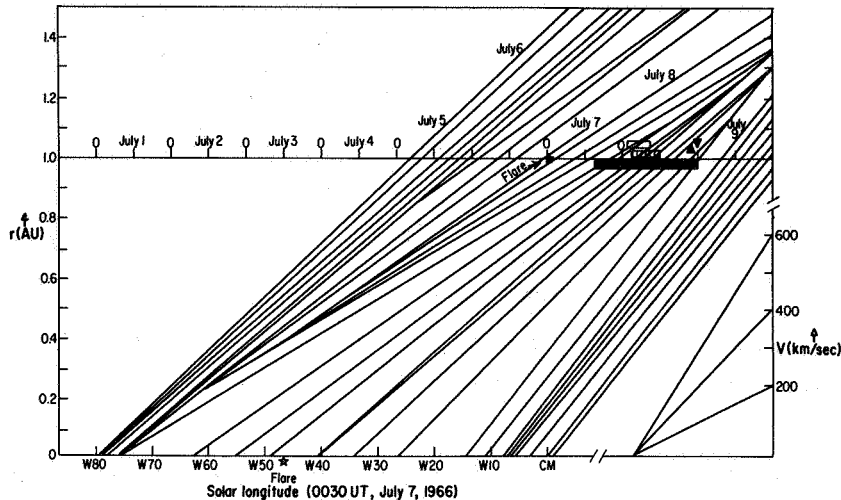


Figure 1. Solar wind streams mapped back to the sun (assuming a constant radial velocity). Radial distance from the sun (r) is given in AU and solar longitude (ϕ) (west of central meridian location at 00 UT, 7 July 1966) is given in degrees on the abscissa. The time when the earth is at a given longitude (referred to CM at 00 UT, 7 July 1966) is marked on the line through $r = 1$ AU. This is also the time when the plotted solar wind velocity was observed.

distance from the sun and ϕ is the solar longitude. For those of you who are unfamiliar with the original paper, a spiral shows up as a straight line in such a plot. This is done for the July 7 flare in figure 1. The white box on the time line indicates the duration of the electron core, the striped box is the proton core, and the filled box is the proton halo. It is delightful to come to a conference and find someone reporting findings related to your own but in another region of energies and densities and particles. Professor Davis was talking about the rarefactions due to the interaction between a fast and a slow speed region of the solar wind. We have found that these core-halo events (all the ones we have found) all occurred during a rarefaction of the solar wind. You can read the solar wind velocities off the slopes of the lines using the key in the lower right corner of the figures.

When we map these stream lines back we are happy with an accuracy of something like 10° or 15° as far as the mapping goes and we claim no more accuracy. In figure 1 you will notice the core and the halo map back along the solar wind stream to the position of the solar flare which occurred at W47 about 00 UT on July 7. But there is an even more interesting phenomenon and that is the termination of the halo. It is accompanied by a sudden commencement of a magnetic storm, and a Forbush decrease occurred at the time when we leave the rarefaction of the low speed stream when there is a rapid transition to the fast stream which, in a naive sense, maybe one could say results in quickly switching the connection for the particles from the flare region quite far to the east where particles are no longer injected from the corona. Now, this is a very fortunate event because there were also Pioneer 6 data available. The same plot can be formed from Pioneer 6 data taken 45° to the west of the earth, and the remarkable thing on figure 2 is that we get the same story, although the data are fragmentary. One can identify the end of the proton core. There were no electron observations available at the end of the proton halo. Once

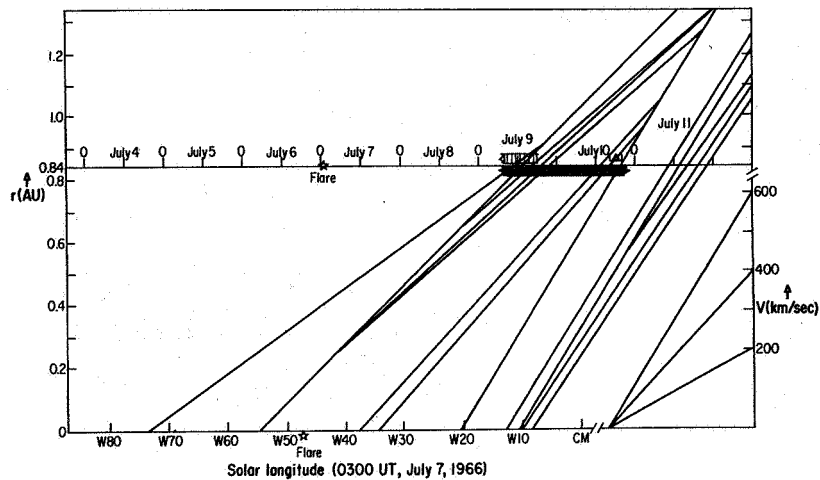


Figure 2. Mapping of solar wind streams as in figure 1 except time line now refers to observations on Pioneer 6 at $r = 0.84$ AU and 45° to west of earth.

again the proton core is connected back to the vicinity of the flare, whereas the halo again terminates at the time when one goes from the rarefaction into the fast solar wind stream. One also notices that this event, which fits well to this picture of solar stream mapping, cannot be explained by a rigid rotation of some sort of a connecting field structure because the expected rigid corotation rate is something over 80 hr. The actual delay is 45 hr. It shows that this fast stream was evolving. Indeed, it means the solar wind velocity was higher on July 10 when it was detected by Pioneer 6 than it was at earth on July 9. And finally, of course, there is no possibility of explaining these proton fluxes by any sort of a radially moving feature because of the 45-hr time delay.

We have found three other events in 1967 that fit the same pattern of the particles being connected back to the flare region along solar wind streams and the halos occurring in the rarefaction region of the solar wind pattern and ending at the time when one enters the fast stream.

DISCUSSION *M. Dryer* Are you saying these particles go out with the shock wave that comes from the flare?

E. C. Roelof No, I'm saying these particles are coming out mainly collimated by the interplanetary magnetic field.

M. Dryer Which has been changed by the faster flowing plasma?

E. C. Roelof Well, the way one interprets those features drawn or the changes in the velocity is in the eye of the beholder. There can be no containment or elimination or shutting off of these particles by such a shock because of the 45 hr delay between the shutting off at earth and at Pioneer 6, which were separated 45° in longitude. So there are shock associations, perhaps there is a shock in the discontinuity in the earth at the time these colliding streams sweep over the earth. But we do not believe this is the fundamental mechanism for what is happening to the particles.

COMMENTS

F. C. Michel I would like to make a few comments about the filamentary structure of the solar wind, which stands in relation to the wind itself as do the trees to a forest. A lot has been said about the forest, so perhaps it is not inappropriate to make a few comments about the trees. The forest, of course, is the uniform plasma outflow from the sun, recognizing as well that there is some modification that leads to the sector structure. What I would like to talk about is the very fine scale structuring which is seen in

interplanetary magnetometer data. The observations reveal extremely chaotic and variable magnetic fields and, in fact, the famous garden-hose spiral structure is generally seen only in long-term averaging of such data.

Figure 1 is from *McCracken and Ness* [1966]. They describe cosmic ray propagation data in terms of the magnetic field-line topology, and they are essentially describing the interplanetary field in terms of filaments.

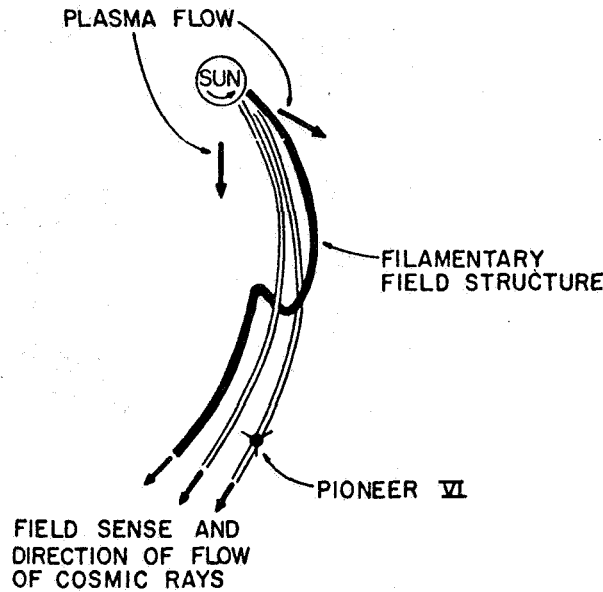


Figure 1. A schematic diagram of a few interplanetary filaments, as viewed from the north ecliptic pole and as sampled by Pioneer 6 on December 30, 1965. Compare this figure with the azimuths recorded in in figure 2 [McCracken and Ness, 1966].

Figure 2 shows the data that led them to this description. The solid line indicates a continuation of magnetic field measurements, successive magnetic field vectors added vectorially, while the arrows that are shown as such are the directions of the cosmic ray anisotropies in the solar wind. One sees that the two line up very well, which indicates that the cosmic rays are ducted along the magnetic field lines, as one might well expect. The curve so constructed in figure 2 would not actually represent a *single* magnetic field line but sort of a superposition of many. Nevertheless, it shows that the magnetic field lines meander about quite a bit.

Figure 3 is from a paper by *Bukata and Palmeira* [1967] and shows their picture for the propagation of flare cosmic rays in terms of filamentary structures. In trying to understand this filamentary structure on a basic picture as shown in figure 4 [Michel, 1967], I started with the assumption that the source of solar wind itself is modulated by propagation of energy from below up into the corona to keep it hot enough so it expands outward and forms the solar wind. This mechanism need not be absolutely homogeneous, and the inhomogeneities can be preserved by virtue of the magnetic field structure; consequently, variations in the source (e.g., acoustic energy propagated up from granulations) would lead to local modification of the solar wind source. This modulation would in turn lead to regions of higher or lower density propagating outward.

Figure 5 is a sketch of how this would appear on the large scale. The dotted lines show the expected garden hose geometry, while in fact the flux tube position varies with the propagation velocity as well as its dimensions, owing to spatial and temporal variations in the source function.

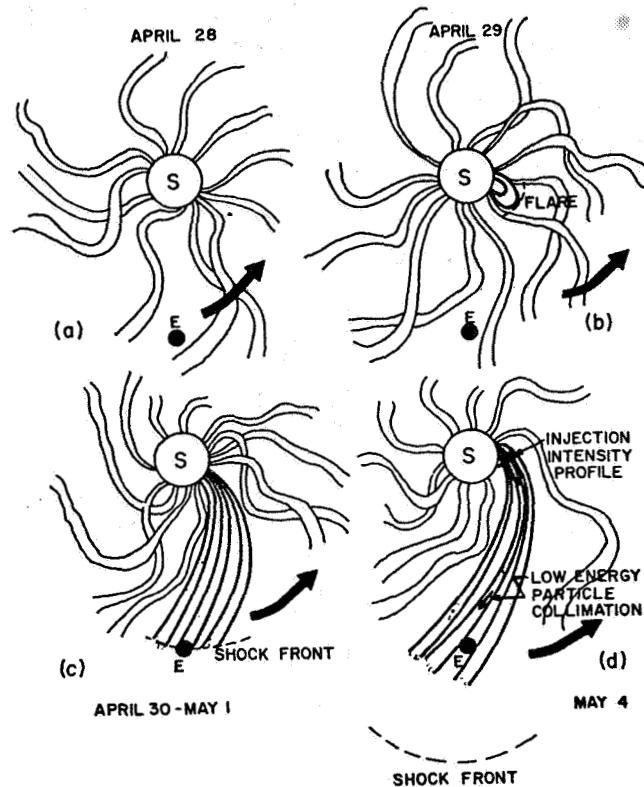


Figure 2. The magnetic field and cosmic-ray azimuths during the interval 1600 to 2000 UT, December 30, 1965. Note the very close correspondence of the two azimuths during the abrupt change in direction around 1800 UT [McCracken and Ness, 1966].

Figure 6 shows the same idea, the filamentary structure is just a small-scale variation. The large-scale sector structure simply refers to the field in the filaments being predominantly of one direction (toward or away from the sun).

Figure 7 is from Bartley *et al.* [1966] showing the "wet spaghetti" model. The basic idea is that one can get large variations in field direction simply by having a tangling of the flux tubes. Thus one might regard the filaments as being distinct individual flux tubes. Jokipii and Parker [1968] have expanded on this idea and discuss how the movement of the source of the flux tube in the photosphere would lead to tangling of the field lines, and this would give, at the earth, a highly variable field wherein the observed field variations are due to encountering first one flux tube, and then another flux tube, and so on. The boundaries between the flux tubes will be tangential discontinuities. These discontinuities have been observed in abundance from many spacecraft and since they are not waves, not shock waves or anything but just flux tubes frozen-in to the solar wind, the total pressure must remain constant as one crosses such a discontinuity. Burlaga [1968] has analyzed magnetometer and particle data to show quantitatively that in fact total field pressure plus gas pressure is indeed constant across these discontinuities.

Finally, the scale for the discontinuities projected down onto the sun is of the correct general size. The scale of fluctuations seen in the solar wind, if projected back to the sun—a reduction factor of about 200—is not quite the same scale as the granulations. It's a little larger, and Newkirk prefers the supergranulation as the more likely characteristic dimension, but the same idea essentially applies. In this way we can understand at least qualitatively some of the detailed phenomena, such as plasma flow out of the ecliptic plane (just flowing along a flux tube) and the abundance of discontinuities on the solar

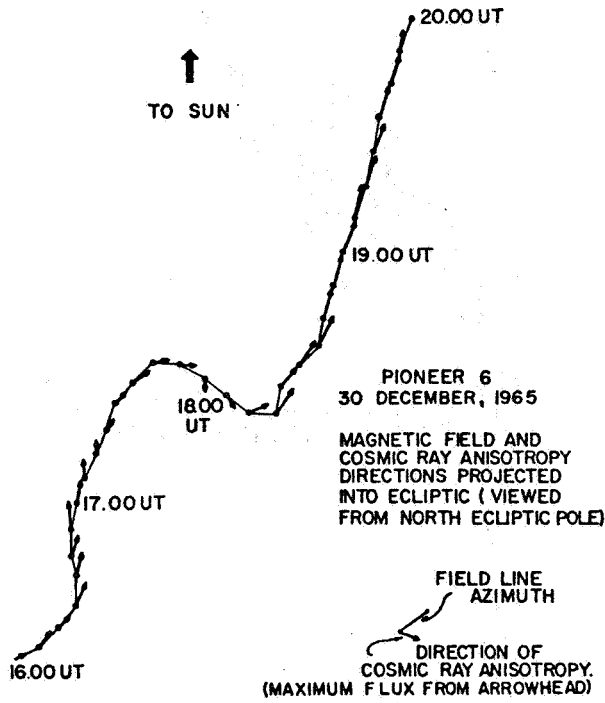


Figure 3. Grossly exaggerated representation of the time-history of the interplanetary magnetic field configuration from late April to early May 1960. Solar particles generated in the flare event of May 4 are being preferentially injected into a single well-ordered magnetic filament created in the west limb flare event of April 29. The presumptuous, highly exaggerated, disordered magnetic filamentary structure depicted for the fields removed from the localized west limb flare activity is presented solely for contrasting the two filamentary magnetic regimes and is not intended to be taken at face value [Bukata and Palmeira, 1967].

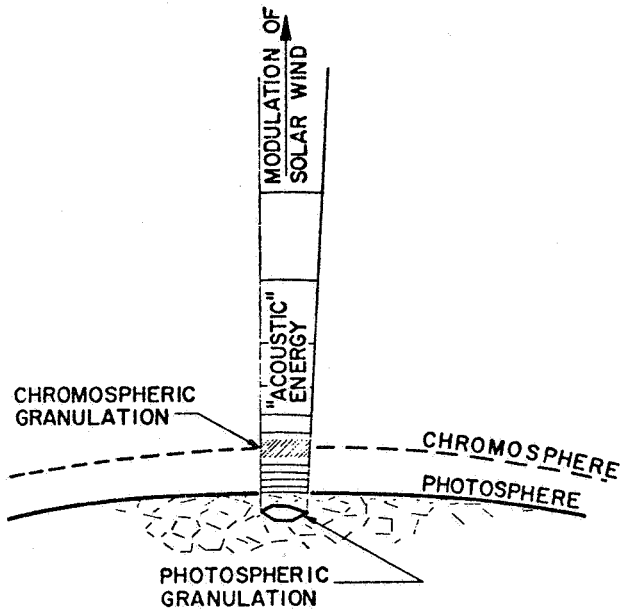


Figure 4. Hypothetical interrelation between photospheric and chromospheric granulations and the modulations of solar wind flow.

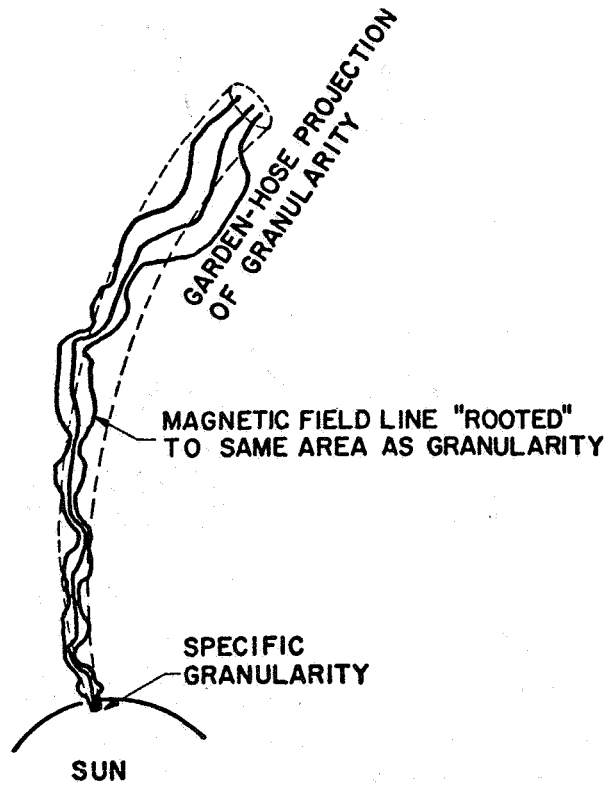


Figure 5. Schematic of field-line configuration showing relation between the garden-hose extension of a granulation and the magnetic field lines.

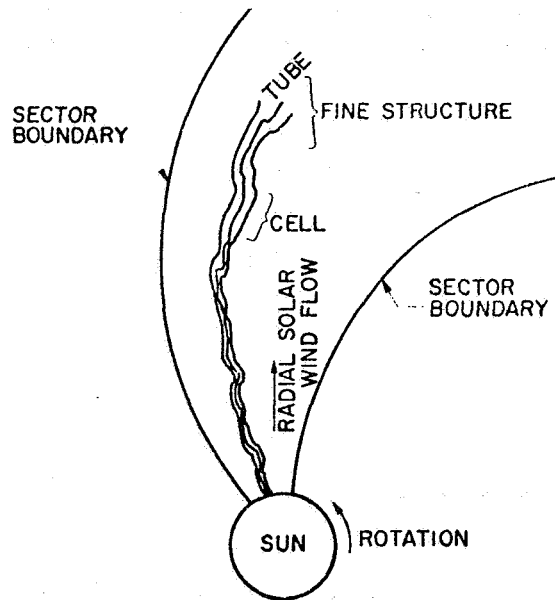


Figure 6. Schematic of structure within the solar wind illustrating cellular structure within the interplanetary magnetic field. The field lines passing through a given cell tube lead to the site of cell origin.

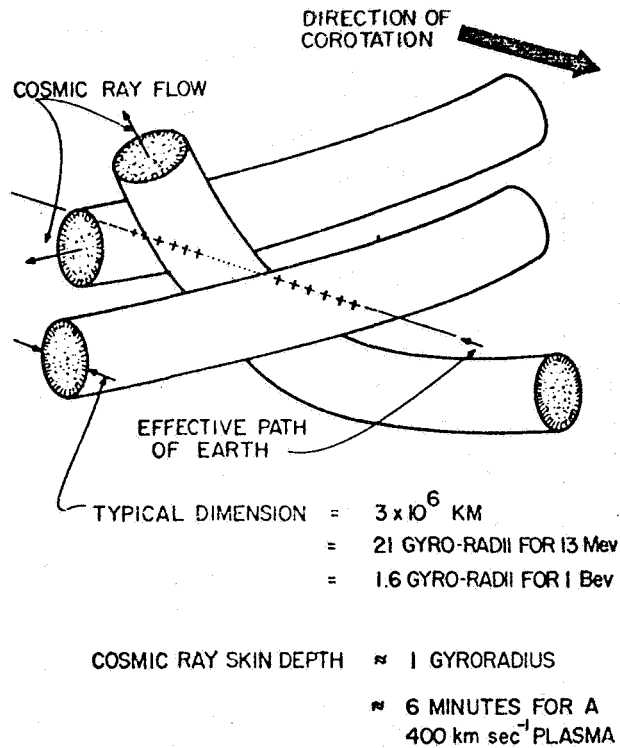


Figure 7. Simplified model of filamentary structure of interplanetary magnetic field. Each filament can be thought of as a bundle of tubes of force. The cosmic rays of low energy are constrained to travel along the filament by the magnetic field [Bartley et al., 1966].

wind. Thus the structure of the solar coronal rays, which can readily be seen in eclipse photographs, is just the manifestation near the source of the very fine structuring observed locally in the solar wind.

I should remind you of the cosmic-ray arrival time data [Bryant et al., 1965], wherein one takes the energy versus arrival time spectrum and corrects it for the time of flight. There one finds that protons with energies from almost 500 meV down to 2.2 meV have arrival times that all scale as if the particles all followed essentially the same path from the sun to the earth. Of course, that again is consistent with the idea that the basic solar wind structure is filamentary and the effective path length (6 or more astronomical units) results simply from detouring the cosmic rays out along the filaments.

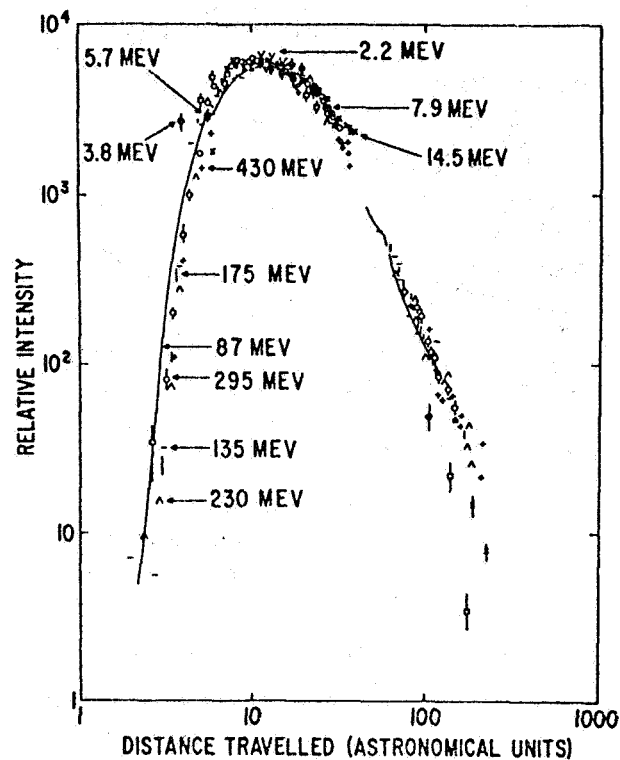


Figure 8. Normalized (same maximum) intensity versus distance traveled (time of observation after flare \times particle speed) for interplanetary flare protons [Byrant et al., 1965].

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A. J. Dessler Is there any contradiction between the source surface model that Schatten has talked about with the start of the magnetic field at about one solar radius out and only using part of the solar surface, and your using the granulation?

F. C. Michel Well, naively, one would say one is mapping from the granulations out to 1 AU. But, of course, one has to realize that you do have these arcades with the field lines closed, so you don't get all the map, you get chunks cut out of the map where the field lines actually close and the granulations connect to one another. But other than that distortion one essentially maps outward.

E. C. Roelof I would just like to point out that we are forced to certain exceptions to what must be a very physical phenomenon, the braiding or random walking of these field lines. And those exceptions are unique low-energy particle events, the examples of which are becoming more and more numerous, in which there are clearly enhanced fluxes whose width is only something like 3° or 4° at the earth. These are not temporal events, these are spatial features that are more or less being quasirigidly rotated in the interplanetary field. We can tell this in multiple spacecraft observations, using two or sometimes three spacecraft. Since these particles have to be stored or be continually accelerated from an active region these field lines must be connecting back to an active region. Consequently, this puts a limit on the random walking or the braiding of these field lines above active regions. This limit, as far as I can see from the low-energy particles, then, is only something like 3° or 4° and this, of course, does not in any sense invalidate the process of a general braiding at the general surface of the sun. It just says there is something peculiar and rather fateful about the mapping of field lines out to the earth above active regions that are producing low-energy particles. But these are exceptions.

J. M. Wilcox That last comment calls to mind another possible exception to the random walk process of Jokipii and Parker, namely, the sector boundary, and a particular case where a sector boundary may persist for a year or more, coming back every 27 days. Naively one would think that the random walk process would eat away at that sharp boundary and finally cause it to disappear. One can help the situation somewhat by having an arcade or a loop structure near the photosphere, but then maybe you would get the time up to a month or so. But a year still seems too long. It seems there is something of interest occurring there.

E. C. Roelof Well, I didn't mean to give the impression that I thought all the fluctuation was due to the random walk. Some of it is due to just the variations in the sizes of the filaments, and also possibly the most important process is the variation in the velocity, within individual filaments, which will cause certain ones to slip through or meander, and get well ahead of the general trend. So I don't think it is very well sorted out which are the important physical factors there.

L. Davis Since the random walk and speed of the field lines came up I just felt that I wanted to remark that these field lines continue deep on down into the sun, and I am worried that they may not walk at random over long periods. They may move at random for short periods, but they may stay somewhat anchored to the same spot and may not accumulate the square root of the distance over weeks and months.

G. Newkirk Is there any characteristic size for the noodles in interplanetary space?

F. C. Michel Well, I think again that is in the eye of the beholder.

G. Newkirk No, that's a question of frequency analysis.

F. C. Michel But I think it varies. I don't think there is a single number.

E. C. Roelof It's the same old problem we've had for a long time, what do we want to call a filament? The whole problem of the mixing of the data makes it a bit difficult to identify something you wish to call filament. If you plot the field direction you see all sorts of assorted things. So the point of view that I take is let's drop the word *filament* as it's gotten all sorts of meanings now, and concentrate on the other things, the discontinuities and waves, because we've got theory behind us on that. If you look at the

discontinuities, pick them out in space, you find out they are not paired; they have orientations which change from one to the next. And given that situation we have almost completely lost the idea of a filament. So I personally prefer to simply drop the idea of filament and work with the more fundamental ideas of the current sheet and the discontinuities.

I don't recall the author but I do know that a Russian author many years ago suggested that granulation could give rise to small cellular features in the interplanetary magnetic field. The idea is very similar to yours.

F. C. Michel If you are willing to say that the discontinuities are boundaries of different filaments, then one can answer the question. I would say they probably run by about once every 30 minutes. We can say that would be plausible. It comes down to about 10° of arc or 5° of arc in the sun, something like that.