MAGNETIC FIELD SPECTROHELIOGRAMS FROM THE SAN FERNANDO OBSERVATORY

DALE VRABEC

San Fernando Observatory, The Aerospace Corporation, El Segundo, Calif., U.S.A.

Abstract. Zeeman spectroheliograms of photospheric magnetic fields (longitudinal component) in the Ca I 6102.7 Å line are being obtained with the new 61-cm vacuum solar telescope and spectroheliograph, using the Leighton technique. The structure of the magnetic field network appears identical to the bright photospheric network visible in the cores of many Fraunhofer lines and in CN spectroheliograms, with the exception that polarities are distinguished. This supports the evolving concept that solar magnetic fields outside of sunspots exist in small concentrations of essentially vertically oriented field, roughly clumped to form a network imbedded in the otherwise field-free photosphere. A time-lapse spectroheliogram movie sequence spanning 6 hr revealed changes in the magnetic fields, including a systematic outward streaming of small magnetic knots of both polarities within annular areas surrounding several sunspots. The photospheric magnetic fields and a series of filtergrams taken at various wavelengths in the Hα profile starting in the far wing are intercompared in an effort to demonstrate that the dark strands of arch filament systems (AFS) and fibrils map magnetic field lines in the chromosphere. An example of an active region in which the magnetic fields assume a distinct spiral structure is presented.

1. Introduction

It appears that an intimate relationship exists between magnetic fields and most of the structure so far observed on the Sun. The more these magnetic fields are studied, the more evident it is becoming that magnetic features of increasingly finer detail play a fundamental role. With this in mind, The Aerospace Corporation has recently placed into operation at its San Fernando Observatory a 61-cm aperture vacuum solar telescope and spectroheliograph (Vrabec and Rogers, 1968; Mayfield *et al.*, 1969) designed to produce Zeeman spectroheliograms of magnetic fields with relatively high spatial and temporal resolution, preliminary examples of which are presented here.

2. Method

Figure 1 illustrates the basic method employed, which is the one devised by Leighton (1959). Magnetic fields are visible in the upper two spectroheliograms where they appear as light patches that are different in the two strips. The spectroheliograph is equipped with a polarizing beamsplitter which separates the dispersed light into two complementary optical channels. A bandwidth of approximately 0.1 Å set 0.07 Å in the blue wing of the Zeeman-sensitive 6102.7 Å line of neutral calcium is used, and the two spectroheliograms are exposed simultaneously so that seeing variations are identical in both channels. The two channels discriminate between the two oppositely circularly polarized Zeeman components produced by the longitudinal magnetic field, each transmitting only the component which is blocked in the other channel. Wherever there is a magnetic field, a differential exposure results between the two channels, the

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sign of which depends upon the polarity of the field. This is the effect visible in the two upper strips. Sunspots and background mottling due to photospheric granulation and velocity fields appear in both spectroheliograms. To obtain a record in which only the magnetic fields appear, the upper spectroheliogram is subtracted from the middle one by means of photographic subtraction, thereby cancelling common-mode features and enhancing the magnetic fields. Polarities are distinguished by whether the photographic density is greater or less than the density of the field-free background. The original spectroheliograms are exposed on two separate rolls of 70-mm cine film, and a cine optical printer is utilized for the photographic subtraction. Care is necessary to maintain precise registration between the images and the perforations of the two film rolls in the spectroheliograph camera, and between the films sandwiched in the optical printer.

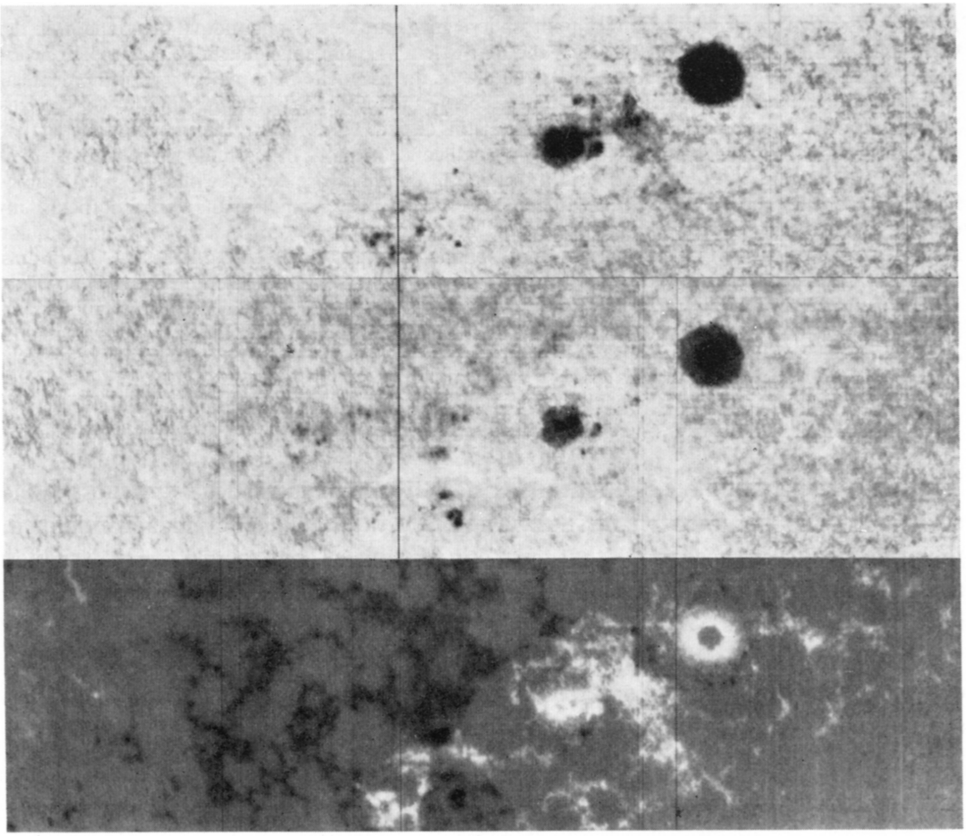

Fig. 1. Leighton's technique to obtain Zeeman spectroheliograms of magnetic fields is illustrated by reference to the three strips. The upper two are the original spectroheliograms simultaneously exposed 0.07 Å in the blue wing of the Ca I 6102.7 Å line by means of a polarizing beamsplitter. The lower strip, obtained by photographically subtracting the upper from the middle strip, shows only the photospheric longitudinal magnetic field component.

3. Description of a Typical Zeeman Spectroheliogram

Figure 2 depicts a typical bipolar magnetic region (BMR) photographed on 21 February, 1970. On a large scale, opposite magnetic polarities are separated into two distinct regions which conform to Hale's law. Localized intrusions of one polarity into a region dominated by the opposite polarity occur, particularly where the two main regions interface. The fields are resolved into a partially fragmented, mesh-like, cellular network that is highly localized, but the resolution (~2.5 arc s, or ~1 800 km) is insufficient to show the network resolved into individual points. We can anticipate that it should exhibit such fine structure on the basis of the superb CN spectroheliograms taken by Sheeley (1969). These reveal a photospheric network formed from clumps of individual bright points, where the photospheric temperature is higher than its average value. Chapman and Sheeley (1968) have shown that this bright network is co-spatial with photospheric magnetic fields. Our Zeeman spectroheliograms, which map the longitudinal magnetic field component, complement the CN spectroheliograms of Sheeley, and are especially useful because they reveal the *polarities* of individual features.

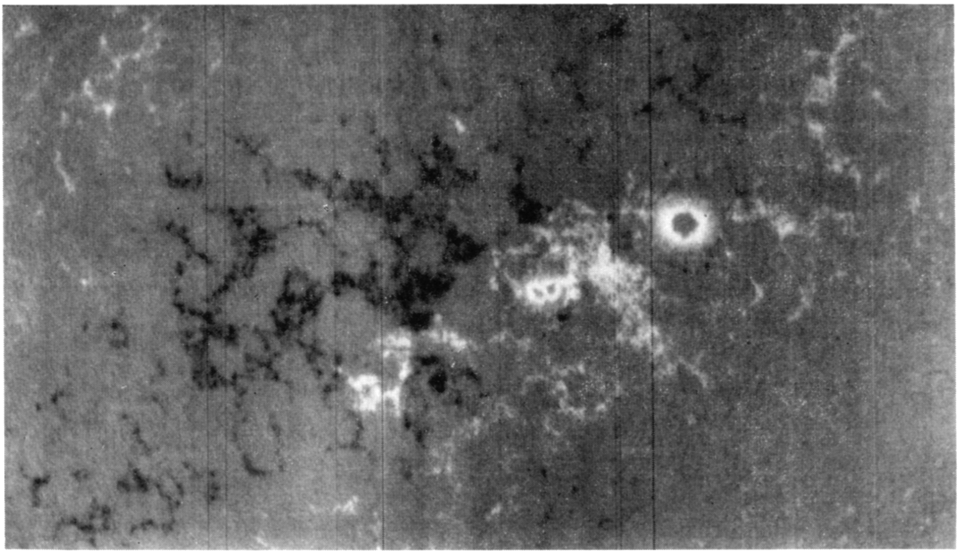

Fig. 2. **Zeeman spectroheliogram of a typical bipolar magnetic region (BMR) near the center of the disk, taken 21 February, 1970 at 1915 UT.**

Several types of isolated magnetic features are visible in Figure 2. The most prominent of these (besides sunspots) are white-light pores, such as the dark magnetic feature just below the sunspot with the double umbra. Others appear to simply be network fragments. These may be associated with the network structure of the BMR, itself, or may be fragments of adjacent, intermingling magnetic regions, remnants of decaying regions which preceded the BMR, or newly emerging field. The smallest of the isolated features, and the most interesting to us, are the concentrations of both polarities which cluster around the principal sunspots in Figures 2 and 3. The majority of these do not have any corresponding continuum features that can be identified on filtergrams of approximately 1.5 arc s resolution, so the fields must be relatively strong in order to be visible on the (presently uncalibrated) spectroheliograms. Whether or not white-light features corresponding to these field concentrations exist, can only be answered when concurrently exposed, higher resolution photographs become available. It is very likely that the concentrations we observe correspond to those 'magnetic knots' observed by Beckers and Schröter (1968) that were located near sunspots, and to the 'satellite sunspots' reported by Rust (1968), though the latter were confined to features of opposite polarity to the associated sunspot. A distinctive feature of these particular magnetic concentrations is that they display a characteristic of streaming radially outward from their associated sunspots. Outflow of bright points from sunspots was first noted by Sheeley (1969) in the CN spectroheliograms referred to previously, and in the following section we will describe our own observations.

Perhaps the most important point to stress in this section is that our data support the evolving concept that outside of sunspots, magnetic fields on the Sun appear to exist in small concentrations of essentially vertically oriented field that exhibit a tendency to become clumped together, forming a localized magnetic network imbedded in the otherwise (vertical) field-free photosphere.

4. Short-Term Time-Dependent Behavior of Magnetic Fields

To study the time-dependent characteristics of the magnetic fields exhibited in our Zeeman spectroheliograms, we prepared a time-lapse movie consisting of 47 individual magnetic field spectroheliograms of a complex region crossing the central meridian on 26 January, 1970. The data span 6 hr, beginning at 1735 UT. Figure 3 shows the first spectroheliogram of this series, together with concurrent Hα filtergrams of the same region taken at selected wavelengths in the profile of this line. The fields exhibit considerable complexity. The 'stranded' appearance of the fields between the principal sunspots is seen to be associated with chains of pores visible in the far-wing filtergram. In the movie the most conspicuous changes in the fields occur along these same strands, which is also where a conspicuous flare commenced during the period of observation. The area immediately surrounding the principal sunspots is seen to be relatively free of organized magnetic network. The network nearest the sunspots appears to either assume the form of a fragmented garland encircling the sunspots, or to present a curved boundary roughly concentric with the sunspot. Not infrequently, this network is comprised of segments of both polarities.

The following types of time-dependent behavior of magnetic fields were noted in this 6 hr movie.

(1) Associated with the principal sunspots there is a persistent, approximately

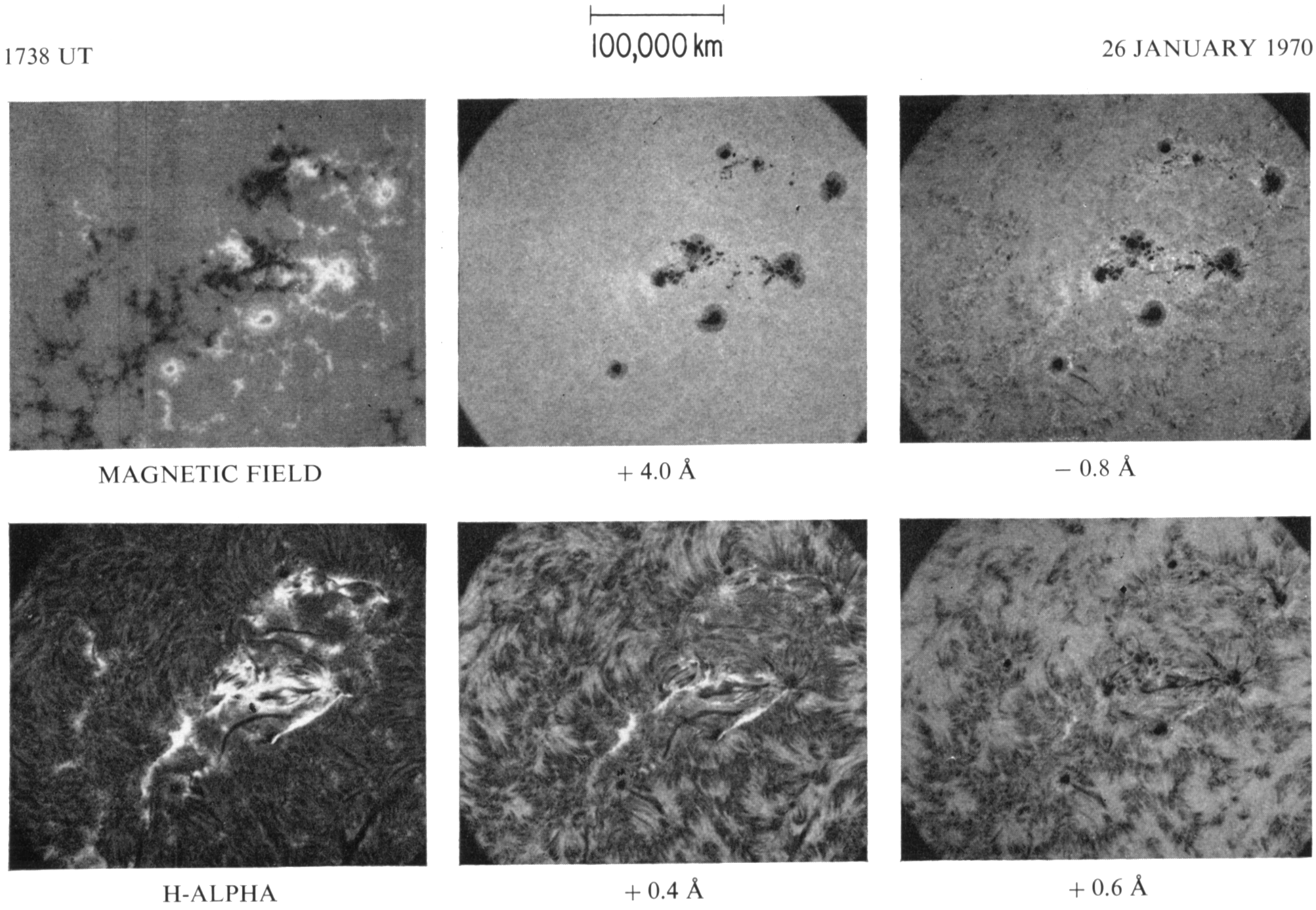

Fig. 3. The intimate relationship existing between photospheric magnetic fields and Hα chromospheric structure is seen by intercomparing the sequence of filtergrams exposed at different wavelengths in the Hα profile with the Zeeman spectroheliogram at the upper left.

radial outflow of small concentrations of magnetic field of both polarities throughout the annular region extending from the outer boundary of the sunspot penumbra, out to the radius where the network first appears. Stationary features, other than pores, occur infrequently in this annular zone, and the existence of horizontal streaming throughout this zone suggests that conditions there are unfavorable for the maintenance of a stable network structure, which therefore only begins at the periphery of the zone. What the source of this moving magnetic flux is, and to what extent this flow contributes to the flux in the surrounding network, are not presently clear. Although some of these 'streaming flux knots' first appear at the outer edge of the sunspot penumbra on our spectroheliograms, where unfortunately the penumbra is photographically saturated, many first become visible at a greater radius, especially those of opposite polarity to the sunspot. Some streaming flux knots disappear before reaching the surrounding network; others appear to merge with the network when they reach it, especially when their polarity is the same. Improvement in resolution by a factor of two would help to clarify these important processes, since the majority of these features are only marginally visible in these preliminary data.

(2) Outside of these regions we observe examples where a number of separate network fragments of the same polarity converge, become concentrated into an irregular unresolved patch which sometimes then fades. The reverse also occurs where a compact patch of network expands and separates into distinct fragments of the same polarity, some of which disappear.

(3) Movement of field concentrations along curved arcs occurs.

(4) Field concentrations underlying the extreme opposite ends, or 'feet', of arch filament systems (AFS) frequently seen in Hα, exhibit a tendency to separate with time. When this occurs near sunspots, the field concentrations may move towards these sunspots. Several AFS can be seen in the two filtergrams taken nearest line center.

(5) In several cases, apparent interaction between small concentrations of opposite polarity occurs, where the area of one polarity dwindles and the area of opposite polarity increases.

(6) The most conspicuous movement of magnetic fields occurs in the 'strands' referred to earlier. Here the magnetic features of each polarity are roughly organized into separate strands, each of one polarity. The features comprising one of these strands move coherently towards the associated sunspot to which the strand appears connected, which is of the same polarity. The free end of this strand 'slides' past the free end of the strand of opposite polarity and displaces it laterally. The movement of the strands gives the impression of causing them to straighten out.

5. Hα Structure and Photospheric Magnetic Fields

Hα photographs reveal a rich progression of complex structure suggestive of an intimate relationship to associated magnetic fields. Dark filaments are known to demarcate the boundary between regions of opposite magnetic polarity (Babcock and Babcock, 1955), and bright Hα plage to only occur over the strongest magnetic field concentrations in the network (Howard and Harvey, 1964). It seems apparent that fibrils must map magnetic field lines, yet the details remain obscure. A technique we have been using in our investigations is to obtain concurrently with the Zeeman spectroheliograms, Hα filtergrams using a Zeiss filter that is sequentially tuned through the line profile from the far red wing into the far blue wing. These filtergrams range from pure photospheric to pure chromospheric, and record the majority of Doppler-shifted features. The filtergrams and Zeeman spectroheliograms are then intercompared (Figure 3). An important result of this sequential wavelength scanning technique is that the complete locus of features which have a velocity structure can be traced, provided the Doppler shifts are within the range of tuning. This has proved to be essential in locating the 'feet' of AFS which can only be seen in the red wing of Hα, when observed near the center of the disk (Bruzek, 1969). In this manner, in all the AFS that appeared in the region shown in Figure 3 during the period of observation, the ends of the dark strands have been found to be imbedded in magnetic fields of opposite polarity, the dark arch structure in all likelihood mapping the field lines as they extend through the chromosphere.

With reference to Figure 3, in the far wings of Hα essentially only sunspots, pores, and photospheric granulation appear, except near the limb, where the photospheric network is also visible (faculae). Away from the limb, the bright photospheric network only becomes visible when the continuum begins to be significantly depressed by line absorption, and attains maximum visibility at approximately 1 Å from line center. A one-to-one correspondence between the bright elements of the photospheric network and magnetic concentrations comprising the network of photospheric magnetic fields, independent of polarity, is evident.

Elongated, dark, jet-like features bordering the bright photospheric network are the first traces of the dark Hα chromospheric network. It is seen that these dark features generally point away from magnetic field concentrations, one end beginning at the concentration, or very near it. Their upward flaring geometry when viewed obliquely towards the limb is consistent with the conjecture that these features map magnetic field lines in the chromosphere that extend out of the photosphere. As the filter is tuned towards line center many of these features develop into fibrils by lengthening one end in a curvilinear fashion, generally towards the interiors of the network cells, while the opposite end, imbedded in the photospheric fields, remains essentially fixed in position. At the same time the dark chromospheric network thickens and the number of fibrils increases. Viewed obliquely, fibrils appear either to sharply curve over to assume a nearly horizontal orientation immediately outside of the magnetic field network, or to connect with dark features which are inclined substantially out of the vertical. Outside of the magnetic field network, the absence of observable vertical components of magnetic fields implies the presence of predominantly horizontally oriented fields. Although in some areas of Figure 3 it appears possible to trace fibril structure from the fixed end almost continuously until it meets a similar structure extending from a region of opposite polarity, the majority of fibrils fade from visibility, or otherwise lose their identity before such a connection can be traced. Further support for the conjecture that fibrils map field lines comes from the observation that fibrils that are rooted in magnetic fields of the same polarity avoid connecting with each other. Because a basic characteristic of the network is that extended portions of it are of a single polarity, fibrils extending from field concentrations of the same polarity quite frequently come into proximity, in which case they interact by channeling into parallel fibril strands, rather than connecting, as in the case of AFS. Many examples of this are evident in Figure 3, but again, there is a clear need for a substantial improvement in spatial resolution. Differences between filtergrams taken at two wavelengths symmetrically displaced to the red and blue of the center of Hα are evident, so velocities are going to play an important role in any definitive interpretation of fibril structure.

Within a few tenths Ångstrom from line center the bright mottles comprising the bright Hα plage first appear and attain a maximum contrast at the line center, where they overlie most of the network of photospheric magnetic fields visible in the Zeeman spectroheliograms. Bray (1969) has shown that these bright mottles lie substantially lower in the chromosphere than the dark features we have been discussing. The inference is that the stronger fields directly over the network play a role in increasing the transparency of the chromosphere. The dark chromospheric network, when viewed obliquely towards the limb, also gives the impression of being depressed directly over the magnetic field network, as if the mapping was not as fully developed there.

In this example, as well as others for which we have similar data, both regions of leading and following magnetic polarity have associated bright Hα plage, and thus do not conform to the distinction between plage and antiplage made by Veeder and Zirin (1970); i. e., that only following magnetic fields show bright plage in the center of Hα. This does not preclude the possibility that an asymmetry in brightness between leading and following plage may exist on a statistical basis, or possibly at different stages of development of an active region.

6. Example of a Magnetic Field Region Exhibiting a Spiral Structure

Figure 4 is a Zeeman spectroheliogram taken on 29 September, 1969 at 2000 UT. The area is approximately one-quarter the solar disk, centered on a point located roughly on the solar equator, west of the meridian. Two southern hemisphere bipolar sunspot groups, each in a typical BMR, are seen at the bottom left and right. For comparison, at the upper left is a northern hemisphere bipolar group to which Hale's law applies. In the interesting active region at the upper right the distinction between polarities has made visible a pronounced spiral structure. The development of this structure is shown in Figure 5 which also shows the configuration this region had on three previous days. Referring to the magnetic fields near the center of this active region, the areas of opposite polarity lay north and south of each other on September 25, and ended up east and west by September 29; i.e., the line of magnetic polarity reversal

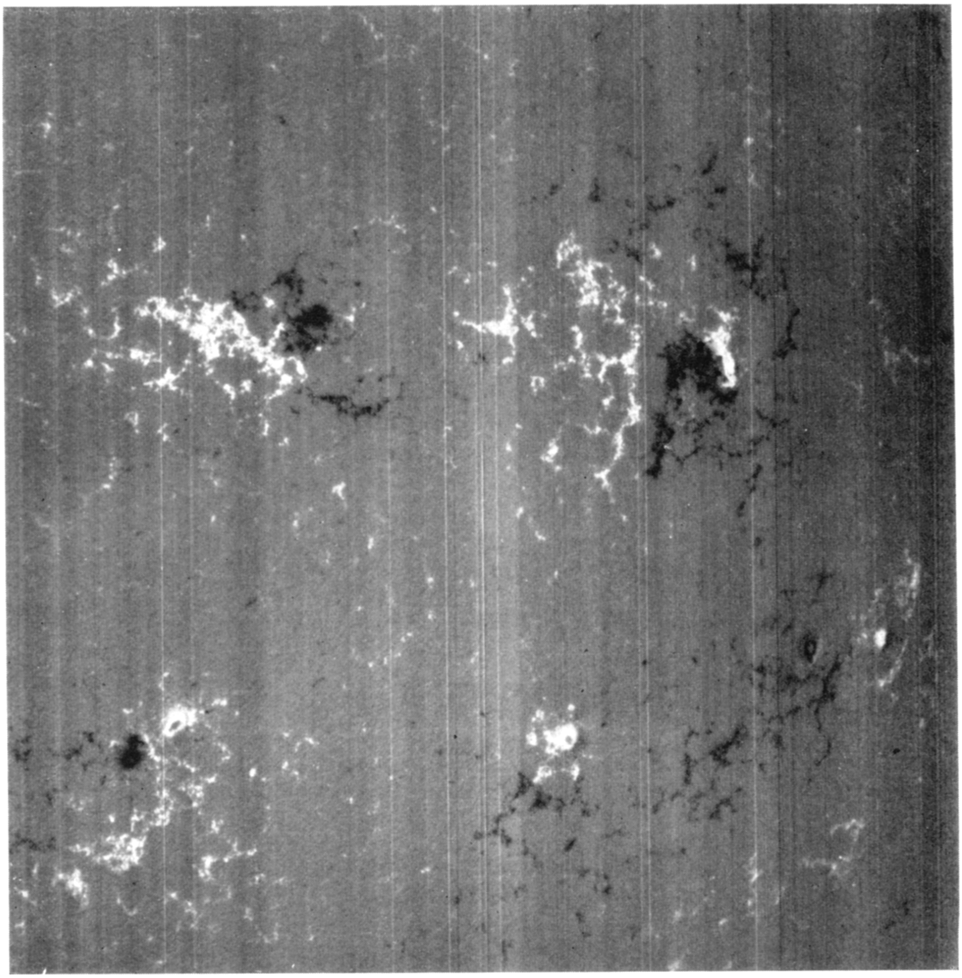

Fig. 4. The network structure of photospheric magnetic fields in the large is seen in this Zeeman spectroheliogram taken on 29 September, 1969 at 2000 UT. Note the distinct spiral structure of the active region at the upper right. In the central region the normal order of polarities is inverted, and there is a high vertical field gradient across the line of polarity reversal.

rotated clockwise as viewed from the Earth, resulting in an inversion of the normal order of polarities. The spiral structure did not simply result from a clockwise rotation of the central area. Its development involved the formation, growth, decline, and disappearance of sunspots of both polarities. On 27 September, 1969, commencing at 0416 UT., a class 3B flare occurred in this region of inverted polarities. This type of complex evolution of sunspot groups involving rotation has been found to be associated with an increased likelihood of occurrence of energetic flares (Sakurai, 1967; McIntosh, 1970a; Sawyer and Smith, 1970). It has been estimated that only a few percent of all active regions develop a spiral geometry of this type (McIntosh, 1970b).

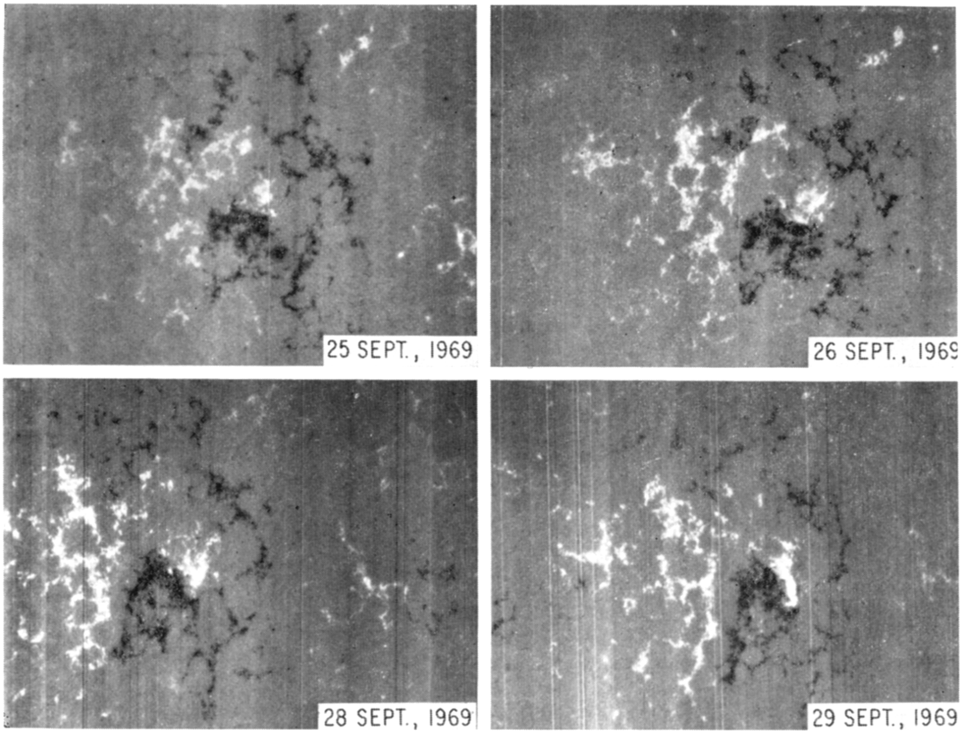

Fig. 5. The development of spiral structure in the magnetic fields can be followed in this sequence which spans 4 days. Changes in the network between successive days are evident. (Magnetic field data for September 27th is missing.)

Acknowledgements

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Discussion

Sheeley: Have you attempted to measure the velocities of the magnetic points that flow out from sunspots?

Vrabec: There appears to be some spread in the horizontal velocities. A rough average is 1 km/s. But in the case of some knots, the velocity appears to be twice as large, and for others, one-half as large. These are approximate values.

Giovanelli: I disagree with you in that I believe that it is the *bright* fibrils that are related to the magnetic fields.

Vrabec: The distinction between the physical nature of bright and dark Hα chromospheric features still appears to be unresolved. This is an important area of investigation.

Leighton: I find the fact that *dark* magnetic fragments may move out of a *light* (opposite polarity) sunspot to be most striking. What flow pattern would the theorists suggest to do this?

Vrabec: Since this question is addressed to the theorists, I had better reserve comment, though we have considered the possibility of arched flux tubes originating in the sunspot whose re-intersections with the photosphere move outward.

Simon, G. W.: You could imagine magnetic flux concentrations 'shooting' up out of the sunspot and reversing their orientation as they re-intersect the photosphere.