PART VI

EVOLUTION OF CHROMOSPHERIC FINE STRUCTURES

STREAMING MAGNETIC FEATURES NEAR SUNSPOTS

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Abstract. Observations prompted by Sheeley's discovery of outflowing CN bright points from sunspots have established that there occur small moving magnetic features (MMF's) near sunspots. These MMF's exhibit a highly ordered pattern of movement directly related to the associated sunspot. The observations are consistent with the concept of magnetic flux outflow (MFO), a process whereby net magnetic flux of the same polarity as the sunspot is transferred from a decaying sunspot to the surrounding magnetic network. Small magnetic flux concentrations are apparently convected outward by a velocity cell centered on the sunspot. Doppler spectroheliograms have provided evidence for such systematic outward velocities extending as far as 10000 to 20000 km beyond the outer edge of the penumbra of some sunspots, which is comparable to the extent of MFO. While MFO is best observed by means of time-lapse movies of the magnetic fields, it is also manifested morphologically on individual magnetograms by features that resemble moats (or bays) and wreaths around only those sunspots where MFO is present. Two examples of magnetic features streaming toward and into rapidly forming sunspots are described, providing evidence for the occurrence of magnetic flux inflow (MFI) associated with the growth phase of sunspot development. It is, therefore, likely that MFI and MFO are basic aspects of the evolutionary development of sunspots. Observational and instrumental aspects relevant to the investigation of MMF's are described in the Appendix.

1. Background

Most of the phenomena that I shall review were unknown five years ago. In August 1968, Sheeley (1969) exposed a 2.3-h sequence of high-resolution CN 3883 Å band head spectroheliograms of a sunspot region with the McMath Solar Telescope at the Kitt Peak National Observatory (see Figure 1). When the 22 spectroheliograms were later converted into a time-lapse movie, he could see a conspicuous horizontal outflow of bright points from the two principal sunspots. This outflow, which had an average speed of 1 km s^{-1}, was present throughout much of the area surrounding the sunspots to distances of 10000 to 15000 km, where it either encountered essentially stationary fragments of incipient network forming from collections of stagnating points or simply died out. Throughout this region of outflow, points moved along approximately radial paths from the sunspots, some points fading or disappearing, others forming or growing. Many of the outflowing points first appeared at the outer edge of the penumbra of the sunspot, while points reaching the outer boundary of the outflow zone merged with the network there, or (Sheeley, 1973) diverged around preexisting network fragments and stopped, thereby forming new network. Sheeley correctly inferred that these moving CN bright points coincided with localized, outflowing magnetic field concentrations, but was unable to ascertain their polarities. Subsequently, using Leighton's (1959) spectroheliographic technique for photographing the line-of-sight component of solar magnetic fields, Vrabec (1971) at the Aerospace San Fernando Observatory obtained time-lapse movies of Ca I 6103 Å Zeeman spectroheliograms, and confirmed that Sheeley's outflowing features were

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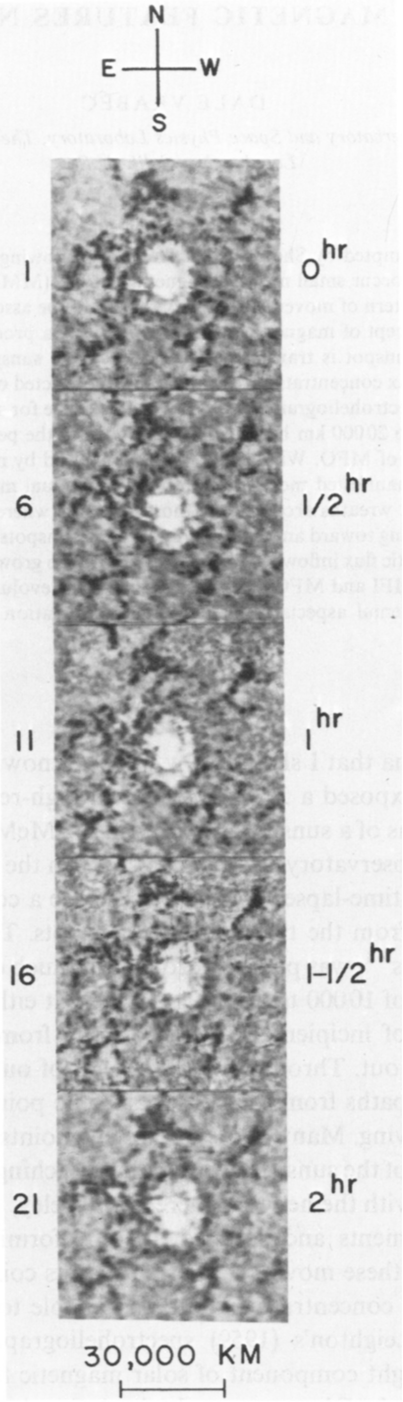

Fig. 1. This sequence of spectroheliogram negatives exposed in the CN band head at 3883 Å is selected from a total of 22 taken on 1968, August 13. Sheeley first detected magnetic flux outflow from sunspots in a time-lapse movie made from these observations. CN bright points and the bright photospheric network appear as dark features. (Courtesy N. R. Sheeley and Kitt Peak National Observatory.)

indeed basically magnetic. In addition, he found that magnetic features of both polarities occur in the outflow around a sunspot of either polarity. (The technique of time-lapse movies has proven indispensible for discerning the ordered motion of these elusive features.) Recently, Harvey and Harvey (1972, 1973) have reported results of a study of a large sample of sunspots, observed with the Kitt Peak 40-channel photoelectric magnetograph, over half of which exhibited magnetic outflow. Due to their large sample and because quantitative measurements of the magnetic fluxes were obtained, their investigation is the most comprehensive of this phenomenon undertaken so far. In addition to confirming the earlier work, Harvey and Harvey obtained new and significant results which are discussed later. In view of these investigations, it can now be considered well-established that there occur around most sunspots, especially during their declining stage of development, numerous small magnetic features in a mixture of both polarities, which exhibit systematic outflow. This is a direct manifestation of magnetic flux transfer from sunspots to their surroundings, which has important implications regarding the evolutionary history of solar magnetic fields. I will call this phenomenon 'magnetic flux outflow' (MFO).

While MFO is by far the best observed, it is important to note that we also observe examples of 'magnetic flux inflow' (MFI) in the form of instreaming magnetic features (Vrabec, 1971) that converge toward and actually enter sunspots. Published descriptions of MFI are scarce, although it appears to play an important role in sunspot formation and growth.

Both MFO and MFI involve a special class of solar features, which can be defined as follows:

(a) All members of the class are magnetic in nature, and this shall be regarded as their primary physical property. (As a consequence, it is necessary that any interpretation of these features be consistent with the physics governing magnetic fields permeating a partially ionized fluid medium, where the appropriate magnetic field strengths, plasma densities, and velocities are properly taken into account. Throughout this review it will be assumed that the magnetic fields are essentially 'frozen' in the photospheric material, in accordance with the generally accepted meaning of this expression.)

(b) All members are associated in some direct way with a visible sunspot, or group of sunspots, and these sunspots are a dominant influence. (I suggest that in the future it may prove desirable in the case of MFI to broaden this definition by substituting for 'visible sunspot' the term 'localized magnetic disturbance,' such as occurs in a region during the incipient phase of sunspot formation whether or not this activity is accompanied by visible sunspots or pores.)

(c) All members exhibit systematic (i.e., nonrandom) motion across the photospheric surface along paths that either diverge from or converge toward the associated sunspot.

A suitable nomenclature is needed for this class of features that are involved in both MFO and MFI. We will adopt the acronym MMF for 'moving magnetic feature,' a term introduced by Harvey and Harvey in their study of MFO. Of course, we must always bear in mind the suppressed prefix 'sunspot-associated' as well as the implicit distinction between outflowing and inflowing MMF's, which will be obvious from the context. It is likely that pores and small umbrae frequently fall in the latter category.

Most of the observations discussed in this review were made with instruments capable of sensing or measuring only the line-of-sight component of the photospheric magnetic field. To avoid tedious repetition, I will not explicitly refer to this each time these observations are described.

2. Magnetic Flux Outflow

2.1. CHARACTERISTICS OF DEVELOPMENT

It appears that magnetic flux outflow plays a very important role in the evolutionary history of a sunspot and manifests itself through the appearance of outflowing MMF's around the sunspot. According to Chapman (1972), Harvey and Harvey, and Allen *et al.* (1973), not all sunspots exhibit MMF's at the time they are observed. Rather, it was found that outflowing MMF's appear almost always in association with decaying sunspots. I have observed MFO in a sunspot that was near its maximum development, but was still growing in area. MMF's are associated with sunspots of all sizes and degrees of complexity. For example, the compact but very magnetically complex group of early August 1972 (Coffey, 1973; Zirin and Tanaka, 1973) exhibited exceptionally well-developed MFO when it was observed by Chapman (1973) on 5 August, while immediately adjacent to it an isolated small umbra independently provided an unusually well-defined example of MFO in its simplest form.

It is apparent that, closely related to the development of the sunspot with which it is associated, MFO must also undergo a characteristic evolution, progressing from its first visible onset through a stage of maximum activity and, finally, presumably dying out along with the dissolution of the sunspot. Unfortunately, our limited observations have afforded us only incomplete views of the overall phenomenon. Despite these severe limitations, I will try to sketch a simplified, but no doubt idealized, picture of MFO development.

During most of the growth stage of development of a sunspot, it is typical for active region magnetic fields surrounding the sunspot to extend right up to it. Active region fields are characterized by a high number density and compact morphology of the small magnetic field concentrations that constitute the fine structure of the fields. If the sunspot develops a penumbra, during this stage its outer edge remains nearly in contact with the surrounding fields, at least over a major portion of its periphery. Under these circumstances we do not observe any conspicuous MFO. As the sunspot approaches or attains its maximum development, the magnetic fields adjacent to it become increasingly fragmented and begin to be dispersed throughout an annular region centered on the sunspot, starting at the outer edge of the penumbra (see Figure 2). The outer boundary of this annular zone, within which the magnetic fields are becoming conspicuously thinned out compared to the fields in the adjacent active regions and network, expands outward up to distances of typically 10000 to 20000 km from the outer edge of the penumbra. Wherever extended areas of active region fields are encountered, an indentation in the latter is produced, resulting in a partially cleared area in the form of a 'bay,' the curved outline of which is concentric with the sunspot. Any network that is encountered assumes in time the circular shape of the boundary, producing the effect of a fragmented wreath of magnetic fields partially encircling the sunspot. This annular zone surrounding sunspots, first pointed out by Vrabec (1971) and Sheeley (1971), has been aptly coined the 'moat' by Sheeley. In some sunspots the moat characteristics do not develop in all azimuths around the sunspot. In the case of preceding sunspots, the undeveloped sector tends to point toward the following sunspot. Harvey (1973) has recently observed the formation of a moat during the course of a single day's observing run. If this single observation is indicative, moats may form very rapidly.

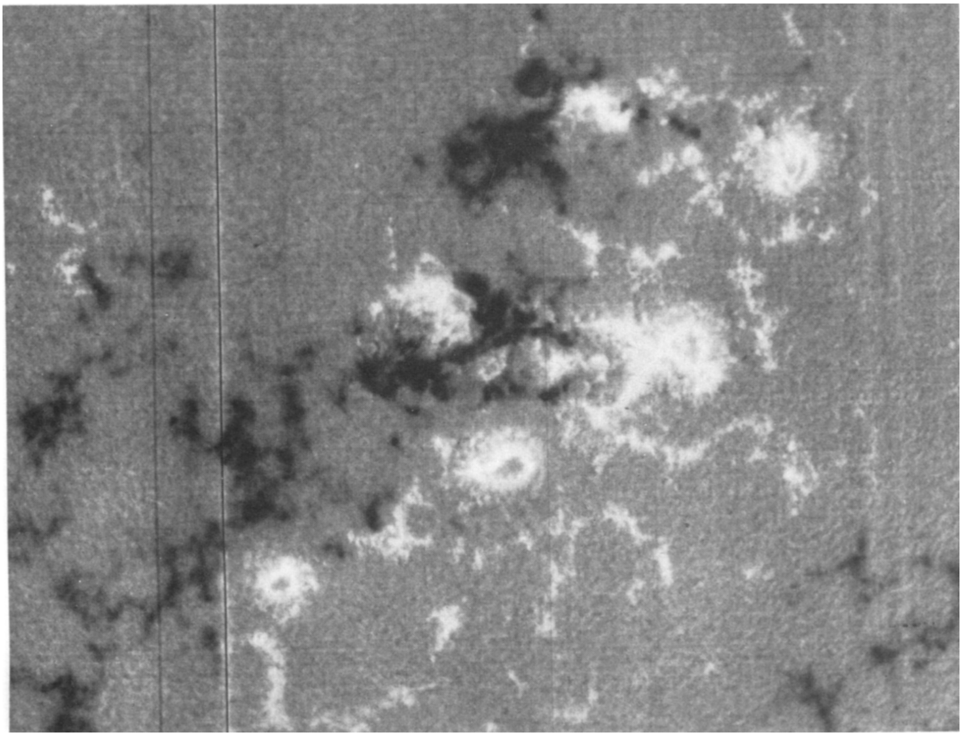

Fig. 2. Magnetic fields associated with McMath Region 10542 are depicted in this subtracted Zeeman spectroheliogram taken in the 6102.7 Å line of Ca I at 1735 UT on 1970, January, 26. White features are positive or north magnetic polarity, the normal polarity of the leading members of this southern group of sunspots. North is up and west is to the right. The height of the spectroheliogram corresponds to 237000 km on the Sun. 'Moats' are conspicuous around the four prominent leading sunspots, and the small magnetic features in these moats are MMF's. Typical 'wreaths' partially surround the two sunspots at the right. The moat around the sunspot at the lower left produces an indentation or 'bay' in the black polarity network adjacent to it. (D. Vrabec, Aerospace San Fernando Observatory.)

By the time bay and wreath forms have developed (Figure 2), the moat around the sunspot has become relatively cleared of magnetic fields with the exception of small fragments of each polarity distributed throughout it (Figure 3). In fact, on low-resolution magnetograms, the moat will appear almost field-free. However, it is these small fragments of field, typically less than 1500 km in size and always located within the moat, that exhibit the interesting property of outflow. These are the MMF's that reveal to us the underlying phenomenon of MFO, namely, the direct transfer of magnetic fields from the sunspot to its surroundings.

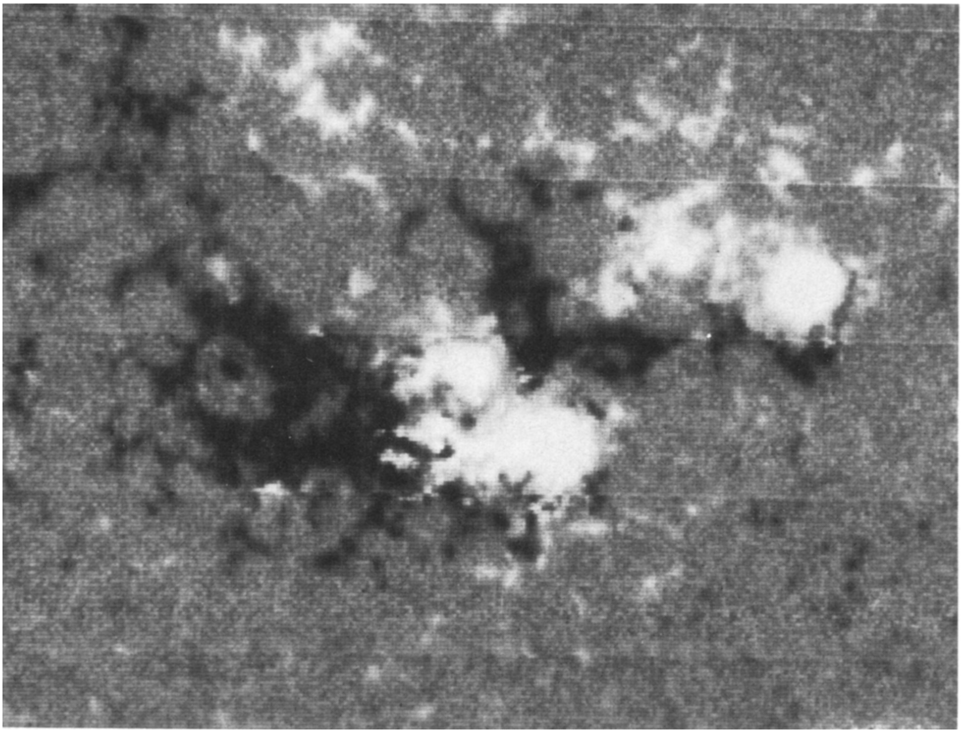

Fig. 3. A conspicuous moat surrounds the black polarity sunspot at the left in this magnetogram taken on 1971, July 2, with the 40-channel photoelectric magnetograph. Note the many small MMF's of both polarities occupying the moat. The height of each horizontal swath produced by the magnetograph probe is roughly 100″. (Courtesy K. Harvey and J. Harvey, Kitt Peak National Observatory.)

From observations of the paths of these outflowing MMF's on time-lapse movies, it is evident that a highly ordered pattern of outward, radial movement from the sunspot occurs throughout the entire area occupied by the moat. Near the outer boundary of the moat, this ordered movement quite abruptly becomes ill-defined. Any magnetic fields at or beyond this boundary appear to remain essentially stationary, undergoing only natural evolutionary change unrelated to the outflow. Thus, these fields appear to be effectively isolated from the dynamic activity occurring immediately inside the moat.

During the declining phase of MFO development, we can anticipate a weakening of the outflow of MMF's accompanied by increased disordering of the characteristic bay and wreath forms in the surrounding magnetic fields as supergranulation encroaches into the moat. According to recent observations by Harvey (1973), termination of MFO can also occur abruptly.

2.2. OUTFLOWING VELOCITY FIELD

Thus far, I have described outflow only as the pattern of organized movement traced out by the proper motions of individual CN bright points or MMF's. However, these motions are so suggestive of the horizontal outflow of material envisioned to occur in a single supergranule cell that Sheeley (1969) interpreted the proper motions of the CN bright points he observed as evidence of horizontal outflow of photospheric material, in the form of a single supergranule centered on the sunspot. If the magnetic fields are indeed 'frozen' in the photospheric material and this material undergoes an ordered flow, then MMF's will appear, and their movements can be assumed to map the streamlines of this velocity field. The moat thus assumes the physical aspect of a single, outwelling velocity cell centered about the sunspot. As noted by Vrabec (1971), stable magnetic fields do not persist within moats. This is additional evidence of a velocity field similar to that in supergranules. Any magnetic field within the moat would be systematically transported with the material out to the boundary, so it would only be at and beyond this boundary that the fields could accumulate.

The evolution of MFO would thus be directly related to the evolution of a velocity cell around a sunspot, which must in turn be related to the development of the sunspot. The observed evolutionary changes in magnetic field morphology around the sunspot just described would to a large extent initially result from the action of this incipient velocity field on magnetic fields adjacent to the sunspot, forming the moat and bays. Subsequently, and to a progressively increasing extent, they would also be altered by the transfer of significant amounts of magnetic field from the sunspot to its surroundings.

Harvey and Harvey have suggested that a necessary condition for the occurrence of MMF's is that the sunspot be at least partially surrounded by a moat since they never observed MMF's around decaying sunspots without a moat. I believe that MMF's must accompany the formation of the moat, but it is likely that, at this incipient stage of MFO, their motions may be too slow and weakly ordered for them to be detected with the magnetograph. Hence, it is reasonable to assume that only when the velocity field has developed sufficiently to have formed definite signs of a moat would MFO be built up to a strength where MMF's are conspicuous.

The following dynamic properties of MMF's are among many described by Harvey and Harvey. MMF's exhibit a distribution of outflow speeds ranging from a few tenths to over 2 km s^{-1}. The speed of any single MMF remains essentially constant over most of its lifetime. There appears to be some indication of fast-moving channels imbedded in the main outflow field. There are no conspicuous differences between the dynamical behavior of MMF's of the same and of opposite polarity as the parent sunspot.

On Aerospace movies, this diversity of speeds is also evident, where many instances of faster moving, small MMF's overtaking slower moving, larger collections of magnetic field are seen as well as indications of high-speed streams. The MMF's exhibiting the highest speeds appear to be interlopers. In addition, the Aerospace movies show a clear example of a circulating eddy near the outer boundary of a moat and the occasional formation of a small network cell within a moat.

If these motions are actually due to an outflow of photospheric material, this outflow should be observable on Doppler spectroheliograms of sunspots located near the limb. Such spectroheliograms are known to show clearly the slower horizontal material outflow in supergranules which are typically only 0.5 km s^{-1} (Leighton *et al.*, 1962), or one-half the average speed of MMF's. Using a technique that eliminated velocity structure due to the 5-min oscillatory component (Sheeley and Bhatnagar, 1971a), these same investigators (1971b) obtained Doppler spectroheliograms showing definite, qualitative evidence of a long-lived, horizontal, photospheric outflow extending as far as 10000 km beyond the outer edge of the penumbrae of three sunspots located near the limb. The most conspicuous velocity features were the Evershed outflow in the penumbrae of these sunspots. One sunspot exhibited many spoke-like extensions of Evershed outflow beyond the average position of the outer edge of the penumbra. These velocity 'spokes' coincided with dark structures visible in the average (summed) wing intensity spectroheliograms, causing the outer edge of the penumbra to have a pronounced ragged structure. One exceptional spoke extended 12000 km beyond the average outer penumbral border and may correspond to the high-speed channels referred to previously. Sheeley (1972) subsequently verified extrapenumbral outflow in six sunspots to a maximum distance of 19000 km and with speeds ranging from 0.4 to 0.8 km s^{-1}. He emphasized that this flow was clearly distinguishable from the much faster and more highly structured Evershed outflow, but on the other hand, very similar to the surface currents of a supergranule, suggesting that the sunspot was roughly centered in one. These Doppler observations strongly suggest that outflow of photospheric material accompanies the observed MFO. It is exceedingly important that this be put to the definitive test of whether both MFO and Doppler outflow occur together in the same sunspot and undergo related development. This will be extremely difficult to accomplish because MMF's are very difficult to observe toward the limb, which is where the observations will have to be made in order to detect the weak Doppler signals produced by the horizontal outflow and also because of the need for synoptic data. Notwithstanding these unresolved questions, it does now seem highly probable that what we observe and call MFO is indeed an outward convection of magnetic flux by a very large velocity cell centered on the sunspot.

2.3. PROPERTIES OF THE MMF'S

2.3.1. *Size*

MMF's appear in a wide range of sizes though they are most frequently $<2''$ (i.e., <1500 km) in extent. Thus, even on good magnetograms of $2.5''$ resolution, most are scarcely discernible, and it is only when time sequences of these magnetograms are converted into time-lapse movies, which average out seeing variations, that it is possible to prove from their persistence that some of these threshold features are real. These movies also reveal otherwise undetectable outflow, perceptible only by an unmistakable ordered movement of unresolved structure on the screen. On the very best magnetograms, which approach 1″ resolution, individual magnetic features appear around sunspots in increasing numbers as their sizes approach the limit of resolution. Beckers and Schröter (1968) carefully analyzed spectra showing 'magnetic knots' in the vicinity of a sunspot, and concluded that their average diameter was 1.3″. It is evident from the fact that these magnetic knots were distributed throughout the entire active region that many of them do not correspond to MMF's, since the latter are confined to moats. However, those magnetic knots that were located in close proximity to the sunspot almost certainly are MMF's. Simon and Zirker (1973), also using spectra, were unable to find magnetic field entities smaller than 1.5″ though their spatial resolution exceeded 0.75″. On the other hand, on CN spectroheliograms, the bright photospheric network characteristically exhibits a more 'point-like' structure than does the corresponding (i.e., co-spatial) magnetic network recorded on Zeeman spectroheliograms taken with the same instrument under similar conditions of seeing. Some CN bright points adjacent to sunspots appear to be less than 1″ in size. Harvey *et al.* (1972) have analyzed observations made with a line-profile Stokesmeter equipped with a 2.5 × 2.5″ probe, using a two-component model atmosphere to interpret their data. Their conclusion is that 0.6″ is the characteristic size of non-sunspot magnetic field fine structure. Thus, it is not presently clear whether the observational lower limit of 1 to 1.5″ for the size of the smallest magnetic field structures is a consequence of instrumental convolution combined with seeing degradation, or whether it is an intrinsic property of magnetic fields to fringe beyond the more compact boundaries of the bright, facular features.

Magnetic features in excess of 5″ are sometimes involved in MFO. Many of these large fragments of field first appear a few thousand kilometers beyond the outer edge of the sunspot penumbra, and then move outward. Some of the MMF's that appear in this fashion are of opposite polarity to the associated sunspot and are possibly remnants of the fields occupying the same region before development of the sunspot, which lay hidden below the photosphere. Invariably, if the resolution permits, these larger fragments exhibit a fine structure which suggests that they are collections of smaller magnetic entities. In general, these larger components of MFO move conspicuously more slowly than the average speed of MMF's, and are frequently overtaken by smaller, faster moving MMF's. Frequently, they appear in the form of extended arcs centered on the sunspot. On lower-resolution magnetic movies, barely discernible wavelike features sometimes appear to emanate from the sunspots. Whether these 'waves' are intrinsic or simply the extended arcs forming in the moats has not been determined.

2.3.2. *Magnetic Field Strength*

The only direct measurements of magnetic field strengths in features positively identified as MMF's are those made by Harvey and Harvey. They found the strongest *measured* longitudinal field to be 300 G, but this unquestionably underestimates the true field strength because of the limited spatial resolution of the magnetograph. They also believe that the fields are primarily vertically oriented with respect to the photosphere since they were unable to detect MMF's around sunspots near the limb. Beckers and Schröter (1968) measured longitudinal magnetic field strengths between 250 and 400 G in the magnetic knots they found scattered around a sunspot located near the center of the disk, and calculated, after corrections for scattered light and inclination of the field lines, field strengths up to 1400 G. As previously noted, some of these features were very likely MMF's.

Recently, Simon and Zirker (1973) measured maximum magnetic field strengths up to 1300 G at the roots of spicules and fibrils in both quiet and active regions of the Sun. The applicability of these related measurements to MMF's remains to be determined.

Clearly, quantitative measurements of magnetic fields in MMF's are both meager and extremely difficult, but it is upon these measurements that the very important determinations of magnetic flux of MMF's are based. Thus, there is a great need for more measurements of the maximum magnetic field strengths in MMF's as well as the distribution of field strengths and the inclinations of the field lines. The fact that the measured strength of a magnetic feature on the Sun is affected by the spatial resolution of the observations as determined by the instrument, by seeing conditions, and by any changes in the profile of the line used for the measurement resulting from differences in physical conditions existing within and external to the magnetic regions is, of course, what makes these measurements so difficult to obtain. The limitations on measuring the transverse magnetic field components are also well known.

2.3.3. *Magnetic Flux*

Harvey and Harvey measured the magnetic fluxes of 34 MMF's of each magnetic polarity. The resulting two histograms are remarkably similar, the fluxes per MMF ranging between 6×10^{17} and 8×10^{19} Mx (G cm^2). The average magnetic flux of an MMF was found to be about 10^{19} Mx, independent of the magnetic polarity. This large range of measured fluxes no doubt reflects the tendency for small magnetic field entities to become clumped together in various numbers, forming a hierarchy of sizes of features that collectively are the MMF's that were observed and measured. On closer examination, these histograms seem to indicate a minimum flux per MMF of about 2×10^{18} Mx if we neglect features whose fluxes are at the indicated noise level of the measurements, a value about three times smaller.

Let us independently calculate the magnetic flux of an MMF whose diameter is the previously noted value of 1.3″ and whose average vertical field component is 400 G. The flux of this idealized MMF is 3×10^{18} Mx. Clearly, this value is subject to considerable uncertainty. For example, an assumed vertical field component of 1400 G would increase this to 10^{19} Mx, the average value obtained by Harvey and Harvey. Later we will use the smaller of these values to estimate the total magnetic flux of MMF's in the moat around a single sunspot.

2.3.4. *Lifetime*

Lifetimes of MMF's are very hard to determine because MMF's are difficult to observe with ground-based instruments and their evolutionary histories and morphological properties are complex. As previously noted, MMF's appear and disappear in the moat in transit, and also merge with one another. Thus, it is extremely difficult to identify a particular MMF when it first makes its appearance near the sunspot, and then to follow it throughout its subsequent history.

From magnetic movies it is obvious that MMF's exhibit a wide range of lifetimes. Some last less than 1 h while the slower-moving, large fragments tend to persist for at least 6 to 8 h, corresponding to the longest intervals of continuous observation of MFO obtained to date. I find that only a small fraction of the total number of MMF's that can be individually seen on the best magnetic field movies obtained at Aerospace persist long enough to complete their transit across a typical moat. This apparently conflicts with the findings of Harvey and Harvey who note that most MMF's persist long enough to reach the network fields at the boundary of the moat. Since the Harveys worked with lower resolution data, it is likely that this discrepancy can be attributed to a bias resulting from their having measured lifetimes of only the largest MMF's, which according to the Aerospace movies, tend also to be the longest-lived. The best time-lapse movies show these largest magnetic fragments to be eroding away at their edges, apparently by the action of the outflowing velocity field. Small pieces appear to be swept away by the faster-moving outflow while, along their trailing side, overtaking MMF's continually merge with them.

At the other extreme, the smallest MMF's tend to be the least persistent. This is very likely an intrinsic property, but it may be partly an observational effect since their visibility depends entirely upon the instantaneous quality of the seeing. In fact, there is always a background of ephemeral, unresolved threshold magnetic features that collectively exhibit MFO as well as the most rapid apparent changes.

Provided one bears in mind the complexity and disparity of the behavior of MMF's, a characteristic lifetime between 2 to 3 h may be assumed, but this should not be taken too literally. Thus, in addition to their systematic outflow, a very distinctive characteristic of MMF's associated with MFO is their continual and generally rapid change as is evident in Figure 4.

2.3.5. *Morphology*

The most distinguishing characteristic of MMF's is their organized motion. However, even if we disregard their dynamic and evolutionary properties, MMF's can be distinguished from all other non-sunspot magnetic fields on the basis of their unique morphology. The basic characteristics of this morphology are: (a) a high degree of fragmentation and reduction of the fields into small-size entities; and (b) the intimate mixing of features of both polarities on a fine scale, producing the effect of 'salt-and-pepper' on magnetograms as shown in Figure 5 (Vrabec and Janssens, 1972).

When we carefully examine the fine structure of the two-dimensional spatial distribution of non-sunspot magnetic fields recorded on high-resolution magnetograms,

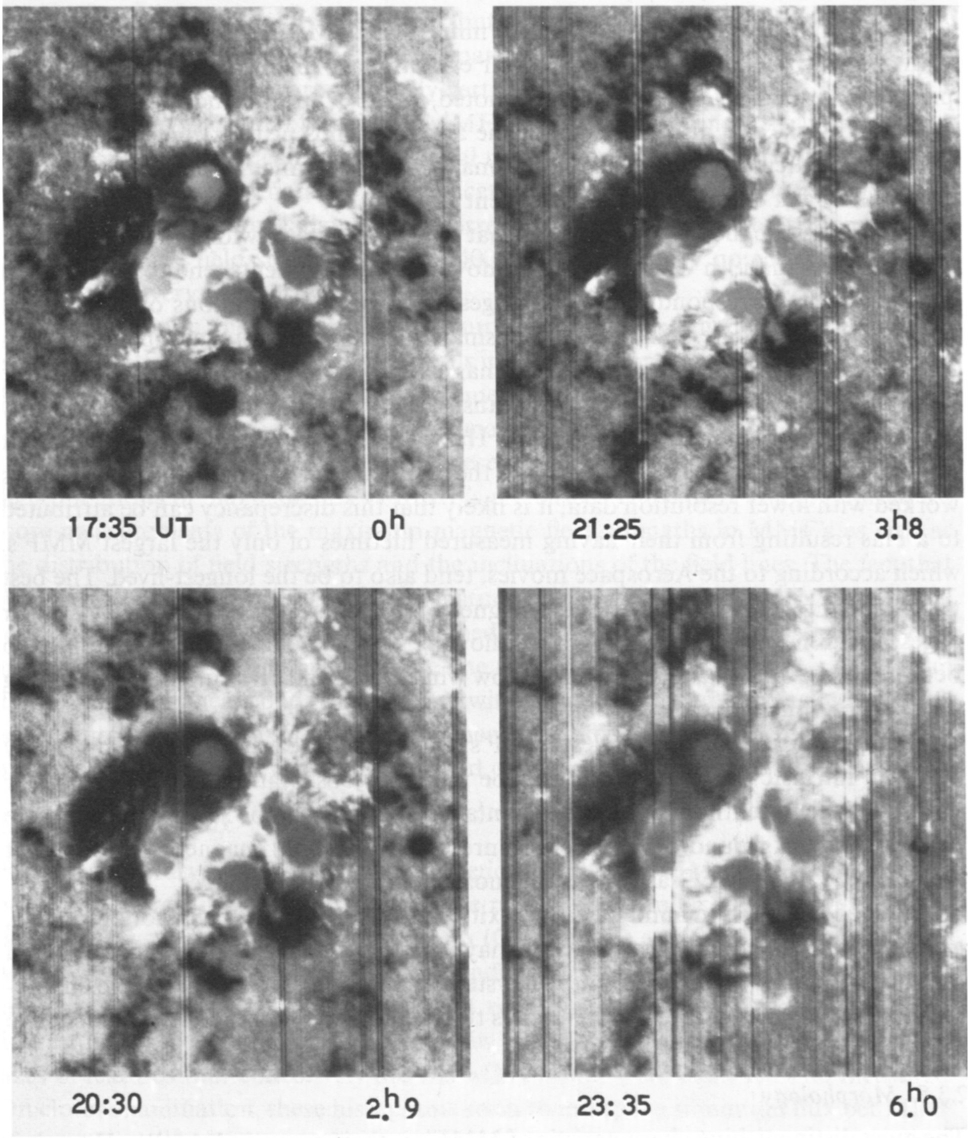

Fig. 4. This sequence of subtracted Zeeman spectroheliograms depicting magnetic fields of McMath Region 11976 was taken on 1972, August 5. The changes occurring in the magnetic fields just outside the sunspot are associated with well-developed magnetic flux outflow in progress during the observations. This MFO is much better seen in the time-lapse movie referenced in the text. (Courtesy G. Chapman, Aerospace San Fernando Observatory.)

we see that this structure is ultimately formed from small magnetic field concentrations of various sizes, most of which are at the limit of resolution (i.e., 1″). Outside of these resolved concentrations, the photospheric surface appears to be essentially field free. Within these concentrations the magnetic field strengths are high, probably of the order of many hundreds to over a thousand Gauss (Sheeley, 1967; Livingston and Harvey, 1969; Harvey *et al.*, 1972; Simon and Zirker, 1973). There is now considerable evidence for magnetic fine structure beyond the limit of resolution of magnetographic instruments operating under the best seeing conditions (Harvey *et al.*, 1972; Howard and Stenflo, 1972; Frazier and Stenflo, 1972). Hence, these instruments directly record the *average* magnetic field strength (not the true field strength) over the effective resolution element projected upon the photosphere, or more correctly, upon the level of line formation. This quantity is the magnetic flux threading the resolution element. Consequently, magnetograms are records of the surface distribution of magnetic

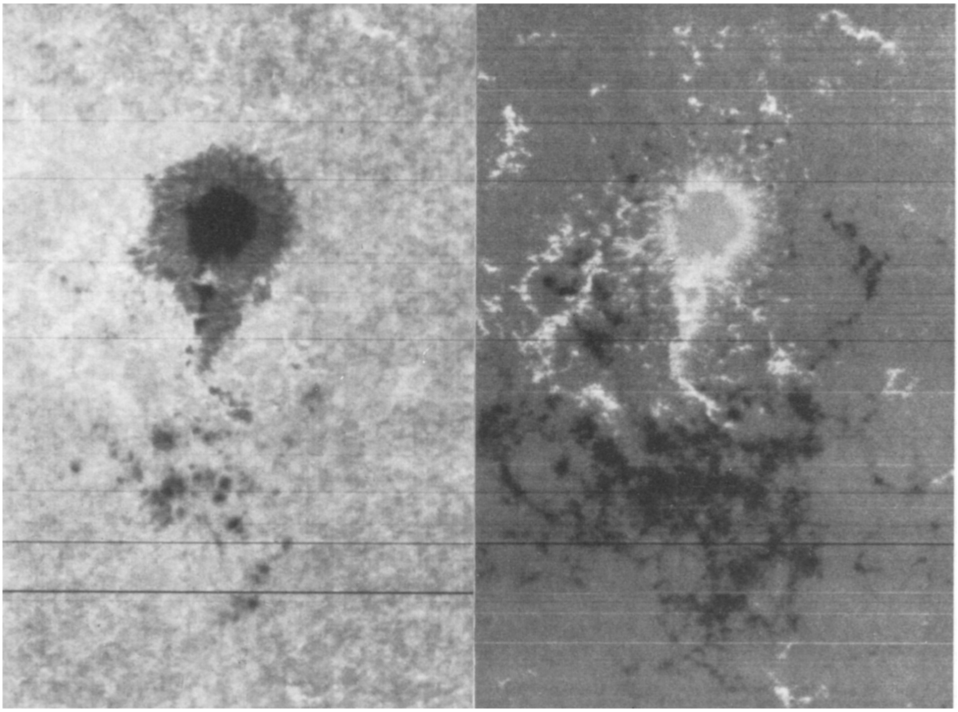

Fig. 5. The subtracted Zeeman spectroheliogram (right-hand photograph) of magnetic fields associated with the sunspot in the left-hand photograph illustrates the fine structure and mixing of both polarities on a fine scale that is a unique characteristic of MMF's. These are seen immediately surrounding the radially oriented, elongated magnetic structures corresponding primarily to the middle portion of the penumbra of the sunspot. The sunspot's underexposed umbra is featureless in this magnetogram taken at 1843 UT on 1971, January 9. (Top is west, left is north.) (D. Vrabec and T. Janssens, Aerospace San Fernando Observatory.)

flux, and the small entities that are just resolved on them correspond to the cross-sectional intercepts with this surface that contain the measured flux. When describing the fine structure recorded on magnetograms, it is necessary to refer to these small concentrations of magnetic flux. I shall therefore call these small-size magnetic field entities 'fluxules,' which emphasizes the fact that magnetic flux rather than magnetic field strength is the physical quantity actually recorded. (Other terms are, of course, more appropriate when referring to the true three-dimensional filamentary structure of the fields not depicted on magnetograms.)

Fluxules clump together in various numbers and with varying degrees of compactness to form different-size aggregates, which in turn collect in a similar manner into larger complexes that comprise the network and active region fields. This results in a clustering hierarchy which probably continues well below the limit of resolution. If this proves to be true, then the smallest fluxules we presently observe are likely to be similarly structured.

In contrast to those observed everywhere else on the Sun, the fluxules occurring within the moats show little tendency to group together to form larger magnetic features. Instead, they exist more or less as individual and independent entities, which we now know are MMF's. Thus, MMF's tend to represent the simplest and most elementary magnetic field structures found anywhere on the Sun's surface. Could this be evidence that the magnetic fields in sunspots are already inhomogeneously distributed, and are gathered into spaghetti-like strands that are swept up by the outflowing velocity field? Presumably, within the moat, the diverging property of the outflow would not favor their collecting into larger associations.

A marked characteristic of magnetic fields in both the active regions and quiet network is that the two polarities occur separated to a high degree. Invariably, we observe large regions of one or the other polarity exclusively, which typically occupy the boundaries of many contiguous supergranules. It is only in the moats around sunspots that we observe the unique distribution of roughly equal numbers of separately identifiable fluxules of both polarities intimately mixed together on a fine scale, which are MMF's.

Notwithstanding these morphological distinctions, MMF's exhibit one remarkable property in common with all other non-sunspot photospheric fields; namely, the fluxules that make up the MMF's are virtually indistinguishable from those that comprise the fine structure components of the fields in general, wherever else they occur outside of sunspots. In other words, magnetic fields imbedded in the photospheric plasma exhibit a propensity to become concentrated into fine flux threads. Apparently this is true all over the Sun, at least wherever the fine structure of the fields is directly observable, which for the time being excludes sunspots. Also, the morphology of this fine structure exhibits a remarkable stationarity in time, evidenced by the similarity between the fluxules that make up MMF's, where the surface fields are just starting their existence outside of sunspots, and those that make up the quiet network fields, which we presume are old remnants of former sunspots. What agency can act upon these diverse fields in a common way to produce and maintain such globally uniform fine structure, and on a sufficiently short time scale to impress its effect upon MMF's when they first appear in the moats? In my opinion, this must be the normal granulation, which has just the necessary spatial, temporal, and dynamic properties. The effect of granulation velocity cells upon the fields can be readily pictured by drawing an analogy with the familiar action of supergranulation on fields to form the large-scale network, applying, of course, the appropriate transformation of length and time scales (Harvey, 1971). The magnetic fields near and including a sunspot are shown in Figure 6. Let us assume, however, that we have at our disposal a 'supermagnetograph' and, instead of a regular sunspot, imagine it to be a very small pore. I expect that the magnetic field fine structure would appear to be distributed in a network pattern very similar to the fields in this picture, cospatial with the intergranular regions, where now the dimensions of these network cells correspond to the sizes of ordinary granules. This network, with its granulation-size cells, would be reshuffled on a time scale of the lifetime of the granulation. Only the most extended areas of field such as those occurring at the cell vertices might be expected to persist over several granulation lifetimes. These may be the fluxules that we are presently barely able to resolve with magnetographs, and which exhibit the wide range of lifetimes and ephemeral characteristics of MMF's and Sheeley's CN bright points. Some evidence of field-free, open

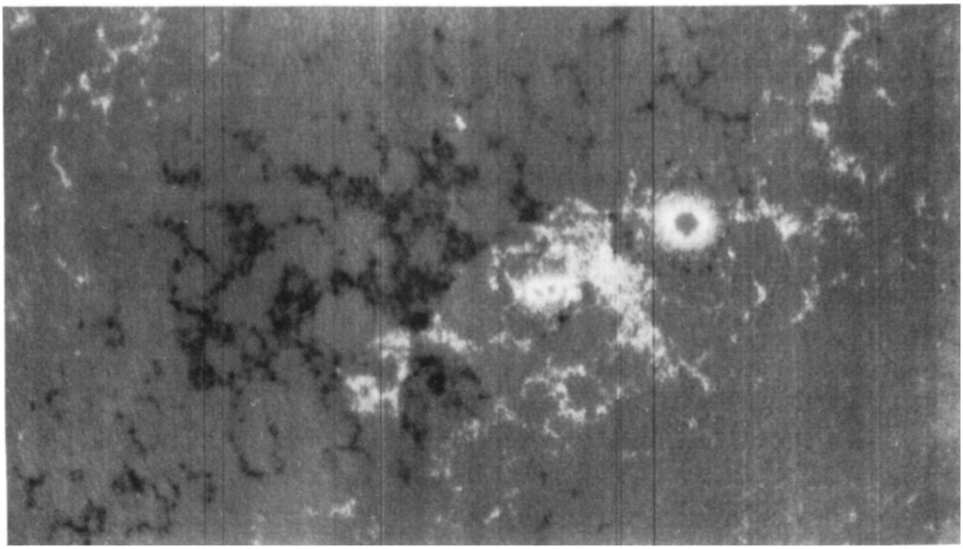

Fig. 6. This subtracted Zeeman spectroheliogram depicting the magnetic fields of McMath Region 10584 (return of McMath Region 10542 shown in Figure 2) was taken at 1915 UT on 1970, February 21. The tendency of network fields to be exclusively of one magnetic polarity over large areas occupying the boundaries of many contiguous supergranule cells is evident. (See text for the suggested analogy drawn between this magnetogram and the fine structure of solar magnetic fields.) (D. Vrabec, Aerospace San Fernando Observatory.)

cell structure presumably corresponding to the largest granules can be discerned on high-resolution magnetograms such as Figure 6.

2.3.6. *Trajectories*

The time-lapse magnetic field movie made from the Aerospace spectroheliograms taken by Chapman (1973) of McMath Region 11976 on 1972, August 5, is so far the only one with sufficient resolution to enable the outflow trajectories of individual MMF's to be studied. Just before leaving for this meeting, I plotted the paths of over 75 individual MMF's distributed around this complex sunspot group. In each case the path of the feature was traced for the entire length of time it could be identified. Several excellent photographs of this group taken on the same day (Bumba and Suda, 1973; Zirin and Tanaka, 1973) were then examined to determine the orientations of the penumbral filaments, which were found to be very complicated (Pfister, 1973). For example, in some places the filaments are highly inclined with respect to a radius drawn from the associated sunspot umbra, and in others their orientations abruptly change.

A comparison between the MMF trajectories and the penumbral filaments revealed the interesting fact that the trajectories appear to match the orientations and even, in many places, the sign of the curvatures of the penumbral filaments when they were projected out into the moat beyond the points where they actually terminated. This strongly suggests that, at this advanced stage of development of a sunspot, the Evershed outflow in the region of the sunspot penumbra is very closely related to the outflow of photospheric material throughout the entire moat surrounding the sunspot, despite the apparently very real difference in speeds of the two phenomena found by Sheeley and Bhatnagar (1971b) and Sheeley (1972).

2.4. MAGNETIC FLUX TRANSFER

The systematic outflow of large numbers of magnetic field concentrations across the moats surrounding sunspots represents a cumulative horizontal transfer of magnetic flux easily shown to be comparable to the flux of the sunspot itself and of the entire active region associated with it. If we assume the previously estimated value of 3×10^{18} Mx to be the flux $\phi_{+,-}$ of an MMF just resolved on the best spectroheliograms, the total magnetic flux $\phi_T = \sum \phi_+ + |\sum \phi_-|$ of the 50 to 200 MMF's typically seen in the moat around a sunspot is 1.5×10^{20} to 6×10^{20} Mx. In approximately 4 h, which is the time an MMF takes to move across a typical 15000-km wide moat, all this flux is replenished, so the corresponding rate of magnetic flux transfer by MMF's is 4×10^{19} to 1.5×10^{20} Mx h^{-1}. At this rate, in 4 days a total flux $\phi_T\,(t = 4d) = 4 \times 10^{21}$ to $1.5 \times$ $\times\, 10^{22}$ Mx has crossed the moat, compared with 10^{21} to 10^{22} Mx, which is considered to be representative of the fluxes of individual sunspots and also of active regions. The actual total flux transferred is probably significantly higher than this estimate, because the signals of unresolved MMF's of opposite polarities will tend to average out to produce no observable flux, and because 4 days is probably an underestimate of the duration of typical MFO.

In order to test the validity of the concept that MFO is the agency by which the magnetic field of a decaying sunspot is transferred into the surrounding magnetic field network, as originally suggested by Simon and Leighton (1964), it is necessary to measure separately: (a) the rate of decrease of flux in the sunspot; (b) the rate of outward transfer across the moat of net flux by MMF's of mixed polarity; and (c) the rate of increase of net flux in the active region magnetic network external to the moat. If this concept is valid, all three of these rates should be equal throughout the duration of MFO. Clearly, these three critically important flux measurements are exceedingly difficult to make. Consider, for example, the measurement of (b). Whether we base our determinations of magnetic flux on counts of individual MMF's or, more accurately, on actual magnetograph measurements, it is quite common to find that the flux involved in MFO is roughly equally distributed between MMF's of positive and those of negative polarity. Since $\sum \phi_+ \approx |\sum \phi_-|$, the net flux transferred $\phi_N = \sum \phi_+ - |\sum \phi_-|$, being the difference of two nearly equal quantities, is only a small fraction of their sum, which is the total flux transferred. The measurement of this net transferred flux is, therefore, very sensitive to errors made in determining the total transferred fluxes of each polarity separately. In many instances, uncertainties in the observations make it difficult to determine even the polarity of the net flux transferred, which is, of course, a very vital piece of information.

In the light of these considerations, a comparison of actual measurements reported by Harvey and Harvey with these estimated values is very interesting. In the case of two sunspots, it proved possible to measure the fluxes of MMF's crossing a boundary established within the moats at a fixed distance from the sunspots. Harvey and Harvey found values for the rate of transfer of total flux $|\dot{\phi}_T| = 3 \times 10^{19}$ to 10^{20} Mx h^{-1} and for the rate of transfer of net flux $|\dot{\phi}_N| = 10^{19}$ Mx h^{-1}, the latter being of the *same polarity* as the associated sunspot. Moreover, they estimated the rate of decrease of the magnetic flux of each of these sunspots by calculating the total flux of the sunspots from measurements of their maximum magnetic field strengths and their areas (see Tandberg-Hanssen, 1967). The decay rate of sunspot magnetic flux was also found to be 10^{19} Mx h^{-1}. This value was further substantiated by the later observation of the dates of final dissolution of these two sunspots. In both cases these dates were in agreement with the dates extrapolated on the basis of the measured rate of net magnetic flux transfer by MMF's (Harvey, 1973). Thus, for these two sunspots, Harvey and Harvey were able to verify the equality of (a) and (b) above; namely, that at the times they made their observations, the rate of loss of flux in each of these sunspots was equal to the rate of transfer of net flux by MMF's moving outward across the surrounding moats. Unfortunately, though they attempted the measurement of (c), they were unable to obtain definitive results.

These important and difficult observations made by Harvey and Harvey add considerable weight to the hypothesis that MFO is the primary process by which sunspots decay. It would, however, be a serious mistake to assume too much on the basis of the presently limited data. Actual observations indicate that MFO is a considerably more complicated process than the idealized one of piecemeal fragmentation of a sunspot into MMF's that are convected away by the velocity field surrounding them. We have simply to note the conspicuous occurrence of MMF's of both polarities in virtually all observed examples of MFO. Many MMF's disappear during their transit through the moat, while others of either polarity first appear not at the outer edge of the sunspot penumbra but, rather, at some distance in the moat from it. This greatly complicates any attempt to measure the magnetic flux transferred out of sunspots by MMF's. Also, all observers have encountered difficulty in keeping track of individual MMF's after they have reached the outer boundary and have merged into the magnetic structure already present there. Virtually nothing is known about the interactions that take place between MMF's of opposite and of the same polarity. In addition, it is not yet clear whether MFO plays as important a role in the dissolution of following sunspots as it appears to for preceding ones. It is interesting to note that in the case of the magnetically complex sunspot group observed on 1972, August 5, where both preceding and following polarity members were compactly grouped together in an unusual polarity configuration, the MFO was overwhelmingly dominated by MMF's of following polarity, which is an exception to the previously noted fact that MMF's tend to occur in roughly equal numbers of each polarity. Clearly, very much more quantitative, as well as synoptic data must be obtained on MFO before its effects can be considered really well-established and its basic nature understood.

3. Magnetic Flux Inflow

Magnetic flux inflow (MFI) is a dynamic, sunspot-associated phenomenon manifested by moving magnetic features that stream toward the sunspot along paths converging upon it. In contrast to MFO, many of the MMF's involved in MFI, but not all, are pores easily observed in integrated light. Some of the MMF's, including pores, move directly into the umbra of the sunspot and coalesce with it. It is almost a certainty that MFI is associated with the growth phase of sunspot development and with the emergence of new magnetic flux at the photospheric surface.

In some respects, there is little new about what I have elected to classify as MFI, since it is well known that in many cases the growth of a sunspot may involve the coalescence of smaller sunspots and pores in the manner just described (McIntosh, 1967 and 1969). However, it is important to recognize the distinction between the MMF's associated with this form of activity and those involved in MFO. Also, I wish to call attention to some dynamic and morphological features of MFI that are certainly relevant to the underlying processes involved in sunspot formation and growth.

I will illustrate MFI with a set of observations made on 1970, January 26, of McMath Region 10542, which contained four major southern hemisphere sunspot groups. These data consist of time-lapse movies of the magnetic fields, produced from Zeeman spectroheliograms, and time-lapse movies of the region in various wavelengths within the profile of Hα, exposed through a birefringent filter which was cyclically tuned during the 6-h observation interval. This combination of concurrent magnetic field and wavelength-tuned Hα data in the form of time-lapse movies has proven to be very effective. The latter permit the full spatial extent of Doppler-shifted features to be traced, provided they fall within the wavelength interval scanned.

Two examples of MFI were noted by Vrabec (1971) to occur in one of the sunspot groups classified $\beta\gamma$. (See Figure 7.) The sunspots comprising this group developed rapidly during the preceding two days, especially the dominant leading member of north magnetic polarity seen at the right in Figure 7. During the observations, the most rapid growth took place in a newly forming bipolar sunspot pair in the following portion of the group, seen in the upper left of Figure 7. The leader of this bipolar pair emerged at the following edge of some small south polarity sunspots probably paired with the leading sunspot at the right. (The magnetic fields associated with this sunspot group can be seen at the center of Figure 2, which covers most of the active region.)

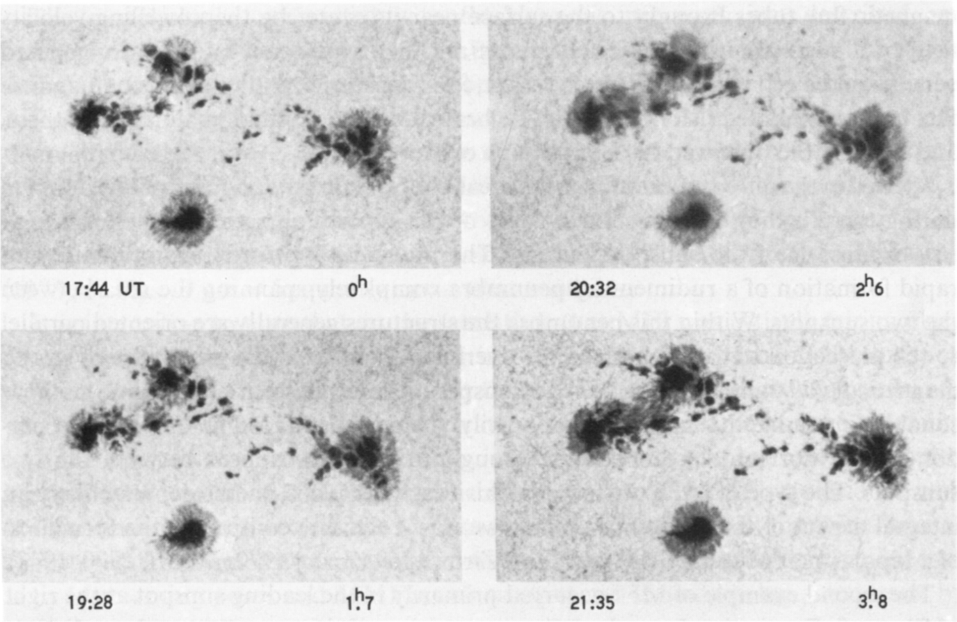

Fig. 7. Magnetic flux inflow is illustrated in this sequence of photographs of sunspots occupying the center of Figure 2. (See Section 3 for description.) (D. Vrabec and W. Mott, Aerospace San Fernando Observatory.)

The Hα filtergrams clearly show that this rapid growth of the new bipolar pair was accompanied by a very conspicuous arch filament system (AFS) (Bruzek, 1967 and 1969) covering the area between the two sunspots. The opposite ends of the arch filaments terminate in magnetic areas of opposite polarity (Vrabec, 1971), in some of which pores formed that were conspicuous on filtergrams exposed approximately +6.5 Å from line center. These filtergrams show only the sunspots, pores, and granulation as they would appear in integrated light.

The magnetic field movie shows a conspicuous instreaming toward each of the two sunspots of MMF's of the same polarity as the sunspot. The paths of these MMF's show marked curvature, corresponding to a pronounced spiral structure somewhat resembling a tilted comma, exhibited by both the umbra and penumbra of the following sunspot. These MMF's exhibit a diversity of horizontal speeds ranging from 0.25 to 1 km s^{-1}. Frazier (1972) has interpreted these oppositely moving, opposite-polarity MMF's to be the photospheric intercepts of the footpoints of arched magnetic flux tubes brought to the surface near its center by the upwelling velocity field of a supergranule. These footpoints are then convected laterally to opposed vertices of the cell where they come to rest, forming sunspots after sufficient magnetic flux has accumulated (McIntosh, 1969). The flux tubes rise, lifting material with them, and become the observed dark structures of the AFS.

Viewed in the off-band Hα movie, the areas of both sunspots approximately doubled during the 6 h they were observed. Most of this growth appeared in the form of *in situ* expansion of the sunspot umbrae. The movie also records the dramatic and rapid formation of a rudimentary penumbra completely spanning the area between the two sunspots. Within this penumbra the structures generally are oriented parallel to the projection of the arch filaments overlying them, providing evidence of strong magnetic fields tightly linking the two sunspots. Under these circumstances, it is reasonable to assume that, at least temporarily, the newly surfaced fields exhibited predominantly horizontal components throughout the photosphere between the two sunspots. The type of MFI observed in this first example is, therefore, very likely an integral aspect of the AFS activity that we now believe accompanies the formation of a bipolar pair of sunspots (Weart and Zirin, 1969; Zirin, 1970; Weart, 1970, 1972).

The second example of MFI occurred primarily in the leading sunspot at the right of Figure 7. Emanating from the following portion of this sunspot are three distinct tail-like chains or aligned strings of pores and small umbrae. The appearance of a three-pronged tail seen in the off-band Hα filtergrams is considerably enhanced in the Zeeman spectroheliogram of the magnetic fields (Figure 2) where the gaps between the pores delineating the prongs are almost continuously filled in with magnetic features. All prong features, including the pores, are of the same north magnetic polarity as the leading sunspot.

MFI is conspicuous in both the magnetic field movie and the off-band Hα movie in the form of highly organized movement localized in these prongs. All MFI is confined to the prongs, and all magnetic features comprising the prongs stream toward the leading sunspot at speeds averaging 0.25 km s^{-1} relative to it. Most noteworthy of the observed characteristics of this second example of MFI is that, within each prong, all instreaming MMF's follow a single path that very nearly coincides with the axis of the prong, producing the effect of threaded beads sliding on a string stretched along this axis.

During the 6-h span of the movie, three conspicuous pores or small umbrae are observed to enter the sunspot, two feeding in from the lower prong and the third from the middle one. A small area of the sunspot penumbra preceding the leading pore and separating it from the following portion of the sunspot umbra, together with a small area of photosphere directly behind it and separating it from the following two pores, moves with the pores into the following portion of the umbra of the main sunspot. In so doing, each of these two confined areas is deformed into a thin light bridge that partitions the umbra of the main sunspot. Both of these light bridges assume a curvature resembling a ‘bow wave’ corresponding to the direction of intrusion.

The morphologies associated with the dynamic processes just described are strikingly similar to those described by Bumba (1965) in a discussion of the forms and evolution of light bridges in sunspots. It is very likely that the forms Bumba described were produced in the same manner, namely, by the intrusion of pores into the main sunspot umbra, a phenomenon that has also been described by McIntosh (1972). Evidence for both this type of MFI and the formation of a similarly curved light bridge can be seen in a sequence of videomagnetograms and continuum filtergrams of a sunspot group discussed by Schoolman (1973). According to McIntosh (1973), strings of pores frequently occur near sunspots.

It is interesting to note that, at the same time that MFI was actively taking place along the three azimuths of the prongs in the following quadrant of the sunspot, well-developed MFO extended uniformly throughout the remaining three quadrants, producing a well-developed moat and wreath. As a consequence, pores were streaming into the sunspot along the outer prongs immediately adjacent to regions occupied by outflowing MMF’s. The latter, as is characteristic of MMF’s associated with MFO, were restricted to features visible only in the magnetic field movie. Thus, at this particular stage of its development, and while magnetic flux was being fed into it by instreaming pores and MMF’s, this sunspot was already being acted upon by the process of MFO by which it would presumably decay.

It should be noted that there also occurred an analogous, but less conspicuous, oppositely directed movement of south polarity features toward the south polarity following member of the new bipolar sunspot pair. All of these magnetic features, including pores and one small sunspot, were similarly organized into an extended linear strand pointed toward this following sunspot. Some of these streaming pores and the small sunspot grew appreciably in area as they approached the following sunspot, evidencing the emergence of new magnetic flux. The observations ended before it could be determined whether or not these streaming features actually entered the following sunspot.

This second example of MFI differs from the first in at least four respects: (a) the MMF’s include a large fraction of conspicuous pores, (b) the loci of these MMF’s and pores are in the form of ‘tails’ or ‘strings’ converging upon the sunspot, (c) MFI is strictly confined to the features comprising these tails or strings, and (d) the motion of MFI toward the sunspot is directed roughly along the axis of these tails or strings. This last characteristic appears to be inconsistent with convective transport of magnetic fields by velocity fields which appears to underly both MFO and the first example of MFI. I am inclined to believe that the explanation should instead be sought in terms of the configuration and dynamics of the subphotospheric magnetic fields of the sunspot.

The two types of MFI just described are schematically illustrated in the upper half of Figure 8. The characteristics of the first example of MFI are consistent with the movement of the magnetic footpoints of upwelling magnetic flux tubes that first appear near the center of a supergranule cell outlined by the dashed lines, and then are transported by the material outflow to the cell boundary where the sunspots also form. A possible explanation for the occurrence of the tails, or aligned strings of pores, characteristic of the second example of MFI is depicted in the second and third diagrams where the magnetic footpoints including pores are shown to be ac-

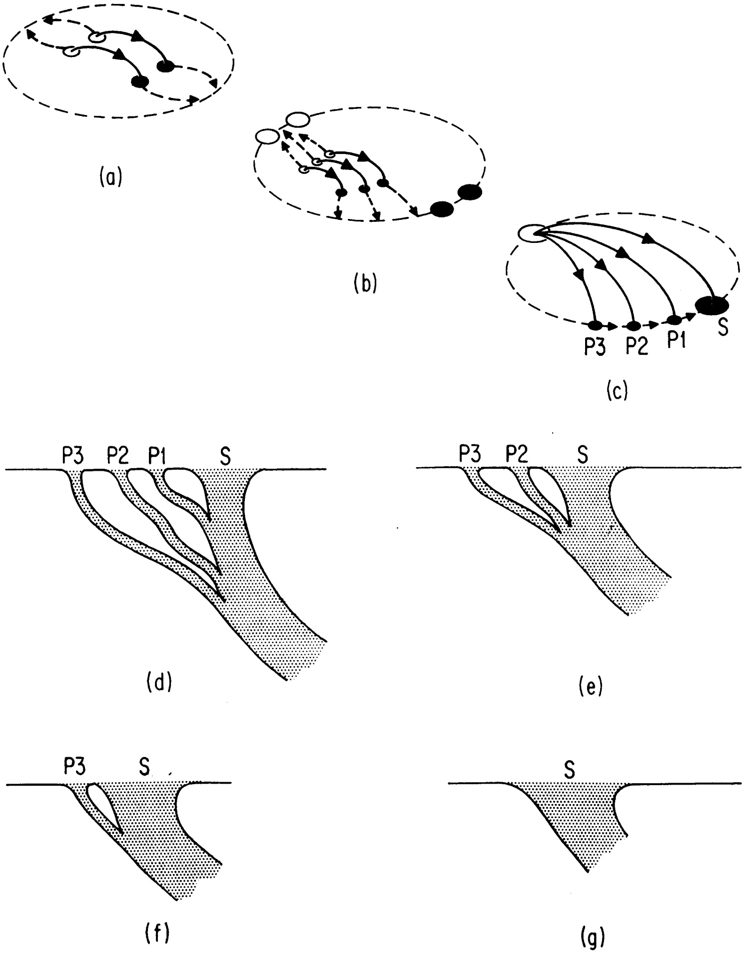

Fig. 8. The two examples of magnetic flux inflow described in Section 3 are shown schematically. In the upper three diagrams, continuous lines denote magnetic field lines, and dashed arrows show the direction of movement of magnetic features. The dashed ellipse delineates the boundary of a supergranule cell. *P* and *S* denote pores and a sunspot, respectively. In the lower four diagrams, the shaded areas represent vertical cross sections of a frayed magnetic flux tube depicted as rising.

cumulating along the same supergranulation cell boundary on which the new sunspots formed. The movement of MMF's and pores into the sunspot along the axis of the 'string' is illustrated in the third diagram. This movement may result from the simple geometry of a rising magnetic flux tube that is frayed just below the photosphere into a number of fine strands that individually produce MMF's and pores where they intercept the photosphere. These strands are assumed to be moved by the material, so they can be transported to the cell boundary to form the observed tails. As schematically illustrated in the remaining four diagrams of Figure 8, if the main flux tube is assumed to rise, the initially separated strands will successively coalesce with the main flux tube when the points at which they join it reach the photospheric surface.

On the basis of these two well-observed examples of magnetic features moving into growing sunspots, we may presume that the same types of MFI accompany the formation and growth of many sunspots. Although we do not know at present what fraction of the total they constitute, it is probable that these two forms of MFI are quite common inasmuch as the first example represents the magnetic aspects of AFS activity generally believed to play a basic role in sunspot formation, and provided we broaden the second example to include the coalescing of small sunspots to form larger ones. It will be interesting to learn what other forms of MFI may occur.

4. Concluding Remarks

Magnetic flux inflow affords us the opportunity to observe directly the surface streamlines of a highly ordered velocity cell in the photosphere and also to observe the convective transport of magnetic fields over the Sun's surface. Because the outflow speed is roughly twice that of a normal supergranule, the moat around a decaying sunspot is an optimum place to repeat Simon's (1966) extremely difficult measurements of a proper motion component of granulation systematically directed toward the boundary of a supergranule cell, as Schmidt has just urged us to do.

The outflow velocity field associated with MFO has been likened by various investigators to supergranulation. I wish to emphasize that we must be very careful to distinguish between the two, since in MFO we are dealing with a velocity cell with unique properties, First, the existence of this velocity field depends upon the presence of a sunspot (presumably, actually upon the magnetic field associated with the sunspot), which completely determines the geometry of the outflow. In contrast, in the case of supergranulation, any magnetic fields present appear to play a passive role. Second, the systematic outward velocities are at least twice as high as those associated with supergranulation. Third, the diameter of a typical moat is roughly twice that of a typical supergranule. Finally, the lifetime of MFO is at least several to tens of days, compared to one day for a supergranule.

The theoretical aspects of MFO and MFI are the subject of the paper by Meyer, Schmidt, Weiss, and Wilson, which will be presented at this Symposium. These investigators have taken care to incorporate much observational data into their theoretical treatment. According to them, magnetic flux is first expelled by supergranule eddies, and is then concentrated by the converging velocity field to form a sunspot. At this point, the concentrated magnetic fields of the sunspot modify the velocity field and, in fact, reverse the direction of circulation, resulting in outflow. The observed slow decay mode of persistent sunspots is explained by turbulent diffusion of flux tubes within the sunspot toward the moat, where they are swept up by the outflow, producing MMF's.

Note: This review concluded with a film that included time-lapse magnetic field movie sequences of MFO occurring in the sunspot groups shown in Figures 2 and 4. In addition, a time-lapse sequence was shown of the sunspot group in Figure 7, illustrating the two examples of MFI described in Section 3.

Acknowledgments

I am indebted to Dr G. Chapman for generously placing his excellent spectroheliograms of 1972, August 5, at my disposal, and to W. Mott who assisted in the observations of MFI. These observations were skillfully converted by R. Maulfair into a time-lapse movie of magnetic fields and MFI, for which J. Paul provided photographic support. Dr P. Wilson provided valuable insight into various theoretical aspects. Karen Harvey, Dr J. Harvey, and Dr N. Sheeley kindly reviewed the manuscript and clarified many points. P. McIntosh contributed detailed information on sunspot growth and development. The preparation of this review was accomplished under The Aerospace Corporation Company-sponsored research. An NSF-USNC-IAU Travel Grant made it possible for me to attend the Solar Symposia in Australia.

Appendix. Observational and Instrumental Aspects

As described by their acronym, MMF's are fundamentally magnetic features that move (and change with time). They are small (typically $<2''$), so the largest can be individually resolved by only a few magnetographs currently in operation, these being of the type designed especially for high-resolution observations. Though MMF's can be observed with excellent resolution as components of the bright photospheric network through a simple filter (Chapman, 1970), such nonmagnetic observations cannot supplant (but may certainly complement) direct magnetic field observations that reveal the polarities of the individual features. Therefore, to observe MMF's, the first basic requirement is a capability for obtaining magnetograms depicting the two-dimensional distribution of photospheric magnetic fields (i.e., of the line-of-sight component) with a resolution of at least $3''$, polarity discrimination, and a magnetic flux sensitivity better than 3×10^{18} Mx. Also, because MMF's are dynamical, evolving entities, it is an essential second requirement to be able to repeat these observations a number of times, spaced over an interval of time long enough for significant changes to be recorded. I would consider three to four such magnetograms spanning 2 h to constitute a minimum requirement for simply detecting MMF's. However, if one intends to study their movements and evolutionary changes, considerably better data are needed. By far the most effective method for both detecting and observing MFO has proven to be the transformation of magnetograms into time-lapse movies (Vrabec, 1971; Sheeley, 1971; Harvey and Harvey, 1972 and 1973; Schoolman, 1972), but these require large numbers of magnetograms and longer time coverage. For example, a recent movie of MFO prepared from observations made by Chapman (1973) with the Aerospace spectroheliograph reveals many interesting details regarding the fine structure, polarities, and patterns of flow of MMF's as well as the manner in which they first appear, subsequently change, interact, or finally disappear. In this instance, a sequence of 92 Zeeman spectroheliograms spanning 7.8 h were obtained on 1972, August 5, of an active sunspot group rich in MMF activity. (See Figure 4.) The resolution ranged from 1.5 to 4″, and the magnetic flux sensitivity was approximately 3×10^{17} Mx. Actually, to study the evolutionary development of MFO, we need observations of this quality repeated over many successive days spanning the development of a sunspot group. Clearly, a major limitation of ground-based efforts is the infrequency of occurrence of sustained good seeing prevailing over extended intervals of time.

To date, it has proven extremely difficult to achieve the resolution of solar magnetic fields adequate to observe MMF's. The instruments used to produce magnetograms are, unfortunately, presently complex and costly, since they must sense or measure the Zeeman effect and transform this information into a pictorial record. Excellent summaries of magnetograph techniques are available for reference (Bray and Loughhead, 1964; Evans, 1966; and Beckers, 1971). With the exception of videomagnetographs (Janssens and Baker, 1971; Smithson and Leighton, 1971), which employ TV cameras and display the magnetic fields in real time, the raw output data of magnetograph systems, whether photoelectric or photographic, must undergo subsequent processing before a 'picture' of the fields is obtained. This has a major impact through the greatly expanded effort required to produce the many individual magnetograms that constitute a single MMF observing record, e.g., a time-lapse movie. To date, the major sources of MMF data have been two spectroheliographs and one photoelectric magnetograph.

The spectroheliographic method of photographing solar magnetic fields was first developed and used by Leighton (1959). Subsequently, MMF's have been observed with the Aerospace spectroheliograph (Vrabec, 1971; Chapman, 1973) and with the Kitt Peak spectroheliograph (Sheeley, 1971). Examples of high-resolution Zeeman spectroheliograms appear in Livingston (1972), Vrabec and Janssens (1972), and Chapman (1972). Because this method involves the photographic subtraction of a pair of spectroheliograms to produce each Zeeman spectroheliogram, a special cine optical-printer facility has been found to be indispensible for producing the magnetic field movies used extensively at Aerospace. When quantitative results are not required, film offers many advantages for recording and storing magnetograms, especially in the large numbers required for making movies.

Currently, the only photoelectric scanning magnetograph capable of resolving MMF's is the 40-channel Kitt Peak magnetograph (Livingston and Harvey, 1971), soon to be supplemented with a 512-channel linear array of diode pairs (Livingston, 1973). Examples of the magnificent results obtained with this instrument can be seen in Harvey (1971), Livingston (1972), and Figure 3. Harvey and Harvey utilized computer-generated movies of solar magnetic fields recorded with the Kitt Peak magnetograph in their investigation of MMF's. These calibrated, digitized magnetograms remain to date the only source of quantitative measurements of the field strengths of MMF's and of the magnetic fluxes involved in MFO. As we have seen, these quantitative data are vital for ascertaining to what degree MFO transfers the magnetic flux of a sunspot into its surroundings. The extraction of quantitative magnetic field measurements from the spectroheliographic data has been impeded by the well-known difficulties encountered in photometrically transforming two-dimensional photographic images, compounded by the large number of images involved, but these are being overcome. In a number of ways, these two basically different instruments complement each other.

In both the spectroheliograph and the photoelectric magnetograph, resolution is degraded by the necessity to use a finite-aperture slit or probe and to scan the solar image over an extended interval of time during which the seeing may vary considerably, leading to inhomogeneity in the quality of the data from point to point in the magnetogram. These variations constitute 'noise', in the presence of which the elusive MMF's must be detected. Eventually, both these currently effective methods will be supplanted by magnetographic instruments that utilize narrow-band filters and, therefore, are limited only by seeing and the resolution of the telescope. Moreover, instantaneous records can be made of the entire field of view without scanning.

The earliest instrument to exploit these advantages was the Culgoora magnetograph (Ramsay *et al.*, 1971), with which time-lapse movies showing evolutionary changes in magnetic fields have been obtained (Schatz, 1971). The tunable narrow-band filter upon which this instrument is based consists of three automatically controlled Fabry-Pérot interferometers in series, and has been described by Ramsay *et al.* (1970). 'Hybrid' filters consisting of a Fabry-Pérot interferometer blocked by means of Lyot-type birefringent elements (Zirin, 1966; Title, 1970) are used in both the Aerospace and Caltech-Big Bear videomagnetographs referred to previously. Smithson (1972, 1973b) has reported observations of evolutionary changes in the magnetic field network of quiet regions seen on time-lapse movies obtained with the latter instrument. In principle, the real-time videomagnetographs are ideally suited for making time-lapse movies because it is a very simple matter to photograph the magnetic fields automatically directly off the monitor screen.

Preliminary, high-resolution, nonmagnetic observations obtained with a 'universal,' continuously tunable, birefringent filter have been presented by Beckers (1973). A straightforward modification will convert this into an extremely high-resolution photographic magnetograph, particularly in consideration of the fact that this filter is being used in conjunction with the high-resolution Sacramento Peak vacuum telescope. The interacting (or coherently-phased) Fabry-Pérot interferometric narrow-band filter (Title, 1970) is also a new development in narrow-band filter technology with direct application for improving magnetograph resolution while also greatly simplifying the design of the instrument. Multichannel diode arrays (Dunn and Spence, 1973; Smithson, 1973a) are ideally suited for the real-time differential photometry involved in generating quantitative magnetic field data, and will no doubt play a significant role in a new generation of magnetographs that will far outperform the present ones.

Measurements of the total vector magnetic field within MMF's will be necessary for determining whether or not their appearances and disappearances are a result of changes in the orientation of their fields. For this, the line-profile Stokesmeter (Harvey *et al.*, 1972) offers considerable promise. For obtaining the most complete spectroscopic data on which to base in-depth astrophysical analyses of the physical conditions, velocities, and the complete magnetic vector field in MMF's, the classical spectro-enregistreur des vitesses, as utilized by Michard *et al.* (1961) or its modern equivalent, the spectra-spectroheliograph (Title and Andelin, 1971), both photograph spectra of a two-dimensional area on the Sun, from which the spectrum line profiles and mean wavelengths of all individually resolved features within the area can later be retrieved.

As was stated previously, one of the most outstanding needs of MMF research is to obtain continuous, synoptic magnetic field observations over extended intervals of many days so that the complete evolutionary history of MFO and MFI, as they relate to the evolutionary development of sunspots, can be observed. Ultimately, such observations will come from space observatories, but it should be realized that it is also feasible to obtain continuous solar data with a suitable network of ground-based observatories distributed in longitude, or from a single installation at a sufficiently high latitude (Janssens, 1970; Rogers, 1970).

While direct observations of MMF's and MFO of the types described will always prove indispensible, these must also be combined with concurrent observations of a nonmagnetic nature if we are to understand what relationships exist between them and other solar phenomena. For example, we need to relate MMF's and MFO to chromospheric fibril structure, Ellerman bombs, and Hα bright points observed around sunspots. Thus, it is very important to obtain, in addition to the direct magnetic field data, simultaneous, tuned Hα filtergrams. For investigating the velocity structure of MFO, we need Doppler spectroheliograms or filtergrams. CN and various other bright photospheric network observations in addition to white-light or continuum data are clearly essential for locating precisely where in sunspot penumbrae many MMF's first appear as well as for studying MFI and the role of pores. These are but a few examples of the wide range of data constituting a third, general requirement which must be satisfied by any serious observational program directed toward improving our present meager knowledge of MMF's and the underlying processes of magnetic flux inflow and outflow.

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DISCUSSION

Wilson: You mentioned that the lifetime of the MFO's is about four days and yet these are found in association with slowly decaying spots which may last for weeks. If a spot lasts for several weeks as it may well do, will the MFO's persist for that time or for something like four days?

Vrabec: That is a very good question and I knew I would get in trouble if I gave you too many numbers. The problem in citing numbers is that there is such a large dispersion in the observations. I chose four days to illustrate that even if we make a conservative estimate for the duration of MFO, a lot of flux is transferred by this process. Four days is probably a minimum value. I know that moats persist for at least this long, but by the time the sunspot has become dispersed, the whole phenomenon weakens and is difficult to observe. Karen Harvey has informed me that she has seen moats disappear very suddenly – during the course of a single day.

Sturrock: One of the questions in my mind is whether the fluxules are being swept out by a general motion of the photospheric gases, or whether they are being moved through a comparatively stationary gas. In the former case one would expect fluxules of different strengths to move with the same velocities, whereas in the latter case one would expect the more intense fluxules to move faster than the weak fluxules.

Vrabec: Sheeley and Bhatnagar and Sheeley have measured, by means of Doppler spectroheliograms, an outflow of material from the sunspot. These velocities turn out to be somewhat less than those of MFO, ranging from 0.4 to 0.8 km s^{-1}, whereas the moving magnetic features have velocities averaging 1 km s^{-1}. However, the velocity of the magnetic features and the gas velocity have not been measured simultaneously so it is only by inference that I have assumed that the two are associated. We need more observations to answer this question. In answer to the second part of your question, we do observe a large spread in velocities of the magnetic features in the moats, and I think I see the large features acting as a sort of barrier in the moat. They tend to be sluggish in their motion. The smaller features (and by 'small' I mean smaller in area, not smaller in the field strength, because most of the fluxules, I believe, have about the same field strength) are the most mobile and include the fast interlopers.

Sturrock: What you say suggests that the outward force moving the gas out is the magnetic force on the fluxules, and that the moving fluxules tend to drag the surrounding gas along with them.

Giovanelli: Have you any model for the appearance of fluxules of opposite polarities in the decaying stages of sunspots?

Vrabec: A number of people have worried about this. The Harveys suggested a model in which the lines of force going out of the sunspot get vertically kinked, and these kinks move outward away from the sunspot. Then, depending on how many kinks are in the magnetic field lines, you may have an excess of one polarity over the other. For one kink you can have a two-to-one excess, and for many kinks essentially an equal number of each of the two polarities. The other popular idea is that we have an umbrella of field lines which leave the sunspot and return in the moat. Another possible picture is that the subphotospheric fields are tangled, and fields of opposite polarity existing below the surface are carried upward to the surface by the velocity fields. This could bring up polarity opposite to that of the sunspot and result in MMF's of opposite polarity.

Athay: One feature of the magnetic field pattern that seems to stand out is the persistence of rather small features of the field through a great height range. The network extends from the upper photosphere through the chromosphere without really diverging very much. Sunspots are observed in the center of the Hα line and are not very much larger than sunspots seen in the photosphere even though the height difference is 1000 km or more. In view of this, isn't it quite likely that the magnetic features extend more or less intact into the subphotospheric layers and, if this is the case, isn't it likely that the guiding forces that move around the magnetic field elements are associated with subphotospheric motions that may have nothing directly to do with the types of motions that we observe at photospheric levels such as the supergranulation.

Wilson: A short answer to that question is yes, but we will have more to say about this in a later paper presented by Meyer.

Vrabec: The concept we have is analogous to seaweed that is anchored to the bottom at some depth below the surface where it is observed. The seaweed tendrils move about with the motion of the water, but they are still anchored down below. The same may be true of the magnetic flux tubes observed at the photosphere in that they may be anchored to some more permanent feature of the field at deeper levels.

Zwaan: Could you say anything about possible differences in the velocity distributions of the MMF from one sunspot to another?

Vrabec: I don't think we have enough data to answer that question, but the movies you just saw were the ones used for the initial estimate of 1 km s^{-1} for the magnetic features. Sheeley had previously estimated 1 km s^{-1} for the bright CN features. After studying 34 sunspot groups, the Harveys came up with 1 km s^{-1} for the average velocity, but with a wide range of velocities from 0.2 km s^{-1} extending up to 2 km s^{-1}. The average seems rather well determined but there is a large dispersion. I should remark that, as the resolution of our observations improves, we see more and more of these features not visible in lower resolution observations. The features that are near the limit of resolution tend to have the shortest lifetimes. They come and go faster than the larger, more conspicuous ones and I have the impression that they move faster. The smallest features may be moving with the fluid velocity, whereas the slower moving large features appear to act somewhat as obstructions to the flow.

Grossmann-Doerth: I wonder whether these moving fluxules can be connected in one way or another to the Ellerman bombs? Could it be that the Ellerman bombs are related to two fluxules of opposite polarity that possibly annihilate each other, and can it be shown that the Ellerman bombs occur in the same areas and are associated with the moving fluxules?

Vrabec: Zirin showed examples in his talk of what was described many years ago by Bruzek – that when we have an arch filament system and emerging flux loops, these are regions where we see bright points in Hα. It's very difficult, however, with only a filter to distinguish between Ellerman bombs and other bright features in Hα. There are many bright features that extend for only about an Ångstrom into the line wings whereas the true Ellerman bombs show brightening many ångströms beyond the line. So the Ellerman bombs are very distinctive and exceptional bright points. We do see, as Zirin showed in his pictures, that the bright points also ring sunspot penumbrae. Aside from the fact that they occur where the fields have dynamic properties, such as near the feet of the surfacing arch filaments, we do not have an explanation for the bright points.

Meyer: I wanted to come back to this point of the velocity of the moving magnetic features with respect to the gas velocity in the moat. Following Harvey, the four authors of the paper to be presented on the theory of sunspot growth and decay suggest that in the subphotospheric layers the flux tubes are carried along more or less horizontally and that the kinks developed in the magnetic field, possibly by granular action, constitute the moving magnetic features. The velocity of the moving magnetic features in this picture should be a little bit higher than the gas flow because they should travel with the Alfvén speed superposed on the speed of the moat flow. In a very general estimate, the numbers seem about right and the magnetic features should move a little faster than the gas flow itself.

Vrabec: Is there anything in the theory that suggests that if they are moving faster than the material they may cause a local excitation such as the bright points?

Meyer: No, I did not intend to imply that.

Zwaan: There is one observation that has a bearing on Grossmann-Doerth's suggestion and that is that Ellerman bombs tend to show a recurrence for a couple of hours. As far as I know this observation reported by early observers is still valid.

Vrabec: I will make the point that in the few cases that I, as well as others, have looked into, a necessary condition for an Ellerman bomb is that there be a concentrated field at the same place. However, there are many concentrated fields constituting MMF's, and we have not found what circumstances are sufficient for bombs.

Wilson: Does the MFI show both polarities or only that of the spot to which they move?

Vrabec: Only the latter.

Wilson: Does the moat lifetime of four days which you quote apply to the spots with lifetimes of several weeks?

Vrabec: No. It is just a typical figure limited by the length of our observing runs.