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During this program we have learned the following new information about the solar cycle and the changing magnetic fields that comprise the solar cycle:

(1) Every solar cycle has a duration of 18-22 years even though the peak between successive cycles is approximately 11 years. This means that there are two solar cycles on the sun nearly all of the time; the possible exception is the few years preceding solar maximum.

(2) A large-scale velocity field was discovered around the perimeter of one of the major active regions that developed during the rise of the current solar cycle. If averaged over a several month interval, the velocity would be of the same order of magnitude as the velocity pattern of the torsional

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oscillation signal that varies systematically over the solar cycle. The newly discovered velocity pattern can be interpreted as either (a) a severe contamination to the torsional oscillation signal or (b) another way of observing the torsional oscillation velocity field.

(3) Our analyses of small-scale magnetic fields on the quiet sun has shown that network magnetic fields are continuously being replaced by intranetwork magnetic fields. The replacement occurs when intranetwork magnetic fields collide with network magnetic field; both polarities are observed to cancel each other at a mean rates of 10^{18} Maxwells hr^{-1} . The non-cancelling components of the intranetwork magnetic field replace the cancelled components of the network. No net long-term increases or decreases in magnetic flux occur as a consequence of these processes. However, in the short term of a few days, some new network fields appear as a result of the merging of intranetwork fields of the same polarity.

Our new, high quality observations of the sun show that bipolar regions are the only other source of new magnetic fields in addition to the intranetwork magnetic fields. The bipolar regions, large and small, are the magnetic fields of the solar cycle. Contrary to some current concepts of flux emergence, these bipolar regions do not appear as large-scale loops breaking through the photosphere; they appear as many small-scale elementary bipoles (interpreted as loops having dimensions of a few arc seconds or less). The elementary bipoles successively and simultaneous appear in small localized areas that are only one-two tenths of the diameter of the average supergranule cell. They do not coincide with the sites of emergence of the intranetwork magnetic fields but tend to appear on or very close to the boundaries or vertices of the supergranule cells.

There is a statistical ordering of the motion of many of the elementary bipoles such that many poles of the same polarity merge together. However, many of the more randomly oriented elementary bipoles collide and cancel with other bipoles when their opposite polarities come into close proximity of one another. It is hypothesized that the cancellation is a form of magnetic reconnection that takes place at the photosphere; it is envisioned that flux is pulled out of the photosphere during the reconnection and hence seems to disappear. The flux that is pulled out of the photosphere would be reconfigured such that it becomes part of the horizontal component of flux in the low corona or upper chromosphere.

(4) Our studies of small-scale magnetic fields also led to our further work on the changes that take place at and around large-scale polarity inversion zones as seen in magnetograms of the line-of-sight component. The significance of polarity inversion zones is that they are major sites of cancelling magnetic fields where magnetic flux disappears from the photosphere. These are also the sites of flares, erupting filaments, surges and virtually all of the high energy phenomena that occur on the sun. It is proposed that filaments (prominences) are the most direct biproduct of cancellation and that flares are a secondary consequence. It is suggested that filaments are built when the horizontal components of the magnetic field is increased as a consequence of photospheric reconnection. Flares are thought to occur as a consequence of rapid reconnection in the corona, primarily above polarity inversion zones (often above or below filaments) when the horizontal component of the magnetic field has exceeded a threshold that depends on the total magnetic flux in the locality.

STUDIES OF SOLAR MAGNETIC FIELDS
 DURING THE RISE OF SOLAR CYCLE 22

FINAL TECHNICAL REPORT

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A. RESEARCH OBJECTIVES

Our primary objective has been to acquire a better understanding of the solar cycle. This includes learning more about the solar cycle as a whole as well as acquiring greater knowledge of the details of the changing magnetic field components that comprise the solar cycle. We sought to achieve this goal by several approaches: through analyses of small, newly developed magnetic fields known as ephemeral active regions, by studying the relationships of ephemeral active regions to the background intranetwork magnetic fields, by observing and measuring the evolution of selected, individual magnetic regions and their velocity fields, and by investigating interactions between new active regions and the more slowly changing background magnetic and velocity fields that eventually result in the reversal sign of the polar magnetic fields at approximate 11 year intervals. We thought such a multi-faceted approach would give us the greatest chance of finding new and significant results. In selecting data for our studies our emphasis was on acquiring and analyzing data during the rise of the current solar cycle, 22, including the years 1986-1990.

The solar cycle is the composite of various patterns of magnetic fields that develop on the sun over periods of 11 to 22 years. The duration of a solar cycle depends on which phenomena are selected for analyses, the method of data collection, and the type of measurements that are made. If one uses sunspot number as an index of the solar cycle duration, successive solar cycles have an approximate 11 year duration. However, if one measures the solar cycle by the numbers of active regions and their magnetic orientations, irrespective of the presence of sunspots, then the solar cycle has a duration of at least 18 years. If one counts the solar cycle, as the time required for the magnetic polarity of either the north or south polar field to return to the same magnetic polarity, then the solar cycle has a duration of 22 years.

At the outset of this study, it was debatable whether the study of the birth and early appearance of new magnetic regions would reveal anything fundamental about the solar cycle as a whole. Current concepts and theories of the solar cycle are very rough; none account for all observations. With the science in this state, we thought that it was (and still is) important to investigate all aspects of solar activity that might give us any clues about the physics of the origin of active regions. Hence, over the course of this program, we have endeavored to acquire many high, resolution time-lapse sequences of the quiet sun, active regions, and decaying active regions in order to study the appearance and disappearance of all forms of magnetic flux. Our most significant results have come from this work.

Irrespective of how one measures the solar cycle, the most fundamental questions that we ask are 'How do the solar magnetic fields of the active regions originate?' and 'How do the magnetic fields of the active regions disappear?'

B. SUMMARY OF ACCOMPLISHMENTS - FY 1986-1989

B.1 INTRODUCTION

This 3 year investigation included: (1) a review of various types of data which indicate that successive solar cycles have a much longer duration than previously understood, (2) studies of the evolution of high latitude active regions, (3) the relationship of coronal holes and polar magnetic fields to high latitude active regions, (4) an analyses of large-scale velocity fields around a selected active region, and (5) research on phenomena uniquely related to polarity inversion zones, the sites where magnetic flux disappears from the photosphere.

Our investigations resulted in 9 research papers that have been published or submitted for publication. In this section, we summarize the results of these studies topic by topic and discuss their significance. The next section, C, contains the abstracts of the research papers as published or submitted for publication.

B.2 THE EXTENDED SOLAR CYCLE

Our first effort was participating in a research-review paper on the extended solar cycle. We compared various sets of published and not-yet-published data to try to determine how many years preceding solar maximum and how many years after a solar maximum various solar parameters could be identified as belonging to a given solar cycle. We found that the traditional 11 year cycle, as known from active regions having sunspots, actually has a duration of 18-22 years. The extended solar cycle can be seen in 5 types of data: (1) statistical counts of small active regions that do not have sunspots, (2) measures of the green-line corona as a function of latitude over time, (3) measures of large-scale weak velocity fields.

The combination of these various sets of data provides compelling evidence that two solar cycles exist concurrently on the sun almost all of the time. The possible exception is the 3 year period around and preceding solar maximum as measured by sunspot numbers.

The significance of these research-review is that it casts a lot of doubt on the Babcock theory and similar dynamo theories of the solar cycle which presume that each 11 year solar cycle plays a role in generating the next 11 year cycle.

As a follow-up to the research-review on the extended solar cycle, we made a graphical illustration of the active regions present on the sun during the solar minimum between solar cycles 21 and 22. The active regions were identified with the incoming and outgoing solar cycles by their latitude and magnetic orientations. The old active regions were mostly within 10 degrees in latitude of the solar equator while the active regions of the new cycle, 22, were mostly in the latitude range of 20-40 15 degrees. One way to define the solar minimum is the time at which the new cycle regions outnumber the old cycle regions. This occurred in October 1986.

B.3 LARGE, HIGH-LATITUDE ACTIVE REGIONS

The Initial Study of a High-Latitude Active Region

At the outset of this research program, it was thought that studies of late evolution of large, high latitude active region would give us an opportunity to see how magnetic flux migrates to the polar regions and how the trailing polarity might cancel the opposite polarity negative magnetic flux in the polar region. It was assumed that this process, repeated for many active regions, would eventually result in the reversal of the polar magnetic fields. The reversal is expected around the time of solar maximum.

W.H. Marquette and S.F. Martin selected the largest region that had formed by the end of 1987 as a beginning subject for this study. The region first appeared on the sun in October 1986 in the northern solar hemisphere; its magnetic fields could be identified for 5 months. Contrary to our expectations, no interaction with the polar fields was observed. As the magnetic flux of the region dispersed, a lot of the trailing, positive polarity flux migrated south of the leading, negative polarity flux. This left a substantial portion of the leading negative polarity magnetic flux north (poleward) of the positive polarity flux. As a consequence, no cancellation was observed between the negative-polarity polar fields and the positive-polarity magnetic flux of the new active region. Instead, the leading polarity flux merged with and became indistinguishable from the polar fields. It has been learned that the reversal of the polar field is a more complicated or different process than envisioned by Leighton(1964).

The unusual evolution of this active region, however, warranted further study. They found that the active region also exhibited an unusually fast proper motion of one of its sunspots. The most westward, negative-polarity sunspot migrated away from the other large negative polarity sunspot at a rate of .13 km/sec faster than the mean differential rotation at its latitude of 21 degrees. From the overall evolution of this region and the rapid sunspot motions, it is concluded, in the first research paper on this region, that a large-scale velocity field of unknown origin was responsible for the unusual evolutionary properties of this active region.

Confirmation of a Large-scale Velocity Field

During FY 1988, the second year of this program, a second research project was initiated on this active region by C.J. Schriver (a visiting astronomer) and S.F. Martin. They sought to use the new Megavision image processor to measure and study its velocity fields. By correcting for random motions related to supergranules, and subtracting out the systematic motion due to differential rotation, they successfully confirmed the existence of the large-scale velocity field having a mean rate of 30 m s^{-1} . They characterized it as a slow, river-like flow over an extensive latitude region of about 300 000 km in latitude and at least 400 000 km in longitude. Much of the active region acted like a rock anchored in the bed of the river with the flow being concentrated around the periphery of the region and accelerating on the westward side. The leading negative polarity sunspot and surrounding magnetic fields were caught in the flow and resulted in the proper motion of the sunspot. The discovery and confirmation of the large-scale velocity field has important implications to research on the solar cycle. During the interval that it is observed, the magnitude, direction, and scale of the flow pattern are all comparable or larger than the velocity fields now known as the 'torsional oscillation'. The data can be interpreted in two ways: (1) that it is identical with the torsional oscillation velocity fields or (2) that it is a different velocity field that adds to the velocity field of the torsional oscillation. In the first interpretation, the torsional oscillation has sporadic character that has not previously been recognized. In the second interpretation, the torsional oscillation would have to have a much smaller magnitude in the active region zone than previously determined and might not increase in magnitude over the solar cycle to the extent previously thought.

Coronal Holes and High Latitude Active Regions

In order to better understand the torsional oscillation and the

relationship of flow patterns to the solar cycle, it was deemed important to search for and identify other possible examples of large-scale velocity fields. During FY 1989, the third year of this program, W.H. Marquette, in collaboration with A. Cannon at the University of Sydney, initiated such a study for the active regions during the rise of solar cycle 22. This resulted in another research paper on the evolution of selected, large, active regions. The regions were found to evolve in a spectrum of patterns; the region studied by Marquette and Martin was at the extreme end. At the other end of the spectrum are the regions for which the trailing polarity preferentially migrates poleward in the classical way envisioned by Leighton(1964).

During this study, Cannon and Marquette also rediscovered a little known relationship between polar coronal holes and high latitude active regions. Three other of the regions in their study showed a merging of the leading polarity magnetic flux of the active regions with the polar fields similar to the first case studied by Marquette and Martin. In all four cases they found that the polar coronal hole developed an extension to lower latitudes that encompassed part of the leading polarity component of the active regions, the same polarity as the polar magnetic fields. This typically happened during or subsequent to the second solar rotation (27 day interval) after the regions formed.

The significance of this latter finding is still unknown. However, it is known that coronal holes tend to form or migrate to successively lower latitudes throughout the solar cycle. At the same time the polar holes diminish and eventually disappear during the cycle maximum; this coincides with the weakening of the polar fields prior to their reversal of sign. The reappearance of the polar holes and the appearance of the first, high-latitude ephemeral regions of the next solar cycle both occur soon after solar maximum. Is this a coincidence?

Further study of the occurrence of the new cycle regions in relationship to the development of the polar coronal holes is recommended during the present solar cycle.

B.4 SMALL-SCALE MAGNETIC FIELDS

The Identification and Interaction of Network, Intranetwork and Ephemeral Region Magnetic Fields

From acquiring and analyzing the most sensitive magnetic field observations currently available, we find that new magnetic flux appears in only two basic forms: (1) active regions that grow as distinct bipolar entities of magnetic flux and (2) intranetwork

magnetic fields. The unipolar network magnetic fields bordering the intranetwork magnetic fields as well as the polar magnetic fields, are only the combined bi-products of the new active regions and the intranetwork magnetic fields.

We observe only two forms of magnetic flux interaction: (1) the merging of magnetic fields of the same polarity and (2) the cancellation of magnetic flux of opposite polarity when they appear to come into contact. Cancellation is defined as the mutual disappearance of opposite polarity magnetic fields as a common boundary as seen in magnetograms of the line-of-sight component. The merging and cancellation of magnetic flux occurs between any magnetic flux fragments irrespective of their origin, age or magnitude.

The Formation of Active Regions and Ephemeral Active Regions

Some investigators have argued that active regions and ephemeral active regions are two different types of solar activity. However, in our data, we find no properties of active regions that suggest to us that there are fundamentally different types of active regions. It appears that any division of active regions into two groups is an arbitrary splitting of a category of phenomena that has a wide but continuous range of magnitudes and other properties.

In our best observations of the line-of-sight component of magnetic flux, it can be seen that the magnetic flux initially appears as successive pairs of tiny opposite polarity magnetic fields. We have named these small building blocks of active regions 'elementary bipoles'. The smallest active regions consist of only a single pair of elementary poles. Larger ephemeral regions consist of pairs of successively forming elementary poles. As more elementary bipoles appear, many of the like-polarity poles merge. The apparent growth of the regions is due to the merging of the elementary poles. After they have merged with adjacent poles, the individual elementary poles are no longer spatially resolvable in our current magnetograms. The merging of fields of the same polarity results in the development of sunspots. Our observations indicate that there is a critical threshold of flux density for sunspot development and that sunspots develop anytime this threshold is exceeded. It appears then that sunspots might be a surface phenomena rather than fundamental structure that emerges from the interior of the sun. The basic questions about active region formation is 'How do the elementary bipoles form? At what depth do they form?'

We have observed a few large active regions develop. The larger active regions can have several sites where elementary bipoles are successively appearing rather than a single source site. The elementary bipoles are observed under the arch filament systems

observed in H-alpha.

Intranetwork Magnetic Fields

A lot of new information about the intranetwork magnetic fields was learned during the course of this program. The intranetwork magnetic fields are weak magnetic fields associated with the solar convection cells called 'supergranules'. Supergranules have a mean diameter of about 30 000 km. They first appear near the boundaries of pre-existing supergranules and gradually expand to diameters of as much as 50 000 km in a period of 2 days. Their lifetimes are of the order of 50 hours or more (Wang, 1990)

In the videomagnetograms from Big Bear Solar Observatory, the intranetwork magnetic fields are observed to emanate from specific source sites near the centers of each supergranule cell. The intranetwork fields are tracers of the approximate radial flow of plasma from the centers of the cells to their boundaries. Near sun center, the fields appear to be enhanced as the intranetwork patches flow to the boundaries of the cells. This might be due to the changing configuration of the field. If it emerges as tiny loops of magnetic flux, in our line-of-sight magnetograms, we would not detect the horizontal component at the top of the loops; but as the loop expanded, its line-of-sight component in the legs of the loops would appear to increase. Additionally, we have observed that the fields can increase due to the coalescence of patches of flux of the same polarity.

Most of the intranetwork magnetic flux is less than 10 Gauss; however, coalesced knots of intranetwork magnetic flux can sometimes reach peak magnitudes of tens of Gauss. Although we assume that the intranetwork fields originate as bipolar units of flux, we rarely can identify which negative and positive polarity intranetwork features consist of a bipolar unit because the intranetwork fields are close to the limit of sensitivity and spatial resolution of the magnetograms.

The intranetwork fields are important in the context of our solar cycle studies because they provide an indirect means of detecting the velocity fields associated with the supergranule convection. Their presence then allows us to identify where ephemeral active regions and active regions form with respect to the convection cells. We have observed that the majority, if not all, of new ephemeral active regions and small active regions, form at the boundaries and vertices between the supergranule cells. If active regions and ephemeral active regions emerged from the depths of the solar interior, we should expect that the bipolar regions would either appear predominantly within the center of the cells or would appear to push the convection cells aside as they emerged. There is a lack of such patterns in our most sensitive and highest resolution magnetograms. The formation of

both ephemeral active regions and active regions at the boundaries and vertices of the cells can be interpreted as evidence that the ephemeral active regions and small active regions are phenomena that form close to the interface between the photosphere and chromosphere. Additionally, because we also find no fundamental differences in the way that flux emerges in ephemeral active regions and in larger active regions, we suspect that all active regions are a phenomena that form near the photosphere-chromosphere interface.

B.5 STUDIES RELATED TO POLARITY INVERSION ZONES

The Significance of Polarity Inversion Zones

All of the highly energetic phenomena on the sun are related to polarity inversion zones. Polarity inversion zones are locations in or between active regions where the where the magnetic field sharply changes direction. In magnetograms of the line-of-sight component, the field is positive on one side of a polarity inversion zone and negative on the other. Where magnetic field gradients are very high, the polarity inversion zone is the line that separates opposite polarities; this line has often been called the neutral line. However, at the so-called 'neutral line' the magnetic field is horizontal. It is known to be horizontal from the directions of structures in H-alpha filtergrams and from transverse magnetograms. In some stages of an active region development, the horizontal structures appear to directly connect the opposite polarity magnetic fields on opposite sides of the polarity inversion zone. This configuration approximates a potential magnetic field. However, in other stages of development, the horizontal component is orthogonal to an imaginary line connecting the nearest opposite polarity, line-of-sight fields. This is a non-potential configuration, a configuration in which more energy is stored in the magnetic field than in the potential configuration (minimum energy configuration).

The largest and most energetic solar flares are initiated at sites where the polarity inversion zone has the extreme non-potential configuration, that is where the horizontal component is orthogonal to a line joining the closest magnetic fields of opposite polarity.

Filaments (prominences) only form at polarity inversion zones where the magnetic field has the extreme non-potential configuration. We assert from our studies of filaments that filaments almost always form concurrently with the development of the extreme non-potential configuration. However, where magnetic field gradients are extremely high, the filaments can be extremely

narrow and sometimes are not obviously present. Nevertheless, the formation of filaments is an extremely reliable indicator of the development of the extreme non-potential configuration. As such they are also the markers of probable flare sites. However, because filaments mark the approximate sites of flare initiation, they also sometimes exhibit a lot of mass motions prior to solar flares and usually erupt during solar flares. It is common for the filament to begin to ascend in the corona within a few minutes to a few hours preceding a solar flare. There is recent evidence that the expulsion of magnetic flux from the visible hemisphere of the sun occurs only during coronal mass ejections which accompany solar flares (Feynman,). On the visible hemisphere of the sun, coronal mass ejections are almost always accompanied by the the eruption of filaments.

In the context of trying to understand the solar cycle, we are necessarily interested in where and how magnetic flux originates and where and how magnetic flux disappears. The hypothesis that magnetic flux is only expelled from the sun only during coronal mass ejections is of great importance because it is provocative evidence that the key magnetic field changes, associated with the expulsion of magnetic flux, occur at polarity inversion zones.

We believe we have observed and studied an important part of the key magnetic field changes that result in the creation of the extreme non-potential magnetic field configurations and also result in the development of filaments, the occurrence of the most energetic flares, and the expulsion of magnetic flux from the sun. We have accomplished this by studying the changes in the line-of-sight magnetic fields that accompany the development of filaments and solar flares. The important observations are of the 'cancellation' of magnetic flux that occurs when opposite polarity magnetic fields either migrate or are pushed together at polarity inversion zones. This process is described below in the sections on the association of cancelling magnetic fields to solar flares and the formation of filaments. Both are the topics of published research papers under this research program and listed in Section D.

mThe Association of Cancelling Magnetic Fields to Solar Flares

An invitation to give a paper on cancelling magnetic fields and solar flares at the IAU Colloquium on Solar and Stellar Flares, Stanford University, August 1988, was received by S.H.B Livi, visiting astronomer from Puerto Alegre, Brazil). After the initial presentation, a collaborative paper on this subject was written by S.H.B. Livi, S.F. Martin, H. Wang and G. Ai (Huairou Solar Observing Station of the Beijing Astronomical Observatory.

In the literature on solar physics, solar flares have been associated with many types of magnetic field changes: the

building of high magnetic field gradients (Severny, 1958, 1960), emerging flux (Rust, 1972, 1974; Martin et al., 1983, 1984), sites where the magnetic flux is increasing on one side of a polarity inversion zone and decreasing on the other side (Martres, 1968a,b), and most recently with the convergence and cancellation of magnetic fields at polarity inversion zones (Martin et al., 1985). From our studies of cancelling magnetic fields, we propose that cancelling fields are the common denominator for all flares because cancelling magnetic fields occur along with all of the above other magnetic changes associated with flares. Furthermore, cancellation has special significance because it is the only change that is associated with flares when none of the other changes, except convergence, occur. The convergence of opposite polarities also precedes and accompanies cancellation. We propose that convergence and cancellation of magnetic flux are necessary conditions for solar flares.

We have also proposed in our paper on this subject that cancelling fields are still an indirect rather than a direct trigger of solar flares. This is because the time scale of cancelling fields is much longer than the time-scales of the associated flares. Hence, we view cancelling fields as a necessary evolutionary condition for flares, not to be confused with the abrupt reconfiguration of the magnetic field we suppose takes place in the corona during a solar flare.

More on the evolutionary reconfiguring of magnetic fields prior to solar flares has been learned by studying the formation of filaments in association with cancelling magnetic fields. These are summarized in the next section.

The Formation of Prominences (Filaments) as Inferred from Optical Observations

During the final year of this program, an invited research-review paper was prepared by S.F. Martin for the IAU Colloquium on Prominences held in Hvar, Yugoslavia, September 1989.

In this paper, the phenomena most commonly observed during the formation of Prominences are reviewed. It is then proposed that 3 of the conditions are essential to prominence formation: (1) the existence of a coronal magnetic field arcade connecting the opposite polarity fields, (2) the convergence of opposite polarity magnetic fields under the arcade and (3) the cancellation of these fields. It is hypothesized that the persistence of these conditions for a sufficient length of time will invariably result in the formation of a prominence. The research review includes illustrations of all of the conditions associated with prominence formation.

This is the first paper to propose a set of necessary and sufficient observational conditions for prominence formation. The paper also gives some insight into possible causes of prominence eruption. It suggests that the same conditions that lead to prominence formation also eventually result in the eruption of a prominence due to the continued build-up of the horizontal component of the magnetic field of a prominence after its formation.

Mass Motions Associated with Solar Flares

S.F. Martin was invited to give a review paper on mass motions associated with solar flares at the IAU Colloquium on Solar and Stellar Flares at Stanford University in August 1988. Although this subject deviates from the subject of the program, the invitation was accepted. The author felt that a clarification of the types of mass motions associated with solar flares along with clear illustrations would be a worthwhile contribution to this colloquium that would promote a broader understanding of solar flare phenomena.

This review attempts to distinguish between fundamental flare structures and their mass motions from secondary structures and associated mass motions. Motions within flare loops and at the footpoints of flare loops are considered fundamental and common to all flares. Mass motions within filaments, surges, and flaring arches are all considered to be secondary flare phenomena. The paper includes illustrations of one or more examples of each type of mass motion. In addition, a H-alpha time-lapse film was presented which presents the dynamics much better than can be shown in published illustration or slides.

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C. ABSTRACTS OR SUMMARIES OF RESEARCH PAPERS

C1. THE EXTENDED SOLAR ACTIVITY CYCLE

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Extended Abstract

The solar cycle has been defined in terms of a sequential periodic variation in sunspot numbers, the period being the interval between successive minima, currently averaging ~11.2 years. However, a number of previous observations have indicated that the "activity" cycle may begin at higher latitudes prior to the emergence of the first sunspots of the new cycle. We here report results from sunspot cycle 21 concerning the ephemeral active regions, the coronal green-line emission, and the torsional oscillation signal, which confirm the earlier suggestions.

We have analysed the latitude and orientation distributions of the ephemeral active regions (ER) occurring during the declining phase of sunspot cycle 21. The ER results for cycle 20 are qualitatively reproduced. We report the appearance of a high-latitude population of ERs in the declining phase of sunspot cycle 21, with orientations which tend to favour those for cycle 22 rather than 21. Extending the analyses of LaBonte and Howard (1980, 1981, 1982), we have further analyzed both old and the recent Mount Wilson velocity data derive the torsional shear (i.e. the derivative of the torsional pattern with respect to latitude) for solar cycles 20 and 21. Three branches of this pattern may be found in either hemisphere. The first, a low-latitude branch from 1967 to 1979, closely matches the butterfly diagram for cycle 20.

The second is first identified at high latitudes in 1967 and progresses continuously to lower latitudes, where it connects with the butterfly diagram for cycle 21 and accompanies it towards the equator. The third begins at high latitudes in 1979 and it seems likely that this third branch will connect with the butterfly diagram for cycle 22, but this remains to be tested.

We have obtained photoelectric maps of the corona in the 5303 line, averaged over several rotations and extending over 13 years from 1973 to 1986. One component of the coronal emission clearly corresponds to the second branch of the torsional pattern, not only at sunspot latitudes but also at higher latitudes in 1973. However, from 1980 a high-latitude component of the emission is seen to follow the third branch of the torsional pattern, displaying an equatorward progressing pattern. This component appears to be linked to the second branch by a poleward moving component between 1975 and 1980, which may also be related to a similar branch of the torsional pattern. These branches may reflect the poleward motion of the large-scale flux reported by Howard and LaBonte.

Taken together, these recent data confirm earlier findings that sunspot activity is simply the major phase of a more extended cycle which begins at high latitudes prior to the maximum of a given sunspot cycle and progresses towards the equator during the next 18-22 years, merging with the conventional butterfly diagram as it enters sunspot latitudes. Since the torsional oscillation signal links the sunspot and the high-latitude phases of activity together, the origin of this signal may hold the key to an understanding of the extended cycle. This extended cycle is quite different from the 22-year magnetic cycle, which simply consists of two 11-year sunspot cycles.

We conclude that the evidence from cycle 21 supports and extends the earlier suggestions of an extended activity cycle, and, in order to place this in some perspective, we propose a system of azimuthal convective rolls forming near the poles every eleven years. This system provides the driving mechanism for a dynamo wave and generates the toroidal magnetic fields. At high-latitudes it is assumed that the rolls are complete and the magnetic toroid gives rise to only the weaker forms of activity (the ERs and the coronal emission features). As the wave progresses to lower latitudes, we suggest that the rolls break up into giant cells having an east-west velocity component, and the large active regions are generated from the sub-surface toroid. Thus a coherent picture of a plausible mode of operation of the extended cycle and the large scale convection is beginning to emerge and should provide a basis for further testing during the current sunspot cycle.

References

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C.2 EVOLUTION OF A HIGH-LATITUDE ACTIVE REGION

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Abstract

We describe the decay phase of one of the largest active regions of solar cycle 22 that developed by the end of June 1987. The center of both polarities of the magnetic fields of the region systematically shifted north and poleward throughout the decay phase. In addition, a substantial fraction of the trailing magnetic fields migrated equatorward and south of the leading, negative fields. The result of this migration was the apparent rotation of the magnetic axis of the region such that a majority of the leading polarity advanced poleward at a faster rate than the trailing polarity. As a consequence, this region could not contribute to the anticipated reversal of the polar field.

The relative motions of the sunspots in this active region were also noteworthy. The largest, leading, negative polarity sunspot at N24 exhibited a slightly slower-than-average solar rotation rate equivalent to the mean differential rotation rate at N25. In contrast, the westernmost, leading, negative polarity sunspot at N21 consistently advanced further westward at a mean rate of 0.13km/sec. with respect to the mean differential rotation rate at its latitude. These sunspot motions and the pattern of evolution of the magnetic fields of the whole region constitute evidence of the existence of a large-scale velocity field within the active region.

C.3 LARGE-SCALE VELOCITY FIELDS IN AN ACTIVE REGION

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Abstract

We have analyzed the systematic large-scale flow and the small-scale random-walk displacements of magnetic flux fragments in and around active region #19824 (CMP 23 Oct. 1986). We traced the lateral motion of 170 flux-tube concentrations in magnetograms from the Big Bear solar Observatory covering an interval of just over five days. We found a persistent, non-uniform large-scale pattern of flow superposed on smaller-scale random motions. After correction for differential rotation, the overall large-scale pattern of flow in the 5 day interval gives the impression that the core of the active region is an object anchored in a westward-flowing river. The flow is faster and more pronounced around the southern side of the core of the region than around the northern side. These two branches converge and accelerate westward of the core of the region. The large-scale flow appears to drag along the westernmost sunspot and some of the surrounding magnetic flux. The long-term evolution of the active region suggests that the flow persists for several months.

In order to study the random motions of the flux-tube concentrations, we first subtract the large-scale component. The random component has the spacing of the supergranule convection cells and spreads at a rate consistent with the random-walk diffusion of magnetic flux. However, in the periphery of the active region, the random component is characterized by a diffusion coefficient of $\sim 260 \text{ km}^2 \text{ s}^{-1}$ while in the central part of the active region (excluding the areas of highest flux density), the diffusion coefficient is only $\sim 110 \text{ km}^2 \text{ s}^{-1}$. The lower diffusion coefficient in the core of the active region appears to be caused mainly by a smaller mean distance between concentrations of flux rather than a distinct difference in velocities.

C.4 THE CANCELLATION OF MAGNETIC FLUX ON THE QUIET SUN

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Abstract

The mutual loss of magnetic flux in closely spaced, opposite polarity magnetic fields is herein defined as 'cancellation'. The combination of two cancelling components is referred to as a cancelling magnetic feature. In this paper, a classification scheme for cancelling magnetic features according to the origins of their two components is proposed; the observed properties of flux cancellation are summarized. The cancellation appears to be the observational evidence of magnetic reconnection taking place in or above the photospheric layer.

**C.5 THE IDENTIFICATION AND INTERACTION OF NETWORK,
INTRANETWORK AND EPHEMERAL REGION MAGNETIC FIELDS**

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Abstract

Network magnetic fields, ephemeral active regions, and intranetwork magnetic fields are illustrated and discussed in several contexts. First, they are presented in relation to the appearance and disappearance of magnetic flux. Second, their properties in common with all solar magnetic features are discussed. Third, their distinguishing characteristics are emphasized. Lastly, their interactions are illustrated.

Network magnetic fields are no longer considered to be just the aged remnants of active regions. The network is the dynamic product of the merging and cancelling of intranetwork fields, ephemeral regions, and the remnants of active regions. Intranetwork fields are magnetic fields of mixed polarity that appear to originate continuously from localized source sites in between the network. The intranetwork magnetic fields are characterized by flow of successive fragments in approximately radial patterns away from their apparent source sites and by the relative weakness of their magnetic fields. Ephemeral active regions are small, new bipoles that grow as a unit or a succession of bipolar units and whose poles move in opposite directions from their apparent site of origin. Large ephemeral regions are not distinguishable from small active regions.

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Abstract

Small-scale solar features identifiable on the quiet sun in magnetograms of the line-of-sight component consist of network, intranetwork, ephemeral region magnetic fields, and the elementary bipoles of ephemeral active regions. Network fields are frequently observed to split into smaller fragments and equally often, small fragments are observed to merge or coalesce into larger clumps; this splitting and merging is generally confined to the borders and vertices of the convection cells known as supergranules. Intranetwork magnetic fields originate near the centers of the supergranule convection cells and appear to increase in magnetic flux as they flow in approximate radial patterns towards the boundaries of the cells.

Large ephemeral active regions which develop magnetic flux in excess of 5×10^{19} Mx often exhibit a secondary substructure of 'elementary bipoles' identical with the substructure that larger active regions exhibit during their first hours or day of development; the elementary bipoles often appear to be randomly oriented with respect to the axis of the initial bipole and these elementary poles often cancel with the initial poles or other elementary poles of opposite polarity.

Network, intranetwork and ephemeral region magnetic fields all encounter and interact with one another. Encounters of the same polarity result in the merger and adding of the magnetic flux from different features. Encounters of opposite polarity usually result in cancellation - the mutual disappearance of magnetic flux of opposite polarity at their common boundary. It is deduced that the mixed-polarity network originates primarily from the separated poles of ephemeral regions and secondarily from merged clusters of intranetwork fields.

THE ASSOCIATION OF FLARES TO CANCELLING MAGNETIC FEATURES
ON THE SUN

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Abstract

Previous work relating evolutionary changes of photospheric magnetic fields to flares are reviewed and reinterpreted in the light of recent observations of cancelling magnetic fields. In line-of-sight magnetograms and H-alpha filtergrams from Big Bear Solar Observatory, we confirm the following 3 associations: (a) the occurrence of many flares in the vicinity of emerging magnetic flux regions (Rust 1974), but only only at locations where cancellation has been observed or inferred (b) the occurrence of flares at sites where the magnetic flux is increasing on one side of a polarity inversion line and concurrently decreasing on the other (Martres et al. 1968; Ribes 1969), and (c) the occurrence of flares at sites where cancellation is the only observed change in the magnetograms for at least several hours before a flare (Martin, Livi and Wang 1985). Because cancellation (or the localized decrease in magnetic flux) is the only common factor in all of these circumstances, we suggest that cancellation is the more general association that includes the other associations as special cases. In magnetograms of high sensitivity, obtained since 1985, we have not observed flares in the absence of either observed or inferred cancellation. Because of the invariableness of this association of cancelling magnetic fields with flares, we propose the hypothesis that cancellation is a necessary, evolutionary precondition for flares. We also confirm Martin, Livi and Wang (1985) that the initial parts of flares occur in close proximity to cancellation sites but during later phases, the flare emission can spread to other parts of the magnetic field that are weak, strong, or not cancelling.

**C.8 CONDITIONS FOR THE FORMATION OF PROMINENCES
AS INFERRED FROM OPTICAL OBSERVATIONS**

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Abstract

In the optical region of the electromagnetic spectrum, the conditions most frequently associated with the formation of prominences are: (1) the existence of opposite polarity photospheric magnetic fields on opposing sides of a prominence, (2) a coronal arcade that connects the magnetic fields on opposing sides of a prominence, (3) a transverse magnetic field configuration in the chromospheric and photospheric polarity inversion zones that is approximately perpendicular to the direction of maximum magnetic field gradient between adjacent patches of opposite polarity, line-of-sight magnetic flux, (4) in active regions or decaying active regions, the alignment of chromospheric fibrils in a polarity inversion zone approximately parallel to the transverse magnetic field component and parallel to the long axis of the future prominence, (5) the long-term (hours to days) converging flow of small patches of opposite polarity magnetic flux towards a common polarity inversion zone, and (6) the cancellation of encountering patches of magnetic flux of opposite polarity at a photospheric polarity inversion boundary (interpreted as the transport of magnetic flux out of or into the photosphere). Because these are observed conditions found from magnetograms and filtergrams at various wavelengths, they do not necessarily represent independent physical conditions. Although none of these conditions have proven to be individually sufficient for prominence formation, a combination of 3 of these conditions might prove to be both necessary and sufficient. The following hypothesis is offered for study and evaluation: condition (2) and the combination of conditions (5) and (6), if dynamically maintained for a sufficient length of time, will invariably result in the formation of a prominence.

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Abstract

Mass motions are a principal means by which components of solar flares can be distinguished. The initial mass motions in flare loops are always from the tops of the loops in the corona downward to the footpoints of the loops in chromosphere. The initial motion of electrons streaming downward is invisible and only inferred from the pattern of Doppler shift of the chromospheric flare ribbons into the red wing the H-alpha line. Following the initial phase, some energized chromospheric electrons then stream upward in to the newly formed flare loops. As mass accumulates in the newly formed flare loops, the density increases and the temperature decreases. The loops then become visible in H-alpha only if the density is sufficiently high. In H-alpha, the mass motions are always from the tops of the loops downward.

Flaring arches are a secondary flare phenomena in which mass flows into and along pre-existing coronal magnetic fields. These mass motions differ from flare loops in that the flow enters the coronal arch near the flare loops and ribbons and subsequently flows to a distant secondary footpoint . The secondary footpoint is usually caused to brighten but to a lesser degree than the brightest parts of the flare ribbons. The initial flow is fast and invisible. It is followed by a slower mass flow of particles moving at speeds of several thousand kilometers per second. This phase is detected in x-rays. The last phase of flow consists of more dense mass visible in H-alpha streaming along the arch at speeds from tens to hundreds of kilometers per second.

The mass flow in surges is similar to that in flaring arches. However, the energy of the events is not as great and the mass usually falls back to its starting site, having insufficient energy to reach the top of the arch. The majority of surges are seen as absorption features rather than as emission features.

Mass flow in filaments associated with flares fall into 3 categories: preflare ascending and descending mass motions, mass motions injected into filaments which have an end near a flare, and mass motions induced by flare waves or particles which impact a filament broadside or from the top.

D. PUBLICATIONS: FY1989

D.1 Research Papers - Published

1. "The Extended Solar Activity Cycle" by P.R. Wilson, R.C. Altrock, K.L. Harvey, S.F. Martin and H.B. Snodgrass, Nature 333, 748 (1988).
2. "The Identification and Interaction of Network, Intranetwork and Ephemeral Region Magnetic Fields by S.F. Martin, Solar Physics, Solar Phys. 117, 243 (1988)
- 3 "The Cancellation of Magnetic Flux on the Quiet Sun" by J. Wang, Z. Shi, S.F. Martin, and S.H.B. Livi, Vistas in Astronomy, 31, 79 (1988).
4. "Evolution of a High-Altitude Active Region," (co-author W. H.Marquette), Solar Physics 117, 227 (1988).
5. "Mass Motions Associated with Solar Flares," Solar Physics 121, 215 (1989).
6. "Relationships of Flares to Cancelling Magnetic Flux" (co-author S.H.B. Livi, H. Wang and G. Ai), Solar Physics 121, 197 (1989).

D.2 Research Papers Submitted for Publication

1. "Large-scale Velocity Fields in an Active Region" by K. Schrijver and S.F. Martin, submitted to Solar Physics.
2. "Small-Scale Magnetic Features Observed in the Photosphere" by S.F. Martin, submitted to Springer-Verlag through editor J.O. Stenflo for inclusion in special volume with papers presented at the IAU Symposium on the Solar Photosphere: Structure, Convection, and Magnetic Fields, May 1989, Kiev.

D.3 Research Papers in Preparation for Publication

1. "The Formation of Prominences as Inferred from Optical Observations" in preparation for submission to Springer-Verlag for inclusion in the volume with papers presented at IAU Colloquium on Prominences, Hvar Yugoslavia, Sep 1989

E. PROFESSIONAL PERSONNEL ASSOCIATED WITH THE PROJECT

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F. INTERACTIONS

F.1 Papers Presented at Formal Scientific Meetings

1. "Intranetwork Magnetic Fields" by S.F. Martin, given at Solar Cycle Workshop II, Stanford Conference Center, Lake Tahoe, California, May 1987
2. "Mass Motions Associated with Solar Flares" by S.F. Martin, given at IAU Colloquium No. 104 on 'solar and Stellar Flares' at Stanford University, Aug. 1988
3. "Small-Scale Magnetic Features Observed in the Photosphere", Invited paper presented at I.A.U. Symposium on 'Solar Photosphere: Structure, Convection, and Magnetic Fields', Kiev, May 1989
4. "Elementary Bipoles of Active Regions and Ephemeral Active Regions," Oral paper presented at meeting on the 'Solar Atmosphere and Interior, Tucson, Aug. 1989
5. "Conditions for the Formation of Prominences as Inferred from Optical Observations," Invited Paper presented at IAU Colloquium 117, Hvar, Yugoslavia, Sep. 1989

F.2 Other Scientific Presentations

1. Poster paper on "The Evolution of a Large Active Region in the Early Phase of New Solar Cycle 22" by W.H. Marquette and S.F. Martin displayed at Solar Cycle Workshop II, Stanford Conference Center, Lake Tahoe, California, May 1987
2. Poster paper presenting a statistical study of "Old Cycle (21) Versus New Cycle (22) Active Regions" by W.H. Marquette, R.J. Fear and S.F. Martin displayed at Solar Cycle Workshop II, Stanford Conference Center, Lake Tahoe, California, May 1987
3. Poster paper on "A Sampling of Distributions of Ephemeral Active Regions in 1985" by B. Popp and S.F. Martin displayed at Solar Cycle Workshop II, Stanford Conference Center, Lake Tahoe, California, May 1987
4. Invited Colloquium presentation on "The Appearance and Disappearance of Magnetic Fields on the Sun, given at the University of Utrecht, August 1987
5. Invited Colloquium presentation on "The Appearance and Disappearance of Magnetic Fields on the Sun, given at the University of St. Andrews, September 1987
6. "Small-Scale Magnetic Features Observed in the Photosphere", Talk given at the Astronomical Institute at Irkutsk, USSR, May 1989
7. "Small-Scale Magnetic Features Observed in the Photosphere", Talk given at the Beijing Astronomical Observatory in Beijing, China, June 1989
8. "Small-Scale Magnetic Features Observed in the Photosphere", Talk given at the Kunming Astronomical Observatory in Kunming, China, June 1989