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Solar Magnetic Fields Derived from Hydrogen Alpha Filtergrams

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The distribution and polarity of solar magnetic fields can be inferred from photographs taken with narrow band-pass filters centered on the Hα spectral line. Structures observed in Hα, including filaments, filament channels, fibrils, arch-filament systems, and plage corridors are used to infer positions of neutral lines in the radial component of the solar magnetic fields. This source of magnetic-field information, although it is not strictly objective and quantitative, offers a number of important advantages over the solar magnetograph. The inferred data can be obtained with the existing global network of flare patrol observatories at low cost, high speed, and complete reliability from day to day. Patrol films allow the filling of interruptions in magnetograph data and the extension of the magnetic-field data base back in time to the first spectroheliograms near the beginning of the century. The large-scale Hα patterns are more precisely outlined than their large-scale counterparts on magnetograms. The continuity of Hα markers of polarity reversals from active centers to quiescent, large-scale structures reveals associations and patterns not previously studied. The inferred magnetic data have important applications in solar-activity forecasting, detection of interplanetary-sector boundaries, and the inference of structures in the solar corona.

In solar-physics research, the man with the better magnetograph gets a path beaten to his door. The people running down that path are not only solar physicists; they are also space physicists and geophysicists. The early Mariner 2 measurements began to show that the interplanetary magnetic fields were but extensions of the magnetic fields on the surface of the sun [*Ness and Wilcox,* 1964; *Davis,* 1965]. Continuous monitoring of the interplanetary medium has made it more obvious that interplanetary conditions vary in detailed response to changes in solar magnetic fields [*Wilcox,* 1968; *Severny et al.,* 1970]. The interplay of interplanetary magnetic fields with the earth's magnetic field is an important ingredient in geomagnetic storms and lesser disturbances in the geomagnetic environment. To understand solar magnetism is to better understand interplanetary magnetism and its effects on the earth.

Appetites for good solar magnetic-field data have grown faster than the number and quality of magnetographs have increased. The satisfaction of these appetites is frustrated by a number of difficult problems in magnetic-field observations. Recent developments in instrumentation and computer science are leading to new magnetographs with higher spatial resolution, faster rates of observation, and faster data reduction [*Howard,* 1971]; these new observations are certain to make important advances in understanding the sun. Nevertheless, the data will still fail to provide means for dealing with some of the important questions about solar origins of interplanetary disturbances. The gaps in magnetic-field data that will continue are products of the small number, complexity, and high expense of solar magnetographs; the restriction to measuring only the longitudinal component of the magnetic field; and the lack of continuous observations covering more than one solar cycle. A means to partially fill these gaps appears to exist in the careful inference of magnetic-field data from good-quality photographs of the Hα chromosphere [*Ramsey and Smith,* 1966; *Zirin,* 1966; *Veeder and Zirin,* 1970; *McIntosh,* 1972]. The chromosphere is the layer of the solar atmosphere lying immediately above the surface visible as the white-light solar disk. The strongest lines in the solar spectrum, including the primary line of hydrogen (Hα), are formed in the chromosphere.

Early in this century, *Hale* [1908] inferred a connection between magnetic fields and the fine structure that he first observed on early Hα photographs. The patterns surrounding large sunspot groups appeared remarkably similar to patterns of iron filings scattered around a bar magnet. This analogy led to investigations that proved that sunspots were seats of very strong magnetic fields, but further studies with spectrographs revealed such complex gas motions associated with the fine structure that their magnetic origin became obscure [*Hale,* 1927]. The improved magnetic-field data resulting from Babcock's development of the magnetograph [*Babcock,* 1953; *Babcock and Babcock,* 1955] renewed the comparisons between magnetic fields and Hα structures. It was immediately apparent that the giant ribbons of dark material meandering across the solar chromosphere, the filaments, were faithful markers of the boundary between areas of opposite magnetic polarity (Figure 1). Each improvement in resolution in magnetic-field measurements has extended the correspondence to smaller structures [*e.g., Bhatnagar,* 1971]. By combining numerous studies made over the past two decades, *McIntosh* [1972] has formulated detailed procedures to allow observers to reliably infer positions of polarity reversal (the so-called neutral lines) and polarities from routine flare patrol photographs, which were obtained with small telescopes equipped with narrow band-pass Hα filters. The procedures do not include estimates of magnetic-field strength. Now Hα patrol films become more than just a record of solar flares; they become an inexpensive magnetograph for the past as well as the future.

THE INFERENCE PROCEDURES

The inference of magnetic polarities and patterns from Hα photographs makes use of five basic structures and patterns, and their inter-relationships and evolutions. The basic structures are: filaments; filament channels (neutral bands); fibrils (fibrilles, threads, false filaments); arch-filament systems (bright regions with loops, nascent bipolar regions); and plage corridors. The parenthetical terms are labels for the same features used by other authors. Of these structures, only filaments and fibrils are discussed in the most recent texts on solar astronomy [*Smith and Smith,* 1963; *Zirin,* 1966; *Tandberg-Hanssen,* 1967]. The other three structures have received detailed attention only in technical literature

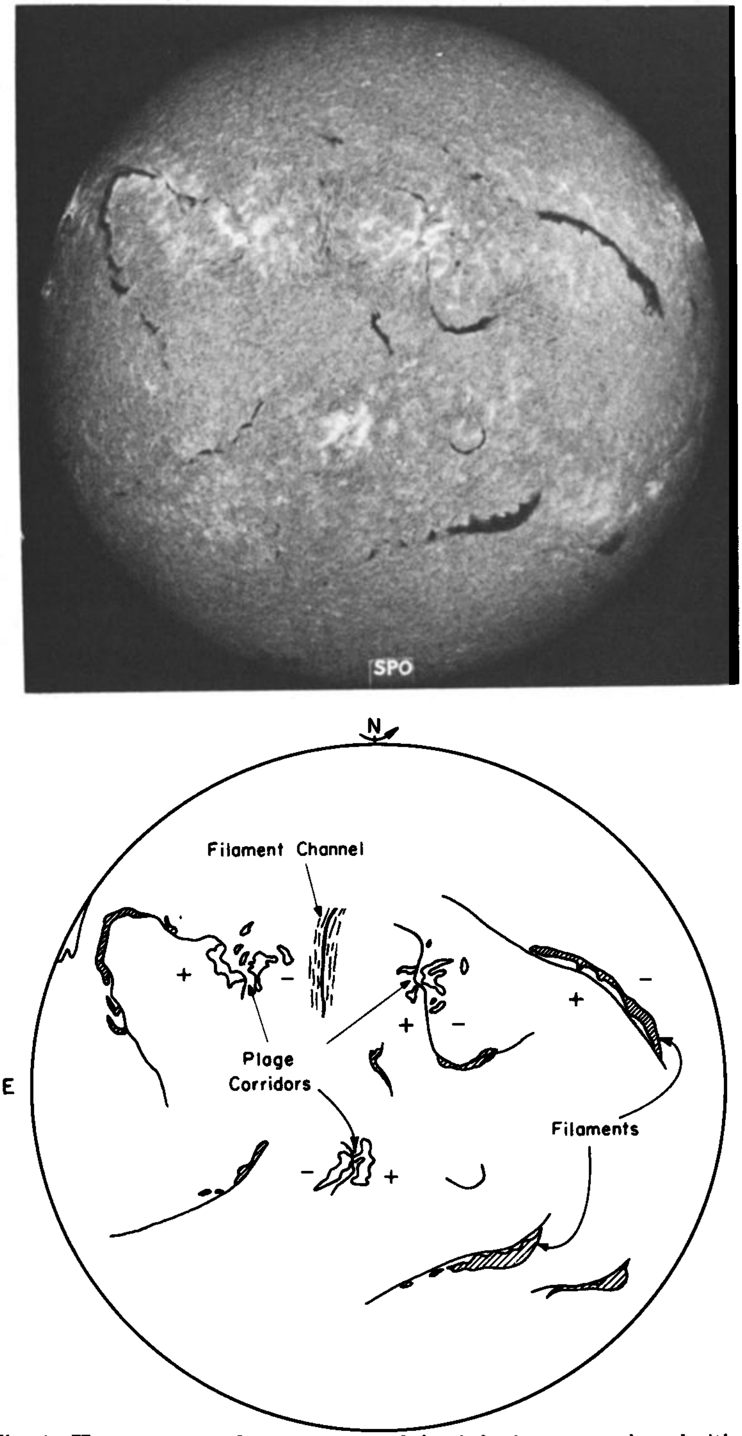
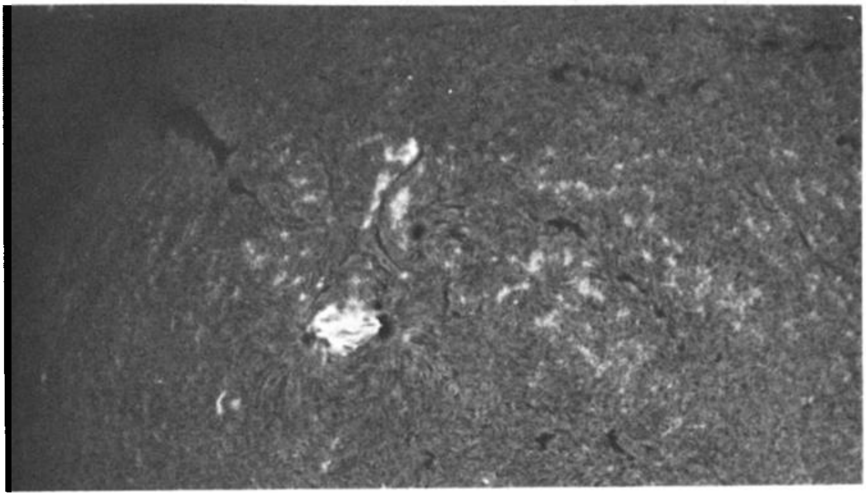


Fig. 1 Hα patterns and structures used for inferring magnetic polarities. Hα patrol filtergram for January 2, 1969, from the Sacramento Peak Observatory, Air Force Cambridge Research Laboratories. [From *McIntosh,* 1972*a*.]



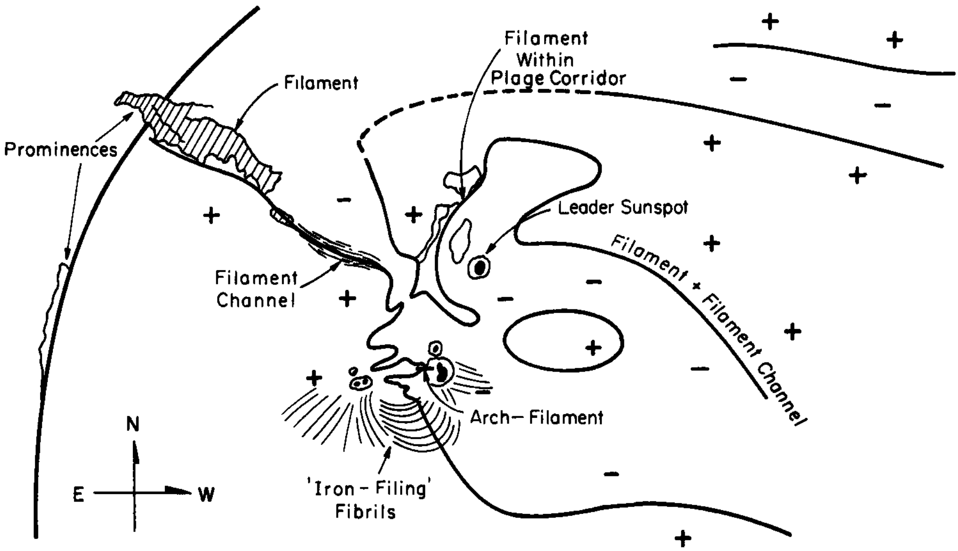


Fig. 2. Photograph enlarged from patrol filtergram obtained by the NOAA-operated NASA Solar Particle Alert Network observatory in Boulder, Colorado, on June 18, 1968. Inferred neutral lines and polarities are indicated below.

of the past five years. These structures are illustrated in Figures 1 and 2 as seen on small-scale, full-disk filtergrams from flare patrol films. Their identification is particularly easy on the high-resolution emulsions in use since 1966.

Filaments are fencelike clouds of gas with heights of about 50,000 km, a thin profile of about 7,000 km, and lengths up to the diameter of the sun. Filaments consistently lie on the line between regions of opposite polarity except in the vicinity of sunspots or complex plage. Filament channels are patterns of fine, linear structures (fibrils) that form bands that lie in the same positions as filaments. The filament channel sometimes forms before the filament and often appears after a filament disappears. Filament channels connect separated segments of filaments, connect filaments to active regions, and sometimes connect one active center to another. Fibrils are the linear structures that give the impression of iron filings in a magnetic field. There are now numerous comparisons of magnetic fields and Hα that indicate that these structures do map the lines of force lying parallel to the solar surface in the chromosphere. Arch-filament systems are small but vivid bright areas with embedded absorption features that signal the emergence of new bipolar flux loops from beneath the solar surface [*Bruzek*, 1967]. The dark absorption features mark the top of the loops, where the polarity reverses sign. Plage corridors are lanes occurring between areas of bright plage of opposite polarity. Most active centers evolve into two distinct clusters of plage and sunspots corresponding to the two polarities. Plage and sunspots both are responses to localized strong magnetic fields. Plage forms at field strengths an order of magnitude lower than the strength for sunspots. Sunspots are best seen in integrated sunlight; plage is best seen in monochromatic light from spectral lines formed in the chromosphere.

The five basic Hα features are used as interconnecting and complementing patterns. Filaments and filament channels extend into plage corridors or blend with the bipolar pattern of fibrils surrounding active centers. Difficulties in identifying one type of structure can be compensated by inferring its identity from its location relative to other structures. This complementation allows practical use of low-resolution observations and provides a means of mapping large-scale magnetic features.

The study of solar features as a function of time is a great aid in the interpretation of the features as magnetic fields. The arch-filament system soon evolves into a plage with a corridor perpendicular to the position of arch-filaments. Corridors grow wider with age and eventually form filaments and filament channels within them. The configuration of magnetic fields changes slowly from day to day, unless new active centers are forming, permitting magnetic maps of previous days to show where to expect polarity reversals today. The expanding magnetic fields from a new active center alter the patterns surrounding it, forming complex and confusing patterns during the process of blending new and old magnetic fields. Study of a time sequence of photographs covering a period of blending magnetic fields often removes much of the confusion in interpreting complex patterns. The sign of polarities can be inferred by using some well-behaved patterns of active region formation. Polarities of all regions are assigned by first identifying leader spots or leader plage in regions arranged in the typical east-west orientation and then alternating polarities across each inferred line of polarity reversal. We refer the reader to *McIntosh* [1972*a*] for more detailed discussion of the inference procedures.

ACCURACY OF INFERRED SOLAR MAGNETIC FIELDS

It has not been readily accepted that magnetic fields can be derived from these observations of Hα structures. The simple relationships between the Hα

features and magnetic fields mentioned previously are valid in a statistical sense with a correlation slightly less than 100%. It is easy to find counterexamples to these relationships, or at least it is easy to find active areas on the sun that are extremely difficult to analyze. Examples such as those in Figures 1 and 2 serve only to suggest the procedures for inferring magnetic fields. The use of a time series of photographs covering several days and the value of experience in dealing with many complex regions cannot be overemphasized as factors in obtaining successful inference of magnetic information from these observations.

Important support for the inference procedures comes from intensive use of these techniques in the NOAA (National Oceanic and Atmospheric Administration) Space Environment Forecast Services. Daily analysis has been made of all active regions since late 1969, with inference of polarities of the most active regions extending back to October 1967. Mt. Wilson polarity measurements for sunspots have been transmitted daily to Boulder for the same period, permitting continuous comparison of the inferred and measured data. Allowing for difficulties in directly measuring small spots and complex regions near the solar limb, the inferred data appear capable of correctly depicting the polarities of slightly more than 90% of the active regions. The best practice is to use Hα photographs together with directly measured magnetic fields, since there are situations where the chromospheric structures are very difficult to interpret. As more of the difficult areas are analyzed with the combined data, the interpretation of their complex features is becoming more clear.

The combination of filaments and filament channels maps much of the large-scale distribution of weak magnetic fields (Figure 1) lying outside active regions. Synoptic charts of the entire sun (Figure 3) have been constructed for the large-scale Hα features for most of the period 1967–1969 and for selected periods in 1970 and 1971. These large-scale maps have been compared with the full-disk magnetograms made daily at the Mt. Wilson Observatory and, as in the comparison with sunspot polarities, the agreement is nearly perfect. Three solar rotations have been selected at random for a detailed comparison of the inferred and measured magnetic patterns and polarities. Only solar latitudes within 40° of the solar equator were compared, since the effects of foreshortening and extremely weak field strengths provide the magnetograph with little meaningful signal at higher latitudes. Synoptic maps from the two sources were in perfect agreement over all but 1% of the solar surface.

The few areas of disagreement are difficult to evaluate numerically, since the importance of the disagreement depends on the use made of the data. In some areas of weak magnetic fields the Hα structures are not sufficiently ordered by the magnetic field to allow inference of polarity reversals. On the other hand, other areas of equally weak fields contain filaments or filament channels that allow continuation of inferred neutral lines into areas of little or no signal on the magnetogram. Plage corridors and embedded filaments in bright plage can become so narrow that poor atmospheric seeing conditions cause them to go undetected on the Hα photographs, thus leading to many of the differences between inferred and measured magnetic maps. Small isolated poles of one polarity often are seen on the magnetogram but are missed on the inferred maps because these poles are

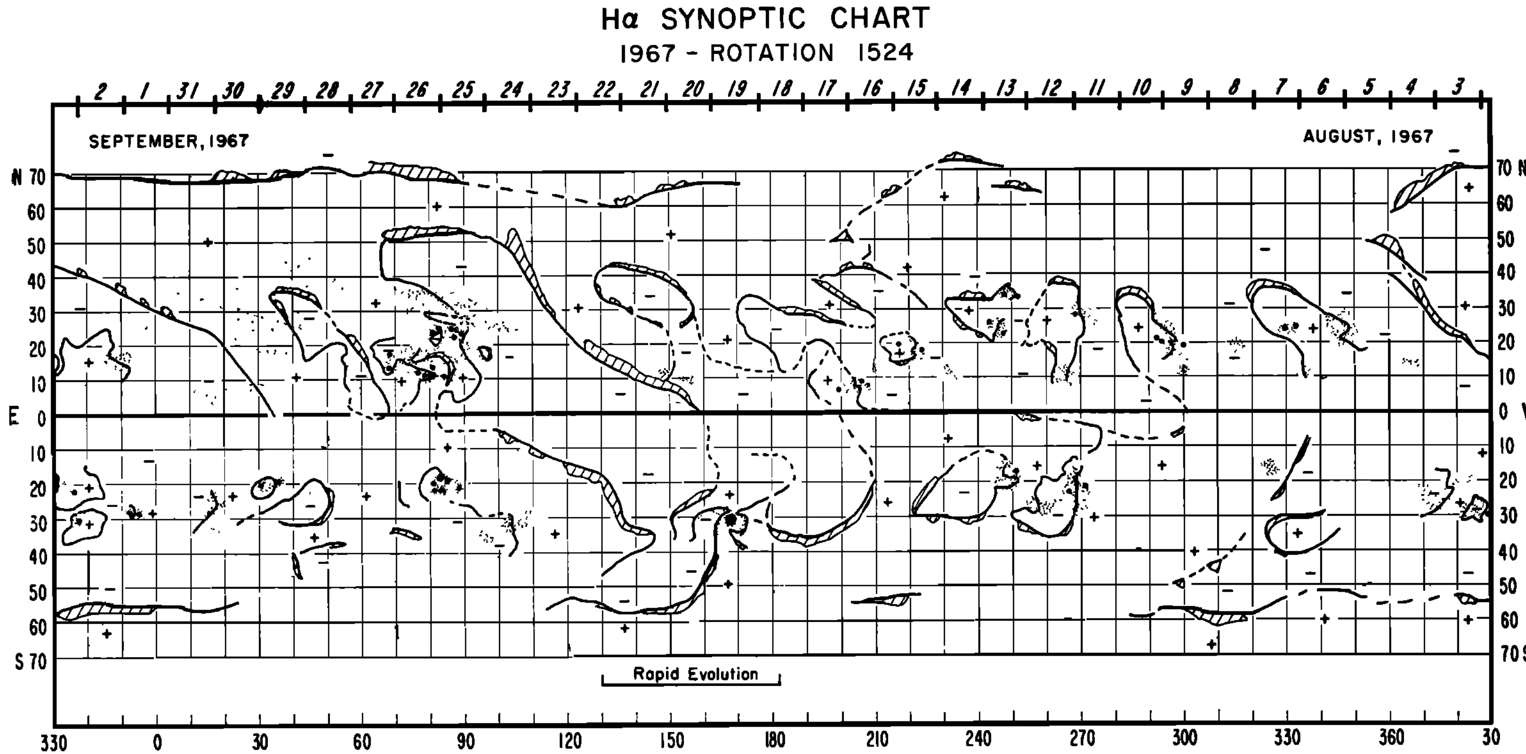


Fig. 3. The Hα features showing polarity reversals were mapped for an entire solar rotation to form this synoptic chart of the entire sun. Filaments are cross hatched, filament channels are solid lines, estimated or extrapolated lines are dashed, plage is light stipple, and sunspots are heavy dots.

seldom part of the interrelated systems of structures basic to the inference procedures. Fortunately, most of the small isolated poles are short-lived features associated with only minor solar activity.

ADVANTAGES OF INFERRED MAGNETIC-FIELD DATA

The use of Hα photographs as a source of solar magnetic-field data provides a number of important advantages over the conventional magnetograph. These benefits more than offset the occasional problems that result from the subjective interpretation of the complex and often ill-resolved fine structures in the Hα photographs. The chief advantages of the inferred magnetic-field data can be listed as (*a*) low cost; (*b*) high time resolution; (*c*) rapid access to the data; (*d*) global distribution of existing observatories with fast communications to central analysis centers; (*e*) reliable production of data on every day; (*f*) data base extending over 70 years; (*g*) improved mapping of active regions near the solar limb; (*h*) mapping of transverse magnetic fields through use of the 'iron filing' fibril structures; (*i*) direct association of active regions with large-scale magnetic-field patterns; (*j*) more complete and more sharply defined boundaries to large-scale magnetic-field patterns.

APPLICATIONS

These advantages suggest a number of applications for the inferred solar magnetic-field data. The necessity that led to formulating procedures for making systematic use of inferred solar magnetic-field data was the need for improved solar-flare forecasts. *Smith* [1972] and *Lemmon* [1972] have demonstrated the utility of Hα data in this application. The improved information on large-scale magnetic fields implies an improved source of information on the origin and evolution of structures in the solar corona [*McIntosh,* 1972*b*]. Hα can supplement magnetograph data in the computation of coronal fields [*Newkirk and Altschuler,* 1970; *Schatten et al.,* 1969], and an independent estimate of the coronal forms can be made by assembling a map based on correlations between coronal forms and underlying Hα patterns (*Bohlin* [1970]; S. F. Hansen, R. T. Hansen, and C. J. Garcia, 'Evolution of Coronal Helmets during the Ascending Phase of Solar Cycle 20,' High Altitude Observatory preprint, 1972).

SUMMARY

Solar magnetic fields inferred from Hα observations can be criticized for being less 'objective' than data from solar magnetographs. Philosophers and scientists since Plato have distrusted the impressions gained from the human senses. This distrust has evolved in the unfortunate direction of requiring that scientific truth come from electronic computers, and that the greater the abstraction the purer and higher the truth. The magnetograph separates the parameter of magnetic-field strength from the context of two- and three-dimensional forms involved in the magnetic fields. The inferred magnetic patterns retain much of this important context and are therefore less an abstraction of the sun. It is this context superposed on magnetic-field strength that leads to the perception of large-scale associations. It is this context that provides a system of checks on the accuracy of inferred polarity reversals. The inference procedures are basically procedures of pattern recognition blended with a large memory for complex patterns of past observations and their correlations with measured magnetic fields. Pattern recognition is a task at which the human mind excels. Human, 'subjective' data processing is required for reasons of speed and efficiency. The disadvantages of subjective processing of the Hα images are minor concessions for the richer content of the inferred magnetic-field maps.

It has been the intention of this review to show that Hα solar-patrol observations have much more to offer than a means to record solar flares. The careful interpretation of Hα fine structure converts the flare patrol into a 'poor man's magnetograph.' This use of Hα observations does not compete with the solar magnetograph, but complements it. Accurate and objective measures of polarities and field strengths must continue to come from the magnetograph, but their interpretation is improved by adding the patterns derived from Hα observations. The inferred magnetic fields do compete with the magnetograph when speed, economy, 24-hour coverage, and complete reliability are required. For these reasons, solar-activity forecasting will continue to rely on inferred data for some time to come.

The new perspective on large-scale magnetic patterns gained from Hα may become the most important result of attempts to infer magnetic fields from flare-patrol films. The evolution of magnetic fields from young emerging bipolar regions to expansive weak fields in the polar regions of the sun becomes clear in the inferred magnetic patterns. A more fundamental understanding of solar magnetism may come from a study of large-scale Hα patterns. The tie between interplanetary magnetic fields and the sun may become more complete as inferred magnetic patterns are correlated with satellite observations. From these studies will come new understanding of the interplanetary medium.

REFERENCES

Babcock, H. W., The solar magnetograph, *Astrophys. J., 118,* 387, 1953.

Babcock, H. W., and H. D. Babcock, The sun's magnetic field 1952–1954, *Astrophys. J., 121,* 349, 1955.

Bhatnagar, A., Fine-scan velocity and magnetic-field measurements in solar active regions, *Solar Phys., 16,* 40, 1971.

Bohlin, J. D., Solar coronal streamers, 2, Evolution of discrete features from the sun to 1 AU, *Solar Phys., 13,* 153, 1970.

Bruzek, A., On arch-filament systems in spotgroups, *Solar Phys., 2,* 451, 1967.

Davis, Jr., L., Mariner II observations relevant to solar fields, in *Stellar and Solar Magnetic Fields,* edited by R. Lüst, pp. 203–207, Interscience, New York, 1965.

Hale, G. E., On the probable existence of magnetic fields in sunspots, *Astrophys. J., 28,* 315, 1908.

Hale, G. E., The fields of force in the atmosphere of the sun, *Nature, 119,* 708, 1927.

Howard, R., Ed., *Solar Magnetic Fields,* I.A.U. Symposium 43, D. Reidel, Dordrecht, Netherlands, 1971.

Lemmon, J. J., Forecasting flares from inferred magnetic fields, in *Solar Activity Observations and Predictions,* edited by P. McIntosh and M. Dryer, MIT Press, Cambridge, Mass., in press, 1972.

McIntosh, P. S., Inference of solar magnetic polarities from H-alpha observations, in *Solar Activity Observations and Predictions*, edited by P. McIntosh and M. Dryer, MIT Press, Cambridge, Mass., in press, 1972*a*.

McIntosh, P. S., Large-scale solar magnetic fields and H-alpha patterns, in *Proceedings of the Asilomar Solar Wind Conference, NASA Spec. Publ.*, edited by D. S. Colburn, C. P. Sonett, and J. M. Wilcox, in press, 1972*b*.

Ness, N. F., and J. M. Wilcox, Solar origin of the interplanetary magnetic field, *Phys. Rev. Lett., 13,* 461, 1964.

Newkirk, G., and M. Altschuler, Magnetic fields and the solar corona, 3, The observed connection between magnetic fields and the density structure of the corona, *Solar Phys., 13,* 131, 1970.

Ramsey, H. E., and S. F. Smith, Solar filament structure, *Rep. LR-20444,* Lockheed Solar Observ., Burbank, Calif., 1966.

Schatten, K. H., J. M. Wilcox, and N. F. Ness, A model of interplanetary and coronal magnetic fields, *Solar Phys., 6,* 442, 1969.

Severny, A., J. M. Wilcox, P. H. Scherrer, and D. S. Colburn, Comparison of the mean photospheric magnetic field and the interplanetary magnetic field, *Solar Phys., 15,* 3, 1970.

Smith, H., and E.v.P., Smith, *Solar Flares,* 322 pp., MacMillan, New York, 1963.

Smith, J. B., Predicting activity levels for specific locations within solar active regions, in *Solar Activity Observations and Predictions,* edited by P. McIntosh and M. Dryer, MIT Press, Cambridge, Mass., in press, 1972.

Tandberg-Hanssen, E., *Solar Activity,* 464 pp., Blaisdell, Waltham, Mass., 1967.

Veeder, G. J., and H. Zirin, The chromospheric magnetograph, *Solar Phys., 12,* 391, 1970.

Wilcox, J. M., The interplanetary magnetic field, solar origin, and terrestrial effects, *Space Sci. Rev., 8,* 258, 1968.

Zirin, H., *The Solar Atmosphere,* 495 pp., Blaisdell, Waltham, Mass., 1966.

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