CORONAL HOLES AND SOLAR MAGNETIC FIELDS†

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Abstract. Since 1972, nearly continuous observations of coronal holes and their associated photospheric magnetic fields have been made using a variety of satellite and ground-based equipment. The results of comparisons of these observations are reviewed and it is demonstrated that the structure and evolution of coronal holes is basically governed by the large-scale distribution of photospheric magnetic flux. Non-polar holes form in the decaying remnants of bipolar magnetic regions in areas with a large-scale flux imbalance. There is strong indirect evidence that the magnetic field in coronal holes is always open to interplanetary space but not all open-field regions have associated coronal holes. The well-observed declining phase of the last solar cycle was characterized by stable magnetic field and coronal hole patterns which were associated with recurrent, high-speed wind streams and interplanetary magnetic field patterns at the Earth. The ascending phase of the current cycle has been characterized by transient magnetic field and coronal hole patterns which tend to occur at high solar latitudes. This shift in magnetic field and coronal hole patterns has resulted in a less obvious and more complicated association with high-speed wind streams at the Earth.

1. Introduction

It has been known for many years that exceptionally low density regions exist in the inner solar corona, especially at the Sun's poles (Waldmeier, 1957). Such features are now called coronal holes. Over 90 years ago the general appearance of the corona at times of total solar eclipses suggested the presence of a fairly strong, large-scale coronal magnetic field (Bigelow, 1889). It is now known that solar magnetic fields dominate the structure and dynamics of the lower corona and also influence the structure of the heliosphere well past the orbit of the Earth. The purpose of this review is to describe research which ties together the separate phenomena of coronal holes and solar magnetic fields.

The study of coronal holes has been a major part of solar physics research in the 1970's for several reasons. Among these reasons are the appreciation that coronal holes are major factors in the mass and energy flows of the corona and that the holes may provide diagnostic information about physical processes inside the Sun. In addition, coronal holes appear to be the base of high-speed solar wind streams which frequently cause geomagnetic storms; holes are the long-sought 'M-regions' of Bartles (1932). Coronal hole research has also been greatly stimulated by the

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availability of excellent sets of observations obtained by various spececraft experiments. Especially valuable were observations conducted on the Skylab satellite during June 1973 through January 1974.

Coronal hole research has resulted in a large number of publications including several excellent review papers (Bohlin, 1976; Wilson, 1976; Zirker, 1976; Zirker, 1977a; Orrall, 1977) and a monograph consisting of results from a workshop on coronal holes and high-speed solar wind streams (Zirker, 1977b). The major part of the research and review literature concerns the observations obtained with Skylab and it is widely recognized that this period, while possibly typical of one phase of a solar cycle, does not represent all phases of a cycle. In this review we have tried to broaden the base of the Skylab results by including results from observations obtained during the five years since the Skylab mission. However, the scope of this paper is limited to results of research which link coronal holes and solar magnetic fields. We emphasize that our knowledge regarding cycle variations is still incomplete since high-quality observations are not yet available which cover a complete solar cycle.

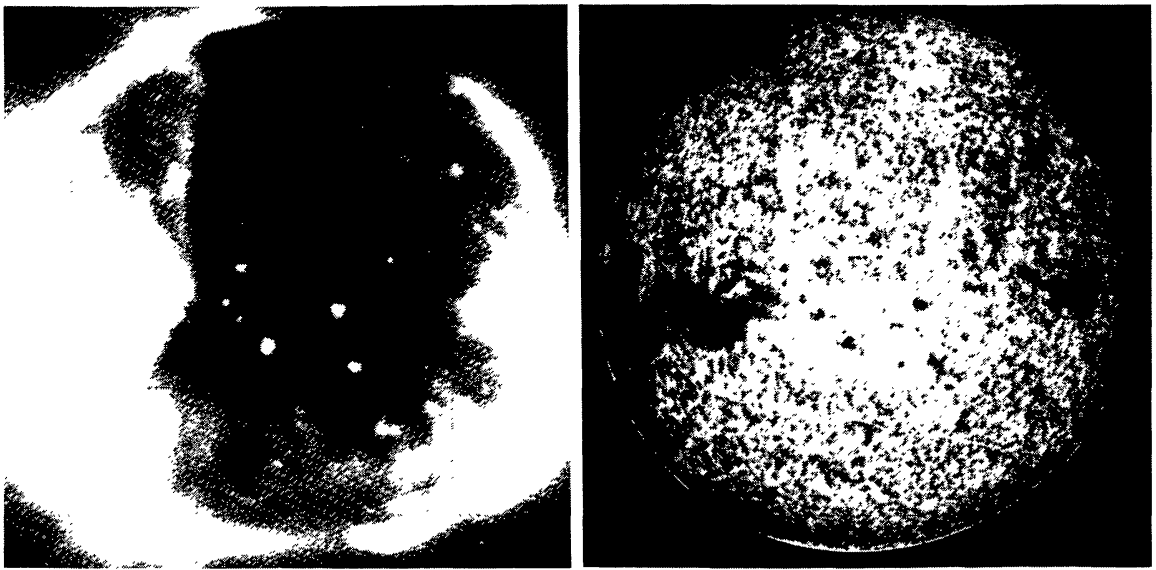
2. The Nature of the Observations

2.1. CORONAL HOLES

Any technique which reveals the corona is suitable, in principle, for the study of coronal holes. Bohlin (1977a) gave a detailed review of various techniques. The most dramatic observations of coronal holes are those obtained at soft X-ray wavelengths which show the corona against the solar disk. Once such observation of a large coronal hole is shown in Figure 1.

At longer wavelengths, broad-band observations from roughly 250 to 630 Å reveal coronal holes (Brueckner and Bartoe, 1974). So do spectroheliograms made in various emission lines formed at temperatures above 5×10^5 K. Below this temperature coronal holes become difficult to detect (Huber *et al.*, 1974). However, the ultraviolet helium line and continuum radiation (formed in the transition region and chromosphere) is unique among low-temperature radiations in showing coronal holes prominently as a weakening of the chromospheric network. The reasons for this anomalous behavior are not well understood (Mango *et al.*, 1978).

None of the above types of observations are regularly available. Nor are total solar eclipses regularly available but they do provide an extensive historical base of coronal hole observations which has not yet been exploited in the light of recent advances. Artificial eclipses produced using ground and satellite-based, visible-light coronagraphs have been used to study coronal holes (e.g., Fisher and Musman, 1975; Altschuler *et al.*, 1972; Hansen *et al.*, 1976; Munro and Jackson, 1977). Since these observations are limited to the corona which is visible above the solar limb, the rapid evolution of a particular feature which is seen only twice per solar rotation cannot be followed.



1948 UT AS & E 8-37,44-60 Å 1700-1740 UT KPNO 10830 Å

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Fig. 1. Nearly simultaneous images of the Sun taken with soft X-rays (left) and He I 10830 Å (right). In this and all other illustrations north is at the top and east to the left. A large coronal hole is visible in the X-ray image as a dark area covering the central part of the disk. The hole appears on the helium image as a bright area of generally reduced helium absorption and especially reduced visibility of the dark chromospheric network. (X-ray photograph courtesy of American Science and Engineering.)

Fortunately, the unique behavior of the helium emission in the ultraviolet pertains as well to helium absorption lines accessible from the ground (Harvey and Sheeley, 1977) and it is possible to infer the location of coronal holes from He I 5876 Å (Harvey *et al.*, 1974) and He I 10830 Å (Harvey *et al.*, 1975; McCabe *et al.*, 1977) spectroheliograms which can be obtained regularly. One of these observations is shown in Figure 1. A program of regular 10830 Å spectroheliograms has been carried out at Kitt Peak starting in 1974 and these data provide the basis for much of the remainder of this paper. It is important to emphasize that these observations do not show the corona directly so that holes can only be inferred. On the other hand the observations offer the advantage of allowing holes to be traced down to specific structural features in the chromosphere and photosphere which are not visible in coronal observations.

Manifestations of coronal holes have been sought in ground-based observations of other visible spectral lines (Munro and Withbroe, 1972; Vaiana *et al.*, 1973; Marsh, 1977) but the effects, while physically important, are too subtle for use in routine mapping.

Coronal holes have also been sought at various radio wavelengths: 3.5 mm (Kundu and Liu, 1976), 8.6 mm and 2.0 cm (Wefer and Bleiweiss, 1976), 3 cm (Fürst and Hirth, 1975), 3.8 cm (Wefer and Papagiannis, 1977), 8 cm (Shibasaki *et al.*, 1978), 10.7 cm (Covington, 1977), 11.5 and 21 cm (Papagiannis and Wefer, 1978), 21 cm (Dulk *et al.*, 1977), 73 cm and 1.8 m (Chiuderi Drago *et al.*, 1977) and 1.8 and 3.75 m

(Dulk *et al.*, 1977). According to the analysis of the radio spectrum of coronal holes by Wefer and Papagiannis (1977) coronal holes at radio wavelengths first become visible as slight intensity enhancements around 2 cm and then intensity reductions increasing in contrast from 2.8 cm to a maximum contrast around 21 cm. The contrast decreases at longer wavelengths until the holes are no longer visible at 3.75 cm. Figure 2 illustrates the appearance of coronal holes at two different radio wavelengths.

In all coronal hole observations it is necessary to distinguish between true coronal holes and the low-intensity coronal regions surrounding prominences known as filament cavities or channels. At times of high activity, drawing this distinction can be difficult (Broussard *et al.*, 1978).

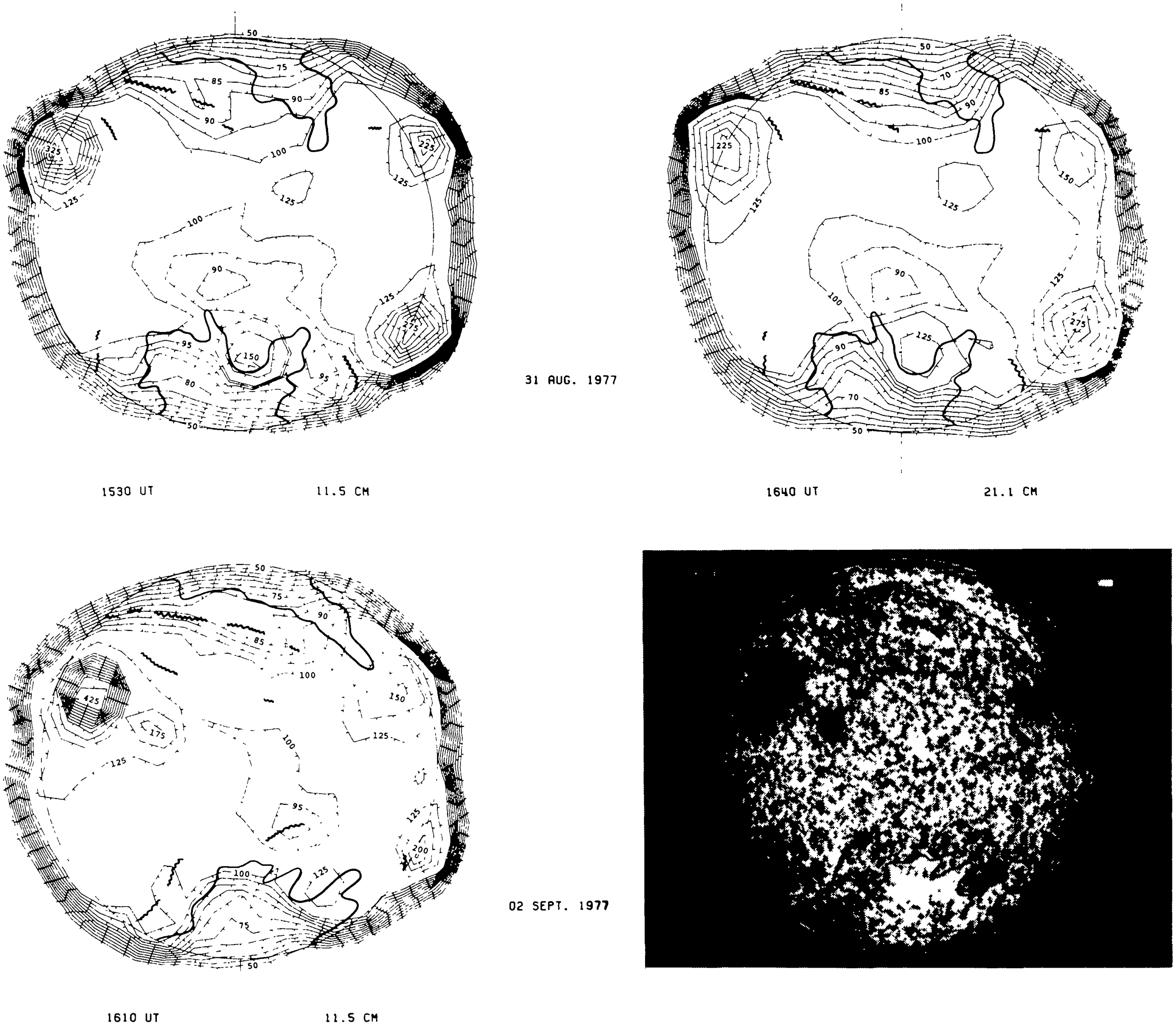

Fig. 2. A comparison between three radio heliograms and a He I 10830 Å image. The solid dark lines are boundaries of the polar coronal holes inferred from helium observations. The left images were obtained at a wavelength of 11.5 cm and the right radio image at 21.1 cm. The upper images were made on 31 August 1977 and the lower images on 2 September 1977. Jagged lines indicate the location of prominences. (Courtesy of M. D. Papagiannis and F. L. Wefer (1978).)

The quality and frequency of coronal hole observations have steadily increased with time. Ground-based coronagraph observations have long been available, but are best suited to the study of large, stable holes since only observations at limb passages are possible. Since the early 1960's occasional rocket flights have produced useful hole observations (Broussard *et al.*, 1978). The OSO-4, -6, -7 satellites provided hole observations during the intervals October to November 1967, August 1969 to May 1970, and October 1971 to about December 1973 respectively. Very high quality hole observations were obtained with telescopes on board Skylab from June 1973 to January 1974 from which two hole atlases have been prepared (Bohlin and Rubenstein, 1975; Nolte *et al.*, 1976). Since February 1974 the disk locations of holes have been inferred from 10830 Å spectroheliograms taken regularly at Kitt Peak. It is expected that satellite observations of holes will resume in winter 1979 with the launching of the Naval Research Laboratory XUV monitor and white-light coronagraph on the USAF Space Test Program Satellite P78-1.

Thus regular observations of coronal holes suitable for detailed analysis of evolution and comparison with magnetic fields are available from late 1971 to the present, i.e., during the last four and one-half years of solar cycle 20 and the first two years of cycle 21, or only slightly more than half a solar cycle.

2.2. Magnetic fields

Dulk and McLean (1978) have recently reviewed measurements of coronal magnetic fields. None of the available techniques are applicable to coronal holes and it is necessary to rely on extrapolations from observations of magnetic fields in the photosphere. Techniques for measurement of photospheric fields have been reviewed many times (e.g., Harvey, 1977; Livingston, 1977; Stenflo, 1978). Briefly, the most reliable techniques provide maps of the *line-of-sight component* of the photospheric magnetic field averaged over a spatial area from a second of arc or so to several arc minutes. These measurements are subject to several systematic effects which require careful attention by users of quantitative results. At the present time it appears that measurements made at Kitt Peak, for example, are probably not systematically in error by more than a factor of two.

A useful technique for inferring the locations of boundaries between large-scale, opposite magnetic polarity regions has been developed by McIntosh (1972), based on the effect of magnetic fields on chromospheric structures visible in the Hα photographs. A direct comparison of the inferred boundaries (neutral lines) and those observed with low-resolution, high-accuracy magnetograms shows reasonably good agreement (Duvall *et al.*, 1977).

A key result from magnetic field observations for the purposes of this paper is that although the photospheric structure of the magnetic field is dominated by fragmented, fine-structured elements, these elements are organized into clearly defined, large-scale patterns. These patterns consist of large areas (cells) within which one magnetic polarity dominates.

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3. Comparisons Between Coronal Hole and Magnetic Field Observations

Nearly all published comparisons of holes and magnetic fields refer to the period of Skylab observations (June 1973–January 1974). In this section some of the major conclusions of these studies will be presented and confronted with more recent data. Again we note that little more than half a solar cycle of regular observations are available and general conclusions may be premature. We draw heavily on the summaries by Bohlin (1977a), Kreiger (1977), and Levine (1977a).

3.1. CORONAL HOLE LOCATIONS

(1) Coronal holes are present nearly all the time at the Sun's poles and their area waxes and wanes with the net amount of magnetic flux present at the poles (Broussard *et al.*, 1978). Recent unpublished observations suggest a decrease in the amount of magnetic flux at the poles, especially in the north where new-cycle activity has been stronger. This magnetic flux decrease has been accompanied by poleward movement of the stable pole-hole boundaries from a latitude of about 60° to roughly 70°, thus confirming the conclusions from earlier observations. We expect the polar holes to shrink further with the continued development of the new solar cycle and the attendant weakening of the polar magnetic field.

(2) Coronal holes occur at all latitudes and are frequently connected to the polar holes. This result continues to be true in recent observations although the relative frequency of both low-latitude holes and of holes connected to the poles is declining. At the present time most holes appear at mid- to high-latitudes (Sheeley and Harvey, 1978).

(3) With the exception of observations made with the helium lines; the chromosphere, photosphere and magnetic field beneath coronal holes are undistinguished from other quiet regions (Altschuler *et al.*, 1972; Vaiana *et al.*, 1973; Gurman *et al.*, 1974; Levine, 1977b). Marsh (1977) detected a subtle intensity reduction in the chromosphere beneath a hole observed with Ca II 3933 Å and the polar coronal holes are visible on a spectroheliogram made in the blue emission peak of Lα (Bruner, 1977), but otherwise the conclusion is still valid. In particular, comparison of 4 yr of magnetic and hole observations at Kitt Peak has not led to any method of determining the location of coronal holes from a simple inspection of magnetic field observations. Figure 3 illustrates the undistinguished nature of the photospheric magnetic field beneath coronal holes. Finally, a recent study of the 5-min oscillation of the photosphere shows no difference in and out of hole regions (Dittmer *et al.*, 1978).

(4) Coronal holes are located within large-scale magnetic areas dominated by one polarity and having a diverging (open) field geometry (Altschuler *et al.*, 1972; Vaiana *et al.*, 1973; McIntosh *et al.*, 1976; Bohlin and Sheeley, 1978). The large-scale unipolar areas within which holes are located are not well visible in Figure 3. When the spatial resolution is reduced and contrast enhanced we confirm the first of the conclusions. However, the balance between positive and negative flux is sometimes

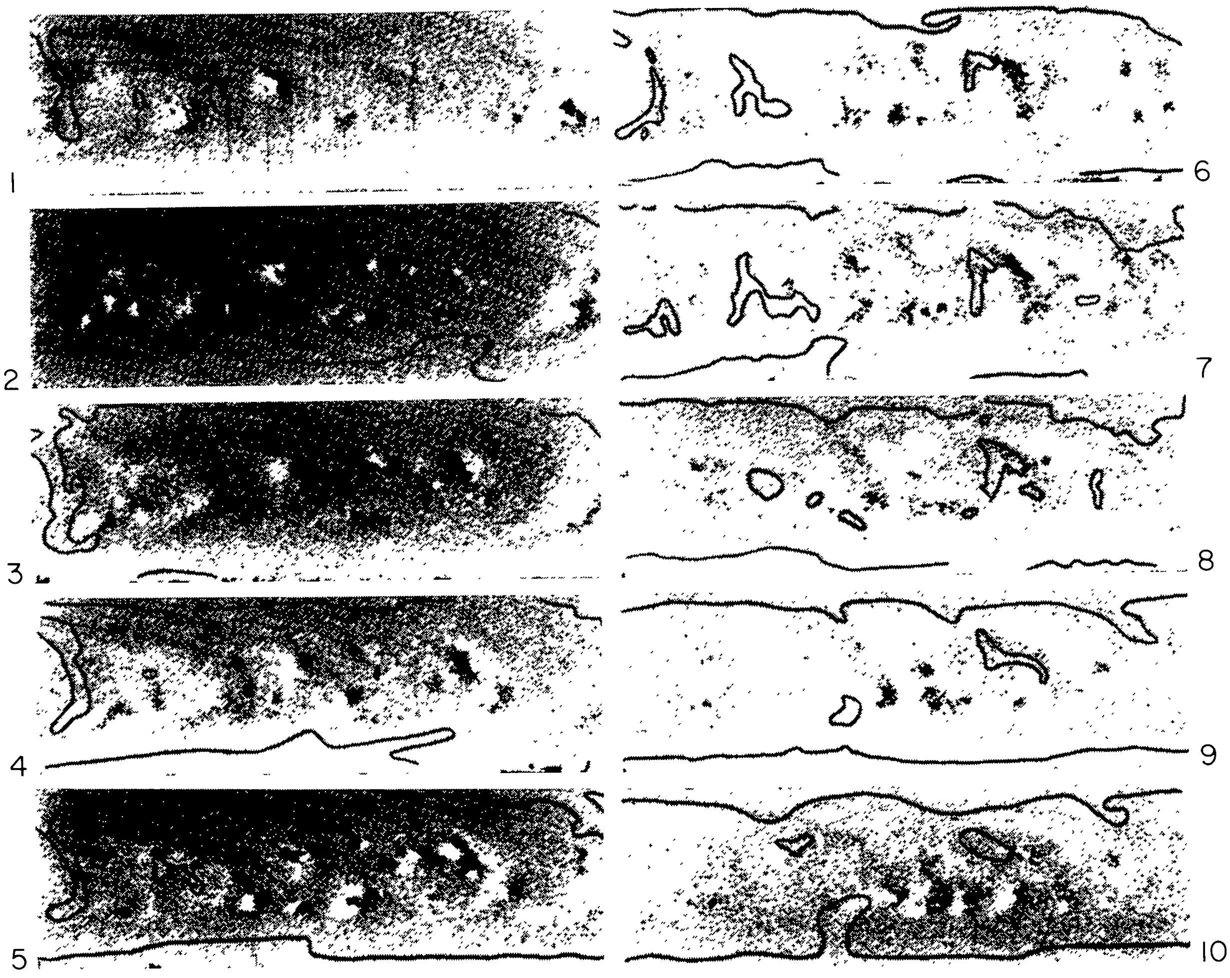

Fig. 3. Synoptic maps of the line-of-sight component of the solar magnetic field covering Carrington rotations 1601–1610 (May 1973–January 1974, the Skylab period). The boundaries of coronal holes, with a few gaps in coverage, are drawn in black lines. Each map is an equal-area cylindrical projection with the north pole at the top and the south pole at the bottom. Note the great area of the polar coronal holes. Carrington longitude increases to the right. Positive (negative) magnetic fields are shown as darker (brighter) than gray.

so close that the dominance of one polarity becomes difficult to establish quantitatively. On a small scale the magnetic field beneath a hole may locally be of opposite polarity to the average throughout the hole area. This seems not to have any local effect on the hole and we conclude that the coronal hole is a phenomenon of the large-scale magnetic field. Evidence supporting the open geometry of the magnetic fields in holes is all indirect (Bohlin and Sheeley, 1978) and we return to this question in Section 4.

(5) The average magnetic field strength beneath holes ranges from 7 to 0.5 G and decreases with increasing age of the hole (Bohlin and Sheeley, 1978). Howard and Harvey (1976) compared Mt. Wilson and Kitt Peak magnetic field observations obtained during the Skylab mission and concluded that the average field strength in the photosphere under holes was typically 3 G. Svalgaard *et al.* (1978) have

concluded that during 1976–1977 the average polar field strength ranged from a peak of about 12 G at the poles to about 3 G at the equatorward boundary of the polar holes. In 1975 we observed low-latitude holes with average photospheric field strengths up to 15 G so it appears that the 7 G value given above should probably be doubled. Figure 4 is a qualitative example of the weakening of the average field with increasing hole age.

(6) Coronal holes tend to occur in magnetic regions having the same polarity as the polar caps in the same hemisphere (Bohlin, 1976; Bohlin and Sheeley; 1978). While this result was true during the Skylab period and has been valid in the subsequent 4 yr (e.g., Figures 4 and 5), there have been several holes which violate a

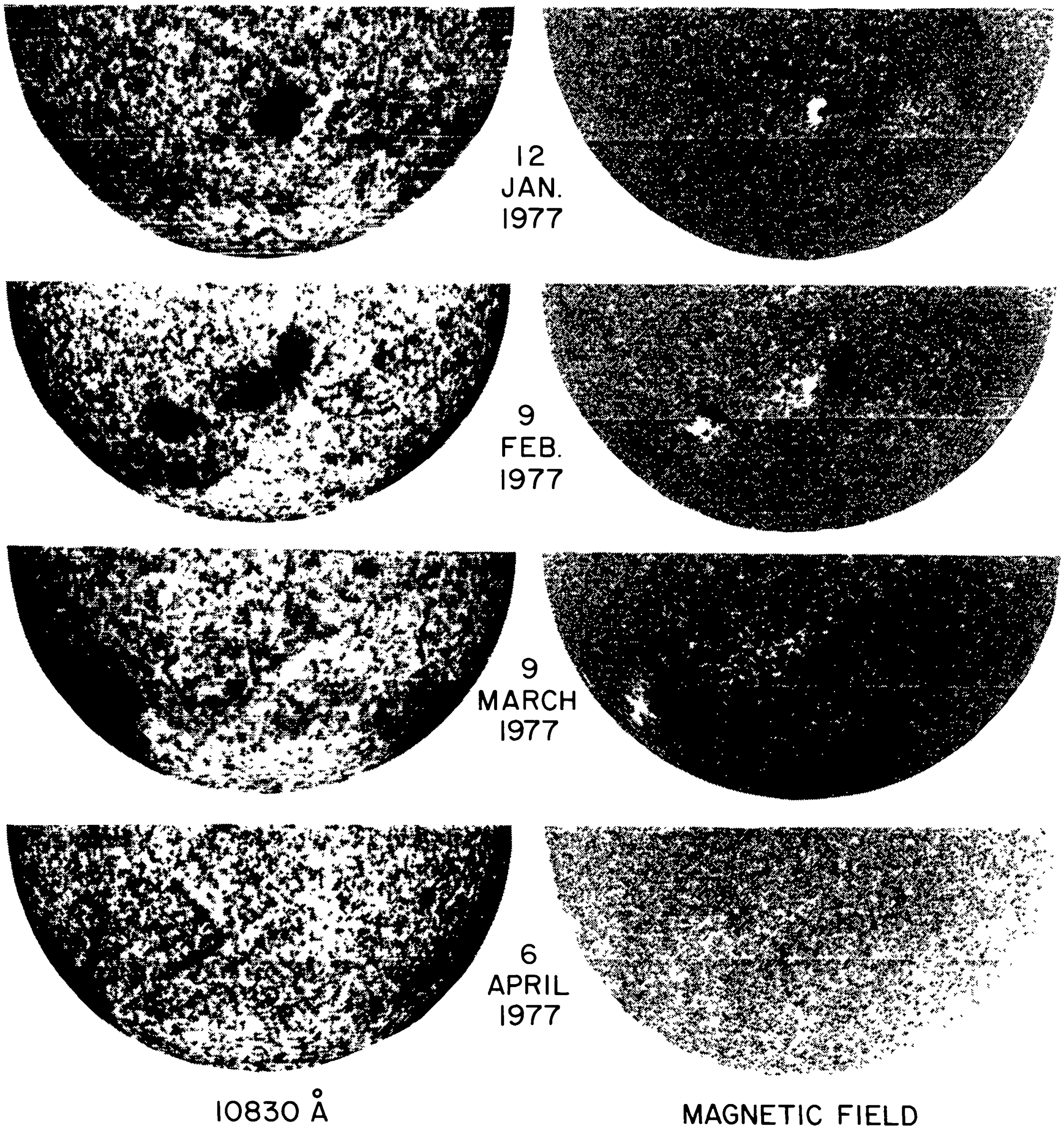

Fig. 4. The development of a weak coronal hole over four solar rotations. The hole is the slightly brighter area to the right of the dark active region in the 10830 Å images. The hole is connected to the polar hole in the middle two images.

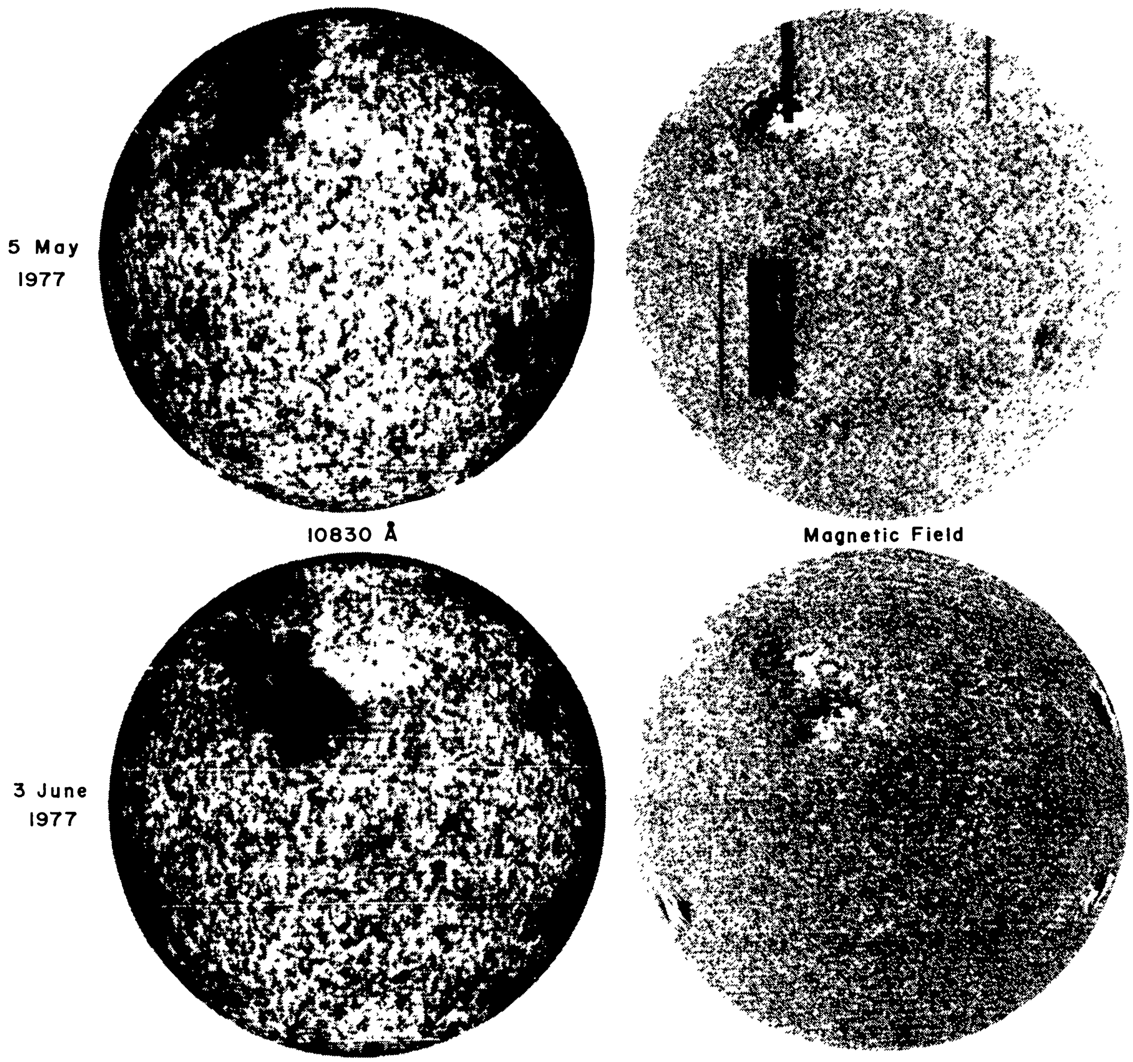

Fig. 5. Helium images (left) showing a coronal hole as a light region above the disk center compared with images of the line-of-sight component of the photospheric magnetic field (right). The lower pair of images was obtained 29 days later than the upper pair. The coronal hole has been strengthened by the favorable development of a new active region below the original one. Positive (negative) magnetic fields are shown as brighter (darker) than gray.

strict 'rule' (Sheeley and Harvey, 1978). Since the polar field around the time of the minimum of activity has the same polarity as the following (leading) parts of old (new) cycle active regions it follows that holes tend to form behind old cycle active regions and in front of new cycle regions. Again, this statement is generally true but there have been several exceptions (e.g., Figure 6).

(7) Coronal holes exist directly adjacent to disk activity (Bohlin and Sheeley, 1978). This statement requires qualification since the polar holes are obvious violations. Figures 4–6 show typical agreements with the statement away from the poles. However, there have been frequent examples of holes which appear to be far from any active regions at a given time, as for example, in Figure 4. In these cases, as shown in Figure 4, it is possible to trace the hole back to an origin adjacent to an

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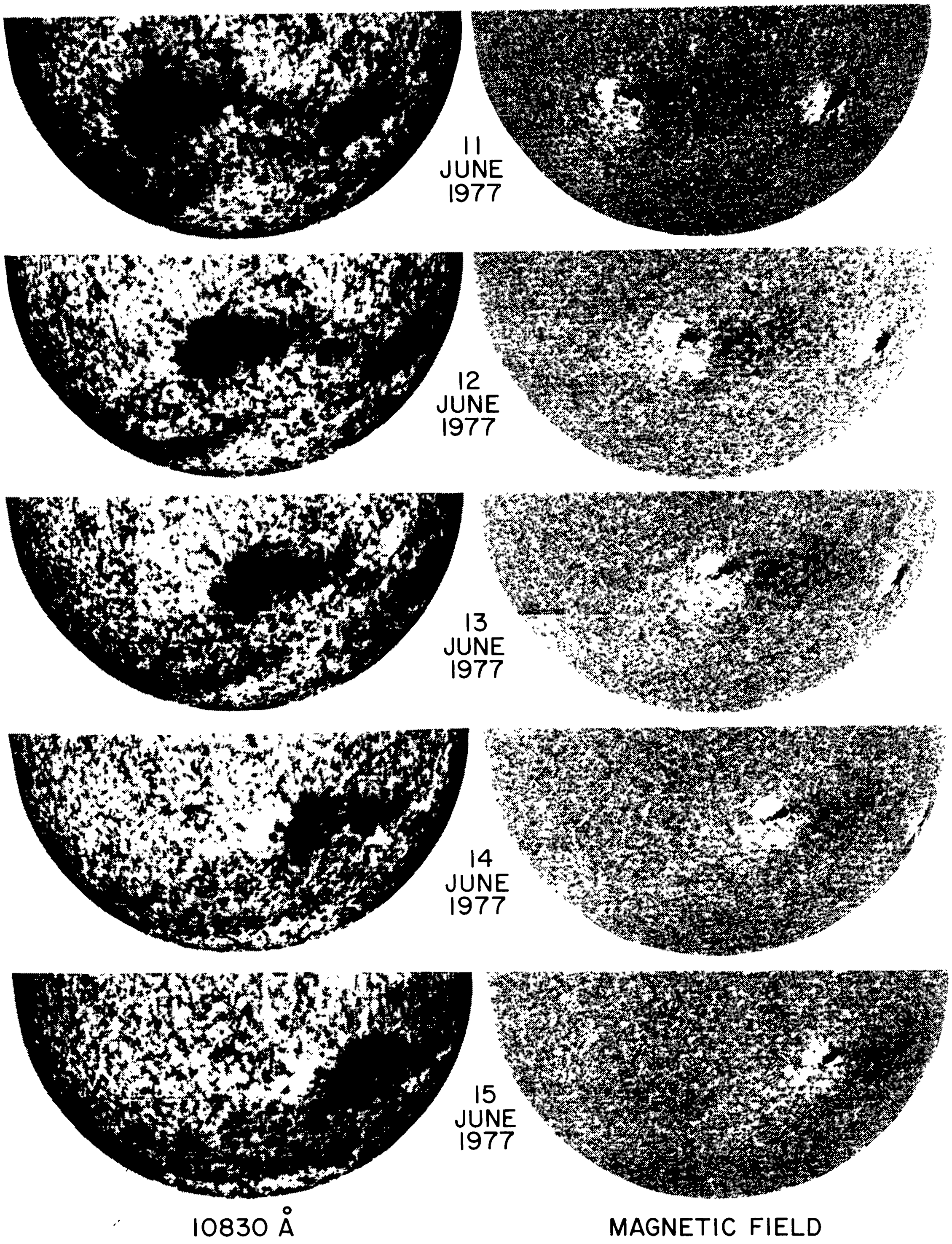

Fig. 6. Rapid birth and development of a coronal hole east (left) of a small active region. Holes usually form in the same magnetic polarity as the polar fields of the same hemisphere. This hole is a violation of that tendency.

active region at an earlier time. Thus, holes are the result of eruptions of magnetic flux. However, as Figure 3 demonstrates, not all flux eruptions produce holes.

3.2. Evolution and rotation of individual coronal holes

(1) The lifetime of coronal holes has a mean value of 6 solar rotations and a range from 3 to 20 (Bohlin, 1977b). This result applies to the Skylab period when large-scale magnetic patterns were unusually stable and of course excludes the polar holes. In the recent, ascending phase of solar cycle 21 long-lived magnetic patterns and holes are the exception rather than the normal rule (Sheeley and Harvey, 1978). The mean lifetime of coronal holes is now more nearly 1 or 2 rotations and the range is from 1 day to perhaps 8 rotations.

(2) The long-term areal growth and decay of holes occurs at a rate of about 1.5×10^4 km^2 s^{-1} which is consistent with the diffusion rate of magnetic fields (Timothy *et al.*, 1975; Bohlin, 1977b). The numerical value of this rate appears to be too large to fit the growth and decay rates of the polar holes on a time scale longer than the duration of the Skylab mission. A value of about 5×10^3 km^2 s^{-1} better fits the decay of the area of the polar holes since the end of 1973 and also the variation of polar hole area during the preceeding solar cycle (Broussard *et al.*, 1978). Of course the polar magnetic fields vary more slowly than lower-latitude magnetic regions and as noted earlier there is good agreement between the rates of growth and decay of the polar coronal holes and magnetic fields. Using more detailed definitions of diffusion rates Nolte *et al.* (1978a) and Mosher (1977) found rather discordant values of 8×10^3 km^2 s^{-1} and 3×10^3 km^2 s^{-1} for holes and magnetic fields respectively.

(3) The area of coronal holes changes mainly by sporadic, large-scale shifts of the boundaries (Nolte *et al.*, 1978a, b). There are two distinct parts to this statement. First, Nolte *et al.* (1978b) established that discrete changes of large portions of the boundaries of holes can occur on a short time scale. These changes appear to be primarily changes in emission rather than motion of structures. Second, Nolte *et al.* (1978a) established that the frequency and magnitude of discrete boundary changes are sufficient to account for the long-term variations of coronal hole area. They concluded that the evolution of holes is governed predominantly by a coronal process, probably the opening and closing of field lines. Nolte *et al.* (1977b) have also found evidence to suggest that the decay of coronal holes is accompanied by an increase in the number of small X-ray bright points (cf. Vaiana *et al.*, 1973) within the hole. These bright points are known to be associated with the eruption of small, bipolar magnetic regions (Golub *et al.*, 1977) so the implication is that the decay of coronal holes may be associated with an increase in the eruption of small-scale magnetic flux. Possibly related to this is the finding by Marsh (1978) that eruption of small-scale magnetic flux can significantly accelerate the effective diffusion rate of magnetic flux in the photosphere.

(4) The birth of a coronal hole takes place in less than a day (Solodyna *et al.*, 1977). In the cited study, a relatively low-intensity coronal region declined in brightness by about a factor of 5 to form a hole in less than 1 day. The areal change

produced at a rate at least three times greater than the magnetic diffusion rate while no obvious change was noted on photospheric magnetograms. Figure 6 shows an example of the rapid formation of a coronal hole in 1 day with little obvious change in the photospheric magnetic field. On 28 June 1977 we observed a fairly large but weak coronal hole which was not visible on the preceding or following days. These results suggest that, while the conditions necessary to produce a hole might be established by a relatively slow magnetic diffusion, a faster process is responsible for the actual formation and decay of the hole.

(5) The boundaries of established coronal holes can be altered by nearby prominence eruptions, and short-lived coronal holes can be produced by prominence eruptions and flares. Webb *et al.* (1978) determined that about 70% of all prominence eruptions (transients) near established coronal holes were followed within a day by a large-scale change in the hole boundary. Curiously, nearly all the changes decreased the hole area. This result is supported by Kitt Peak observations, such as the eruption-related reduction in the polar hole boundary shown in Figure 7.

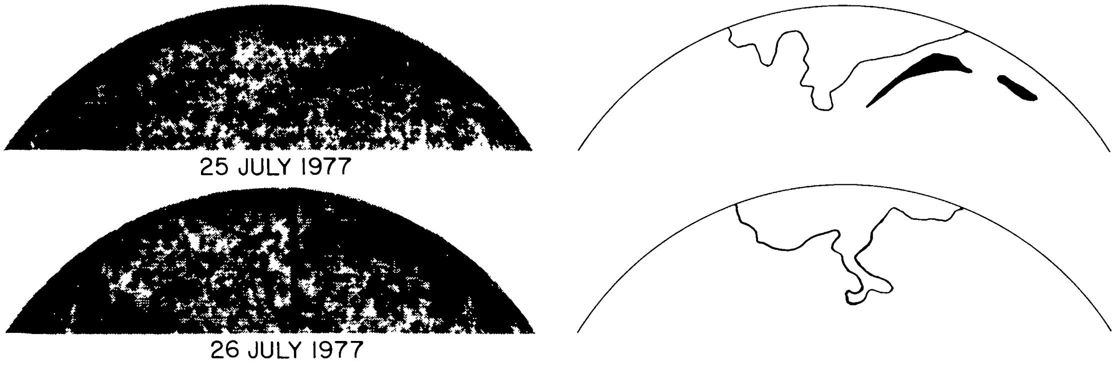

Fig. 7. The eruption of a large prominence (black in the upper right diagram) caused the contraction of the nearby polar hole boundary in less than one day.

The eruption of prominences distant from existing holes can produce short-lived appearances of small coronal holes (Solodyna *et al.*, 1977). Flares may also produce similar transient holes. For example, Figure 8 illustrates what appears to be the formation, or at least a great strengthening, of a small hole in association with the great solar flare of 28 April 1978. Valdez and Altschuler (1970) presented evidence that similar large proton flares produce large-scale openings of the coronal magnetic field. Our observations are consistent with this idea but further analysis is required.

(6) The rotation of coronal holes is nearly independent of latitude and has a synodic period of about 27.2 days (Timothy *et al.*, 1975; Wagner, 1975; Bohlin, 1977b). Three independent studies yield essentially the same results. However during the time intervals studied (1972–1974) there were very few holes at higher latitudes. At lower latitudes the rotation rate of holes is identical with other magnetically-associated features. Only at high latitudes does the rotation rate of

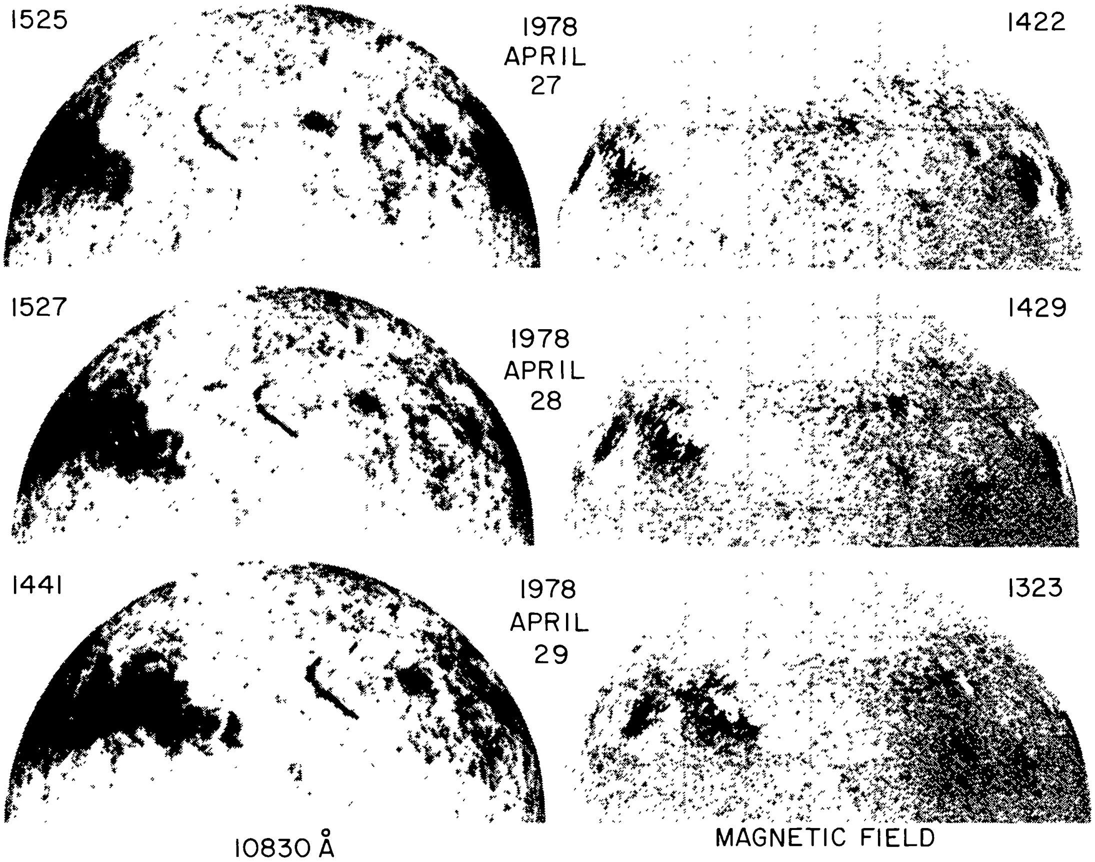

Fig. 8. The apparent formation of a coronal hole in association with the great flare of 28 April 1978. The hole is indicated by an arrow on an observation made about 2 hr after the maximum of the flare. Universal times of the observations are indicated in the margins. The bright points in the active region on 28 April are remnants of the flare.

holes seem anomalous. Therefore a key question is to what extent the high-latitude rotation rate of a few holes during May 1972–January 1974 pertains to other holes at other time periods. Stenflo (1977) found variations in the rotation rate of magnetic fields at various latitudes throughout the solar cycle though at no time was the degree of rigidity as large as for the holes in 1972–73. Antonucci and Svalgaard (1974) studied the rotation of the corona in general through two solar cycles and found nearly rigid rotation during a two-year interval between maximum and minimum solar activity and found further that very long-lived coronal features rotate rigidly at all times. In a later study Antonucci and Dodero (1977) confirmed the implication of the earlier result by noting that the corona in general showed rigid rotation during 1972–74. Chromospheric features such as K_3 mottles (Antonucci *et al.*, 1977) and Hα prominences (Adams, 1976; Adams and Tang, 1977) rotated more rigidly during 1972–73 than the solar cycle average rate but not as rigidly as the coronal features. Our recent observations of coronal holes (Sheeley and Harvey, 1978) show a synodic rotation rate for high latitude holes which is more nearly 29 days (see Figure 5) and is consistent with the cycle-averaged rate of other magnetically-associated features at high latitudes. The preceeding results demonstrate clearly that the high-latitude rotation rate of magnetic fields and their associated phenomena vary during the solar cycle.

4. Magnetic Fields within Coronal Holes

There are no direct measurements of the coronal magnetic field in holes. Observational evidence which suggests that the field has an open and diverging geometry comes from the diverging, approximately radial orientation of emission features in holes (Bohlin and Sheeley, 1978). Remaining evidence is based on upward extrapolation from the photosphere or modeling of the magnetic field in the holes which we discuss next.

Because of the large scale of coronal holes, extrapolations of the photospheric field have generally been done on a global basis. Nevertheless, Vorpahl and Broussard (1978) succeeded in showing the change of the extrapolated magnetic field in a small region from a closed to a more open configuration in association with the growing boundary of a coronal hole. Levine (1977a) has reviewed the techniques of global magnetic field extrapolation. Briefly, one uses photospheric magnetic field observations obtained during a solar rotation as a lower boundary condition, assumes that no currents flow in the corona, introduces a fictitious equipotential source surface at some radius above the surface to force the magnetic field to be radial above that surface, and solves Laplace's equation for the magnetic field potential. Recently, Schulz *et al.* (1978) have replaced the spherical source surface used previously with a physically more realistic, non-spherical isogauss surface. Most of the comparisons of coronal holes and extrapolated potential fields have been done using either a fixed-mesh, numerical solution of Laplace's equation (Adams and Pneuman, 1976) or a Legendre polynomial series solution of the equation (Altschuler *et al.*, 1977). These techniques give essentially similar results. More important, both techniques are limited to time resolution of one solar rotation. This relatively low temporal resolution did not seriously affect the results obtained during the Skylab mission when magnetic patterns were relatively stable. However, such low time resolution may be a serious limitation at other periods, such as now, when evolution is more rapid.

The major result of comparisons of coronal holes and extrapolated fields is that significant coronal holes are invariably associated with extrapolated field lines which reach up to the source surface (typically 1.5 solar radii above the photosphere) and are thus considered to be open to interplanetary space (Altschuler *et al.*, 1977; Levine *et al.*, 1977a; Levine *et al.*, 1977b; Levine, 1977b; Pneuman, 1977; Pneuman *et al.*, 1977; Burlaga *et al.*, 1978). These studies also showed that 'open' field lines originate from only a small fraction of the total area of the Sun, and that some open field lines are not associated with holes but rather with active regions and regions either formerly or yet to be coronal holes. Thus coronal holes are a phenomenon of some but not all open field regions.

To extract more detailed information from the potential field line extrapolations is risky owing to the neglect of coronal currents and of short-time variations. A few attempts to construct approximate MHD models of holes have been made in order to take advantage of additional observational material and physical relations (Pneuman, 1976; Riesebieter, 1977; Suess *et al.*, 1977). The first two studies used observations of the photospheric field as boundary conditions while Suess *et al.* (1977) varied an assumed polar field geometry and strength until observed densities were satisfactorily matched. It has not been possible in any of these studies to construct a model which quantitatively matches all the observations although the qualitative match is generally excellent. Part of the discrepancy involves the magnetic field strength. When the observed photospheric field is used as a boundary condition the models yield field strengths at 1 AU which are too low by a factor of 2–4. When the photospheric field is a parameter (Suess *et al.*, 1977) an average photospheric field strength is required which is twice as large as can be derived from observations (Svalgaard *et al.*, 1978).

Several explanations of the flux discrepancy may be possible; (1) as yet undetected errors in the photospheric field observations, (2) origin of the open magnetic flux only from small areas within the boundaries of a hole where the mean field strength is higher; or (3) the presence of currents in the corona which make the potential model inappropriate. Burlaga *et al.* (1978) have mapped open field lines from the ecliptic down to the photosphere and then averaged the field strength along the locus of this restricted set of field line footprints. They found that the discrepancy between interplanetary and photospheric flux measurements then vanished. Why this should be a more valid procedure than simply averaging the photospheric field over the area of the coronal hole or the area enclosed by the locus of all open field lines is not clear. More work on this important problem is required.

5. Origin of Coronal Holes and Behavior During the Solar Cycle

There is as yet no complete physical model to explain the origin of coronal holes. However it is clear that coronal holes form in fairly large areas dominated by a single magnetic polarity and having a moderate, average field strength. This result stimulated a phenomenological model for the formation of coronal holes by Timothy *et al.* (1975) which has been further developed by Bohlin (1976), Bohlin and Sheeley (1978), and Broussard *et al.* (1978). According to this model, non-polar holes form whenever the magnetic flux from bipolar magnetic regions (BMRs) interacts to produce a large region of locally unbalanced flux. (If we assume that the polar flux originates in BMRs then this statement applies to all holes.) The implication is that the field lines from such a region extend upward and have such a strength that they are convected outward and opened by the solar wind rather than returning to the Sun directly in a distant region.

This model is very successful in accounting for many of the observed characteristics of holes. However, it does have two limitations: the term 'locally unbalanced' is not precisely defined and the burden of explaining the origin of holes is shifted to explaining why magnetic fields erupt, interact and dissipate in the way they do. Nevertheless the model forms a useful framework for interpreting the behavior of holes and magnetic fields through the solar cycle which we do next following Broussard *et al.* (1978).

Near the minimum of the solar cycle the net flux at the poles reaches a maximum value and the polar holes have their greatest extent. Only weak magnetic patterns and weak holes exist at lower latitudes. As BMRs of the new solar cycle erupt at high latitudes, the trailing part of such new flux diffuses preferentially toward the poles which reduces the net flux there and eventually replaces it with net flux of the opposite polarity. This corresponds to the shrinking, possible disappearance, and new growth of the polar holes through the solar cycle.

In the early ascending phase of a new solar cycle the leading part of new cycle BMRs at high latitudes may diffuse to form locally unbalanced flux patterns in proximity to the polar flux. This will preferentially produce holes in front of active regions which are frequently connected to the polar hole (Figures 4 and 5).

Near the time of maximum activity the polar flux is so weakened that little or no polar hole remains. Large patterns of locally unbalanced flux from the trailing parts of BMRs then exist poleward of the BMRs and these patterns should occasionally form small holes. A few patterns from the leading parts of BMRs may also exist and contain holes. Rapid changes in the large patterns occur due to frequent eruptions of BMRs and also the shearing effect of differential rotation at high latitudes. Consequently holes in these patterns should tend to have short lifetimes. Equatorward of the BMRs, occasional, locally unbalanced flux patterns form but these lead only to small, transient holes.

With reduced eruptions of low-latitude BMRs in the declining phase of the cycle and the growth of the net polar flux, magnetic patterns become more stable and holes tend to become larger, longer-lived and to form in magnetic patterns having the same magnetic polarity as the polar field of that hemisphere. Large low-latitude holes become dominant. As the cycle minimum is reached the reduction in the amount of magnetic flux at low latitudes results in the less frequent low-latitude holes.

As emphasized by Broussard *et al.* (1978) this idealized scenario ignores the large fluctuations which characterize the progress of a typical solar cycle. Nevertheless it is consistent with presently available observations. Systematic observations during the next few years will provide a test of this model because only relatively few and low-quality observations were obtained during this phase of the previous cycle.

The discussion above describes a systematic variation of the occurrence of coronal holes with *latitude* during a solar cycle. We may ask if there is any evidence for a systematic variation of the occurrence of holes with *longitude* on some time scale, particularly in view of the existence of long-lived magnetic sector structures (Svalgaard and Wilcox, 1975, 1976). McIntosh (reported by Levine, 1977a), and Svalgaard and Duvall (1977) suggest that such a longitudinal organization does exist.

This leads us to the question of what governs the production and systematic evolution of large-scale magnetic field patterns.

There are at least two distinct views about the cause of long-lived, longitudinal magnetic structures. For example, Leighton (1969) argues that persistent patterns occur when initially random flux eruptions are acted upon by amplification processes to produce correlated phenomena in one area for a period much longer than the lifetime of a single event. On the other hand, Svalgaard and Wilcox (1975) argue that this process cannot explain the duration of observed patterns for more than one sunspot cycle. They suggest that at least part of the magnetic or velocity field of the sun originates in or is modulated by a long-lived, subsurface structure, possibly certain modes of a solar dynamo. In the specific context of coronal holes, Gilman (1977) and Stix (1977) both ascribe the large-scale organization of magnetic patterns favorable to the formation of holes to dominance by a few modes of a solar dynamo. New magnetic flux is then supposed to erupt in favored locations in such a way as to maintain a large-scale pattern. A further review of the extensive topic of the origin of magnetic fields is beyond the scope of this paper.

6. Conclusion

The phenomena of coronal holes and solar magnetic fields are now known to be intimately associated. Magnetic fields erupt and sometimes form large-scale patterns, some of which contain open magnetic fields. Coronal holes are formed within these open-field regions. This simple picture depends heavily on intuitive concepts of potential magnetic fields. However, the precise association between holes and magnetic fields must depend to some degree on coronal currents. The magnitude of such a dependence is not yet known but recent observations (Duvall, 1977) suggest that powerful, large-scale current systems do exist in the corona. We should therefore expect some changes in our present picture of the association of coronal holes and magnetic fields.

The practical aspect of coronal hole research is the association between holes and geomagnetic activity with high speed solar wind streams as the link. This association during the period of the Skylab Mission was thoroughly discussed by Hundhausen (1977). Sheeley and Harvey (1978) demonstrate that the association between holes and geomagnetic activity has significantly changed in step with the major changes which have occurred in magnetic patterns on the Sun during the last 6 yr. Currently, only a few holes can be linked with geomagnetic activity.

There are several topics in this paper which require more work and which we now briefly list. Observationally we need regular, high-quality observations of coronal holes and magnetic fields through an entire solar cycle. Relying solely on indirect observations of holes made with the 10830 Å line or on poor time and spatial resolution coronagraph observations may lead to erroneous conclusions. There are strong and weak coronal holes but we do not yet know what causes this distinction and how it might relate to the high-speed wind streams which emanate from open-field regions (cf. Nolte *et al.*, 1977a; Sheeley and Harvey, 1978). Solid observational proof that the magnetic field in holes is actually open is still lacking. Why the eruption of the current systems associated with prominences should close some of the open fields of nearby holes is an interesting question. We have not discussed in this paper the strong possibility that miniature coronal holes may exist within some young active regions (cf. Švestka *et al.*, 1977; Bohlin and Sheeley, 1978) and that they may contribute significant flux to the interplanetary medium. The details of the evolution of holes must be studied using many more holes than were observed during the Skylab Mission.

In the realm of modeling magnetic fields and coronal holes, efforts such as those of Sakurai and Uchida (1977) and Yeh and Pneumann (1977) to include currents in the corona should be developed. At the least, some way to increase the time resolution of potential field models will probably be required to follow the rapid evolution of holes during the ascending and maximum phases of the solar cycle.

Finally, we expect coronal holes to be closely related to basic mechanisms of magnetic field production. Only the first steps to understand this important relation have been taken.

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