THE EVOLUTION OF THE POLAR CORONAL HOLES

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Abstract. He I 10830 Å synoptic maps, obtained at the Kitt Peak National Observatory during 1974–1979, show that the Sun's polar coronal holes have contracted significantly during 1977–1978. Prior to the accelerated increase of sunspot activity in mid-1977, the area of each polar cap was on the order of 8% of the Sun's total surface area ($4\pi R^2$), whereas toward the end of 1978 these areas fell below 2% of $4\pi R^2$. Synoptic polar plots show that the vestigual holes had irregular shapes and were often well removed from the poles themselves. These results are consistent with the changes that one would expect when the polar magnetic fields are weakening just prior to sunspot maximum.

1. Introduction

Several previous studies have indicated that the sizes of the polar coronal holes vary during the sunspot cycle. Some of these studies have been based on synoptic ground-based coronagraph observations (Waldmeier, 1951) or on isolated X-ray and XUV observations (Muney and Underwood, 1968; Broussard *et al.*, 1978). Others have been based on well-understood properties of coronal holes together with an empirical knowledge of the sunspot magnetic cycle (Hundhausen, 1977; Bohlin and Sheeley, 1978; Harvey and Sheeley, 1979).

In principle, the evolution of the polar holes should reflect the variation of the polar magnetic fields in which these holes are located. At sunspot minimum when the polar fields are strong, the polar holes should be relatively large and symmetric. Near sunspot maximum when the polar fields weaken and reverse, the polar holes should contract and disappear.

This paper concerns the evolution of the polar holes during the five-year, post-Skylab period 1974–1979. This interval includes the relatively quiet years around sunspot minimum (1976) when the polar holes should have been large, as well as the increasingly active years (1977.5–1979) when the polar holes should have been contracting. Consequently, observations during this interval provide a test of our present understanding of the evolution of the polar coronal holes.

Polar coronal holes are visible on He I 10830 Å spectroheliograms that have been obtained almost daily at the Kitt Peak National Observatory (KPNO) since February 1974 (cf. Harvey *et al.*, 1974, 1975; Livingston *et al.*, 1976; Harvey and Sheeley, 1977, 1979; Sheeley and Harvey, 1978). At KPNO, these helium images have been used to construct synoptic maps of coronal holes routinely since January 1977 (*Solar-Geophysical Data* 1977–1979) and occasionally prior to that time. The measurements described in this paper are based on these synoptic maps.

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2. Data Reduction Techniques

The polar coronal holes were transferred from the rectangular synoptic charts to polar coordinate maps in order to improve their visualization. In each hemisphere, the direction of the azimuthal coordinate was chosen to give the image the same parity that it would have if it were viewed from above the pole. However, in this presentation, the size of each hole is somewhat smaller (relative to the full disk) than it would appear from above the pole because the radial coordinate is linear with respect to solar colatitude rather than with respect to the sine of the colatitude.

The polar holes have been plotted as they would appear in a coordinate system whose synodic rotation period is 30 days rather than approximately 27 days. This 30-day period was chosen empirically so that long-lived, high-latitude lobes of the polar holes would remain stationary on consecutive rotations. (The precise, high-latitude period was taken to be 400 degrees of Carrington longitude.) Of course, this transformation produced a loss of synchronization with respect to the Carrington system because slightly more than one synoptic map was required to construct each polar plot.

Finally, these plots were used to derive the solar surface area of each polar hole. this area was determined by integrating the areal element, $R^2 \sin\theta \, d\theta \, d\varphi$ (θ and φ are colatitude and azimuth, respectively), over the region within the boundary of each polar hole. In practice, the θ-integration was performed first, and the resulting function of φ was integrated numerically at 18° intervals around the boundary of the hole. Finally this surface area was expressed in units of the surface area of the spherical Sun ($4\pi R^2$).

While the 30-day coordinate system is ideal for studying the long-term evolution of the polar holes, the resulting areal measurements can still be compared directly with previous measurements that were made in the 27-day Carrington system. In the 27-day system, the loss of synchronism with the high-latitude rotation rate induces areal fluctuations that are $\lesssim 0.5 \times 1\%$ from rotation to rotation. Such fluctuations are smaller than the evolutionary changes that occur during a 27-day interval, and are negligible compared to the evolutionary changes that occur during a sunspot cycle (cf. Figure 2). In any case, the fluctuations associated with the loss of synchronism average out after several rotation periods.

3. Results

Figure 1 is a sample of polar plots for the equinoctal seasons of 1975 and 1978. The area of each hole is indicated as a percentage of the surface area of the Sun ($4\pi R^2$). A seasonal effect seems to be present in the sense that each polar hole is largest at the time of the year that it is most visible from the Earth. Thus, during 1975 the north polar hole is larger in October than in April and the south polar hole is larger in April than in October. This same result holds in 1978 for the months of March and September. However, as we shall see later, the magnitude of this effect is comparable

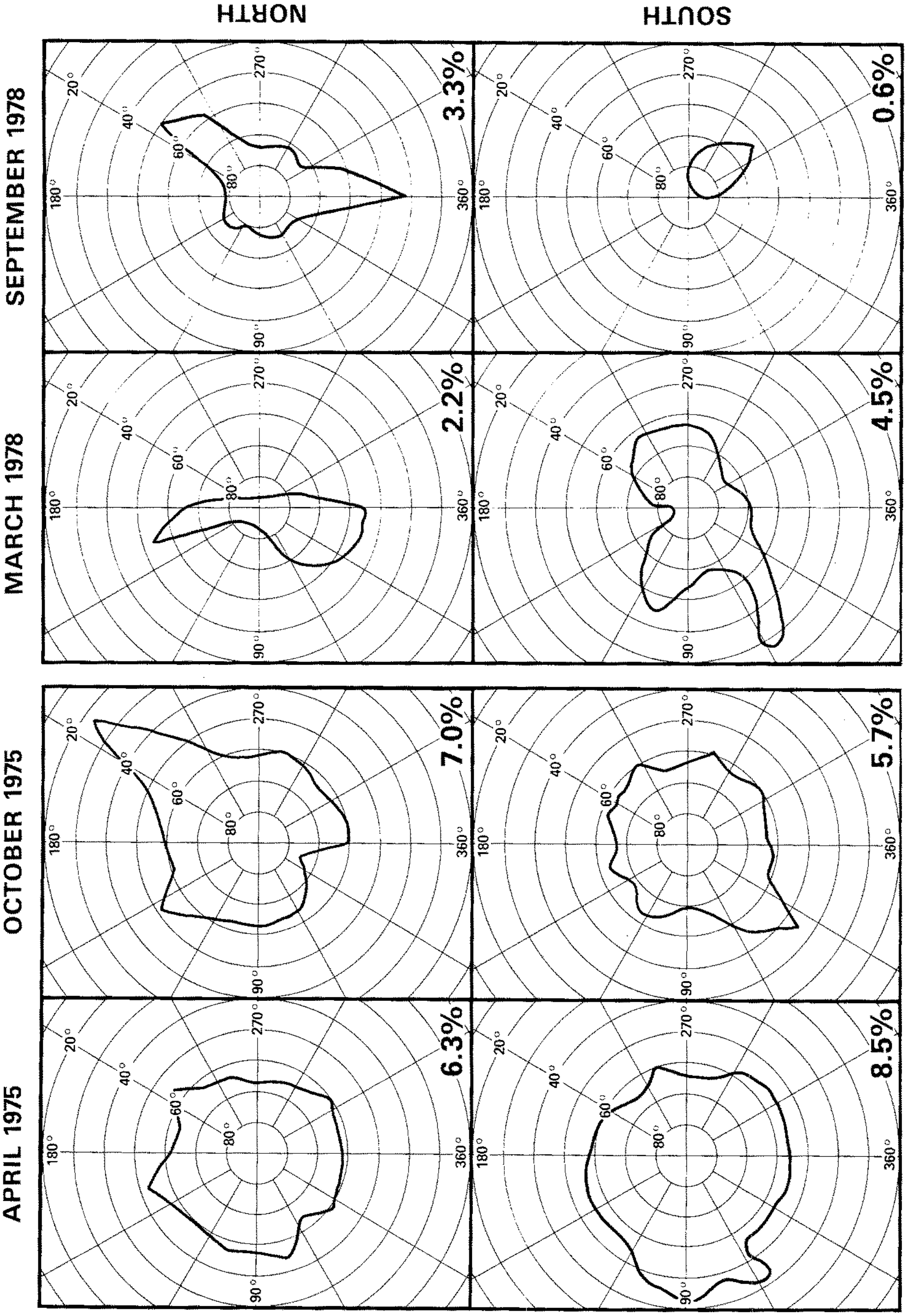

Fig. 1. A sample of polar plots illustrating the fact that the polar coronal holes were smaller and less confined to the poles in 1978 than in 1975. The surface area of each hole is indicated as a percentage of the surface area of the Sun ($4\pi R^2$).

to the variations of polar cap area that occur naturally in a duration of a few to several months. Consequently, this result may seem more convincing than it really is (despite the fact that the plots were not selected to advocate a seasonal effect).

The most significant aspect of Figure 1 is the fact that in 1978 the polar holes are much smaller than they were in 1975. Furthermore, in 1978 they seem less inclined to occur at the poles themselves. Although large lobes did occur in 1975, they extended equatorward from relatively large holes that were more-or-less centered on the poles. In contrast, during 1978 most of the coronal hole area seems to be confined to lobes and relatively little encircles the poles. In September 1978, the south pole lay just outside of the 'polar hole'. This effect was not an isolated incident that could be attributed to measurement error because it occurred on several consecutive months in the southern hemisphere, as well as at other times in the northern hemisphere.

Figure 2 presents all of these measurements of polar hole area together with the previous measurements of Bohlin (1977) and Broussard *et al.* (1978). Bohlin used synoptic He II 304 Å images obtained during the Skylab mission to construct polar plots whose area he measured and expressed in units of $4\pi R^2$. Broussard *et al.* measured the visible surface area of polar holes on isolated X-ray and XUV images, but expressed these 'half areas' in terms of $2\pi R^2$. Consequently, all of these measurements should be approximately comparable with the possible exception of Broussard *et al.*'s high-latitude, but non-polar holes (solid squares). Assuming that these holes were entirely visible in the X-ray and XUV images, their areas should have been expressed in units of $4\pi R^2$ rather than $2\pi R^2$ to be comparable to the other measurements. Thus, in Figure 2 the area of Broussard *et al.*'s high-latitude holes (solid squares) probably should be reduced by a factor of one half.

In Figure 2, one can see that the areas of the polar holes have decreased considerably from their Skylab-era values of approximately 8%. A linear fit to the measurements during 1977–1978 indicates a rate of decrease of approximately 5%/year in each hemisphere corresponding to an areal decrease of $(1.0 \pm 0.1) \times 10^4$ km^2 s^{-1}. In each case, the projected time of zero area is early 1979.

On the right side of Figure 2, the scale refers to the latitude at which the boundary of each hole would lie if the area of this hole were distributed symmetrically about the pole. Although this equivalent latitude was approximately 60° in the quiet years near sunspot minimum (1976), it exceeded 70° toward the end of 1978. Of course, the concept of equivalent latitude may not be useful for the recent holes because their irregular shapes differ greatly from that of a classic polar cap.

In Figure 2 the helium measurements have a rather large scatter of roughly 2–3%. As we have discussed earlier, part of this variation may be a visibility effect associated with the changing heliographic latitude of the Earth during the year. However, an equally large part of it is also due to real short-term changes of polar hole area. Such changes typically occurred as lower-latitude holes formed and temporarily merged with the polar holes. The areas of such lobes were included as part of the areas of the polar holes. Although this effect was relatively unimportant when the polar holes

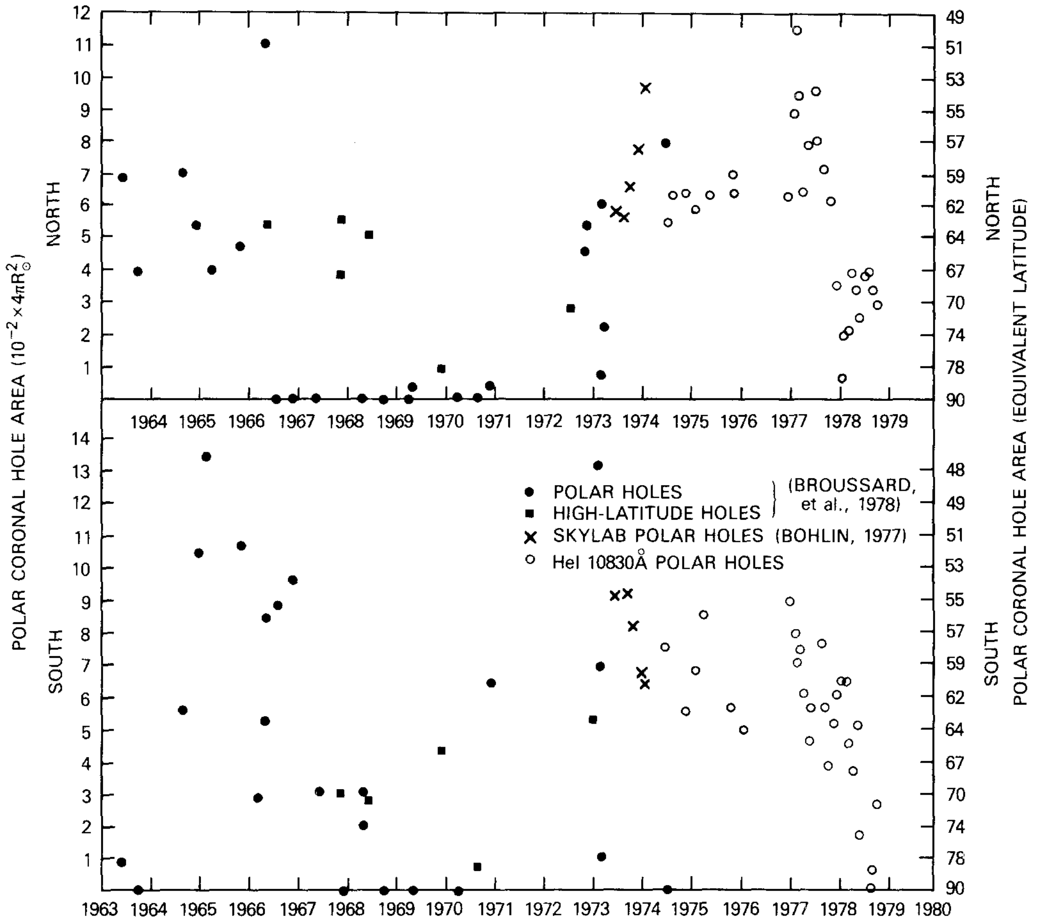

Fig. 2. Measurements of the areas of polar holes during 1963–1979. The measurements of this paper (open circles) are combined with measurements by Bohlin (1977) and Broussard *et al.* (1978) to indicate the long-term trend.

were large, it is particularly serious now that they are small. Indeed, Broussard *et al.* (1978) found that such non-polar holes were the main source of high-latitude coronal hole area during this phase of the previous sunspot cycle (square data points in Figure 2).

4. Discussion

The measurements in Figure 2 continue to support our expectation that the polar coronal holes vary during the sunspot cycle. The formation of these holes in 1972–1973 during the declining phase of the cycle has been discussed extensively in several studies of the Skylab and OSO-7 observations (cf. Bohlin and Sheeley, 1978, and references contained therein). In effect, the formation of the polar holes resulted from the increasing magnitude of the polar field strengths together with the decreasing influence of active regions. By 1972–1973 each polar cap had apparently accumulated enough unipolar magnetic flux to satisfy the connection requirements of nearby magnetic regions and still to have unbalanced flux left over to form a hole.

This process has been reversing since sunspot minimum in 1976. Although unipolar magnetic regions still remained at the Sun's poles toward the end of 1978, on the average they have become less able to support large coronal holes. Indeed, the measurements in Figure 2 show that the area of each polar hole decreased at the average rate of 1.0×10^4 km^2 s^{-1} during 1977–1978. This value is remarkably close to the areal rate of magnetic flux transport according to Leighton (1964) (1.0×10^4 km^2 s^{-1}) and not significantly different from Mosher's (1977) correction to this rate (0.5×10^4 km^2 s^{-1}). It is also comparable to the values that Bohlin (1977) (1.5×10^4 km^2 s^{-1}) and Nolte *et al.* (1978) (0.8×10^4 km^2 s^{-1}) obtained for Skylab observations of coronal holes. Together, these facts continue to support the idea that the long-term evolution of the polar holes is systematically controlled by the corresponding evolution of the large-scale magnetic field.

As we have already mentioned, the polar hole boundaries have become markedly eccentric with respect to the Sun's poles. This fact suggests that the high-latitude, large-scale magnetic fields are becoming increasingly affected by new-cycle flux that is migrating poleward from the sunspot belts. As this process continues during the advance to sunspot maximum, we may expect such migrating regions to be the principal source of the high-latitude coronal holes (as Broussard *et al.* (1978) found during the corresponding phase of the previous sunspot cycle).

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