The Contraction and Disappearance of the Polar Coronal Holes

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ABSTRACT

He I 10830 Å spectroheliograms obtained routinely during 1974-1979 have been used to study the evolution of the Sun's polar coronal holes. Synoptic polar plots show that the holes have decreased in size to the point that only vestigial holes remain and even these remnants fluctuate with detailed sunspot activity. During 1977.5-1979, the area of each hole fell from \(8\% \times 4\pi R^2\) to less than \(2\% \times 4\pi R^2\) at the areal rate of \(1.0 \times 10^4 \text{ km}^2/\text{sec}\).
I. 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 10830Å 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.

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. 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, \( R^2 \sin \theta \, d\theta \, d\phi \) (\( \theta \) and \( \phi \) are colatitude and azimuth, respectively), over the region within the boundary of each polar hole. In practice, the \( \theta \)-integration was performed first, and the resulting function of \( \phi \) was integrated numerically at \( 18^\circ \) intervals around the boundary of the hole. Finally, this surface area was expressed in units of the surface area of the spherical Sun \((4 \pi R^2)\).

3. Results

Figure 1 is a sample of polar plots for the equinoctal seasons of 1975 and 1978. The surface 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 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 304Å images obtained during the Skylab mission to construct polar plots whose area be 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 areas 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$^2$/sec. 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 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 1972-73 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.

In this paper we shall consider the inverse process in an attempt to understand the contraction of the polar holes during 1977-1978. Since sunspot minimum in 1976 the influence of active regions has been increasing and presumably the
polar magnetic field strengths have been decreasing. Apparently by 1978 the polar caps no longer had enough unipolar magnetic flux to always satisfy the connection requirements of nearby magnetic regions and still to have enough unbalanced flux left over to form large polar holes. The north polar hole almost vanished in January 1978 (0.4%) and the south polar hole nearly vanished in August (0.1%) and September (0.6%).

The fact that these near-vanishings have been short-lived indicates that they have been caused by short-term changes in the nearby magnetic regions rather than by a reversal of the polar fields themselves (which incidently have not yet reversed). Presumably these intermittent vanishings will occur for progressively longer intervals until the polar fields themselves reverse. Then the location of high-latitude holes will be determined entirely by the distribution of flux that is diffusing poleward from the sunspot belts.

Finally, it is interesting to note that while short-term variations of the polar holes accompanied the fluctuations of nearby lower-latitude fields, the long-term contraction of the polar holes occurred at a well-defined rate of (1.0±0.1)x10⁴ km²/sec. This rate is comparable to the values of 1.5x10⁴ km/sec and 0.8x10⁴ km/sec obtained by Bohlin (1977) and Nolte et al. (1978), respectively, for Skylab observations of coronal holes. It is also comparable to Leighton's (1964) rate for the dispersal of magnetic flux (1.0x10⁴ km²/sec) as
well as to Mosher's (1977) correction \((0.5 \times 10^4 \text{ km}^2/\text{sec})\) to this rate.

Despite the encouraging order-of-magnitude agreement between these measurements, it is still not obvious that the polar holes should close at the areal rate of magnetic flux transport. Rather, the rate should depend on the rate of change of open flux in the polar cap. In turn, this flux rate should depend on the location, magnitude, and occurrence rate of the low-latitude flux sources as well on the areal rate with which it diffuses. All of these factors must be considered before even this rudimentary aspect of the problem can be understood quantitatively.

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References


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 \(4 \pi R^2\).
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.