OBSERVATIONS OF CORONAL STRUCTURE DURING SUNSPOT MAXIMUM†

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Abstract. This paper presents some of the results that have been obtained from the Kitt Peak observations of coronal holes and the NRL observations of coronal transients during the recent years near sunspot maximum (1979–1981). On the average, low-latitude coronal holes of comparable size contained 3 times more flux near sunspot maximum than near the previous minimum. In the outer corona, transients occurred at the observed rate of at least 2 per day, and quiet conditions persisted during less than 15% of the observed days. We describe a sample of the more than 800 events that we have observed so far, including the observation of a comet apparently colliding with the Sun.

1. Introduction

The objective of this review is to list a few recent observations that add to our knowledge of coronal structure near sunspot maximum. The first subject concerns the discovery by Harvey et al. (1981) that coronal holes had greater average field strengths at their bases in 1979 and 1980 than they did during 1973–1978. This result may simply reflect the fact that there was more magnetic flux on the Sun at sunspot maximum than at minimum. Nevertheless, such a sunspot-cycle variation of coronal hole field strength was not anticipated in 1975–1976 when coronal holes were being studied intensively at the first Skylab Workshop Series (Zirker, 1977).

The second subject concerns the great number and variety of coronal transient phenomena that have been observed by the NRL Earth-orbiting coronagraph during 1979–1981. With only 40% of the data yet reduced, routine observations of the white-light corona between 2.5 and 10.0R have already shown 495 mass ejections on a time scale of a few hours or less and 332 additional, slower events. With processed images for parts of 390 days, this corresponds to an average of at least 2 events per day. Truly quiet days were rare with only 63 days (15%) showing slow evolution without transients.

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2. Magnetic Measurements of Coronal Holes

During the Skylab Workshop Series on Coronal Holes, it was suggested that the average magnetic field strength at the base of a coronal hole might be as large as 10 G (see for example, Hundhausen (1977), and references contained therein). This conclusion was based on the conservation of magnetic flux within a hypothetical tube that extended from the base of a coronal hole at the Sun's surface to a corresponding feature in interplanetary space. Thus, by measuring the interplanetary field strength, $B_{ip}$, and estimating the ratio of coronal hole area, $A_{ph}$, to the assumed area of the corresponding interplanetary feature, $A_{ip}$, one could deduce the average field strength at the photosphere, $B_{ph}$, from

$$B_{ph} = B_{ip} \left( \frac{A_{ip}}{A_{ph}} \right).$$

(1)

In this way, the interplanetary measurements led to values of $B_{ph} \approx 10$ G for the coronal holes that were observed in 1973–1974 during the Skylab mission. However, direct measurements of the photospheric magnetic flux within these same coronal holes gave average field strengths in the range 0.3 – 7.2 G, with 2–3 G being the most commonly occurring values (Howard and Harvey, 1977; Bohlin and Sheeley, 1978).

Since the end of the final Skylab mission in February 1974, direct observations of coronal holes against the solar disk have been limited to relatively few X-ray images obtained from one or two rocket flights per year. However, helium images show the location of these X-ray holes as regions where the chromospheric network is weak or absent (Tousey et al. 1973; Harvey et al. 1975a, 1975b; Harvey and Sheeley, 1979), and He I 10830 Å images have been obtained almost daily at Kitt Peak since February 1974. Combined with the Skylab images during 1973–1974, this sequence of helium images provides high-quality synoptic observations of coronal holes over a 9-year interval that spans most of a sunspot cycle.

In the process of analyzing these long-term synoptic observations, Harvey et al. (1982) noticed that some holes in 1979 and 1980 seemed to contain considerably more net flux then the holes that occurred during the declining phase of the cycle and near sunspot minimum (cf. Harvey and Sheeley, 1980).

They also noticed that the central meridian passage dates of the new low-latitude holes often correlated with the days of enhanced mean solar magnetic field as observed from Earth, just as Scherrer and Svalgaard (1977) had found earlier. This latter result suggested that coronal holes may sometimes contribute a significant fraction of the Sun's net flux as seen from Earth. By 1979 the Sun's mean field strength often reached 0.5 G and even exceeded 1.0 G on some days. This latter value corresponds to a net flux of $15 \times 10^{21}$ Mx averaged over the solar disk. Harvey et al. noted that to account for even half this amount of flux, a typical coronal hole of area $4 \times 10^{20}$ cm$^2$ would have an average field strength of 19 G.

In pursuit of this idea, Harvey et al. (1982) measured the areas and magnetic fluxes at the base of 33 coronal holes on 63 separate days during 1975–1980. Also, to test the
consistency of their measurement technique, they remeasured the fluxes and areas of some of the earlier holes in 1973–1974.

We shall describe their general technique and typical results with the aid of Figure 1. First, coronal holes were identified on the helium images (left) as regions where the chromospheric network was weak or absent. In this figure, the holes are outlined by white contours. Second, these contours were transposed to the corresponding photospheric magnetograms (right). In the magnetograms, lighter-than-average features indicate positive line-of-sight components of field (toward the observer) and darker-than-average features indicate negative fields. Third, the net fluxes and areas within each contour were measured, and the mean field strength was computed from their ratio. As the caption indicates, the resulting mean field strengths ranged from 5.2 to 25.7 G for these four coronal holes.

Fig. 1. He I 10830 Å images (left) and photospheric magnetograms (right) illustrating the variety of coronal holes that contributed to the broadening as well as the shifting of the coronal hole field strength distribution in 1979 and 1980. The fluxes and average field strengths within these holes are:

<table>
<thead>
<tr>
<th>April 25</th>
<th>May 10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>N 16.9 G</td>
<td>N 12.7 G</td>
</tr>
<tr>
<td>S −25.7 G</td>
<td>S 5.2 G</td>
</tr>
<tr>
<td>3.6 × 10^{21} Mx</td>
<td>12.9 × 10^{21} Mx</td>
</tr>
<tr>
<td>−3.7 × 10^{21} Mx</td>
<td>2.9 × 10^{21} Mx</td>
</tr>
</tbody>
</table>

(from Harvey et al., 1982).
Harvey et al. found that prior to July 31, 1978 all of the measured average field strengths lay within the 0.3–7.2 G range that Bohlin and Sheeley (1978) had reported for holes during 1973–1974. However, after July 31, 1978 most of the measured field strengths exceeded 7.2 G. During 1979, five independent holes had average field strengths exceeding 20 G, and one ‘transient’ hole had a strength of 36.3 G.

### Table 1

<table>
<thead>
<tr>
<th>Interval</th>
<th>Number of measurements</th>
<th>Field strengths (G)</th>
<th>Fluxes (10^{21} Mx)</th>
<th>Areas (10^{20} cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>February 1975–July 1978</td>
<td>30</td>
<td>4.1(1.7)</td>
<td>1.6(1.1)</td>
<td>4.0(2.4)</td>
</tr>
<tr>
<td>August 1978–June 1980</td>
<td>38</td>
<td>11.9(7.5)</td>
<td>5.0(3.9)</td>
<td>4.5(2.7)</td>
</tr>
</tbody>
</table>

*The numbers in parenthesis are the root-mean-square deviations from the averages.

Table I contains average values of field strength, flux, and area of coronal holes before and after July 31, 1978. The average areas of the holes that they measured changed by only a factor of 1.1 from 4.0 to 4.5 \times 10^{20} \text{ cm²}. In contrast, the fluxes increased by a factor of 3.1 from 1.6 to 5.0 \times 10^{21} \text{ Mx}. The average field strengths also increased by a factor of 3.1 from 4.1 to 11.9 G. As shown by the numbers in parenthesis, the standard deviations of flux and field strength also increased substantially from 1.1 to 3.9 \times 10^{21} \text{ Mx} and 1.7 to 7.5 G, respectively. Harvey et al. concluded that the distributions of flux and field strength shifted to higher values and broadened. As we have already seen in Figure 1, these broadened distributions include some relatively low values that are comparable to the ones obtained earlier as well as some values that are very much higher than the earlier ones.

Harvey et al. supposed that this increase in coronal hole field strength simply reflected the fact that there was more flux on the Sun near sunspot maximum then near minimum (3 times more flux according to Howard and LaBonte, 1981), and that the coronal holes received their proportionate share of the extra flux. They also noted that a comparable amount of open flux from the large polar holes had disappeared by 1979–1980 as the polar fields vanished. Thus, they speculated that the relatively constant amount of interplanetary flux that persisted throughout this time (King 1979, 1981) may have had its origin in smaller areas on the Sun at sunspot maximum than at minimum. This leaves us with the question of whether or not such an increased flux tube divergence might account for the relatively low speeds of solar wind streams at Earth during sunspot maximum. Evidently the theoretical treatments of this problem have given contradictory results (Kopp, 1977).

### 3. Coronal Transients During 1979–1981

The NRL white light coronagraph has been obtaining full field images of the Sun’s outer corona (2.5–10.0R) routinely since it began operating in Earth-orbit on March 28, 1979.
With few interruptions, this instrument has obtained images at 10 min intervals during the 1 h sunlit portion of each 97 min satellite polar orbit. This instrument and its initial observations have been described in detail elsewhere (Sheeley et al., 1980a).

Observations have been processed for 390 days since March 28, 1979. The processing consists of constructing one ordinary coronal image for each satellite orbit and one difference image which shows the change that has occurred between that orbit and the start of that day (or mid-day for orbits in the second half of each day). When obvious changes are detected, the remaining 4 difference images in each orbit are processed to show the temporal evolution of each change.

With data reduced for parts of 1979, 1980, and 1981, we have observed 495 mass ejections on a time scale of a few hours or less and 332 additional events on a time scale of 6–12 h. As we have described earlier (Sheeley et al., 1980b), during sunspot maximum coronal transients, like coronal streamers, occurred at all position angles. Hildner et al. (1981) have also noted this result for observations during March–September 1980 with the coronagraph on the Solar Maximum Mission Satellite. Also in accord with the SMM observations, we found that the coronal transient angular distribution had maxima at the sunspot belts during 1979–1981. Some preliminary statistics such as speeds (150–900 km s\(^{-1}\)) and masses (7 \times 10^{14} – 2 \times 10^{16} g) were described by Poland et al. (1981) using relatively few events. We have not yet extended the measurements of ejected coronal masses, but we have seen both lower (50 km s\(^{-1}\)) and higher (1200 km s\(^{-1}\)) speeds in our larger sample of events.

Fig. 2. Coronal mass ejection associated with the disruption of a pre-existing coronal streamer. In this figure and all subsequent figures, a small white disk in the center of the field indicates the size and location of the Sun's photosphere.
At least 151 (30%) of the 495 primary transients have a characteristic spike structure in our 2.5–10.0R field of view. Figure 2 shows a 2-pronged spike transient which was the origin of an interplanetary shock at Helios 1 on May 28 (Schwenn, 1981). Sometimes such 2-pronged events show a complete loop structure as they begin to rise through our field of view, but this one did not. Comparisons of similar events obtained simultaneously with other observations at smaller radial distances show that some of our spike transients began as bright loops in the lower corona (Wagner et al. 1980), and some did not (Fisher, 1981). In the latter case, the events began as expanding depletions that developed bright spikes along their sides (cf. Fisher, 1982). In Figure 2 a comparison of the ordinary images (below) with the subtracted images (above) suggests that this May 27, 1979 event involved the splitting of a bright, pre-existing coronal streamer. Such 'streamer blowouts' are relatively common.

Figure 3 shows a much smaller 2-pronged event on the morning of June 9, 1979. One can see that this event, unlike the May 27 event, began in our field of view as a complete loop, but eventually lost its top as it progressed outward. However, like the May 27 event, this June 9 one has a darker-than-average region at its base, indicating a coronal depletion. It too may have been a 'streamer blowout'. This was one of the 13 events (3%) that we called 'small loops' rather than 'spikes'.

Fig. 3. Evolution of a coronal transient from a 'small loop' to a '2-pronged spike' configuration.
Fig. 4. Evolution of a 'big loop' coronal mass ejection (in the 18:05 UT image, the narrow streak extending SW to the edge of the field of view is an artifact).

Figure 4 shows a mass ejection during the afternoon of June 9, 1979. We call this event a 'big loop', although there are certainly some spike structures that follow the loop out into the field of view. We have classified 55 (11%) of our 495 major events as big loops, but this event is one of the few that was sufficiently well defined to show definite curvature in its height-time plot. Between 16:13 UT and 18:05 UT the front of the loop accelerated from approximately 275 to 600 km s\(^{-1}\) as it progressed from 3.8 to 7.3\(R\).

This event also seems to have been the source of an interplanetary shock at Helios 1 (Schwenn, 1981).

Figure 5 shows another loop-shaped mass ejection that was sufficiently well-defined to show definite curvature in its height-time plot. In this May 24, 1979 event, the loop accelerated rapidly from 375 to 1000 km s\(^{-1}\) in only 41 min. This trailing prominence material accelerated more slowly from 400 to 950 km s\(^{-1}\) in 127 min as it traversed the field of view. We have seen obvious prominence material in only 8 (2%) of our 495 major events.

Figure 6 shows a very large event that was already in progress at 07:35 UT on September 1, 1980 when we first observed it. We have called 9 (2%) such events 'quadrant fillers', but many of the events that we have called 'big loops' eventually
Fig. 5. Evolution of a 'big loop' followed by an eruptive prominence.

Fig. 6. A large 'quadrant filling' mass ejection in progress.
developed into such quadrant fillers. An interesting feature of this September 1, 1980 event is the dark hole that can be seen progressing radially out through the field of view during 07:35–08:14 UT. Its speed in the plane of the sky was approximately 1200 km s\(^{-1}\). Like nearly all ‘quadrant fillers’ and ‘big loops’, this event was the origin of an interplanetary shock (Schwenn, 1981).

As we have already mentioned, near sunspot maximum, coronal transients occur at all position angles. Figure 7 shows a 2-pronged event centered at approximately N 60° on the west limb on June 9, 1980. The depletion that is visible in the difference images during 09:21–10:00 UT corresponds to the pre-event streamer that is visible in the ordinary image at 01:21 UT. The depletion indicates that this streamer was destroyed during the mass ejection. Figure 8 shows another transient projecting nearly over the north pole a year earlier on June 10, 1979. This spike event has no depletion, and consists of diffuse emission bordered by a pair of bright spikes. At present we do not know whether such events usually originate at high latitudes in association with (for example) eruptive polar prominences, or whether they are associated with low-latitude active regions (for example) on the front side or back side of the Sun and simply appear to be at high latitudes when they are seen in projection against the plane of the sky.
Finally Figure 9 shows the intensity changes in the coronagraph's field of view during August 30–31, 1979 when a comet (Howard-Koomen-Michels 1979 XI) approached and apparently collided with the Sun (Michels et al., 1981, 1982). Preliminary calculations based on the pre-perihelion images (left) suggest that this comet was a member of the Kreutz group of sungrazers (Kreutz, 1888, 1891, 1901; Marsden, 1967, 1981), and that it collided with the Sun during the interval 22:00–23:00 UT on August 30, 1979. The difference images in Figure 10 show the intensity changes that occurred since 23:44 UT on August 30, and suggest that the evolving pattern had 2 components.

One component consists of diffuse emission spread over a broad range of position angles from the northeast to the southwest. It first appeared beyond the occulting disk at 03:06 UT and spread in a northwest direction to eventually fill the entire northwest quadrant before it faded substantially by 23:48 UT. This pattern is unlike any coronal structure we have ever seen. However, it does match reasonably well the projected patterns that we have calculated for cometary dust assumed to be released from the inbound nucleus and driven into hyperbolic trajectories by the combined effect of solar radiation pressure and gravity. This fit is obtained for plausible values of the orbital elements (Michels et al., 1982) and effective dust sizes ($G_{\text{dust}}/G_{\text{gravity}} \approx 2–3$).*

The other component consists of a relatively narrow fan of emission extending almost due northward and resembling the coronal mass ejection in Figure 8. The intensity of

* Since the presentation of this paper, Keller and Richter (1981) and Sekanina (1981, 1982) have reached essentially the same conclusion from their own calculations of the projected pattern of cometary dust.
Fig. 9. Intensity changes in the coronagraph’s field of view as comet Howard-Koomen-Michels 1979 XI approached the Sun (left) and after perihelion/collision (right). Venus is at the extreme left.

this component was greatest during 10:59–14:11 UT and decreased relatively slowly so that by 23:48 UT at least part of it dominated the fainter diffuse component. Like the June 10, 1979 coronal transient in Figure 8, this narrow component was broken by the polarizing ring at 5R which suggests that this radiation was produced by Thomson-scattered emission from electrons in the plane of the sky. In contrast, in the northward direction the diffuse component was not cut off by the polarizing ring. These facts (and the knowledge that this northward location was the site of unusually high transient activity during the few days prior to the arrival of the comet) lead this writer to suspect that the narrow component was a coronal transient unrelated to the comet and that the broad diffuse component was cometary dust. Work is in progress to resolve this question.
Fig. 10. Intensity changes in the coronagraph's field of view since 23:44 UT August 30 (shortly after perihelion/collision). Venus is at the upper left.

4. Conclusion

All of the results presented here were derived from routine observations over a long period of time ranging from at least 3 yr for the NRL coronagraph to at least 8 yr for the KPNO magnetograph and spectroheliograph. A characterization of coronal holes and their interplanetary effects over the sunspot cycle is just beginning as the data begin to span an 11-yr interval. The time-consuming job of processing the enormous data base of coronal observations has delayed our analysis of coronal mass ejections near sunspot maximum. In that respect, the current review could contain only those qualitative results that are immediately obvious. Of course, the exciting discovery of the comet was an unexpected result that adds even more emphasis to the importance of synoptic observations.

Although we have only begun to analyze these coronal hole and coronal transient observations both separately, together, and with other data such as the Helios and ISEE interplanetary measurements, one general result is clear. During the recent years near sunspot maximum, the corona was characterized by strong magnetic fields and incessant change. We do not yet know whether this change simply reflected the high rate of magnetic flux emergence at this phase of the cycle, or whether it was related to the solar flares and eruptive prominences that intermittently accompanied the flux emergence. We are beginning to learn that these coronal changes lead to relatively slow solar wind streams (at least in the ecliptic plane) and an increased frequency of interplanetary shocks. The next step is to examine these new observations in detail in order to understand the physical processes in the corona near sunspot maximum.
References