CORONAL HOLE EVOLUTION BY SUDDEN LARGE SCALE CHANGES

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Abstract. We have compared sudden shifts in coronal hole boundaries observed by the S-054 X-ray telescope on Skylab between May and November, 1973, within 1 day of CMP of the holes, at latitudes ≤40°, with the long-term evolution of coronal hole area. We find that large-scale shifts in boundary locations can account for most if not all of the evolution of coronal holes. The temporal and spatial scales of these large-scale changes imply that they are the results of a physical process occurring in the corona. We conclude that coronal holes evolve by magnetic field lines opening when the holes are growing, and by fields closing as the holes shrink.

1. Introduction

In a companion paper (Nolte *et al.*, 1978, hereafter called Paper I) we have discussed the short term evolution of coronal hole boundary locations. In that study we examined coronal hole evolution on a time scale of 1 day. We found that, on the average, 38% of the coronal hole boundary length which we observed shifted by more than 1° heliocentric in the one day between images. One important aspect of these changes was that 30% of these boundary positions, or 11% of the entire boundary length, shifted on a large scale. By large-scale shifts, we mean uniform changes over a boundary length greater than three times the average supergranulation cell length ($\sim 9\times10^4$ km), or over an area greater than three times the average supergranulation cell area ($\sim 2.7\times10^8$ km^2).

On a time scale of one day, these shifts occur as discrete events, not continuous slow motion. These events involve spatial changes much larger than supergranulation cells, but occur in times shorter than or comparable to one supergranule lifetime (e.g., Rogers, 1970). They appear to be changes in emission, not motion of pre-existing structures.

In this paper we address the question of the nature and significance of these large-scale shifts and their relation to long-term evolution of coronal holes. In Section 2 we demonstrate that the large-scale events have a significant effect on the long-term evolution of coronal holes. In Section 3 we discuss the physical interpretation of these events.

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2. Large-Scale Events and Coronal Hole Evolution

As in Paper I, the data which we have used for this study consists of 256 s soft X-ray exposures through a filter with 0.5% passbands of 2–32 and 44–54 Å. We have used three images, separated in time by about one day, taken near the central meridian passage (CMP) of each hole observed by the S-054 X-ray telescope on Skylab. We have examined changes in the boundaries of the holes at latitudes less than 40°. The restrictions to low latitudes, and to times, within ~1 day of CMP were used to reduce any possible viewing effects due to rotation of high X-ray emitting features. The first goal of this analysis is to demonstrate that the large-scale events are indeed significant in the evolution of coronal holes. We began by measuring the change in coronal hole area due to each event. An increase in hole area was considered a positive change, and a decrease, negative. For each hole on every rotation we then calculated an observed net rate of change of area due to these large-scale motions $(\mathrm{d}A/\mathrm{d}t)_{LS}$, by algebraically summing the areas of all events seen in the two days spanning CMP of the hole and dividing by 2 days (1.73×10^5 s). We estimated the long-term average rate of change $(\mathrm{d}A/\mathrm{d}t)_{LT}$ for each hole on every rotation by subtracting the area measured on the previous rotation from that found on the subsequent one and dividing by 54 days, or 4.67×10^6 s. Of the six holes reported by Nolte *et al.* (1976), hole 5 was observed on only one rotation, and hole 6 on only two. Therefore, we could not form reliable estimates of $(\mathrm{d}A/\mathrm{d}t)_{LT}$ for these two holes. These two holes represent only a small fraction of the entire data (see Table I of Paper I) and only one large-scale event occurred on their boundaries. Therefore, their exclusion does not greatly affect the study.

In Figure 1 we show the comparison of the observed rate of change of area due to large-scale events with the expected rate of change estimated from rotation-by-rotation measurements for the 20 CMP's of holes for which we could make the estimates. The two estimates of the rate of change in coronal hole area are of the same order of magnitude. Moreover, they follow the same trends with time though individual points vary substantially. The scatter in the observed large-scale rates is expected since only a small number of events is used in each estimate of the rate due to large-scale changes. The large-scale changes range in size from 1.1 to 7.6×10^9 km^2, with an average of 2.7×10^9 km^2. Therefore, a single average-sized change occurring during the two days of observation would result in an estimate for $(\mathrm{d}A/\mathrm{d}t)_{LS}$ of 1.6×10^4 km^2 s^{-1}.

From Figure 1 it appears that the large-scale events may play a significant role in long-term coronal hole evolution. We have examined each of the points mentioned above further, by comparing the large-scale and long-term rates statistically. As a first comparison, we note that the average magnitude of the rate due to large-scale events on these 20 rotations was $(1.27 \pm 0.41) \times 10^4$ km^2 s^{-1}. This is comparable to, or larger than, the average magnitude of the long-term rate of $(8.4 \pm 1.6) \times 10^3$ km^2 s^{-1}. (Here, and also below, the uncertainties include both errors in

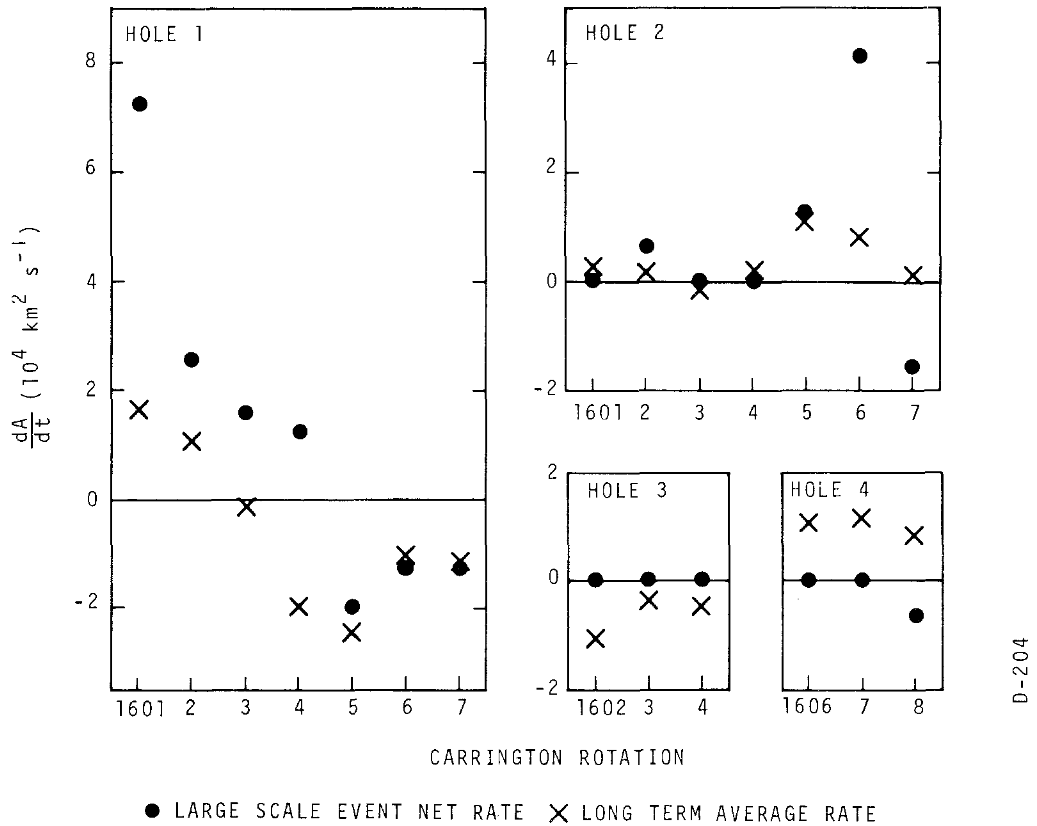

Fig. 1. A comparison of the rate of change of coronal hole area due to sudden large-scale boundary shifts with the long-term average rate of change of hole area.

measurement and statistical uncertainty in the mean of a small sample of points.) Thus the rate due to the large-scale events is certainly large enough to affect the long-term evolution of coronal holes.

We next tested the hypothesis that the large-scale changes are solely responsible for the long-term changes in the area of coronal holes, i.e., that the large-scale and long-term rates are different measurements of the same quantity. If they are, then the average of $(\mathrm{d}A/\mathrm{d}t)_{LS} - (\mathrm{d}A/\mathrm{d}t)_{LT}$ should tend to zero. We find an average value of this difference to be $(6.2 \pm 4.1) \times 10^3$ km^2 s^{-1}. Thus there is only a slight (1.5σ) tendency for the large-scale rates to be larger (more positive) than the long-term rates.

We have also examined the individual large-scale events which occurred near the 12 CMP's when the long-term rate was greater than 6.4×10^3 km^2 s^{-1}, i.e., on only those rotations when the long-term average rate was larger than the large-scale rate from a single small event would be. For these 12 cases, it is meaningful to say whether or not the large-scale change was in the same direction as the long-term rate. Of the 25 events which occurred near these 12 CMP's, 18 changes of area were in the 'right' direction, and 7 were of the opposite sign from that of the long-term evolution.

If the large-scale events were not related to long-term coronal hole evolution, then we would expect half of the events to be of each sign relative to the long term rate. Applying the x^2 test [(observed-expected)^2/expected] yields $x^2 = 4.84$, which is significant at the 2.8% level. Thus there is a significant bias in the sign of the change in area of the large-scale events, and this bias supports the conclusion that the large-scale events are intimately related to the long-term evolution of coronal holes.

We therefore conclude that the large-scale events are a significant factor in long-term coronal hole evolution. There is also a less than significant hint that the large-scale events may preferentially increase the area of coronal holes. If this is true, then another process, either the small-scale changes noted in Paper I, or some process occurring too slowly to be noticed in a day-to-day comparison might also be involved in decreasing the size of the holes.

3. Discussion: Magnetic Field Structure and Large-Scale Changes in Coronal Hole Boundaries

We next examine the process of coronal hole evolution by large-scale changes in the context of other known properties of coronal holes. This will be done primarily through a qualitative consideration of the magnetic field geometry.

We would expect any large-scale photospheric motion to have a substantially longer time scale than the supergranulation lifetime. However, the large-scale changes in coronal hole boundary positions occur in times shorter than or comparable to the lifetime of the supergranulation cells. Therefore, we conclude that the observed large-scale boundary motions are most likely a manifestation of coronal processes, and not simply a motion of coronal field lines in response to photospheric motions. This conclusion is also consistent with the appearance that the large-scale events are not the motion of pre-existing structures (Paper I).

We also found in the previous section that large-scale changes account for most, if not all, of the net displacement of coronal hole boundaries, even though small-scale changes on the average account for 70% of the boundary length which shifts during the course of a day (Paper I). This result implies that the small-scale changes are not biased as strongly in the direction of the long-term rate as are the large-scale changes. We therefore infer that the large-scale displacements involve a different process from that in at least some of the small-scale changes. We conclude that it is a coronal process which is predominantly responsible for coronal hole evolution and that this process is preferentially associated with large-scale events.

The most likely possibility for this process is suggested by the magnetic field structure of coronal holes. Holes are regions of open field lines, while the boundary magnetic structures are closed (Altschuler *et al.*, 1972; Krieger *et al.*, 1973; Timothy *et al.*, 1975). In this context, 'open' means extending to the interplanetary medium above the Alfvén radius, and 'closed' means not open. The observational evidence currently available indicates that closed field lines do not normally extend above $3R_\odot$ from Sun center.

A hole cannot grow from a small size, with little net magnetic flux, to a much larger size, with a much larger net flux, without additional field lines opening. Therefore, the coronal process involved when a hole is growing may well be the opening of field lines, which may be simply the expansion of arcades or arches into the solar wind.

It also seems quite unlikely that all of the magnetic field from the hole remains open when a hole decays and disappears. As a hole decays, the process may therefore include (or consist primarily of) the closing of field lines, which must involve a reconnection of magnetic fields.

The suggestion that the large-scale shifts in coronal hole boundary locations are due to opening and closing of magnetic field lines appears to be even more reasonable upon consideration of the other possibilities. For reference, we present an example of a large-scale change in Figure 2 (shown also as Figure 3 of Paper I).

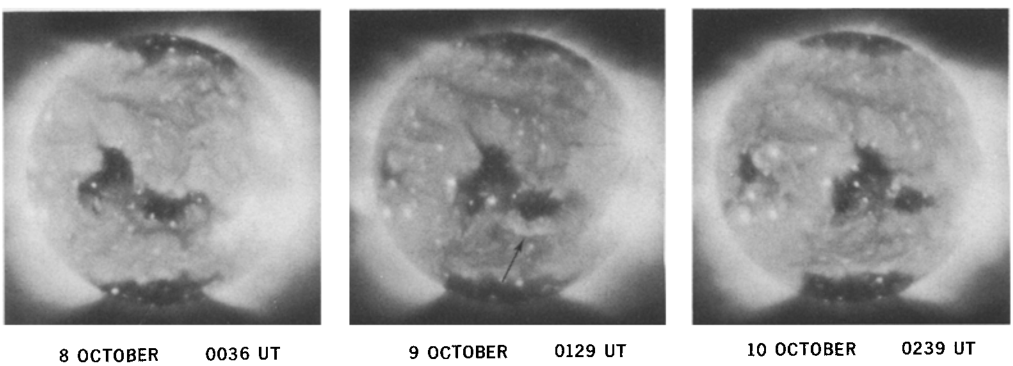

Fig. 2. Coronal hole 2 on 8–10 October, 1973. Note the transient X-ray brightening on 9 October (arrow), and the narrowing of the hole just north of this location on 10 October.

In X-rays, the boundary structures are bright, or at least significantly emitting in X-rays in the wavelength passband 2–32, 44–54 Å of our thinnest filter. The coronal hole is dark. On 9 October, a transient brightening in the corona near the boundary of the hole can be seen (indicated by the arrow). Between 9 and 10 October, the part of the coronal hole just north of the transient brightening became narrower by ~3° heliocentric over a length of ~15°. After the hole decreased in size, the intensities of X-ray emission both inside and outside the new boundary were comparable to those seen before the change (compare the 8 and 10 October images).

Since, for temperatures between 1 and 7.4×10^6 K the intensity observed through this filter is nearly proportional to $n_e^2 T^2$, where n_e is the electron density and T the temperature (Kahler, 1976), a change from bright to dark, or dark to bright, in a structure implies a change in the plasma pressure. Such a change could be caused by either a change in the energy input into the corona, or a change in one of the energy loss processes.

The mechanism for heating the solar corona is not well understood. However, it is entirely unrealistic to assume that this mechanism would change suddenly and uniformly in a region such as shown here with no observable difference on either side of the region which changes. Furthermore, in the events we have observed, the coronal hole generally had a well-defined boundary before the change, and again after, but in a different place. While it may be possible that the energy input into the corona could change suddenly and nearly uniformly over such a large, but sharply defined region, it does not seem likely that this is the case.

We therefore conclude that the change in plasma pressure is due to a sudden change in the energy lost from the corona. Because of arguments similar to those in the paragraph above, we feel that changes in the conductive losses to the chromosphere are quite unlikely to cause the large-scale events. Changes in the radiative losses would have to be in the opposite direction from the change in emission which we see. Therefore, the observed changes in plasma pressure (both positive and negative) must be due to changes (positive or negative) in the conductive or convective losses to the solar wind. In order to change these losses suddenly and by a large enough amount to change the emission by as much as is observed, the coronal field lines must open to increase the losses, or close to decrease them.

To recapitulate, we conclude that opening or closing of magnetic fields on a large-scale is the predominant method by which coronal holes evolve.

An important implication of this conclusion is that conditions favorable for the evolution to occur must be established first; then the corona adjusts in a relatively short time. That is, the coronal magnetic fields do not respond immediately in detail to photospheric motions of their footpoints. Rather, it would seem that the photospheric motions stress and distort the coronal fields, which respond in large jumps when the stresses become large enough. Physically, this means that the opening or closing of coronal fields in adjusting to photospheric motions is a threshold process. Thus it is likely that the onset of a plasma instability initiates the large-scale shifts in coronal hole boundaries which we see.

The interpretation that coronal fields do not open or close immediately in response to photospheric motions also provides an explanation for a phenomenon found by Levine *et al.* (1976). They found that the development of the photospheric magnetic field pattern, and the associated open field lines calculated using a potential approximation from photospheric field measurements, precedes the development of growing coronal holes as seen in X-ray photographs by at least one-half to one solar rotation. This result is expected if, as we have inferred, conditions favorable for opening or closing of magnetic fields must be established before the fields can actually open or close.

As a final point, we note that either growing or decaying coronal holes are possible sources of outward-moving fields and plasma in the outer corona. For growing holes and opening field lines, the field lines would be in the form of expanding arches or arcades. Near the boundary of a decaying hole, when field lines reconnect, the outward-moving field lines would be U-shaped. Although it is not obvious that the material in these events associated with coronal hole evolution would be observable, the fact that significant changes in coronal hole boundaries do occur on a large-scale suggests that coronal hole evolution may be related to at least some transient mass ejections from the sun, such as reported by Gosling *et al.* (1974).

4. Conclusions

We have demonstrated that, during the Skylab period, coronal holes evolved primarily by sudden, large-scale shifts in the positions of their boundaries. We have argued that these events were the opening or closing of coronal magnetic fields, followed by changes in the X-ray emission.

The large-scale opening and closing of magnetic fields implies that coronal fields (at least on coronal hole boundaries) did not adjust continuously to the photospheric motions of their footpoints. Rather, the photospheric motions established conditions favorable for the fields to open or close, which then occurred as sudden, large-scale changes.

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