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THE OBSERVATION OF POSSIBLE RECONNECTION EVENTS IN THE BOUNDARY CHANGES OF SOLAR CORONAL HOLES

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Abstract. Coronal holes are large scale regions of magnetically open fields which are easily observed in solar soft X-ray images. The boundaries of coronal holes are separatrices between large-scale regions of open and closed magnetic fields where one might expect to observe evidence of solar magnetic reconnection. Pre- vious studies by Nolte and colleagues using Skylab X-ray images established that large scale ($\geq$ 9 x 10^4 km) changes in coronal hole boundaries were due to coronal processes, i.e., magnetic reconnection, rather than to photospheric motions. Those studies were limited to time scales of about one day, and no conclusion could be drawn about the size and time scales of the reconnection process at hole boundaries.

We have used sequences of appropriate Skylab X-ray images with a time resolution of about 90 min during times of the central meridian passages of the coronal hole labelled "Coronal Hole 1" to search for hole boundary changes which can yield the spatial and temporal scales of coronal magnetic reconnection. We find that 29 of 32 observed boundary changes could be associated with bright points. The appearance of the bright point may be the signature of reconnection between small-scale and large-scale magnetic fields. The observed boundary changes contributed to the quasi-rigid rotation of Coronal Hole 1.

Introduction

Coronal holes are regions of unusually low density and temperature in the solar corona. They are present at all phases of the solar cycle, but reach their maximum extent in the two or three years before solar minimum. Over a decade ago Krieger (1977) in his review of the temporal behavior of coronal holes posed several fundamental questions about the evolution of holes that have yet to be completely answered. In particular, he asked: 1) What is the relationship between the stochastic diffusion of photospheric magnetic flux and the large-scale boundary changes? 2) What is the characteristic time scale for coronal hole boundary changes? 3) What is the role of emerging flux? 4) Are the large-scale boundary shifts cases of field line reconnection or of the evacuation of previously opened field lines?

An examination of the boundary changes of coronal holes was carried out by Nolte and colleagues (Nolte et al., 1978 a,b,c) using Skylab X-ray images from the period of May to November 1973. For each central meridian passage (CMP) of the Skylab coronal holes they compared the boundaries observed in three X-ray images: an image at CMP, an image 1 day earlier, and an image 1 day later. This procedure allowed them to study boundary changes with a time resolution of 1 day. Because of a concern with the possibility that the boundaries could move as a result of the diffusive motion of the field lines, they considered two classes of changes. Small-scale changes ranged from ≈ 1.2×10^4 km, the smallest changes they could measure, to 9×10^4 km. Large-scale changes were those exceeding 9×10^4 km, ≈ 3 times the average supergranulation cell length. This criterion was used to preclude the possibility that large-scale changes could arise from the chance association of random motions. Nolte et al. (1978a) found statistically that about 38% of the boundary lengths showed a significant change over 1 day. The small-scale changes accounted for 70% of this total, and the large-scale changes for the remaining 30%.

In their second paper Nolte et al. (1978b) inferred that the large-scale changes (which they referred to as "sudden") must involve a process different from that of at least some of the small-scale changes because the large-scale changes were found to account for most of the long-term (rotation-to-rotation) changes in coronal hole areas whereas the small-scale changes seemed poorly correlated with the long-term changes.

In the third paper Nolte et al. (1978c) studied the specific coronal structures which seemed to play roles in the growth and decay of coronal holes. They found a general agreement with the hypothesis that holes are born and grow in conjunction with active regions. They also found evidence that holes decayed when the number of X-ray bright points in the longitude bands containing the holes was relatively high. X-ray bright points are pointlike X-ray emitting features associated with small bipolar magnetic features (Golub et al., 1974).

We might expect that the detailed studies of Nolte et al. (1978 a,b,c) would have explored Krieger's (1977) questions to the limit of the X-ray observations. However, those studies were based only on comparisons of X-ray images obtained at 1-day intervals. Appropriate X-ray images were regularly obtained at roughly 6-hr intervals through most of the Skylab mission and in some cases, which we discuss here, the observations were made at least once per orbit (≈ 90 min) for sequences of 3 to 7 consecutive orbits. We use these images to study coronal hole boundary changes on this substantially shorter time scale.

Analysis

The X-ray spectrographic telescope built by American Science and Engineering, Inc. flew on the Skylab spacecraft in 1973 and 1974. During the 8-month operational lifetime of the mission soft X-ray images of the sun were recorded on film with a spatial resolution of ≈ 2 arc sec. Six different broad-band filters and a large dynamic range of exposure times were used to image various solar features and provide effective temperature diagnostics. The instrument has been described in detail by Vaiana et al. (1977), and an atlas of daily full-sun images of the X-ray corona was published by Zombeck et al. (1978).

The optimum images for studying the faint features of coronal holes are those obtained with the largest X-ray fluence. These are the 256 s exposures taken through the thinnest filter (filter 3) with passbands of 2-32 and 44-54 Å. Usable images in this mode were obtained from 1973 May 28 to November 21 (Nolte et al., 1976). We examined a catalog of all such sun-centered images obtained during 5-day periods centered on the CMPs of low-latitude coronal holes determined by Nolte et al. (1976) to look for images in three or more consecutive orbits. We restricted the images to those with coronal holes near CMP and limited the regions of interest to latitudes of ± 40° to minimize the projection effects of optically thin structures at hole boundaries (Nolte et al., 1976). Since we wanted to study hole boundary changes, we sought large area holes with extensive boundaries. For that reason we eliminated the sequences of images of coronal holes 2 (on May 29 and August 18) and 3 (on August 12 and 13) because of their small areas (Nolte et al., 1976) and concentrated on Coronal Hole 1 (hereafter CH 1, following the designation used by Timothy et al. (1975) for the first coronal hole observed during the Skylab mission). The only images satisfying our requirements were obtained on 3 consecutive orbits on June 2, 7 orbits on August 19, 4 orbits on August 20, and 4 orbits on August 21.

Full-disk X-ray images of CH 1 at each CMP have been published by several authors (i.e., Figure 9 of Timothy et al. (1975); Figure 1 of Nolte et al.(1978c); and Figure 1 of Maxson and Vaiana (1977)) and will not be repeated here. It was the largest of the Skylab coronal holes, extending from the north pole to about S 20° with a width of order 15° at the equator. The extensive boundaries of the hole allow us a good opportunity to study the details of the boundary changes.

The changes of the hole boundaries were examined by a visual comparison of second-generation transparencies with a disk diameter of 10.8 cm. Since the positions of the boundaries and the changes in those positions over several consecutive orbits involves a subjective determination, we first listed all suspected boundary changes in all sets of images and then repeated the effort to get only the clearest examples. We eliminated cases where the area changes were so small as to be questionable or where the brightness change of a boundary feature was not sufficient to cause one to redraw the boundary. Although they claimed that coronal hole boundaries are sharp, Maxson and Vaiana (1977) presented cross sections of photographic density through the filter 3, 256 s images that clearly display the low spatial gradients of brightness at the boundary that render the boundary determination uncertain by perhaps 10-30 arc sec. Our boundary changes, characterized as one-dimensional features, ranged from ≈ 10 arc sec (≈ 7×10^3 km) to ≈ 1 arc min (4.3×10^4 km). Our lower limit is slightly less than that (≈ 1.2×10^4 km) of Nolte et al. (1978a) who examined hole boundary shifts on a time scale of 1 day.

In the examination of the boundary changes it was immediately apparent that bright points played an important role. This can be seen in Figure 1, which shows the sequences of filter 3, 256 s images of CH 1 during the times of 7 consecutive orbits on August 19. In the figure black arrows point to the bright points associated with coronal hole expansions and white arrows point to the bright points associated with coronal hole shrinkages. One case of a hole shrinkage with no bright point association is shown with the lower white arrow at 0651 UT in Figure 1. In the images of August 20 and 21 there were two cases of coronal hole expansions without any observed associated bright point. In the images of all four dates we found 32 boundary changes of which 29 could clearly be associated with bright points.

The most common kind of boundary change is simply the appearance of a new bright point or the disappearance of a pre-existing bright point at the coronal hole boundary in such a way as to cause an apparent shift in the boundary by about the dimension of the bright point itself. Most of the boundary changes of Figure 1 are of this type. In some cases an X-ray region somewhat more extensive than just the bright point itself will brighten or dim. Two examples in Figure 1 are shown by the lower white arrow at 0226 UT, in which a relatively large X-ray structure in the hole attaches itself to the boundary, and by the black arrow at the eastern boundary at 0415 UT, where a large bright region surrounding the bright point slowly fades after the transient appearance of the bright point.

A summary of the time and size scales of the three kinds of boundary changes is given in Table 1, where we have averaged the measured sizes and the number of orbits over which the brightening or dimming of the X-ray structure was observed. Since the time resolution is $\approx$ 90 min, the actual time scales could be significantly less than the observed values, and we have given them as upper limits. To compare these boundary changes with those expected from supergranulation motions, we can use the time and size scales to calculate a characteristic speed for the boundary changes of $\geq 6 \times 10^3$ km$\cdot$hr^{-1} for all categories of changes. Assuming a supergranulation cell size of 3.2×10^4 km and cell lifetime of 20 hr, we see that the speeds of the boundary changes exceed the supergranulation speed of 1.6×10^3 km$\cdot$hr^{-1} by at least a factor of 4. These boundary changes are therefore not due to supergranulation motion.

The dimensions of the 32 observed boundary changes ranged from 7×10^3 km to 4.5×10^4 km with an average of 1.7×10^4 km; only one event exceeded 3.2×10^4 km. We therefore find no evidence for large scale boundary shifts of a size exceeding three times the supergranulation cell size ($\approx 9 \times 10^4$ km) discussed by Nolte et al. (1978a).

Most of the bright points associated with the boundary changes are much fainter than those used by Golub et al. (1974) for bright point statistics studies. Those authors used bright points visible on 4 s exposures, while we have used 256 s exposures. Comparing bright point counts in coronal holes on 4 s and 256 s images, Golub et al. found about 100 times more bright points visible on the longer exposures. They also found a correlation between the maximum areas and the lifetimes of bright points. The bright points we have observed are generally small in area (< 20×10^7 km^2) and short lived (1-5 hrs), consistent with this correlation.

The tendency of CH 1 to rotate quasi-rigidly rather than to participate in the solar differential rotation was discussed by Timothy et al. (1975). To see whether the 32 boundary changes we found in the sequences of images contributed to that quasi-rigid rotation, we establish two categories of boundary changes. X-ray brightenings on the western boundary and dimmings on the eastern boundary of the hole result in an eastward shift of the hole boundary. Conversely, X-ray brightenings on the eastern boundary and dimmings on the western boundary shift the hole boundaries westward. We used Stoneyhurst disks to measure the latitude of each boundary change and then compared the eastward shifts with the westward shifts as a function of latitude. The summed results for all four dates are shown in Table 2. Coronal holes will be sheared by differential rotation as the low-latitude regions are shifted westward relative to the high-latitude regions. We see that within the limited statistics of Table 2 the observed shifts oppose the differential rotation by being predominately eastward at low (≤ 20°) latitudes and westward at high (> 20°) latitudes. This result may perhaps have been anticipated from our previous knowledge of the quasi-rigid rotation (Timothy et al., 1975), but it provides supporting evidence that the boundary changes associated with bright points are the changes important to the development of the coronal hole.

Discussion

Recent work on modeling coronal fields by the Naval Research Lab group (Nash et al., 1988) has provided an explanation for the rigid rotation of coronal holes near solar minimum. Using a potential field model with differential rotation, diffusion and meridional flow, they found that the outer coronal field rotates more rigidly than the underlying photospheric field because it depends on only the lowest-order harmonic components. The motion of the hole boundary is uncoupled from that of the underlying photospheric flux elements by continual reconnection of magnetic field lines. The details of the reconnection process are not specified. One possibility is that this reconnection occurs in the high corona. The time scale of the boundary changes (≈ 1-5 hrs) is consistent with this, but no bright point involvement would be expected.

The appearance of X-ray bright points in boundary changes suggests that we examine the weak photospheric fields for the source of the reconnection process. The structure of the magnetic fields at hole boundaries is characteristic of the quiet sun fields consisting of network clusters at supergranular cell vertices and of weaker intranetwork fields (Zwaan, 1987). The latter weak (< 50 G) fields consist of mixed polarities and do not extend into the outer corona. We suggest that reconnection occurs between the small-scale structure and the larger scale magnetic field as shown schematically in Figure 2. The X-ray bright points associated with the hole boundary changes may correspond to the small loop in A or C of the figure or to the reconnection region in B. The separatrix is drawn between the two closed field regions in C because it separated the small scale structure from the large scale structure and because the bright point will be faint either before the sequence C,B,A or after the sequence A,B,C. The size and time scales of the proposed reconnection scenario are those given in Table 1. A somewhat similar schematic was proposed by Marsh (1978) to explain the relationship between bright point flares and supergranulation network flux elements. He observed several cases of an Hα brightening at the network element followed by a fibril system linking the network element with one of the poles of the bipolar region.

Nolte et al. (1978c) found a statistical relationship between the bright point density in coronal holes and the rate of shrinkage of the hole area. They suggested that this was due to two reasons. First, the hole was being filled in by X-ray-emitting closed-field remnants of the bright points. A problem with this idea is that we have no evidence that the bright points grow to the observed sizes of large-scale structures. The brightest bright points have lifetimes of less than a day (Golub et al., 1974). The second reason proposed by Nolte et al. (1978c) was that the bright points enhanced the rate of reconnection of open field lines at the hole boundaries. However, if a bright point reconnects with an open field line, one end of the bright point bipole must also be open after the reconnection process. Thus the proposed reconnection scenario will not result in a net closing of large-scale open field lines. In contrast, in our Figure 2 we see that the bright point in C interacts with adjacent closed field line flux to produce a shrinking of the hole area in the C,B,A sequence by motions of previously closed field lines. A further observational problem with the Nolte et al. idea is that a more detailed examination of the bright point densities in coronal holes by Davis (1985) showed no association between bright point density and the rates of hole growth or decay.

At the time of their discovery it was obvious that bright points were bipolar magnetic structures (Golub et al., 1974). They were interpreted as regions of emerging flux by Golub et al. (1974) and others. This view was challenged by Harvey (1985), who used He I 10830 Å dark points as a proxy for X-ray bright points and found that about two-thirds of the dark points were associated with chance encounters of features of opposite magnetic polarity. In a recent study Webb and Moses (1988) compared bright points observed in rocket solar X-ray images with bipoles observed in simultaneous videomagnetograms. The great majority of bipoles were not associated with X-ray bright points, but 11 of 16 observed X-ray bright points were associated with cancelling bipoles and only one with an emerging bipole. Webb and Moses concluded that their results were consistent with the Harvey (1985) interpretation that most bright points are associated with encounters of opposite polarity features. Our observations suggest that the bright points form due to coronal heating at some time during the reconnection process. X-ray bright points are known to flare on a time scale of minutes (Golub et al., 1974), but it is not clear how the flare event or the formation and disappearance of the bright point are related to the reconnection scenario of Figure 2.

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TABLE 1. Time and Size Scales of Boundary Changes

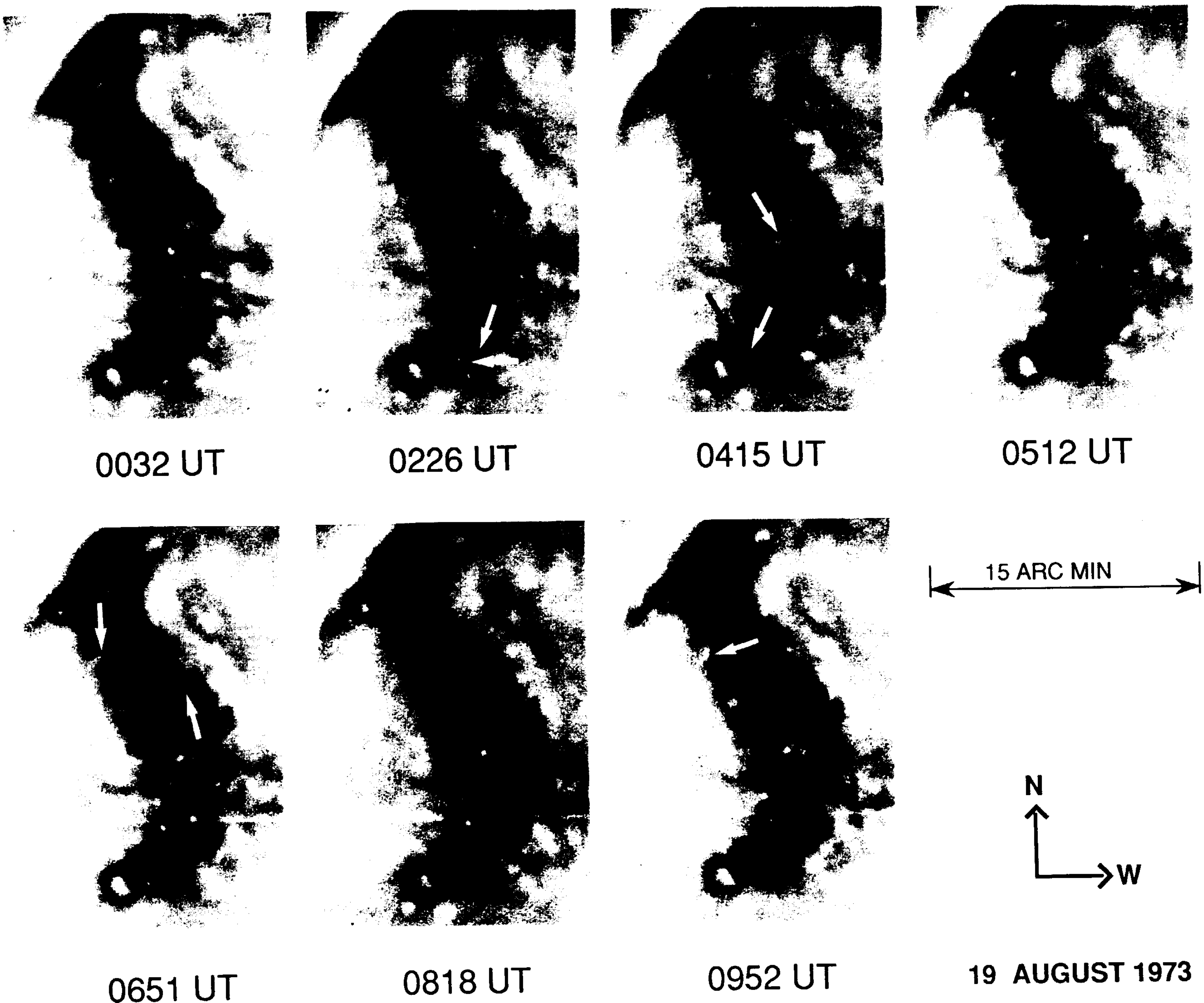
Boundary Change	Dimming	Brightening
Bright Point Only	11 cases 1.3×10^4 km $\leq$ 2.3 hr	9 cases 1.4×10^4 km $\leq$ 1.8 hr
Bright Point and Extended Structure	6 cases 2.2×10^4 km $\leq$ 3.0 hr	3 cases 2.3×10^4 km $\leq$ 4.0 hr
Extended Structure Without Bright Point	2 cases 2.3×10^4 km $\leq$ 3.0 hr	1 case 2.0×10^4 km $\leq$ 3.0 hr

TABLE 2. Observed Boundary Shifts of CH 1

Shifts	Latitude			
	01°-10°	11°-20°	21°-30°	31°-40°
Eastward	4	9	2	1
Westward	3	4	6	3

Fig. 1. Skylab X-ray images of CH 1 during seven consecutive orbits on 1973 August 19. The five bright points which were associated with expansions of the hole area are shown by black arrows; the six bright points associated with hole shrinkage by white arrows. One case of a hole shrinkage with no obvious bright point association is shown by the lower white arrow at 0651 UT.

Fig. 2. Schematic for reconnection of magnetic fields at coronal hole boundaries. Dotted regions are closed fields; the wavy line is the separatrix between open and closed fields. Reconnection occurs in B in the shaded region. The sequence A,B,C corresponds to an expansion of the hole area; C,B,A corresponds to a shrinking of the hole area.


0032 UT
0226 UT
0415 UT
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0651 UT
0818 UT
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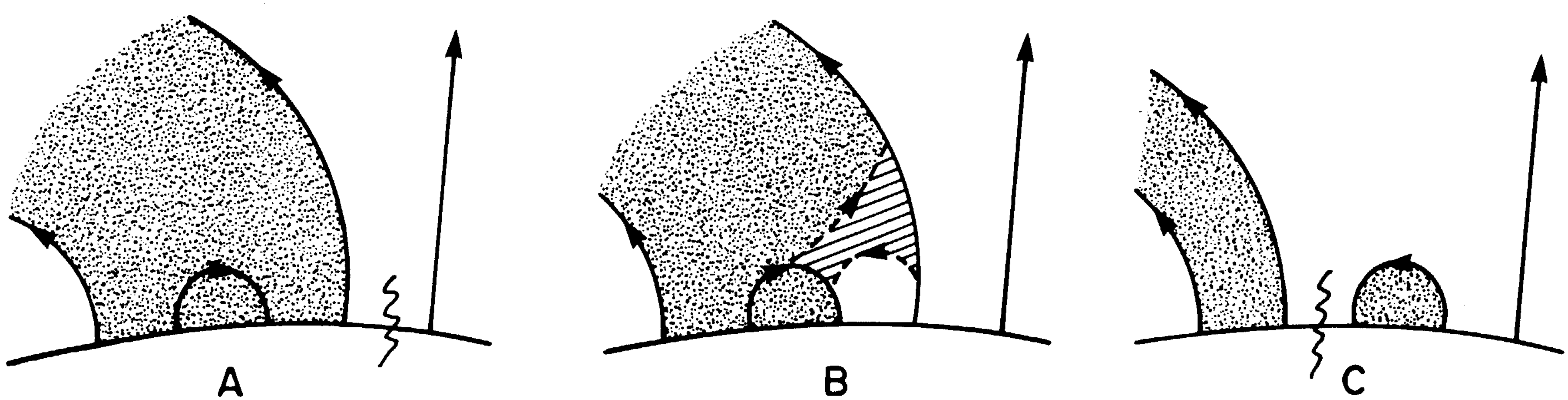
A
B
C

4.21 X-Ray Bright Points and He I 10830 Dark Points

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