CORONAL HOLES AS SEEN IN SOFT X-RAYS BY YOHKOH

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ABSTRACT

This paper reviews literature on the 10-plus years of *Yohkoh* soft X-ray observations of coronal holes (CHs), which span almost half a Hale cycle. They thus extend and generalize the results of *Skylab*, providing better sampling and duration. These modern X-ray data confirm the tendency towards rigid rotation of equatorward extensions of polar holes, but show no clear sign of the mechanism of magnetic reconnection that makes this possible. Coronal-hole boundary evolution does not seem to depend upon transient magnetic activity such as X-ray bright points or large-scale arcade events associated with transient coronal holes. The morphology of the coronal holes as seen in X-rays differs from that seen in He I λ10830: X-rays generally do not do so well with the polar holes or other holes near the limb, because of foreground confusion, but they show narrow features better.

Key words: coronal holes; solar wind; X-rays.

1. INTRODUCTION

The phenomenon of the coronal hole (*e.g.* Zirker, 1977) presents us with a problem of definition. Observationally a coronal hole (CH) shows up as a dark (X-ray) or depleted (visible) region, as in Waldmeier's "koronale löcher." On the other hand we know that the CHs provide the magnetic field embedded in the high-speed streams of the solar wind. Should this property (open field) define the CH instead? There are substantial reasons for suspecting that CHs and open-field regions do not have a one-to-one relationship. We have no clear theoretical understanding of how open fields actually develop, and cannot at present predict the open flux except by empirical models. We do know observationally, however, that the open flux varies with time (Lockwood, 2001), but that it varies by only a small factor (less than an order of magnitude) over solar-cycle time scales. We also do not understand the mechanism of this regulation theoretically; as Gold (1962) noted, each CME appears to add new open field lines, but the interplanetary field intensity B does not therefore increase monotonically. This is the "flux catastrophe" noted by McComas *et al.* (1992). The regulation of the open field implies the existence of a process of field-line reconnection, but the timing and geometry of this process remain controversial.

The open field lines of the solar wind must thread back through the coronal magnetic field to reach the photosphere. In the lower solar atmosphere they meet stresses imposed by photospheric convective motions and line-tying, and through the corona and solar wind they traverse a highly conducting and collisionless medium (see Gary, 2001, for a recent discussion). It seems natural, therefore, to look at the low corona to gain an understanding of perplexing problems mentioned above. The TRACE data, for example, appear to show a ready adjustment of newly emerged magnetic field to the pre-existing coronal field (Handy and Schrijver, 2001). The relevant data for this purpose include He I λ10830Å spectroheliograms and magnetograms, plus EUV and soft X-ray images. This paper will concentrate on the latter, for which *Yohkoh* has provided a data base exceeding ten years in length. Kahler and Hudson (2001, 2002) have provided initial surveys of the morphology of these data. The objective of this paper is to review the CH observations made by *Yohkoh* SXT and to contrast these results with those from other approaches for defining CHs.

In addition to X-rays and He I λ10830Å as methods for determining the open flux, we also have semi-empirical models. These typically take the observed photospheric magnetic field and make a potential-field extrapolation interior to a spherical "source surface" at 2.5 $R_\odot$ (Altschuler and Newkirk, 1969; Schatten *et al.* 1969). Field lines reaching the source surface become open, by definition, and extend outwards radially thereafter. The mathematical artifice of the source surface substitutes for a more correct non-potential extrapolation, and also simplifies the physics of coronal heating and expansion. The relationship of the source surface to the "top of the corona," which might be defined as the surface at which the outward flow speed exceeds the Alfvén speed, remains unclear, but this kind of model is in universal application and serves reasonably well to predict solar-wind flow speeds and the physical locations of coronal holes (*e.g.* Wang, 2002). From the point of view of actual coronal physics, a source-surface model has no relevance, however. The energy storage needed for flares or CMEs cannot be described by such a model, since the corona is represented as a potential field and cannot store energy. Further, most applications of the source-surface model depend upon synoptic representations of the coronal structure, *i.e.* using data from an entire Carrington rotation. On shorter time scales such models should be viewed with caution.

In this review I summarize the morphology of CHs as observed in the *Yohkoh* soft X-ray imaging, starting with the "Elephant's Trunk" CH (Section 2) and continuing to other topics. Section 6 discusses the difference between the modern soft X-ray morphology and that of the more standard He I 10830Å CH definition. Section 7 comments on the implications of the data for cartoon models of how coronal open fields develop. The *Yohkoh* database has exceptional advantages over previous soft X-ray observational material, specifically in time sampling, but in fact there is little published material on this important topic yet. Thus, in Section 9, I point to possible future directions for research.

2. THE "ELEPHANT'S TRUNK"

In 1996 there appeared a remarkably solitary major activity complex (NOAA 7978). It had old-cycle polarity, and its magnetic consequences in the solar corona persisted for several rotations (Hudson *et al.*, 1997; Démoulin *et al.*, 2002). In accordance with the pattern of development of a "non-axisymmetric" magnetic flux perturbation as described by Wang and Sheeley (1993), the north polar coronal hole developed an equatorward extension (see Harvey and Hudson, 200). This CH became the object of intensive study through observing campaign activities involving *Yohkoh*, SOHO, and other data sources (Gibson *et al.*, 1999; Bromage *et al.*, 2000).

In Section 3 we describe the morphology of equatorward extensions during higher solar activity, so it is instructive to consider the appearance of such a phenomenon at solar minimum. During such conditions the general corona has lower temperatures and becomes markedly less visible in the *Yohkoh* images. Figure 2 shows a *Yohkoh* image of the Sun on August 26, 1996 (approximately two rotations after the initial flux emergence of AR 7978); the corona around the active region has become brighter (hotter), whereas the corona on the opposite side of the equatorward CH extension remains rather faint.

Figure 3 shows east-west line scans, as indicated, for three different image-summation levels. The signal-to-noise ratio increases with increasing summation level, but the location and general shape of the boundaries do not appear to vary significantly over the one-day interval. The coronal intensity at the CH boundary drops rapidly, on the order of a factor of two in two Mm. Gibson *et al.* (1999) used a variety of models, including MHD approximations as well as source-surface models, to represent the Elephant's Trunk structure successfully.

3. CORONAL HOLE BOUNDARIES

The equatorward extensions of the polar coronal holes tend to rotate rigidly, rather than with the flow field of the photospheric differential rotation (*e.g.* Zirker, 1977). At the CH boundary there must therefore be a process of reconnection enabling field lines to close off (at a "closing boundary") and possibly also at the "opening boundary." Nash *et al.* (1988) have explained this process by using a source-surface model, finding that the rotation rate of an equatorial-extension CH to be determined by the rotation of the active region responsible for perturbing the coronal field structure. For example, in the northern hemisphere: latitudes north of the region latitude the CH will appear to rotate faster than the underlying photosphere, so that its *eastern* boundary will be the closing boundary, and the opposite south of this latitude. How do the closing field lines find opposite-polarity fields with which to reconnect?

Kahler and Hudson (2002) have studied the CH boundary morphology in *Yohkoh* soft X-ray observations. One objective of this study was to identify any plasma activity associated with the boundary motions, specifically energy release involving magnetic reconnection. They find three types of boundary: ragged, smooth, and loopy. Figure 1 illustrates the differences among them. This classification is based upon the examination of SXT synoptic images for three CHs observed to extend towards the equator from the polar CH: two (YCH1 and YCH2) in 1991 and 1992, and the third (YCH3) in 2000. These are all solar-maximum CHs, since the high-temperature response of SXT makes the diffuse corona at solar minimum less detectable, so that CH boundaries become more difficult to trace.

The loopy and diffuse CH boundary types, the majority types, pose a problem of interpretation that will be described in Section 7. Namely, these boundaries appear to consist of short loops, rather than loops that can reach outwards to a streamer cusp and thence back down into another coronal hole.

The data show that the CH boundaries, whatever their type, do not evolve rapidly except during special occasions in which magnetic activity (flare and/or CME) occurs (see Section 5). Figure 4 illustrates this, showing the disk passage of one of the *Yohkoh* CHs (Kahler and Hudson, 2002). The boundaries show no manifestation of energy release associated with magnetic reconnection. Flaring X-ray bright points in particular do not seem to mediate CH boundary motion, as previously suggested (Kahler and Moses, 1990).

4. CORONAL HOLE CHANNELS

As illustrated in Figure 5, a narrow CH can sometimes escape detection in He I λ10830Å and still be seen in soft X-rays (and often in the model field-line calculations). The figure shows a narrow CH channel extending diagonally across disk center. It is clear in the soft X-ray view but not in He I λ10830Å, presumably because of its small transverse dimension. How much magnetic flux can go unaccounted in the CH area defined by He I λ10830Å, although visible in soft X-rays and perhaps the models? Figure 6 shows another example, in which the CH channel occurs in a relatively strong-field region.

The soft X-ray observations are ambiguous to a certain extent. Whereas some channel features clearly are CH and show up as such even in source-surface models, we must recognize that filament channels also appear as elongated dark structures. These can be distinguished by their morphology, especially at the limb: a CH channel appears as a notch in the corona, with diverging field above it, whereas a filament channel appears (ideally) as an O-type geometry, sometimes with a bright central core (Hudson *et al.*, 1998).

5. CORONAL TRANSIENTS

5.1. Dimming

The idea of the "transient coronal hole," (TCH) discovered in the *Skylab* data (Rust, 1983), has been generalized in the modern era by the discovery of several types of coronal dimming (e.g. Hudson and Webb, 1997). These include the TCH type, but also more widespread depletions, including clear signatures of large-scale transequatorial loops (*e.g.* Khan and Hudson, 2000). The TCH type often takes the form of "double dimmings" associated with the activation (Sterling and Hudson, 1997) of a sigmoid coronal structure (Rust and Kumar, 1996).

These dimming events resemble what their name implies, namely the temporary appearance of a CH near the site of a flare and/or CME. The appearance of a TCH in conjunction with a CME provides dramatic evidence of the association of a dark coronal region with solar-wind flow, in this case the appearance of enhanced flow as a part of or following the CME itself. Superficially then a TCH and an ordinary CH both appear to show us open field lines and regions of solar-wind origin.

The physics of formation of TCHs and CHs obviously differs, however. The observable lifetime of a TCH is at most a few days, implying a more rapid boundary evolution during the recovery phase. In many cases the foreground/background structure of the 3D corona makes the estimation difficult, however, and there are suggestions (Solanki *et al.*, 2002) that extremely long time scales (years) may be involved as well. The initial dimming appears to keep in step with the flare brightening (Zarro *et al.*, 2000). Kahler and Hudson (2001) found that the TCH recovery phase may show a pattern of shrinkage from the exterior boundary (remote from the flare) as well as from the interior boundary (site of the post-flare loop system). They found no clear evidence that TCH occurrence systematically affected the regular progression of CH boundaries as forced by the photospheric differential rotation. Thus coronal magnetic activity, specifically X-ray bright points and TCHs, does not appear to play a fundamental role in CH boundary formation.

5.2. Activity within coronal holes

In the ideal view, the magnetic field within a CH is unipolar and extends outward into the solar wind. In practice a salt-and-pepper pattern of mixed polarities also occurs at the photospheric level. The TRACE data show the canopy of closed field lines resulting from this (Handy and Schrijver, 2001) but we do not understand quantitatively how the open field lines thread through this "carpet" in the low corona, nor the consequences of magnetic reconnection needed to maintain it. Recently Chertok *et al.* (2002) have found a case of strong magnetic activity within the boundaries of a CH observed in soft X-rays as a dark region. The event they detected appeared to be a typical quiet-Sun arcade event accompanied by a CME. Such an observation apparently shows the conversion of a unipolar open-field region into one with an embedded polarity, the minority polarity of the CME's magnetic structure. This implies the existence of transient complexities in the current-sheet structure of the middle corona, possibly extending beyond the critical surface (see Gosling *et al.*, 1994, for a description of high-latitude disturbances of the solar wind). On larger scales the heliospheric current-sheet structure seems reasonably well-predicted by the source-surface model, and typically does not have secondary current sheets (*e.g.* Wang, 2002).

5.3. Association with streamers

At solar minimum, the field lines of the two polar coronal holes define the streamer structure in a tidy manner. This is not the case at solar maximum, during which several lines of evidence indicate that open fields also come out of active regions. What does this imply for the streamer structure seen in coronagraphic images? New flux emergence (active-region formation) can result in substantial closed field within the envelope of a CH, and the results reported in Section 5.2 suggest that new bipolar open field lines can occur within the boundaries of a CH. Figure 7 shows another *Yohkoh* example in which as many as five separate bipolar regions have emerged to form a mass of closed structures within a single unipolar CH region.

According to LASCO images of this system as it crossed the limb (Figure 8), no streamer resulted from the complex magnetic structure enveloped by the CH. Thus in this case, unlike that suggested for the event studied by Chertok *et al.* (2002), we see no evidence for a complex heliospheric current sheet above the structure studied. Note that Shibata *et al.* (1994) found a large X-ray jet, presumably associated with opening field lines, which came from an "anemone" active region embedded in a coronal hole.

6. HELIUM OR X-RAYS?

Coronal EUV and soft X-ray emissions excite chromospheric He I, increasing the absorption in the 10830Å line. A He I 10830Å spectroheliogram thus appears bright in a CH. This fact, together with criteria on the size and texture of the image and comparison with magnetograms, allows CH areas to be defined routinely from these data (*e.g.* Harvey, 1995). Thus the relationship to X-ray intensity is indirect, and one might ask whether or not the direct imaging of soft X-rays might not provide a more accurate measure. For one thing, the coronal radiation responsible for He I 10830Å excitation comes from higher altitudes and therefore larger spatial scales, which serves to make the apparent He I 10830Å CH boundaries diffuse. This immediately suggests that He I 10830Å observations may not detect the smallest CHs. By contrast the high thermal conductivity of the corona implies that CH boundaries extend, sharply-defined, down to the lowest corona.

On the other hand, the direct soft X-ray images also have an obvious systematic bias. The corona is optically thin to soft X-rays, so that foreground or background coronal emission can mask the occurrence of a CH near the limb. This of course includes the polar CHs, which we believe to contain the bulk of the open field during solar minimum. We can therefore best use the more sharply defined soft X-ray CH observations near disk center, where foreground/background confusion cannot occur.

Neither He I 10830Å nor soft X-rays can unambiguously determine the area of a CH, however, if we define it physically as the locus of the open coronal field lines. Because of the difficulty of measuring the coronal field directly (but see Aschwanden *et al.* 2000), we have no empirical way (other than by charged particles; see for example Larson *et al.*, 1997) to determine the geometrical structure of the coronal magnetic field. Thus models based upon extrapolation of the photospheric field measurements also must be considered, in spite of their flaws. Variants of the source-surface model dominate this view of the corona.

7. DISCUSSION

The observations reported here have good time resolution and we have used them to study CH boundary evolution on time scales much less than one solar rotation. Ideas derived from source-surface modeling of the coronal open field thus have little validity (see also Section 1), because such models normally require data from a full solar rotation (synoptic map) for input (but see Zhao *et al.*, who use updated synoptic maps to study variability on time scales of days).

Does the superior resolution of the *Yohkoh* database translate into better physical knowledge of the physical processes taking place at the boundaries of CHs? A simple inflation of the magnetic field, as observed by Uchida et al. (1992) in the *Yohkoh* data, could in principle create bipolar CH areas, as we seem to see in the TCH phenomenon. However to move the boundary of a given unipolar CH region may require magnetic reconnection with a structure outside the CH boundary. This must happen in such a manner as to leave the allow apparent motion of a CH boundary with little area change on a presently ill-determined time scale.

Kahler and Hudson (2002), as noted, found three general types of boundary structure, including small-scale loop systems (see Section 3). The cartoons in Figures 9 and 10 show attempts to describe what might happen (in each cartoon, the top is before and the bottom, after; the CH boundary moves from right to left). Figure 9, adapted from Fisk *et al.* (1999), suggests reconnection between an open and a closed field line, which preserves the open flux;reconnection of two open field lines is required if the CH area is to change. Because we apparently observe newly opened field lines in CMEs, such a cartoon cannot represent the actual situation. This requires open field lines of opposite polarity to meet and reconnect somehow.

Direct reconnection of opposing open field lines, as envisioned for open-field regulation at the streamer cusp, runs into a complication if the CH boundary consists of short loops. The majority of the *Yohkoh* CH boundaries have this property, and bear no obvious association with the base of a streamer. In fact this statement is a bit imprecise, since we do not really understand what the base of a streamer looks like in the low corona. However, it should contain large-scale fields since it abuts CHs. If the boundary loop is instead short, the simple reconnection picture of Figure 9 is not adequate, because the other end of such a loop would be embedded in quiet corona or an active region rather than than another CH. Thus the reconnection might involve the presence of open field lines scattered through the normal corona, possibly the initiation of the process described by Wang and Sheeley (1993) as a "wave of reconnection." We illustrate this possibility in Figure 10, similar in spirit to Figure 5 of Fisk and Schwadron (2001). If the wave of reconnection proceeds rapidly, open field lines can find one another and preserve a constant open flux; if not, the open flux must change with time.

It is worth noting (*e.g.* Kahler and Hudson, 2002) that a finite time scale for open-open reconnection requires the creation of solar-wind field lines with a U-shape (Gosling *et al.*, 1995; Larson *et al.*, 1997), which should be detectable as "heat flux dropouts" in the solar wind.

8. CONCLUSIONS

In this review I have summarized the work to date on the modern soft X-ray database from *Yohkoh*. At coronal temperatures the soft X-ray signal S scales monotonically approximately as a power of the electron pressure p_e: $\partial ln(S)/\partial ln(p_e) \sim 2$ (Kahler, 1976; see Tsuneta *et al.* for the *Yohkoh* response functions). Soft X-rays therefore in principle sharply define a CH boundary because of large contrast. The study of coronal holes via soft X rays is only beginning, somewhat surprisingly, in spite of the full record we have from the *Yohkoh* SXT database and from its predecessors. Specifically we have not gone beyond morphology enough to understand the physical mechanisms at work. Given the need for magnetic reconnection at least at the closing boundary of a CH as it moves through the photosphere, this database is an obvious place to search for activity that would tell us how this process works. Morphological surveys (Kahler and Hudson 2001, 2002) have not shown any direct evidence for this reconnection, and in fact have upset the previously-held view that magnetic activity (X-ray bright points, TCHs, heating due to magnetic reconnection) show where CH boundaries evolve.

The essentially empirical source-surface models, as well as more recent theoretical work, only crudely represent the processes that relate the photospheric magnetic field to that seen in the solar wind. For example, the Fisk theory (*e.g.* Fisk and Schwadron, 2001) is based on the idea of a *constant* open flux; meanwhile the flare/CME theories of the Kopp-Pneuman type (*e.g.* Hudson and Cliver, 2001) envision short-lived (*hours*) reconnection processes following an eruption; finally systematic models of the open flux (*e.g.* Solanki *et al.*, 2002) suggest recovery time scales on the order of *years*. The breadth of our ignorance seems staggering! This paper proposes that at least some of this reconnection takes place via open-field elements in the network, rather than between field lines in opposite-polarity coronal holes at streamer boundaries. The location of the remainder of the reconnection remains unclear. Some of it appears to occur high in the corona, in the vicinity of the streamer cusp (Wang *et al.* 1998; Van Aalst *et al.* 1999).

9. FUTURE DIRECTIONS

As mentioned above, the new X-ray data have led to surprisingly little research on coronal holes in the low corona, in spite of the fascinating problems they pose. The results reviewed in this paper have been mainly morphological. In this section I suggest some directions for future work.

1. How do CH boundaries vary with observing wavelength? Bromage *et al.* made a comparison of UV, EUV, and soft X-ray (*Yohkoh*) appearance for the "Elephant's Trunk" CH in 1996, but somewhat surprisingly found sharper boundary structures (steeper gradients) in the EUV than in soft X-rays. Systematic comparisons, especially during solar maximum conditions, would help to define the CH boundary structure in the low corona and possibly point to the boundary field connectivities.

2. How do CH boundaries interact with the supergranulation? The suggestion of Figure 10 is that the open-flux readjustment occurs at network vertices, so there is a prediction of a close spatial relationship.

3. How much open magnetic flux occurs in the CH channels, which may be missed by He I 10830Å? More generally, how well does the apparent open flux match that determined by the interplanetary field (Lockwood, 2001), especially on time scales less than one rotation?

4. Do the higher-resolution TRACE observations show heating related to CH boundary evolution?

5. What is the solar-cycle behavior of CHs as seen in the low corona via soft X-rays?

The underlying idea in this list is that we have new tools (the soft X-ray and EUV observations from *Yohkoh*, SOHO, and TRACE) for observing the boundaries of CH in the low corona. Such boundaries identify separatrices of the coronal magnetic field and help to define its large-scale current systems. It is likely that further study of these boundaries would teach us a great deal about the physics involved in the evolution of large-scale coronal structure, all of which is invisible to the traditional source-surface methods.

ACKNOWLEDGMENTS

NASA supported this work under contract NAS8-40801. *Yohkoh* is a mission of the Institute of Space and Astronautical Sciences (Japan), with participation from the U. S. (NASA) and U. K. (PPARC). The author appreciates the hospitality of the Astronomy and Astrophysics Group, University of Glasgow, during the preparation of this paper. He would also like to thank the EIT and LASCO teams, for ready access to their SOHO observations. He also would like to thank S. Gibson and J. Luhmann for helpful comments on the draft of this paper.

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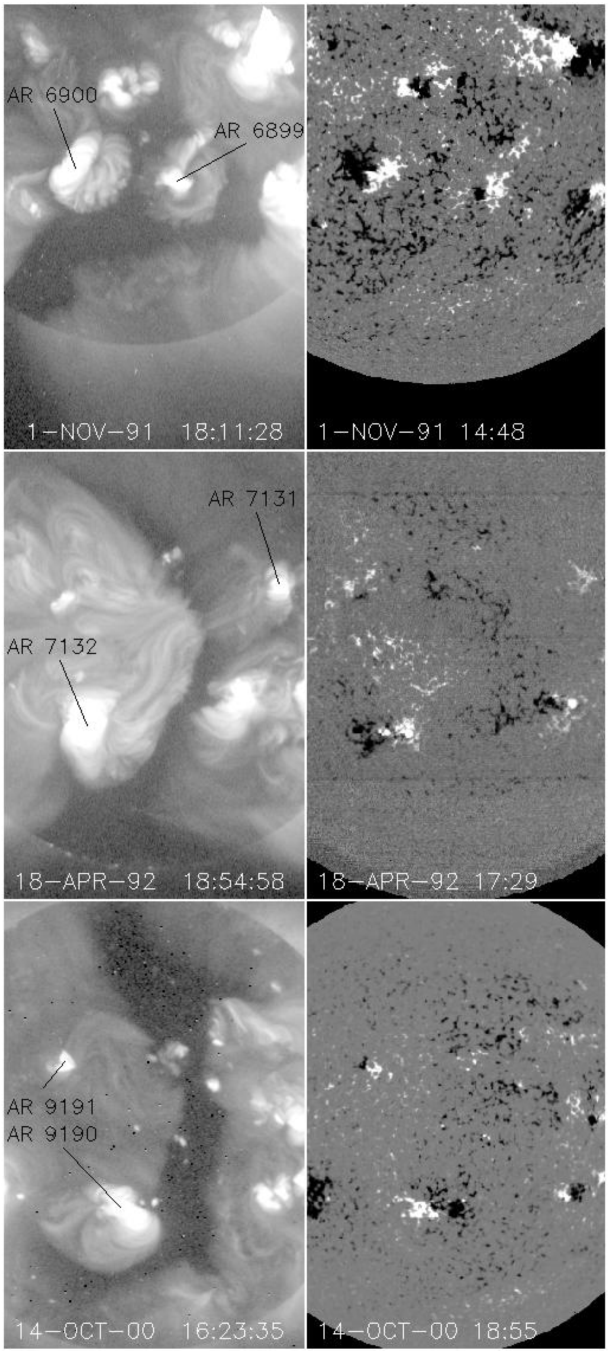

Figure 1. Illustration of the three categories of coronal hole (CH) boundaries found by Kahler and Hudson (2002). "Ragged" boundaries predominate, as for example in the lower panel; the middle panel shows a "smooth" boundary at the extreme southwest, and the upper panel shows a "loopy" boundary at the embedded active region. Solar north is up, west to the right in each frame.

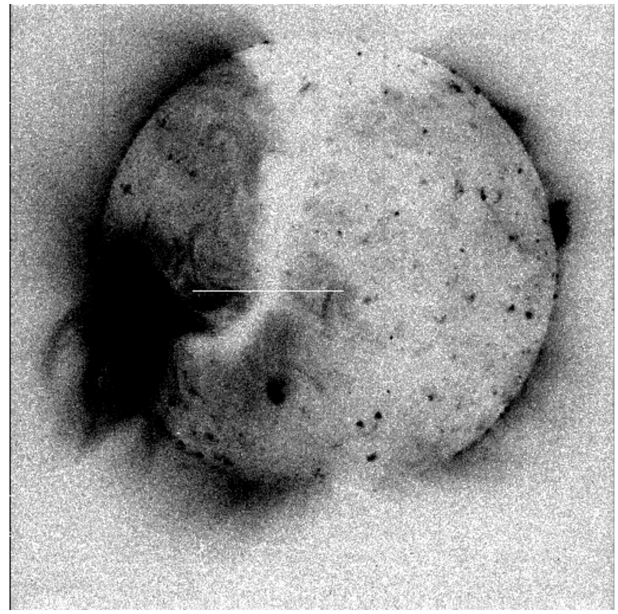

Figure 2. The "Elephant's Trunk" coronal hole on August 26, 1996, as observed by Yohkoh (negative image, square-root compression). The horizontal line shows the location of the brightness scan shown in Figure 3. This image is an example of a new Yohkoh data product, the "SSC" secondary database with improved corrections.

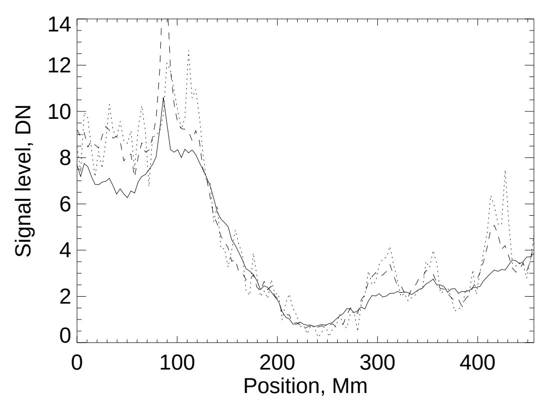

Figure 3. Brightness distribution along the cut shown on Figure 2. The dotted line shows a single image (01:44:37 UT, August 26, 1996); dashed, the sum of 6 (covering about two hours), and solid, the sum of all 37 Yohkoh images in the AlMg filter, 4.92″ pixel size, for that date. The reference point for image registration was E 15°, N 0° in the first image.

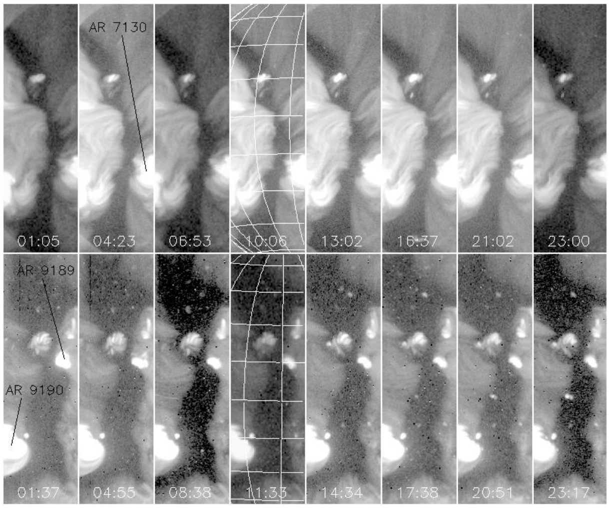

Figure 4. *Disk passage of a Yohkoh CH, showing the slow development of its boundaries (Kahler and Hudson, 2002). The Yohkoh data allow much better time resolution but in general do not show rapid boundary changes. Each sequence lasts for about one day, and the imposed heliographic grid has a 10-degree spacing.*

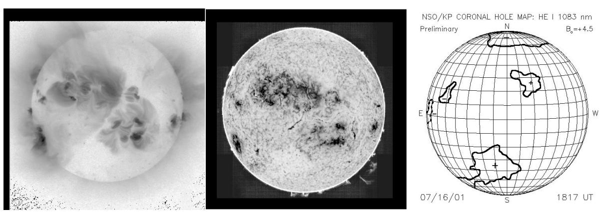

Figure 5. *Example comparing X-ray (left) and He* I *10830Å views of the Sun (center) on July 16, 2001. As the Kitt Peak magnetogram (right) shows, the diagonal CH channel has been missed.*

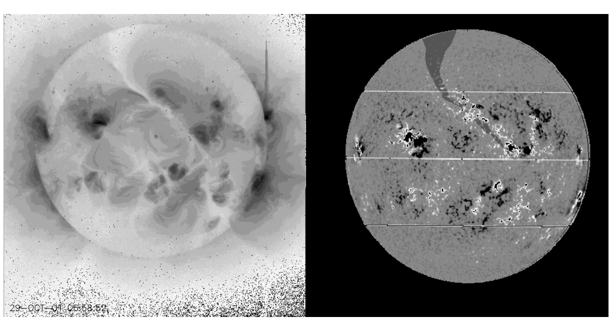

Figure 6. *Another example of a coronal-hole channel (Yohkoh image on the left), in this case a clear equatorial extension. The CH area is shown on the Kitt Peak magnetogram on the right as a shaded region.*

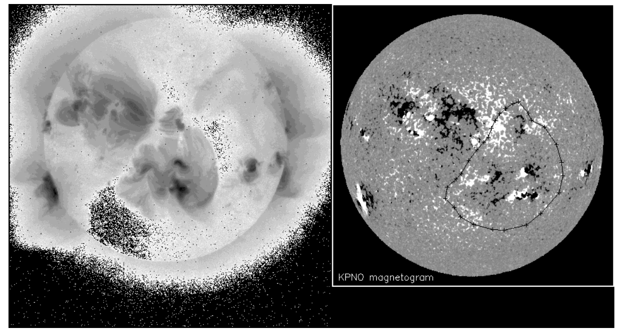

Figure 7. *Multiple closed-field active regions occurring within the apparent boundary of a single CH (Yohkoh observations, left; Kitt Peak magnetogram, right). The line on the magnetogram shows the location of the coronal-hole channel surrounding the active regions.*

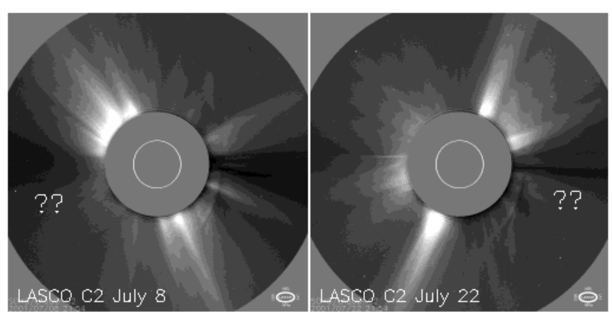

Figure 8. *Limb views above the active-region complex shown in Figure 7, as seen with the LASCO C2 coronagraph. No streamer structure appears at either limb, implying the absence of a secondary heliospheric current sheet above these regions.*

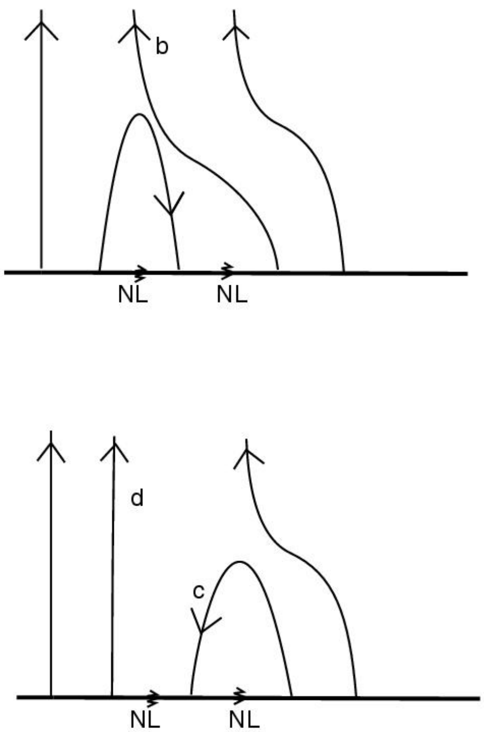

Figure 9. Cartoon adapted from Fisk et al. (1999), showing how reconnection at a "closing boundary"(see text) might move the CH boundary. The open field line to which the closing CH field reconnects would need to come from another CH. Note that this common representation of this process does not correctly show the CH boundary at the upper right – it should not be a neutral line (NL), since CH boundaries normally occur in unipolar regions.

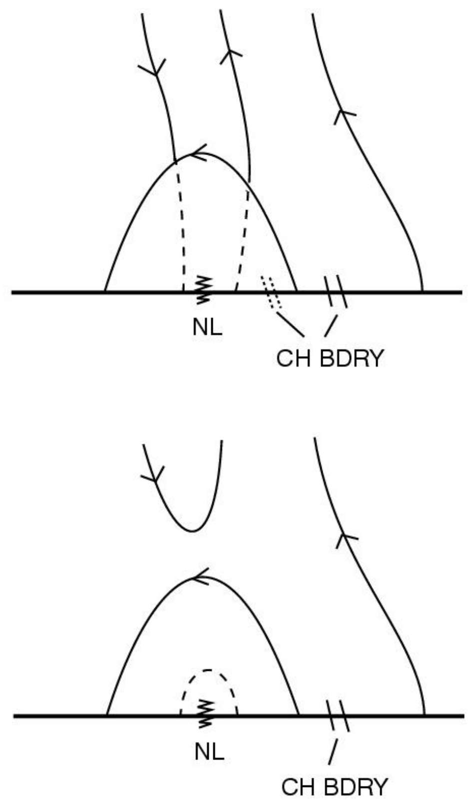

Figure 10. A cartoon describing the same situation as in Figure 9, but suggesting the participation of network fields. The dashed lines are a guide to a 3D view. A field line at the closing boundary of a CH initially finds an adjacent open field line within the diffuse corona, rather than one from a different CH. The feet of the reconnecting field lines are shown as dashed, to suggest the third dimension. The supposition is that these field lines can meet at a vertex of the network. Following this initial reconnection, the open field line migrates across the diffuse corona by a random walk until it finds a CH.