The Astrophysical Journal, 513:L83–L86, 1999 March 1

A STABLE FILAMENT CAVITY WITH A HOT CORE

H. S. Hudson,[1] L. W. Acton,[2] K. L. Harvey,[3] and D. E. McKenzie[2]
Received 1998 June 22; accepted 1998 December 31; published 1999 January 25

ABSTRACT

We present observations of a long-lived solar filament cavity with soft X-ray sources along its axis. This structure appeared above the southern polar crown polarity-inversion line for approximately three rotations during 1997 June–August, centered at a west-limb passage on approximately July 3. At the limb, the *Yohkoh* soft X-ray data showed a bright region situated above and around the projected filament location but near the axis of the cavity. We describe measurements of the geometry of the cavity, which we interpret as a flux rope that is partially embedded in the photosphere, and use the *Yohkoh* data to describe the physical parameters of the structure. We find that the core consists of an unresolved mass of filamentary substructures, with a volume filling factor significantly less than unity for the soft X-ray telescope (SXT) resolution. The core has a higher temperature than the cavity surrounding it, ruling out explanations in terms of a transition region supported by thermal conduction. Transient activity occurred in the polar crown region, but no detectable destabilization or eruption of the cavity structure resulted from it. We suggest that the bright structure at the core of the cavity corresponds to higher altitude coronal segments of the field lines that support the filament material.

Subject headings: Sun: corona — Sun: filaments — Sun: magnetic fields — Sun: prominences — Sun: X-rays, gamma rays

1. INTRODUCTION

Solar filaments represent an invasion of cool material into the corona. The temperatures and densities of filament material provide mysteries for solar physicists. Foremost among these is the mechanism by which the cool dense material is supported against gravity; almost certainly, the support is accomplished by locally concave-upward (i.e., "dipped") magnetic field lines. But also, what is the source of the material? Does some of it condense from the surrounding corona, creating the evacuated filament-channel cavity, or does it rise from the chromosphere?

The magnetic field lines form a channel in which the filament forms and resides. The filament lies above the magnetic inversion line in the photosphere, but not all inversion lines produce filaments, and the nature of the field supporting the filament remains unclear. As first observed systematically by *Skylab*, the filament channel (alternatively "filament cavity") appears as a void in coronal soft X-ray emission (see Engvold 1989 for a review). On the disk, a filament channel appears as an elongated empty area with bright edges corresponding to chromospheric "ribbons." The brightness of the edges results from the line-of-sight integration of X-ray emission along the roughly vertical (i.e., nearly parallel to the line of sight) legs of overarching coronal loops.

At the limb, the geometry of the cavity enclosure becomes more visible because of projection against the background sky. One typically then sees a white-light coronal streamer, often with a hollow cavity underneath. Such cavities sometimes form long-duration X-ray arcade events and launch coronal mass ejections (CMEs) of the "streamer blowout" type. At this time, a restructuring of the magnetic field occurs, and we see large-scale mass motions and coronal dimming (Hudson & Webb 1997).

In this Letter, we describe a particularly well-observed and stable filament channel that appeared in the southern polar crown region over three solar rotations in 1997 June–August. Solar-minimum conditions as well as the nearly linear east-west orientation of this filament channel allowed a relatively unobstructed view of the cavity during its limb crossings. Moreover, the images at the limb revealed an unanticipated X-ray source in the core of the cavity, lying (in projection) around and above the prominence. In this Letter, we give a first description of the cavity's appearance and structure, as well as measurements of the physical properties of the X-ray source in its core.

2. OBSERVATIONS

Yohkoh soft X-ray telescope (SXT) images show the solar corona in broad spectroscopic bands in the 0.1–3 keV range (Acton et al. 1992). We have used the routine full-Sun images with 4″.92 pixels and two of the SXT filters (Al.1 and AlMg) in the analysis described below. The ratio of fluxes through these filters allows temperature measurements in the range below a few times 10^6 K (Tsuneta et al. 1991). The SXT data have been discussed abundantly elsewhere, but we emphasize one important point of interpretation here: at these wavelengths, the corona is optically thin. Thus, confusion along the line of sight always needs to be considered.

Figure 1 shows the subject of this Letter, the southern polar crown filament channel, as projected against the sky during seven limb crossings. The striking feature of this cavity at the limb, best seen in the image shown for 1997 July 4, is the unexpected and persistent presence of X-ray emission from the core of the cavity. The association of this core X-ray source with the prominence material in the cavity appears in Figure 2, which overlays the He I λ10830 and X-ray observations for 1997 July 4.

As the channel crossed the limb, it displayed overarching loops against the background of the sky, as in a typical streamer base seen in SXT images, but with a sharply defined void containing a bright core. The passage of the cavity over the limb took 2–3 days, suggesting an extent in longitude of some tens of degrees. The core source appeared during five of the seven limb crossings shown in Figure 1. We suppose that a

[1] Solar Physics Research Corp. (SPRC)/Institute of Space and Astronomical Science (ISAS), 3-1-1 Yoshinodai, Sagamihara-shi, Kanagawa, 229, Japan.
[2] Montana State University, Bozeman, Montana 59717-0350.
[3] SPRC, 4720 Calle Desecada, Tucson, Arizona 85718.

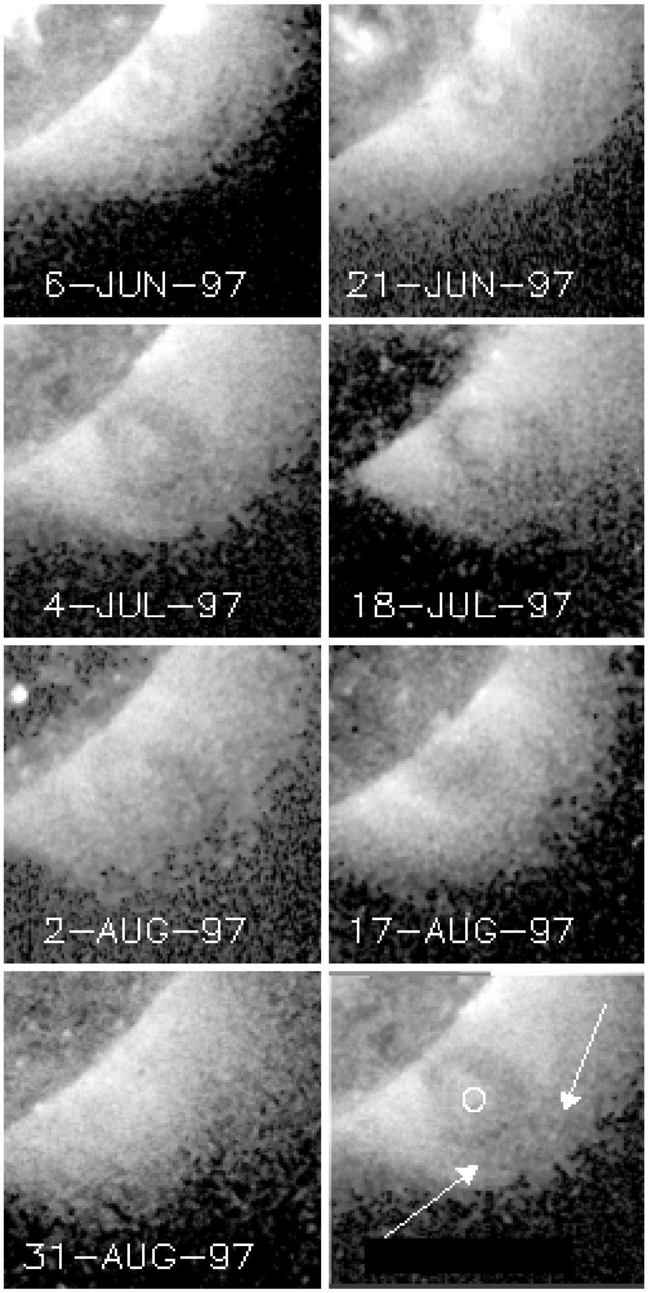

FIG. 1.—The appearance of the filament channel during seven consecutive limb passages, as viewed in soft X-rays by the *Yohkoh* SXT. The orientation is correct (north is up, and west is to the right) for the west-limb passages (note 1997 July 4 particularly) and has been reversed for the east-limb passages (in these cases, north is up, and east is to the right). The image in the bottom right-hand panel shows the definitions of the parameters listed in Table 1.

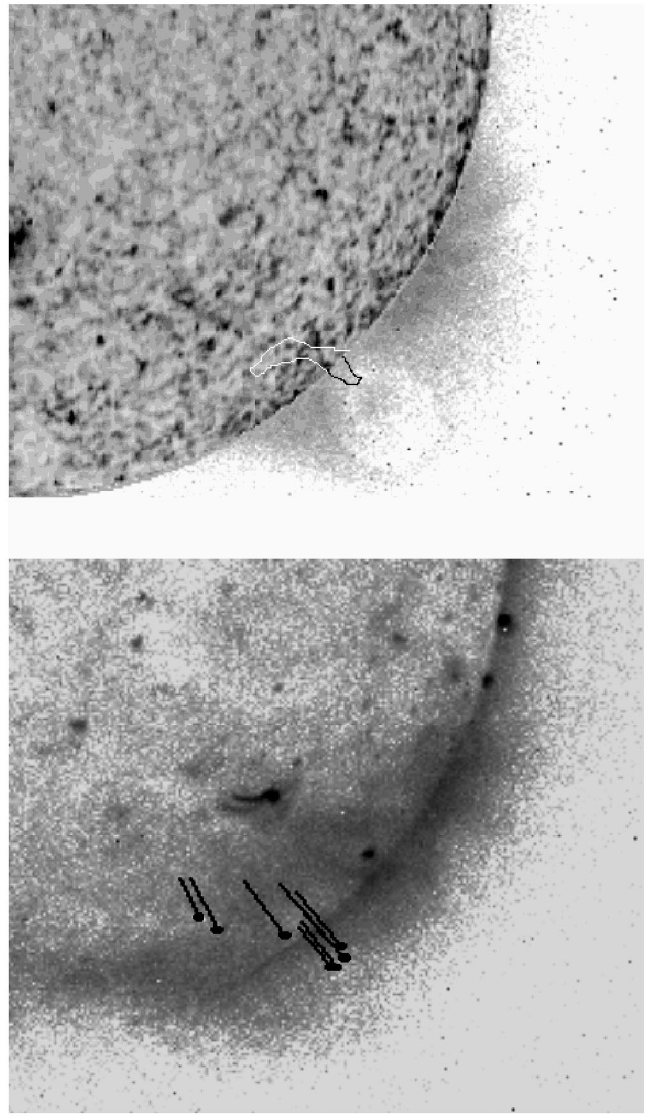

FIG. 2.—Overlays of the cavity projected on the limb on 1997 July 3–4 with He I λ10830 observations of the filament. The upper panel shows the outline of the filament cavity seen in He I; the lower panel shows an SXT image, with symbols showing the positions of the bright core at the times of the data given in Table 1 but rotated to their approximate positions on June 30, thus making the assumption that each individual image lies in the plane of the sky. The X-ray source envelopes the filament and extends to higher altitudes. The indirect soft X-ray information on the location of the filament channel on the disk resembles the more direct He I image.

long line-of-sight path was also necessary to make the bright core visible in the first place, since it is not obviously present at the central meridian passage. The core source appears to lie around and above the cool filament material, as seen in the contour overlay of the He I λ10830 profile in Figure 2.

Figure 3 shows a single SXT image (AlMg filter) from near the time of the central meridian passage of the main part of the cavity (1997 June 27). Neither this image nor the summed images with larger total exposure time show the cavity and its bright core directly. The edges of the cavity appear as irregular bands oriented approximately on parallels. To understand the structure better, we have measured the apparent location of the core center, and other geometrical points, at various times during the July 2–5 crossing. The core center measurements appear in Figure 3 at the positions corresponding to solar rotation at the rate appropriate for the latitude and assuming that each measurement corresponds to a point directly above the limb. In Table 1, we list the measurements of core position and the "shoulders" of the structure surrounding the cavity. The shoulder is defined as the location of the peak edge height, as indicated in the sketch (*bottom right-hand panel*) in Figure 1.

The stability of the filament channel over a long period of time makes this projection reasonable, but even so one cannot expect there to be an exact mapping between limb-crossing and on-disk appearances because the structure may change shape and orientation over time. The next subsequent disk pas-

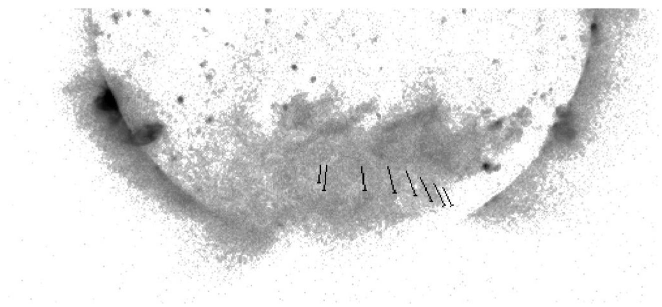

FIG. 3.—A single long-exposure image from the *Yohkoh* SXT AlMg filter taken in 1997 June 27 as the cavity rotated across the central meridian. The symbols show the positions of the bright core seen during July 2–5, rotated from the plane of the sky at the times of two images per day, corresponding to the data in Table 1.

sage, for example, had a substantially different appearance. From this comparison, we conclude that the bright diffuse structures seen on the disk do correspond to the walls of the cavity, as seen on the limb, but this kind of comparison is imprecise because of the likelihood of time variability, the faintness of the features, and the confusion in line-of-sight integration through the optically thin medium.

Finally, we comment that other (briefer) glimpses of the bright-core phenomenon in quiescent filaments have appeared in the *Yohkoh* SXT observations, but not for such a long period as in 1997. We do not exclude the possibility that linear or "spine" features, appearing mainly during eruptions (Kano 1994; Khan et al. 1998; McAllister et al. 1998; Solberg 1997), have a physically similar origin to the quiescent bright core described here. The transient features associated with CMEs and arcade formation, however, are typically much brighter than the quiescent core brightening described here.

3. PHYSICAL PROPERTIES

We have examined the temperature distribution as observed at the July 3 limb appearance using the Al.1 and AlMg filters of SXT. Faintness makes the analysis difficult, and we report only preliminary results for the bright-core region. This estimation involved the following steps. First, we summed successive AlMg and Al.1 exposures (approximately 113 and 55 s, respectively) over the time range of 09:54–23:16 UT, 1997 July 3, following alignment, stray-light, and dark corrections by standard *Yohkoh* software. Next we used different methods (Table 2) to estimate an interpolated background level against which the bright core is detected; this background results from solar foreground and background structures, scattered light, and the residual instrumental effects remaining from the image corrections for dark and stray light. This resulted in peak excess signal levels of a few DN s^{-1}, as compared with approximately 30 DN s^{-1} (DN = "data number") for the darkest part of an uncorrected SXT image. The temperatures obtained were 1.63, 1.65, and 1.84 $\times$ 10^6 K, respectively, with no correction, a linear correction, and a quadratic correction based on the intensity variation across the core in the north-south direction. We prefer the quadratic correction here because it appears to fit the large-scale structure of the foreground/background sources better, both in this projection and also in the east-west cross section. The corresponding emission measure is 6.0 $\times$ 10^{25} cm^{-5}.

TABLE 2
CORE TEMPERATURES AND EMISSION MEASURES

Background Method	Temperature (MK)	Emission Measure (cm^{-5})
Total	1.63	$10^{26.43}$
Constant	1.65	$10^{26.18}$
Quadratic	1.84	$10^{25.78}$

We proceed now to an estimate of the density of the core region. For this, we need to know the line-of-sight thickness. From the assumption that the core material follows the curvature of the photosphere for a length of time corresponding to the period of visibility at the limb, we would need a thickness on the order of 5 $\times$ 10^{10} cm. An alternative, extreme assumption would be that the line-of-sight thickness simply equals the width of about 6.8 $\times$ 10^9 cm projected on the plane of the sky. These extreme assumptions correspond to densities on the order of 3.4 $\times$ 10^7 and 9.4 $\times$ 10^7 cm^3, respectively. The effective temperature of the core material resembles that of the corona outside the cavity as observed by SXT (see, e.g., Wheatland, Sturrock, & Acton 1997). However, by either estimate, the density is improbably low for a closed-field region in the corona. We can compare this with models of the open-field regions identified with the base of the solar wind flow, which typically require densities on the order of 10^8 cm^{-3} (see, e.g., Withbroe 1988). From these density estimates, therefore, we infer the presence of a filamentary structure in the bright core of the cavity. At the resolution of the images analyzed, this material would have a volume filling factor substantially smaller than unity.

The analysis reported here suggests strongly that the bright-core region is hotter than the cavity surrounding it. It is difficult to assess the systematic error terms, which greatly exceed the random error from photon statistics. We use the pixel-to-pixel fluctuation in the 8 $\times$ 8 pixel array at the center of the bright core to estimate a temperature error of about 0.16 $\times$ 10^6 K in the present analysis, per pixel. Subtracting the foreground/background contribution results in an increase of apparent temperature by about this amount (Table 2). We believe, on this basis,

TABLE 1
GEOMETRY IN 1997 JULY 2–5

Date (UT)	Core P.A., Height (deg, $R_\odot$)	South Shoulder P.A., Height (deg, $R_\odot$)	North Shoulder P.A., Height (deg, $R_\odot$)
July 2 (02:46)	218, 1.09	213, 1.19	222, 1.15
July 2 (13:08)	219, 1.11	216, 1.21	224, 1.17
July 3 (01:31)	221, 1.13	217, 1.23	226, 1.24
July 3 (12:56)	223, 1.14	220, 1.27	227, 1.23
July 4 (01:43)	224, 1.15	219, 1.26	228, 1.25
July 4 (19:44)	224, 1.14	221, 1.25	230, 1.22
July 5 (10:45)	224, 1.14	221, 1.23	230, 1.23
July 5 (23:41)	224, 1.10	221, 1.23	231, 1.21

that the bright core is hotter than its surroundings. However, the background subtraction does not tell us directly about the temperature of the cavity, because we do not know for sure that its signal dominates the foreground/background component without a three-dimensional reconstruction.

4. INTERPRETATION

The existence of the bright core will help us to learn about the structure of the supporting field and the mechanisms by which mass becomes trapped within it. The proximity to the filament of the hot material in the cavity core suggests a theory proposed by Antiochos & Klimchuk (1991) following Pikelner (1971). They argue that asymmetric heating along portions of a dipped magnetic flux tube could supply prominence mass in a manner analogous to "evaporation" in a solar flare resulting from corona overpressure. Our observations nicely match an expectation from this theory, namely, that filamentary hot branches of the filament-supporting field lines would envelop the prominence seen at the limb. Intermittency would also be expected, since the support of a quiescent prominence seems to involve material motions, and such an intermittency would again be consistent with our finding of a low filling factor.

An alternative view of the bright core might associate it with a transition region between the filament material and the surrounding corona. Such a transition region could support a pressure variation, unlike the normal chromosphere/corona transition region in regions of vertical magnetic field (see, e.g., Chiuderi Drago, Engvold, & Jensen 1992). In fact, radio observations require a nonconstant pressure across the filament/corona transition (Kundu, Melozzi, & Shevgaonkar 1986). We do not feel that conduction from the corona into the filament can explain the bright-core source discussed here because it appears to be hotter than the surrounding corona.

5. CONCLUSION

The detection of stable bright-core regions in a filament cavity was unexpected; previous related soft X-ray observations found that elongated hot structures occur in filament channels, but primarily at the times of eruptions. The observations show that a bright core need not result from activation related to the occurrence of a flare or a CME and, instead, *may be an integral part of the process of filament maintenance*. The hot features that we see appear to surround the cold filament itself. We suggest here that they represent the hot segments of field lines that support the filament material.

Although the feature reported here is definitely a polar crown quiescent prominence, we note striking similarities to the unusual solar flare reported by Tsuneta et al. (1992), which displayed a well-defined cavity with a central cusp-shaped core brightening. We speculate that the core flare brightening was associated in some manner with filament reformation by an evaporation process analogous to the one seen in this much fainter and stabler example.

More thorough data analysis, including the *Solar and Heliospheric Observatory* (*SOHO*) and *Transition Region and Coronal Explorer* (*TRACE*) observations, would be extremely desirable in view of the difficulty of using SXT observations to determine the density, for example, of the cavity region or even the core itself. The geometry of the cavity/core structure cannot be inferred directly from individual images, but the stability of the features described suggests that tomographic techniques might be able to reveal the true three-dimensional structure and provide better estimates of the cavity temperature and density. The "insulation" provided by the magnetic surface defining the cavity might leave it cooler (see, e.g., Low 1996), or, contrariwise, the longer field lines of the cavity region (flux rope, by assumption) might suggest that it should be hotter than the adjacent corona, depending on the nature of the coronal heating mechanism at work.

This work was supported by NASA contract NAS8-37334. *Yohkoh* is a mission of the Institute of Space and Astronautical Sciences (Japan), with participation from the US and UK. The authors thank A. McAllister for bringing the Solberg thesis to their attention and R. C. Canfield for comments about the prominence/corona transition region. This work benefited greatly from the Third *SOHO*/*Yohkoh* Data Analysis Workshop (ISAS, Japan, 1998 April 6–10), and we would especially like to thank B. J. LaBonte for leading the subgroup that studied these phenomena.

REFERENCES

Acton, L. W., et al. 1992, Science, 258, 591

Antiochos, S. K., & Klimchuk, J. A. 1991, ApJ, 378, 372

Chiuderi Drago, F., Engvold, O., & Jensen, E. 1992, Sol. Phys., 139, 47

Engvold, O. 1989, in Dynamics and Structure of Quiescent Solar Prominences, ed. E. R. Priest (Dordrecht: Kluwer), 47

Hudson, H. S., & Webb, D. F. 1997, in Coronal Mass Ejections (Geophys. Monogr. 99), ed. N. Crooker, J. A. Joselyn, & J. Feynman (Washington, DC: AGU), 27

Kano, R. 1994, in X-Ray Solar Physics from *Yohkoh*, ed. Y. Uchida et al. (Tokyo: Universal Academy Press), 273

Khan, J. I., Uchida, Y., McAllister, A. H., Mouradian, Z., Soru-Escaut, I., & Hiei, E. 1998, A&A, 336, 753

Kundu, M. R., Melozzi, M., & Shevgaonkar, R. K. 1986, A&A, 167, 172

Low, B. C. 1996, Sol. Phys., 167, 217

McAllister, A. H., et al. 1998, in ASP Conf. Ser. 150, New Perspectives on Solar Prominences, IAU Colloq. 167, ed. D. F. Webb, B. Schmieder, & D. M. Rust (San Francisco: ASP), in press

Pikelner, S. B. 1971, Sol. Phys., 17, 44

Solberg, F. C. R. 1997, Candidatus Scientiarum thesis, Univ. Oslo

Tsuneta, S., et al. 1991, Sol. Phys., 136, 37

Tsuneta, S., Hara, H., Shimizu, T., Acton, L. W., Strong, K. T., Hudson, H. S., & Ogawara, Y. 1992, PASJ, 44, L63

Wheatland, M., Sturrock, P. A., & Acton, L. 1997, ApJ, 510, 518

Withbroe, G. L. 1988, ApJ, 325, 442