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CORONAL DIMMING ASSOCIATED WITH A GIANT PROMINENCE ERUPTION

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ABSTRACT

We report the results of our investigation of a giant eruptive prominence (initial mass ~6×10^{16} g) using microwave, X-ray, and white-light observations. The prominence erupted from the northwest limb of the Sun on 1994 April 5. The speed of the prominence was only ~70 km s^{-1} when it reached a height of ~0.5 $R_\odot$ above the solar surface. In X-rays, a large region with reduced X-ray emission was observed enveloping the initial location of the prominence and extending to much larger heights. At the bottom of this depletion and beneath the eruptive prominence, an X-ray arcade formed, progressively spreading from south to north along the limb. This is the first time a direct detailed comparison is made between coronal dimming and a prominence eruption. We were able to confirm that the coronal dimming is indeed a near-surface manifestation of the coronal mass ejection (CME). The orientation of the structures involved did not allow the observations of the coronal cavity, but all the other substructures of the CME could be identified. The mass expelled from the Sun in the form of the eruptive prominence and the coronal dimming are comparable. The estimated total mass is somewhat larger than that reported in other X-ray–dimming events.

Subject headings: Sun: corona — Sun: flares — Sun: prominences — Sun: radio radiation — Sun: X-rays, gamma rays

1. INTRODUCTION

Prominence eruptions are often associated with coronal mass ejections (CMEs) and hence are very useful in predicting geo-effective solar disturbances. Optical and radio observations of filament and prominence eruptions are good indicators of the arrival of CMEs at Earth 2–3 days later (for well-connected events). Unlike the white-light CMEs, the eruptive prominences can be observed close to the solar surface and hence are part of the near-surface manifestation of CMEs. Hα observations provide only an incomplete picture of the eruptive events because changes in the corona at intermediate and high temperatures have to be observed at other wavelengths (see, e.g., Gopalswamy, Hanaoka, & Lemen 1998). Simultaneous observations in microwaves and X-rays show that a coronal volume much larger than that of the prominence is affected during the eruption (Gopalswamy et al. 1996, 1997a). This is consistent with the fact that the eruptive prominence is a substructure (known as the core) of CMEs. The large-scale change in the coronal volume, therefore, signifies the launch of a CME. Coronal depletion (Hansen et al. 1974; Rust & Hildner 1978), transient coronal holes (Rust 1983; Manoharan et al. 1996), and coronal dimming (Hudson, Acton, & Freeland 1996) are possible manifestations of the large-scale coronal change. In most of these works, the coronal depletion is dealt with in relation to the CME frontal structure and probably the rising coronal cavity. In this Letter, we study the relationship between the coronal dimming and the inner part of the CME, viz., the eruptive prominence. This study enables us to integrate the dimming and prominence eruption phenomena into the familiar three-part structure of CMEs (frontal structure, coronal cavity, and prominence core) established from white-light observations (see, e.g., Hundhausen 1993). In addition, we determine the physical extent of the depletion and the amount of mass ejected in the form of depletion and as the eruptive prominence material.

2. OBSERVATIONAL RESULTS

2.1. *Prominence Eruption in Microwaves*

The eruptive prominence was imaged by the Nobeyama Radioheliograph (Nakajima et al. 1994) at 17 GHz with a spatial resolution of about 10″. The eruption occurred on 1994 April 4 around 23:00 UT and continued on the next day from above the northwest limb of the Sun. The prominence could be traced back to 1994 March 19, when it appeared from behind the east limb. In Figure 1 (Plate L13), we have shown its evolution for a period of nearly 2 weeks (March 25–April 5). When the prominence was first observed on the disk on March 25, it was relatively dark and was mostly north-south. It was very long (~475,000 km) and narrow (width ~36,000 km), extending from close to the equator toward the north pole. As it moved across the disk, it slowly became curved. The south end of the filament had its extension into a bipolar active region. On 1994 April 4, we can see that the filament was partly on the disk and partly above the limb, providing a perfect example of a filament becoming a prominence. The maximum height attained by the prominence in the pre-eruption phase was about 175,000 km above the limb. From the locations of the northern and southern ends of the prominence when it was on the disk, we infer that the northern end is probably behind the limb at the time of the eruption. The appearance of the prominence was identical in radio and Hα wavelengths.

In Figure 2, we have shown the details of the prominence eruption as a series of microwave snapshots. We see lots of internal structure with two major substructures at the ends. As the prominence erupted, it showed multiple threads moving with slightly different speeds; the legs thinned down first, while the apex portion maintained its size for some distance. Downflowing material could be seen along both legs of the erupting prominence, which was very clear when the images were played as a movie. There was no microwave emission within

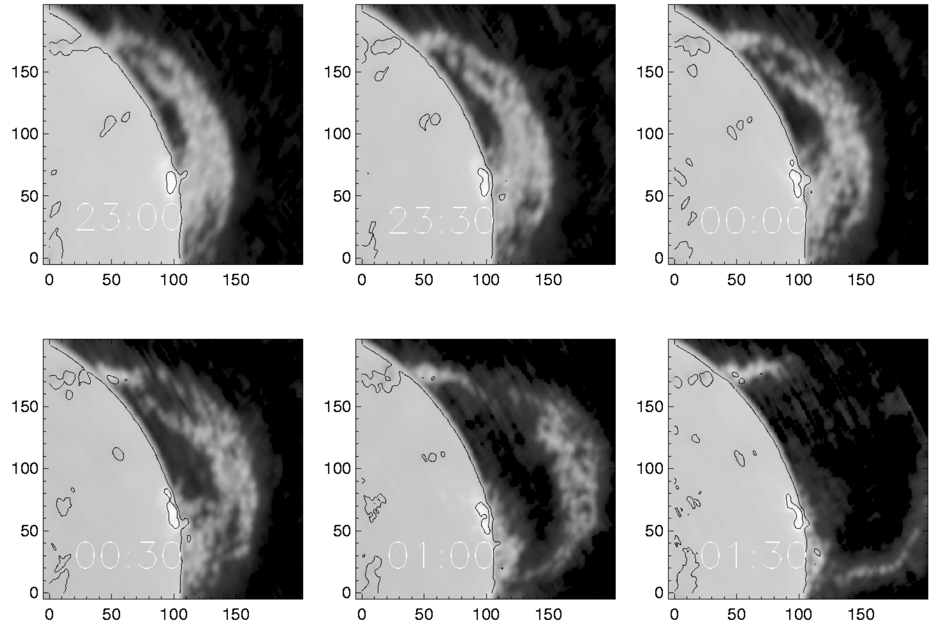

FIG. 2.—Nobeyama radioheliograms displaying the prominence as it erupts above the northwest limb. The eruption begins at about 23:00 UT (April 4), and it had left the field of view by 01:30 (April 5). The axes are in pixel coordinates (1 pixel = 4″.92). A single radio contour at 10,000 K is plotted to mark the limb.

the void under the prominence at any time, suggesting that there was no cool material in that region.

2.2. *Height-Time History of the Prominence*

We measured the height of the leading edge of the prominence every 5 minutes from about 22:50 UT (April 4) to 01:41 UT (April 5), when it reached the edge of the field of view. During the first hour, the height change was very small, but there was a lot of internal changes in the prominence. Thereafter, the prominence took off. Figure 3 shows the height-time plot of the prominence. The heights were measured only at the apex of the prominence. In Figure 3, we have plotted the parabolic fit (*solid curve*) to the data points (*crosses*). The acceleration was only about 10 m s^{-2}, and the last measured speed (at 01:41 UT) was 68 km s^{-1}. The acceleration is similar to those of disconnection events observed following coronal mass ejections (see, e.g., Gopalswamy, Kundu, & St. Cyr 1994).

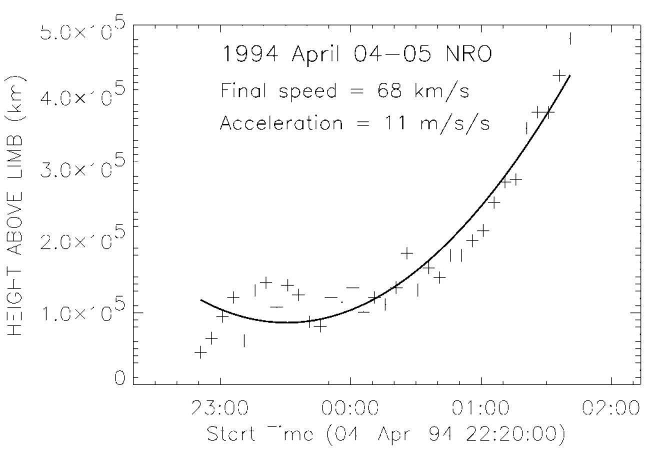

FIG. 3.—Height-time history of the prominence. The solid line is the parabolic fit to the data points (*crosses*).

2.3. *Coronal Dimming*

The soft X-ray telescope (SXT; Tsuneta et al. 1991) on board the *Yohkoh* satellite routinely obtains full-frame images of the Sun roughly every 2 minutes, and we make use of the data for the present study. We are particularly interested in the coronal volume affected in association with the prominence eruption. Despite the poor image cadence available, we were able to obtain information on the coronal evolution in the vicinity of the eruptive prominence, with an effective time resolution of ~2 minutes. In X-rays, the event manifested as a coronal depletion or dimming all around the prominence and as an X-ray arcade formation on the solar surface.

Coronal changes are best seen in difference images obtained by subtracting a pre-event image from the event image. We chose image pairs of the same filter and exposure times for differencing. The difference between the 20:51 and 20:31 UT images did not show any noticeable change. When the image at 20:51 UT was subtracted from that at 21:14 UT, we found a small vertical dark lane on the disk close to the limb and a small dark region above the limb (see Fig. 4). In the difference between the 23:58 and 20:31 UT images, a large depletion was found above the limb where the prominence was located. This was the first instance when a fully formed depletion was observed. The depletion can be seen best in the difference image at 00:04 UT (with the 22:23 UT image on April 4 subtracted; see Fig. 5*a* [Pl. L14]). The depletion could also be seen partly on the disk, but it is not so clear. The depletion region appears nearly circular in projection, with a diameter of about 0.7 $R_\odot$. In order to find the location of the depletion region with respect to the prominence, we have superposed a radio image (*contours*) on the SXT image in Figure 5*b*. The prominence was still close to the surface at this time (00:04 UT), and the depletion completely enveloped the prominence. In Figure 6

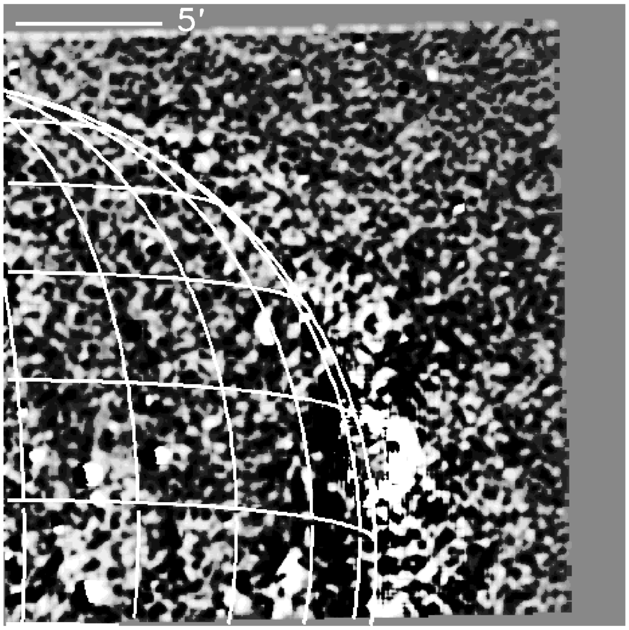

FIG. 4.—SXT difference image showing the earliest phase of the event (21:14 UT minus 20:51 UT). The heliographic grid is overplotted (every 15°). The bright region at the limb represents the change in the nearby active region.

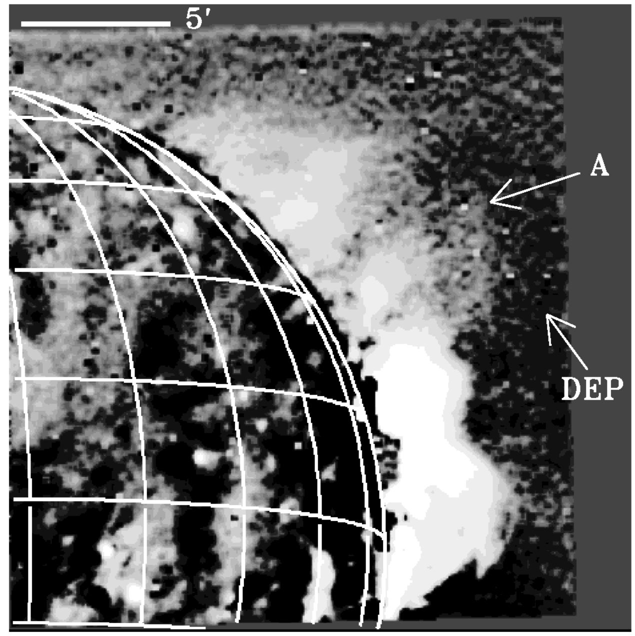

FIG. 7.—SXT difference image showing the late phase of the event (06:41 UT minus 20:51 UT), the fully formed, long-enduring X-ray arcade (A). The arcade partly masks the depletion region (DEP).

(Plate L15), we have shown the difference image corresponding to a later time, 01:20 UT, when the prominence had moved to the edge of the SXT field of view (Fig. 6*b*). At this time, a bright arcade had fully formed at the bottom of the depletion region, parallel to the limb. Expanding loops can be seen at the southern end of the arcade. These were interconnecting loops that slowly expanded in association with the eruption. At the northern end, the arcade continues probably behind the limb. It is not clear whether there was a cusp structure at the northern end or whether we see such a structure because of intervening structures corresponding to the end of the depletion region. The arcade was also clearly observed in microwaves because of free-free emission, as in other events (Hanaoka et al. 1994; Gopalswamy et al. 1997a). The X-ray arcade persisted for many hours, slowly rising in height. Figure 7 shows the arcade at 06:41 UT (marked "A") partially covering the depletion region. Note that the arcade had increased in height significantly as compared with what is shown in Figure 6.

3. MASS ESTIMATES

3.1. *Mass of the Prominence*

The mass of the quiescent prominence can be estimated from its observed dimensions. Let us recall that the dimensions of the prominence are ∼470,000 km (length), ∼36,000 km (width), and ∼175,000 km (height). Thus, the approximate volume of the prominence is 3×10^{30} cm^3, assuming the prominence is a thin slab (ignoring fine structures). Quiescent prominences have a typical density in the range of 10^{10}–10^{11} cm^{-3} (see, e.g., Tandberg-Hanssen 1995). Taking the low-end value of the density range and assuming that each electron is associated with a mass of 2×10^{-24} g, we determine the prominence mass as 6×10^{16} g. This is similar to the mass of the largest of CMEs. The radio observations indicate that a considerable fraction of this mass might have fallen back to the solar surface when the prominence erupted. Schmahl & Hildner (1977) studied a well-observed quiescent prominence eruption in association with a CME and found that all but 10% of the coronal prominence material drained back to the solar surface. Even if such a small fraction was ejected in the present case, it amounts to about 6×10^{15} g. It must be pointed out that we have ignored the fine structure in the prominence and assumed a unit filling factor. For a filling factor less than unity, the estimated prominence mass will be accordingly lower.

3.2. *Mass Loss Due to Dimming*

Determination of the mass that escaped to create the depletion in X-ray emission is more uncertain. The main uncertainty comes from the lack of knowledge of the line-of-sight depth of the depletion. We expect the coronal loops overlying the prominence to form a cylindrical arcade in the pre-eruption stage, typical of helmet streamers. We expect the length of this arcade to be similar to that of the prominence (4.7×10^{10} cm). Using the measured radius of the depletion region (250,000 km), we estimate a volume of $\sim 4.6 \times 10^{31}$ cm^3, an order of magnitude larger than that of the prominence. We were able to determine the (log) emission measure of the corona above the prominence in the pre-eruption stage from SXT filter ratios as ∼42.3 pixel^{-1}. Assuming that the entire overlying coronal structure contributed to the emission, we get a coronal density of about 1.8×10^{7} cm^{-3}, so that the escaped mass can be estimated as 1.7×10^{15} g. This is about 35 times smaller than the initial prominence mass and comparable to the estimated mass loss in the form of the eruptive prominence. Thus, we can confidently say that the eruptive event involved a mass loss comparable to that during large CMEs observed in white light (see, e.g., Kahler 1992) and in metric wavelengths (Gopalswamy & Kundu 1992) and somewhat larger than the mass estimates from X-ray observations (Hudson et al. 1996; Gopalswamy et al. 1997a; Sterling & Hudson 1997).

4. DISCUSSIONS

The X-ray and radio data show that the prominence eruption was part of a full-fledged CME event with all the substructures: frontal structure (observed as the coronal dimming in X-rays), prominence core, and the X-ray arcade formation beneath the eruptive prominence. For geometrical reasons (see below), the only substructure not detected is the coronal cavity. When the frontal structure expands, the cavity might have caused additional dimming.

We examined the Mauna Loa K-coronameter data for 1994 April 4 and 5 to check if there was a CME associated with the prominence eruption. On April 4, the images were taken from 17:22 to 21:07 UT. This interval corresponds to the pre-event phase of the eruption, so there were no significant changes between different images. However, these images show the presence of a helmet-streamer structure overlying the prominence. The first image obtained for the next day (April 5) was at 17:23 UT. When we made a difference between the April 4 and 5 images, there was a clear depletion on April 5, which was at the same position angle as the X-ray depletion and the eruptive prominence. The extent of the depletion observed in X-rays was consistent with what was revealed by the Mauna Loa K-coronameter difference images. We therefore conclude that the prominence eruption event was accompanied by a CME. We have found similar signatures of a CME in white-light data in association with X-ray ejecta (Gopalswamy et al. 1997b). The north-south orientation of the prominence is not favorable when observing the coronal cavity because the foreground part of the helmet streamer completely blocks it. The cavity can best be seen when the prominences (and hence the axis of the overlying arcade) are oriented east-west.

The depletion was way ahead of the erupting prominence, as in most CME events containing a prominence core. The beginning of the dimming at 21:14 UT (April 4), which quickly extended over a large coronal volume by 23:58 UT, suggests the launch of a CME between these two times. The coronal depletion seen in X-rays has roughly the same lateral extent as the initial extent of the prominence, but the radial extent was much larger; in fact, the depletion extends beyond the field of view at 00:04 UT. The coronal depletion above the rising prominence is a clear indication that the corona overlying the erupting prominence has already been dynamic even before the prominence liftoff. The region of X-ray dimming fully envelops the eruptive prominence, as expected in a classic CME with three-part structure.

Although the coronal depletion is a solid signature of a CME launch, we must point out that it shows up only in difference images. On the other hand, the arcade formation is observed even in X-ray images without differencing.

5. CONCLUSIONS

We have studied the eruption of a massive prominence (initial mass $\sim 6 \times 10^{16}$ g) that occupied nearly the entire northwest quadrant of the solar limb during 1994 April 4–5. We have found further evidence that a coronal volume much larger than the erupting prominence was involved in the eruption. The prominence volume was an order of magnitude smaller than the coronal volume inferred from the observed X-ray dimming. Coronal depletion inferred from X-ray and white-light observations confirm that the prominence eruption was associated with a CME. Microwave observations show significant draining of the eruptive prominence, but the resultant ejected material ($\sim 6 \times 10^{15}$ g) could be as massive as a typical CME. The coronal dimming also represented a mass loss ($\sim 1.7 \times 10^{15}$ g) comparable to the ejected prominence material. Various features of the eruption observed in X-rays and radio conformed to the substructures of a canonical CME with three-part structure and X-ray arcade formation, thus confirming that the coronal dimming is indeed a signature of a CME launch. The results that the coronal dimming started much earlier than the prominence eruption and that a large volume above the prominence was evacuated are very important when considering magnetic field changes due to eruptive events. These results point out that it is not enough to consider the magnetic field changes just around the prominence and that we have to consider changes over a larger scale in order to understand the launch of CMEs.

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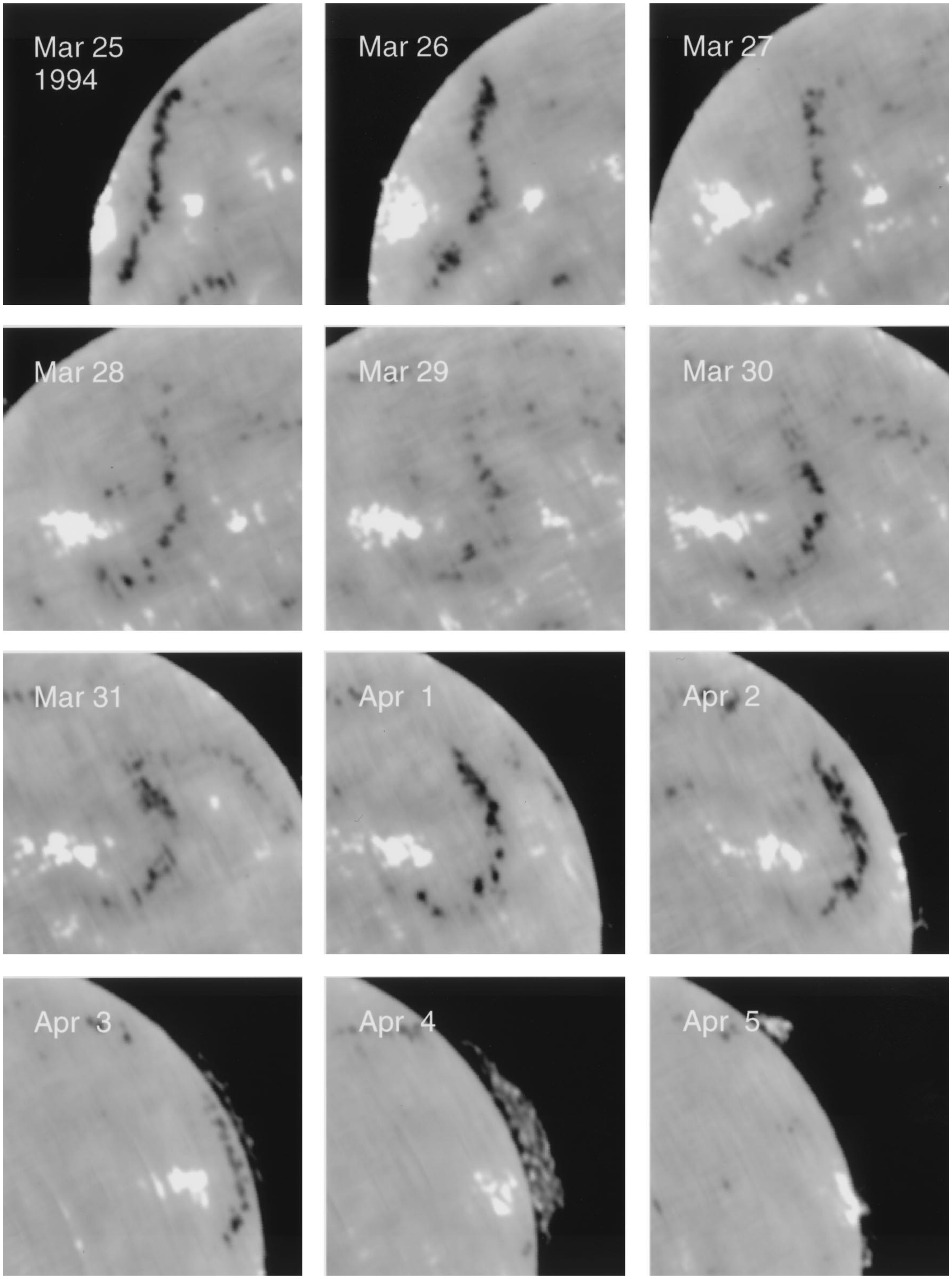

FIG. 1.—Long-term evolution of the prominence as seen by the Nobeyama radioheliograph before eruption. It was first seen above the east limb on 1994 March 19. Here we have shown it from 1995 March 25–April 5. Here and in all the figures, solar north is to the top, and east is to the left. The times of the images are marked on each image. The bright region on the limb near the southern leg of the prominence is an active region.

GOPALSWAMY & HANAOKA (see 498, L179)

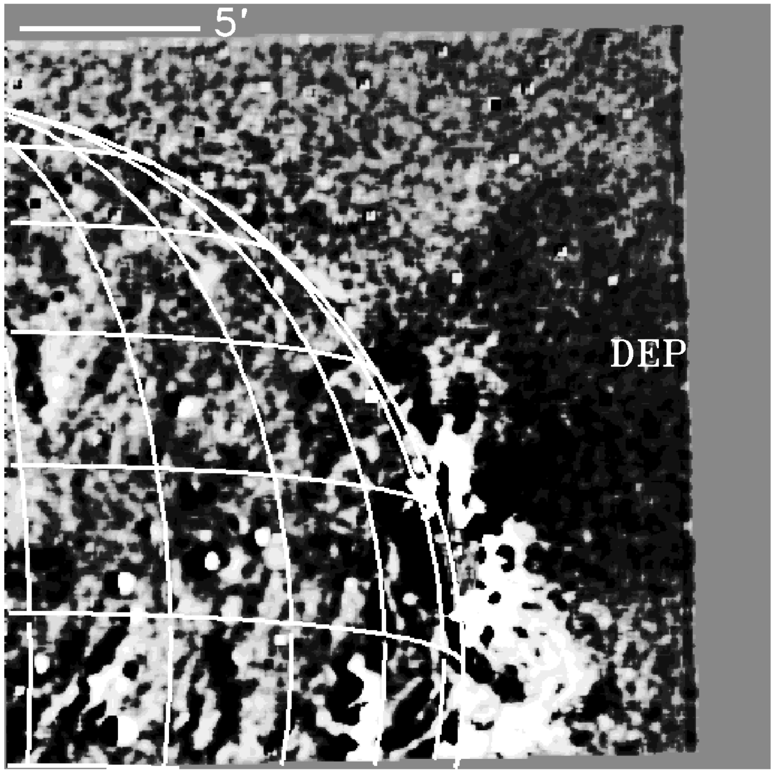

FIG. 5*a*

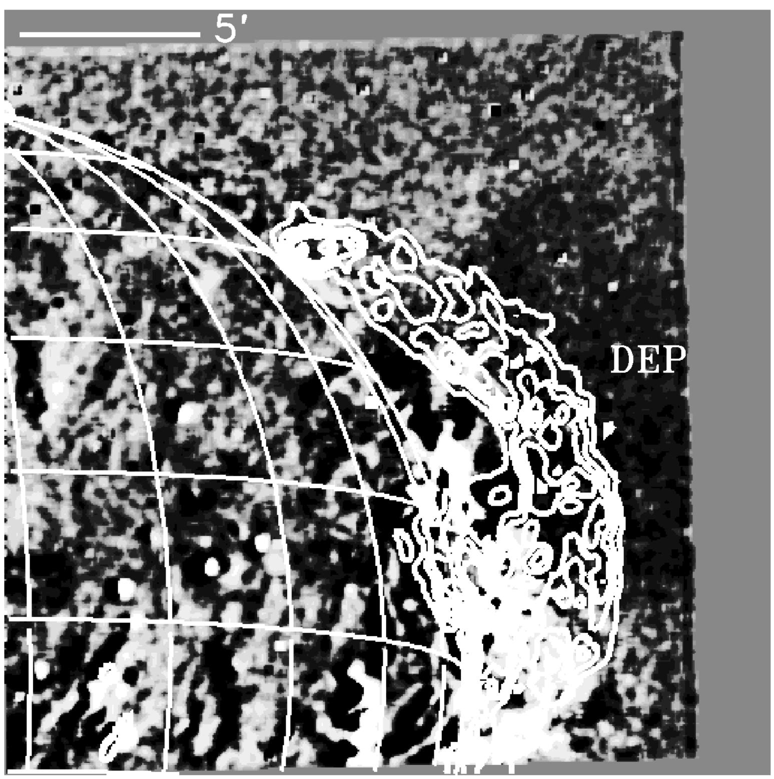

FIG. 5*b*

FIG. 5.—(*a*) SXT difference image at 00:04 UT (the image at 23:23 UT, April 4 was subtracted) showing the coronal dimming (marked "DEP") above the northwest limb. (*b*) Superposition of the prominence in contour representation on (*a*). The contours are at 1000, 3000, 5000, 7000, and 9000 K.

GOPALSWAMY & HANAOKA (see 498, L180)

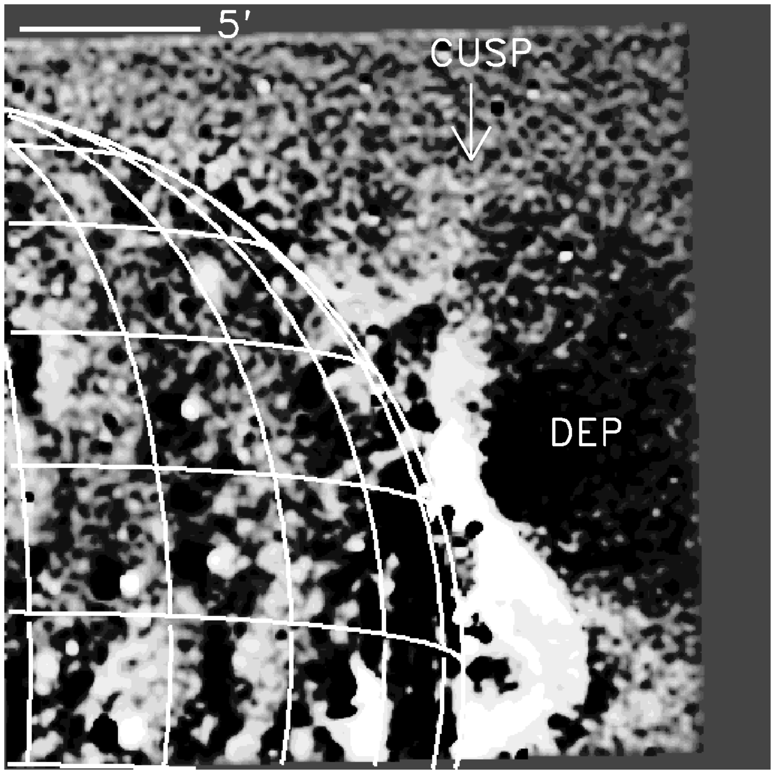

FIG. 6*a*

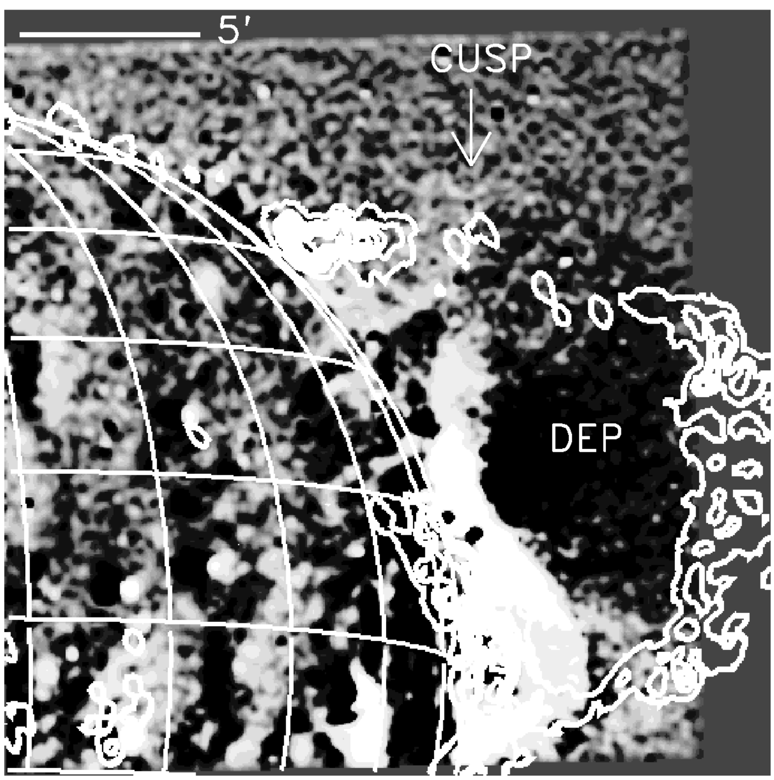

FIG. 6*b*

FIG. 6.—(*a*) SXT difference image at 01:20 UT (the image at 20:51 UT, April 4 was subtracted) showing the coronal dimming (DEP) above the northwest limb. (*b*) Superposition of the prominence in contour representation on (*a*). The contours are at 500, 2000, 4000, 6000, 8000, and 10,000 K. We have marked the cusp-shaped X-ray structure (CUSP).