New Perspectives on Solar Prominences, IAU Colloquium 167
ASP Conference Series, Vol. 150, 1998
David Webb, David Rust, and Brigitte Schmieder (eds.)

Radio and X-ray Investigations of Erupting Prominences

N. Gopalswamy

Physics Department, The Catholic University of America, Washington, DC 20064, USA

Y. Hanaoka

Nobeyama Radio Observatory, Minamisaku, Nagano-321, Japan

J. R. Lemen

Lockheed Martin Advanced Technology Center, Palo Alto, CA 90034, USA

Abstract. Prominence eruption is one of the most important solar phenomenon because of the possibility of using it as proxy of geoeffective solar disturbances. In a series of investigations using Nobeyama radio observations in conjunction with Yohkoh data we have found that there is more to a prominence eruption than the simple picture portrayed by Hα observations. The extent of coronal volume associated with the eruption is much larger than the prominence. We illustrate this with several examples and discuss the implication of the results for understanding the interplanetary manifestation of coronal mass ejections.

1. Introduction

Prominence eruption is the most common signature of coronal mass ejections (CMEs) near the solar surface. X-ray and microwave observations can provide information on eruptions close to the solar surface, which is difficult to obtain from coronagraphic observations. After the advent of the Yohkoh/Soft X-ray Telescope (SXT, Tsuneta et al. 1991) and the Nobeyama radioheliograph (Nakajima et al. 1994), it has become possible to study the near surface manifestations of CMEs in detail. Recent studies have shown that X-ray emission can originate from an arcade formed beneath the erupting filament (Hanaoka et al. 1994), the filament itself (McAllister et al. 1992) and from the CME frontal structure (Gopalswamy et al. 1996, 1997a). What seems to be a simple CME in white light seem to contain complex structures and multithermal plasmas with violent mass motions near the solar surface (Gopalswamy et al. 1997b). In radio, we can observe the cooler, optically thick structures such as prominences (in emission above the limb) and filaments (in absorption on the disk), in addition to the hot flare plasma. Thus, a combination of radio and X-ray observations can prove to be very powerful in studying the origin of CMEs. In this paper, we present a summary of a few such studies that combine radio and X-ray observations.

2. Radio Observations of Filaments and Prominences

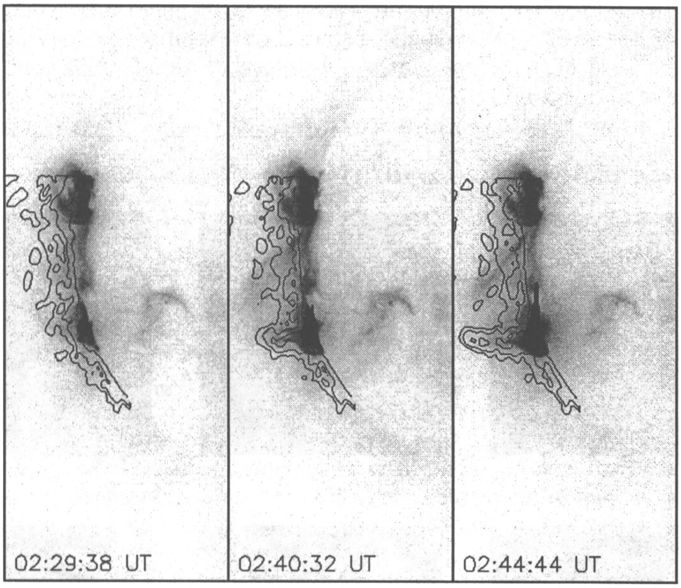

Figure 1. Overlay of the 17 GHz contours of the November 23, 1992 prominence on Yohkoh/SXT images at three instances. The X-ray intensity is inverted so darker regions are brighter.

The prominence is a cool structure suspended in the corona with a typical temperature of 8000 K and an electron density of about 10^{10}–10^{11} cm^{-3}. In order to see how a prominence is observed in microwaves, let us estimate the free-free opacity of the prominence material from the formula,

$$\tau_{ff} = 0.2 \int n_e{}^2 dl f^{-2} T^{-1.5}$$

where n_e is the electron density, f is the observing frequency, and T is the temperature. For $T = 8000$ K, $f = 17$ GHz, and $n_e = 10^{11}$ cm^{-3}, the prominence is optically thick for $L = 1$ km. Therefore, the observed brightness temperature at 17 GHz is very close to the temperature of the prominence. Since the corona contributes very little to the microwave emission, the prominence is observed in emission above the limb against the cold sky background. The solar disk has a brightness temperature of about 10,000 K at 17 GHz. Therefore, the prominence appears dark on the disk as it absorbs the underlying quiet Sun emission similar to Hα dark filaments. Typically, the filament shows up as a depression in the range $(2-3) \times 10^3$ K below the quiet Sun.

The events presented in this paper were observed by the Nobeyama radioheliograph and the Yohkoh/SXT. The Nobeyama radioheliograph obtains the

https://doi.org/10.1017/S0252921100047916 Published online by Cambridge University Press

visibility data of the sun for about 8 hours every day with a time resolution of 100 ms at two frequencies (17 and 34 GHz). Images can be made at any suitable time resolution above 100 ms. The typical spatial resolution of the images is about 10″ at 17 GHz and about 5″ at 34 GHz. The SXT images the Sun with a wide range of combinations of spatial and temporal resolutions. The full disk images used here have a spatial resolution of about 4″.92 and a temporal resolution of about 2 minutes.

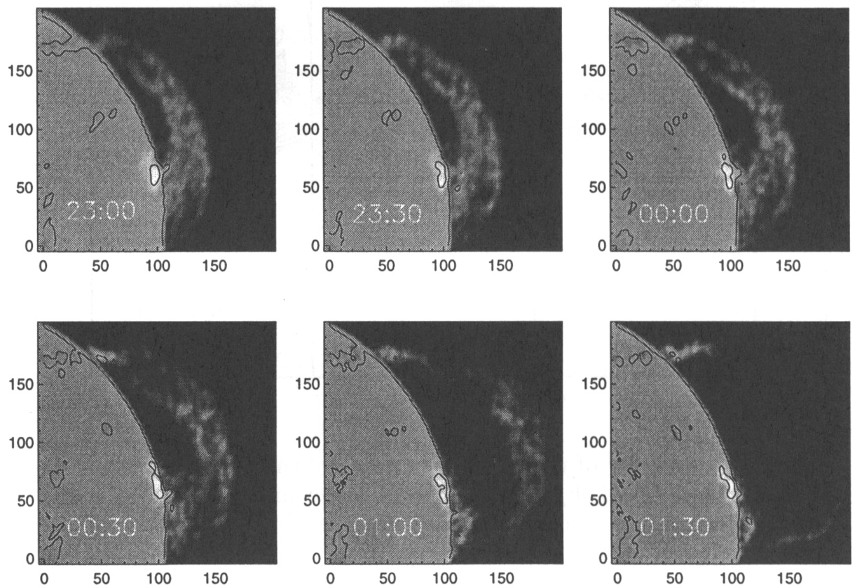

Figure 2. Eruption of the April 4–5, 1994 prominence as observed at 17 GHz. The images are in pixel coordinates (1 pixel=4.92 arcsec).

2.1. The November 23, 1992 Compact Eruption

A gradual X-ray event took place close to the west limb on November 23, 1992 between 02:20 and 03:40 UT. An active prominence erupted from this flare site and moved into the corona about 1 $R_\odot$ above the limb. Figure 1 shows this eruption in X-rays (grey scale) and in microwaves (contours) at three instances: 02:29:38, 02:40:32 and 02:44:44 UT. In the first panel, there is no appreciable radio signature. In the next panel, the ejection is underway and has reached a height of about 0.2 $R_\odot$ above the limb. At the same time we can see a large faint X-ray structure overlying the erupting prominence. The width of the X-ray structure is about 5 times larger than that of the prominence. In the third panel, the prominence has moved to a larger height (speed $\sim$ 240 km s^{-1}) and part of the overlying X-ray structure seems to have opened up. In addition, we see

https://doi.org/10.1017/S0252921100047916 Published online by Cambridge University Press

the outward movement of X-ray structures from under the prominence in the last two panels. Most of the GOES full-sun X-ray flux and the microwave flux came from the base of the prominence. The radio emission at the base of the prominence lasted for more than an hour, after the prominence had departed. This event clearly demonstrates that a coronal volume much larger than that of the prominence is affected during the eruption.

2.2. The Giant Quiescent Prominence Eruption of April 5, 1994

Quiescent prominences are large-scale cool structures lying along neutral lines separating opposite magnetic polarity regions. Eruption of these quiescent prominences can signal the start of a geoeffective solar disturbance (Joselyn and MacIntosh 1981). Some workers think that eruptive prominences might become magnetic clouds in the interplanetary medium (Bothmer and Schwenn 1994). Do the quiescent prominences show changes in the corona similar to the active ones? We show that large scale changes do take place in the corona ahead of the eruption. Figure 2 shows the eruption of a quiescent prominence during April 4–5, 1994. The prominence starts to rise around 23:00 UT (April 4) and slowly accelerates (11 m s^{-2}) to reach a speed of only about 70 km s^{-1} before reaching the edge of the field of view. The X-ray image taken around this time showed nothing spectacular. However, when we made a difference of the images at 00:04 UT (April 5) and 22:23 UT (April 4), we found a large depletion above the prominence (see Figure 3 left), similar to coronal dimming observed by Hudson et al. (1996). When we superposed the image of the erupting prominence on the contemporaneous X-ray difference image, we found that the depletion had a much larger radial extent and a comparable lateral extent. There was no depletion when we made differences of earlier X-ray images. The depletion was clearly ahead of the erupting prominence, and occupied a volume much larger than that of the prominence itself.

2.3. Prominence Eruption in a Quadrupolar Coronal Structure

On June 10, 1993 a loop-like prominence erupted from the east limb (Figure 4). In microwaves the prominence started from an initial height of 50,000 km and moved to about 300,000 km in about 45 min. The initial width of the prominence was about 300″ and remained roughly the same throughout the event. The X-ray coverage of this event was not very good, but was sufficient to understand the dynamics of the prominence environment. The top panel shows at two times the prominence overlain on simultaneous X-ray images. The prominence is located between two weak X-ray structures (marked N, S in Figure 4) above the west limb. In the bottom panel, we have shown the prominence at two later times superposed on X-ray difference images. The X-ray structures S, N on either side of the erupting prominence have expanded. The overall structure of the eruption seems to be quadrupolar, with one neutral line at the location of the prominence and the other two associated with the two X-ray structures. As in other events, we see a bright and compact arcade formation at the base of the filament located between the two X-ray structures. This was indeed a long-duration event (LDE; marked as ARCADE in Figure 5). The changes in the southern X-ray structure were correlated with the LDE (marked as SOUTHERN ARCADE). Although the prominence was observed in

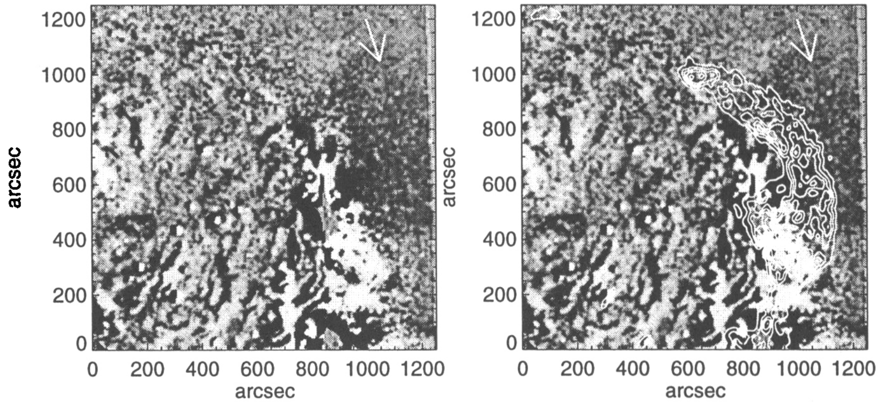

Figure 3. Association between coronal depletion in X-rays (arrow) and the eruptive prominence (contours) above the northwest limb. The X-ray and radio data correspond to the same time. The X-ray depletion is clearly above the prominence. A preevent image was subtracted from the X-ray image. The X-ray image without the overlay is shown on the left for comparison.

projection against the plane of the sky, we think the prominence was of relatively small size compared to the large X-ray structures on either side. According to theoretical investigations, one needs reconnection of a structure overlying both the X-ray structures and the prominence (Antiochos 1997).

2.4. Filament Eruption During the February 7, 1997 CME

We finally present an event on February 7, 1997 with complex filament eruption from the southern hemisphere. The filament eruption was associated with a spectacular partially Earth-directed CME observed by SOHO/LASCO (Gopalswamy et al. 1997c). Figure 6 shows the superposition of a microwave image on a Yohkoh/SXT image. There was activity in the entire southern hemisphere along a long neutral line and the associated filament channel. A small fragment (P) from the northwest end of this activity channel erupted; it could be tracked beyond the limb and became the core of the CME. As soon as the filament started moving, an X-ray arcade started to form and spread to the southeast (see Figure 6). The horizontal portion (H) of the filament channel showed continuous activity even after the CME had moved to a height of several solar radii. In Figure 7, we have plotted the average radio brightness temperature in a box around the horizontal portion of the filament channel. The darkness of the filament increased for about two hours after the initial eruption and then the darkness slowly declined over several hours. The darkening corresponds to the enhanced absorption by optically thick material expanding out of the filament channel. There is evidence for the heating of the filament material when we compared the radio data with observations at other wavelengths. It is important to

https://doi.org/10.1017/S0252921100047916 Published online by Cambridge University Press

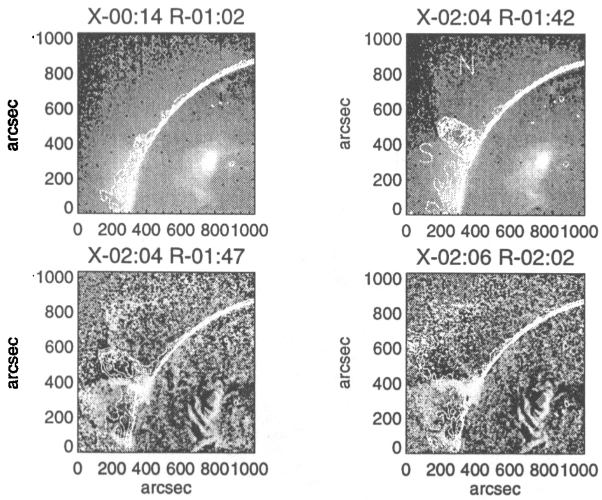

Figure 4. (top): Radio prominence (contours) of June 10, 1993 superposed on Yohkoh/SXT images. The times of radio (R) and X-ray (X) images are given at the top of each image. S and N are the two X-ray structures on either side of the erupting prominence. (bottom): X-ray difference image at 02:04 and 02:06 UT showing the continued filament eruption and the X-ray structures.

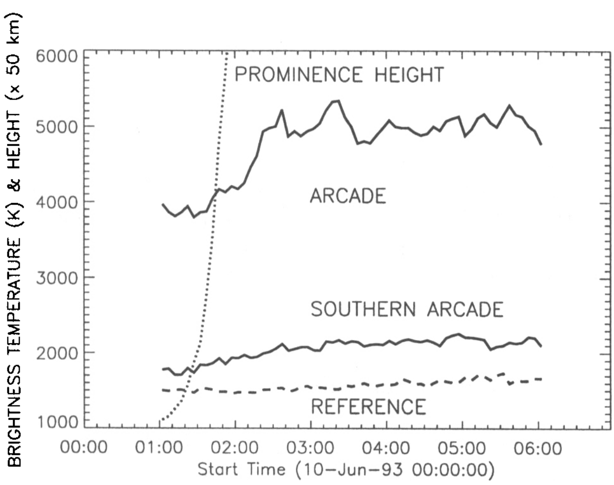

Figure 5. Brightness temperature of the arcade and the southern X-ray structure compared to the height variation of the prominence (dotted line). We have also included the brightness temperature of an active region for reference (dashed line).

https://doi.org/10.1017/S0252921100047916 Published online by Cambridge University Press

note that the X-ray arcade formation extended almost over the entire neutral line, although the tightly packed section was located only on the northwest to southeast section of the neutral line. If we had only white light observations, only the small northwest fragment of the filament would have been observed as the core of the CME and all the activity on the disk and the X-ray arcade formation would have been missed.

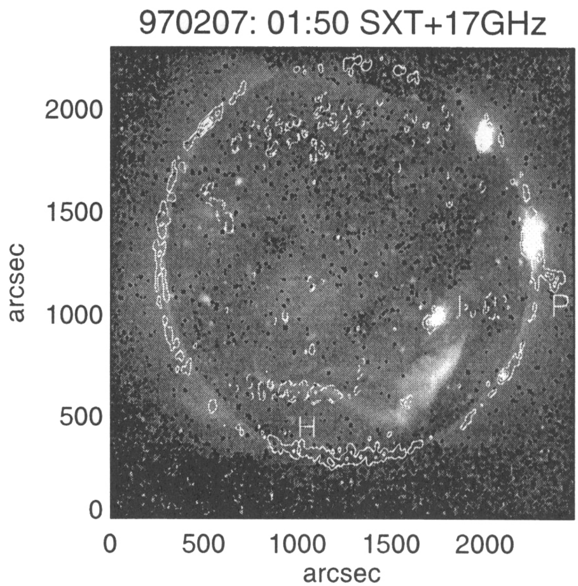

Figure 6. Overlay of radio contours (solid for enhancement and broken for depression with respect to the quiet sun) on Yohkoh soft X-ray image showing the arcade formation in the southwest quadrant on February 7, 1997. P is the erupting prominence which moved from the location marked I near the active region. H is the horizontal section of the filament channel.

3. Discussion and Conclusions

We have presented a representative set of observations which clearly demonstrate that prominence eruption is a small part of a large coronal change. X-ray images obtained simultaneously with the radio data show that a coronal volume much larger than the prominence is affected during the eruption. Therefore, prominence eruptions can be very useful predictors of geoeffective solar disturbances over a time scale of 2 days or more. Since the prominence eruptions can be observed on the disk, they are especially good indicators of Earth-directed CMEs. It must be remembered that the prominence itself lags behind the CME frontal structure and, hence, will be the last to arrive at the Earth. The implica-

https://doi.org/10.1017/S0252921100047916 Published online by Cambridge University Press

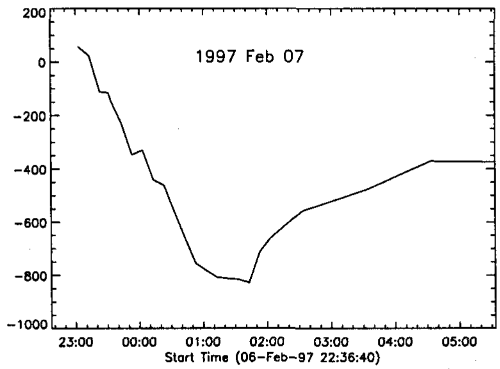

Figure 7. Average brightness temperature with respect to the quiet sun from around the filament channel H on February 7, 1997.

tion is that magnetic clouds, the interplanetary manifestation of the CMEs, may not be due to the prominences as suggested by Bothmer and Schwenn (1994). The interplanetary counterparts of the prominences may be the pressure plugs sometimes observed at the rear of magnetic clouds (see, e.g., Burlaga et al. 1998, Gopalswamy et al. 1998).

Acknowledgments. We thank H. Hudson for help in the analysis of the November 23, 1992 event. NG thanks the scientific organizing committee for their generous financial support to attend the IAU Colloquium 167. NG and JRL were supported by NASA contracts NAG-5-6139 and NAS-8-40801, respectively.

References

Antiochos, S. 1997, BAAS, 56, No. 3, 189
Bothmer, V. and Schwenn, R. 1994, Space Sci. Rev., 70, 215
Burlaga, L. et al. 1998, J. Geophys. Res., 103, 277
Gopalswamy et al. 1996, New Astronomy, 1, 207
Gopalswamy et al. 1997a, ApJ, 475, 348
Gopalswamy et al. 1997b, ApJ, 486, 1036
Gopalswamy et al. 1997c, BAAS, 29, No. 2, 908
Gopalswamy et al. 1998, Geophys. Res. Lett., in press
Hanaoka, Y. et al. 1994, PASJ, 46, 205
Hudson, H. S., Acton, L. W. and Freeland, S. 1996, ApJ, 470, 629
Joselyn, J. A. and McIntosh, P. S. 1981, J. Geophys. Res., 86, 4555
McAllister, A. et al. 1992, PASJ, 44, L205
Nakajima, H. et al. 1994, Proc. IEEE, 82, 705
Tsuneta, S. et al. 1991, Solar Phys., 136, 37

https://doi.org/10.1017/S0252921100047916 Published online by Cambridge University Press