SOLAR SCIENCE WITH THE BRAZILIAN DECIMETRIC ARRAY

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ABSTRACT

The Brazilian Decimetric Array (BDA) is a unique solar dedicated radio imager operating at short wavelengths probing the corona where most of the phenomena of heliospheric consequence originate. Currently, the Very Large Array (VLA) is the only instrument in the American continents that observes the Sun in this wavelength range, but it is not a solar dedicated instrument. The Siberian Solar Radio Telescope operates at a single frequency (5.7 GHz). BDA has wide open the radio window in the frequency range 1-6 GHz with an important band at 2.8 GHz not used by the VLA. Radio images obtained by BDA correspond to the region where flux ropes form and propagate into the interplanetary medium carrying nonthermal electrons. These images provide important information on the physical state of the eruptive structures and the post-eruption arcades left behind in the corona. The BDA with its wide field of view will be well-suited for observing prominences and filaments, which are the core structures of coronal mass ejections. The BDA can also observe the other source of space weather, viz., coronal holes, which produce high speed streams and geomagnetic storms. This paper provides an overview of these important issues that will be addressed by BDA.

INTRODUCTION

Coronal mass ejections (CMEs) and coronal holes are two large-scale structures of the Sun that seriously affect the space environment of Earth. CMEs drive shocks, accelerate particles, and produce geomagnetic storms. Coronal holes accelerate high speed solar wind that collide with slow solar wind to form corototating interaction regions (CIRs), which also produce geomagnetic storms and lead to electron acceleration in the magnetosphere. CMEs have been extensively studied since their discovery in the early 1970s (Tousey, 1973) primarily using white light coronagraphic data. Coronagraphs detect the Thomson-scattered photospheric light which is about a million times weaker than the direct photospheric light. To detect such a weak signal, the coronagraphs employ an occulting disk to block the direct sunlight which causes some restrictions on the observability of CMEs: (i) the occulting disk blocks an area larger than the solar disk, so we miss information on where the CMEs are rooted on the Sun, (ii) because of the occulting disk, CMEs occurring on the disk (Earth-directed) are not very well observed, and (iii) the Thomson-scattered signal is strongest when the CME is in the plane of the sky and hence produces a biased sample of CMEs. In the past, information on the near surface manifestations of CMEs could be obtained mainly from Hα spectroheliograms which show eruptive prominences and two-ribbon flares. We now know that both of these phenomena provide only partial information on CMEs; we need multiwavelength observations to get a complete picture of the CME
onset and early evolution. Microwave, EUV, and X-ray observations of CMEs can be very useful for this purpose because they do not have the limitation of occulting disks and they can observe eruptions at any longitude. Plasmas of different temperatures are involved in these eruptions and one has to use instruments sensitive to a wide range of temperatures (a few thousand K for prominences to several MK for flares). CMEs produce the most dramatic space weather effects. CIRs are also important because they are more frequent and produce effects different from those of CMEs. In this paper, we show that the Brazilian Decimetric Array (BDA) can make crucial information on both CMEs and coronal holes.

CORONAL MASS EJECTIONS

CMEs are multithermal plasmas typically consisting of a frontal structure, a cavity, and a prominence core (see e.g., Hundhausen, 1997). When the CMEs erupt, they leave behind post-eruption arcades also known as flare loops. During the eruption, electrons are accelerated, which result in intense nonthermal microwave emission. While the nonthermal microwave emission gives information on the magnetic properties of the post-flare loops, the thermal emission gives information on the CME structures. Here we focus on the CME observations. The frontal structure and the filament cavity are coronal features optically thin at microwave frequencies. On the other hand the prominence core is very dense and relatively cool and hence optically thick in microwaves. The arcade formation is a hot coronal structure but of much higher density.

The observability of CME substructures in microwaves can be assessed using the simple formula for free-free optical depth (Gopalswamy, 1999):

$$t_{ff} = \alpha \int n^2 f^{-2} T^{-3/2} \, dl,$$

where $\alpha \sim 0.2$ for $T > 10^4$ and $\sim 0.08$ for $T < 10^4$, $n = \text{electron density}$, $f = \text{observing frequency}$ and $T = \text{electron temperature}$. $\int n^2 \, dl$ is the emission measure of the structure we are interested in, $dl$ being the elemental length along the line of sight. Let us evaluate the optical depth for various substructures.

The frontal structure and cavity

The typical temperature and density of the frontal structure are 2 MK and $\sim 10^8 \text{ cm}^{-3}$ respectively, so at an observing frequency of 5.6 GHz, one needs a line of sight depth of $4 \times 10^{13} \text{ cm (3 AU)}$ to make the CME optically thick. If we use a realistic thickness of $\sim 1 \text{ solar radius}$, equation (1) gives an optical depth of $1.6 \times 10^3$ and the frontal structure will be at a brightness temperature of only 3142 K. The same argument applies to the cavity which is of similar size and lower density and hence the contribution will be still smaller. It must be noted that at meter wavelengths, the conditions are more favorable. At 50 MHz, a CME of 1 solar radius thickness will be optically thick and can be readily observed. Such CMEs were observed by radioheliographs at Clark Lake (Gopalswamy and Kundu, 1992; 1993b) and Culgoora (Sheridan et al., 1978). A simulation study by Bastian and Gary (1997) on the detectability of CMEs in microwaves resulted in a similar conclusion.

The prominence core

The cool dense prominence has a large opacity in microwaves: for typical temperature ($\sim 8000 \text{ K}$) and density ($\sim 10^{10-11} \text{ cm}^{-3}$), the prominence core becomes optically thick even for a small line of sight depth of 0.3 km. Hence the prominence core can be readily observed by BDA at 5.6 GHz, similar
to what is observed at 17 GHz (Hanaoka et al., 1994; Gopalswamy et al., 1996; 1997a; Gopalswamy and Hanaoka, 1998; Gopalswamy, Hanaoka and Hudson, 1999b). Since the corona is optically thin and contributes very little to the microwave brightness temperature, it results in a “cold sky” in microwaves. A prominence observed against the cold sky appears as a bright structure, very similar to a prominence in Hα. The brightness temperature is typically ~ 8000 K in microwaves. During eruptive events, the prominence can expand and drain considerably and can become optically thin as shown by Fujiki (1999). Because of the inverse-square frequency dependence of the free-free opacity, the prominence can easily become optically thin at higher frequencies (Irimajiri et al., 1995), although it can remain optically thick at lower frequencies such as 17 GHz. At 5.6 GHz, the prominence will remain optically thick even at greater distances from the Sun, and hence can be readily tracked by BDA. Figure 1 shows a bright eruptive prominence observed by the Siberian Solar Radio Telescope at 5.7 GHz, a frequency used by the BDA.

Fig. 1 - Snapshots of the Sun in microwaves obtained by the Siberian Solar Radio Telescope 5.7 GHz, similar to BDA. Northwest quadrant of the Sun is shown. The eruptive prominence can be seen to increase in height over a period of ~ 50 minutes. (Courtesy: V. V. Grechnev)

Filaments

The solar disk (“the microwave quiet Sun”) has been estimated by Zirin et al. (1991) at various frequencies and found to follow the relation,

\[ T_b = A f^{-2.1} + B, \]  

(2)
where \( A = 140077 \) and \( B = 10880 \) (the temperature of the chromosphere in K). At 5.6 GHz equation (2) gives a brightness temperature of \( \sim 14640 \) K. Therefore, the prominence when observed on the disk, appears as a depression (dark filament) with respect to the quiet Sun, by \( \sim 6640 \) K. The contrast is much better than what is observed by the Nobeyama radioheliograph, and hence will be very useful in tracking filaments, which are one of the best indicators source regions from where CMEs erupt. When the filament erupts, it can often get heated up and becomes indistinguishable from the quiet Sun (“disappears”). The radio disappearance is due to a different physical mechanism compared to the \( \text{H}\alpha \) disappearance; the latter happens when the filament ceases to absorb the \( \text{H}\alpha \) line radiation when its temperature increases. Since the prominence remains optically thick for a long time after eruption, the 5.6 GHz observation can track eruptive prominence for a longer time.

![Fig. 2 - U-shaped dark filament on the disk (left) and the same filament becoming an eruptive prominence on the right. Post flare loops can be seen after the filament eruption. Locating the filament and flare using the same instrument provides a great advantage in identifying CME sources.](image)

### Post-eruption arcade (Flare)

Hanaoka et al (1994) imaged the arcade formation of the 1992 July 30–31 event in microwaves. The imaging was possible because the free-free emission from the arcade was high enough to be detected in microwaves. From \( \text{Yohkoh}/\text{SXT} \) images, the average temperature and density of the arcade were derived to be 3.5 MK and \( 2.4 \times 10^9 \) cm\(^{-3} \) respectively. Using the measured size (28000 km) of the arcade at the brightest region as the line of sight depth, equation (1) gives an optical depth of 0.0017 and results in a brightness temperature of \( \sim 6000 \) K, similar to what was observed. After accounting for the difference in spatial resolution of radio and X-ray data, Hanaoka et al (1994) showed that the observed and computed brightness temperatures were in close agreement. For the same parameters, BDA will observe an order of magnitude higher brightness temperature because of the inverse-square dependence of the optical depth on frequency. The optical depth becomes 0.016 and
the brightness temperature is 55000 K. Figure 2 shown an actual observation from SSRT at 5.7 GHz showing the filament before and during eruption as well as the flare after the filament has lifted off.

**The coronal cavity**

The coronal cavity is typically at the same temperature as the frontal structure of the CME, but of lower density. If the density is an order of magnitude lower, one gets an optical depth of ~0.00016, so the brightness temperature becomes ~320 K. Thus, one should be able see the cavity as a dark feature between the prominence and the corona. It is possible that the cavity on the disk also will be observed as a depression as an extension of the prominence. It has been demonstrated by Gopalswamy et al. (1991) that the filament cavities are readily observed at 1.5 GHz. Multifrequency observations using the BDA should be able to readily observe the cavity on the disk as well as above the limb.

![Fig. 3 - A quiet Sun image of the Sun at 1.5 GHz by the Very Large Array (VLA) on September 17, 1988. F and H denote filaments and coronal holes, respectively. Other compact bright regions are active regions. BDA will be able to image all these features in a dedicated manner.](image)

**CORONAL HOLES**

Coronal holes are important large-scale structures on the Sun, which produce high-speed solar wind streams (HSS). When HSS collide with the neighboring slow solar wind, they produce large-scale magnetized plasma structures known as the corotating interaction regions (CIRs). CIRs are responsible for a different type of geomagnetic storms that are known for producing MeV electrons in Earth’s magnetosphere. These electrons can be hazardous to satellites in the magnetosphere, and hence important for space weather prediction. Observing coronal holes in the equatorial region of the Sun is
thus very important. BDA can readily observe the coronal holes at all frequencies as depressions. Figure 3 shows an example of the quiet Sun showing filaments and coronal holes observed by the Very Large Array (VLA) at 1.5 GHz. This frequency will be used by the BDA, so coronal holes can be tracked and studied. In addition, coronal holes will appear as depressions at all the BDA frequencies, so the structure of coronal holes can also be studied.

SUMMARY

In summary, the Brazilian Decimetric Array (BDA) will make important contributions to the field of space weather by observing the solar sources of adverse weather in geospace. Coronal mass ejections and coronal holes are the two sources of mass emission from the Sun that result in geomagnetic storms and energetic particles. Coronal mass ejections on the solar disk are not well observed by coronagraphs. Radio telescopes like the BDA can readily observe the inner parts of CMEs (the prominence core and cavity) when they start on the Sun, thus providing advanced warning of impending adverse space weather at least one day ahead of time. Similarly, the BDA will be able to observe the presence of coronal holes on the disk and forecast high speed streams. We demonstrated the feasibility of making very useful radio measurements by considering the physical parameters of various coronal features applied to the BDA.

REFERENCES