VLA OBSERVATIONS OF THE CORONAL PLASMA

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ABSTRACT. VLA observations at 20-cm wavelength specify the brightness temperature and magnetic structure of plasma constrained within coronal loops in solar active regions. Comparisons with simultaneous SMM observations at soft X-ray wavelengths lead to measurements of physical parameters like electron density, electron temperature and magnetic field strength. Such comparisons also indicate coronal loops can be detected at either radio or X-ray wavelengths while remaining invisible in the other spectral domain, and that the dominant radiation mechanisms can be thermal bremsstrahlung or thermal gyroresonance radiation. VLA observations at the longer 90-cm wavelength reveal the thermal emission of a hot transition sheath enveloping a cooler, underlying Hα filament seen in absorption. The 20-cm VLA observations indicate that the precursor, impulsive and post-flare components of solar flares originate in spatially separated and resolved sources.

I. INTRODUCTION.

This paper provides a brief overview of recent discoveries by the Tufts University group using the Very Large Array (VLA) to study the coronal plasma under the support of the AFOSR and NASA (Section 5). More detailed accounts can be found in the references given in this introduction and in Section 6. Ground-based VLA observations at 20-cm wavelength can detect the hot coronal plasma previously detected by space-bourne X-ray telescopes; detailed comparisons of simultaneous data (SMM and VLA) indicate that physical parameters can be obtained (Section 2), but that some coronal loops are invisible in either spectral domain (Lang, Willson, Smith and Strong 1987a,b). At the longer 91.6-cm wavelength, the VLA detects more extensive emission interpreted as a hot 10^5 K interface between cool, dense Hα filaments and the hotter enveloping rarefied corona (Section 3, Lang and Willson, 1989). The unparalleled spatial resolution of the VLA at 20-cm wavelength has shown that the precursor, impulsive and post-flare components of solar bursts originate in nearby, but separate, coronal loops or systems of loops (Section 4, Willson, Lang and Liggett, 1990).

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2. QUIESCENT 20 CM AND X-RAY EMISSION FROM CORONAL LOOPS

The development of aperture synthesis telescopes like the Very Large Array (VLA) has permitted ground-based observations of coronal loops at 20-cm wavelength; the quiescent, or non-flaring, loop emission has brightness temperatures, T_B, comparable to the million-degree coronal electron temperature. A comparison with simultaneous soft X-ray images of comparable angular resolution and field of view (Fig. 1) indicates that X-ray coronal loops can be imaged at 20 cm.

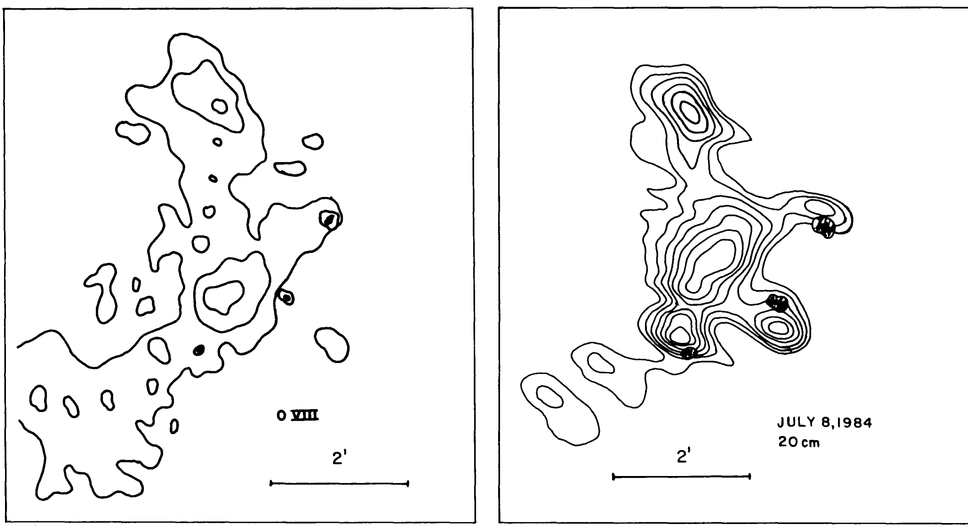

Figure 1. A comparison of soft X-ray (SMM FCS - left) and 20-cm (VLA-right) images of an active region. Here the sunspots are denoted by small black dots with a circle around them (cf. Lang et al. (1987a)) Soft X-ray spectral lines have been used to determine the electron temperature, T_e, and electron density, N_e, of the X-ray emitting plasma that spatially coincides with the 20-cm radiation; for the data shown in Fig. 1, average values of $T_e = 3.0 \pm 0.1 \times 10^6$ K and $N_e = 2.4 \pm 0.4 \times 10^9$ cm^{-3} were obtained. The quiescent X-ray radiation is attributed to thermal bremsstrahlung. The 20-cm emission is optically thin with optical depths $\tau = T_e/T_B = 0.3$. The thermal bremsstrahlung of the X-ray emitting plasma ought to be optically thin at 20 cm, but its thermal gyroresonance radiation should be optically thick at this wavelength. Thermal gyroresonance radiation must account for the intense 20-cm radiation near and above sunspots where no X-ray radiation is detected (also see Fig. 1).

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3. QUIESCENT 90 CM EMISSION FROM FILAMENTS

Although 20-cm VLA observations of the quiet Sun reveal the ubiguitous coronal loops anchored within solar active regions, the VLA results at the longer 91.6-cm wavelength reveal quiescent emission from more extensive structures (angular sizes θ = 3') that are not associated with active regions (Fig. 2 right and left). The 91.6-cm features are similar in shape, position, elongation and orientation to dark Hα filaments; but the radio structures are wider and longer, and they are detected in emission rather than absorption. This 91.6-cm emission has been interpreted as the thermal bremsstrahlung of a hot (10^5K), transition sheath that envelopes the cooler Hα filaments and acts as an interface with the hotter surrounding corona. This transition sheath has been previously detected in absorption with lower brightness temperatures at shorter wavelengths of 6 and 20 cm (Rao and Kundu, 1980; Kundu, Melozzi, and Shevgaonkar, 1986).

Variable physical parameters of the transition sheath can explain controversial reports of the detection of, or the failure to detect, the meter-wavelength counterpart of Hα filaments. If the sheath were substantially thinner, then the optical depth would not be large enough for detection of its 91.6-cm bremsstrahlung; and if the electron density of the sheath was much higher than $N_e = 10^9$ cm^{-3}, then its plasma frequency would exceed our observing frequency and the sheath radiation could not propagate out to be observed.

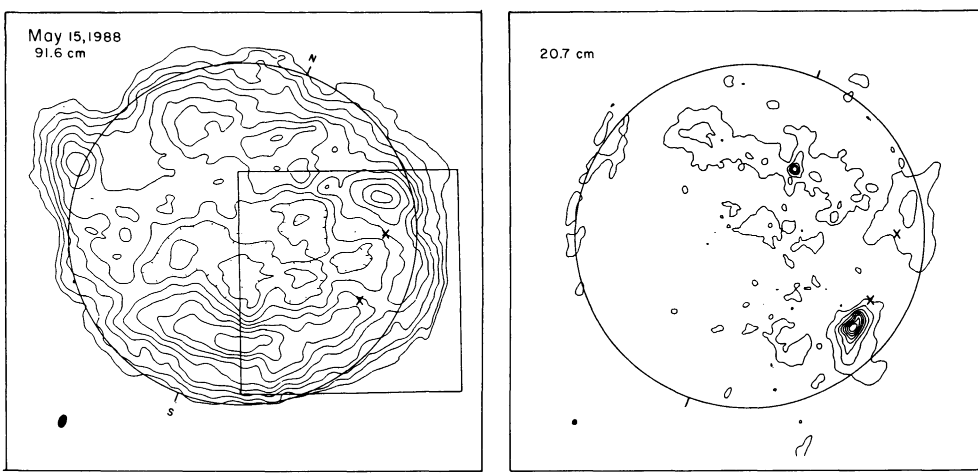

Figure 2. The quiescent 91.6 cm (left) and 20.7 cm (right) emission from the Sun. The 20.7-cm contours delineate active-region coronal loops with a peak brightness temperature of $T_B = 2.5 \times 10^6$ K, while the 91.6-cm contours show more elongated structures that are not associated with active regions and have a peak $T_B = 7.8 \times 10^5$ K. (Adapted from Lang and Willson (1989)).

4. RESOLVING FLARE COMPONENTS

The classical time profile for the microwave or radio emission of solar flares, or eruptions, consists of a low-level precursor, and a rapid powerful impulsive component, followed by a more gradual post-burst, or decay, phase (see Fig. 3). The VLA has now been used to map these flaring components at 3-second time intervals, showing that they originate in spatially separated sources (Fig. 4).

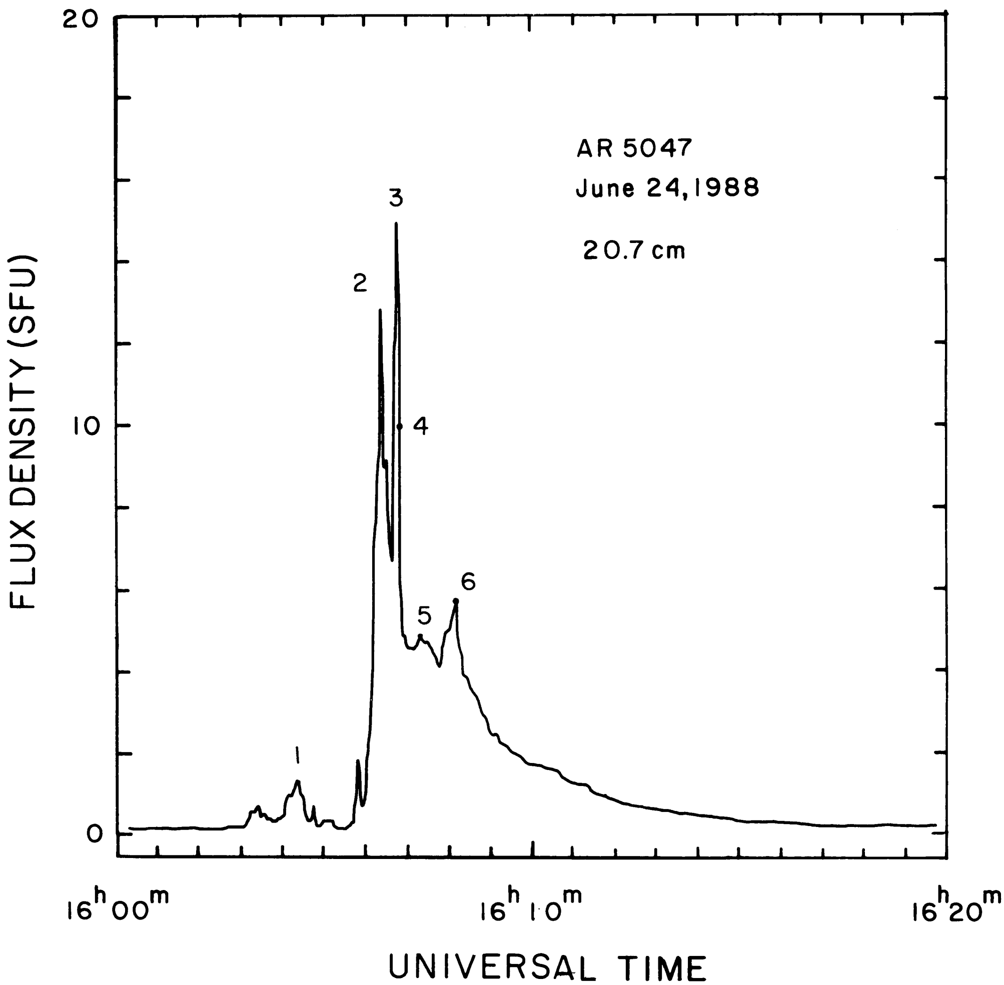

Figure 3. The time profile of a 20.7-cm burst showing the preburst (1), impulsive (2,3), and post-burst (4, 5, 6) phases. The VLA snapshot maps given in Fig. 4 indicate that these three phases originate from spatially separated, resolved components. (Adapted from Willson, Lang and Liggett (1990)).

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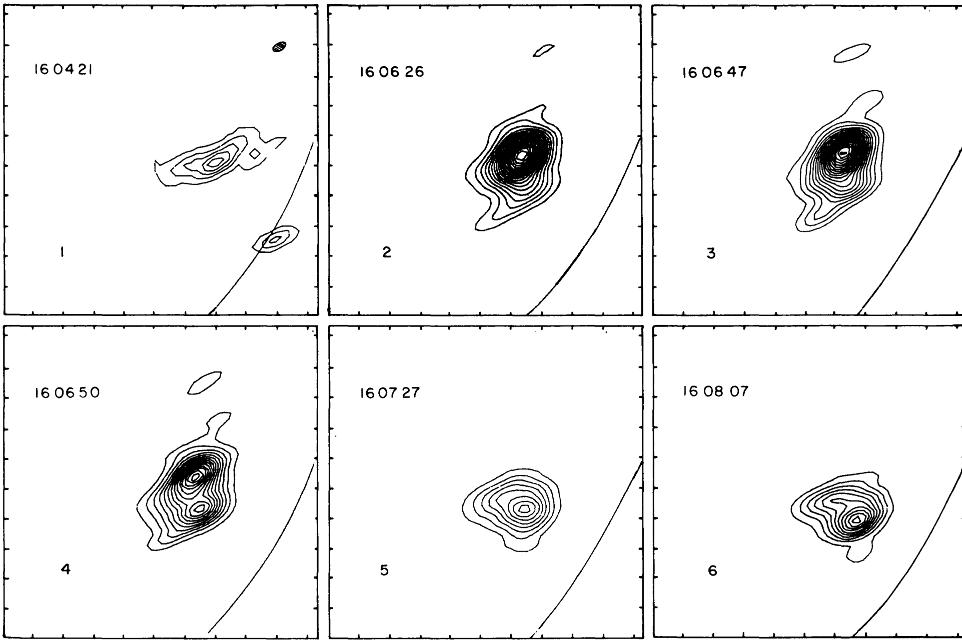

Figure 4. VLA snapshot maps of the total intensity, I, at 20.7-cm wavelength during 3.3-second intervals at the times denoted by 1 to 6 in Fig. 3. The precursor (1) is spatially separated from the subsequent impulsive bursts (2 and 3). The post-burst, or decay, phase (5, 6) originates in another spatially separate source that first becomes detectable during the end (4) of the second impulsive burst (3). The angular scale can be inferred from the 60" spacing between the fiducial marks on the axes. The contour intervals are in units of equal brightness temperature, T_B, with an outermost contour and contour interval of $T_B = 4.4 \times 10^5$ K for 1, and $T_B = 5.5 \times 10^6$ K for the others five images. The maximum value is $T_{Bmax} = 4.4 \times 10^6$, 1.0×10^8, 1.3×10^8, 7.7×10^7, 4.4×10^7 and 5.5×10^7 K for 1, 2, 3, 4, 5 and 6 respectively. (Adapted from Willson, Lang and Liggett (1990)).

These results suggest that solar flares are triggered by interacting coronal loops; emerging coronal loops may interact with adjacent ones, leading to the explosive release of magnetic energy stored within them. Evidence for the magnetic triggering of solar flares by interactng and reconnecting coronal loops has been provided by previous VLA observations at 20 cm and 6 cm wavelength (Kundu et al., 1982; Kundu and Lang, 1985). The system of coronal loops then relaxes to a spatially-different configuration during the decay phase.

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DISCUSSION

CHIUDERI DRAGO: The filament brightness temperatures given by Kundu *et al.* are not the observed ones, but they have been corrected for the coronal contribution. The coronal parameters used by Kundu *et al.* correspond to a coronal pressure $p \simeq 0.2$ dyne/cm^2, one order of magnitude larger than the pressure at the top of the transition region, in their "variable pressure model" - this inconsistency does not affect very much the data at short ($\lambda < 21$ cm) wavelengths, but it would affect very much the T_b at 90 cm. If the parameters you used for the coronal contribution subtraction are the same as those used by Kundu *et al.*, the agreement with the "variable pressure model" gives an inconsistency. If you take, for the computation of the coronal contribution, parameters in agreement with the variable pressure model, then you cannot compare your data with the Kundu *et al.* ones.

VAN BALLEGOOIJEN: Have you ever observed polarization in filament radio emission?

LANG: Our observations of filament emission at 90 cm wavelength were unpolarized, probably because the thermal radiation of the 10^5 K plasma was optically thick. However, these were the first such observations. So, when the Sun becomes less active, we hope to observe some emission that is optically thin and circularly polarized. This will let us determine the shape and strength of the filament magnetic field for the first time. We also hope to carry out strict tests of the theory by observing the same filament at several wavelengths, say 2, 6, 20 and 90 cm, and for varying angles between the line of sight and the magnetic field.

GELFREIKH: How do the size and shape of the radio (90 cm) filaments compare with optical (Hα) filaments?

LANG: The 90 cm filaments have the same size, shape, position and elongation as the underlying Hα filaments, but the radio emission is wider and longer. The transition sheath is thought to be about 100 km thick. We should be able to measure this thickness in future.