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THE PROPOSED NRAO MILLIMETER ARRAY AND ITS USE FOR SOLAR STUDIES

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ABSTRACT

In this report we give a brief summary of the proposed NRAO Millimeter Array discussed at a workshop held in Green Bank, W. Va., September 30-October 2, 1985. We also provide a brief description of the solar studies that can be made with such an array.

THE ARRAY

A millimeter array consisting of two arrays to cover the range of desired resolutions and fields of view was proposed:
(1) A large array of ~ 21 movable antennas of ~ 10 m diameter and a small array of ~ 21 antennas of ~ 4 m diameter which are mounted on a structure ~ 29 m in size in a multi-telescope (M-T) configuration with ~ 50% filling factor and 25 m resolution. Figure 1 schematically illustrates the major options being discussed for configuration of the two arrays. The antennas in both arrays will operate in both aperture synthesis mode and single antenna mode. Figure 2 summarizes the observing modes that will be used to cover all resolutions from the $56''\lambda_{mm}$ beam size of the 4 m antennas down to the resolution of the largest arrays of the 10 m antennas. Single dish observing in total power/beam switching mode covers the largest two size scales, the M-T in aperture synthesis mode covers the next step of a factor of 2.5 in resolution, and the large array configuration $\geq$ 90 m covers all higher resolutions (Hjellming 1985). Mapping by mosaicing is also intended, which involves the combination of 4 m and 10 m data to observe the fields of view of the 4 m antennas with the resolution of the 10 m antennas or array of 10 m antennas. The main reason for two arrays with antennas of two different sizes is to allow imaging of a wide range of spatial scales with reasonable surface brightness sensitivity. The collecting area of the array will be between 1000 and 2000 m^2, and it will operate at 9, 3, 2 and 1 mm, and submillimeter wavelengths, for both continuum and spectral line observations. The VLA-Y or the randomized circle for the large array is believed to be the most suitable configuration.

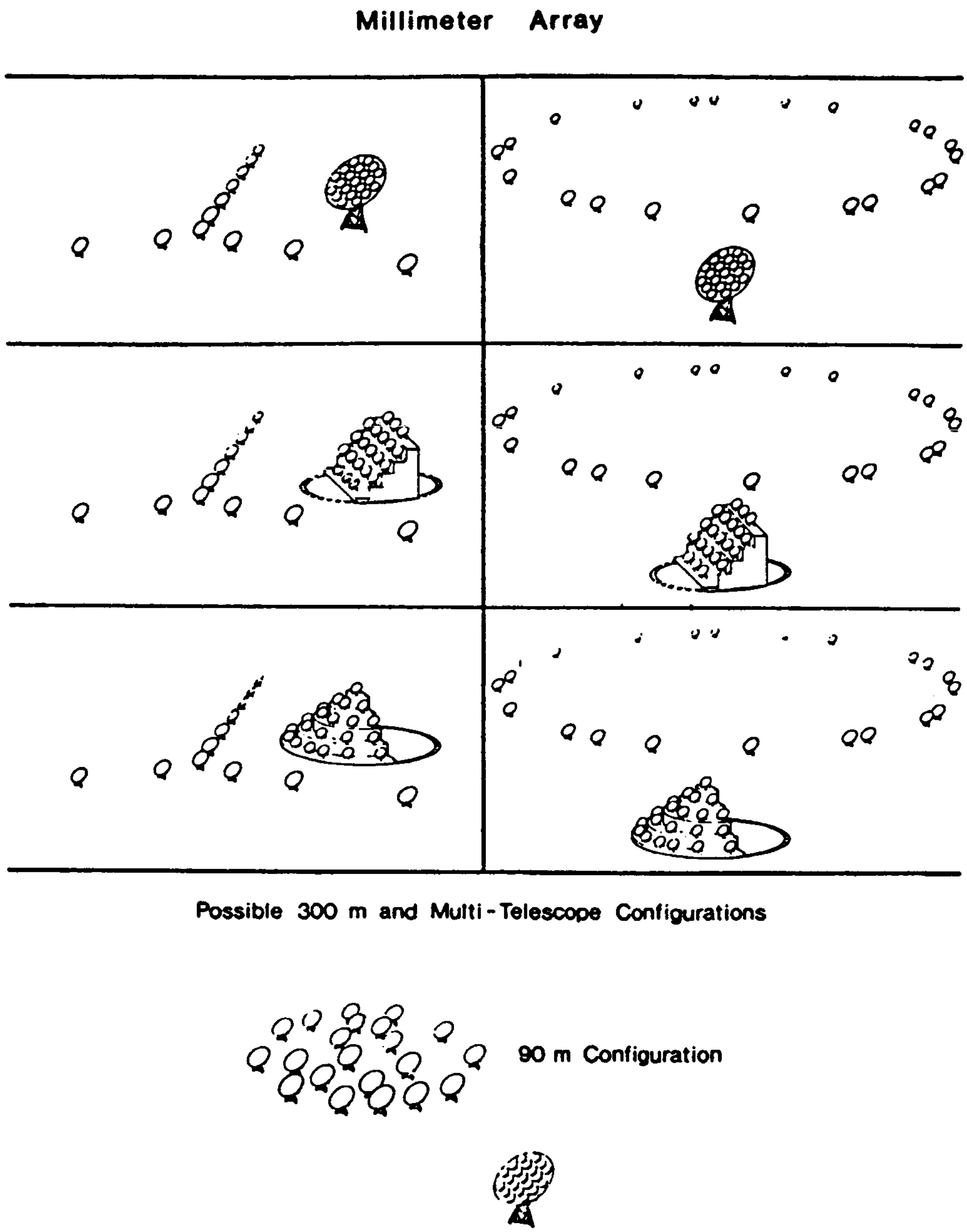

Fig. 1. Various Millimeter Array configurations (see text).

Millimeter Array Imaging/Mosaicking Problem

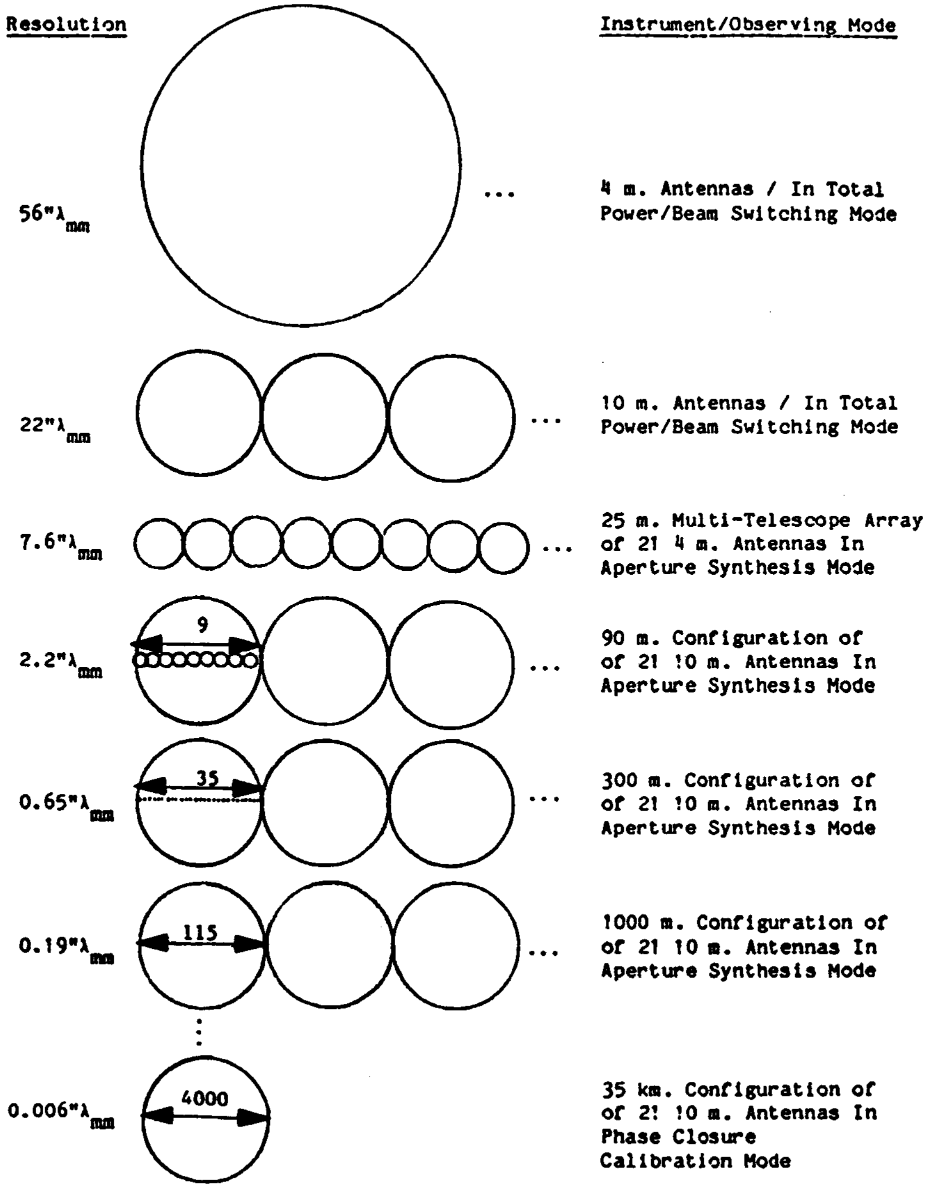

Fig. 2. Spatial resolutions of the array under different mode of observing (see text).

SOLAR STUDIES

I. FLARES

(a) Gamma ray-mm wavelength flares

One important solar problem that can be studied with a mm wave array is that of gamma ray-mm wave flares. In gamma ray-mm wave flares, recent evidence (from Solar Maximum Mission and mm wave observations) has demonstrated that electrons and protons are accelerated almost simultaneously to very high energies. In particular, electrons attain energies of 10 to 100 MeV within one or two seconds of flare onset, and emit both mm waves and continuum gamma rays of high intensity. This continuum radiation is accompanied by nuclear gamma ray lines at energies less than ~ 10 MeV due to protons, and neutrons are sometimes detected at Earth (e.g. Chupp 1984).

At the present time there is no widely accepted explanation for this very rapid acceleration. Some argue that there must be a "first phase" process because of the very short time scale, possibly involving electric fields in double layers. Others argue that shock acceleration can act on short enough time scales (e.g. Decker and Vlahos 1985).

In the radio range, the special characteristic of gamma ray-mm wave flares is that the flux density increases with frequency. Figure 3 shows the spectra of several flares (Kaufman et al. 1985).

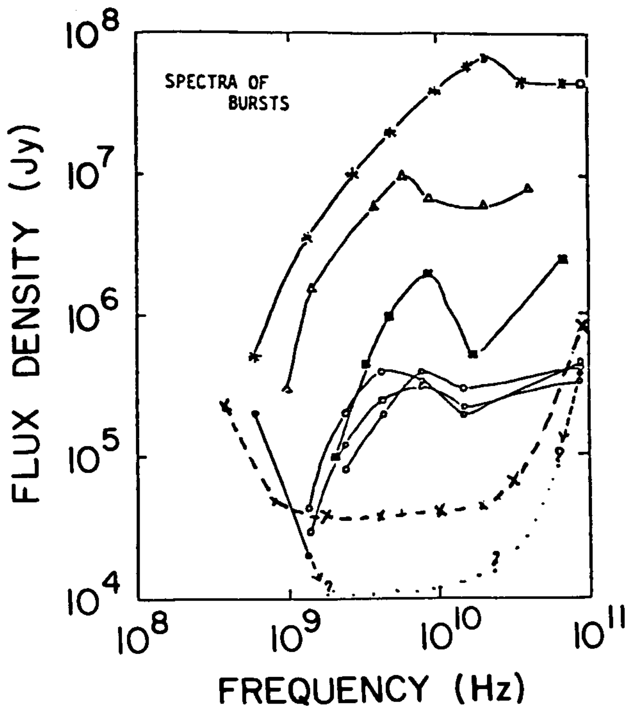

Fig. 3. Flux density spectra of millimeter bursts associated with Gamma ray flares (Kaufman et al. 1985).

Observations at mm waves are obviously of great interest: there have been no spatially resolved studies in either mm waves or gamma rays. Since there are no instruments being designed with arcsec resolution in the energy range > 10 MeV, the mm wave array is probably the next best thing for understanding these very energetic solar flares. In order to study properly the problem of electron and proton acceleration in gamma ray-millimeter flares, one must have $\lesssim$ 0.1 sec time resolution and $\lesssim$ 1" spatial resolution, and measure circular polarization with ~ 1% accuracy. Mapping of wide fields by mosaicing is obviously necessary.

(b) Penetration of electron beams into the lower atmosphere

In many flares, brightenings occur in Hα, EUV and even white light simultaneously with hard X-ray bursts. There is a controversy over the cause of these brightenings, whether due to electrons, protons, or an ion acoustic conduction front. Each method has problems: it is uncertain whether electrons are able to penetrate deeply enough into the dense atmosphere; we do not know how to accelerate an adequate number of protons in the required 1 s; and heat conduction by an ion acoustic front may be too slow (Dulk et al. 1986).

Observations of mm waves can help answer these questions because they originate in the relevant region of the atmosphere, namely the low chromosphere, in contrast to cm waves which originate in the lower corona. If the mm wave emission in some flares is due to thermal bremsstrahlung from the heated plasma, it is relatively easy to relate radio wave brightness to the density-temperature structure in the heated region. The relative timing of mm wave vs. cm wave bursts should help distinguish among the possible causes.

II. MAPPING OF SOLAR ACTIVE REGIONS, SOLAR FILAMENTS AND PROMINENCES

Mm wave emission from active regions is due to free-free bremsstrahlung, and is partially polarized due to the difference between x-mode and o-mode emissivities. It therefore gives information about the magnetic field strength and topology in the low chromosphere, whereas most magnetogram data apply to the photosphere. Changes in magnetic field topology, pre- to post-flare, should be much larger in the chromosphere than the photosphere, and hence much more evident at mm wavelengths (Kundu and McCullough 1972a; Kundu and McCullough 1972b).

Since filaments are optically thick, their brightness temperature should equal the electron temperature determined at optical wavelengths. However, the radio observations indicate that the observed brightness temperature T_b of a filament increases with wavelength. It is believed that this is due to radiation from the transition sheath where T_e increases from 6000 K at the filament to about 10^6 K, the temperature of the surrounding corona. The variation of $T_b(\lambda)$ can provide information on the temperature and density structure of the transition sheath. This is important since the temperature gradient determines the amount of thermal energy conducted into the filament from the corona. Rao and Kundu (1977) studied this problem by considering a model in which the conductive flux from the corona balances the energy radiated away by the transition sheath. They found that best fit to observations is obtaned when almost all of the conductive flux is dissipated in the transition sheath. The observations used by Rao and Kundu were obtained using single dish telescopes with a few arc minute resolution. Obviously there is a need for high spatial resolution observations in both mm and cm domains to determine more precisely the radio spectrum of the filament transition sheath and then address the question of thermal conduction into the filament.

Most centimeter and millimeter observations show that the radio and optical filaments are of very similar size. On the other hand, observations made between 3.5 mm and 11 cm wavelengths (e.g. Kundu and McCullough, 1972a; Kundu et al, 1978) have demonstrated that the radio filaments are sometimes much larger than their optical counterparts. The considerably larger size of the radio filament as compared to the optical filament suggests that the immediate environment of a filament differs from that of the undisturbed corona. This is consistent with white light coronal measurements which show that Hα filaments are sometimes surrounded by low density regions (coronal cavities) with weaker emission than the ambient corona. These low density regions lead to a broadening of the optical Hα filament at radio wavelengths. The radio filament appears as a temperature depression because it is optically thick at radio frequencies and is cooler than the quiet Sun. A high resolution study in both cm and mm domains of the radio structure and spectra of filaments should permit us to understand the physics of coronal cavities.

For these studies, it is necessary to image a field of about 1 arc min with a resolution of about 1 arc sec at 1 mm. This is feasible with a 3 x 3 mosaic, or by under-illuminating the 10 m dishes. Quasi-simultaneous observations at 1, 3 and 9 mm including circular polarization measurements are required.

III. MAPPING OF THE QUIET SUN: QUIET REGIONS AND CORONAL HOLES

At 36 GHz, recent Japanese results (Kosugi et al. 1985), using the Nobeyama 45 m millimeter telescope, demonstrate that coronal holes are brighter than quiet regions (Fig. 4a), contrary to what is observed at almost all other frequencies (e.g. 10 and 98 GHz). Similar results were reported earlier (Fig. 4b) by Kundu and McCullough (1972a) and Efanov et al (1980), although this highly unexpected result was not properly understood, because of the manner the results were presented (namely, contour maps versus spectacular photographic representation). The cause of the anomalous brightening is unknown: it is possibly related to a lower gradient of density and temperature in the transition region of coronal holes compared to average quiet regions, or to a wider temperature plateau in the upper chromosphere. Maps with arc sec resolution are desirable to determine whether the brightness difference is related to fine structures or widespread emission, and to compare brightness distributions at the solar limb where the emission scale height is only about 1".

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Fig. 4a. Polar cap brightening associated with coronal holes observed on July 19, 1984 at 36 GHz by Kosugi et al (1985) using the Nobeyama 45 m milli-meter telescope with 46" resolution

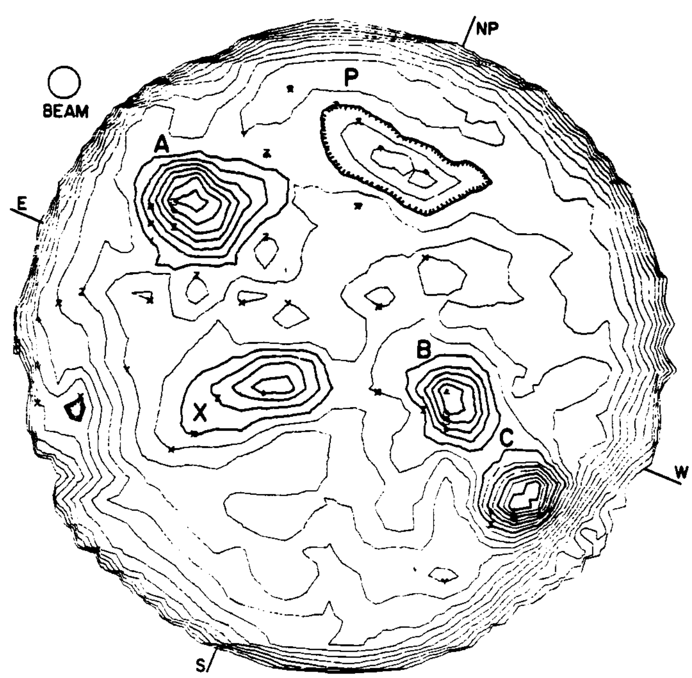

Fig. 4b. Brightening in the polar region (marked "P") observed on February 26, 1971 by Kundu and McCullough (1972a) at 33 GHz with a resolution of 1.′6.

Other studies include the thermal phase of flares, coronal heating, and oscillations (both radial and torsional) and pulsations.

ACKNOWLEDGEMENT

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