HIGH-SPATIAL-RESOLUTION MICROWAVE AND RELATED OBSERVATIONS AS DIAGNOSTICS OF CORONAL LOOPS

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High-spatial-resolution microwave observations of coronal loops, together with theoretical models for the loop emission, can provide detailed information about the temperature, density, and magnetic field within the loop, as well as the environment around the loop. The capability for studying magnetic fields is particularly important, since there is no comparable method for obtaining direct information about coronal magnetic fields. Knowledge of the magnetic field strength and structure in coronal loops is important for understanding both coronal heating and flares. With arc-second-resolution microwave observations from the VLA, supplemental high-spectral-resolution microwave data from a facility such as the Owens Valley frequency-agile interferometer, and the ability to obtain second-of-arc resolution EUV or soft X-ray images, the capability already exists for obtaining much more detailed information about coronal plasma and magnetic structures than is presently available.

It has long been recognized by practitioners of solar radio astronomy that microwave observations provide a means of determining magnetic field strengths in the corona and transition zone (see Kundu and Lang, 1985, for a recent review). Early observations of the sun were encumbered by poor spatial resolution. Arc-second-resolution observations with the VLA, however, have clearly demonstrated that individual coronal loops and other structures can be resolved at microwave frequencies (see Kundu and Lang, 1985). Nevertheless, these single-frequency observations have not led to unambiguous determinations of coronal magnetic field strengths, since two different mechanisms, thermal bremsstrahlung (free-free) and thermal gyroresonance (cyclotron) emission, and possibly nonthermal gyrosynchrotron emission, can contribute to the microwave emission. Free-free emission is sensitive to electron temperature and emission measure, while gyroresonance emission is most sensitive to magnetic field strength (and direction) and electron temperature. Using gyroresonance emission to determine magnetic field strengths requires determining which of several possible harmonics of the electron gyrofrequency is responsible for the observed emission. Simultaneous VLA observations at 1.5 GHz, 5 GHz, and/or 15 GHz have not improved this situation much, since the emission mechanisms are also sensitive to frequency, and entirely different structures are typically observed at these widely-spaced frequencies. In order to confidently extract the desired physical information from these observations, additional observational data and more detailed theoretical modeling are required.

Computations of the microwave and related emissions from model coronal structures are important for obtaining an idea of what microwave signatures might be observed, for determining what combination of observational data is required to obtain the desired physical information, and are necessary for extracting complete information from the observational data. With these considerations in mind, the thermal gyroresonance emission from two-dimensional dipole loop models has been computed by Holman and Kundu (1985). These models were chosen as the simplest non-trivial, but potentially realistic, configuration from which the coronal microwave emission might arise. One of these loop models, and the corresponding 5 GHz

microwave emission, is shown in the figure below. An isothermal, 3×10^6 K plasma is confined between dipole magnetic field lines that cross the y axis at y = 5.0 and 5.2×10^9 cm (the dipole is at the origin). The footpoints of the loop are taken to be at the value of y where the outer magnetic field line becomes parallel to the y axis, marked "surface" in the figure. The field strength at the top of the loop is 300 G, and ⩟1500 G at the footpoints. The loop density falls exponentially with height from ⩟10^{10} cm^{-3} at the footpoints to ⩟10^9 cm^{-3} at the top. The heavy curves indicate locations within the loop where a harmonic (circled number) of the local electron gyrofrequency is equal to the observation frequency, and, hence, locations from which gyroresonance microwave emission may be observed. For this model, thermal bremsstrahlung emission is not significant.

HARMONICS AT 5 GHz   THIN LOOP
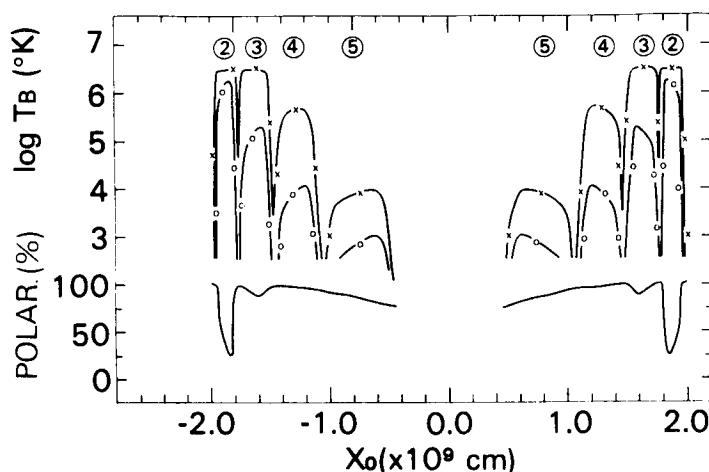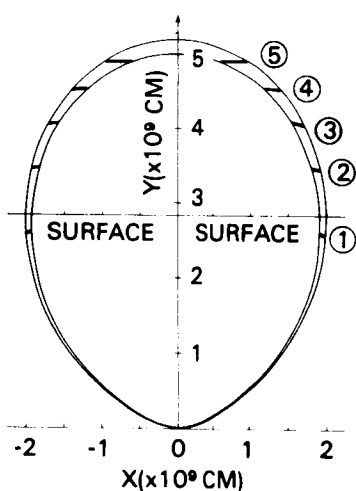
The figure on the right shows the 5 GHz brightness temperature and polarization plotted as a function of position for a scan along the length of the loop with the line of sight parallel to the y axis (the curve labeled with the symbol "x" shows extraordinary mode emission, and "o" denotes the ordinary mode of polarization). The important features are the high degree of spatial and polarization structure. The optically thick harmonics give the loop temperature, and determination of the harmonic number gives the local magnetic field strength. Computations of the loop emission at other nearby frequencies show that the microwave structure is very sensitive to observation frequency. It is also sensitive to the angle at which the loop is observed. This sensitivity can be used to remove the ambiguities present in a single frequency, single aspect angle observation. High-spatial-resolution observations at a series of closely spaced frequencies, such as those recently published by Willson (1985), are particularly valuable in this respect.

Although gyroresonance emission does not provide a sensitive diagnostic of plasma density, the gyroresonance optical depth is density dependent. Also, free-free emission is sensitive to emission measure and, therefore, density. For these reasons it is particularly valuable to have an independent measure of density or emission measure, such as can be provided by EUV or soft X-ray observations. Obtaining simultaneous images at microwave and EUV and/or soft X-ray frequencies provides the most direct means of obtaining detailed information about the magnetic and plasma properties of coronal structures. Simultaneous VLA and high-resolution (rocket) soft X-ray observations of active region loops have been obtained in a

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series of papers by Webb, Davis, Kundu, and collaborators (Webb et al., 1983; Kahler et al., 1984; Webb et al., 1986). (References to other coordinated microwave and soft X-ray observations can be found in these papers.) These papers contain microwave observations of soft X-ray loops at 4.9 GHz (6 cm) and at 1.45 GHz (20 cm). Except for the hotter post-flare loop studied by Kahler et al. (1984), the X-ray loops had temperatures of 2.5 - 3 $\times$ 10^6 K, the X-ray temperature and emission measure did not vary significantly along the length of the loops, and the observations tended to show a relatively compact microwave source at or near the apex of the X-ray loop. These observations are studied in terms of microwave loop models in Webb et al. (1986).

Since the X-ray emission is primarily thermal bremsstrahlung, soft X-ray observations give direct information about the importance of thermal bremsstrahlung at microwave frequencies. For the active region loops observed by Webb et al. (1983, 1986), free-free emission was found to be important for the loops observed at 1.45 GHz, but was found to be unimportant for those observed at 4.9 GHz. The loops observed at 4.9 GHz were generally >30% polarized and had brightness temperatures slightly lower than the electron temperature deduced from the X-ray data. Since the highest optically thick harmonic was found to be the fourth, it was concluded that the 4.9 GHz emission was most likely 4th harmonic gyroresonance emission. This implies a magnetic field strength of 438 Gauss at the location of the microwave sources. Models for the loops observed at 4.9 GHz are shown in the figure below (from Webb et al. 1986).
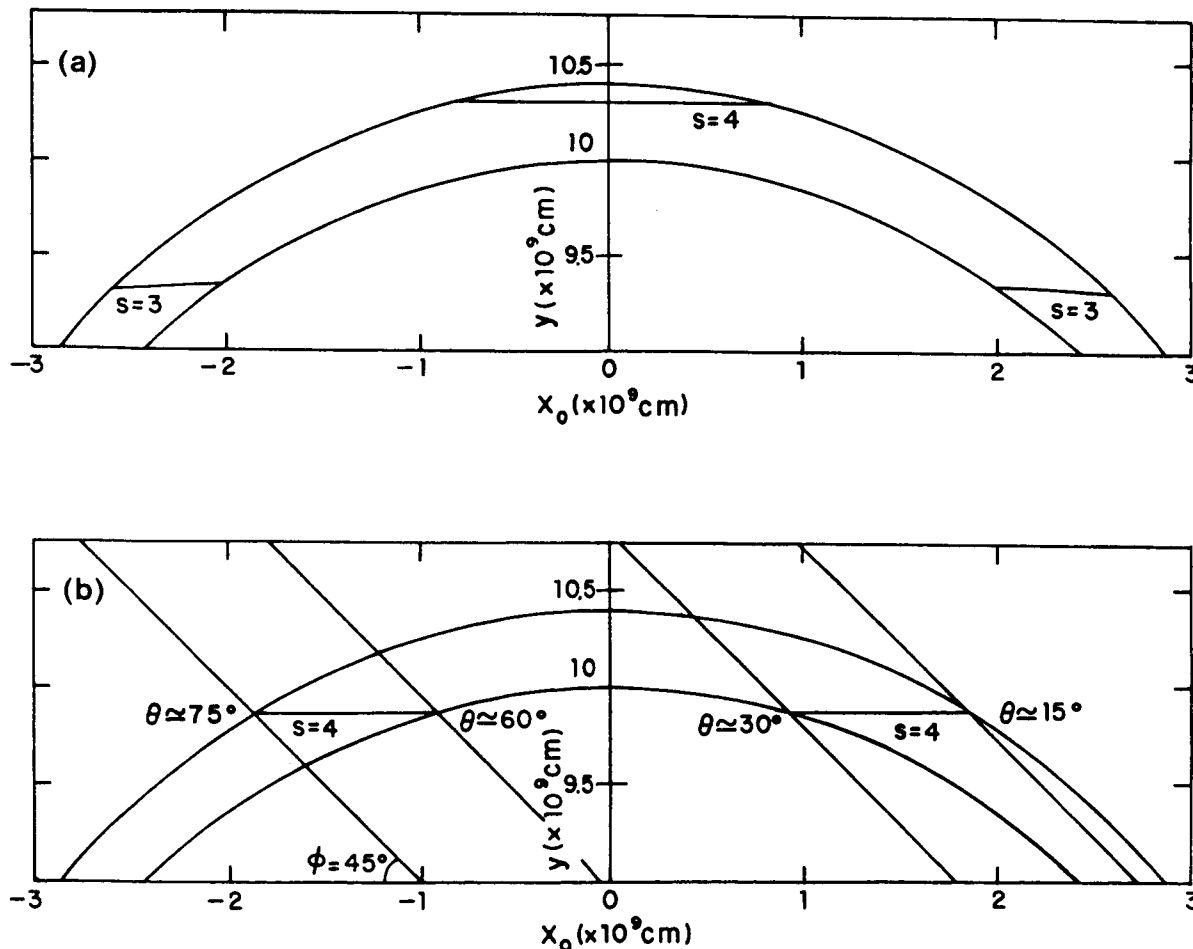
The models in the figure, as in the previous figure, are dipole loop models, for which the magnetic field strength varies along the length of the loop. It was found that if the magnetic field did not vary along the length of the loop, too much of the loop would have been observed at 4.9 GHz. On the other hand, if the field strength varied as much as in the models of Holman and Kundu (1985), lower harmonic emission would have been observed from the legs of the loops. The requirement, then, is that the 3rd harmonic level not be present in the loop or, at least, in the hot, X-ray emitting part of the loop. This restricts the maximum field strength within the X-ray loop to a value less than 580 G. For the model in frame (a) of the figure, the (minimum) field strength at the top of the loop is 425 G and the X-ray emitting plasma terminates above the $s = 3$ level. The microwave emission is only seen from a region around the apex of the loop, as required by the observations.

An alternative possibility is illustrated in frame (b) of the figure. For this case the field strength at the apex of the loop is 375 G and a 4th harmonic level is present in each leg of the loop (the 3rd harmonic level is just below the x_0 axis). If the observer were to look directly down upon the loop ($\phi = 90^\circ$), two microwave source regions would be observed. For the line of sight inclined at an angle of $\phi = 45^\circ$, however, as shown, the source region in the left leg is observed near the center of the projected X-ray loop, while the region in the right leg of the loop would not have been observed. The latter occurs because for small angles θ between the line of sight and the magnetic field, the optical thickness of the 4th harmonic emission is too small for the microwave emission to have been observable. This model places less restriction upon the location of the 4th harmonic level within the loop than model (a). Like model (a), the maximum field strength within the X-ray loop must be less than 580 G.

The information inferred from the 1.45 GHz observations is rather different from the above, since the X-ray loops were found to be optically thick to free-free emission at 1.45 GHz. In order to understand why the entire X-ray loop was not observed down to the $\sim 2 \times 10^5$ K sensitivity of the microwave observations, it was found that the X-ray loop must be enveloped by a cooler plasma with a temperature $\sim 10^5$ K or less. The compact microwave source could be explained if the external plasma ($T = 1 \times 10^5$ K) has a density $\sim 10^9$ cm^{-3} at the top of the X-ray loop that falls off exponentially with height with the gravitational scale length. (The loop density was found to be $\sim 10^{10}$ cm^{-3}.) Most of the loop microwave emission, except for some emission from the top of the loop, is then masked by free-free absorption in the external plasma. This external plasma would have an emission measure $\sim 10^{26}$ – 10^{27} cm^{-5}. A "transition zone" or boundary layer might be expected to be present between the hot loop plasma and the cooler external plasma. The observational implications of, and restrictions upon, such a transition zone are discussed in the following paper (Brosius and Holman, these proceedings; also, Brosius and Holman, 1986).

An alternative model for the 1.45 GHz emission would be for the external absorption to be gyroresonance rather than free-free. This still requires an external plasma temperature of $\sim 10^5$ K or lower, but the plasma density above the loop can be as low as $\sim 10^6$ cm^{-3}. The absorption is most likely to be 2nd harmonic, since 3rd harmonic absorption requires an external plasma density as high as that required for free-free absorption. To obtain the microwave source, the 2nd harmonic level would have to graze the top of the X-ray loop (or graze a transition zone at the top of the loop). This implies a magnetic field strength of 260 G near the top of the X-ray loop. The microwave source would be a combination of gyroresonance and free-free emission.

Highly desirable future observations would be to have a set of high-spatial-resolution microwave maps at primarily closely spaced frequencies, together with high-spatial-resolution EUV or soft X-ray images of the same region. Coordinated high-spectral-resolution observations (with some spatial information so that brightness temperatures can be obtained) from an instrument such as the Owens Valley frequency-agile interferometer would also be desirable. A lot of information can be extracted from a good set of microwave observations alone, but coordinated EUV or soft X-ray observations provide a more direct route to conclusions that are less model dependent. E(or X)UV observations have some advantage over the soft X-ray observations, since a wider range of temperatures can be observed, and some direct density diagnostics can be obtained from line ratios. With either, however, important plasma information is obtained that could only be indirectly deduced from the microwave data alone. There is also much to be done in developing existing models, and in modeling different magnetic and plasma configurations. With more coordinated observations and theoretical modeling, it should be possible to obtain much new, reliable quantitative information about the magnetic and plasma properties of coronal structures.

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