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CORONAL PLASMAS ON THE SUN AND NEARBY STARS

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INTRODUCTION

The Very Large Array (VLA) has been used to observe solar microwave sources with second-of-arc angular resolution. Both the quiescent, or non-flaring, microwave sources and the flaring ones are usually resolved. They are often associated with the apex and/or legs of the ubiquitous coronal loops, which heretofore have been observable only with X-ray telescopes sent above the atmosphere. Multiple-wavelength VLA observations can specify the strength, evolution and structure of the magnetic fields in coronal loops, while also providing constraints on the electron density and electron temperature of the plasma trapped within the coronal loops.

VLA observations are providing new insights to the preburst heating and magnetic interaction that precede eruptions from solar active regions [Lang and Willson, (1983, 1984)]; but these interesting studies are not discussed here [see Kundu and Lang (1985) for a review]. We instead summarize our current understanding of the quiescent, or non-flaring, microwave emission from solar active regions. The next section briefly reviews the thermal radiation mechanisms that account for most of the quiescent emission, while also pointing out that current-amplified magnetic fields or non-thermal radiation may be required in some instances. This is followed by a discussion of the 20 cm radiation of coronal loops and the thermal cyclotron lines that accurately specify their magnetic field strength. The 20 cm and X-ray emission of the coronal plasma are then compared. We next discuss the coronae of nearby stars, where coherent radiation processes seem to prevail, and then conclude our summary with promising research opportunities for the future.

THERMAL RADIATION, CURRENTS AND NON-THERMAL RADIATION

The quiescent microwave emission of solar active regions has been attributed to the thermal radiation of hot electrons trapped within the strong magnetic fields of coronal loops. The microwave brightness temperature is then on the order of the million-degree electron temperature, and either thermal bremsstrahlung or thermal gyroresonant radiation dominate the emission. Bremsstrahlung, or braking radiation, is emitted when the thermal electrons are accelerated in the electric fields of ions and gyroresonant radiation is emitted when the thermal electrons are accelerated by magnetic fields.

Strong evidence for gyroresonant radiation at coronal levels above sunspots was provided by a comparison of microwave, EUV and X-ray observations [Kundu, Schmahl and Gerassimenko (1980); Pallavicini, Sakurai and Vaiana (1981)]. The near equality of the microwave brightness and electron temperatures indicated that the microwave emission was thermal, but the absence of detectable X-ray radiation above sunspots indicated a relatively low electron density there. This meant that the high microwave brightness temperature above sunspots could not be due to bremsstrahlung, but it could be explained by thermal gyroresonant radiation at the second or third harmonic of the gyrofrequency.

Thermal gyroradiation at coronal levels above sunspots was fully confirmed by the detection of circularly polarized ring-shaped or horseshoe structures [Allisandrakis and Kundu (1982); Lang and Willson (1982)] that were predicted using the theory of gyroresonant radiation in the curved magnetic fields above individual sunspots [Gel'freikh and Lubyshev(1979]. These structures were observed at 6 cm wavelength where circular polarizations as high as 100% were detected. Bright sunspot-associated sources observed at 2 to 6 centimeters wavelength are now widely believed to be due to the gyroradiation of million-degree electrons spiralling about strong magnetic fields above sunspots.

But there is another class of compact, bright microwave sources in this wavelength range that are not associated with sunspots. They occur above regions of apparently-weak photospheric magnetic fields. For instance observations at 6 cm wavelength revealed sources with coronal brightness temperatures $T_B > 10^6$ K in regions away from sunspots [Schmahl et al. (1982); Webb, Davis, Kundu and Velusamy (1983)]. Force-free (potential) magnetic field extrapolations from the known photospheric values indicate that the magnetic field in the low solar corona is too weak to account for the observed emission by gyroradiation.

The situation is even worse at shorter wavelengths where stronger magnetic fields are required to produce gyroradiation at the first few harmonies of the gyrofrequency. (Higher harmonics produce insufficient optical depth to account for the high brightness temperatures.) Lang and Willson (1986a-this proceedings) and Willson and Lang (1986) report the presence of compact, bright 2-cm sources that require magnetic field strengths of $H \approx 2{,}000$ G in the low solar corona at regions away from sunspots if they are attributed to gyroresonance radiation.

Bright microwave sources in regions of apparently-weak photospheric fields can be explained by two different hypotheses. First, the emission could be thermal gyroradiation at the second or third harmonic of the gyrofrequency in strong magnetic fields. Currents might amplify the magnetic field in the low corona to values greater than those expected from extrapolations from the photosphere. Alternatively the photospheric magnetograms could be misleading, and strong magnetic fields could exist in isolated regions away from sunspots. Secondly, the emission could be nonthermal radiation in weak magnetic fields. Nonthermal synchrotron radiation from midly relativistic electrons is one possibility, but some as yet unspecified mechanism must be continuously accelerating the electrons [Akhmedov et al. (1986), Chiuderi-Drago and Melozzi (1984); Willson and Lang (1986)].

Figure 1 provides the radiation spectra for the three types of sources usually detected at short centimeter wavelengths [see Akmedov et al. (1986) for greater details]. The most common type of source is the sunspot-associated component (A and C) that is attributed to thermal gyroresonance radiation in the legs of coronal loops that are connected to the underlying sunspots. Source D is a filament-associated component located above a magnetic neutral line in regions of apparently-weak magnetic field. Yet, this source has a steep radiation spectrum and high brightness temperature of $T_B > 7 \times 10^6$ K. It may be attributed to non-thermal radiation or to thermal gyroradiation in current-amplified magnetic fields. Then there is the filament-associated source B that has the flat spectrum of optically-thin thermal bremsstrahlung. Electron densities $N_e \approx 10^9$ to 10^{10} cm^{-3} are consistent with this interpretation, suggesting that in this case we are detecting the same thermal plasma that is observed at X-ray wavelengths from coronal loops. But this plasma is more commonly detected at the longer radio wavelength of 20 centimeters.

Individual cyclotron lines from AR 4398 are shown in Figure 3 together with the flat spectrum of the nearby active region AR 4399. The flat spectrum of AR 4399 is attributed to thermal bremsstrahlung, whereas the spectrum of AR 4398 can be explained by cyclotron line emission from a narrow layer of width $\Delta L \approx 10^8$ cm, electron density $N_e \approx 10^9$ cm^{-3} and a relatively high electron temperature $T_e \approx 4 \times 10^6$ K (solid line). Here the harmonic number n = 4 and the magnetic field strength H = 145 G. A key aspect of this discovery is the extraordinary precision in measuring the magnetic field strength; a change of only ΔH = 20 G shifts the central frequency of the line by 170 MHz.

COMPARISON OF THE 20 CM AND X-RAY EMISSION

As previously mentioned, comparisons between the X-ray and short microwave (3 to 6 cm) radiation from solar active regions provided evidence for a new source of opacity at microwave wavelengths above sunspots. It has been attributed to gyroresonance effects in the legs of coronal loops connecting with underlying sunspots. Recent comparisons of the 6 cm radiation from the apex of coronal loops indicates that its brightness temperature is less than the electron temperature measured at X-ray wavelengths; this has been explained by a cool ($\approx 10^5$ K) external plasma [Holman (1986 - this proceedings); Webb, Holman, Davis and Kundu (1986)].

However, there have been no published comparisons of X-ray data with the 20 cm emission of the coronal plasma. In some instances, there is radiation at 20 centimeters wavelength near sunspots where no X-ray radiation is detected. The radio emission may be attributed to gyroresonant radiation of a low density plasma in magnetic fields of strength H = 145 to 290 G (harmonic n = 4 to 2), [see Lang, Willson, Strong and Smith (1986a) for greater details].

In other cases, the 20 centimeter radiation appears at the apex of coronal loops, but with a slightly lower brightness temperature, $T_B \approx 1.4$ to 1.7×10^6 K, than the electron temperature, $T_e \approx 3.0 \times 10^6$ K, inferred from the X-ray data. This may be explained by a low temperature plasma with $T_e \approx 10^5$ K that lowers the effective brightness temperature of the radio bremsstrahlung while not affecting the X-ray data that only detects the 10^6 K plasma [see Holman (1986 - this proceedings); Lang (1986 - this proceedings); and Lang, Willson, Strong and Smith (1986a) for greater details]. Because the line of sight through the low temperature plasma is greatest along the legs of coronal loops, it can reduce the size of the radio source below that of the X-ray emission. That is, the low temperature plasma can, under the right circumstances, confine the detectable radio radiation to the apex of coronal loops.

As illustrated in Figure 4, there are other instances in which the 20-cm radiation and the soft X-ray emission have the same angular extent. In this case, the maximum brightness temperature of the radio emission has the same value as the electron temperature, $T_e = 3 \times 10^6$ K, inferred from the X-ray data. At first sight it would seem that the 20-cm emission is the thermal bremsstrahlung of the X-ray emitting plasma (electron density $N_e = 2 \times 10^{10}$ cm^{-3}), but in this instance we have also detected a cyclotron line. Preliminary modeling indicates a thin layer of $T_e \approx 4 \times 10^6$ K with a magnetic field strength of H = 145 or 187 G (harmonic n = 4 or 3). The thermal electrons that give rise to the X-ray radiation therefore also seem to produce strong gyroresonant radiation at 20 centimeters wavelength.

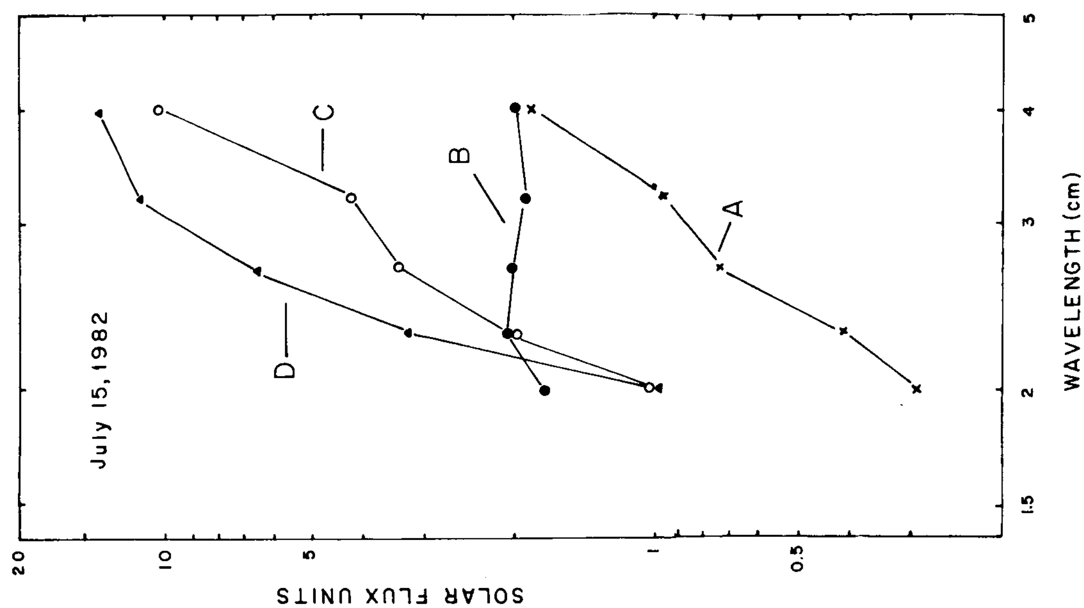

Figure 1. The radiation spectra of four sources associated with an active region. The steep spectrum of the filament-associated source D is attributed to the gryrosynchrotron radiation of mildly relativistic electrons whereas the flat spectrum of the source B is attributed to thermal bremsstrahlung. The sunspot-associated sources A and C are attributed to gyroresonance emission in the legs of coronal loops.

CORONAL LOOPS AT 20 CM WAVELENGTH AND THERMAL CYCLOTRON LINES

Radiation from a post-flare loop at 20 centimeters wavelength was reported by Velusamy and Kundu (1981); but there is a much more extensive literature regarding the quiescent 20-cm radiation of coronal loops [Lang, Willson and Rayrole (1982); Lang, Willson and Gaizauskas (1983); McConnell and Kundu (1983); Shevgaonkar and Kundu (1984); Kundu and Lang (1985); Kundu (1986 - this proceedings); Lang (1986 - this proceedings)]. The radiation at this longer wavelength often comes from the hot, dense plasma trapped within the coronal loop (see Figure 2 for a typical example). The 20-cm coronal loops have peak brightness temperatures of 1×10^6 to 4×10^6 K and extents of about 10^{10} cm. Their radio emission can be attributed to thermal bremsstrahlung or thermal gyroresonant radiation, or both.

Of special interest is the recent detection of thermal cyclotron lines near the apex of coronal loops at wavelengths near 20 centimeters [see Figure 3 and Willson (1985) for greater details]. These cyclotron lines are emitted at harmonics of the gyrofrequency, with a wavelength that depends only on the harmonic number and the magnetic field strength. However, because the magnetic field in the legs of coronal loops decrease uniformly with height, the individual cyclotron lines at short wavelengths will usually merge into a smooth continuum.

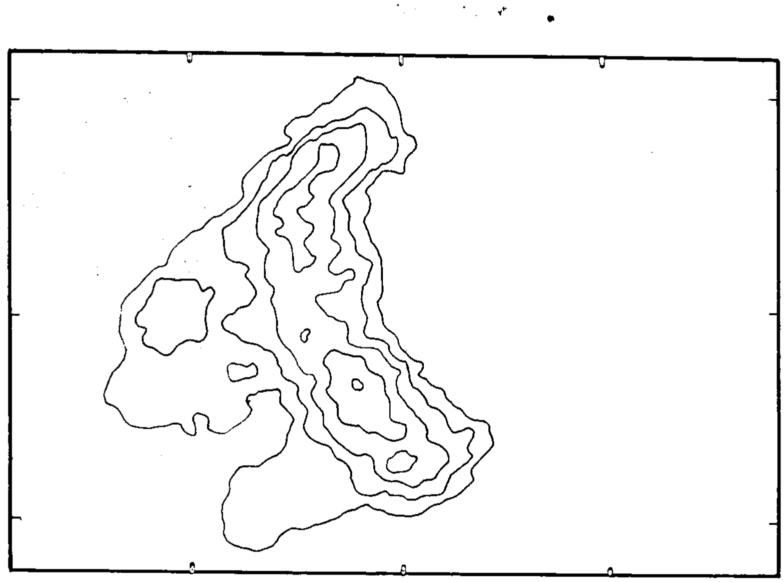

Figure 2. A typical radio wavelength (20 cm) V.L.A. map of the hot, million-degree plasma trapped in a coronal loop. The angular scale between fiducial marks on the axes is 60 arc-seconds.

At 20 centimeters wavelength we can observe the apex of coronal loops where the magnetic field is nearly constant and the spectrum of individual cyclotron lines can be resolved. This will be particularly true if currents or some other process confine the intense emission to a thin, hot layer within the loop apex.

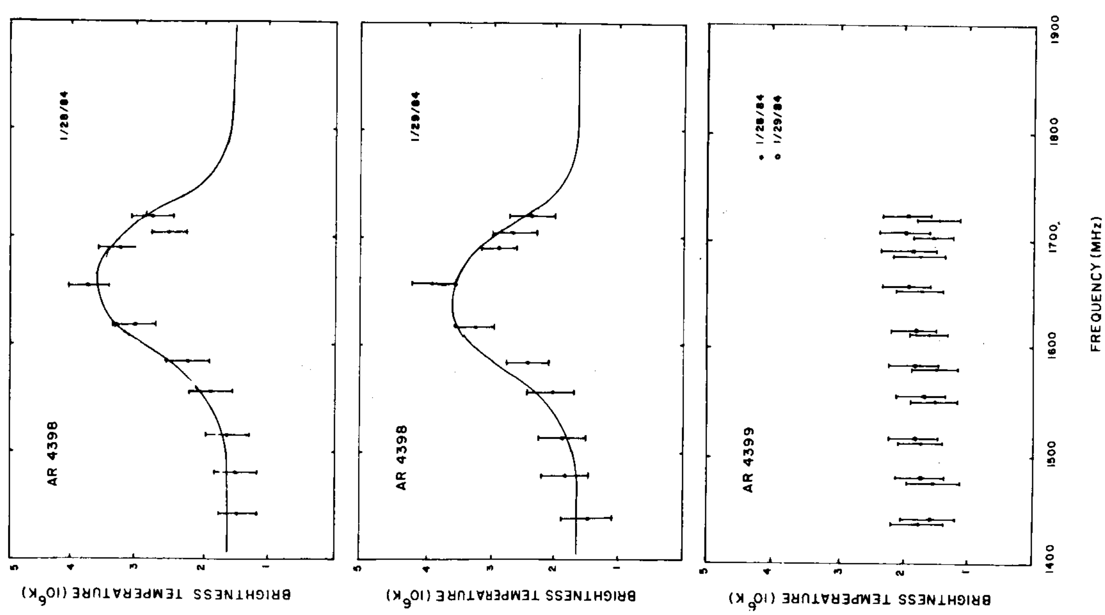

Figure 3. VLA data at ten closely-spaced frequencies near 1446 MHz (20 cm) showing thermal cyclotron line spectra from active region AR 4398 on successive days, together with optically-thick thermal bremsstrahlung spectra from active region AR 4399 on the same days.

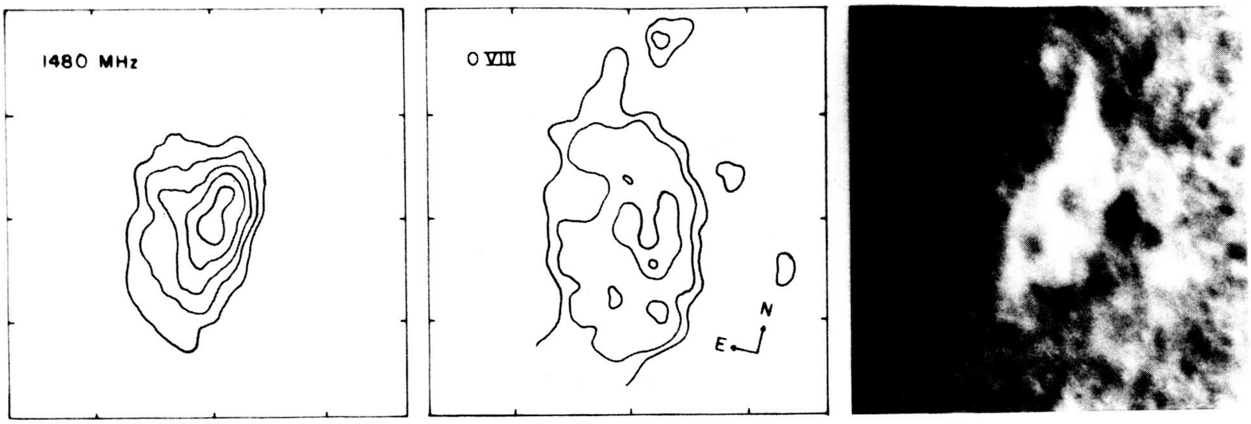

Figure 4. A comparison of the 20 cm emission (V.L.A-left), soft-X-ray (S.M.M.-middle) and Hα (SOON-right) emission of an active region on the same day. The angular spacing between fiducial marks on the axis is 60 arc-seconds.

CORONAE OF NEARBY STARS

Nearby dwarf M stars exhibit slowly-varying, quiescent microwave radiation and microwave bursts that have been detected with the Very Large Array (VLA) and the Arecibo Observatory. Observations with high resolution in frequency and time provide strong evidence for coherent radiation mechanisms in the coronae of these stars [Lang (1986b)]. Such mechanisms provide stringent constraints on the electron density and magnetic field strength in the stellar coronae.

Narrow-band, slowly varying radiation has been detected from the dwarf M star YZ Canis Minoris when using the VLA at wavelengths near 20 centimeters [Lang and Willson (1986b)]. White, Kundu and Jackson (1986) subsequently repeated this experiment, finding narrow-band bursts from the dwarf M stars AD Leonis and UV Ceti. The narrow-band structure cannot be explained by continuum emission processes such as thermal bremsstrahlung, thermal gyroresonant radiation or nonthermal gyrosynchrotron radiation. Although gyroresonant radiation can give rise to narrow-band cyclotron lines, it requires an implausibly large source that is hundreds of times larger than the star. The observations of narrow-band structure can apparently only be explained by coherent mechanisms like electron-cyclotron lines or coherent plasma radiation.

Independent evidence for coherent radiation mechanisms is provided by high-time-resolution observations of the dwarf M star AD Leonis at the Arecibo Observatory [Lang, Bookbinder and Golub (1983), Lang and Willson (1986c)]. As illustrated in Figure 5, quasi-periodic, highly polarized spikes are observed at 20 centimeters wavelength with rise times of less than 5 milliseconds. An upper limit to the linear size of the spike emitting region is $L \leqslant 1.5 \times 10^8$ cm, the distance that light travels in 5 milliseconds. This size is only five hundredths of the estimated radius of AD Leonis. Provided that the emitter is symmetric, it has a brightness temperature greater than 10^{16} K. The high degrees of circular

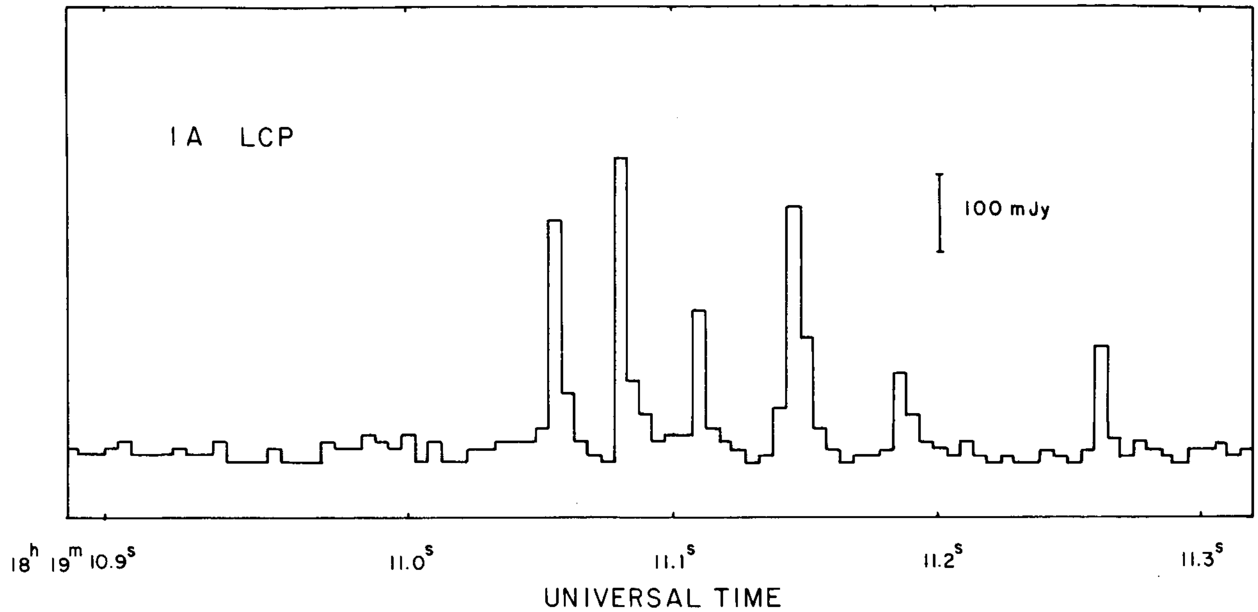

Figure 5. The total power detected at a frequency of 1415 MHz (21.2 cm) while tracking the dwarf M star AD Leonis. The left-hand circularly polarized (LCP) signal has been displayed with a 5 ms integration time. There are five quasi-periodic spikes with a mean periodicity of $T_P = 32 + 5$ ms and a total duration of $\tau_D = 150$ ms. Each of these spikes had a rise time of $\tau_R < 5$ ms, leading to an upper limit to the linear size $L < 1.5 \times 10^8$ cm for the spike emitter. A symmetric source of this size would have a brightness temperature of $T_B > 10^{16}$ K, requiring a coherent radiation mechanism.

polarization (up to 100%) indicate an intimate connection with the star's magnetic field, and the high brightness temperatures suggest a coherent radiation mechanism such as an electron-cyclotron maser or coherent plasma radiation.

The coherent process provides constraints on the electron density, N_e, and the magnetic field strength, H, in the stellar coronae [see Dulk (1985) for the relevant formulae]. If the electron-cyclotron maser emits at the second harmonic of the gyrofrequency, the longitudinal magnetic field strength H = 250 G and constraints on the plasma frequency imply an electron density of $N_e \approx 6 \times 10^9$ cm^{-3}. Coherent plasma radiation at the first or second harmonic of the plasma frequency respectively require $N_e = 2 \times 10^{10}$ cm^{-3} and and $H << 500$ G or $N_e = 6 \times 10^9$ cm^{-3} and $H << 250$ G.

PROMISING DIRECTIONS FOR THE FUTURE

Future VLA observations at 20 centimeters wavelength will continue to provide diagnostic tools for the solar corona. Observations of thermal cyclotron lines offer a promising method of accurately determining the coronal magnetic field strength. Comparisons with soft X-ray spectral lines will help delineate the electron density and temperature, while also specifying the radiation mechanisms. One promising approach that grew out of this conference involves simultaneous observations with the VLA and the Owens Valley Radio Observatory (OVRO). The OVRO will provide spectral information that is not obtainable with the VLA, whereas the high angular resolution of the VLA will remove ambiguities in the OVRO data. Future collaborations between the Tufts University group and the Observatoire de Paris - Nancay Radio Heliograph will provide new perspectives to coherent radiation processes on the Sun. The rapidly growing studies of the microwave radiation from dwarf M and RS CVn stars will continue to provide new insights to physical processes in stellar coronae. The full potential of these studies of the Sun and nearby stars will only be realized by the development of a solar-stellar synthesis radiotelescope. Such an instrument would be dedicated to solar and stellar observations with high angular, temporal and frequency resolution.

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