CORONAL DIAGNOSTICS

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INTRODUCTION

The relatively recent development of satellite-bourne X-ray telescopes and ground-based aperture synthesis radio telescopes has led to an examination of the solar corona with unprecendented resolution in space, time and frequency. The high spatial and spectral resolution of the X-ray instruments aboard Skylab and the Solar Maximum Mission (SMM) satellite have, for instance, showed that coronal loops dominate the structure of the Sun's lower corona [see Vaiana and Rosner (1978) for a review]. Strong magnetic fields hold a hot, dense plasma within the ubiquitous coronal loops.

Observations of soft X-ray spectral lines indicate that the quiescent, or non-flaring, coronal loops have electron temperatures $T_e \sim 2$ to 4×10^6 K and electron densities $N_e \sim 10^9$ to 10^{11} cm $^{-3}$ with total extents $L \sim 10^9$ to 10^{10} cm. Similar temperatures are inferred from radio-wavelength brightness temperatures that are comparable to the local electron temperatures.

The detailed temperature and magnetic structure of the quiescent, or non-flaring, coronal loops has been inferred from radio wavelength synthesis observations. Synthesis maps describe the two-dimensional distribution of source brightness and the two-dimensional structure of the magnetic field [see Kundu and Lang (1985) for a review]. The unique ability to specify the strength and structure of the coronal magnetic fields is an important aspect of the radio wavelength synthesis maps.

Our current understanding of coronal loops is summarized in this chapter. It includes observations from ground-based radio telescopes and from X-ray telescopes lofted above the atmosphere, as well as theoretical interpretations of these observations.

The remaining sections of this introductory overview highlight both the observational and theoretical results that are discussed in greater detail in the following papers. We begin by discussing the three-dimensional structure of coronal loops. Alternative radiation mechanisms are then described within the context of both the radio and X-ray emission. Various methods of determining the strength and structure of the coronal magnetic field are then described. The final sections of this introduction include the coronae of nearby stars and future prospects for radio diagnostics of coronal loops.

THREE DIMENSIONAL STRUCTURE OF CORONAL LOOPS

Observations at different radio wavelengths generally sample different levels within coronal loops, with longer wavelengths referring to higher levels. The heights of the radio structures can be inferred from their angular displacements from underlying photospheric features, and the two-dimensional maps at different radio wavelengths can be combined to specify the three-dimensional structure of coronal loops. The accuracy of these height determinations depends on the geometry of the magnetic field, and the accuracy is greatest near the limb.

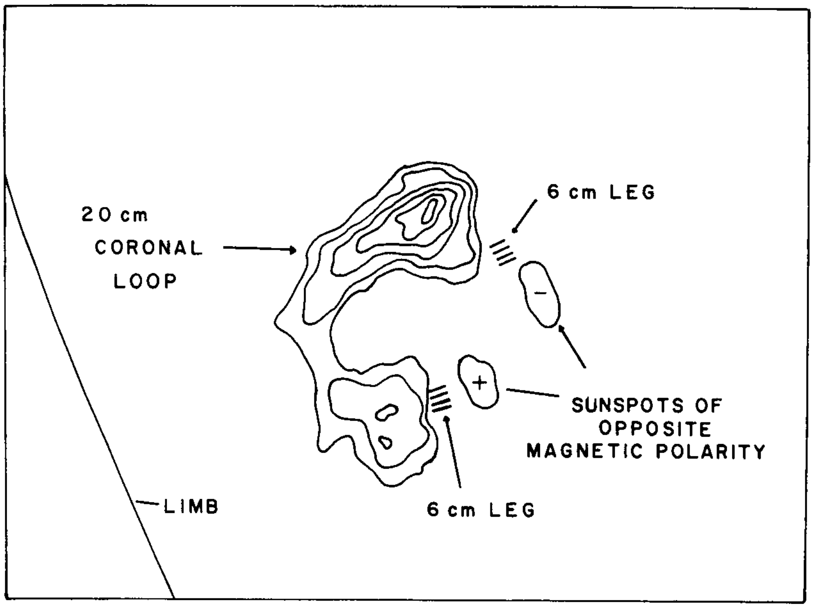

Figure 1. A VLA synthesis map of the total intensity, I, of the 20 cm emission from a coronal loop. The contours mark levels of equal brightness temperature corresponding to 0.2, 0.4, ...1.0 times the maximum brightness temperature of $T_B = 2 \times 10^6$ K. A schematic portrayal of the 6 cm emission, which comes from the legs of the magnetic loops, has been added together with the underlying sunspots that are detected at optical wavelengths.

Multiple-wavelength synthesis observations with the Very Large Array (VLA) have been carried out at wavelengths $\lambda = 20$, 6 and 2 cm (see Figure 1). The radiation at 20 cm can originate at both the apex and legs of coronal loops, and sometimes delineates the hot, dense plasma detected at X-ray wavelengths. The 20-cm coronal loops have brightness temperatures $T_B = 1 \times 10^6$ to 4×10^6 K and extents of $L = 10^9$ to 10^{10} cm. Magnetic field strengths of $H \sim 145$ G have been inferred from cyclotron lines at the apex of the 20-cm loops. Bright, highly polarized 6-cm cores often mark the legs of dipolar loops with $T_B = 2 \times 10^6$ to 5×10^6 K and heights $h \approx 10^9$ cm above the underlying sunspots. Values of H of $\sim$ 600 to 900 G are inferred from the fact that these cores emit gyroradiation at the second or third harmonic of the gyrofrequency. The 2-cm emission has brightness temperatures of $T_B \approx 10^5$ K and often overlies sunspots at heights $h \lessapprox 5 \times 10^8$ cm where H is $\gtrsim 10^3$ G.

The 20-cm coronal loops have been discussed by Velusamy and Kundu (1981), Lang, Willson and Rayrole (1982), Dulk and Gary (1983), and McConnell and Kundu (1984). Multiple-wavelength VLA observations at 2, 6 and 20 cm have been presented by Lang, Willson and Gaizauskas (1983), Shevgaonkar and Kundu(1984), Kundu and Lang (1985) and Kundu (1986 - this proceedings). Most recently, Gary and Hurford (1986) have used microwave spectroscopy during a solar eclipse to delineate the physical conditions at a variety of levels within the legs and apex of a coronal loop (see Figure 2.

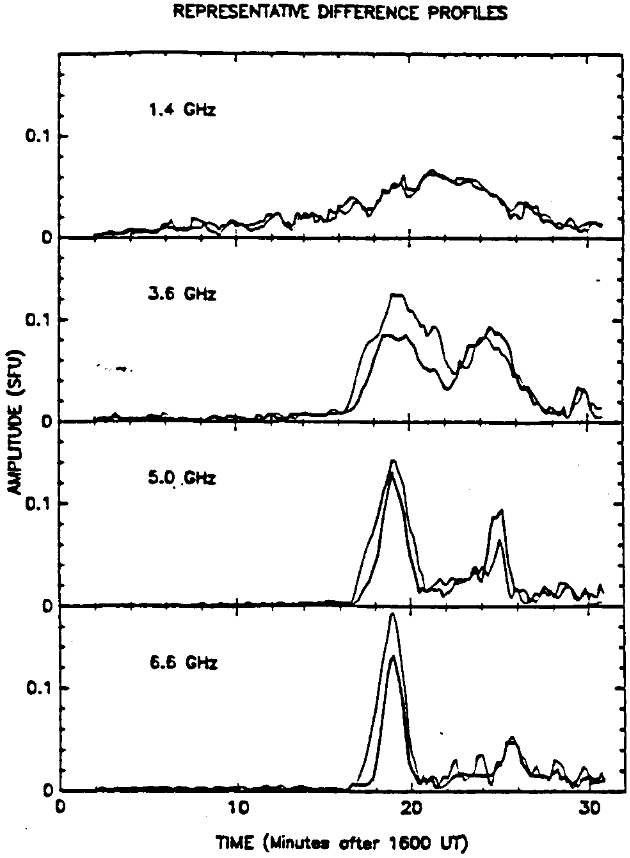

Figure 2. Differenced OVRO time profiles at four representative frequencies. Right hand circular (RH) polarization is shown by the heavy lines, and left hand (LH) polarization by the light lines. Below 3 GHz, the active region appears as a single board source. At higher frequencies, the region bifurcates into two main sources, becoming more localized to the sunspots as the observing frequency increases. The sense of polarization in the two spot sources is consistent with gyroresonance emission.

RADIATION MECHANISMS OF CORONAL LOOPS

The quiescent, or non-flaring, radiation of coronal loops is usually thermal in nature. The soft X-ray radiation is, for example, attributed to the thermal bremsstrahlung of hot million-degree electrons. However, at centimeter wavelengths there are two different thermal mechanisms: the bremsstrahlung of thermal electrons accelerated in the electric field of ions and the gyroresonant radiation of thermal electrons accelerated by magnetic fields can contribute to the emission. While the thermal bremsstrahlung emission is sensitive to the electron temperature and emission measure, gyroresonant emission is sensitive to the local magnetic field and electron temperature. It is this gyroresonant radiation which provides a sensitive measure of coronal magnetic field strength. Thus, it is important to distinguish which of these mechanisms is responsible for the emission from any given source at these wavelengths.

Strong evidence for thermal gyroradiation at coronal levels above sunspots has been provided by comparing the soft X-ray and centimeter-wavelength radiation of active regions [Kundu, Schmahl and Gerassimenko (1980); Pallavicini, Sakurai and Vaiana (1981); Schmahl et al. (1982)]. Although there is intense X-ray emission from the apex of coronal loops, the X-ray radiation often falls to undetectable levels in the legs of coronal loops above sunspots. Yet, intense radio radiation has sometimes been observed from both the apex and the legs of coronal loops. At other times radio emission has been detected from just the apex or just the legs of the loops, depending on the wavelength and observing conditions.

The near equality of the radio brightness and electron temperatures indicates that the radio emission from coronal loops is usually thermal. But the low electron densities inferred from the X-ray data above sunspots indicate that thermal bremsstrahlung is too weak to account for the intense radio radiation. The extra source of opacity has been attributed to gyroresonance absorption at the second or third harmonic of the gyrofrequency.

Figure 3. A Westerbork Synthesis Radio Telescope synthesis map of circular polarization at λ = 6 cm overlaid on an Hα photograph obtained from the observatory at Athens. The contours are in steps of 1.5 x 10^5 K. The circularly polarized horseshoe structure that rings the sunspot umbra is due to gyroresonant emission in the curved magnetic fields of the sunspot penumbra.

Thermal gyroradiation at coronal levels above sunspots has been additionally confirmed by the detection of circularly polarized ring-shaped or horseshoe structures at 6 cm wavelength [Alissandrakis and Kundu (1982); Lang and Willson (1982)]. The highly-polarized (up to 100 percent) structures were precicted by the theory of gyroradiation in the curved magnetic fields above sunspot penumbrae [Gel'freikh and Lubyshev (1979)]. There is no detectable circular polarization above the central sunspot umbrae where the magnetic fields project radially upward into the hot coronal regions (see Figure 3). Depressions in the radio brightness temperature above sunspot umbrae have been attributed to cool material in these regions [Strong, Allisandrakis and Kundu(1984)].

At the longer, 20 cm, wavelength, emission is detected sometimes from both the apex and the legs of coronal loops (Lang, Willson, Strong, and Smith, 1986, and see Figure 4), and sometimes from just the apex (Webb et al., 1986). In the latter case, the electron densities and temperatures inferred from the X-ray spectral lines indicate that the plasma is optically thick at 20 cm, and hence that the observed brightness temperature should be equal to the electron temperature. However, the observed brightness temperature is a factor of 2 - 3 lower than the local electron temperature. Brosius and Holman (1986--this proceedings) and Holman (1986--this proceedings) explain this low brightness temperature in terms of a relatively cool, $<10^5$ K external plasma around the hot 2.5×10^6 K loops. Such material absorbs emissions primarily from the loop footpoints, where the optical depth along the line of sight is greatest. The loops and the external plasma are separated by a thin transition zone. The emission measure distributions for such models have been calculated, and have been found not only to agree well with recent observational emission measure curves for solar active region loops, but also to rise on both the cool and the hot side of the emission measure minimum. This is the first time that a theoretical emission measure curve for a single active region loop has been found to do this (cf. Antiochos and Noci, 1986).

Figure 4. A comparison of the soft X-ray (S.M.M.-left), H (SOON-middle) and 20 cm (V.L.A.-right) emission of an active region on the same day. The most intense soft X-ray emission is well correlated with intense 20 cm and H emission; but the 20 cm emission also extends across the areas near the sunspots where it is also intense. The angular spacing between fiducial marks on the axes is 60 arc-seconds.

Alternative radiation mechanisms may be required for intense radio emission from regions overlying weak photospheric magnetic fields. Observations of these regions have been reported by Akmedov et al. (1986), Lang (1986a-this prodeedings), Lang and Willson (1986a-this proceedings), Webb, Davis, Kundu and Velusamy (1983), and Willson and Lang(1986). A possible explanation, first studied in detail by Chiuderi, Drago and Melozzi (1984), is the nonthermal synchrotron emission of mildly relativistic electrons; but some currently-unspecified mechanism must be accelerating the electrons. An equally plausible explanation is that currents amplify the magnetic field in the low solar corona to strengths that are a factor of ten larger than those inferred from magnetograms of the underlying photosphere. The observed radio emission might then be attributed to the gyroradiation of thermal electrons at the second and third harmonic of the gyrofrequency.

SPECIFYING THE CORONAL MAGNETIC FIELD

Measurements of the spectrum, polarization and angular size of active region sources at centimeter wavelengths have been pioneered by Soviet astronomers using the RATAN 600 [Radio Astronomy Telescope of the Academy of Sciences (Nauk)-see Akmedov et al. (1986)], and further developed and extended using the frequency-agile interferometer at the OVRO [Owens Valley Radio Observatory-see Hurford and Gary (1986) this proceedings)]. By measuring both the angular size and the flux density at a variety of wavelengths, one can uniquely determine the brightness temperature spectrum of the sources. Circular polarization data can additionally be used to specify the magnetic field strength. Hurford and Gary (1986-this proceedings) have used this technique of microwave spectroscopy to measure the field distribution in the lower corona above sunspots.

In fact, both the strength and structure of the coronal magnetic field can be specified along the legs of coronal loops where gyroradiation dominates. The observations indicate that the magnetic fields systematically diverge and decrease in strength at higher heights (longer wavelengths) above single sunspots [see Hurford and Gary (1986) - this proceedings].

The magnetic field strength can also be inferred from individual cyclotron lines when gyroradiation dominates the emission. The observations at a single wavelength refer to a predetermined height where the radiation frequency is at one of the low harmonics of the gyrofrequency. Multiple-frequency observations provide information at a fixed height, regardless of field strength.

Holman and Kundu (1985) and Holman (1986 - proceedings) have pointed out that the emitting layers might be spatially resolved when a thin loop is observed. The magnetic field strength within each layer can then be inferred from the observing wavelength and the relevant harmonic. However, the cyclotron lines may overlap when the loop is thick or when a thin loop is observed along its legs.

The spectrum of an individual cyclotron line may also be obtained when observing at several wavelengths. For example, the spectra of individual cyclotron lines have been observed at wavelengths near 20 cm when the apex of a coronal loop is resolved [Willson (1985), Lang (1986a-this proceedings), Lang, Willson, Strong and Smith (1986)]. This is because the magnetic field strength is relatively constant near the loop apex; the cyclotron lines would merge into a continuum along the loop legs where the magnetic field strength decreases uniformly with height. Neutral current sheets might also play a role, leading to intense radio emission from a thin layer near the loop apex. Both a uniform field and a steep temperature gradient in the uniform region are probably required to detect the cyclotron lines. In any event observations of individual cyclotron lines indicate magnetic field strengths of $H = 145 \pm 5$ G at the apex of some coronal loops.

Solar bursts might also be used to infer the strength and configuration of coronal magnetic fields. Roberts, Edwin and Benz (1984) and Roberts (1984, 1986 - proceedings) have shown that bursts can impulsively generate magneto-acoustic oscillations in a coronal loop. These oscillations may be observed as quasi-periodic radio variations whose onset, duration and periodicity can be used to infer the height, size and magnetic field strength of the emitting region.

THE CORONAE OF NEARBY STARS

Nearby main-sequence stars of late spectral type exhibit quiescent, or non-flaring, X-ray emission whose absolute luminosity may be as much as 100 times that of the Sun [Vaiana et al. (1981)]. This suggests that these stars have hot stellar coronae with large-scale coronal loops and strong magnetic fields. The solar analogy suggests that these coronae might also be detected at radio wavelengths.

Nearby dwarf M flare stars do, in fact, exhibit slowly varying radio emission at 6 and 20 cm wavelength that is analogous to that of solar active regions. However, the X-ray observations rule out detectable thermal bremsstrahlung at radio wavelengths; the temperatures and emission measures inferred from the X-ray data indicate that the radio bremsstrahlung would be at least two orders of magnitude below detection thresholds. Moreover, thermal gyroradiation is an unlikely source of the intense 20 cm radiation from some of these stars; implausibly large coronal loops would have to be up to 10 times larger than the star with magnetic field strengths larger than 100 G at these remote distances. The most likely source of this slowly varying radiation in M-dwarf stars is gyrosynchrotron radiation from nonthermal electrons (Holman, 1986; Lang and Willson, 1986b).

In other words, the fact that we detect radio emission from these stars means that something unusual is happening on them. As an example, radio bursts from the dwarf M, stars have been attributed to coherent emission mechanisms like electron-cyclotron masers or coherent plasma radiation [Melrose and Dulk (1982); Dulk (1985)].

Quasi-periodic and individual spikes have been detected from the dwarf M star AD Leonis at 20 cm wavelength [Lang et al. (1983), Lang and Willson (1986a), Lang (1986a)-this proceedings)]. These spikes are up to 100% circularly polarized with rise times less than 5 milliseconds. The rapid rise time indicates that the emitter's size is less than 0.005 of the star's radius, and that a symmetric emitter has a brightness temperature in excess of 10^{16} K. Such a high brightness temperature requires a coherent radiation mechanism. Similar high brightness temperature spikes have been observed during solar flares. Unlike solar flares, however, the underlying nonspiky emission from the AD Leonis flare is probably also coherent [Holman, Bookbinder and Golub (1985)].

Coherent emission is also suggested by the narrow-band, slowly varying, 20-cm emission from the dwarf M star YZ Canis Minoris [Lang and Willson (1986)], as well as narrow-band 20 cm flares from the red dwarf stars AD Leo and UV Ceti [White, Kundu and Jackson (1986)]. The narrow-band structure cannot be explained by continuum emission processes such as thermal bremsstrahlung, thermal gyroradiation, or nonthermal gyrosynchrotron radiation. Coherent radiation processes seem to be required.

If the radiation is emitted by an electron-cyclotron maser at the second harmonic of the gyrofrequency, then the magnetic field strength is $H = 250$ 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 $H << 500$ G or $N_e = 6 \times 10^9$ cm^{-3} and $H << 250$ G. Thus, the coherent burst mechanisms suggest that the coronae of dwarf M stars have physical parameters similar to those of solar active regions.

FUTURE PROSPECTS FOR CORONAL DIAGNOSTICS

Probable observations of coherent radiation processes on nearby stars are stimulating further searches for coherent signatures in the Sun's radio radiation. In fact, narrow-band structure has been observed in a solar burst [Lang and Willson (1984): Lang (1986b)], and rapid spikes during some solar bursts have been interpreted in terms of electron-cyclotron masers [Holman, Eichler and Kundu (1980); Holman (1983)]. Future observations with high resolution in time and frequency at the VLA, OVRO and Nancay will help determine the role that coherent radiation processes play in solar active regions.

The next decade will also include detailed comparisons of radio and X-ray observations with model coronal loops that include both thermal bremsstrahlung and thermal gyroradiation. Coronal magnetic fields may be directly inferred from observations and models in which the expected radio emission is computed as a function of wavelength, polarization and viewing angle. A comparison of the observed radiation with theoretical expectations will determine magnetic field strengths, electron densities and electron temperatures.

The evolution of coronal loops has strong future potential. Of special interest are the preheating and magnetic changes that trigger solar bursts [see Kundu and Lang (1985) for a review]. Emerging coronal loops and the magnetic interaction of existing coronal loops will be particularly interesting topics.

Future studies of the evolution of the three-dimensional magnetic and plasma structure of coronal loops will lead to valuable new insights to the nature of solar active regions and eruptions on the Sun and nearby stars. Such insights can only be fully 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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