JOINT RADIO AND SOFT X-RAY IMAGING OF AN ‘ANEMONE’
ACTIVE REGION

A. VOURLIDAS* and T. S. BASTIAN
National Radio Astronomy Observatory, P.O. Box ‘O’, Socorro, NM 87801, U.S.A.

N. NITTA
Lockheed Palo Alto Research Laboratory, Palo Alto, CA 95304, U.S.A.

and

M. J. ASCHWANDEN
Department of Astronomy, University of Maryland, College Park, MD 20742, U.S.A.

(Received 5 May, 1995; in revised form 10 July, 1995)

Abstract. The Very Large Array and the Soft X-ray Telescope (SXT) aboard the Yohkoh satellite jointly observed the rapid growth and decay of a so-called ‘anemone’ active region on 3–6 April, 1992 (AR 7124). The VLA obtained maps of the AR 7124 at 1.5, 4.7, and 8.4 GHz. In general, discrete coronal loop systems are rarely resolved at 1.5 GHz wavelengths because of limited brightness contrast due to optical depth effects and wave scattering. Due to its unusual anemone-like morphology, however, several discrete loops or loop systems are resolved by both the VLA at 1.5 GHz and the SXT in AR 7124.

Using extrapolations of the photospheric field and the radio observations at 4.7 and 8.4 GHz, we find that the microwave emission is the result of gyroresonance emission from a hot, rarefied plasma, at the second and/or third harmonic. The decimetric source is complex – 1.5 GHz emission from the leading part of AR 7124 is due to free-free emission, while that in the trailing part of the active region is dominated by gyroresonance emission. We also examine an interesting case of a discrete radio loop with no soft X-ray (SRX) emission adjacent to a hot SXR loop. This observation clearly shows the multithermal nature of the solar corona.

1. Introduction

The highly structured character of the solar corona has been established since the first flights of solar X-ray telescopes in the early 1970’s (Vaiana, Krieger, and Timothy, 1973). Those early images showed that the X-ray emitting plasma is confined to arcades of loops that exhibit a great variety of shapes and sizes and are associated with active regions, bright points, helmet streamers, polar crowns, etc. Here, we investigate active region NOAA 7124 which has a peculiar SXR morphology. In particular, several discrete loops (or loop systems) are visible emanating from the region and connecting to the surrounding area, giving it the appearance of a ‘sea anemone’ (Shibata, Yokoyama, and Shimojo, 1994).

Such structures have been previously found in the Skylab database. They were first reported in EUV observations as ‘fountains’ (Tousey et al., 1973). Their structure has been compared to potential field extrapolations and was found to

* Physics Department, New Mexico Institute of Mining and Technology, Socorro, NM 87801, U.S.A.


© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System
agree in some cases (Poletto et al., 1975) and to disagree in others (Krieger, de Feiter, and Vaiana, 1976). Active regions similar in many respects to our target were reported by McIntosh et al. (1976). Anemone regions are usually observed to emerge in magnetically unipolar areas associated with coronal holes. They reach a relatively small size, have a simple magnetic configuration and can last for at least a few days. Sometimes, they can exhibit violent behaviour such as SXR jets (Shibata et al., 1994). Here, we report on the first joint radio and SXR observations of an anemone active region. The observations are described in Section 2. The VLA and SXT data are compared and analysed in Section 3. Finally, we discuss the results in Section 4.

2. Observations of AR 7124

On 2 April, 1992, AR 7124 emerged at N13 W13 in a large coronal hole (Solar-Geophysical Data, 1992 (SGD)). By the next day, the region had grown 10-fold in size and exhibited a magnificent anemone-type morphology, but by 5 April it rotated close to the limb and most of the loop structure was no longer visible. However, AR 7124 continued growing until it crossed the limb, as measurements of its corrected area showed (SGD). Because of its sudden appearance, we targeted AR 7124 only on 4 April and obtained simultaneous multiband radio and high resolution SXR data. Therefore, the analysis is primarily limited to 4 April. We also compare our radio and SXR data with high-resolution (1.15") KPNO magnetograms taken at 15:10 UT. The magnetic data are used to establish boundary conditions for potential field extrapolations using the well-known Sakurai code (Sakurai, 1982). We have also calculated magnetic field maps at various heights above the photosphere. Such extrapolations serve as a qualitative tool for the interpretation of coronal radio emission.

2.1. Soft X-ray Observations

The SXR observations were obtained by the SXT instrument on board the Yohkoh satellite. The SXT is a broad-band grazing incidence telescope which records images on a 1024 × 1024 CCD detector (Tsuneta et al., 1991). On 3 and 4 April, the telescope obtained both half-resolution (4.91") full-disk images every few hours in two filters (Al 0.1 μm and Al/Mg/Mn) and full-resolution (2.46") partial frame images (PFI) focused on AR 7124 during 19:10—20:10 UT in Al 12 μm and Al 0.1 μm. The full disk images are taken in pairs of short (78 ms) and long (2668 ms) exposures. In this way, the ‘pixel bleed’ in the long exposure images can be corrected by substituting the affected pixels with those from the short exposure images with the appropriate corrections for the different exposure times. The PFI images in each filter were summed and the emission measure and temperature were obtained by taking their ratio (cf., Vaiana, Krieger, and Timothy, 1973). Figure 1
Fig. 1. The 'anemone' active region AR 7124 on 3 (left panel) and 4 (right panel) April, 1992 in soft X-rays. Both images are desaturated but the 4 April map is a composite of 31 $\Delta$12 frames. The contours are 1.5 GHz Stokes I emission. The levels are: 1, 2, 2.5, 4, 8, 10, 12, $15 \times 10^5$ K for 3 April and 0.851 1.7, 2.5, 3.5, 6.8, 10, 14, 15, $17 \times 10^5$ K for 4 April. The loops labelled $\textbf{L1}$ and $\textbf{L2}$ are discussed in Section 3.2.1.
Fig. 2. X-ray analysis results for 4 April, 1992. *Left panel:* electron temperature. The logarithmic contours are between 6.5–6.7 in steps of 0.05. *Right panel:* column emission measure, cm$^{-5}$. The logarithmic contours are between 27–28 in steps of 0.2.
shows the X-ray frames of AR 7124 on 3 and 4 April when its loop structure was most prominent. Maps of the logarithmic temperature and emission measure are shown in Figure 2 where the Al 0.1 μm pixel values < 1.5 were blanked to reduce the noise. The temperature, $T_e$, and emission measure, $\Phi$, maps have been smoothed with a median filter to make the contours easier to read. We see that the X-ray temperatures in AR 7124 are in the range of 3–7 MK. The column emission measure is $\log \Phi \lesssim 28.25$ cm$^{-5}$.

2.2. Radio observations

Radio observations of AR 7124 were carried out with the C configuration of the VLA in three frequency bands: 1.5, 4.7, and 8.4 GHz (20, 6, and 3.6 cm, respectively). The angular resolution of each frequency was approximately $15''$ at 1.5 GHz, $5''$ at 4.7 GHz, and $3''$ at 3.6 cm. The observations were made, in right (RCP) and left (LCP) circular polarizations, between 17:10–22:40 UT at 1.5 GHz, and between 19:16–20:26 UT at 4.7 and 8.4 GHz. The visibility data were calibrated using the NRAO AIPS software package following standard procedures for the reduction of solar observations, including corrections for small offsets between polarization channels (Vourlidas, 1993). The uncertainty in the absolute brightness calibration is $\approx 10\%$ at 4.7 GHz and is $\lesssim 4\%$ at 1.5 and 8.4 GHz. The data were self-calibrated in both phase and amplitude (Cornwell and Fomalont, 1989), separately for each polarization. The resulting maps are of moderate quality, with a dynamic range of $\sim 40:1$ for the 1.5 GHz maps, $\sim 140:1$ for the 4.7 GHz map, and $\sim 120:1$ for 8.4 GHz. For the present analysis, we formed maps of Stokes $I$ and $V$ (Figure 3 and 4) and calculated the degree of circular polarization, $\rho_c = V/I$. The 1.5 GHz maps were corrected for both primary beam taper and the effects of beam squint (Vourlidas and Bastian, 1994b).

2.3. Overview of the data

The co-registration of the SXR, radio and magnetic data was straightforward since the pointing of the SXT, the VLA, and the KPNO was accurately known. The time of the SXT PFI imaging, corresponding to the midpoint of the high frequency radio observations, was adopted as the reference time. The magnetogram was then ‘rotated’ to the reference time, taking proper account of the differential solar rotation rate as well as of the $P$ and $B_o$ angles. The accuracy of the co-registration is of order $\sim 2''$.

Figure 1 shows the location and the morphology of AR 7124 during the two days we investigate here. It emerged inside, but close to the boundary of, a large coronal hole. The reason for calling AR 7124 an ‘anemone’ or ‘fountain’ is apparent on 3 April. There is a spectacular array of loops emanating from the leading spot group. The same morphology is apparent on 4 April, by which time additional compact loops appear between the leading and following spots. Two of the most striking
Fig. 3. Stokes $I$ (left) and Stokes $V$ (right) maps of AR 7124 at 1.5 GHz on 3 April. The contour levels are: 1, 2, 5, 4, 8, 10, 12, 15, $1.5 \times 10^5$ K for Stokes $I$ and 3, 6, 5, 7, 12, 14, 16, $8 \times 10^4$ for Stokes $V$. 
Fig. 4. Maps of Stokes $I$ (left panel) and Stokes $V$ (right panels) of the observed VLA bands, 8.4 GHz (up), 4.7 GHz (middle), and 1.5 GHz (bottom) on 4 April. The Stokes $I$ contour levels are 5, 10, 15, 20, 40, 60, 80, 90, 99% of the maximum temperature at each band ($T_B^{\text{max}} = 1.6, 2.9, 1.7$ MK for 8.4, 4.7, 1.5 GHz, respectively). The Stokes $V$ contours levels are: at 8.4 GHz: $-1, -0.5, 1, 1.5, 2, 3, 4 \times 10^3$ K; at 4.7 GHz: $-4, -3, -2, -1, 0.5, 1, 2, 3, 4, 5 \times 10^3$ K; at 1.5 GHz: $-0.8, -0.5, 1, 1.3, 1.5, 1.8, 2, 2.3, 3 \times 10^3$ K. The common polarization morphology around the trailing part in all three bands is marked by a dash-dotted ellipse.
loop systems, labeled **L1** and **L2** are discussed in Section 3.2.1. The results from the SXR temperature and emission measure analysis on 4 April are shown in Figure 2, superimposed on the composite SXR map. Figures 3 and 4 show the available radio observations of AR 7124 in Stokes I and V for 3 and 4 April, respectively. In Section 3.1 we analyse the radio emission from the sources labelled **G1** and **G2** in Figure 4 while the sources labelled **G3** and **F1**, are discussed in Section 3.2.2.

In Figure 5, a comparison of the observations is made with the photospheric magnetic structure. It clearly shows the dominance of the positive polarity magnetic field in the area surrounding AR 7124. An inspection of these figures leads to the following remarks: as is generally the case in coronal holes, the area around AR 7124 is largely unipolar with magnetic fields of positive polarity. AR 7124 has a magnetic configuration; i.e., is bipolar. The leading spots have negative magnetic polarity. Therefore, the striking appearance of the region is caused by large-scale loops connecting the negative-polarity leading spots to local regions of positive magnetic polarity. Other than compact loops linking the leading spots to the following spots, there are no large scale loops anchored in the following spots because they possess the same magnetic polarity as the coronal hole in which the bipole is embedded.

The 4.7 and 8.4 GHz source components are bright, compact, and highly circularly polarized (Figure 4). Their positions are well-correlated with those of underlying sunspots (Figure 5). These are the characteristics of thermal gyroresonance emission. The 1.5 GHz emission, on the other hand, strongly resembles that in SXR. The most intense radio emission coincides with the tops of the hottest and densest SXR loops (Figure 1). In addition, the anemone-like morphology of AR 7124 is clearly visible in both SXR and the 1.5 GHz emission. The resemblance between the 1.5 GHz maps and the SXT images is not perfect, however, particularly on 4 April when we find that most of the radio emission eastward of the neutral line has no SXR counterpart. As we show below, this emission is the result of gyroresonance emission in the trailing part of the active region. We now analyze the 4.7 and 8.4 GHz data in detail.

### 3. Comparative Analysis of SXR and Radio Observations

Two sources of opacity predominate in active regions at radio wavelengths: free-free absorption and gyroresonance absorption. The former is ubiquitous, but the latter is only relevant in those places where the magnetic field strength is high.

We used the standard formulas for the opacities of the two mechanisms. The free-free absorption coefficient, $\kappa_{ff}$, in the presence of a magnetic field is taken from Lang (1980). Assuming isothermality, the brightness temperature may be calculated from

$$T_B = T_e (1 - e^{-\tau_{ff}}), \quad (1)$$
Fig. 5. Overlays of radio Stokes $I$ and SXR contours on the KPNO magnetogram on 4 April. The reversed polarity at the westward side of the two main spots is due to projection effects. Radio contours are the same as in Figure 4. The SXR logarithmic contours (in counts) are between 1.5–3 in steps of 0.2. 

Fig. 6. Overlay of extrapolated potential field lines on the SXT composite frame (left) and on the edge-enhanced map (right) on 4 April. The white lines are closed field lines while the dark ones are open (see text).
where $T_e$ is the electron temperature and $\tau_{ff} = \kappa_{ff} L$, with $L$ being the characteristic spatial scale of the emitting volume. The gyroresonance opacity is given in the quasilongitudinal approximation by Zheleznyakov (1970), which we write in a frequency-independent form:

$$\tau_{gr} = 1.86 \times 10^{-8} \frac{s^{2s-1}}{2s+1!} (1.77 \times 10^{-10} T_e)^{s-1} n_e \nabla B^{-1} (1 \pm \cos \theta)^2 \sin^{2s-2} \theta,$$

(2)

where $s = \nu/\nu_B$ is the harmonic of the electron gyrofrequency $\nu_B = eB/2\pi m_e c$, $e$ is the electron charge, $m_e$ its mass, and $n_e$ its density. $B$ is the magnetic field strength, and $\theta$ is the angle between the line of sight and the magnetic field. Here the '+' sign refers to the extraordinary mode ($x$-mode) and the '-' sign refers to the ordinary mode ($o$-mode).

3.1. THE MICROWAVE EMISSION

The radio emission in the microwave bands, 4.7 and 8.4 GHz, is well-correlated with the position of the underlying sunspots where the magnetic field is strong (Figure 5), suggesting that emission in both bands arises from gyroresonance absorption at low harmonics of the local electron gyrofrequency. For the present analysis, we chose two areas of AR 7124, labeled G1 and G2 in the 4.7 GHz Stokes I map in Figure 4. G1 is a compact source visible in both the 4.7 and 8.4 GHz bands, as well as the 1.5 GHz band (see Section 3.2.2), and is associated with the maximum of the photospheric magnetic field (1530 G). On the other hand, the 4.7 GHz emission peaks at G2, which coincides with the footpoints of the SXR loops (Figure 7). The observed brightness temperature, $T_B$, and degree of circular polarization, $\rho_c$, of these two areas are given in Table I. Note that the RCP and LCP polarizations correspond to the $x$- and $o$-mode, respectively. A third region, G3, in the 1.5 GHz map is discussed in Section 3.2.2. All three regions are polarized in the sense of the $x$-mode.

Equation (2) shows that, for a given harmonic, the gyroresonance opacity depends on $\nabla B$, $T_e$, $n_e$, and $\theta$. We dismiss the possibility that the observed emission is the result of emission from resonance layers $s \geq 4$ because implausibly large electron densities would then be required at coronal heights ($n_e > 10^{12}$ cm$^{-3}$). Many calculations have shown that, under average coronal conditions, the second harmonic layer is optically thick in both modes whereas the third harmonic layer is usually optically thick in the $x$-mode (e.g., Zheleznyakov, 1970). We proceed with the assumption that the observed $x$-mode emission originates from the second and/or the third harmonic resonance layers. We also assume that the mean electron temperature increases monotonically with height. We use the potential field extrapolation to constrain $\nabla B$, finding that $\nabla B = 0.1$–0.2 G km$^{-1}$ over the regions of interest up to a height of 5500 km. We adopt a value of 0.15 G km$^{-1}$ for numerical estimates. We constrain the remaining physical parameters in the source as follows: the brightness in each mode at a given frequency $\nu$ is

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System
TABLE I
Physical parameters in AR 7124

<table>
<thead>
<tr>
<th>Source Frequency</th>
<th>G1</th>
<th>G2</th>
<th>G1</th>
<th>G2</th>
<th>G1</th>
<th>F1a</th>
<th>G3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8.4 GHz</td>
<td>4.7 GHz</td>
<td>1.5 GHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_{Bx}$ (10^6 K)</td>
<td>0.69</td>
<td>0.70</td>
<td>1.46</td>
<td>2.73</td>
<td>1.2</td>
<td>1.7</td>
<td>0.8</td>
</tr>
<tr>
<td>$T_{Bo}$ (10^6 K)</td>
<td>0.04</td>
<td>0.04</td>
<td>0.62</td>
<td>2.94</td>
<td>0.7</td>
<td>1.7</td>
<td>0.1</td>
</tr>
<tr>
<td>$\rho_e$ (%)</td>
<td>89</td>
<td>89</td>
<td>40</td>
<td>-3</td>
<td>26</td>
<td>0</td>
<td>70</td>
</tr>
<tr>
<td>$\theta_b$</td>
<td>27°</td>
<td>36°</td>
<td>28°</td>
<td>52°</td>
<td>30°</td>
<td>80°</td>
<td>42°</td>
</tr>
<tr>
<td>$B_{s=3}$</td>
<td>1000</td>
<td>560</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>180</td>
</tr>
</tbody>
</table>

a F1 is most likely due to free-free.

Constrained by magnetic field extrapolation.

\[
T_{Bx,o} = T_3 - (T_3 - T_2)e^{-\tau_{3x,o}},
\]

where $T_2$ and $T_3$ are the electron temperatures at the $s = 2$ and $s = 3$ layers, respectively. Implicit in Equation (3) is the assumption that the $s = 2$ layer is very optically thick, while no such assumption is made about the $s = 3$ layer. Hence, $T_2 < T_{Bx,o} \leq T_3$. Rearranging terms yields

\[
\tau_{3x} = \log \left( \frac{T_{Bx} - T_3}{T_3 - T_2} \right), \quad \tau_{3o} = \log \left( \frac{T_{Bo} - T_3}{T_3 - T_2} \right).
\]

The degree of circular polarization is given by

\[
\rho_e = \frac{T_{Bx} - T_{Bo}}{T_{Bx} + T_{Bo}}.
\]

The angle between the line of sight and the magnetic-field vector is determined from

\[
\frac{\tau_{3x}}{\tau_{3o}} = \left( \frac{1 + \cos \theta}{1 - \cos \theta} \right)^2.
\]

Now the third harmonic layer at 8.4 GHz, where $B = 1000$ G, presumably lies somewhat below the second harmonic layer at 4.7 GHz, where $B = 840$ G. Therefore, with the above assumptions, the temperature of the $s = 2$ layer at 4.7 GHz must be $T_2 \lesssim T_B$ (8.4 GHz; $x$-mode). We also have $T_2 < T_B$ (4.7 GHz; $o$-mode). In the case of source G1 (Table I), $0.69 \times 10^6$ K $\lesssim T_2 \leq 0.62 \times 10^6$ K; that is, take $T_2(G1) \approx 0.65 \times 10^6$ K to within the error quoted in Section 2.2. In the case of G2, $0.70 \times 10^6$ K $\lesssim T_2(G2) \leq 2.80 \times 10^6$ K. In the case of the 8.4 GHz, the second harmonic resonance condition, requiring $B = 1500$ G, is not satisfied along the lines of sight G1 and G2; the 8.4 GHz $o$-mode emission...
Fig. 7. Overlays of 8.4 (left) and 4.7 GHz (right) Stokes I contours on the Sohl edge-enhanced SXR map of 4 April. All of the loops seem to originate from region G2 (see text and Fig.4) and connect to a single leading spot. The contour levels are at 8.4 GHz, 20, 40, 60, 80, 90, 99% of the peak (1.6 x 10^7 K) and at 4.7 GHz, 5, 10, 30, 40, 60, 80, 90, 99% of the peak (2.9 x 10^6 K).
Fig. 8. Simple model of thermal gyroresonance. The model is frequency independent and refers to $s = 3$. Top panel: loci of allowed electron densities for the assumed range of $T_3$, for the sources G1 and G2 at 8.4 GHz (dashed lines) and 4.7 GHz (solid lines). Because $T_2$ for G2 at 4.7 GHz can take any value between 0.7–2.9 × 10^6 K (Table I) the corresponding model parameters are represented by the hatched areas. Middle panel: loci of allowed angles, $\theta$ for the same frequencies and temperatures. Bottom panel: loci of the optical depths for the above sources. The $\tau_{3x}$, $\tau_{3o}$ curves are marked by the symbols $x$ and $o$, respectively.
originates from below the transition region, which accounts for the high degree of circular polarization at 8.4 GHz.

To make further progress we let \( T_3 \) be a free parameter ranging between \( 6 \times 10^6 \) K \( \geq T_3 \geq T_{Bx} \). With \( \theta \) determined from Equation (6), the corresponding electron number density may be calculated from Equation (2). Hence, for the observed brightness temperature in RCP and LCP, \( \tau_{3x} \), \( \tau_{3y} \) and therefore \( \theta \), and \( n_e \) may be deduced for a given value of \( T_2 \) and a plausible range of \( T_3 \). The calculated values of \( \theta \) and \( n_e \) trace out a locus of parameter values allowed by the observations. We have carried out this exercise for the points \( \text{G1} \) and \( \text{G2} \) and summarize the results in Figure 8. Obviously, a unique solution cannot be determined from available observations. However, we find that the emission from both \( \text{G1} \) and \( \text{G2} \) is consistent with gyroresonance emission from sources with electron number densities \( n_e \sim \text{few} \times 10^8 - 10^9 \text{ cm}^{-3} \). While higher electron number densities are not ruled out by the radio observations, they are by the SXT observations. In particular, no SXR emission is detected from \( \text{G1} \) so that \( \log \Phi \ll 27 \text{ cm}^{-5} \). This implies electron number densities \( n_e < \text{few} \times 10^9 \text{ cm}^{-3} \) for any plausible scale lengths \( (L > 10^8 \text{ cm}) \).

For \( \text{G1} \), both the 4.7 and 8.4 GHz \( x \)-mode emission is marginally optically thick \( (\tau_{3x} \sim 1) \) in the third harmonic layer, as is the 8.4 GHz \( x \)-mode emission from \( \text{G2} \) (Figure 8). The \( \phi \)-mode emission is very optically thin in the third harmonic layer at 4.7 and 8.4 GHz \( \text{(G1)} \) and 8.4 GHz \( \text{(G2)} \). On the other hand, the 4.7 GHz emission from \( \text{G2} \) in the third harmonic layer is quite optically thick in both magneto-ionic modes; hence the negligible degree of polarization and the high brightness.

We note in passing that inspection of Figure 4 reveals the existence of \( \phi \)-mode polarized features near the spot centers. The degree of polarization is significant \( (\rho_c \lesssim 20\%) \) and it appears relatively often in microwave observations of well-defined sunspots (Webb et al., 1982; Lee, Hurford, and Gary, 1993; Vourlidas and Bastian, 1995). Such features have been reproduced by Gelfreikh and Lubyshev (1979) but there has been no further mention of them. We are currently investigating the phenomenon in detail and will report our findings in a future paper.

We conclude that the observed 4.7 and 8.4 GHz features \( \text{G1} \) and \( \text{G2} \) can be accounted for satisfactorily by gyroresonance absorption at the second and third harmonic layers. We find the electron temperature of the emitting plasma must increase from \( \approx 6.5 \times 10^5 \text{ K} \) where the magnetic field strength is 840–1000 G, to \( 1.5 \times 10^6 \text{ K} \) where the magnetic field strength is 560 G in \( \text{G1} \). Similarly, the electron temperature increases from \( \approx 7 \times 10^5 \text{ K} \) to \( 2.9 \times 10^6 \text{ K} \) where \( B = 560 \text{ G} \) over the same range of magnetic field strengths in \( \text{G2} \).

In principle, the magnetic field extrapolations can provide estimates of the height where the resonance condition \( \nu = s \nu_B \) \( (s = 3) \) is met. However, we make no use of such height information because we regard those values unreliable since they are low when compared with other observations. For example, Aschwanden et al. (1995a) find heights of 3300–11 000 km for 10–14 GHz gyroresonance sources using stereoscopic techniques. Shibasaki et al. (1983) estimate the height of a
4.7 GHz source to be $\approx 6000$ km. Lee, Gary, and Hurford (1993) find an altitude of 7700 km for a 7.2 GHz source. Two remarks are appropriate, however: (i) a large dispersion in the heights of gyroresonance sources is expected since the distribution of magnetic field strengths in active regions is broad; (ii) heights deduced from a potential field configuration should, in any case, be regarded as lower limits since significant field-aligned currents may be present, thereby increasing the coronal magnetic field strength.

3.2. The decimetric and SXR emission

The 1.5 GHz emission from AR 7124 shares several attributes with past observations of active regions: it is far more extended and diffuse than the microwave emission, the intensity maximum is situated above the photospheric neutral line, and it is coincident with intensity peaks of the SXR loops. However, two distinguishing features of these observations are (i) the clear detection of SXR and radio emission from discrete loops in the leading part of the AR 7124, and (ii) the presence of gyroresonance components in the 1.5 GHz emission from the trailing part of AR 7124. We discuss each of these features in turn.

3.2.1. Free-Free Emission from Discrete Loops

The 1.5 GHz radio emission from active regions has most often been attributed to optically thick free-free emission. The temperature and density are typically such that the active region becomes optically thick to free-free absorption at a greater height than is the case for gyroresonance absorption. There are many examples in the literature which are consistent with this interpretation (e.g., Lang, Wilson, and Rayole, 1982; Dulk and Gary, 1983; Vourlidas and Bastian, 1995). The present case is no exception, at least in the central and western parts of the active region which are closely associated with SXR emission. Consider the area over the magnetic neutral line where both the SXR and decimetric emission have their maximum. Their maxima are roughly coincident and correspond to the location of dense loops linking the leading and following sunspots. The microwave source G2 does not seem to have a counterpart at 1.5 GHz since the 1.5 GHz emission there is associated with the tops of the loops rather than their footpoints (Figures 1 and 4). We label the source associated with the maximum of the decimetric emission F1. F1 has low polarization ($\lesssim 5\%$), coronal brightness temperature, is associated with enhanced SXR emission, and lies over the magnetic neutral line.

First, we examine the possibility that the SXR emitting plasma is also responsible for the 1.5 GHz emission. From Figure 2, $\log T_e \approx 6.7$ and $\log \Phi \approx 28.2$ at this location. Then, from Equation (1) we expect $T_B \approx 6 \times 10^5$ K, less than the observed brightness temperature of $1.7 \times 10^6$ K. Therefore, while the SXR-emitting plasma can account for roughly a third of the observed brightness, the SXR plasma cannot alone explain the radio observations. However, the sensitivity of the SXT filter pairs used here is low for temperatures less than about $2-3 \times 10^6$ K. The
bulk of the 1.5 GHz emission could be the result of material to which the SXT is insensitive.

We account for the observed emission in terms of the multithermal model of the free-free emission described by Vourlidas and Bastian (1995). In brief, the model has two free parameters, the positive slope and the peak of the emission measure curve which is taken at a value of $4 \times 10^6$ K, appropriate for the SXT. The temperature is assumed to drop, on the average, with height towards the value of a million degrees which is taken from our observations at 0.33 GHz that are not presented in this paper. Since the source is unpolarized, the magnetic field is set to zero. In the present case, we are not interested in a detailed modelling of the brightness temperature spectrum but rather in showing that the decimetric radio and SXR observations can be reconciled within the context of an inhomogeneous corona. A good fit with the observed spectrum at the decimetric band can be obtained assuming a slope of 2 and $\log \Phi_{\text{max}} = 28.45$ at $4 \times 10^6$ K. This result is in accordance with past observations that the amount of SXR material is decreasing with increasing temperature above about 3 million degrees (Pye et al., 1978; Hara et al., 1992).

We are fortunate to have resolved several loops in the 1.5 GHz maps on 3–4 April (Figure 1). The two most prominent loop features, on 4 April, are labeled L1 and L2. Both structures are stable over a timescale of several hours as an
of the full-disk SXR observations between 14–22 UT reveals. It appears that **L2** is complex, consisting of two X-ray loops, one connecting at a mid-point while the other reaches a bipolar region where a much smaller arch is also visible. Its radio counterpart peaks over that area and it is unclear if the emission is associated with **L2** or with the smaller loop. We, therefore, investigate **L1** which has sharp boundaries in both the 1.5 GHz and SXR emission (Figure 9). We find that a radio loop and a SXR loop are present. Both loops have similar orientation and size but the radio loop lies inside the X-ray loop, occupying an area where no SXR emission is detected. Furthermore, the radio peak lies at the opposite end of **L1** than the X-ray peak. Since the SXT is more sensitive to hot plasmas \( T_e \approx 4–7 \times 10^6 \) K whereas the 1.5 GHz emission is weighted toward cooler material, we conclude that Figure 9 provides direct evidence for the non-isothermality of the coronal medium above active regions. Indeed, the radio loop emission is optically thin free-free emission with brightness temperatures ranging from \( 2.5–3 \times 10^5 \) K and is very weakly polarized \( (p_e \approx 10\%) \) in the sense of the \( x \)-mode. The X-ray loop, on the other hand, is due to material at a temperature between 3.2–6.3 million degrees with \( \log \Phi = 27.1–27.4 \) cm\(^{-5} \). The 1.5 GHz brightness temperature expected from the free-free emission of the soft-X-ray emitting material is \( 0.4–1.1 \times 10^5 \) K, significantly lower than that observed. The identification of discrete loops of differing electron temperatures lends support to the multithermal models of the coronal medium above active regions (Vourlidas, 1993; Vourlidas and Bastian, 1994a).

Although AR 7124 is an uncommon active region with respect to its morphology, Figure 9 provides a possible explanation for the lack of fine structure in the decimetric emission from active regions in general. Maps at this frequency almost always show an extended canopy of emission covering the area where SXR emission appears to be highly structured in arcades of loops. According to Figure 9, the areas between the X-ray loops are not devoid of plasma, but are filled with cooler material which is optically thick at decimetric wavelengths, thereby reducing the contrast from loop to loop as compared to that observed in SXR. The contrast is further reduced by wave scattering on still smaller spatial scales (Bastian, 1994). Similar conclusions have been reached by Aschwanden et al. (1995b).

Finally, we briefly consider the polarization properties of the western portion of the AR 7124. On the basis of a comparison of the 1.5 GHz Stokes V map in Figure 4 with the photospheric magnetogram (Figure 5), it would appear that part of the radio emission from the leading part of AR 7124 is polarized in the sense of the \( o \)-mode since there is no LCP emission detected from the negative polarity spots. The potential field extrapolations (Figure 6, left panel) show that many loops are anchored in the these spots. To clarify the nature of the loop structures we used a generalized gradient filter (Sobel edge enhancement) (Figures 6 and 7). Bright regions denote places where the slope is large, regardless of its orientation. A point source yields a torus while a linear feature produces parallel ridges. An inspection of Figures 6 and 7 suggests that the strong SXR emission originates from a few
loop bundles which are anchored in region G2 and connect to a single leading spot. Furthermore, the edge enhanced image reveals additional loops that connect the leading spots with the surrounding positively polarized area. Thus, the observed RCP emission over the leading part of AR 7124 is associated only with positive magnetic fields and is polarized in the sense of the $x$-mode. Therefore, the LCP emission from the leading spots is probably obscured by the strong RCP emission of the SXR looptops. This effect is probably due to the large viewing angle ($\approx 45^\circ$) and the peculiar morphology of the region.

3.2.2. Gyroresonance Absorption at 1.5 GHz
The role of gyroresonance opacity in solar active regions at decimetric wavelengths has been somewhat unclear. It is often assumed that gyroresonance absorption plays little or no role in solar active regions at decimetric wavelengths, with thermal free-free absorption being the dominant source of opacity. On the other hand, others find that gyroresonance emission may be relevant at decimetric wavelengths in some cases (e.g., McConnell and Kundu, 1983; Shevgaonkar and Kundu, 1984). A case for which both sources of opacity may play a role is described by White, Kundu, and Gopalswamy (1992) where the more highly polarized emission at the edges of the optically thick bremsstrahlung source was attributed to gyroresonance emission.

The anemone-active region AR 7124 shows clear evidence that gyroresonance absorption is significant in the trailing part of the active region. Referring to the 1.5 GHz map of the Stokes $V$ polarization parameter in Figure 4 it is seen that the eastern-most feature (labelled G3) in the 1.5 GHz brightness distribution is highly polarized in the sense of the $x$-mode ($\rho_x \approx 70\%$) and is associated with a small sunspot. The high degree of circular polarization is incompatible with free-free absorption, for which the degree of circular polarization remains small to moderate. The physical parameters of G3 are shown in Table I. Employing the same analysis described in Section 3.1, with $\nabla B \approx 0.03$ G km$^{-1}$ in this case, we find that the brightness and polarization of source G3 are consistent with optically thick gyroresonance emission at the third harmonic. However, the photospheric magnetic field is so low in source G3 ($B \approx 260$ G) that there is no harmonic that can produce significant brightness at 4.7 or 8.4 GHz.

Of greater interest is an intercomparison of the Stokes $V$ maps at 1.5, 4.7, and 8.4 GHz east of the magnetic neutral line in AR 7124 (Figure 4). As discussed in Section 3.1, the 4.7 and 8.4 GHz sources are due to gyroresonance absorption. Excluding source G3, the 1.5 GHz $V$ map is qualitatively similar to those at 4.7 and 8.4 GHz in the trailing part of the active region to the extent that it displays circularly polarized emission distributed around the following spot group. The fact that the diameter of the trailing source in Stokes $V$ is systematically larger with decreasing frequency is consistent with the expectation that the magnetic field diverges with height. A similar structure also exists in the Stokes $V$ maps taken on
Fig. 10. Schematic model of AR 7124 according to the radio/SXR analysis presented here. Gyroresonance and free-free dominated areas are denoted with the letters 'G' and 'F', respectively. The thicker field lines correspond to the extended loops seen in radio and SXR. Some of the sources used in the analysis are also identified in this figure.

3 April (Figure 3) where the unpolarized 'hole' coincides with the location of the underlying trailing sunspot and again no LCP polarization is detected.

The height of the 1.5 GHz emission can be crudely estimated from the apparent displacement of source G1 with frequency. We find that source G1 at 1.5 GHz is displaced to the south by about 13.6" relative to 8.4 GHz. From this we infer that the 1.5 GHz emission is at least 12 000 km above the photosphere where \( \nabla B \approx 0.03 \text{ G km}^{-1} \). The results of an analysis similar to that of Section 3.1 are shown in Table I.

4. Conclusions

We have analyzed the radio and SXR emission from the unusual active region AR 7124 whose extended X-ray loops give the appearance of a 'sea-anemome'. The 'anemone' active region emerged as a small bipolar AR on 2 April inside a
coronal hole of predominantly positive magnetic polarity. The striking appearance of AR 7124 is a consequence of the fact that closed magnetic loops are only possible between the leading spot group and the surrounding region. An extrapolation of the magnetic field into the corona under the assumption that it was a potential field is consistent with the gross topology of AR 7124 although it differs in detail (Figure 6).

Although Yohkoh detected high temperature plasmas in the range of 3–6 million K, with column emission measures, \( \log \Phi = 27.1–28.3 \text{ cm}^{-5} \), most of the decimetric radio emission comes from cooler material \( (T_e \lesssim 3 \times 10^6 \text{ K}) \) to which the SXT is less sensitive. The similarity of the emission between X-rays and 1.5 GHz suggests that they originate from the same structures but the difference between their temperatures reveals the existence of temperature and/or density inhomogeneities. A clear example of hot and cool loops coexisting in the corona is presented in Figure 9.

The microwave radio emission is due to second and third harmonic gyroresonance absorption. Both thermal free-free and gyroresonance absorption are responsible for the 1.5 GHz source. Free-free absorption predominates in the leading part of the AR 7124 and in the hot, dense, X-ray-bright loops linking the leading spots to the following spots. Due to a lack of closed loops over most of the trailing spot group, the coronal environment is relatively rarefied. Free-free absorption therefore becomes insignificant above the trailing spot group at 1.5 GHz, and gyroresonance absorption predominates. As a summary, Figure 10 is a sketch of the atmosphere above AR 7124, as is suggested by the present analysis.

Acknowledgements

The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation. The solar X-ray images are from the Yohkoh mission of ISAS, Japan. The X-ray telescope was prepared by the Lockheed Palo Alto Research Laboratory, the National Astronomical Observatory of Japan, and the University of Tokyo with the support of NASA and ISAS. The NSO/Kitt Peak data used here are produced cooperatively by NSF/NOAO, NASA/GSFC, and NOAA/SEL.

References

*Solar-Geophysical Data (SGD)*: 1992, No. 574, part I.