SESSION II

ACTIVE REGIONS

MICROWAVE, EUV, AND X-RAY OBSERVATIONS OF ACTIVE REGION LOOPS AND FILAMENTS

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1.0 Introduction

In the early years of centimetric radio astronomy, even before high resolution techniques were available, it was found that the apparent brightness temperature of the full disk is made up of a background level (the so-called quiet sun temperature) added to which is a contribution roughly proportional to the sum of the sunspot areas on the disk (Smerd 1964, Pawsey and Smerd 1953). Eclipse observations in 1946 at a wavelength of 10.7 cm (Covington 1947) and in 1948 at 10 cm (Piddington and Hindman 1949) and at 3.2 cm (Hagen et al. 1948) showed that the average bright area occupied about 4-thousandths of the disk, and had brightness temperatures of about 5 million degrees. Subsequent interferometric observations have extended and amplified these early studies in several ways. Kundu (1965) has reviewed the literature up to the early 1960's.

The so-called slowly varying (or S) component of the microwave sun has been sorted out as to position, height of formation, angular size, directivity, polarization and temporal variation. Interferometer and pencil beam observations have shown halo and core contributions to the S-component at 3.2 cm (Kundu 1959) at 9.1 cm (Swarup 1961), at 8 mm (Salmonovich 1962), with the core closely associated with the centroid of a spot group, and the halo being distributed over the plage region. The spectrum of the core region peaks between 3 and 10 cm, with rapid declines below 2 and above 10 cm. (For references see Kundu 1965, Akhmedov 1976). Hence the core emission are strictly a centimeter wavelength phenomenon.

Until the advent of x-ray and EUV observations of coronal structures, radio observers were forced to rely on eclipse and coronagraph observations in white light and forbidden coronal lines for additional diagnostics of the high temperature microwave sources. While these data provided enough material for theoretical insight into the physics of active regions, there was no way to make direct, simultaneous comparison of coronal structures on the disk as seen at microwave and optical wavelengths.

M.R. Kundu and T.E. Gergely (eds.), Radio Physics of the Sun, 71-85.

It has now become possible to make such comparisons, and we will therefore summarize the EUV and x-ray observations indicating at each point the relevance to microwaves.

2. EUV AND X-RAY OBSERVATIONS

2.1 Structure and Morphology

The primary information about the corona that space telescopes revealed in the 1960's and 1970's was that the corona consists of narrow loops and fine filaments, generally associated with underlying photospheric and chromospheric structures, especially the magnetic field structures. This discrete nature of the corona was shown as early as 1968 (Purcell and Tousey 1969) in slitless spectroheliograms and in x-ray images (e.g. Vaiana et al. 1968). Furthermore, the same structures which appear bright in x-rays appear as well in the white light corona. This was shown by x-ray photographs obtained at the time of a solar eclipse (Kreiger et al. 1971). Features in the white light corona near the limb occur (with the exception of hedgerow prominences) with a one-to-one correspondence with x-ray features. More recently the Skylab x-ray and EUV data have provided a wealth of information on structures in the corona (Vaiana et al. 1973; Tousey et al. 1973; Reeves et al. 1976; Underwood et al. 1976; Vorpahl et al. 1977).

Considerable effort has been devoted by members of the Skylab Active Region Workshop to defining the overall structure of an active region in EUV and x-rays. For example, Webb and Zirin (1979) have compared high quality chromospheric filtergrams and photospheric magnetograms with carefully filtered x-ray photographs. (See Fig. 1) A typical active region studied had a dominant spot of one polarity and following plage of opposite polarity. Neutral lines with aligned stable filaments divide the polarities. The x-ray loops were found in four categories:

1. The majority of loops stretch from the leading spot penumbra to the following plage. No x-ray loops end in the umbra, except in flares. This is an important point to which we will return, since the hottest cores in microwaves often appear over spots.

2. Stable arcades arch over neutral lines and filaments. These arcade loops cross the neutral lines acutely, i.e. almost parallel to the neutral line. Observations of microwave components have been reported in these regions, with appropriate bipolar polarity (Alissandrakis 1977; Kundu et al. 1977).

3. Bright, "persistent" loops connect the main spot penumbra to an area of emerging flux.

4. Emerging flux regions are accompanied by x-ray brightenings, with bright loops "cospatial" with dark Hα fibrils. Evidence for association of microwave sources with such flux emergence has been reported by many authors.

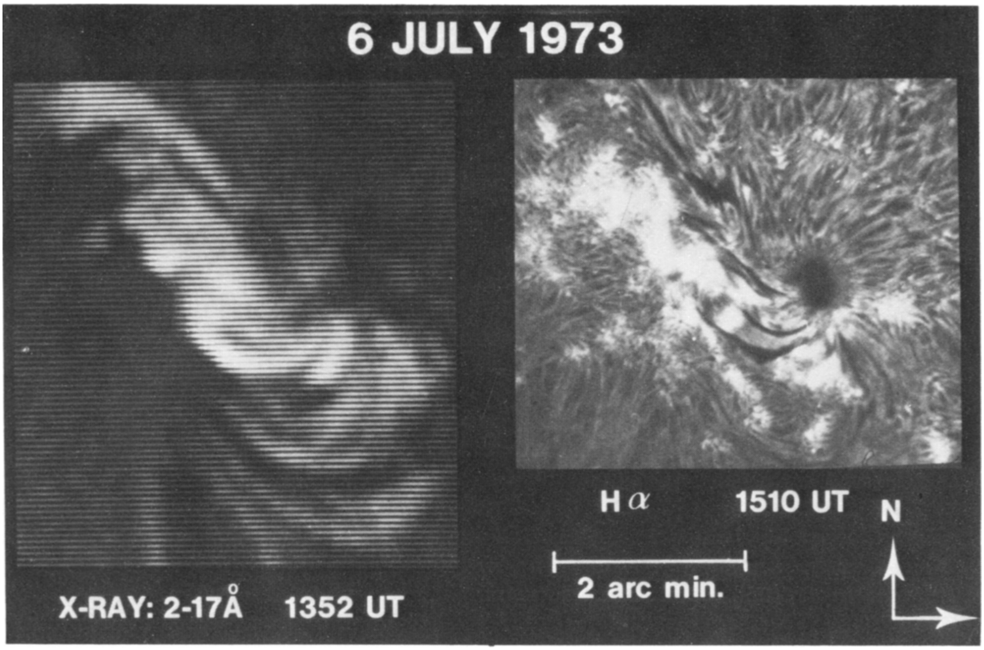

Figure 1. The AS&E x-ray photographs were digitized, Fourier transformed and low spatial frequencies filtered out. The resulting x-ray image, when compared with the B.B.S.O. photograph, shows instances of the four kinds of loops described in § 2.1 (Webb and Zirin 1979).

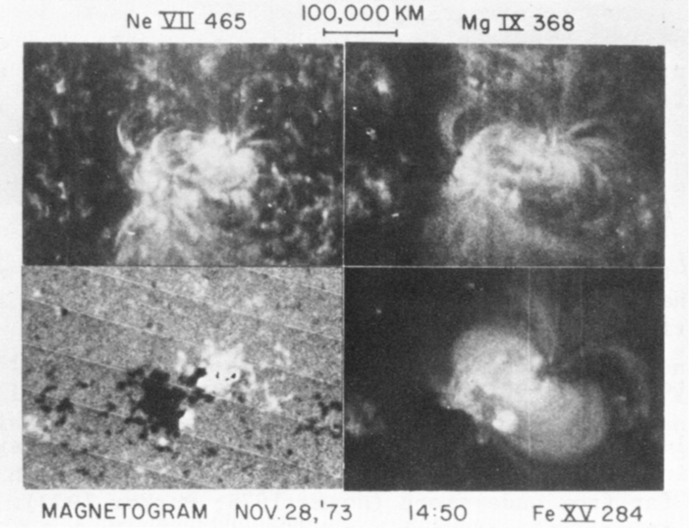

Figure 2. The NRL slitless spectrograph photographed coronal structures with temperatures of 0.5, 1, and 2 x 10^6 K (Ne VII, Mg IX, and Fe XV, respectively). (Sheeley, 1979).

X-ray photography is insensitive to emission from plasma cooler than about 2 million degrees. Therefore, the EUV radiation is essential for delineating the abundant cooler material which also exists in the active region corona. An example (Fig. 2) from the NRL Skylab spectroheliograph (Sheeley 1979) illustrates the distinct differences in the structures of the 1/2, 1 and 2 million degree plasmas.

The 2 x 10^6 K material (seen in Fe XV λ 284) shows very similar morphology to that of x-rays: broad, diffuse loops bridging regions of opposite magnetic polarity. Note the absence of Fe XV emission over the spot. The 1 x 10^6 K material (Mg IX λ 368) appears as finer, more discrete loops.

There is considerable controversy over the spatial relationship between the hotter and cooler material. Foukal (1975, 1976) argues that the loops or plumes footing in sunspots (as shown in the Ne VII or Mg IX images) are surrounded by hotter material (e.g. Fe XV images) and that this may be true for loops in general. Cheng (1979), however, does not find an obvious spatial correlation or physical connection between all the relatively cool and the hotter loops, though this is probably true above sunspots.

2.2 Temporal Variations

Vaiana and Rosner (1978) point out that there are no distinctly defined time scales in the corona, even including flare events. There is complete continuum of time scales in the evolution of loops.

Sheeley (1979, 1974) has examined time-lapse movies made from Skylab/NRL slitless spectrograph photographs. In these sequences, active region loop plasmas are seen to evolve on time scales of about 300 minutes to 6 hours. The cooler loops ($T \sim 5 \times 10^5$ K) last shorter times than the hotter ones ($T \sim 2 \times 10^6$ K). But on the average, the overall geometry of the loops persists even though the plasmas come and go. That is, one infers that usually, the overall magnetic field geometry does not change very much (except possibly in flares) and that material rises or falls within the more or less stable magnetic flux tubes.

Some of the EUV and x-ray variations can, however, be associated with photospheric magnetic field emergence. (See Golub et al. 1977, Little and Krieger 1977).

2.3 Cool Material in Active Regions

The coolest parts of the active region chromosphere have long been known to be in sunspots (Bray and Loughhead 1965), although the reasons for this are far from understood (Noyes 1976; Parker 1977). Abundant evidence for other cool material has been given by Foukal (1978), Schmahl and Orrall (1979). An example of a cool plume over a spot is shown in Fig. 3. That the relative coolness of sunspots persists up into the corona (Foukal 1975) may, however, be puzzling since centimetric cores

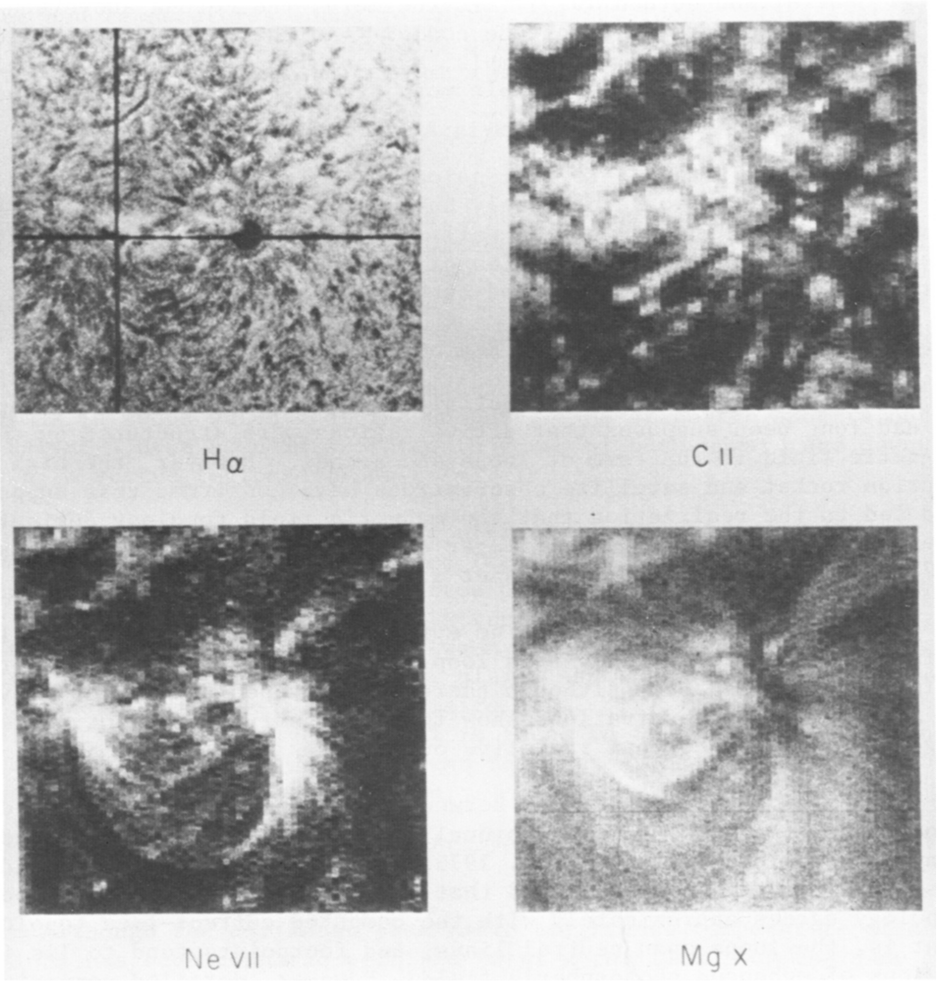

Figure 3. Simultaneous spectroheliograms in transition zone lines (C II λ1335, and Ne VII λ465) and a coronal line (Mg X λ625), show the existence of a relatively cool plume over a sunspot. The absence of emission in Mg X over the spot is typical of large sunspots. (Foukal, 1976).

with $T > 10^6$ K frequently overlie sunspots. The upward temperature gradient in the transition zone is about two orders of magnitude smaller above sunspots than the mean quiet sun (Noyes 1974; Cheng and Kjeldseth Moe 1977; Foukal 1976) and 3 or 4 orders smaller than in active regions (e.g. Gabriel and Jordan 1975). Furthermore, the corona above sunspots is one to two orders of magnitude cooler than the average active region corona. This is shown, for example, by the high plumes over sunspots (Foukal et al. 1974, 1975) visible most strongly in lines formed between 50 and 500 thousand degrees.

A self consistent three-dimensional model of these plumes has yet to be made, but it would certainly have to include radial gradients of temperature from inside-out, as well as from the sunspot up the axis of the plume. A detailed explanation of the EUV, x-ray and microwave observations will ultimately demand such a model.

2.4 Magnetic Fields and Active Region Structure

Even before high coronal spatial resolution EUV and x-ray imaging it had long been supposed that active regions were structured by the magnetic field in the form of loops and arches. However, the high resolution rocket and satellite observations have confirmed this supposition and led to the realization that the magnetic field topology dominates the entire solar atmosphere (Krieger et al. 1973; Noci 1973; Pneuman 1973; Tousey et al. 1973; Vaiana et al. 1973).

In active regions there is no evidence for significant coronal emission from volumes other than loop structures (Vaiana and Rosner 1978; McIntosh et al. 1976). Although there may be "open structures" (Svestka et al. 1977), the observations show that such structures contribute negligibly to the coronal radiative output.

Detailed local comparisons between the magnetic field computed from photospheric magnetograms and coronal loop structures have been made by many authors (see Polleto et al. 1975, and references in Vaiana and Rosner 1978). It has been found that the general EUV or x-ray loop topology agrees approximately with the computed current-free topology; that is, the loops span neutral lines, and footpoints tend to lie in regions of enhanced photospheric field. However, detailed comparison shows discrepancies which imply the existence of coronal currents of sufficiently large magnitude to force the magnetic field structures to depart significantly from a potential configuration.

2.5 Density and Temperatures in Active Regions

The density and temperature structure of active regions as determined by EUV and x-ray images and spectra is inherently model dependent, though in some cases, not strongly so. In a recent review, Dupree (1978) has discussed the methods used for such determinations (see also Withbroe and Noyes 1977; Cook and Nicolas 1979).

It has been found that the gas pressure varies from loop to loop within a single active region, ranging from ∿ 0.1 dyne cm^{-2} in some sunspot loops to ∿ 10 dyne cm^{-2} in hot x-ray emitting loops. Rosner et al. (1978) and Emslie and Machado (1979) have summarized the range of pressures and temperatures found for x-ray and EUV loops. This spatial variability of physical parameters shows the need for simultaneous EUV or x-ray observations to interpret a microwave source in an active region.

2.6 Evidence for Mass Flows in Active Regions

Outside of the obvious flow phenomena associated with flares, surges, eruptive prominences and the like, evidence for mass flows derives from the analysis of line profiles. Withbroe and Noyes (1978) have reviewed the evidence for mass flow in active regions (see also Withbroe 1976, White 1976 and Deubner 1976). In the transition region, nonthermal velocities are observed everywhere in the solar atmosphere. In addition to the nonthermal broadening, the EUV line profiles and analysis of coronal structures indicate systematic downflows of cool ($10^4 < T < 10^6$K) plasmas in loops which foot in sunspots. The stigmatic spectra obtained on Salyut-4 have been interpreted in terms of both upward and downward flows in active regions (Bruns et al. 1977).

Recent rocket flights of the ultraviolet HRTS instrument give abundant evidence with 1/2 arc sec resolution, for flows in active regions (Brueckner et al. 1976, 1977; Bartoe et al. 1979). Not only are systematic downflows in transition zone structures visible above sunspots, but there is a strong correlation between downflows and areas of strong magnetic field everywhere, in spots, plage, and the chromospheric network (cf. also Bruner et al. 1976; Lemaire et al. 1977). The size of the cooler downflow region (or plume) is found to be 4-5" within and above a 20" umbra. Thus only the highest resolution observations would be capable of defining such a region.

3.0 Simultaneous Comparison of Active Regions in Microwave and EUV or X-rays

Although the estimated peak radio brightness temperature of active regions has been compared with the total x-ray flux from the same active regions (e.g. Krieger et al. 1972, Reidy et al. 1968, and Underwood 1967), the observations with highest possible resolution in both microwave and x-ray or EUV have yet to be obtained. Westerbork solar synthesis observations were first made in May and July 1974 (Kundu et al. 1975; Bregnan and Felli 1976), five months after Skylab was shut down. The 6 cm data had 6" resolution and showed highly polarized sources closely associated with sunspots.(see Fig. 4) Synthesis observations with the NRAO three-element interferometer were made during the Skylab period (Kundu et al. 1974a; Kundu 1974). Other interferometric observations during the Skylab period were made by Felli et al. (1977) using the Stanford 5-element array at 2.8 cm. This instrument has a resolution of 16" in the E-W directions and 7' N-S. Graf (1978) has constructed more recent synthesis maps.

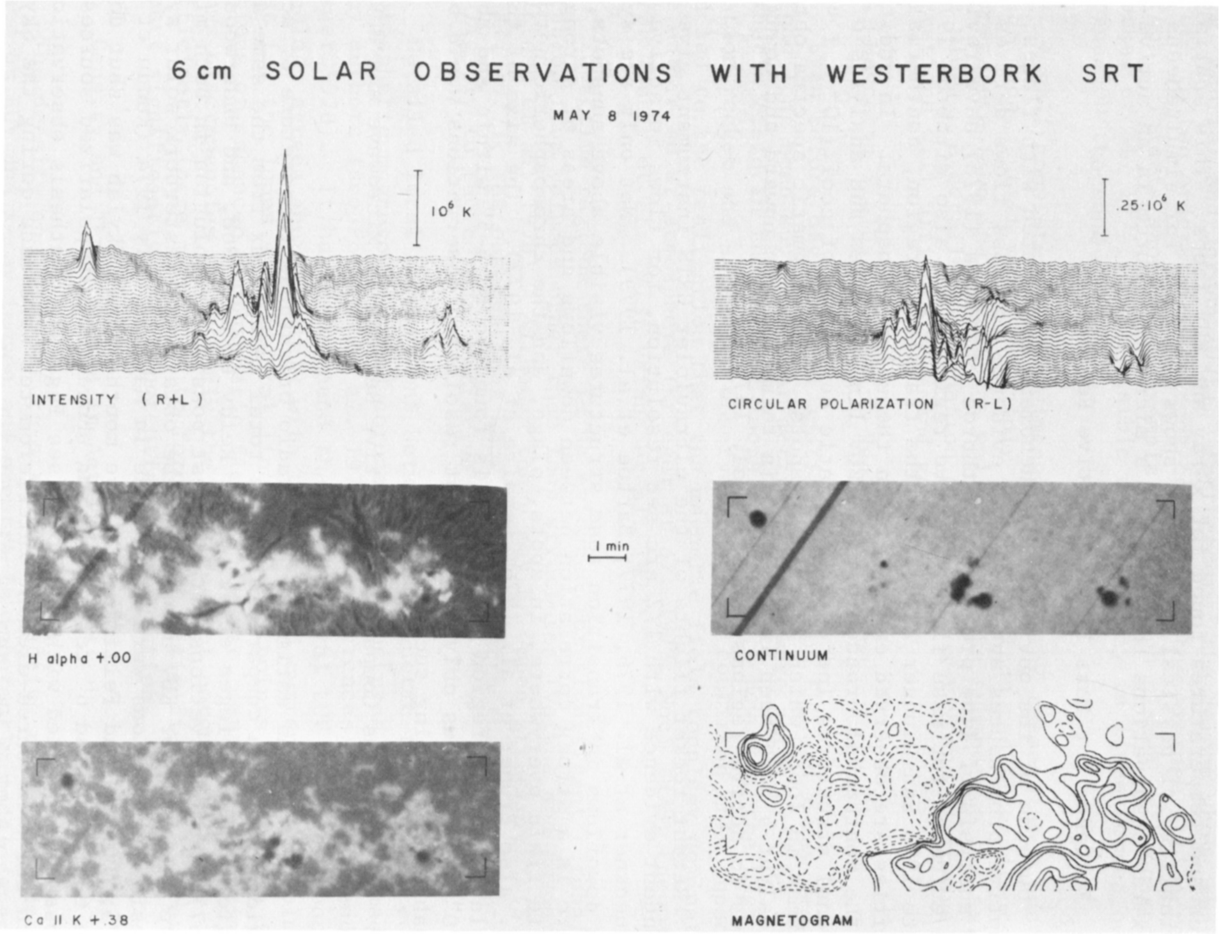

Figure 4. 6 cm maps show intensity peaks in close association with sunspots. (Alissandrakis 1977).

3.1 NRAO Observations

The NRAO interferometer observations at 3.7 and 11.1 cm have been discussed by Kundu et al. (1979). The simultaneous Skylab observations consisted of EUV spectroheliograms in the lines of hot ions (Fe XVI, S XIV and Mg X), and x-ray images in hard and soft filters. The exact relative positions of the radio and optical emitters could not be precisely determined. However, the estimated radio brightness temperature, 2 - 3 x 10^6 K was about equal to the maximum temperature of the EUV and x-ray loops. The region with this temperature (assumed thermal) must, therefore, have been optically thick. As expected from known loop densities, this could not be due to thermal bremsstrahlung absorption, which was borne out by the densities computed from the EUV and x-ray emission measures and the observed scale lengths. The inferred source of absorption then is gyroresonance absorption (Zheleznyakov 1962; Takakura and Scalise 1970; Kundu 1965), which would require that the emitting layer have a gyrofrequency such that the observing frequency be a small multiple, say the 2nd 3rd, or 4th harmonic. Fig. 5 shows contours of unit-optical depth at 3 harmonicsas functions of N_e, T and θ. The observed densities imply that the 3rd harmonic is the highest optically thick layer. This implies that the field strength in the loop be ∿ 300 gauss. The gas pressure in the loop was determined from the EUV and x-ray observations to be ∿ 13 dy cm^{-2}, which implies that the plasma β (plasma over magnetic pressure) be less than 1%.

3.2 Stanford Observations

There is some controversy concerning whether gyroresonance absorption necessarily occurs in active regions. Pallavicini et al. (1978) analyzed the spatial positions of hot active region radio cores at 2.8 cm wavelength using the one-dimensional Stanford data, acquired during the Skylab period. They found that the cores usually overlay sunspots to within the beam width of 16". The x-ray photographs were comapred to see if the center of x-ray emission coincided with the microwave position. (see Fig. 6) In fact, it was found in a significant number of cases that the emission peaks did not agree. That microwave emission often peaks close to sunspot umbras, has been amply confirmed by high resolution observations using the Westerbork array (Kundu and Alissandrakis 1975; Kundu et al. 1977), the Very Large Array (Lang and Willson 1979, Velusamy and Kundu 1979), the Ratan 600 (Efanov et al. 1978, Pariiskii et al. 1976, and at time of eclipse (e.g. Boldyrev et al. 1978).

However, it is also well established that x-ray emitting loops do not have their footpoints in sunspot umbras (Webb and Zirin 1979; Vaiana et al. 1973; Vaiana et al. 1976). The x-ray emission above sunspots is not precisely zero, but may be mostly scattered light from nearby bright plage areas (Maxson and Vaiana 1977). Pallavicini et al. (1978) argue further that the observations by Foukal et al. (1974), Foukal (1976, 1978) of sunspot plumes of material substantially cooler than 10^6 K may possibly rule out the existence of optically thick hot layers. The authors admit, however, that they had not yet done realistic modelling

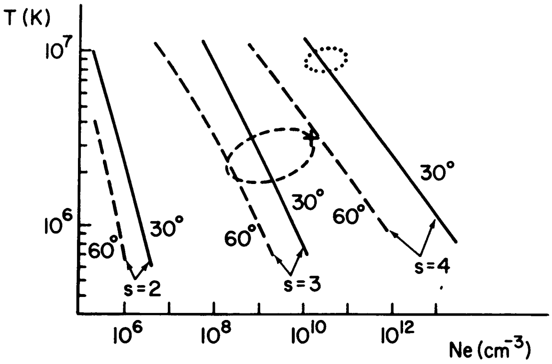

Figure 5. Contours of constant optical depth (τ = 1) at three harmonics (s = 2, 3, 4) of the gyrofrequency, and two angles (30°, 60°) between the magnetic field and the line of sight. The dashed and dotted curves illustrate the range of temperatures and densities (summarized by Rosner et al. 1978) for active region and post-eruptive loops. The cross indicates the density and temperature estimated for the loop observed at microwave, EUV, and X-ray wavelengths. (Kundu, Schmahl, and Gerassimenko 1979).

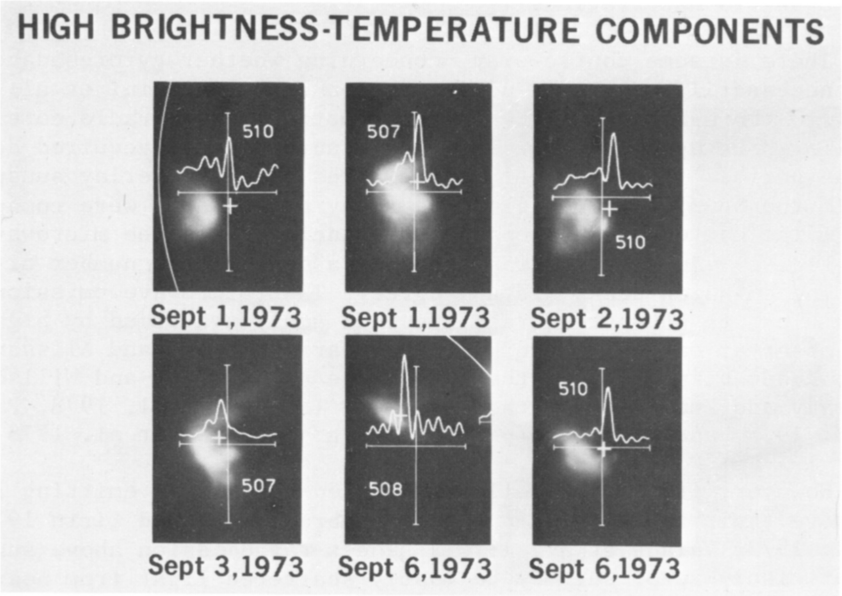

Figure 6. One-dimensional synthesis scans, made by the Stanford array, compared with AS&E x-ray images. High brightness temperatures are frequently associated with absence of soft x-rays. (Pallavicini et al. 1979).

of such sunspot plumes, and they could not resolve the issue. (But see Pallavicini, this symposium.)

3.3 Superthermal Interpretations

The only other alternative to gyroresonance is the emission by non-thermal gyrosynchrotron electrons. By analogy with what has been suggested for impulsive microwave bursts (Takakura 1967), Pallavicini et al. (1978) estimated that the lifetime of the emitting electrons due to gyrosynchrotron losses is $\sim 250^s$, much smaller than the lifetime of bright microwave cores in active regions. This mechanism would, therefore require continuous acceleration (which might not be too improbable in emerging flux regions). Despite this difficulty many authors have suggested the possibility of superthermal phenomena outside of flares (see Gel freikh 1979; Kane and Pick 1976). Kovalev (1978), Dulk (1978), and Mätzler (1978) have discussed superthermal gyrosynchrotron sources. However, it may be possible to rule out superthermal sources, since one might expect more polarization diversity (Kovalev 1978) than is actually observed over sunspots, where in fact the polarization usually agrees with x-mode emission in the observed photospheric magnetic field (Kundu et al. 1977).

3.4 Models

More modelling along the lines of Alissandrakis et al. (1979) is needed to determine which parameters (density, temperature, magnetic fields, and their gradients) best fit the observations. It may be possible to construct an empirical model of sunspot atmospheres which is consistent with low brightness in x-rays, high brightness in cooler plumes seen in EUV, extreme spatial variations of these properties, and still match the observed high brightness temperatures in x-rays.

4.0 Current and Future Observations

VLA observations in 1977, 1978 and 1979 are currently being analyzed. (See Velusamy, this symposium). Various microwave features occur in the active regions which were observed. Circularly polarized sources sometimes overlie regions of one magnetic polarity. This polarization is usually consistent with that expected from gyroresonance absorption. Some emission also appears over neutral lines, where one might expect x-ray and EUV arcades (Webb and Zirin 1979). This can perhaps be explained on the basis of gyroresonance absorption since the extraordinary mode opacity becomes very large when the angle between the line of sight and the magnetic field is approximately 90°. There is also considerable emission from regions of changing magnetic flux.

The most recent observations with the VLA were made in conjunction with the P78 x-ray satellite. It is hoped that the x-ray spectroheliograms, currently in transmission from satellite ground stations, will shed light on the problems and possibilities given by simultaneous microwave and x-ray comparisons. Future high resolution microwave observations are planned to be made in conjunction with the Solar Maximum Mission. It is hoped that the simultaneous hard and soft x-ray, EUV and microwave observations which are planned will resolve some of the controversies that exist concerning the interesting magnetized plasmas which the radio and optical regions of the spectrum show above and around sunspots.

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DISCUSSION

Benz: It is interesting that EUV and soft x-ray observations have not shown wavelike phenomena but rather stochastic brightenings of small regions. The high time resolution radio fluctuations observed in Bonn and Arecibo may thus have another interpretation than waves. I suggest that one observes in these radio fluctuations the heating and cooling of regions of various sizes, some very small and possibly yet undetected.

Schmahl: There haven't been any really high resolution observations with very fast time resolution. Of course, it's practically impossible without some instrument like the VLA. Perhaps that will be done in the next few years.

Benz: How to get agreement between the fluctuations in the x-ray range and the considerations of Dr. Hirth, who claimed sound waves to be responsible for the fluctuations?

Schmahl: In order to identify the source as being precisely identical to the x-ray source you really should have high spatial resolution in the radio domain.

Hirth: My talk dealt with the fluctuations in relatively deep layers of the solar atmosphere (the transition zone).

The x-ray measurements refer to coronal plasma at great height. It is not so easy to compare phenomena in these two different plasmas.

Kundu: I think Bonn measurements you are referring to have got a time resolution of 50 milliseconds and the high resolution cm-λ measurements have been made with time resolutions of either 30 seconds or 10 seconds. 10 seconds with the VLA and 30 seconds with the Westerbork telescope. Until you get similar spatial and time evaluation, I think we will always be talking about comparing elephants with horses. There may be different kernels which will be brightening up, which may be giving pulses and so on, but we will not know where it is coming from. I think it will be to much to extrapolate from high time resolution data to the high spatial resolution data.

Golub: Dr. Sheeley and I have recently completed a study of the time scale of changes in very small closed coronal loops. We find that, in a region which consists of just a few small loops, the individual loops come and go with the most rapid time scale possible, i.e., a combined radiative and conductive cooling time of a few minutes. However, I believe that many possible heating mechanisms such as acoustic waves, intermittent currents or several others are consistent with these observations, unless more sophisticated modelling is added.