ON THE ORIGIN OF MICROWAVE EMISSION FROM SUNSPOTS

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ABSTRACT. Coordinated high-resolution XUV and centimetric observations of active regions obtained from Skylab and Stanford are compared with the aim of determining the nature of the centimetric radiation. It is concluded that the thermal gyroresonance process is the most likely emission mechanism for the bright compact radio sources associated with sunspots.

With the advent for high-resolution interferometric techniques, it has become increasingly evident that the slowly varying component of solar radio emission consists of two parts, one associated with spots and the other with plages. In particular, compact radio sources with brightness temperatures of up to several million degrees are usually observed at centimetric wavelengths above large sunspots, while more extended, lower brightness temperature components ($T \sim 10^5$ K) overlie plage areas (Felli et al. 1975, 1977; Kundu et al. 1977).

The extended low brightness temperature radio sources can be interpreted as originating by thermal free-free emission from the transition region and corona above active centers. On the contrary, there is still considerable uncertainty as to the emission mechanism of the sunspot associated components. The nature of these radio sources can be investigated either by means of intensity and polarization measurements at several frequencies (Kakinuma and Swarup 1962) or by comparing radio measurements at a single frequency with simultaneous observations at other wavelengths. For this purpose, high-resolution X-ray and extreme-ultraviolet observations from space appear the most promising, since they give information about the same atmospheric layers from which microwave emission from active regions originate.

The latter approach is presently being followed in a research program which makes use of coordinated high-resolution 2.8 cm interferometric observations from Stanford and XUV data from Skylab. In a previous paper (Pallavicini et al. 1979) we have compared the radio data with X-ray photographs obtained nearly simultaneously by the American Science and Engineering experiment on Skylab. The amount of

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hot coronal material that we have deduced from the X-ray data to lie above large sunspots is far too small to give a coronal source optically thick at 2.8 cm by the free-free absorption process, thus allowing us to rule out this mechanism for the bright radio sources.

X-ray and microwave data can be brought into agreement if the optical thickness at centimetric wavelengths of the corona above sunspots is mostly due to thermal gyroresonance absorption (Zheleznyakov 1962). This mechanism requires a high magnetic field at coronal levels (such as may exist over sunspot umbrae) and imposes far less severe requirements on the ambient coronal density, thus allowing one to overcome the difficulty encountered by the free-free absorption process in accounting for the observed weak X-ray emission. Simple model calculations performed by assuming typical parameters for coronal active regions and extrapolating the photospheric magnetic field to coronal levels in the current-free approximation confirm this interpretation.

However, it can be argued that the formation of compact radio sources with brightness temperatures $\gtrsim 10^6$ K by the gyroresonance process conflicts with recently reported extreme-ultraviolet observations of sunspots (Foukal et al. 1974, Foukal 1976) which indicate that the geometrical thickness of the upper transition region is increased over sunspots by more than one order of magnitude with respect to plages, a conclusion further supported by the observation close to the limb of plumes of cool material extending up to heights of the order of $\sim 10^5$ km above sunspot umbrae. With this model atmosphere, the gyroresonance absorbing layers, whose height is limited by the magnetic field scale-height to be of the order of 10^4 km or less, are located inside the transition region at levels where the electron temperature is substantially lower ($10^5 \lesssim T_b \lesssim 10^6$ K) than the coronal temperature. It should therefore be impossible to obtain brightness temperatures $\gtrsim 10^6$ K via gyroresonance absorption.

Should the gyroresonance hypothesis be abandoned, a non-thermal process must be postulated for the bright radio sources. A possibility is gyrosynchrotron emission by non-thermal electrons. This process would require a continuous acceleration of non-thermal particles for periods as long as several days, in order to explain the observed stability of the sunspot associated sources. No direct evidence for this exists so far and the difficulties of the gyroresonance theory, therefore, must be investigated carefully before the alternative of a non-thermal process can be seriously considered.

With the purpose of checking the relevance of the above mentioned objection against thermal gyroresonance, we have recently undertaken an extensive analysis of extreme-ultraviolet observations obtained by the Harvard College Observatory experiment on Skylab for the same period (1973 August 28-September 13) and for the same active regions already studied at X-ray and centimetric wavelengths.

A first quick look at the data has shown an expected agreement with previously reported results. However, we have found that the presence of a high column of cool transition region material above a sunspot can effectively prevent the formation of radio sources with brightness temperatures $\gtrsim 10^6$ K by gyroresonance only when the cool column covers the whole sunspot umbra and is observed mainly along the line of sight. In our sample of data one case exists (McMath 501) for which this situation is in fact occurring. The brightness temperature observed above the sunspot ($T_b \sim 5 \times 10^5$ K) is substantially lower than the coronal temperature in active regions, although larger than the brightness temperature computed on the basis of the UV data for thermal free-free absorption. The simplest interpretation is that the observed sunspot-associated radio component is mostly due to gyroresonance absorption occurring at a level where the electron temperature has a value pertaining to the upper transition region.

In more general cases, in which brightness temperatures $\gtrsim 10^6$ K are observed (e.g. McMath 510), a detailed analysis of the ultraviolet data shows that localized regions (possibly cool columns or plumes) of enhanced UV emission do not fill the whole umbral area, but only a small fraction of it, indicating the coexistence above the same sunspot of both cool and hot loops which are not resolved by the radio instrument. In other cases, an angle between the line of sight and the axis of the cool column can also help in reconciling the UV data with the gyroresonance interpretation of the radio data.

In summary, a preliminary analysis of coordinated high-resolution soft X-ray, extreme-ultraviolet and centimetric observations of active regions points to the thermal gyroresonance process as the most likely emission mechanism for the stable high brightness temperature radio components associated with sunspots. A non-thermal process does not seem to be required.

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DISCUSSION

Schmahl: a) Did I understand that you argue in favor of gyroresonance absorption even in the case of plasmas with $T = 1$ to 5×10^5 K?

b) It seems improbable to me that the gyroresonance opacity can be large for $T \lesssim 10^6$ K.

c) In any case a definitive model may well answer the question.

Pallavicini: In all cases in which we observe compact radio components with brightness temperatures greater than about one million degrees, the gyroresonance interpretation appears the most likely; in the one case in which we observe over a large sunspot 2 compact radio sources with brightness temperatures of the order of 5×10^5 K, the gyroresonance interpretation is not so obvious; however, if you use the differential emission measure derived from UV data, you find that the brightness temperature should be substantially lower for pure thermal free-free emission; some contribution to the opacity should therefore come also from other mechanisms, possibly from gyroresonance absorption. This is not unlikely if you take into account the fact that the gyroresonance optical depth at the third harmonic of the gyro-frequency is proportional to NT^2 (where N is the density and T the temperature); thus the optical depth is proportional to PT, where P is the pressure. For constant pressure, a decrease of T by a factor 2 should not change the results very much, especially if one takes into account the dependence of gyroresonance absorption on a number of unknown parameters, such as the magnetic field scale-height and the angle between the magnetic field and the line-of-sight. Even if the pressure above sunspots has a value substantially lower than typical values for active regions, an optical thickness greater than one can be reached for $T \sim 5 \times 10^5$ K and for the extraordinary mode at the second harmonic of the gyro-frequency. It is clear, however, that for lower temperature values, the importance of gyroresonance absorption decreases with respect to thermal free-free absorption.

Vlahos: You have shown that your results do not necessarily suggest non-thermal particles but if I understand correctly you cannot exclude them either. It is important to know if energetic particles are present in the low corona, since as you know we frequently find them in storms for hours or days.

Pallavicini: I agree that my results do not rule out a non-thermal mechanism. As I discussed in my previous paper (Pallavicini et. al. 1979, Ap. J. 229, 375), gyrosynchrotron emission by non-thermal electrons can easily explain the EUV, X-ray and centimetric observations; however, as far as I know, there is no stringent experimental result that requires a continuous acceleration of non-thermal electrons in sunspot regions. This process remains therefore an interesting, although so far speculative, hypothesis.