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17 GHz Mode Coupling in the Solar Corona

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Abstract

We studied the development of microwave polarization of a group of active regions for a period of 10 days during April, 1993 using data obtained by the Nobeyama radioheliograph. The observed sense of polarization at 17 GHz changed with the active region position on the solar disk. This change of polarization can be explained by the mode coupling theory according to which a weak coupling between the ordinary and extraordinary electromagnetic modes takes place when the radiation crosses a region of transverse magnetic field and results in a polarization reversal. Since the strength of the mode coupling depends on the physical parameters (and their gradients) of the quasi-transverse region, observations of polarization changes can be used to obtain key values of the magnetic field and field gradient in the active region corona. Using the intensity and polarization images of active regions, we found that the coupling constant is typically $> 10^3$ corresponding to a weak coupling regime. We determined the mean value of the transition frequency to be $\sim 5.3 \times 10^{11}$ Hz, below which the weak coupling effect is important. For all the active regions studied in this paper, there seems to be a similarity in the position on the solar disk where the mode coupling effects become important. The polarization reversal always occurred when the active regions were farther than the 500 arc sec mark from the disk center. Using this fact and extrapolated photospheric magnetic field we are able to estimate heights of both the quasi-transverse layer and the source region. Assuming a value of ~ 70 G, we obtain a value of 2.2×10^4 km for the Q-T layer height.

Key words: Sun: active region, Sun: radio radiation

1. Introduction

Active regions are produced by strong magnetic fields arising from the sub-photospheric layers into the corona. The plasma trapped in such magnetic fields, called coronal arches, emits polarized radiation either by thermal bremsstrahlung and/or by gyroresonance processes (low and high polarization level, respectively). When the emitted radiation crosses a perpendicular magnetic field layer it is possible, depending on the characteristics of the layer, to have mode coupling, i.e., the ordinary and extraordinary modes going out of the quasi-transverse region can be different from the modes entering the layer. One typical manifestation of the mode coupling phenomena is the reversal of polarization when the modes cross the quasi-transverse layer.

The reversal of polarization has been known for many years, both during microwave bursts (Kakinuma 1958; Tanaka and Kakinuma, 1959) and when active regions crossed the solar disk (Kundu and Alissandrakis, 1984). Nevertheless, a detailed study of mode coupling using high resolution and long time observations is still lacking. A clear understanding of the mode coupling process is essential for a proper interpretation of radio emission at all wavelengths (Gopalswamy et al. 1994).

In a recent work (Lara et al. 1998b) we studied the polarization evolution of a group of active regions observed during 10 days of April 1993. We found polarization reversals when the ARs cross the solar disk, namely, when an AR is near the solar limb their emited polarization is mostly unipolar with the polarization of the diskward side of the AR. When the AR is near the center of the disk, inside the 30 deg of heliographic longitude, the observed polarization is fully bipolar. In our period of study six regions presented similar polarization changes.

This behavior of the sense of polarization suggests that microwave emission originating on the limb side of the active region encounters a transverse magnetic field. The mode coupling theory predicts that the emission crossing such a quasi-transverse magnetic field layer reverses its sense of polarization if the coupling is weak.

The fact that the change of polarization occurs at almost the same heliographic longitude ($\sim \pm 30\,\mathrm{deg}$) for all regions can be understood if the height of the quasi-transverse layer is similar in all the active regions studied. In other words, the geometrical structure (at least the altitude) of the active regions is similar.

In this work, we use the observed mode coupling and extrapolated (photospheric) magnetic field to estimate the height of both the 17 GHz emitting arches and the quasi-transverse layer in active regions.

2. Data

The microwave data used in this work were obtained by the Nobeyama Radio Heliograph (NoRH) in Japan, a solar dedicated radio interferometer operating at 17 GHz (1.76 cm) with a bandwidth of 33.6 MHz. The NoRH images the Sun in both right (R) and left (L) circular polarizations and has a field of view of 40' with a spatial resolution of $\sim$ 10 arc sec (Nakajima et al., 1994).

For the 1993 April 17 - 28 period, nine R and L maps per day were used to obtain the daily total intensity ($I = \frac{R+L}{2}$) and circular polarization ($V = \frac{R-L}{2}$) maps. From these I and V maps, we determine the characteristics of the mode coupling process.

We complete our data set with soft X-ray solar images from the Yohkoh Soft X-ray Telescope and magnetograms from the Solar Vacuum Tower Telescope at Kitt Peak.

3. Mode Coupling

According to the mode coupling theory (Cohen 1960; Zheleznyakov 1996) the conditions of the quasi-transverse region in the path of the radio emission are described by the coupling parameter:

$$G_{\perp} = \frac{\pi \omega_p^2 \omega_B^3}{8 c \omega |\frac{d\alpha}{dl}|} \tag{1}$$

where ω_p is the plasma frequency, ω_B is the electron gyro-frequency, ω is the observing frequency, α is the angle between the magnetic field and the direction of propagation, c is the speed of light and l is the coordinate along the ray path.

When $G_{\perp} \gg 1$ the coupling is weak, the ordinary and extraordinary modes are conserved during passage through the quasi-transverse layer. However, since the direction of the magnetic field changes, the sense of polarization of the two modes is reversed. On the other hand, when $G_{\perp} \ll 1$ the coupling is strong and the modes are interchanged, with no change in sense of polarization.

The critical frequency at which the coupling constant changes from weak to strong ($G_{\perp} = 1$) is given by:

$$\omega_t = \left(\frac{\pi^2 e^5 N B^3}{2 m^4 c^4 |\frac{d\alpha}{dl}|} \right)^{1/4} \tag{2}$$

Where N and B are the electron density and the magnetic field in the quasi-transverse region, e and m are the charge and mass of the electron.

Then, for a given region (N and B known) we know at which frequencies the mode coupling is weak ($\omega \ll \omega_t$) or strong ($\omega \gg \omega_t$). Using the mode coupling theory, it is thus possible to identify the transition frequency and hence obtain the limiting values for the density and magnetic field in the quasi-transverse layer.

In order to calculate the coupling constant and the transition frequency (Lara et al. 1998b), we use the computed magnetic field necessary to produce the observed degree of polarization at both maximum I (B_I) and V (B_V) and the density computed using Yohkoh/SXT images (assuming thermal free-free emission, Lara et al. 1998a). Also, we assume that the gradient of the angle between the magnetic field and the ray path is approximately equal to the inverse of half of the active region size. We can estimate an upper limit to the magnetic field scale length as the distance that an active region crosses between the two positions that cause polarization inversion which is 1.3×10^{10} cm.

Then, using equation (1) we obtained a mean value of 1.3×10^6 for $G_{\perp}(B_V)$ and 1.0×10^5 for $G_{\perp}(B_I)$. In either case, $G_{\perp} \gg 1$ and the mode coupling must be weak. Also, we get mean values of $\omega_t(B_V) \sim 5.3 \times 10^{11}$ Hz and $\omega_t(B_I) \sim 2.0 \times 10^{11}$ Hz. Comparing these values with the observing frequency ($\omega \sim 1.1 \times 10^{10}$ Hz) we can establish that the mode coupling should be weak.

4. Q-T layer structure

In order to obtain a three dimensional view of the active region, we use the Sakurai (1982) code to extrapolate the photospheric magnetic field of AR7477 when it was near the center of the disk on 1993 April 22. Figure 1. shows a view perpendicular to the line of sight of the magnetic field lines. The color code of magnetic lines is as follows:

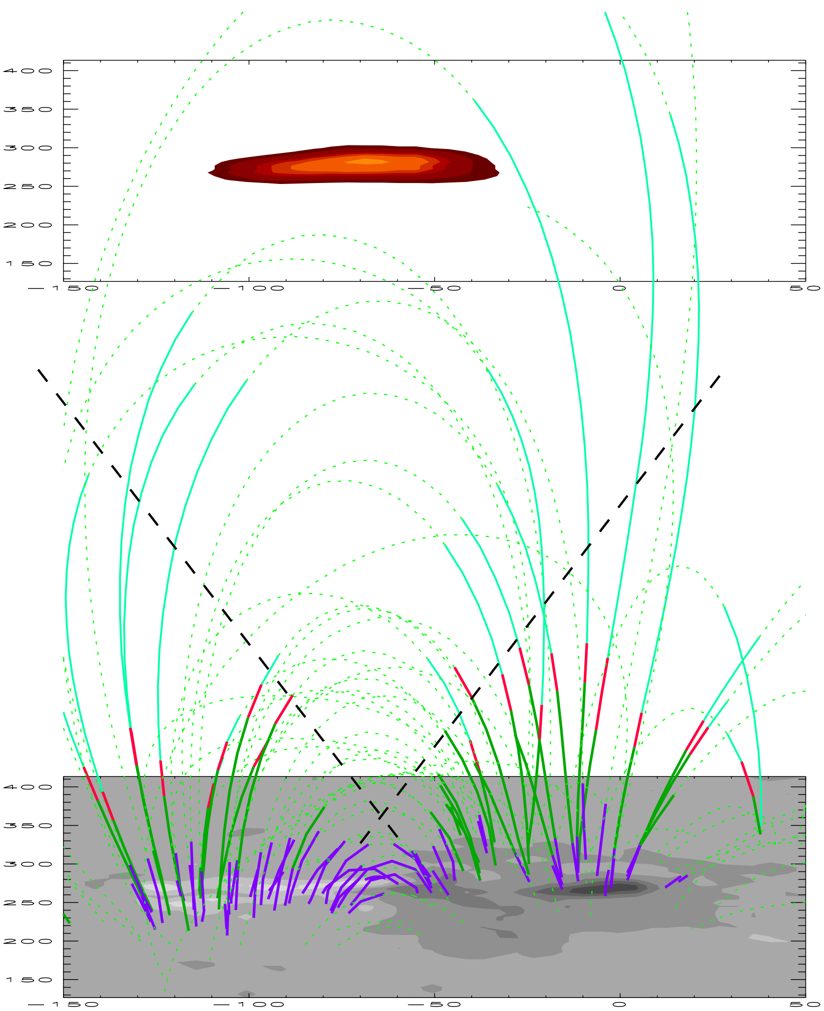

Fig. 1.. In gray scale are the photospheric magnetic (bottom) field and 17 GHz total flux (top) of AR7477 on April 22, 1993. Extrapolated magnetic lines are over-plotted (see text for the color code)

- purple: 17 GHz emitting loops. Using the observed degree of polarization we computed the source magnetic field; the purple lines represent magnetic field intensity from 250 to 850 G.

- red: mode coupling layer for a specific value of magnetic fields. Assuming a magnetic field between 60 and 80 G, and an angle greater than 40 degrees between the magnetic lines and the vertical direction, we determined the quasi-transverse layer on the extrapolated lines.

- blue: magnetic lines that can produce quasi-transverse layers. Lines with an angle greater than 40 degrees with the vertical are perpendicular to the ray path when the active region is outside of the 30 deg of heliographic longitude range. These lines could cause an inversion of polarization, even though the magnetic field strength is low.

- black. The black dashed lines represent the "light cone" where mode coupling is not observed. This constrains the height of the Q-T layer.

In gray scale are the photospheric magnetic field (bottom) and the observed total flux at 17 GHz (top). Figure 2. is a view parallel to the line of sight of the system. It is interesting to note the correspondence between the most probable emitting loops (purple) and the 17 GHz source. This correspondence shows that the method to deduce the magnetic field from the observed degree of polarization is a good approximation.

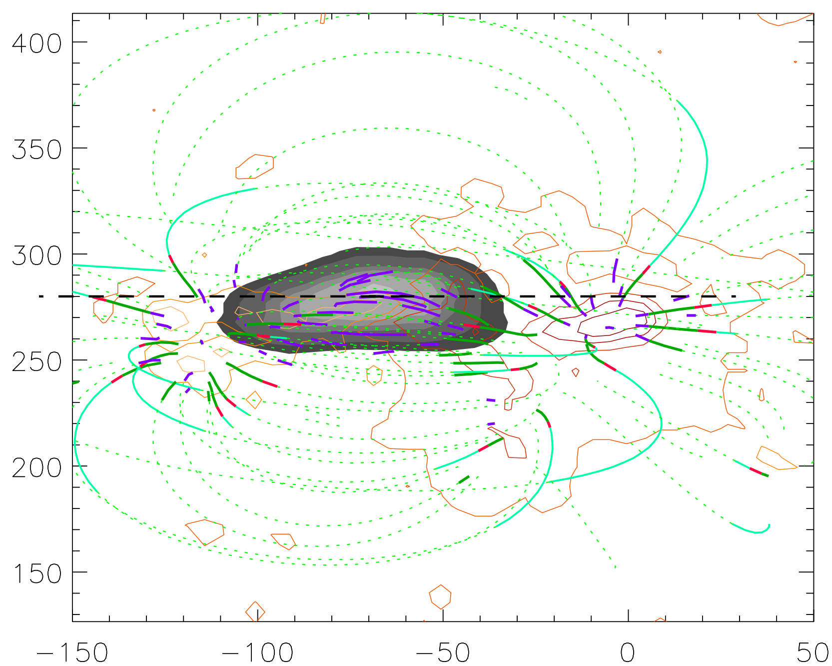

Fig. 2.. Top view of fig. 1.. Scales are in arc sec and solar north is to the top.

From the extrapolated magnetic field lines, we can compute the height of the mode coupling layer and the emitting loops. In Fig. 3. (left) we present a histogram plot of the height of the quasi-transverse layer. There is a well defined peak around 2.2×10^4 km. The height of the emitting loops is very low, $\sim$ 900 km, although the distribution correspond well to the transition zone - low corona height levels, up to $\sim 6 \times 10^3$ km (Fig. 3. right).

5. Conclusions

In this work we analyzed the change of observed circular polarization of microwave emission from several active regions when they crossed the solar disk. Our main results are:

Using the computed magnetic field necessary to produce the observed degree of polarization, the density obtained from SXT/YOHKOH images and half of the size of each active region as the magnetic field scale length, we found that the coupling constant is typically $> 10^3$.

In the same way, we found that the transition frequency is $\sim 3 \times 10^{11}$ Hz. The observing (angular) frequency of $\omega \sim 1.1 \times 10^{10}$ is smaller than the transition frequency and hence weak mode coupling operates.

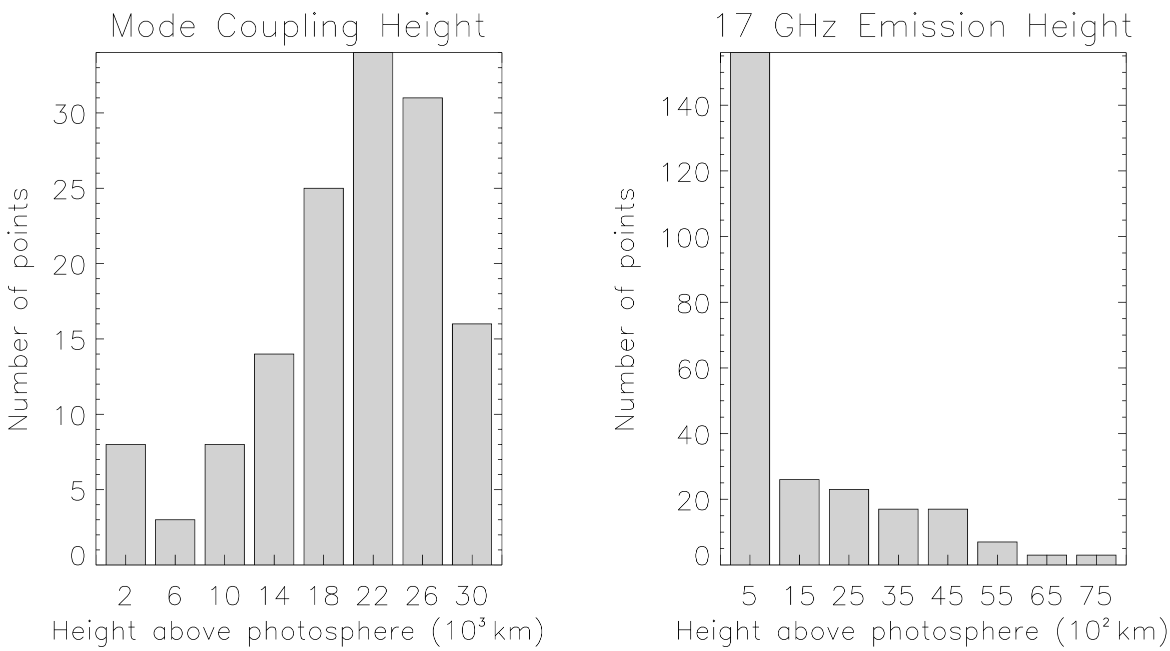

Fig. 3.. Computed heights for both the Q-T layer (left) and 17 GHz source region.

Most active regions have similar behavior of polarization reversal. The reversal typically occurs when the region reaches ±500 arc sec mark from the central meridian (approximately 30 deg of heliographic longitude).

This result means that most of the active regions during our study period seem to have similar geometrical structures, principally the altitude.

Extrapolating photospheric magnetic field we found:

- For a magnetic field of ~ 70 G, the height of the quasi-transverse layer is between ~ 1 and 3×10^4 km. The peak of the distribution is near 2×10^4 km.
- The height of the radio emitting magnetic loops is in the 0.9 to 6×10^3 km range and the peak seems to be low ~ 900 km.

In this preliminary work, we also show that the observed polarization of the AR microwave radiation can be used to deduce the magnetic and geometric structure of the low-coronal emitting loops.

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References

Cohen R. 1960, ApJ 131, 664
Gopalswamy N., Zheleznyakov V. V., White S. M. and Kundu M. R. 1994, Solar Phys. 155, 339
Kakinuma T. 1958, Proc. Res. Inst. Atmospherics, Nagoya U., 5, 71
Kundu M. R. and Alissandrakis C. E. 1984, Solar Phys. 94, 249
Lara A., Gopalswamy N., Kundu M. R., Pérez Enríquez R., Koshiishi H. and Enome S. 1998, Solar Phys. 178, 353
Lara A., Gopalswamy N., Pérez Enríquez R. and Shibasaki K. 1998b, In press
Nakajima H., Enome S., Shibasaki K., Nishio M., Takano T., Hanaoka Y. et al. 1994, Proc. IEEE, vol 82, p. 705
Sakurai, T. 1982, Solar Phys. 76, 301
Tanaka H, and Kakinuma T., 1959, Paris Symposium on Radio Astronomy, p. 215.
Zheleznyakov V. V., 1996, in Radiation of Astrophysical Plasmas, Kluwer Academic Publisher