Solar active regions at millimeter wavelengths

M. Loukitcheva[1], V. Nagnibeda[1], and B. Rozanov[2]

[1] Astronomical Institute of St.Petersburg State University, St.Petersburg, Russia
[2] Bauman Moscow State University, Moscow, Russia

Introduction

Investigation of solar radio emission at millimeter wavelengths provides clear diagnostic tool for physical conditions in the solar chromosphere and the transition region. Millimeter-wave emission is generated above the temperature minimum level and includes information on physical conditions in the region where temperature inverse starts. In addition, such kind of studies have several distinct advantages in comparison with optical and UV observations. Firstly, radio emission of slowly varying component is generated under conditions of local thermodynamic equilibrium (LTE). Secondly, millimeter-wave emission has a thermal nature and is formed due to bremsstrahlung, while magnetic bremsstrahlung in magnetic fields of highly developed sunspots do not contribute significantly into the emission. Nevertheless, there are some disadvantages in mapping of the Sun at short mm-wavelengths because at present the angular resolution available is relatively modest, moreover it is limited by strong influence of terrestrial atmosphere. Nowadays solar observations at millimeter range are carried out episodically, with a few instruments and at one wavelength as a rule. Therefore, conclusions about mm-wave emission based on data obtained at instruments with different angular resolution turn out to be contradictory (Nagnibeda et al., 1987). Furthermore, observational results are in conflict with prevailing homogeneous chromosphere models due to presence of inhomogenities in chromosphere structure at mm-wavelengths.

Using instruments with angular resolution of several arc seconds at cm-wavelengths it was obtained that the spectra of sources of slowly varying component associated with strong sunspots show a marked maximum in the flux density spectrum at a wavelength of about 10 cm and a continuous decrease towards both shorter and longer wavelengths (Zheleznyakov, 1964). Some uncertainties are accompanied with the flux density spectrum at mm-wavelengths. Thus, some authors claim for a flat slope of the spectrum of sources emission towards mm-wavelengths (see, e.g., Kundu, 1965) that corresponds to the emission of an optically thin coronal condensation. But the spectral data for the sources with an increase in flux density towards short wavelengths in the range 20 mm to 2 mm were published by Efanov et al. (1972). Steffen (1980) has shown that different types of mm-wave spectrum can coexist. All these contradictions in behavior of spectra make the problem of studying spectral characteristics of S-component sources very urgent.

Another question which is worth studying is the fine structure of S-component sources at millimeter wavelengths. At centimeter wavelengths the structure of sources is various due to different characteristics of the magnetic field of sunspots and active regions and due to contributions of different mechanisms of generation (thermal, non-thermal, gyroresonance). Towards shorter millimeter wavelengths the structure is simplified because the thermal mechanism begins to dominate and in S-component source structure at least two components can be derived. They are sunspots and plages. At 8 mm wavelength a bright narrow source above sunspot was detected during eclipse observations (Apushkinskij et al., 1970). When wavelength decreases the brightness and contrast of sunspot component should decreases also and at some wavelength (at some chromosphere level) a bright source should regenerate as a dark spot. The location of this level which is responsible for the modification in energy release processes is of great interest.

Observational results

For the purpose of studying of S-component at mm-wave region we considered two-dimensional solar intensity maps obtained with the 7.5 m radio telescope RT-7.5 of Moscow State Technical University at 3.4 mm wavelength (spatial resolution of 2.5 arc min) and solar maps obtained with Nobeyama heliograph at 17.6 mm wavelength (spatial resolution of 10 arc sec). About 40 maps obtained simultaneously with RT-7.5 and Nobeyama over the period of 1993-94 were chosen for the sake of comparison. The sources of S-component under consideration belong to the active regions of various types, e.g. with highly developed sunspots, with weak sunspots, and active regions with plages only. The deconvolution procedure could help to improve the spatial resolution of solar maps but it requires an excellent knowledge of the telescope response function (beam). An attempts in this direction for the beam of RT-7.5 have been carried out but haven't been completed yet. In order to get equal characteristics for comparison and to avoid possible methodical errors for the maps obtained at instruments with different angular resolution the procedure of convolving Nobeyama brightness distribution with 2.5 arc min beam, that corresponds to the beam of RT-7.5, was applied.

Source structure: At least two components in the source structure can be derived from Nobeyama maps: a wide source that can be associated with plage emission and a bright source over sunspots, which is completely determined at centimeter wavelengths by magnetic bremsstrahlung. However, at 17.6 mm wavelength the required magnetic field for gyroresonance emission is over 3500 Gauss and it has not been reached in active regions under consideration. As a result, we conclude that 17.6 mm-wave emission of a source over sunspots as well as of a wide plage source are formed due to bremsstrahlung, which also dominates at 3 mm. Nevertheless, direct investigations of fine source structure at 3 mm are impossible for the reason of relatively modest spatial resolution of 2.5 arc minutes of RT-7.5, which is not enough to resolve the active region into individual components. This fact requires the assumption about similarity of source fine structure at millimeter wavelengths. Thus, assuming the similarity of fine source structure at millimeter wavelengths, for further analysis we consider that plage and sunspot components at 3 mm wavelength have equal brightness temperatures. Under this assumption fluxes and brightness temperatures for two wavelengths and for two components in mm-wave emission of a S-component source have been obtained and these spectral characteristics have been carefully studied. A detailed description of the reduction procedures can be found in Nagnibeda et al. (1991).

Spectral characteristics: It is difficult to speak about the mm-wave spectrum of the S-component source using two frequency data of only. Nevertheless, several conclusions about the spectral behavior of mm-wave emission can be made from this data. Firstly, for different sources the spectral behavior of mm-wave emission is different. The analysis has shown that this fact can be explained by the considering of active regions of various types, e.g. active regions with highly developed sunspot groups, with weak sunspots or without them. Secondly, in general there is an increase in flux density towards short wavelengths at mm-wave range. The slope of the flux density spectra for the plage component is more steep comparing to the sunspot component. It was found that the spectral flux index of the plage component is close to -2, while for the sunspot component it is close to 0. The division of a source mm-wave emission into plage and sunspot components was confirmed by the statistical investigation of the dependence between the flux density of a source and the corresponding active region size. Actually, there is a good correlation at 17.6 mm between the source flux density and the sunspot area, meanwhile, correlation with the total active region area is absent. At 3.4 mm the flux revealed a linear correlation with the total active region area where plage area dominates and no correlation with sunspot area. Thus, the basic contribution into radio emission at 3.4 mm wavelength is made by plages. As for sunspot component it does not exceed 10% of the total source flux. At 17.6 mm wavelength the contributions of both source components are of the same order.

For further comparison with chromosphere models we assume the following values : at 3 mm wavelength plages have brightness temperature of 7050 K and for sunspots is 7400 K, at 17.6 mm wavelength plage brightness temperature is 13700 K and for sunspots is 28300 K.

Discussion

We present here the results of calculations of mm-wave emission for different elements of chromosphere and transition region of the quiet Sun and S-component namely elements of chromosphere network, sunspot groups, and plages. The calculations were performed on the basis of standard optical and UV models (Vernazza et al., 1981), and their modifications (Fontenla et al., 1993). We also considered the sunspot model by Lites and Skumanich (1982), S-component model by Staude (see Kruger et al., 1985) and modification of VAL and FAL models namely NET and CELL models (Bocchialini et al., 1996). Radiation transfer was estimated under the assumption that radio emission at mm wavelengths is mainly due to bremsstrahlung. Detailed description of the estimating procedure can be found by Zlotnik (1968). We compare these model calculations with observed characteristics of components of solar mm-wave emission obtained with the radiotelescope RT-7.5 MGTU (3.4 mm wavelength) and Nobeyama radioheliograph (17.6 mm wavelength). We obtained that theoretical values of brightness temperature are systematically higher than observed ones for all considered components of radio emission : the Quiet Sun, sunspot emission and plage emission, or they are not correspond to the actual dependence of brightness temperature vs wavelength. Our analysis has shown that observed radio data are clearly in dissagrement with all the considered models. Finally, we propose further improvement of chromospheric and transition region models based on optical and UV observations with taking of mm-wave radio data into account.

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