Bremsstrahlung diagnostics of coronal magnetic fields

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1. Basic theory to measure magnetic fields

It is well known (for more than a half) century that the main part of the solar radio emission is generated by thermal bremsstrahlung. The astrophysists call this normally as free-free (or simply f-f) emission. The physical nature of the mechanism is rather simple: the emission is due to acceleration of electrons in electrical field of ions, mostly protons. The accurate theory is not an obvious task, however, due to the fact that in most cases the electrical field responsible for the electron acceleration is a result of many particles, inside Debye sphere. For the radio wavelength range in all practically important cases we deal with the thermal emission bremsstrahlung, implying Maxwell distribution in their velocity space.

When we have an anisotropic plasma, that with the external magnetic field two effects became important for an analysis of its thermal continuous radio emission. First, the gyroresonance effects appear at frequencies around harmonics of the electron gyro frequencies

$\omega = s \cdot \omega_B$

In case of the typical parameters of the solar corona harmonic numbers $s < 4$ should be taken into account. Though this type of emission is of resonance monochrome frequency destribution

$\frac{\Delta f}{f} \approx \frac{v_T}{c}$

However, due to no homogeneity of magnetic field the emission (absorption) is of continuous nature.

The second effect due to the magnetic field is variation of the acceleration law, while an electron is collided with proton, that certainly results in polarization parameters of the bremsstrahlung from an anisotropic plasma. As far as for stronger magnetic fields ($s \leq 3$) dominates gyro resonance effects we may limit our consideration to rather equal magnetic fields

$B \leq \frac{3570G}{\lambda[cm]}$ $(s > 3)$

If so, for most cases approximation of QL propagation can be used with the case of circular polarization of normal modes. In the case of an isotropic plasma the absorption coefficient

$\kappa = \frac{\zeta \cdot N^2}{T^{3/2} f^2}$

Logarithmic coefficient $\zeta \approx 0.12 - 0.18$, depending on plasma parameters, frequency of observation, chemical compounds and approximation used. Important consequence of this equation is that emission coefficient

$\epsilon = \frac{\zeta' N^2}{\sqrt(T)}$

and does not depend on the frequency (or wavelength). It follows that for optically thin region both the intensity and the flux density are also frequency independent being just

$I = \int \epsilon \cdot dl$ or $F = \int \epsilon \cdot dV$.

For the case of significant optical thickness we have

$I = \int \epsilon \, exp(-\tau) dl$ it follows

$\frac{\partial I}{\partial \lambda} \leq 0.$ because $\tau \propto -\lambda^2$.

In the case of anisotropic plasma the expression for absorption coefficient becomes

$\kappa = \frac{\zeta N^2}{T^{3/2} f^2 (1 - Y_l)^2}$

where $Y_l = \frac{f_B}{f} \cdot cos(\alpha)$ or $Y_l = \frac{eB_l}{mcf}$, B_l

being the longitude component of the external magnetic field. This formula assumes that QL propagation approximation is valid. The latter is correct in the wide range of directions of the magnetic field if the strength is rather weak. In the case of thermal bremsstrahlung we analyze the resulted radio emission as dominating only if magnetic field is weaker than that found from from the equation with $s = 3$.

The strongest (circular) polarization and probably most reliable case for an analysis is the situation of a coronal condensation transparent for the radio wave ($\tau \ll 1$). If so,

$P\% \approx 2 \frac{\cdot f_B}{F} cos(\alpha)$ and $B_l = \frac{54}{\lambda} \cdot P\%$

with an excess of an x-mode. To check that this approximation is valid one should have

flux/intensity

$I(\lambda) = const$ or $T_b \propto \lambda^2$

and polarization $P \propto \lambda \; T_b^v \propto \lambda^3$

In case of significant optical thickness

($\tau \geq 1$) and isothermal plasma structure we get

$T_b^x = T_b^o = T_e$ - no polarization.

However, usually we deal with nonisothermal plasma and this result in polarization effect: the x-mode is generated from higher level and o-mode from lower level as compared from the case of isothermal plasma of the same

T_e and N_e distributions. The simplest way to measure the magnetic field is using the formula obtained from equation in approximation of $f_B \ll f$:

$P\% \approx n \cdot \frac{f_B}{f} \cdot cos(\alpha)$

where $n \equiv \frac{\partial ln(T_b)}{\partial ln(\lambda)}$

For the strength of longitude component of the magnetic field we get

$B_l = \frac{107}{n \cdot \lambda}$

and for spectral index we may use approximation

$T_b \propto \lambda^n$

Certainly in all equation above we proposed the inhomogeneous magnetic field. If it doesnt work a model computations are to be used. Still a simple case of condensation above the chromosphere is still worth consideration in an analytic form.

2. Objects to study: some examples

Consider the structure of an active region. At short cm wavelength practically all emission is generated by thermal bremsstrahlung. The situation is illustrated by radio maps obtained with the Nobeyama radio heliograph at λ=1.76 cm for I and V Stoke parameters. In some cases above sunspots the magnetic field in the corona is strong enough ($B \geq 2000G$) to produce gyroresonance (thermal cyclotron) emission at the third harmonic of the electron gyrofrequency.

Sunspots and Faculae

Important features of comparing these figures with optical observations of the same active regions¡ magnetograms including are: 1. Sunspots with their strong magnetic fields are clearly seen on the V-maps and on maps they are not remarkable. However in case of coronal (or subcoronal) gyroresonace they may be the brightest features in intensity. 2. The faculae regions with their moderately strong magnetic fields are clearly seen on the V-maps (or P-maps). However, the degree of polarization is rather low (of the order of 1and one needs some additional procedure (higher averaging and cleaning) to achieve the necessary sensitivity. 3. Besides the gyroresonance coronal emission above sunspots the most prominent features of the local sources of the active regions are situated mostly along the neutral lines of the magnetic field (found from photospheric magnetograms).

Prominences

Due to the relatively low temperatures (usually $T < 10^4$ k) the prominences in cm wavelength range are optically thick structures observed behind the limb. It follows that the polarization is due to the gradient of temperature and for reliable measurements of magnetic fields one needs spectral observations. At the same time when you have detailed spectral-polarization analysis the information on gradients of magnetic field and temperatures is also available.

We illustrate such situation with an example obtained with the PAS observations made with the RATAN-600.

Coronal Holes

CHs are known as sources of the fast solar wind and elongated magnetic field structures of significant scale. Those features make them of special interest both the problems of space weather and of the physics of the solar plasma release of nonthermal energy including. Though it is quiet clear that magnetic fields plays the central role in their physics we have hardly proper methods to analyze magnetic fields inside CHs, and measure magnetic fields strength rspecialy.

One-dimensional structure normally used with the RATAN observations essentially limit the number of cases for detailed analysis of the polarization structures in the CHs. Nevertheless we can illustrate this opportunity by an example. It represents probably the first case of direct measurements of magnetic field in the CH and yields some data on its gradients too.

Cycle variations of the solar activity

It is well known nowadays that the 11-year solar cycle is essentially 3D process with the central role playing by the magnetic field. The study of the spatial distribution of magnetic field over the whole solar sphere and its time variation is the basis to understanding and forecasting the solar activity. Though these magnetic fields on many cases are weak the illustration based the Nobeyama radio heliograph observations show that the 11-year variations of the fields at all heliographic latitudes are also acceptable to the methods of the radio magnetography.

3. Technical requirements for the instrument

General Remarks

Coming to the central topic of my report dealing with the methods of the radio magnetography based on the analysis of the thermal bremsstrahlung I would like to first to stress the difference between the routine methods of optical magnetography and the radio one. When measuring magnetic fields from Zeheman splitting of optical spectral lines we deal with rather thin photospheric/chromospheric levels. And the magnetogram radio is a map of magnetic field over spherical surface in som projection of cause. In analyzing radio distribution of I and V Stokes parameters brightness we work with essentially 3D structures in the plasma of the solar atmosphere. So, we are trying to get 3D structure of the magnetic fields (tomography of the solar atmosphere).

Choice of the wavelengths

According to the formula () we can get better sensitivity while using longer wavelength range, especially for optically thin structures. The limits on the longer wavelength is defined by the following obstacles:

- Thermal gyroresonance emission
- Nonthermal stable sources
- Optically thick isothermal sources

These limitations in each situation should be considered with the analysis of the spectra of the radio emission. As based on the above shown examples we would recommend:

1 5 cm for an analysis of general magnetic structure of an active region with separation of chromospheric and coronal magnetic field, both on the disk and behind the limb 1-20 cm for study magnetic fields and temperature distribution in prominences

3-30 cm for analysis coronal holes and the general magnetic field of the sun.

Polarization parameters

The sensitivity to the weak circularly polarized signals seems to be the main problem in realizing the above observational methods of analyzing different magnetic structures in the solar atmosphere as based on the spectral-polarization measurements of the microwave radio emission. With increase of the resolution the power of the measured signal drops as θ^2 while the collecting area grows as θ at best. If we make instrument for simultaneous mapping of the hole disk the sensitivity in wide range does not depend on the size of a single antenna as the noise is produced by the whole solar disk and grows with the diameter of single antennas.

So. as compared with the parameters of Nobeyama radio heliograph or SSRT the number of antenna should be increased several times to get the same level of sensitivity. Let me remind you that with the Nobeyama we used the ten minutes averaging to make the proper radio magnetogram of an active region. Some progress may be achieved using longer averaging up to several hours. The other way is to include in system larger dishes and use e.g. multi beam modes with proper feed system. Effective cleaning procedures are also necessary to measure some minor fraction of 1polarization degree.

Modelling Approach

In any case effective 3D magnetography (tomography) needs usage of combination of all radio methods of measuring magnetic fields of the sun.

4. Radio magnetography with the FASP

Wide range of wavelength allows us to choose optimal waves to study magnetic field in different solar plasma structures. In contrast with an analysis of magnetic fields based on gyroresonance emission the strength of the magnetic field practically does not result in increase of the brightness. To understand the situation it is reasonable to consider separately the cases of transparent and opaque plasmas.

The case of coronal condensation above an active region behind the limb (Plasma in tops of coronal loops). Longitude components of the general magnetic field may also be analyzed in this approximation. The choice of the bremsstrahlung emission is based on the flat spectra if the intensity (or $T_b \propto \lambda^2$ in terms of brightness temperatures). The magnetic field (averaged longitude component) is found from formula

$B_l = \frac{54}{\lambda} \cdot P\%$

To get higher sensitivity we would like to use longer wavelength. However, when we deal with the loops of the active regions the continuous presence of the fast particles (seen as the growth of the spectra above I(λ)=const) limits the method. It is highly reasonable in this case go behind the λ=3cm. So, 1% in the channel of circular polarization correspond to 18 G. If we achieve accuracy about 0.1%, we can measure magnetic field of several G sensitivity enough to find magnetic field strength in upper parts of coronal arches even for weak ARs. The increase of density in coronal arches and sensitivity to the longitude component of the field make this method effective. More than that, observation for a number of dates due to solar rotation may open way to measure the field in different levels of an arch (loop).

Outside the solar ARs we may try to measure the general magnetic field of the sun behind the limb at different levels of the solar corona. In this case we have no limitations mentioned above. So, measurements at dm wavelengths with higher sensitivity to the magnetic fields are possible. With the sensitivity of about 0.1% we can study the field of the order of 1G and less. The main problem of cause is connected with the direction of the field: we measure the longitude component while the general field is expected to have meridian direction. In fact, however, the field is not as simple and have both components their variation within the solar cycle is of great interest for understanding the nature of the 11 (23) year variations of the solar magnetic fields. Rotation of the sun may be used while restoring the 3D coronal magnetic structure. Certainly this program should be based on the usage of all accessible observations of the solar corona and use model computation.

Now we are coming to the case of opaque for radio waves plasma. The polarization of bremsstrahlung in this case is due to the gradient of temperature. (For the case of isothermal plasma no polarization is observed). Practically the main case of our program is polarization due to gradients in the chromosphere of the solar ARs. The positive temperature gradient results in an excess of the x-mode (right-handed polarization corresponds to the north magnetic polarity). The growth of the magnetic field leads to higher V Stokes parameter (or percentage PThe point is that we simultaneously get emission in x-mode from higher (hotter) and o-mode from lower (colder) level. In this way (as I demonstrated above using Nobeyma data) we can get normal magnetogram of any active region referring to the chromosphere level. In case of FASP the special resolution is higher similar to that of optical magnetography and spectral analysis gives the spectral index n useful for the magnetogram calibration:

$B_l = \frac{107}{n\lambda} \cdot P\%$

For magnetography of the chromosphere of the solar ARs it is reasonable to choose shorter waves 1.5-2.0 cm where the effect of gyroresonance and nonthermal emissions is weak or absent. Such observations give also significant information about gradient of temperature in the solar chromosphere.

Similar method of analyzing both magnetic fields and temperature structure may be used for prominences behind the solar limb (see illustration above based on the Rratan-600 obsrvations).

The most typical situation take place when we deal with polarization due to both chromosphere and coronal magnetic field. So, the registered V Stokes parameter is the sum of polarized signal produced in the two layers of the solar atmosphere with probably different strength of the field. In the corona we see a kind of variation of density (condensation in a coronal loop). In the limits of the wavelengths with flat spectrum of intensities we have got

$T_b^v \propto B_{cor} \cdot \lambda^3$

For the chromosphere we can get very insignificant variation of brightness in intensitybut measurable polarization:

$T_b^v \propto B_{chrom} \cdot \lambda^{(n+1)}$, where n is spectral index of chromosphere brightness at these wavelengths. The observed polarized brightness with good accuracy is the sum of both:

$T_b^v(\lambda) = T_b^v(chrom) + T_b^v(cor)$

It follows that while making spectral observation you find n in two spectral regions (around λ_1 and λ_2). Then from observation of polarization at both wavelength and solving the above equation you find magnetic fieldxs at both levels in corona and chromosphere. The chromospheric magnetic field is well located in a narrow layer of the solar atmosphere. The coronal magnetic field is an averaged one over a significant scale (say of condensation) with the weight of N_e^2.

The above approach is certainly simplified and more accurate solution could be found but it gives a good idea of the main solution and possibilities of the method.

5. Conclusion

When completed we get with the FASP quite a new basis to study most of the energetic phenomena on the sun and their physical nature. The reason: we come from some estimations of parameters of the magnetic field structures in the outer regions of the solar atmosphere to their quantitative analysis based on the 3D measurements of the corona magnetic field (radio tomography instead of magnetography). The expected results of observational study may open new ways to solve such fundamental problems of the solar physics (more generally speaking of astrophysics) as:

- the nature and parameters of plasma structuring - corona heating - energy sources of the solar (star) flares - CME energy sources - acceleration of solar fast particles

and some more.

The success of such programs depends essentially on the level of realization of parameters of the FASP. The essentially more complicated 3D approach to coronal magnetography as compared with the traditional optical 2D magnetography of the photosphere should be based on a number of different physical phenomena connected both with the generation and propagation of radio waves in anisotropic plasma. So, central efforts to gain success in radio tomography of solar magnetic field Should be directed to two groups of the problems:

- realization of high polarization sensitivity (fraction of percent) in combination with detailed spectral analysis in wide microwave band; - development of methods and software to restore 3D structure of magnetic fields in the solar corona as based on combined 3 or 4 methods to measure magnetic field from spectral-polarization analysis of different structures of the microwave solar radio emission.

References

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