MICROWAVE AND SOFT X-RAY RADIATION DURING FLARES EVOLVING IN STRONG MAGNETIC FIELDS

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Abstract. Microwave and soft X-ray bursts associated with Hα flares protruding over major sunspot umbrae are studied. The probability for a detectable microwave radiation is larger in flares protruding over umbrae with a stronger magnetic field. The peak fluxes of microwave radiation measured at about 3 GHz are exponentially larger for stronger umbral fields. The slope of the established relation is independent on the importance of the flares in the sample. The soft X-ray flux data measured onboard the GOES satellite were used to estimate the effective plasma temperature in the flaring volume. Statistically, the temperature is higher in flares occuring in stronger magnetic fields.

1. Introduction

The relation between flare characteristic and the underlying photospheric magnetic fields was studied in a number of papers. The energy release in flares often intensifies when the chromospheric flare ribbon "penetrates" into a region of stronger magnetic fields, usually seen as a "contact" of the ribbon and a sunspot (Dodson and Hedeman 1960, Martres and Pick 1962, Dodson and Hedeman 1970, Hagen and Neidig 1971, Axisa et al. 1973, Zanelli, Zlobec and Koren 1980, Kosugi 1982, Dwivedi et al. 1984, Ruždjak et al. 1986, Vršnak et al. 1987a, 1987b). Several aspects of the relation between the magnetic field and flare characteristic were presented in a series of papers by Ruždjak et al. (1987, 1989) and Zlobec et al. (1990). Three categories of spotless flares (flares occuring far from sunspot groups) were established in the study of their Hα morphology, X-ray, microwave and metric radio emission, revealing that different amounts of energy are released, depending on the magnetic field environment (Ruždjak et al. 1987). The soft X-ray emission from spotless flares (further denoted as G-flares), "normal flares" (flares appearing in sunspot groups but not pro-
truding over major sunspot umbrae (further denoted as N-flares) and Z-flares (the flares "covering" major sunspot umbrae) was compared, and an energy scaling was found, as well as a statistical difference in the deduced effective temperatures (Ruždjak et al. 1989). Finally, the probability of type III radio burst appearance (evidence of electron beam propagation) in Z-flares was studied (Zlobec et al. 1990). Also a difference between the dynamical and compact flares (Švestka 1985) was found, however in both cases the probability for type III emission was larger in flares associated with a stronger underlying magnetic field. The dependence of the type III occurrence on the flare location within the bipolar region was confirmed as well (Axisa 1974).

In this paper we present the study of the properties of microwave and soft X-ray radiation in Z-flares. We selected a sample of 270 Z-flares which were not overlapping in time with other flares and had reported magnetic field strengths of the underlying spots. The flare data of the Kanzelhöhe and Hvar observatories were checked to reduce the probability of eventual erroneous reports in Solar Geophysical Data (SGD). The sample consisted of 186 subflares, 63 flares of importance 1 (imp=1), 15 flares of imp=2 and 6 imp=3 flares. A δ-class magnetic field configuration was notified if reported, as well as a unipolar configuration. The magnetic field (B) of the spots "covered" by Hα emission was taken from the Solnechnye Dannye Byulleten' (SDB) and will be further expressed in Tesla. The field strengths reported in SDB might not be accurate in individual cases, but can be considered of sufficient accuracy for statistical studies.

2. Properties of Microwave Radiation

Investigating the probability of type III bursts (Zlobec et al. 1990) we have revealed that the probability of the observable microwave emission in the range of 3 GHz is related to the magnetic field strength. The radiation at about 3 GHz was chosen for the study, since it reveals the presence of trapped accelerated particles (Krüger 1979).

For 97 flares from our sample (36%) no microwave bursts were reported, indicating that the flux ($F_{\mu\nu}$) was below the instrumental threshold. We show the probability for a microwave burst above the observational threshold in Fig. 1a. The results are presented separately for subflares and flares (imp=1,2,3) to reduce the effect of the flare importance. The values represent the probabilities in four intervals of the magnetic field strength: $B \leq 0.20$, $0.21 \leq B \leq 0.25$, $0.26 \leq B \leq 0.30$ and $0.31 \leq B$. The presented probabilities are averages of five values obtained for each 0.01 T step within a given 0.05 T interval and the error bars are the related standard deviations.

The probability for the simultaneous appearance of a type III burst in the case when a microwave burst was reported, was also considered in order to investigate if the escape of the accelerated electrons and electron beam creation are also governed by the magnetic field strength. The results are presented in Fig. 1b.

The distribution of peak fluxes is presented in Fig. 2 where we included only subflares in order to reduce the dependence on the flare importance. The peak fluxes
Fig. 1. (a) Probability of microwave burst appearance as a function of the magnetic field intensity $B$ presented separately for subflares (squares) and for the whole sample of flares (circles). The mean values are given, as well as the standard deviations for groups of five 0.01 T steps within an 0.05 T interval. (b) Probability of type III bursts associated with flares having a registered microwave burst.

Fig. 2. Distribution of microwave burst intensities (classes: 1, 2, 3 and 4 represent $F_{\mu\nu}=0$, $0<F_{\mu\nu}\leq10$, $11\leq F_{\mu\nu}\leq100$, $101\leq F_{\mu\nu}$, respectively) for three intervals of the magnetic field strength: (a) $B\leq0.2$, (b) $0.21\leq B\leq0.25$, (c) $B>0.25$, where only subflares were taken into account. Note that the number of flares in the intensity classes 1 and 2 decreases with increasing $B$, while it increases in the classes 3 and 4.

are divided into classes: 1) $F_{\mu\nu}=0$ sfu; 2) $0\leq F_{\mu\nu}\leq10$ sfu; 3) $11\leq F_{\mu\nu}\leq100$ sfu; 4) $F_{\mu\nu}>100$ sfu, and the distribution is presented separately for three intervals of $B$: a) $B\leq0.20$, b) $0.21\leq B\leq0.25$, c) $0.26\leq B$. Fig. 2 indicates a shift of the distribution towards higher fluxes for stronger magnetic fields, as the number of flares in the flux intervals 1 and 2 decreases, while it increases in the intervals 3 and 4 for stronger magnetic fields. The average values of microwave fluxes in the chosen intervals of $B$ are: $5.6\pm17$ sfu; $9.6\pm19$ sfu; $21.3\pm34$ sfu, respectively.

Fig. 3. Mean microwave peak fluxes presented in the logarithmic scale as a function of the magnetic field intensity $B$, separately for imp=1,2,3 flares (circles and the solid line) and subflares (dots and the dashed line).

Fig. 4. The soft X-ray flux presented as a function of magnetic field strength. The mean value $\log F_\nu$ is presented for three intervals of the magnetic field strength.
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The mean peak fluxes ($F_{\mu\nu}$) taken as averages of $F_{\mu\nu}$ over all flares with the same magnetic field strength for each $\Delta B=0.01$ step are shown in Fig. 3 in the logarithmic scale (dots: subflares, circles: imp=1,2,3 flares). The solid line represents the exponential fit for imp=1,2,3 flares (superscript f) and the dashed line the exponential fit for subflares (superscript s):

$$\log F_{\mu\nu}^f = (6.0 \pm 0.9)B + (0.82 \pm 0.22)$$ (1)

$$\log F_{\mu\nu}^s = (6.2 \pm 0.4)B - (0.50 \pm 0.10)$$ (2)

where the statistical weights of the values presented in Fig. 3 were taken into account. Equations (1) and (2) show that $F_{\mu\nu}^f/F_{\mu\nu}^s=20$ and that the slopes are almost equal.

Microwave radiation at 3 GHz is an evidence of accelerated particles trapped in the magnetic field (Krüger 1979). A stronger photospheric magnetic field indicates a stronger overlying coronal magnetic field. Generally it is assumed that the acceleration process is more effective in stronger fields (Spicer 1977), and moreover, gyrosynchrotron radiation is more efficient (Tucker 1975). This is also consistent with the fact that the energy release intensifies when the flare ribbon approaches the umbra of a spot (Dwivedi et al. 1984, Ruždjak et al. 1986, Vršnak et al. 1987a, 1987b). Fig. 1b illustrates that the probability for the escape of the accelerated particles and beam formation also depend on the magnetic field strength (Zlobec et al. 1990), and not only on geometry, as found by Axisa (1974).

3. Properties of soft X-ray radiation

For measurements and study of soft X-ray bursts 74 Z-flares from our sample were suitable. The fluxes were registered by the GOES-satellite in the 1–8 Å and 0.5–4 Å channels and given in SGD. We denote the peak fluxes measured in these GOES channels as $F_s$ and $F_t$, respectively. The selected flares were not overlapping in time with other flares. The precision of the flux values used, was determined by the accuracy of the data given in SGD. The sample used for the study of soft X-ray bursts consisted of 17 subflares, 36 imp=1 flares, 16 imp=2 flares and 5 imp=3 flares. An effective temperature of the soft X-ray emitting plasma was estimated from the ratio of fluxes in the two GOES channels ($R$) according to Thomas, Starr and Cranell (1985).

Investigating a sample of Z, N and G flares observed at Kanzelhöhe and Hvar observatories during the Cycle XXI Ruždjak et al. (1989) have found that the peak flux values $F_s$ are in average scaled from G over N to Z flares, indicating qualitatively that flares occurring in stronger magnetic fields produce more intense soft X-ray bursts. In this paper we compare the flux $F_s$ directly with the measured magnetic field strength in the underlying umbra for Z-flares. The magnetic field intensity was divided in three intervals: $B \leq 0.2$, $0.21 \leq B \leq 0.25$ and $0.26 \leq B$, and each interval contained roughly the same number of flares with different importances. In Fig. 4 we show the relation $\log F_s(B)$, and the linear least square fit of the form $\log F_s=8.5B-6.5$. 

Fig. 5. (a) Distributions of the soft X-ray parameter $R = R_1/R_3$ presented for three classes (1: $R \leq 0.1$, 2: $0.1 < R \leq 0.2$, 3: $0.2 < R$) separately for three intervals of magnetic field strength ($B \leq 0.2$, $0.21 < B \leq 0.25$, $0.26 \leq B$). (b) The dependence $\bar{R}(B)$ (circles and solid line) for $\Delta B = 0.05$ T intervals, and corresponding effective temperatures (crosses and the dashed line).

In Fig. 5a we present the distribution of the values of the parameter $R = R_1/R_3$ for three categories: 1) $R \leq 0.1$, 2) $0.1 < R \leq 0.2$, 3) $0.2 < R$, separately for three intervals of $B$: A) $0.20 \leq B$, B) $0.21 < B \leq 0.25$, C) $0.26 \leq B$. The categories contained 10, 39 and 25 flares and one finds the average values of $B$ as: 18.2±1.3; 23.6±1.4 and 27.7±1.5, and the corresponding average values of the parameter $R$ as 0.116±0.038, 0.143±0.069, 0.202±0.037, respectively (Fig. 5b). Fig. 5a illustrates a shift in the distribution towards higher $R$ values in stronger magnetic fields. Fig. 5b shows the dependence $\bar{R}(B)$.

The dependence $R(B)$ is presented for all flares in Fig. 6a. Subflares are indicated by crosses and flares of imp=1,2,3 by circles. Bold, dashed and thin lines represent the linear least square fit for imp=1,2,3 flares, subflares and the whole sample respectively, and the relations are:

$$R_f = (0.98 \pm 0.21)B - (0.067 \pm 0.052)$$ \hspace{1cm} (3)

$$R_s = (0.70 \pm 0.35)B - (0.053 \pm 0.085)$$ \hspace{1cm} (4)

$$R_{all} = (0.96 \pm 0.20)B - (0.075 \pm 0.050)$$ \hspace{1cm} (5)

with the coefficients of correlation of 0.53, 0.46 and 0.50.

The values of the parameter $R$ provide an estimate of the effective temperature in the soft X-ray emitting region (Thomas, Starr and Cranell, 1985). In Fig. 6b we present $T_{eff}(B)$ where the circles represent imp=1,2,3 flares and the squares represent subflares. Each point in Fig. 6b represents the average value for a group of neighbouring points where each group has approximately the same number of representatives. To relate the thermal energy to the magnetic field energy we performed the least square fits of the form $T = aB^2 + T_0$. Considering the original sample presented in Fig. 6a, the fit for the whole sample, the fit for the sample consisting only of imp=1,2,3 flares and the fit for the sample embracing only subflares give:


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Fig. 6 (a) The values of the parameter R as a function of B presented separately for imp=1,2,3 flares (circles and the solid line) and subflares (crosses and the thin dashed line). The thick dashed line represents the fit for the whole sample. (b) Using values of the parameter R, the effective temperature is estimated. Groups of neighbouring points (each group containing approximately the same number of points) are averaged to emphasise the nonlinearity of $T(B)$. Circles represent imp=1,2,3 flares and dots represent subflares. The fits of the form $T=aB^{\alpha}+T_0$ are obtained using all the points presented in Fig. 5a.
\[
T = (89 \pm 20)B^2 + (6 \pm 1) \\
T^f = (89 \pm 20)B^2 + (7 \pm 1) \\
T^s = (70 \pm 30)B^2 + (6 \pm 2)
\]  

where \( T \) is expressed in \( 10^6 \) K. The coefficients of correlation are 0.52, 0.54 and 0.52, respectively.

4. Discussion and Conclusions

Our study shows that microwave emission is statistically more intense when the underlying photospheric field is stronger. The soft X-ray radiation of a thermal plasma statistically shows an effective temperature which is larger for a stronger photospheric magnetic field. Assuming that the energy is released in a current sheet where the reconnection takes place and where strong induced electric fields are present, the ion–sound (or some other) turbulence should occur and in such a current sheet the plasma temperature should be proportional to the square of the Alfvén velocity in the inflowing region (Vršnak 1989). This relation is certainly modified by the "evaporation" process in the chromosphere, but still it should statistically depend on the original temperature of the current sheet i.e. Alfvén velocity, as is supported by the statistical dependence \( R(B) \) presented in Sect. 3. In a two–dimensional representation one can express the conservation of the magnetic flux in the form:

\[
u_{ch} B_{ch} = u_c B_c
\]

where \( v_{ch} \) is the velocity of the ribbon front expansion, \( B_{ch} \) is the chromospheric magnetic field, \( u_c \) is the reconnection velocity (velocity of plasma inflowing into the current sheet) and \( B_c \) is the coronal magnetic field. The 3–D effect can be introduced by a parameter showing the dispersion of field lines in the third dimension. So, the induced electric field \( E_r = u_c B_c \) is related to the underlying magnetic field. On the other hand, this induced field can accelerate particles either directly, or by collective plasma processes (Melrose 1980).

References

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Izvorni znanstveni članak

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Sažetak. Istražuju se provale mikrovalnog i mekog rendgenskog zračenja povezane s Ha bljeskovima koji se protežu iznad umbri velikih pjega. Vjerovalnost zamjetljivosti mikrovalnog zračenja raste s jačinom magnetskog polja prekrivene umbre. Slično, maksimumi toka mikrovalnog zračenja izmjerenog na frekvenciji od oko 3 GHz eksponencijalno rastu s jačinom magnetskog polja prekrivene umbre. Oblik ustanovljene relacije ne ovisi o važnosti bljeska. Za ocjenu efektivne temperature plazme u volumenu zahvaćenom bljeskom korištena su mjerenja toka mekog rendgenskog zračenja sa satelita GOES. Ustanovljeno je da je statistički temperatura plazme viša u bljeskovima koji se odvijaju u jačim magnetskim poljima.