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HIGH RESOLUTION OBSERVATIONS OF SOLAR RADIO AND X-RAY BURSTS AND THEIR INTERPRETATION

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Abstract

High resolution observations in the radio range from the ground and X-rays from satellites during the past few years have provided new insights into the nature of emission processes and energies of solar eruptions. It is becoming increasingly clear that the strength, evolution, and structure of magnetic fields play a fundamental role in the burst mechanisms in the corona. Magnetic changes that occur before solar flares provide important clues on the interaction between emerging coronal loops and existing two or more loops, resulting in magnetic reconnection and triggering the release of microwave and hard X-ray emission. In this overview, the recent results pertaining to some microwave and hard X-ray events are presented. Their interpretation in terms of coronal physics is given. It is obviously clear that to remain in the forefront of research in solar physics in the next decade we have to consider seriously to set up dedicated high resolution multifrequency microwave observation facility and at the same time have our solar hard X-ray monitor payload in one of the Indian scientific satellites to be launched in the near future.

1. Introduction

In 1960's and 1970's, solar radio astronomers increasingly realised the importance of high resolution microwave observations over a wide frequency range and particularly from solar active regions since these regions have intense magnetic fields. The microwave observations provide direct measurement of the strength and structure of magnetic fields in the transition region between the photosphere and the corona and in the low coronal region. The brightness temperature of microwave emission under nonflaring condition increases with wavelength from 6000 K at 2 mm in the low chromosphere to $\sim 10^6$ K at 20 cm in the low corona and exhibits high degree of circular polarization due to the presence of intense magnetic fields. The dominant emission mechanism, whether thermal bremsstrahlung and/or gyroresonance, depends upon the wavelength and the physical situations prevalent in the active region. When gyro-resonance process dominates, the circularly polarized radiation is emitted at the second or third harmonic of the gyro-frequency. It is possible to infer the longitudinal magnetic field strength from the degree of circular polarization and the optical depths (Kundu and Lang, 1985).

The emergence of aperture synthesis technique at radio wavelengths in 1970's provided information on microwave source sizes that could be compared with high resolution H-alpha and X-ray pictures. These observations showed that the impulsive component of microwave bursts usually came from the top of magnetic loops and changes in brightness and polarization occurred well before solar flares (Marsh and Hurford 1982, Kundu and Vlahos 1982). In recent years, multiple wavelength observations and snapshot synthesis mapping are increasingly becoming available with 1 arcsec angular resolution and 10 sec in time. With still greater resolutions planned, important advances are expected to be made in the near future in understanding the three-dimensional structure of active regions and burst phenomena.

One of the most outstanding features that has withstood the test of time is the establishment of close similarity of time profiles between microwave and hard X-ray bursts during flares. This suggests of a single population of energetic electrons giving rise to these two kinds of emissions. The production of energetic electrons in the impulsive phase of many solar flares is a basic feature for the emission of X-rays from electron bremsstrahlung and microwaves from gyro-synchrotron radiation (Takakura 1972; Kane 1974). High energy X-rays and microwave emission have shown very good temporal correlations, right from rapidly varying time structures of one second or less to durations of tens of minutes (Parkes and Winkler 1969; Kane and Anderson 1970; Frost and Dennis 1971; Takakura et al. 1983a, b). Hence it is widely believed that observations of solar hard X-rays and microwaves provide the most direct clue to the spectrum and flux of energetic electrons during flares and their subsequent evolution.

It has been possible to make deductions about evolution of electron population on the basis of theory and observed hard X-ray and microwave spectrum during solar flares (Batchelor 1984). However, the observations are not yet highly spatially resolved, without which the characteristics of the source region in which electrons interact cannot be uniquely found from the analysis of either X-rays or microwaves alone. But by combining the information of both kinds it is possible to specify the density, magnetic field, volume of the source region, electron distribution and temperature, etc. (Hoyng et al. 1976; Crannel et al. 1978; Martens et al. 1985).

2. High Resolution X-ray and Microwave Observations

With the launch of Solar Maximum Mission satellites by NASA in 1980 and the Japanese Hinotari satellite in 1981, thousands of solar hard X-ray events were observed upto 1982-83, in the period when the solar activity was maximum. The X-ray photons were counted over the energy range from about 20 keV to 400 keV at very high time resolution of ~10 milliseconds. Figure 1 shows an example of hard X-ray time profile and microwave time profile at 17 GHz for the solar event observed on August 11, 1981 and October 15, 1981. The X-ray intensity is in counts per sec and is shown for three channels only for convenience, though the data exists for all the seven channels covering the energy range from 30 to 360 keV. These data were obtained from the Japanese Hinotari satellite and the microwave data from Nobeyama Solar Observatory in Japan. It can be seen from Figure 1 that there is a time delay between the peaks of occurrence of low energy X-rays and that of microwaves at 17 GHz on August 11, 1981 whereas no time delays are observed for the event on October 15, 1981. This is an important point which has been discussed in detail by Takakura et al (1983b) and Degaonkar (1985) as it gives information on the time required for electron acceleration from low to high energies during solar flares in a single or two step process.

From observations of a gradual type of solar hard X-ray event observed on April 1, 1981 it was found that the low energy end from 30 to 40 keV shows the highest X-ray counts for about 30 minutes beginning 0129 UT, in individual peaks well separated in time. The common feature is that the count rate decreases with increasing energy of X-rays. The hard X-ray spectra are obtained by plotting the observed photon flux as a function of energy at any short time interval of 2 to 3 seconds. The spectra are fitted with simple thermal model spectrum also. It was surmised that the thermal model shows a better fit with the observed values at 0153 UT while the nonthermal model fits better at 0135 and 0156 UT. The power law index is typically about 3.5 and the electron temperature about 10^8 K.

Takakura et al. (1982) have obtained the hard X-ray source images in two dimensions with spatial resolution of about 10 arc sec from solar X-ray telescope onboard the Hinotari satellite. They found that the image appears stationary throughout the time period depicting a loop like structure projected on the solar disk. Bipolar sunspots are found to be located near the foot points of the loop. A comparison of the X-ray image with an one-dimensional brightness distribution scan at 35 GHz during the same event shows that the radio peak coincides very well with the centre of the X-ray image indicated by a cross. This shows that the microwave emission at 35 GHz due to gyro-synchrotron process by MeV electrons takes place in the same loop as the X-ray source.

Degaonkar (1985) has studied the X-ray and radio spectra during some impulsive and gradual events observed in 1981 and derived the source parameters by fitting simple thermal model spectra. The radio spectra for the six events at the time of the peak intensity are shown in Figure 2. The shape of the spectra changes from event to event and so it is not easy to interpret them. The turnover frequency from optically thick low frequency region to optically thin high frequency region occurs usually around 10 GHz. From the observed flux at the turnover frequency, it is possible to calculate the burst source parameters and the source size assuming gyro-synchrotron mechanism to be operative (Crannel et al. 1978; Takakura 1972; Degaonkar et al. 1981). Wiehl et al. (1985) have derived similar results using SMM X-ray data and microwave data at Bern for 13 strong events. They tried a single temperature and multi-temperature models to fit the data but no clear answer could be obtained.

3. Relation Between Hard X-rays and Microwaves

Kai et al. (1985) found approximate relations by plotting microwave peak fluxes at 17 GHz against hard X-ray peak fluxes integrated over 67-152 keV for 55 impulsive bursts with duration shorter than 10 min and 6 extended bursts with duration longer than 10 min. The dependence of radio flux on X-ray flux is given by $F_R = 37.2\ F_X^{0.77}$ for impulsive bursts and $F_R \approx 60\ F_X^{1.1}$ for extended bursts with scatter of data points less than 0.3 orders of magnitude r.m.s. The main features that emerge from their study are: (i) the scatter of points is strikingly small though the physical conditions are expected to vary unsystematically from one flare to another, and (ii) the extended bursts are in general more intense than impulsive bursts. The explanation for these has to be sought in the magnetic field values and the total number of electrons at the burst source. It appears that the energertic electrons are more abundant than previously thought and the electron energy distribution has an extended tail towards high energy from 1 MeV to 10 MeV with reduced power-law index.

4. High Resolution Synthesis Maps

Instruments like Westerbork Synthesis Radio Telescope in Holland and Very Large Array in USA have provided high angular resolution maps of solar active regions at multiple wavelengths, mainly at 2, 6 and 20 cm. The emission at these wavelengths originates at different heights within the coronal loops which bridge sunspots of opposite magnetic polarity. Synthesis maps of total intensity show the two-dimensional distribution of brightness temperature of the source while those of circular polarization of Stokes parameters show the two-dimensional structure of longitudinal magnetic field. With height information of microwave structures inferred from their angular displacement from photospheric features and with multi-wavelength maps, it is possible to construct the three dimensional structure of active regions. The following table summarises the properties of the quiescent radio emission from active regions.

Table 1

Quiescent Radiation from Active Regions

λ, cm	Emission height above sunspot, km	Magnetic field, gauss	Brightness Temp. °K	Mechanism
2	5×10^3	10^3	10^5	Thermal-Bremsstr.
6	3×10^4	600	3×10^6	Gyro-radiation
20	10^5	200	3×10^6	Gyro-resonant/ Thermal Bremsstr.

Apart from quiescent radiation from solar active regions, occasionally solar eruptions take place in the form of powerful bursts which last for short durations. The magnetic fields in the active regions provide the energy needed for those eruptions. Much work has gone into understanding the nature of these bursts, their energetics and their occurrence probability. The VLA results indicate preflare changes in intensity and polarization of microwave emission due to preburst heating in coronal loops and to changes in the coronal magnetic field configuration. Single coronal loops or arcades of loops begin to heat up about 15 minutes before the impulsive burst takes place. Preburst activity is also detected in coronal loops which exist near the site of bursts. New bipolar loops can emerge and interact with the existing ones and current sheets can be produced when loops with different polarities interact. These current sheets can trigger the bursts.

The microwave bursts are characterized by a strongly polarized compact with scale sizes 5 arc sec to 30 arc sec impulsive component showing brightness temperature of 10^7 to 10^9 K and lasting between 1 and 5 minutes. A post-burst component which is larger in size and longer in duration follows the impulsive component which is due to the gyro-synchrotron radiation by mildly relativistic electrons having energies of the order of 500 keV. The impulsive emission is seen to come from the top of the loop whose footpoints manifest in the H-α kernels seen on the two sides of the loop. The gradual component is larger and elongated along the magnetic field lines joining the H-α kernels. Evidence for sequential triggering of microwave bursts in adjacent coronal loops for intense bursts and in the same loop for weak bursts was given by Kundu and Lang (1985).

The general interpretation is that in the arcade model of flares the energy release takes place in the coronal part of the loop or loops through magnetic reconnection. A non-thermal tail of high energy electrons (> 100 keV) would be produced at this time. The hot plasma within the conduction fronts moves downward towards the footprints of the loop with ion-acoustic velocity (Brown et al. 1979, Smith and Lilliequist 1979). Electrons moving faster than the ion-acoustic velocity will not be confined and so will penetrate deeper into the lower loops and would produce high frequency microwaves by gyro-synchrotron process and hard X-rays by bremsstrahlung. The escaping electrons are unstable to the generation of electro-static plasma waves which scatter the particles in pitch angles to nearly isotropic distribution (Holman et al. 1984), which in turn enhances the microwave emission from the upper part of the loop. The loop in the optically thick region thus looks larger than in the optically thin region and the loops sometimes drift radially toward the limb as indicated by the movement of the source in the impulsive events or alternatively it could be due to sequential triggering of emission at higher levels in the corona.

5. Discussion and Conclusions

Crannel et al. (1978) deduced the X-ray and microwave parameters using OSO 5 hard X-ray data for 22 events observed in the 1969-70 in the previous solar activity maximum period. However, the solar activity in that cycle was considerably lower than in the recent solar cycle which had maximum in 1979-81. Consequently, Degaonkar (1985) found that the values of source parameters such as temperature, emission measure, volume and total energy were considerably higher in 1981 than those obtained by Crannel et al. (1978).

Sub-second time structures in X-rays and microwaves have been reported by Takakura et al. (1983a) and the energy dependent time delays in X-rays and the frequency dependent time delays in microwaves are discussed in depth by Takakura et al. (1983b). They found that the time delays between the peaks of X-rays and microwaves are generally one second or less in most impulsive bursts but delays of 5 second or more are noted in some exceptional cases having gradual rise time profiles. In those events where the time of peak intensity shifts with increasing energy of X-rays, the peak associated with microwave burst at 17 GHz (or perhaps are still higher frequency) nearly coincides

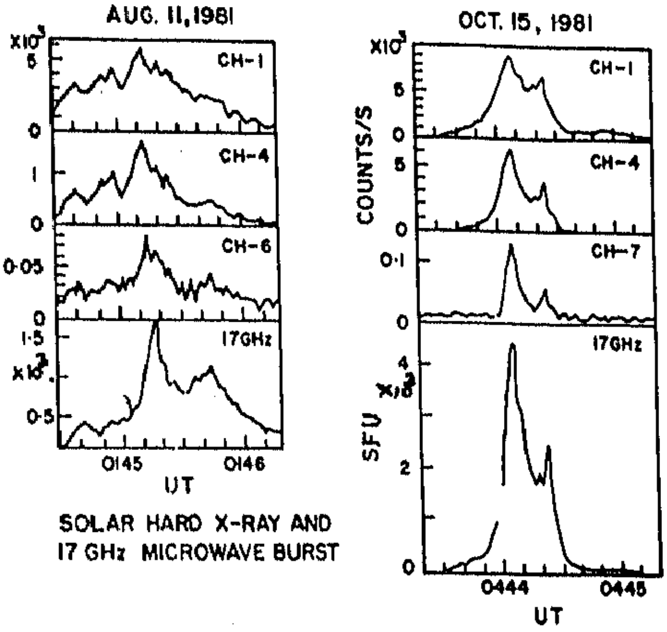

Fig.1. Impulsive solar hard X-ray and microwave burst at 17 GHz observed on August 11, 1981 and October 15, 1981, showing time delay and no time delay respectively between the X-ray and microwave peaks. Only a few channels in X-ray data are shown as examples. Note the high temporal correlation between X-rays and microwaves (From Degaonkar 1985)

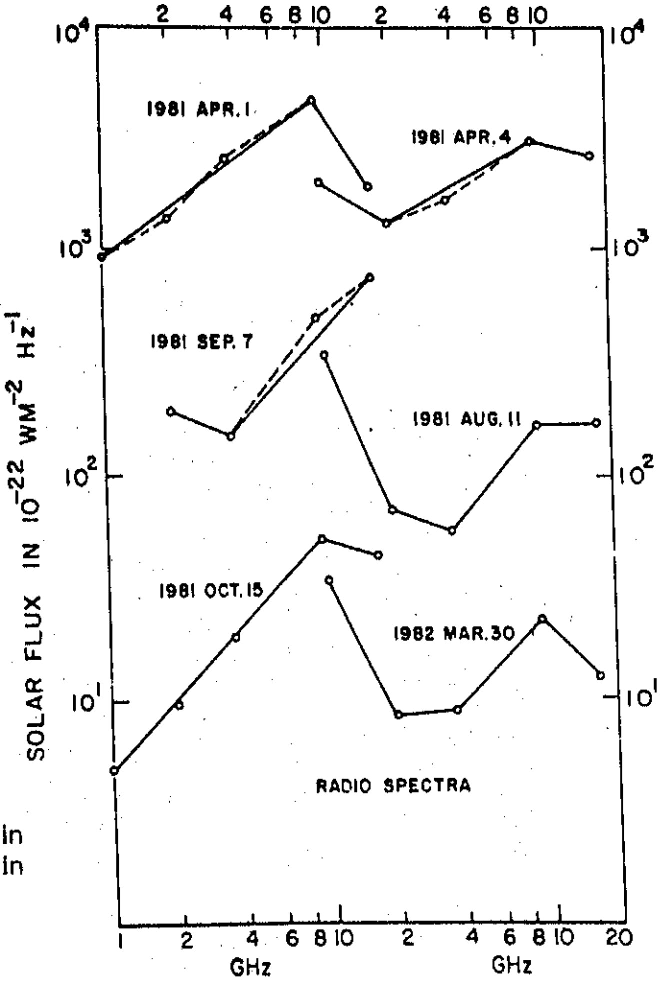

Fig.2. Radio spectra during six solar events in 1981-82. Note the complex spectral shapes in each case (From Degaonkar 1985)

with that of the X-ray burst in the high energy range. This is understandable since the gyrosynchrotron emission from solar flares at high frequencies is due to high energy (above 100 keV) electrons (Takakura 1972). The low energy electrons however make the source optically thick (optical depth greater than unity) at low frequencies due to self absorption of radio emission. The observed time delays from low energy X-ray peak to that of high energy may be viewed as the time taken for electrons to get accelerated in one or more steps. To understand this process thoroughly, we need to have the high energy X-ray spectra above 360 keV with good time resolution of 1 sec or less. Long time delays between X-rays and microwaves in gradual events could be considered as the time taken for the increase of the total number of electrons above 300 keV as compared to that below 100 keV and also to the temporal increase in the size of the burst source in the optically thick part of microwave frequencies.

The microwave spectra in general are more complex and it is uncommon to find a spectrum truly varying with the square of the frequency as it would be in the case of a blackbody emission. In many cases, the U-shaped spectra appear in the microwave band following large solar flares indicating proton events. The radio emission at frequencies higher than about 10 GHz is guided by the strength of high energy tail of the velocity distribution of the electrons.

In conclusion, we would like to emphasize that the high resolution observations in hard X-rays and microwaves over a wide frequency range will provide rich material for understanding the physical processes in the solar chromosphere-coronal region. To achieve that end we must establish appropriate experimental programmes well before the next solar activity maximum expected in 1990-91.

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References

Batchelor, D.A. 1984. Ph.D. Thesis, NASA/GSFC TM 86102.
Brown, J.C., Melrose, D.B. and Spicer, D.S. 1979. Astrophys. J. **228**, 592.
Crannell, C.J., Frost, K.J., Matzler, C., Ohki, K., and Saba, J.L. 1978. Astrophys. J. **223**, 620.
Degaonkar, S.S. 1985. Paper presented at Workshop on Radio Continua during Solar Flares, Trieste, Italy, May 27-31.
Degaonkar, S.S., Alurkar, S.K., Bhonsle, R.V., Calla, O.P.N. and Lokanadham, B. 1981. Bull. Astr. Soc. India, **9**, 291.
Frost, K.J. and Dennis, B.R. 1971. Astrophys. J. **165**, 655.
Holman, D.G., Kundu, M.R. and Papadopoulos, K. 1984. Astrophys. J. **257**, 354.
Hoyng, P., Brown, J.C. and Van Beek, H.F. 1976. Solar Phys. **48**, 197.
Kai, K., Kosugi, T. and Nitta, N. 1985. Publ. Astron. Soc. Japan, **37**, 155.
Kane, S.R. 1974, in IAU Symp. 57, Coronal Disturbances, ed. by Newkirk, Jr. (Dordrecht: Reidel) pp.105-141.
Kane, S.R. and Anderson, K.A. 1970. Astrophys. J. **162**, 1003.
Kundu, M.R. and Lang, K.R. 1985. Science, **228**, 9.
Kundu, M.R. and Vlahos, L. 1982. Space Sci. Rev. **32**, 405.
Marsh, K.A. and Hurford, G.J. 1982. Annu. Rev. Astron. Astrophys. **20**, 497.
Martens, P.C.H., Van den Oord, G.H.J. and Hoyng, P. 1985, Solar Phys. **96**, 253.
Ohki, K., Nitta, N., Tsuneta, S., Takakura, T., Makishima, K., Murakami, T., Ogawara, Y. and Oda, M. 1982. Proc. Hinotori Symp. on Solar Flares, Published by ISAS, Tokyo, pp.69-88.
Parks, G.K. and Winckler, J.R. 1969. Astrophys. J. Letters, **155**, L117.

Smith, D.F. and Lillequist, C.G. 1979. Astrophys. J. **232**, 582.

Takakura, T. 1972. Solar Phys. **26**, 151.

Takakura, T., Ohki, K., Tsuneta, S., Nitta, N., Makishma, K., Murakami, T., Ogawara, Y. and Oda, M. 1982. Proc. Hinotori Symp. on Solar Flares, Published by ISAS, Tokyo, pp.142-161.

Takakura, T., Kaufmann, P., Costa, J.E.R., Degaonkar, S.S., Ohki, K. and Nitta, N. 1983a. Nature, **302**, 317.

Takakura, T., Degaonkar, S.S., Ohki, K., Kosugi, T. and Enome, S. 1983b. Solar Phys. **89**, 379.

Wiehl, H.J., Batchelor, D.A., Crannell, C.J., Dennis, B.R. and Price, P.N. 1985. Solar Phys. **96**, 339.