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OBSERVATIONS ON THE FINE STRUCTURES IN SOLAR DECAMETRIC RADIO EMISSION

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Abstract

The solar decametric radio emission consists of a variety of fine structures. This reflects the complexity of the corona at this level. Two observations, viz. absorption bursts and short duration narrow band bursts are presented. An interpretation of each of these observations is provided.

1. Introduction

The solar decametric radiation emanates from the region of 1-2 solar radii. The decametric noise storms consist of a continuum which may last for one to several hours. Superimposed over this continuum are a variety of fine structures. The most often observed features are the type III, type IIIb, drift pairs, S bursts and so on (Sawant 1982). However, there are large periods of time when the continuum alone is observed (Gergely and Kundu 1975). In addition to the above mentioned fine structures, Sastry et al. (1983) observed sudden reductions in the decametric continuum called the absorption bursts. Also, short duration narrow band bursts which have a small drift rate were observed recently (Gopalswamy et al. 1983b). In this paper, we discuss the absorption bursts and the short duration narrow band bursts and provide a physical interpretation for them. These observations provide information about the complex magnetic structure in the outer corona. The decametric corona is one region to which sufficient attention has not been paid. The significance of this region is reflected in the following facts: (i) the co-rotation of the corona ceases at this level (ii) the magnetic field configuration changes predominantly from closed to open field structures (iii) new spectral features appear which are absent in the higher frequency region.

Our observations do not always have flare associations. Hence, the physics of these observations pertains to the 'quiescent' corona by which we mean that the changes in magnetic field are small and may correspond to the signatures of an evolving active region. The examples we are considering seem to reflect the 'transition' character of the magnetic field in the decametric corona. The short duration narrow band bursts which occur relatively rarely may correspond to the existence of closed magnetic field configurations while the absorption bursts indicate open field lines. Both these configurations are possible as it is a transition region.

2. Absorption Bursts

2.1. Observations

The absorption bursts are seen as dips in the continuum flux for a short duration. Detailed observations are provided elsewhere (Sastry et al. 1983, Gopalswamy et al. 1983a). The most important characteristics can be summarised as follows:

(i) The absorption duration, on an average is about 2-3s,

(ii) The absorption bursts occur over a relative bandwidth of about 5%,

(iii) The absorption bursts do not have any drift in the frequency time plane,

(iv) Large number of absorption bursts have a simple time structure. However, there are double and triple structures observed and sometimes multiple time structures,

(v) The intensity reductions are $\gtrsim$ 40%.

Typical examples are shown in Fig.1. The frequency observed is around 34.5 MHz.

2.2. Interpretation

The sudden reductions are also observed in high frequency levels. (e.g. Benz and Kuijpers 1976, Fokker 1982). The cause of absorption depends upon both the generation and propagation characteristics of the continuum radiation. Since the radiation generation and their propagation outwards are different at different frequency regions, the interpretation should take account of these facts. So, one can classify the interpretations into two catagories:

(i) Absorption at the generation stage where the process of plasma wave generation or the process of conversion of plasma wave into electromagnetic radiation could be stopped temporarily to cause the observed reduction,

(ii) Absorption could be attributed to the propagation effect in that a

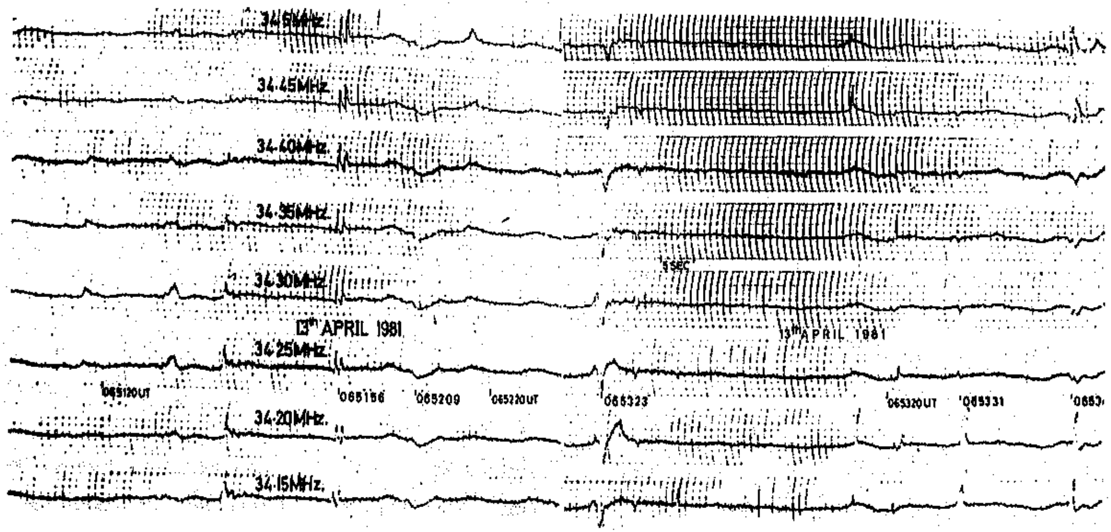

Fig.1. Eight channel record of absorption burst obtained on April 13, 1981. The ordinate is the intensity of radio emission. The absorption bursts are at 065323 UT and 065209 UT.

'screen' is present on the path of the radiation for a short while that causes the intensity reduction.

Benz and Kuijpers (1976) regarded that the sudden reduction in the decimetric continuum must be due to filling of loss cone of electron distribution trapped in the closed magnetic configuration which caused the decimetric continuum. While the loss cone is filled by the newly injected electrons, the loss cone instability for plasma waves is stopped and hence one sees a reduction in the radiation. Fokker (1982) pointed out the drawback of Benz and Kuijper's theory and proposed that the reduction could be due to inhomogeneities created on the path of radiation by solitons or shocks which impinge on the flux tubes into which the continuum radiation is ducted. The problem with Fokker's idea is that it needs open flux lines at decimetric levels which are quite rare.

If one wants to apply these theories to decametric continuum, one faces many difficulties. The decametric continuum is explained as a result of the Rayleigh scattering of enhanced plasma fluctuations caused by a diffuse electron beam along open magnetic field lines (Levin 1982). Since the theory of Benz and Kuijpers needs a closed field configuration, the loss-cone filling mechanism is not appropriate here. Fokker's (1982) idea contains the correct ingredients but one has to be sure of the ducting of continuum radiation at decametric region. There is no concrete evidence for the existence of low density plasma in the coronal streamers to cause the radiation ducting. Moreover, the inhomogeneities created by shocks are solitons of small scale lengths which may not be able to reduce the flux by 50%. Adhering to the idea of Fokker (1982) one must consider an important aspect of the shock waves such as the creation of low frequency turbulence in the shock front and its wake (Galeev, 1976). The extent over which the plasma turbulence exists is sufficiently large ($\sim 10^9$ cm) so that the large decametric continuum source of size 10' (Kundu, 1983) could be screened temporarily. When the continuum radiation passes through this region of turbulence, it interacts with low frequency turbulence (ion-sound turbulence is the one generated in the shock front and exists in the wake with a high level of energy density). The result is the generation of Langmuir waves at the expense of the continuum radiation. Once the Langmuir waves build up to a certain level, the reverse interaction of generation of radiation becomes important and hence the saturation occurs in the absorption. The ion-sound turbulence decays because there is no free energy available for its generation after the shock passage. Once the intensity of ion-sound turbulence falls below a critical level, there is no effective conversion of continuum radiation into Langmuir waves and hence the intensity recovers to the original continuum level. This critical level of ion-sound turbulence could be estimated from the requirement that the optical depth of the turbulence layer exceeds unity. From weak turbulence theory one can obtain the optical depth of the turbulence layer and calculate the critical level in terms of the effective temperature T_s of the ion-sound turbulence: $T_s > 2.4 \times 10^9$K. From the observed bandwidth and the scalelength of coronal inhomogeneity, one can obtain the linear extent of the turbulence layer as $\sim 10^9$ cm. The collisional damping time of the ion-sound turbulence is in the right range of observed duration of absorptions.

The non-drifting character of the absorptions support the fact that shock waves are propagating perpendicular to the radial magnetic field and hence perpendicular to the line of sight. A schematic model is proposed in Fig.(2), for the origin of such a shock wave. When an emerging magnetic field line opens in a neighbouring site, it can drive a low Mach number shock across the open field lines. The multiple fine structures could be interpreted as the passage of successive shocks. The different time structures would then correspond to the different time intervals between successive shocks. The mathematical details have been given by Gopalswamy et al.(1983a).

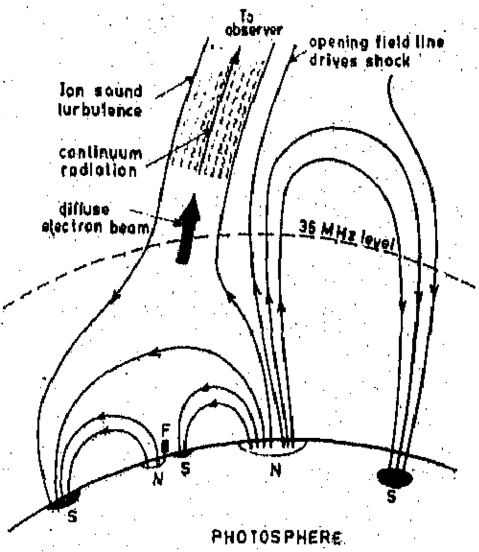

Fig. 2. A model for the absorption process.

If the shock propagates through the source region itself, then the enhanced plasma fluctuations will get converted into radiation which propagates perpendicular to the line of sight and hence one can observe a reduction in the continuum flux.

3. Short-duration Narrow-band Bursts

3.1. Observations

The short-duration narrow band bursts are identified as type I bursts at low frequencies. The solar origin of these bursts is established in several ways. Interference due to lightning, static ignition, etc. are of broad band with zero frequency drift. The broadcast interference is of narrow band but again, it has no frequency drift. The characteristics of these bursts could be summarised as follows: (see Fig.3).

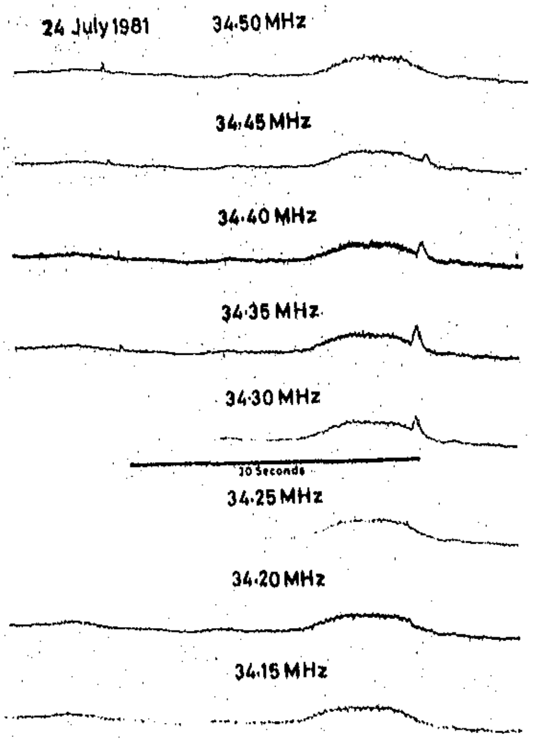

Fig. 3. Eight channel record obtained on July 24 1981. The ordinate is the intensity of radio emission.

(i) The frequency drift is very small which is ~250 KHZ S^{-1}.

(ii) The single frequency duration is ~300 ms.

(iii) The bandwidth is very narrow ~3%.

(iv) The single frequency duration increases with decreasing frequency. The total increase is ~100 ms.

(v) The bursts are superimposed over weak continuum.

The short duration narrow band bursts cannot be S-bursts (McConnel 1982) as the latter have very large drift rates. Though the drift rates are similar to type II bursts, one can rule out the possibility of type II because the type II's have a very large single frequency duration of several seconds. These bursts therefore have to be type I bursts. Since the occurence of closed magnetic fields in decametric region is relatively rare, the frequency of occurence of the type I bursts is also rare, which is consistent with the observations.

3.2. Interpretation

The bursts could not have been generated by electron cyclotron mechanism which is acceptable only when the plasma frequency is less than or close to the gyrofrequency of the electrons. The burst generation due to electron beam could also be ruled out because in this case the drift rates will be extremely large and contradict the observations. There is another possibility of getting the drift rate: a radio signal generated at a particular level is of finite extent in time. So, different Fourier components of the signal travel with different velocities because the refractive index is different for different frequencies. For such a process to be effective, a calculation of the dispersion measure shows that, the electron column density is extremely small and one may need six orders of magnitude more. Based on these facts one can clearly come to the conclusion that the bursts must be created by a weak shock wave moving out in the corona and can explain the observed slow drift.

Spicer et al. (1981) proposed the emerging flux theory to explain the type I bursts and the same thing is regarded as a working model (Wentzel 1982). The basic ingredients of the theory are two wave modes and a hot particle distribution. The high frequency wave mode is created by the hot particles. The low frequency mode produces the hot particle distribution by stochastic acceleration. The interaction between the two wave modes produces the radiation. The scenario is as follows. Newly emerging magnetic field pushes against the pre-existing coronal magnetic fields and produces shocks. In the shock front and its wake, a high level of lower hybrid (LH) waves are generated. Part of these LH waves stochastically accelerate electrons which are subsequently trapped in the closed magnetic arches and develop loss-cone anisotropy. The free energy in this electron distribution is fed into the upper hybrid waves (UH). A weak shock of slightly super Alfvénic velocity can generate the condition necessary for radio-emission and the drift rate of the bursts is the velocity of the shocks. The emerging flux theory can explain our observations. If the observed bursts are caused by a weak shock then the density jump across the shock should be directly related to the observed bandwidth. Therefore the observed bandwidth and the estimated shock velocity (from the drift rate) could be used in conjunction with the Rankine-Hugoniot relations to estimate the ambient magnetic field at decametric levels. The result is of the order of 1 G which is in very good agreement with other estimates such as frequency splitting and polarization measurements of type I bursts (ter Haar and Tsytovich 1980). This agreement is an indirect confirmation of the emerging flux theory in addition to some observational evidence provided by Karlicky and Jiricka (1982).

According to the emerging flux model, type I source is very tiny and the radiation is emitted instantaneously (Wentzel 1982).

The observed duration must be due to the finite extent of the generated radiation beam in which the rays making larger angle with the direction of the magnetic field lag behind those at smaller angles. This mechanism explains the short duration of the bursts. As the shock proceeds to lower frequencies, the extent of radiation beam may increase and also, there could be an increase in the range of angles in which the radiation is emitted. These two changes can cause increase in duration with decrease in frequency as observed. The weak continuum over which the bursts are superimposed must have been created by the interaction of UH waves with some unknown low frequency fluctuations.

In fact a weak shock can generate a variety of low and high frequency turbulences depending upon the strength of the shock and the coronal conditions which the shock faces as it propagates through the corona. The high frequency turbulence (Buneman Instability) is excited only at the initial portion of the shock front where the gradients are steep. Among low frequency waves, the LH waves are generated for isothermal conditions. The ion-sound waves are generated only when there is non-isothermality. Because of this the generation of ion-sound turbulence is always viewed with suspicion. But if there is an initial steep gradient, then the Buneman Instability generated can be quenched by essential heating of electrons and thereby causing non-isothermality (Tidman and Krall, 1971). In fact, the characteristic time scale for electron heating through Buneman instability is $\tau_B \simeq \surd 3 (m_e/m_i)^{1/3} \; \omega_{pe}^{-1} \sim 10^{-7}$s. This is very small compared to the shock transit time $(\omega_{pe} V_1/C)^{-1} \sim 5.8 \times 10^{-5}$s ($V_1$ - shock velocity). Hence the non-isothermality will be met within about 1/100th of the shock thickness. Under such a situation, therefore, ion-sound instability, could be excited. A detailed calculation of the ion-sound instability has been reported elsewhere (Gopalswamy et al. 1983b).

For the UH waves to provide the adequate brightness temperature, the low frequency waves should have an energy density (Melrose, 1980);

$$\frac{W^{\sigma}}{nT_e} \gtrsim \frac{6\surd 3}{\pi} \qquad \frac{V_e c}{\omega_{pe} L_n V_{ph}}$$

where

$\frac{W^{\sigma}}{nT_e}$ - energy density of low frequency mode σ interacting with the UH waves,

n - electron density of the corona

V_e - electron thermal velocity

V_{ph} - phase velocity of the low frequency waves

L_n - coronal density gradient scale length

c - velocity of light .

For $n = 10^8$ cm^{-3} and $T_e = 10^6$K, the above inequality becomes ;

$$\frac{W^{\sigma}}{nT_e} \gtrsim 2.4 \times 10^{-6} .$$

The energy density of LH waves is calculated by Spicer et al. (1981) as ;

$$\frac{W^{LH}}{nT_e} = \frac{\omega_{ce}^2}{\omega_{pe}^2} \quad \frac{V_A}{C_s} \quad \frac{\Delta B}{B} \quad \frac{M_A - 1}{M_A} \quad \left(\frac{m_e}{m_i}\right)^{1/2}$$

where V_A is Alfvén velocity, $\frac{\Delta B}{B}$ is the relative jump in magnetic field across the shock,

M_A is the Alfvénic Mach number, (m_e/m_i) is the ratio of electron to ion mass and C_s is the sound velocity. Following the similar procedure one can calculate the energy density of ion-sound waves by extending the one-dimensional calculation of Krall and Book (1969) to three dimensions (Gopalswamy et al. 1983b) as;

$$\frac{W^s}{nT_e} \approx \frac{C_s V_A}{V_e^2} \frac{\Delta B}{B} \frac{M_A^2-1}{M_A} \frac{2}{2-\beta} \left(\frac{m_i}{m_e}\right)^{1/2} \times \left[1 + \ln \frac{\omega_{pe}^2}{\omega_{ce}^2}\right]^{-1} .$$

For identical conditions of the shock in the decametric corona,

$$\frac{W^{LH}}{nT_e} \simeq 7.7 \times 10^{-6} \quad \text{and} \quad \frac{W^s}{nT_e} \simeq 2.8 \times 10^{-4} ,$$

so that

$$\frac{W^{LH}}{W^s} \simeq 2.7 \times 10^{-2} .$$

This estimate shows that the LH waves only marginally satisfy the energy density requirement while the ion-sound wave density is much larger than the threshold value. Moreover, the ion-sound waves are generated over a wide range of wave numbers compared to that of LH waves, thereby satisfying the resonance condition more easily, i.e., the overlap between UH waves will be more in the case of ion-sound waves. Then, subject to the condition that the ion-sound waves are generated, they are better candidates compared to the LH waves.

Another important aspect of the emerging flux theory is the generation of UH waves. In the theory of Spicer et al. (1981), the LH waves stochastically accelerate the electrons parallel to the magnetic field. But UH waves are generated by a loss-cone distribution of electrons. Therefore, the accelerated electrons, travelling essentially parallel to the magnetic field should convert a major part of their parallel energy into perpendicular energy. Vlahos et al. (1982) have proposed anomalous Doppler resonance instability to generate a loss-cone distribution through pitch angle scattering. However, if the low frequency turbulence involved is due to ion-sound waves, there is another possibility of generating high frequency plasma turbulence. Since the ion-sound frequencies are of the same range as the whistlers, they can get non-linearly scattered into whistler waves in a time-scale of 0.01s (Kaplan & Tsytovich, 1973). The whistler polarization is such that the energy of the electrons is increased predominantly in the direction perpendicular to the magnetic field due to the whistler absorption. The time-scale over which the transverse energy of the electron increases is of the order of 0.5 s (Kaplan & Tsytovich, 1973). Since both these time scales are much less than the collisional damping time of the ion-sound waves, an anisotropic electron distribution could be produced, the free energy content of which could be fed into high frequency plasma oscillations through a mechanism similar to one discussed by Levin (1982).

In conclusion we would like to point out that while the emerging flux theory can adequately explain our observations as well as other type I phenomena, the low frequency models that provide the opacity could be different depending upon the exact conditions prevailing in the shocks and the corona.

4. Conclusions

We have presented some observations of the fine structures in the decametric solar radio emission. We have provided representative events which reflect the complex structure of the decametric corona. Our observations and their interpretations indicate the importance of this special region of the corona in understanding the radio physics of the Sun. As the decametric corona has not received much attention from theorists, a detailed investigation of the radio processes from this level will provide an opportunity for a better insight into outer corona as well as interplanetary phenomena.

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DISCUSSION:

BHATTACHARYYA: In all the cases mentioned for absorption events did you find any suitable loop configuration from optical pictures?

GOPALSWAMY: Yes, that is what I was just discussing with Dr. R.N.Smartt. But, we have not specifically identified any event. He has promised to send some photographs in this regard. I am planning to search from our own optical records.