Beam Driven Return Current Instabilities and White-Light Flares

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Abstract. It has been shown that the low ionization levels in the deep chromosphere of solar flares can cause the return current driven by a thick target flare beam to be unstable to ion acoustic wave generation, contrary to previous conventional wisdom. We investigate the possibility that anomalous heating as a result of this instability may produce sufficient heating to power the white-light flare. Four white-light flares observed by Yohkoh are examined: 1991 October 27; 1991 November 15; 1992 January 26 and 1992 February 14.

1. Introduction

If an electron beam is introduced into the solar atmosphere then the resultant sudden change in magnetic field and charge structure will induce electric fields opposing the primary current. This induced field drives a return current of ambient plasma electrons. Beam current neutralization then requires a plasma electron drift current density of $j_p = n_e e v_D = -j_b$ at speed $v_D$ where $n_e$ is the electron density given by $n_e = n(x + x_M)$ with $n$ the total (neutral and ionised) hydrogen density, $x$ the degree of hydrogen ionisation, and $x_M$ the correction for metallic electrons which we take as $10^{-4}$.

If we consider an electron beam with power law spectrum, $F_b = (\delta - 1) F_1 E_1^{\delta - 1} \int_{E_{\text{max}}(E_1, \sqrt{3KN})}^{\infty} E_0^{-\delta} dE_0$, at injection of spectral index $\delta$, total flux $F_1$ (cm$^{-2}$ s$^{-1}$) above cut-off energy $E_1 = 25$ keV and zero pitch angle; then allowing for Coulomb scattering and energy losses, following Brown (1972) we have:

\footnotesize
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\end{itemize}

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\[
\dot{j}_b(N) = \begin{cases} 
F_1e^{-N} & N \leq N_1 \\
F_1e\left(\frac{N}{N_1}\right)^{(1-\delta)/2} & N > N_1,
\end{cases}
\]

where \( N_1 = E_0^2/3K \) and the constant \( K = 2\pi e^4\Lambda \) in the Coulomb cross-section \( K/E^2 \) has been assumed independent of \( N \).

Then

\[
R(N) = \frac{v_D}{v_{is}} = \frac{F_1}{n(N)(x(N) + x_M)(kT_e(N)/m_i)^{1/2}} \times \begin{cases} 
1 & N \leq N_1 \\
\left(\frac{N}{N_1}\right)^{(1-\delta)/2} & N > N_1.
\end{cases}
\]

Mikhailovskii (1974) gives the criterion \( R = v_D/v_{is} > 1 \) for ion-acoustic wave growth. The onset of ion-acoustic turbulence will result in an increase in the effective collision frequency and hence in the development of anomalous resistivity. Anomalous resistivity increases the rate of Ohmic return current dissipation and the beam may be strongly decelerated over a very short distance (van den Oord, 1990). At the point where this occurs there will be significant energy deposition enhancement in the atmosphere.

It has been shown (Matthews et al., 1996) that low ionization levels in the deep chromosphere of solar flares can cause the return current associated with a thick target electron beam to be unstable to the growth of ion-acoustic waves. We investigate the correlation between the onset of such an instability and the white-light emission in solar flares.

2. Analysis

Four white-light flares were analysed: 1991 October 27; 1991 November 15; 1992 January 26 and 1992 February 14. Here, to illustrate our findings, we show only the results from the analysis of the event of 1991 November 15. This flare occurred in NOAA active region 6919 on 1991 November 15 at 22:34 UT. This flare showed a double source structure in both hard X-ray and white-light emission.

A series of white-light images was used to produce light curves for each kernel of white-light emission and these were compared with the variation of \( R = v_D/v_{is} \) for the corresponding hard X-ray emission. The drift velocity, \( v_D \), and the ion sound speed, \( v_{is} \), were calculated from spatially resolved spectra of the hard X-ray footpoints and atmospheric information. In doing this the assumption was made that the photon spectrum could be well described by a single power law, and then the spectral parameters, \( (A, \gamma) \) were calculated for each image in the hard X-ray movie. If the parent electron spectrum is then also assumed to be a power law the parameters of the electron spectrum can be inferred from the photon spectrum assuming a thick target process. The area of the electron beam, assuming that the whole of this contributes to the area of the corresponding hard X-ray emission, can be calculated from the hard X-ray movie. We take the atmospheric parameters to be those given by Basri et al. (1979) for the semi-empirical model atmosphere P.
3. Results

All of the four events so far studied have, in general, shown good spatial and temporal correspondence between the areas of white-light and hard X-ray emission, as indicated in Figure 1 showing a greyscale image of the whitelight flare emission on 1991 November 15 at 22:37:52 UT overlaid with hard X-ray contours from the HI channel at 22:37:30 UT. However, we note that in the event of 1992 January 26 seven areas of hard X-ray emission can be identified, whilst only five white-light kernels are visible.

The agreement between the onset of the white-light flare emission and the probable onset of ion acoustic wave generation also appears to be good. Figure 2 shows the light curve of the white-light flare emission in the upper kernel of the 1991 November 15 flare, and Figure 3 the variation of $R = v_D/v_{ls}$ with time for the corresponding hard X-ray footpoint. It can be seen from these figures the white-light emission begins 22:36:40 UT with a significant rise occurring 22:36:50 UT and the peak of the white-light emission occurs at 22:37:40 UT. In the $R$ curve we see that the criterion $R > 1$ is satisfied at 22:36:40 UT, reaching its maximum at 22:37:35 UT.

4. Discussion and Conclusions

From the temporal and spatial coincidences between the white-light and hard X-ray emission in this event the probability that both these phenomena are produced by the same electron distribution is high, and the results of the spectral analysis of the individual footpoints of the hard X-ray emission when compared to the corresponding white-light patches certainly appear to lend support to this idea. In the other events analysed we also, in general, find a good correlation. However, we also find a few cases where there is no obvious spatial correspondence between one or more of the hard X-ray and white-light sources, suggesting perhaps that there may be more than one mechanism producing the white-light emission.
Figure 2. The variation of $R = v_D/v_{is}$ with time for footpoint B of 1991 November 15, calculated at the $N = 5.0 \times 10^{20}$ cm$^{-2}$ level in model atmosphere P of Basri et al. (1979).

Figure 3. The light curve of the white-light emission from source B of 1991 November 15.

In conclusion, although it cannot be claimed that this mechanism is the unique answer to the origin of the white-light flare, it seems at this stage that it is worthy of further investigation.

References

Mikhailovskii, A.B. 1973, Theory of Plasma Instabilities