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Extreme Ultraviolet Emission during Flares

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Extreme ultraviolet emission during flares

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A number of time profiles are presented which show how the flux of radiation in the wavelength bands 0.1 to 0.3 nm, 0.3 to 0.9 nm, 0.8 to 1.6 nm and at 30.4 nm change during flares. The first sign of a flare is often a decrease of flux at 30.4 nm followed by an increase in the X-ray emission. In general, the higher the photon energy, the earlier the peak flux is reached, although any increase observed at 30.4 nm seems to peak before the X-ray flux.

It is concluded that a model in which a mass of gas in the upper chromosphere is heated by shock waves or incident energetic particles does not explain the observations. What appears to be a more suitable model is suggested. Cool plasma from low in the chromosphere passes through a region of magnetic instability and is heated during the passage. In this way the material of the X-ray emitting region is heated to a high temperature a little at a time. The intensity of X-rays observed in each waveband is proportional to the volume of gas produced up to that time at the corresponding temperature. As the instability decays the gas passing through it can no longer be heated to the temperatures reached earlier and the emission of longer wavelength X-rays becomes dominant. The emission of γ-rays and radio waves can also be explained

1. INTRODUCTION

A number of authors (de Jager 1965; Kane 1969; Hudson, Peterson & Schwartz 1969) have commented that the short-wave emission from flares is produced as a result of interactions involving electrons which have a 'quasi thermal' energy distribution (these will be called thermal electrons in the following discussion) and also as a result of collisions involving electrons which have a non-thermal energy distribution. Observations of flare emission at energies greater than tens of kiloelectronvolts show that the non-thermal particles are sometimes responsible for bursts of radiation lasting for the order of a minute. It is suggested that the flux remains high for much longer periods when observations are carried out at lower energies because the longer-lived thermal particles account for the bulk of this emission. The ratio of the intensities of photons produced by the two processes will be a function of wavelength and would be expected to change from flare to flare.

In this paper it will be shown that X-rays of wavelength 0.1 to 1.6 nm are produced predominantly by thermal electrons and that it is sometimes possible to observe when the energy input to the plasma takes place.

2. METHODS OF OBSERVATION

The satellite OSO IV, launched 18 October 1967, carried two packages built in the United Kingdom. One instrument, a proportional counter spectrometer designed by the Mullard Space Science Laboratory and the University of Leicester, allowed the flux of X-rays to be monitored in the wavebands 0.1 to 0.3 nm, 0.3 to 0.9 nm, and 0.8 to 1.6 nm (Culhane *et al.* 1969). Although a pulse-height analysis of the outputs from each detector is available, in this present paper the total number of counts from each detector is plotted as a function of time.

The second instrument was a small grating monochromator built for the Mullard Space Science Laboratory (Bowles *et al.* 1968). This allowed observation of the flux of solar emission in a waveband about 1 nm wide centred at 30.4 nm. Within this range the Sun emits two relatively intense spectral lines. The Lyman-α line of He II is at 30.378 nm and a second line, emitted by Si XI, is at 30.331 nm. During rocket observations the helium line was about four times as intense as the other, but since they are produced in plasma at significantly different temperatures (about 5×10^4 K and 1.3×10^6 K respectively) the ratio must change with the state of solar activity.

Both these instruments give relatively good time resolutions. An X-ray spectrum is obtained in about 15 s and the flux at 30.4 nm is obtained once every 2 s. The high time resolution makes them good instruments for following the changes in solar flux during flares. To smooth out fluctuations so that general trends can be followed, the 30.4 nm data have been averaged over periods of about 16 s. No spatial information is obtained with these instruments, so it is not possible to obtain details on the development of the dimensions of the flares.

3. Discussion of time profiles of flares

Two extreme examples of flare increases are shown in figures 1 and 2. In the first case the peak flux is probably reached in the order of 1 min from onset, whereas in the second figure the rise time is more than 5 min. Spectral data on the flare of 2 November 1967 are not available because the detector count rates during this type 2B flare were too high for the energy response to be linear. However, the event was accompanied by bursts of type III and type IV radio emission as well as a very marked increase in flux at 30.4 nm.

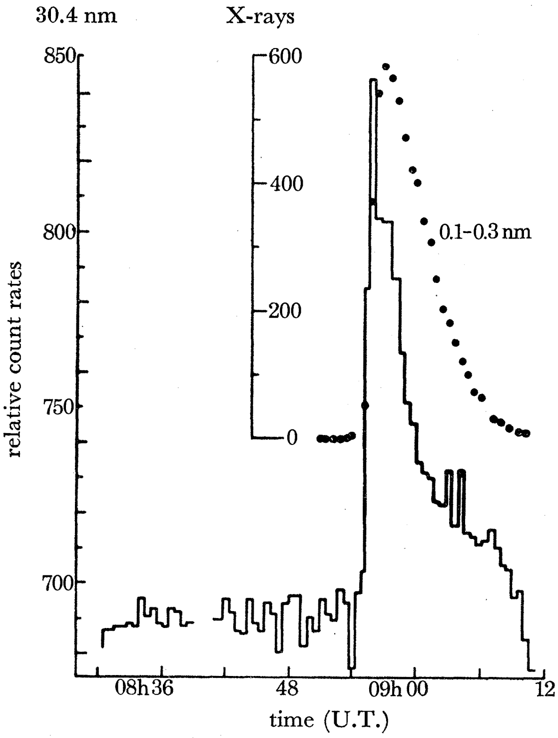

Figure 1. Changes of flux observed during a visible type 2B flare on 2 November 1967.

The event in figure 2 is characterized by the long rise-time, and it is seen that the longer the wavelength, the later the peak flux is observed. In spite of this, the emission at 30.4 nm reached a high value very early in the flare. There was a slow increase in the radio emission at 2800 MHz accompanying the event, indicating a rise in temperature or density. No reference has been found to observations of energetic radio events.

X-rays emitted during the event of 2 November 1967 might be supposed to have been produced in non-thermal processes such as the bremsstrahlung process. Yet there are several reasons which suggest that this was not the case. First, a similar but smaller event has been analysed by Culhane & Phillips (1970) who concluded that the energy spectrum of the non-thermal electrons would need to be much flatter than is observed from γ-ray observations if the long decay time of the X-ray flare is to be explained. More important, however, is the fact that the time profile of 30.4 nm radiation is very similar to the X-ray time profile. Since the ultraviolet emission is produced in spectral lines, the radiation will have been produced by thermal, or 'quasi-thermal', interactions.

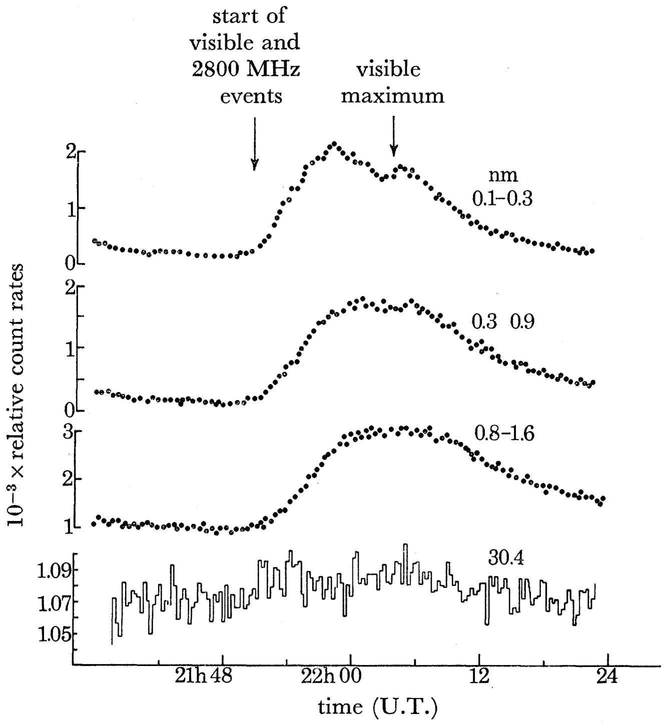

FIGURE 2. Changes of flux observed during a visible type 1N flare on 25 October 1967.

Furthermore, it does not seem possible that the emission during the rising phase of the flare was produced by non-thermal processes, while thermal emission became important during the decay phase. Had this been the case there would probably have been a noticeable jump in intensity during the transition stage as is shown schematically in figure 3. In fact, examples of this transition in the time profiles of the γ-ray flux have been observed by Kane (1969) and by Frost (1969).

The conclusion must be that the soft X-ray emission from flares is produced predominantly by thermal processes. This conclusion seems to be confirmed by the occurrence of the type 1N flare shown in figure 4. Although the rising phases in the bands 0.1 to 0.3 nm and 0.3 to 0.9 nm are rapid, the effect is not so marked in the 0.8 to 1.6 nm band, suggesting that a hot plasma is produced rapidly but that longer wavelength emission is produced more slowly as cooler material is formed. An important feature to note in this flare is the way in which the fluxes observed in the

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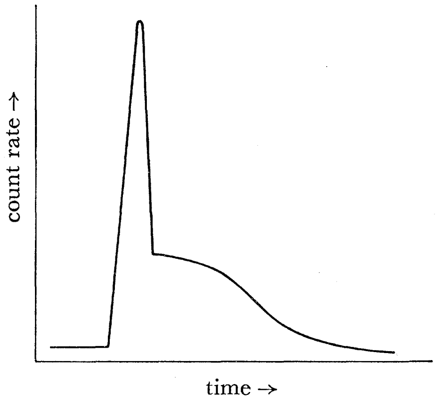

FIGURE 3

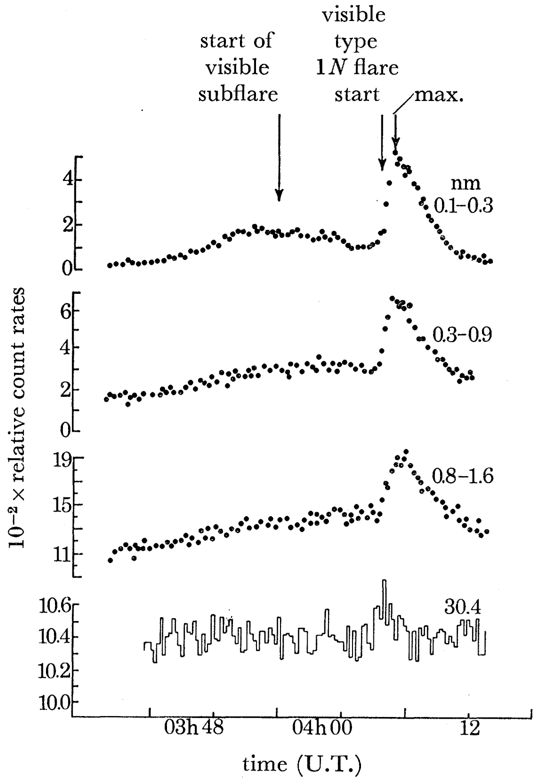

FIGURE 4

FIGURE 3. Time profile of X-ray flux to be expected if the initial emission were produced by short-lived non-thermal processes while thermal emission becomes important later in the event.

FIGURE 4. Changes of flux observed during activity in a single plage region on 28 October 1967.

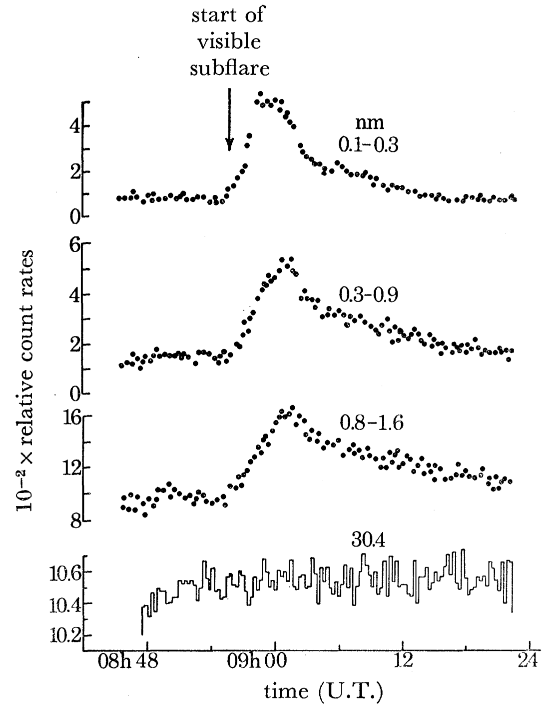

FIGURE 5. Changes of flux observed during an optical subflare on 26 October 1967.

two higher-energy bands decay slowly until the maximum flux is reached in the third X-ray band at 04h08 U.T. This must surely indicate that energy is fed into the plasma until this time, although the rate at which this occurs decreased slightly about 2 min earlier when the higher energy photons reached peak intensity.

A similar effect is shown in figure 5. At about 08h57 U.T. the energy input to the hot component of the plasma decreased substantially while the heating mechanism became unimportant about three minutes later. Thereafter the plasma continued to cool.

4. The onset of flares

Flare bursts are sometimes preceded by a small increase in intensity 5 min or more before the main event. Good examples are shown in figures 4, 6 and 7. No data are available for the peak of the 29 October 1967 flare but some interesting changes occurred during the period shown. The plage region with which the flare was associated was on the limb and a prominence was observed to be active between 23h04 and 23h35 U.T. (A subflare was observed in an entirely different plage region at 23h27 U.T. so it is not certain that the 'precursor' observed was entirely associated with the large flare. However, there can be little doubt that the flux increase which started at 23h38 U.T. was part of the main event.)

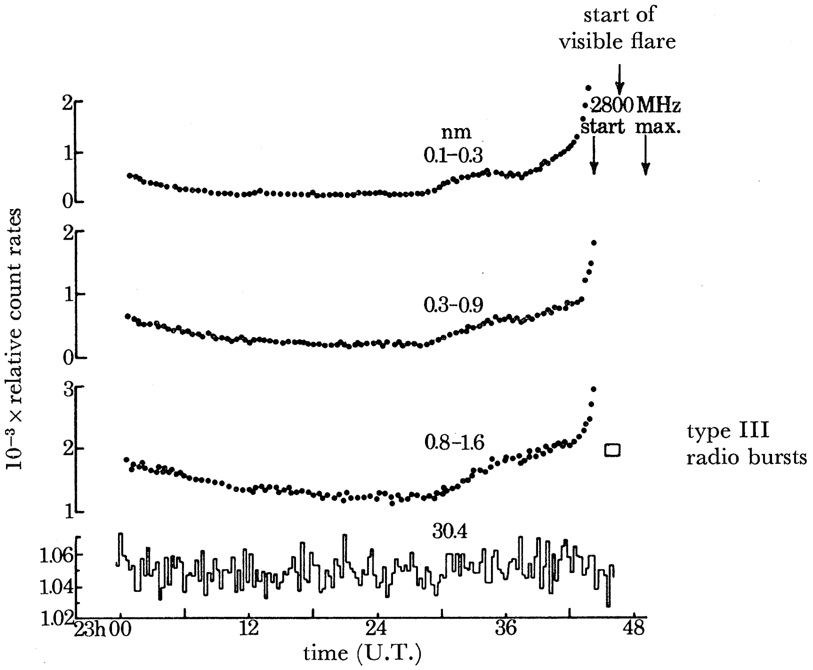

Figure 6. Changes of flux measured during a type 2B visual limb-flare on 29 October 1967. Activity associated with a prominence was observed between 23h04 and 23h35 U.T. from the same plage region. It is not certain whether the initial increase in X-ray emission at 23h29 U.T. is associated with this large flare or with a subflare in a different plage group.

An observation which has not been reported by other authors is the fact that the flux of 30.4 nm radiation often reaches a minimum at the time when the X-ray flux begins to increase. This is particularly striking in figures 1 and 7, although similar effects are seen in figures 4 and 6. In addition, there is a marked minimum flux observed before the flare increase in figure 8, for which no X-ray data are available.

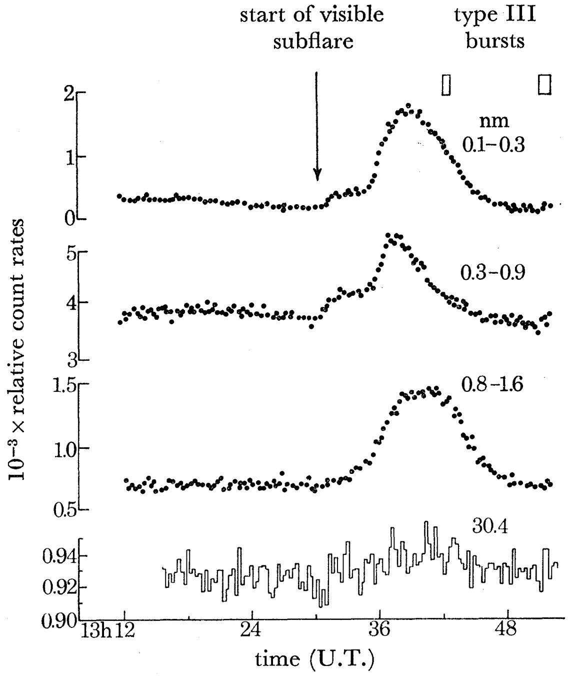

FIGURE 7. Changes of flux observed during an optical subflare on 31 October 1967. The relatively fast decay of radiation within the wavelength band 0.3 to 0.9 nm possibly arose because the detector was saturated.

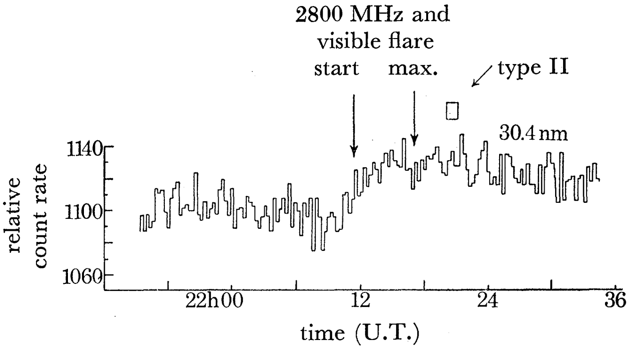

FIGURE 8. Change of flux observed at 30.4 nm during a visible type 1B flare on 22 October 1967. The flux reached a minimum value just before the flare increase.

5. DISCUSSION OF OBSERVATIONS

It is possible to enumerate a number of general conclusions from the previous discussions:

(1) Emission of soft X-rays during flares comes predominantly from a heated plasma. In some flares it is possible to tell from the time profiles of the flux measurements when the heating mechanism becomes unimportant.

(2) The emission at 30.4 nm often decreases at the onset of the X-ray flare. Where there is an intensity increase of this radiation during a flare the peak is reached before the X-ray peaks.

(3) The shorter the X-ray wavelength within the band 0.1 to 1.6 nm, the earlier the peak flux is observed during a flare. However, it is not possible to observe a dependence of the start time of the flare on photon energy.

(4) It is possible to observe various features in the profiles of emission in the higher energy X-ray bands when there are no corresponding changes observed at lower energies. Examples are:

(*a*) The second peak of the flare in figure 2. This is not observed as a separate feature in the 0.8 to 1.6 nm band.

(*b*) The initially slow rates of decrease in flux after the peaks in figures 4 and 5 as well as the rapid flux increase in the 0.1 to 0.3 nm band after 08h57 U.T. in figure 5.

(*c*) Precursors are observed in the two high-energy X-ray channels in figure 7 but not in the 0.8 to 1.6 nm band.

The dependence of the time of peak flux on photon energy is usually explained by assuming that a volume of plasma is heated rapidly to a high temperature from which the radiation is predominantly at short wavelengths. As the material then cools the emission at longer wavelengths becomes more important. However, observations of the type shown in figures 4 and 5 would appear to discount this model. In these two events it appears possible to recognize, from the profiles of photon fluxes in the wavelength bands 0.1 to 0.3 nm and 0.3 to 0.9 nm, the periods of time during which energy is fed into the plasma. It should be noted that the flux of photons in the 0.8 to 1.6 nm band begins to decrease when the energy input ceases, whereas the model would predict that this flux should continue to rise.

A further point to note is that an increase in flux within the band 0.1 to 0.3 nm never seems to be accompanied by a decrease in the band 0.8 to 1.6 nm. Such a change might be expected if a plasma at a temperature of millions of kelvins is heated further. This point has been noted by Neupert (1968) who finds that although the flux of photons produced by Fe XX to Fe XXV increases during flares, so does the flux from Fe IX to Fe XVII. Neupert suggests that the X-ray emission from a flare arises not by the heating of coronal material but by the injection of even hotter material into the corona. The present results tend to confirm this.

Finally it seems strange that in a flare with a long rise-time (see figure 2) the emission at all wavelengths should not peak together. It would be expected that when the plasma is heated slowly the volume of relatively cool material should be proportional to the volume of hot plasma. On the other hand, if a volume of plasma is heated very rapidly to a high temperature, there should be a long delay before the volume of cooler plasma reaches a maximum. This does not seem to be the case in the observations.

6. MODEL FOR HEATING OF PLASMA

It seems necessary to conclude from the discussion in § 5 that X-rays are not produced by a constant mass of gas which is heated by shock waves or injected high energy particles. A better explanation would appear to be that hot plasma is produced a little at a time, and that the material was not in the corona before the onset of the disturbance.

A possible model will now be discussed. The intention is to show that the observations can be explained if it is assumed that cool plasma flows through a small volume of magnetic instability. It is not the intention to support any particular flare mechanism for the conversion of magnetic energy, but it is convenient to consider the production of anti-parallel fields in the description.

Suppose a volume of cool gas is held at the base of the solar atmosphere. The walls of this 'balloon' would be a magnetic field. If the 'balloon' burst the gas would flow out, but the 'nozzle' produced would be a region in which anti-parallel magnetic field lines exist (see figure 9). This is just the type of region where magnetic fields might be annihilated. However, the cool gas would flow through this unstable region and would gain heat in so doing. In this way, the gas reaching some storage region in the solar atmosphere has already been heated so that the quantity of gas emitting X-rays increases with time for as long as the magnetic instability is active. The main features of this model may be summarized as follows:

(*a*) The greatest changes in magnetic field configuration should occur at the onset of the instability. It would not be surprising therefore if electrons in the field were accelerated to high energies at this stage. What happens to these electrons depends upon the depth of the instability in the chromosphere in each particular flare. In some cases the density of surrounding material will be so great that the bulk of the energy will be lost in the bremsstrahlung process and γ rays will be produced. In other flares the electrons will encounter lower plasma densities and type III radio bursts will be produced.

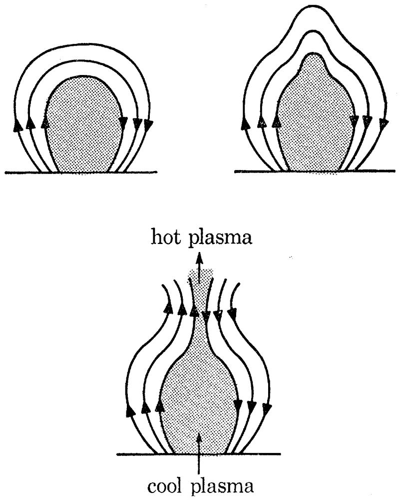

FIGURE 9. Three stages are shown during the development of a flare: (*a*) a volume of cool plasma is trapped within a magnetic field; (*b*) the field lines are distorted; (*c*) a region of instability is produced in the magnetic field and the gas is heated as it flows through the region. The model is intended to show that small quantities of plasma can be heated at any particular time rather than to indicate any particular field configuration.

(*b*) A decrease in intensity might be observed at 30.4 nm if the initial instability occurs near the helium layer of the chromosphere. In this case the layer might be destroyed locally for a short-time interval. Later the reformed layer might be heated so that an increase in He II flux is observed.

(*c*) At the next stage the rate at which the magnetic field is annihilated remains fairly constant. The plasma emerging into the corona has a temperature distribution such that a range of X-ray wavelengths is produced, although the bulk of the material is relatively very hot.

(*d*) A stage is reached where the energy produced in the field is insufficient to produce the very hot plasma, so material emerging becomes progressively cooler as time proceeds. As a result, the peak flux is reached at progressively longer wavelengths.

(*e*) Finally the plasma flow stops and the condensation cools by radiation loss.

(*f*) Although a stage might be reached where the heating of plasma ceases to be important, this might be a temporary situation in some events and the annihilation mechanism later becomes more active. This could explain the precursor events and the second peak at high energies in figure 2.

Although it is possible to describe the sequence of events observed during a flare with this model, it is not clear what the magnetic field configuration is before, during and after the event. However, this is the main difficulty in all models. It is clear in this case that the magnetic 'balloon' is not produced from a simple curved field visualized in figure 9*a*. The reason is that if the 'balloon' burst the field lines would straighten immediately and no 'nozzle' would be produced. However, it must be reiterated that the intention has not been to discuss the field configuration but rather to discuss the heating plasma as it flows through an instability.

7. Conclusion

The results presented tend to confirm the observation by Neupert (1968) that the material which gives rise to X-ray emission during flares is at a temperature lower than that of the corona before the event. It is suggested that this plasma is heated a little at a time so that at no stage is it possible to observe the material at a temperature intermediate between its pre-flare and maximum values.

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