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ENERGY INPUT IN SOLAR FLARES AND CORONAL EXPLOSIONS

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ABSTRACT

A coronal explosion is a density wave observed in X-ray images of solar flares. The wave occurs at the end of the impulsive phase, which is the time at which the flare's thermal energy content has reached its maximum value. It starts in a small area from where it spreads out, mainly into one hemisphere, with velocities that tend to rapidly decrease with time, and which are between ~ 10^3 and a few tens of km s^{-1}. We interprete them as magneto-hydrodynamic waves that (mainly) move downward from the low corona into denser regions.

CORONAL EXPLOSIONS

Time sequences of images of solar flares in the energy range 3.5 to ~ 20 keV, obtained with the Hard X-ray Imaging Spectrometer (HXIS,/1/) have shown a hitherto unknown phenomenon, christened "coronal explosions" (/2,/3/,/4/). Their signature is a systematic movement over the field of view of the time at which maximum brightness is reached in the various pixels of the field of view. This is illustrated in a one-dimensional example in Figure 1 (cf. /5/) where it appears that for three equidistant pixels situated at one line each, the time of maximum of the X-ray intensity varies monotonically along the line.

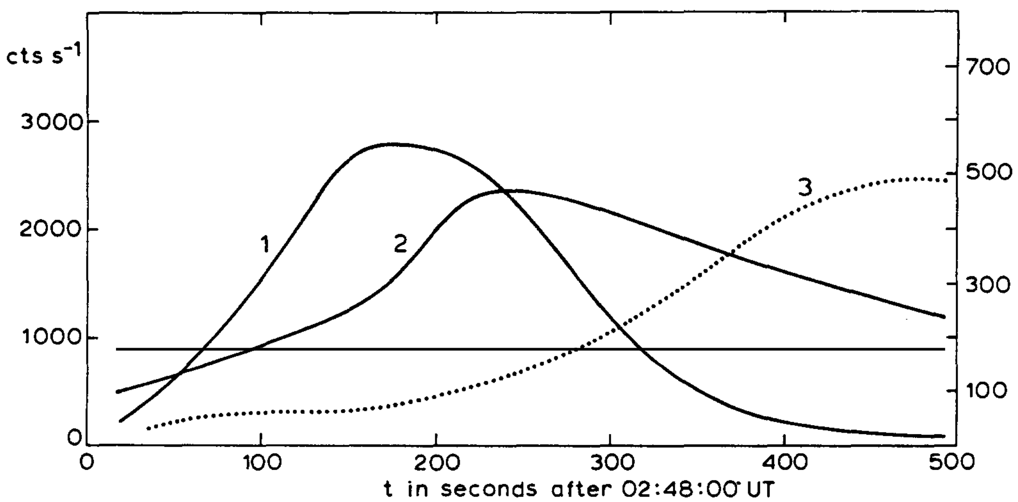

Fig. 1. One-dimensional cross-section through a coronal explosion. The diagram shows intensity-time diagrams for three areas in a solar flare (12 Nov. 1980; 02:50 UT). The areas are 8" x 8" squares, along a N-S line at distances of 16".

A real case is shown in in Figure 2 which contains the most important elements of the explosions: There are two sources, situated close to the flare footpoints but not exactly there. From these areas a wave of local brightness maximum spreads over the flaring area, with initially high and gradually decreasing velocity. Another aspect is that the explosions tend to occur at the end of the impulsive phase of the flare, apparently when the thermal energy content has reached a maximum value. This suggest that they are caused by an instability related to the input of energy into small areas of the flare.

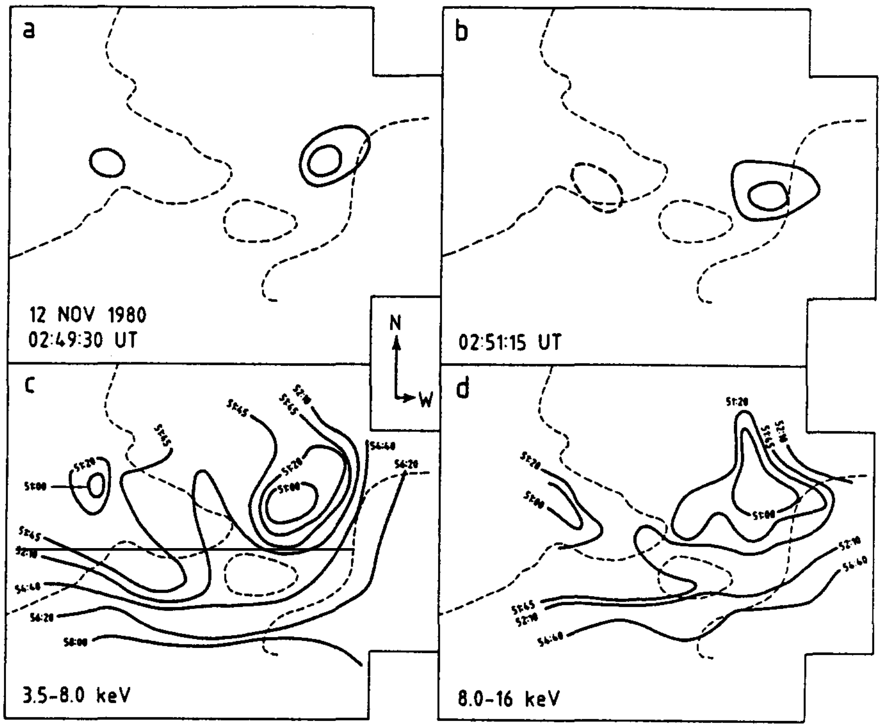

Fig. 2. Upper part: "Footpoints" of the flare of 12 Nov. 1980, 02:50 UT observed in 11-32 keV X-rays, during the emission of two hard X-ray bursts. Lower part: the coronal explosion in two energy channels (noted in the corner of the diagram). The isochrones are labeled with the time in minutes after 17:00 UT. The sources of the explosion are apparently situated close to but not at the footpoints.

An essential question is that of the physical explanation of the explosion: is it a density wave or a thermal wave? The answer can be given by determining, similarly, isochrones connecting for the various pixels the times at which temperature maximum is reached (Figure 3).

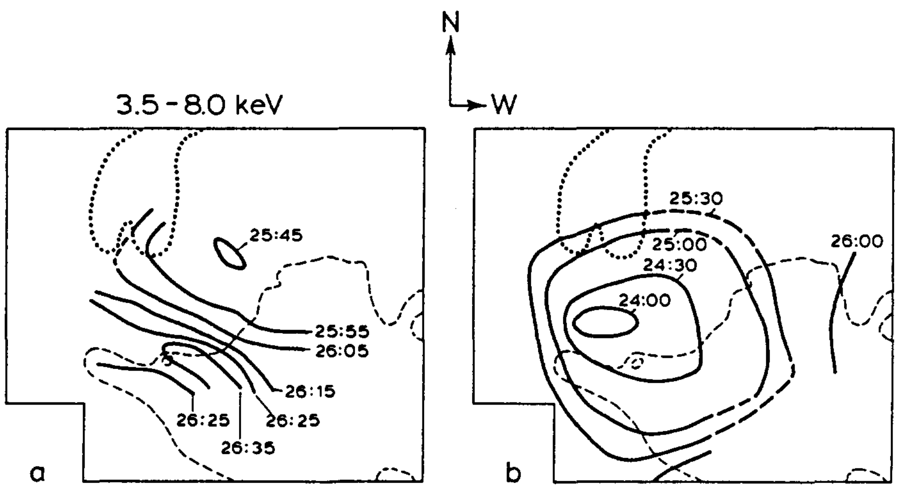

Fig. 3. Isochrones for the brightness maximum (left), and for the temperature maxima (right) for the flare of 11 November 1980; 17:25 UT. The disagreement between the two diagrams shows that the explosions are not thermal waves.

It then appears that the isochrones for the temperature-maximum are uncorrelated to those for the maximum count-rate. This shows that the isochrones of the coronal explosions are not related to thermal or conduction fronts, and since the count-rate is approximately proportional to the emission measures, hence to the particle density (other things remaining equal), the most probable assumption is that the explosions represent density waves. Another property of these waves is that they are apparently not guided by the magnetic field as follows from a comparison of their direction of motion with the magnetic field pattern. Hence they must be identified with fast manetosonic (shock) waves if $B \ll 1$ or with ordinary sound (shock) waves if $B \gg 1$.

ENERGY INPUT IN THE IMPULSIVE PHASE

The many recent high-energy observations of flares, chiefly with the Solar Maximum Mission, but also with the spacecraft P78-1 and Hinotori has led to a consistent scenario of the energetics of the impulsive phase: a reconnecting instability in a magnetic loop system causes beams of energetic ($10-10^2$ keV) electrons to move along the legs of the loops and to bombard the denser lower layers. The energy deposit leads to heating of the relatively cool chromosphere causing "evaporation" or "ablation" of chromospheric gas, which acquires temperatures of $\sim 2 \times 10^7$ K and hence moves upward convectively, thus eventually forming a large diffuse elevated cloud of particles with temperatures of $\sim 2 \times 10^7$ K. By radiative and conductive losses that cloud gradually cools down.

Quantitative support for this scenario is given by the approximate equality of (a) the total kinetic energy of the energetic electron beams, (b) the kinetic energy of the convective motions, and (c) the thermal energy constent in the diffuse cloud. Each of these values is a few times 10^{29} to 10^{31} erg, depending on the flare.

ENERGY OF THE EXPLOSIONS

The kinetic energy E_k in the explosions can be estimated by calculating $E_k \approx \frac{1}{2}\theta N m_H v^2$, where θ is the fraction of the number of the flare particles involved in the explosion. For the flare of 12 November 1980, 02:50 UT /2/ we have at 02:51 UT, which is in the early part of the explosion: $\log(N \phi^{-1/2}) = 38.9$, where ϕ is the filling factor. Further, $v = 200$ km s^{-1} at that time /4/. Hence $E_k \cdot \phi^{-1/2} = 3 \times 10^{29}\,\theta$. For comparison: for the whole flare $\log(E_{th} \cdot \theta^{-1/2}) = 30.8$ at that time. Hence the kinetic energy of the explosion is only a small fraction of the thermal energy content of the flare. If, for instance, $\theta = 0.1$ we have $E_k/E_{th} \approx 0.005$.

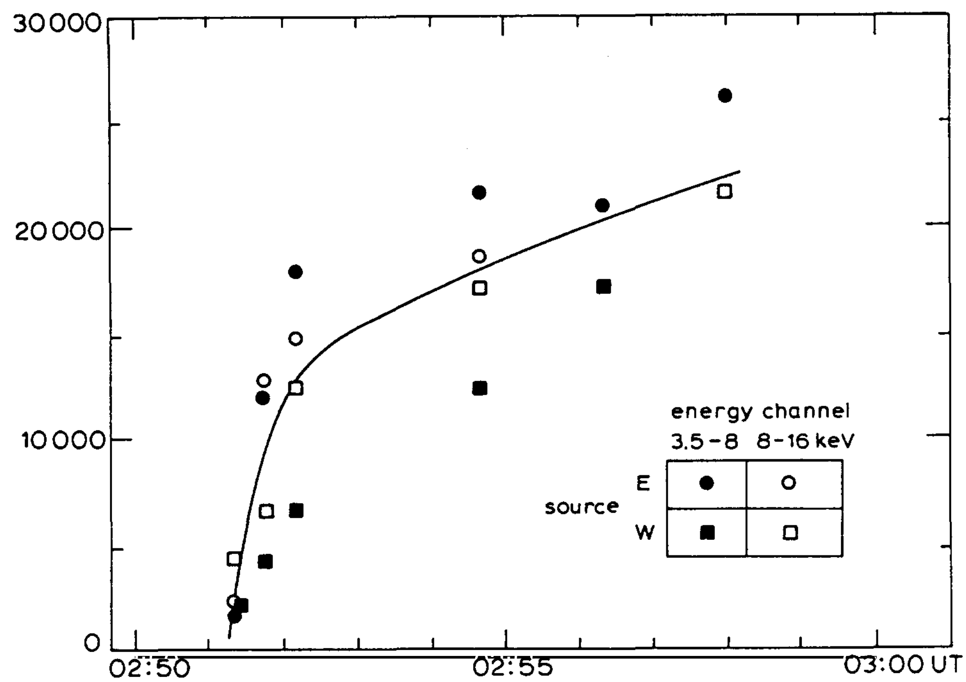

Fig. 4. Distances from the sources travelled by the explosion of 12 November 1980; 02:50 UT. There is a near-discontinuity at 02:52 UT.

PHYSICS OF THE CORONAL EXPLOSIONS

Several authors, to start with Somov and Syrovatskii /6/, /7/, cf. also Somov et al. /8/ and Syrovatskii and Somov /9/, and later McNiece et al. /10/, Wu /11/, have investigated the hydrodynamical response of the chromosphere to a sudden local heating. Their results differ in details but have in common that a hydrodynamic wave appears to spread out from the source. There are two components. One consists of upward moving heated plasma at supersonic speed, but the other component is a compression wave that is predicted to move downward towards the photosphere.

The velocity of the latter wave depends on the energy input, and on the density in the ambient medium. The velocity decreases with increasing density. In the upper chromosphere typical values are of the order of 100 km s^{-1} /9/. This value is of the same order as the data extracted from our observations. Interesting is the flare of 1980, Nov. 12, 02:50 UT (Figure 4) which shows a clear jump in the velocities, from ~200 km s^{-1} to ~ 20 km s^{-1} /4/. A likely interpretation is that the wave meets a density discontinuity, and with more observations of this kind the explosion waves could therefore be used as a means to sound the chromospheric density structure. To that end, however, we should also possess a thorough theoretical analysis of the downward component of the explosions.

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