CORONAL RESPONSE TO ENERGY RELEASE DURING SOLAR FLARES

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ABSTRACT. The observations obtained with high resolution spectrometers flown in the past solar maximum, in the years 1979-1981, have shown that the soft x-ray plasma during the impulsive phase of solar flares is characterized by upflows, as well as by isotropic flows, at velocities of a few hundred km s^{-1}. Isotropic flows can be directly related to the primary energy release process. While, upflows are an indication of chromospheric material heated to coronal temperatures and evaporating along the magnetic fluxtubes; they are therefore related to the development of the coronal soft x-ray source in the flare region.

1. INTRODUCTION

The response of the solar corona to the sudden conversion of magnetic energy into thermal and kinetic energy, occuring during solar flares, has been studied during the past solar maximum by observing, for the first time, the soft x-ray lines formed at temperatures above 10^7 K and the spatial structures of the flaring regions in hard x-rays. Several experiments operating onboard of the three satellites dedicated to active corona studies, the Air Force P78-1, the Solar Maximum Mission and the Hinotori satellites, were in fact devoted to high resolution spectroscopy of hot flare lines and to imaging in high energy photons up to 40 keV. Both the spectroscopic and imaging observations achieved a high temporal resolution appropriate to the study of impulsive phenomena. The ensemble of these systematic observations, carried on for extended periods covering most of the solar activity peak, has brought a wealth of new information mainly on two important aspects of the flare phenomenon: that is, on the dynamical evolution of the flare thermal plasma and on the geometry and relative locations of the sources of soft and hard x-rays. These two aspects are both relevant for their relation to the energy release process and to the development of the coronal phenomena observed during flares. In what follows the aspect concerning the dynamics of the soft x-ray high temperature plasma will be discussed

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in more detail, as well as the results obtained from the observations of the soft and hard x-ray images relevant to the study of the plasma dynamics.

2. IMAGING AND HIGH RESOLUTION SPECTROSCOPY OF THE ACTIVE SOLAR CORONA

The onset of solar flares is clearly signaled by impulsive bursts in hard x-rays with complex temporal structure. The energy released either in form of accelerated particles or in form of localized hot sources is expected to cause local chromospheric heating in the magnetic fluxtubes involved in the energy release processes. Such localized heating during the impulsive phase of flares has been directly observed in hard x-rays with the Hard X-Ray Imaging Spectrometer (the instrument is described by van Beek et al., 1980) on board of the Solar Maximum Mission. At flare onset, the emission in hard x-rays at energies above 16 keV has been observed to be confined in distinct areas. These areas of diameter of about 10" belong to opposite magnetic polarities and coincide with brightenings in chromospheric lines (Hoyng et al., 1981). These observations have been interpreted as evidence for hard x-ray brightenings of the foot-points of fluxtubes bridging the inversion line. The spatial resolution of 8" was, however, not yet sufficient to distinguish the individual fluxtubes. The observations obtained with the Hinotori satellite have confirmed, although not in all the cases, this interpretation (Tsuneta et al., 1982; Ohki et al., 1982). The hard x-ray images cannot give an accurate indication of the height of the emission in the fluxtube. This information can, however, be obtained from the stereoscopic observations of solar hard x-ray bursts from different spacecrafts which show that such emission is confined in the chromosphere, within 2500 km above the photosphere (Kane et al., 1982).

The simultaneity of the footpoint brightenings in hard x-rays suggests that the emission is probably due to heating by non-thermal particles accelerated in the energy release sites (Hoyng et al., 1981; Duijvemann, Hoyng and Machado, 1983). Additional indications in favour of a predominance of chromospheric heating due to local interactions of non-thermal particles, with respect to heating by conduction from hot sources within the magnetic structure, result from recent microwave observations. Kundu (1985) observed brightenings of the fluxtube footpoints during a solar event in the 2 cm emission which are interpreted as due to the presence of a beam of non-thermal electrons.

The high resolution spectroscopy of hot soft x-ray lines gives direct information on the emission measure, electron temperature, density and ionization conditions of the flare plasma, which is on the average at a temperature of a few 10^7 K. In addition, information on the dynamics of the thermal plasma is derived from the accurate measurements of line profiles. Line profiles are characterized by drastic changes predominantly at the onset and during the impulsive phase of flares, signaling that the response to the energy release is essentially a dynamic one. The spectroscopic regions which have been predominantly studied with the solar maximum experiments are the calcium XIX, iron XXV and XXVI regions. The high resolution spectrometers operating in these regions are described by Doschek et al. (1979), Acton et al. (1980) and Tanaka et al. (1982a). Strong satellite lines due to dielectronic recombination and inner-shell transitions are associated with the helium-like and hydrogen-like calcium and iron lines in these regions; their intensities can be used to derive the electron temperature and the abundance of the emitting ions (Gabriel, 1972; Bely-Dubay et al., 1982a, b). The temperature of emission of these lines is above 10^7 K; they are therefore typical of flare conditions.

While at the peak of the thermal phase and during the decay of flares, lines are in general thermally broadened and no Doppler shifts due to mass motions are observed in the soft x-ray source, the situation at flare onset is completely different. The flash phase is characterized by the onset of strong blue-shifted components, simultaneous to the onset of the impulsive hard x-ray (>25 keV). In addition at this stage the hot flare lines show significant non-thermal broadenings. A typical x-ray spectrum can be described as consisting of a symmetric component, non-thermally broadened, and a secondary blue-shifted component. The non-thermal excess in line width can be parametrized in terms of random velocities of the order of 100 to 200 km s^{-1}; while the blue-shifts observed in the calcium lines is indicating line-of-sight velocities of the order of 300 - 400 km s^{-1} (Doschek et al., 1980, Feldman et al., 1980; Antonucci et al., 1982). Since blue-shifts disappear in limb flares, these motions are considered to be predominantly upwards (Antonucci et al., 1982). The higher temperature iron lines do present even more complex profiles during the impulsive phase of large flares, with higher velocity components not observed in calcium emission (Antonucci and Dodero, 1986). A rather exhaustive discussion of the recent results on plasma motions during flares can be found in Doschek et al. (1985). The two effects of non thermal line broadenings and Doppler shifted components will be discussed separately in the following sections.

3. INTERPRETATION OF NON-THERMAL BROADENINGS IN HOT FLARE LINES

Several interpretations have been recently given for the non-thermal excess observed in soft x-ray lines during the impulsive phase. One of the simplest interpretations is suggested by the fact that Doppler shifts in the soft x-ray spectra are in general accompanied by non-thermal broadenings. Hence, broadened lines may result from a superposition of convective flows along the magnetic loops. Indeed recent numerical simulations predict both upward and downward flows in a magnetic fluxtube in case of asymmetric heating or asymmetric loop geometry, although, since upflows are predominant, blue wings are expected in the non-thermally broadened lines (Cheng et al., 1984). Broadening can also arise from line-of-sight effects for certain projections of a complex of magnetic loops (Doschek et al., 1985). De Jager (1985) has proposed to explain the broadening effect of soft x-ray lines in terms of high ion temperatures in the sites of chromospheric heating. This is suggested by the fact that the temperature found for the hard x-ray (16 keV) observed at the flare footpoints is consistent with the Doppler temperature derived from line broadenings. Bornmann (1986) has proposed to interpret the non-thermal line widths in terms of turbulent motions driven by the upflowing material observed during the impulsive phase. The discussion is limited to consider fluid turbulence.

All the above interpretations relate the origin of broadenings to the presence of impulsive chromospheric heating or the consequent convective motions. The following interpretations do instead relate the effect directly to the energy release process and are independent of the evaporation process. Locally isotropic motions at the ion sound speed are predicted by the maser model proposed by Melrose and Dulk (1984). Small coronal plasma regions expand as a consequence of local heating to temperatures of about 10^7 K, due to local absorption of photons produced via a gyrosynchrotron loss cone instability. In this process free energy residing in the motions perpendicular to the magnetic field is transformed into radio frequency radiation. Locally isotropic motions can also derive as a result of superposition of jets originating in the reconnection sites during the conversion of magnetic into kinetic energy at flare onset, as proposed by Antonucci, Rosner and Tsinganos (1986). This interpretation links the origin of flares to topological instabilities arising when a magnetic system is perturbed. The process of local reconnection and formation of magnetic islands, induced by the local departure from equilibrium and static conditions, can evolve to produce regions of overlapping islands. This leads to the onset of field line stochasticity, strongly enhanced reconnection and acceleration of the fluid ejected at the Alfven velocity from the reconnection sites.

Let us discuss the above interpretations at the light of the observed properties of line broadenings. Such properties derived from the high temporal resolution observations of the Bent Crystal Spectrometer, onboard of the Solar Maximum Mission satellite, are reported by Antonucci et al. (1982) and Antonucci, Gabriel and Dennis (1984). A link between line broadenings and convective flows is suggested by the temporal behavior of the velocity parameter characterizing line widths and the upflow velocity derived from blue-shifts. Both are larger at flare onset and decrease during the impulsive phase reaching the lowest values, near zero, at the peak of the thermal phase. However, in all the events which have statistically significant soft x-ray emission before the flash phase, the degree of non-thermal excess in ilne width increases considerably one or two minutes before the onset of convective flows. While, convective motions and the related hard x-ray brightenings at the loop footpoints, signaling strong chromospheric heating, initiate simultaneously in coincidence with the onset of the impulsive hard x-ray emission (flash phase). Therefore it does not seem plausible, at least in the pre-flash phase, to relate non-thermal broadenings to effects consequent to the impulsive chromospheric heating. The same conclusion seems to be valid also during the impulsive phase since the degree of broadening does not change significantly after the onset of convective motions, indicating that the same process predominates before and during the flash phase (Antonucci and Dodero, 1986). This work also shows that lines emitted by ions of different mass give the same broadening parameter. This would exclude differences in ionic and electron temperatures in the emitting source. The most probable interpretation is that we are in presence of mass flows and since the contribution of convective motions to line width is certainly not the predominant one, mass flows are locally isotropic. That the contribution of convective flows to line broadenings is not determinant can be also inferred from the lack of helio-longitude dependence of the broadening itself. Since convective flows are predominantly along the fluxtubes, their contribution would in fact decrease with increasing longitudes.

In the pre-flash phase hard x-rays, emitted at moderate intensity, are observed simultaneously to the large non-thermal broadenings appearing in the soft x-ray lines. This indicates that energy is already released, although not impulsively. It is plausible then to interpret the observed isotropic mass flows as a direct signature of the onset of the energy release process, as proposed in the models by Melrose and Dulk (1984) and Antonucci, Rosner and Tsinganos (1986). In addition, in the case of the model based on topological instabilities, the isotropic mass flows are directly related to the process of magnetic reconnection. An interesting feature of the latter model is that a process of the same nature can give origin to flaring, micro-flaring and active region heating, depending on the perturbation conditions. In addition, this model remains valid independently of the nature of the external perturbation on the magnetic system, that can be identified either in pre-flare motions, such as those observed in the sunspots associated to the active region, or in disturbances deriving from the emergence of new magnetic flux.

4. INTERPRETATION OF CONVECTIVE FLOWS IN THE HIGH TEMPERATURE PLASMA

Blue-shifts in the soft x-ray spectra have been observed during the impulsive phase with all the spectrometers operating during the last solar maximum (Doschek et al., 1980; Antonucci et al., 1982; Tanaka et al., 1982b). The blue-shifted emission has been recognized as signature of chromospheric evaporation (Antonucci et al., 1982; Antonucci, Gabriel and Dennis, 1984; Tanaka and Zirin, 1985) because of the following observational characteristics.

Plasma upflows start in concidence with the flash phase and are time correlated with the impulsive hard x-ray emission. They in fact disappear when energy is no longer released. The peak velocity observed in a flare is correlated with the spectral index of the power law representing the energy distribution of the hard x-rays (Antonucci and Dennis, 1983). These two effects are an indication that upflows are associated with the impulsive energy release and the consequent heating of the chromosphere at the footpoints of the flaring loops. This is also confirmed by the coincidence of the hard x-ray footpoint brightenings with the appearance of upflows. Moreover, the images obtained at flare onset with the Hard X-ray Imaging Spectrometer indicate that, when upflows initiate, the same footpoints of the magnetic fluxtubes bright in hard x-rays are also bright in soft x-rays. Hence, the soft x-ray material is first formed near the footpoints. The soft x-ray sources then migrate in time toward the apex of the magnetic structure, merging in one unique source as expected in case of plasma supplied to the corona from the chromosphere. In addition, the migration time of the soft x-ray sources is consistent with the travel time of the evaporating material along the magnetic loop derived from spectroscopic measurements of the upflow velocity (Antonucci et al., 1985). Plasma ascending with velocities of a few hundred km s^{-1} from the footpoints has also been observed by de Jager and Boelee (1984). That is, convective flows represent the response of the chromosphere to impulsive heating and they are driven by the pressure difference caused by the heating of the dense chromospheric material to coronal temperatures.

The emission measure of the soft x-ray coronal source increases until plasma upflows are observed. In addition, the rate of increase in the emission measure is correlated with the velocity observed for the upflows. Both effects indicate that the formation of the soft x-ray source is associated with convective flows, suggesting that upflows supply hot plasma to a magnetically confined coronal region giving origin to the soft x-ray source.

If chromospheric evaporation is the main cause of the formation of the soft x-ray coronal source, the energy transferred to the chromosphere from the site where it is released has to be consistent with the energy required to form the soft x-ray source itself. The energy input in the chromosphere, computed in the assumption of hard x-ray radiation caused by thick target interactions of particles with energy sufficient to penetrate the chromosphere (>25 keV), is found to be indeed consistent with the soft x-ray flare energy requirements. To act as transport mechanism, convective flows have to transfer in an average flare a number of electrons of the order of 10^{38} and an energy of a few 10^{30} ergs. This can be achieved, given the observed emission measure, upflow velocity and duration of the dynamic source, if the density and electron temperature of upflows are on the average respectively of the order of 10^{11} cm^{-3} and 10^{7} K. These values, reasonable for chromospheric convective flows, do ensure in general the pressure difference between chromosphere and corona required to set up and maintain convective motions during the impulsive phase (Antonucci, Gabriel and Dennis, 1984). Fisher has compared the results of the numerous models simulating the hydrodynamic response of a magnetic fluxtube to sudden heating or non-thermal particle injection (Doschek et al., 1985;

Fischer, Canfield and McClymont, 1984). Below an energy flux of 10^{10} erg cm^{-2} s^{-1} supplied to the chromosphere, the upward velocities of the evaporating material are approximately the same for both thick target and thermal models. Above that threshold, the thick target calculations predict explosive conditions with velocities approaching an upper limit, defined uniquely on the basis of the pressure difference between evaporating material and corona. For the same energy flux, if the chromosphere is heated by conduction the upward velocities are relatively lower. It is, therefore, in principle possible to distinguish between the two mechanisms of chromospheric heating, since blue-shifted components have been observed for fluxes exceeding the threshold of energy flux (Antonucci, Gabriel and Dennis, 1984). The high upward velocities, exceeding 600 km s^{-1}, derived from high temperature ions such as iron XXV in the case of large flares indicate that at least in these cases explosive conditions are reached. This represents a further indication of chromospheric heating preferentially by accelerated particles, and in turn of a preferential conversion of magnetic energy directly into kinetic energy in solar flares.

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