N87-21812

FAST TEMPORAL CORRELATION BETWEEN HARD X-RAY AND ULTRAVIOLET CONTINUUM BRIGHTENINGS

Marcos E. Machado*

Space Science Laboratory, ES52
NASA Marshall Space Flight Center
Alabama 35812, U.S.A.

Pablo J. Mauas

Instituto de Astronomia y Fisica del Espacio
Buenos Aires, Argentina

ABSTRACT

Recent Solar Maximum Mission (SMM) observations have shown fast and simultaneous increases in hard X-rays (HXR, E>25 keV) and ultraviolet continuum (UVC, $\lambda\lambda \approx 1600$ and 1388 A) radiation. We give a simple and natural explanation for this phenomenon to happen, which does not involve extreme conditions for energy transport processes, and confirms earlier results on the effect of XUV photoionization in the solar atmosphere.

1. INTRODUCTION

Recent SMM observations, see Orwig and Woodgate elsewhere in these proceedings, have shown that besides the close temporal correlation between UV line emission originating in the transition zone (TZ) and HXR emission at E > 30 keV (Woodgate et al., 1983), a similar relationship exists between HXR´s and ultraviolet continuum (UVC). As shown by Orwig and Woodgate, the correlation holds in some cases to better than 0.1 s, with details that can be found in their paper, thus extending the relationship between HXR and UV emission to radiation originating in deep atmospheric levels around the temperature minimum region (TMR).

As shown by Vernazza et al. (1976, 1981) for the quiet Sun and Machado et al. (1980) and Machado and Hénoux (1982) for the case of flare atmospheres, the continuum radiation within $\lambda\lambda$ 1350 -1680 A originates close to the TMR and is primarily due to SiI. It is also known (Vernazza et al., 1981) that the source function of the silicon continua, with edges at 1682 and 1525 A, is significantly decoupled from the local Planck function, due to the strong effect of the photoionization term in the ionization balance equation

$$n(\mathrm{SiII})/n(\mathrm{SiI}) = \frac{4\pi \int (\sigma_\lambda J_\lambda/h\nu)\, d\lambda + C}{R}, \qquad (1)$$

*NAS/NRC Research Associate, on leave from CNIE, Argentina.

where C and R are the collisional ionization and recombination rates respectively, and σ_λ is the photoionization cross section which we take from Vernazza et al. (1976). Since the radiation field that SiI "sees" is characterized, even in the quiet Sun, by a radiation temperature larger than the local electron temperature, T_e, it results that the source function of the continuum, S_λ, is

$$S_\lambda(\mathrm{SiI}) > B_\lambda(Te) \;, \qquad (2)$$

where B_λ is the Planck function, at and around the optical depth unity ($\tau = 1$) level in both continua. This, in turn, leads to emergent intensities characterized by radiation temperatures larger than the local T_e at those depths.

Therefore, any increase in the UVC radiation, which basically reflects an increase in S_λ(SiI) at $\tau \approx 1$ for each of the continua, may either be due to an increase in the J_λ term of equation (1), which would further increase the S_λ decoupling with respect to $B_\lambda(T_e)$, or by a strong increase in the collisonal term C, associated with an increase in the local temperature at the TMR. If by some means, presumably a large increase in the electron density n_e, the C term becomes dominant under flare conditions, then $S_\lambda \approx B(T_e)$ and the brightness temperature changes, which have been reported to be $\Delta T_b > 560$ K (see below) for uniform filling over the observed area (Woodgate, private communication), would represent local changes in the TMR temperature during the flare. Such an increase would then imply a change in the internal energy of the plasma,

$$\Delta E = 1.5\, n_H\, k\, \Delta T > 460 \text{ erg cm}^{-3} \;, \qquad (3)$$

where we have taken $n_H = 4 \times 10^{15}$ cm^{-3} at the depth of SiI continuum formation. Considering that radiative loss rates, primarily due to H^-, can be estimated to be of the order of 10 erg cm^{-3} s^{-1} under such conditions (Machado et al., 1986; Mauas and Machado, 1986), the large ΔE value from (3) implies extremely large energy deposition rates at the TMR, unlikely to be attained by any canonical energy transport mechanism like accelerated particles or XUV heating, not to mention heat conduction which is totally ineffective at those depths (Emslie et al., 1981).

Furthermore, it can be easily demonstrated (Mauas and Machado, 1986) that nonthermal electron beam ionization of hydrogen (Ricchiazzi and Canfield, 1983), which can lead to a local increase in n_e without any accompanying large change in T_e, is rather ineffective at these depths, due to the strong attenuation of the beam above the TMR.

We are thus left with either the possibility that strong and rapid local heating, as specified in (3), occurs at the TMR during the HXR/UVC bursts, or that the observed increase is due to a change in the J_λ term of equation (1). Bearing in mind the unlikeness of the first, for conventinal energy transfer conditions, we explore in the next section the effect of the second.

2. THE EFFECT OF ULTRAVIOLET IRRADIATION

As shown by Machado and Hénoux (1982), the photoionization term on the right hand side of equation (1) can be decomposed into a J^{o}_{λ} term, reflecting the undisturbed quiet Sun conditions, and an additional J^{T}_{λ} term which corresponds to flare irradiation from lines formed in the chromosphere/corona TZ. The net effect of J^{T}_{λ}, which is principally related to the increase in the CIV line emission at 1549 A, is to alter the SiII/SiI ionization balance, through photoionization from the ^{1}D level (1682 A continuum) which is very effectively coupled through collisions, and thus in detailed balance, with the most populated ^{1}S level (1525 A continuum, see Vernazza et al., 1981; Machado and Hénoux, 1982). Therefore, the effect of the largely increased flare J^{T}_{λ} term is to overionize SiI through the TMR, as compared with the results of equation (1) for undisturbed model atmospheres like those of Vernazza et al. (1981).

The effect of the increase in n(SiII)/n(SiI) is twofold, it increases the depth at which τ (continuum) = 1 in the atmosphere, while at the same time it enhances the already present decoupling between S_{λ} and $B_{\lambda}(T)$, increasing the inequality of equation (2) and leading to brightness temperatures much larger than the local T_e.

Using spatially averaged values of UV irradiation, I(UV), as measured by Skylab, Machado and Hénoux (1982, see references therein) found that for I(UV) = 4×10^5 erg cm^{-2} s^{-1} sr^{-1} the variation of S_{λ} leads to a $\Delta T_b \approx 280$ K, without any associated increase in the local temperature as compared with the Vernazza et al. (1976) values. We have now performed a similar calculation using Vernazza et al. (1981) model C atmospheric parameters, with ad-hoc constant irradiation values $1 \times 10^6 \leq I(UV) \leq 5 \times 10^6$ erg cm^{-2} s^{-1} sr^{-1}, which are more appropriate for flare kernels during the impulsive phase as compared with the averaged flare decay values of Machado and Hénoux. The details of these straightforward statistical equilibrium calculations, in which we have kept all model C parameters and ionization equilibrium of elements other than SiI unchanged, will be reported elsewhere in conjunction with a self consistent, time varying modeling of specific burst observations (see below). It suffices to say here that these increased irradiation values lead to correspondingly larger equilibrium T_b increases, of the order

$$360 \text{ K} \leq \Delta T_b \leq 690 \text{ K}, \tag{4}$$

in both the 1525 and 1682 A continua. These values are to be compared to the $\Delta T_b \approx 560$ K as observed at $\approx$ 1600 A in the 20 May, 1984 event, and $\Delta T_b = 870$ K at 1388 A in the 24 April, 1985 flare (Woodgate, private communication; see Orwig and Woodgate in these proceedings).

Furthermore, the characteristic rate of increase of n(SiII) at the optical depth unity level in the ^{1}D continuum (h $\approx$ 400 km in the irradiated model C), is given by

$$dn(SiII)/dt \approx 7.8 \times 10^{10} \, dF(UV)/dh = 1.32 \times 10^{10} \text{ cm}^{-3} \text{ s}^{-1}, \tag{5}$$

for $I = 10^6$ erg cm^{-2} s^{-1} sr^{-1}, for $F = 2\pi I$ and assuming that the ionizing flux is concentrated in the CIV line. This gives, for characteristic silicon densities at these depths (see Vernazza et al., 1981), a characteristic e-folding time of SiII increases of the order of ≈ 1.7 seconds, and conmensurably shorter values for larger ionizing fluxes.

3. DISCUSSION

In the preceding section we have reported that increases in the UVC brightness temperature can be effected, as far as steady state statistical equilibrium calculations show, by the strong photoionization effect of transition zone UV irradiation under flarelike conditions. Irradiation fluxes of the order of $\approx 10^7$ erg cm^{-2} s^{-1} seem to be enough to explain the observed increases in the UVC brightness and, furthermore, they should occur extremely rapidly.

On the other hand, we would like to clearly note here that our results are of very preliminary nature, since they are based on ad-hoc conditions of constant UV irradiation, as compared with the spiky nature of the bursts. In a subsequent study we shall model the HXR-TZ emission-UVC correlation for a set of events, taking into account the observed temporal dependence and absolute value of the TZ irradiation. In spite of these shortcomings in our present study, there are a few aspects worth pointing out in the results which would still stand up after a more detailed study:

a) The strong temporal correlation between TZ and UVC bursts was a definite prediction of the irradiation model (Machado and Hénoux, 1982; Machado et al., 1986), which has been at least qualitatively confirmed by the SMM observations.

b) A temporal correlation between HXR and UVC bursts can only be possible, in our model, through an equally strong correlation between HXR's and transition zone UV emission. Since this correlation is known to exist (Tandberg-Hanssen et al., 1983; Woodgate et al., 1983) and to support the nonthermal thick target model, the HXR/UVC correlation also supports the thick target model for as much as the previous one does, even though there is no direct cause-effect relationship between particle heating or ionization and UVC increases.

c) We further note that the observed increases can simply be due to a relatively minor energy transport towards the deep atmosphere, as compared with any model that invokes localized heating at and around the TMR. For example, instead of the $\approx 10^7$ erg cm^{-2} s^{-1} needed in our computations, Aboudarham and Hénoux (1986) have found that in order to heat the TMR by electron beams, the power in the accelerated particles should exceed 10^{11} erg cm^{-2} s^{-1} for electrons with energies above 20 keV.

ACKNOWLEDGEMENTS

We thank A.G. Emslie, E. Tandberg-Hanssen and B.E. Woodgate for useful discussions and for providing data in advance of publication.

REFERENCES

Aboudarham, J. and Henoux, J.-C., 1986, Astron. Ap., in press.
Emslie, A.G., Brown, J.C. and Machado, M.E., 1981, Ap. J. 246, 337.
Machado, M.E., Emslie, A.G. and Brown, J.C., 1978, Solar Phys. 58, 30.
Machado, M.E. and Henoux, J.-C., 1982, Astron. Ap. 108, 61.
Machado, M.E., Emslie, A.G. and Mauas, P.J., 1986, Astron. Ap., in press.
Mauas, P.J. and Machado, M.E., 1986, Proceedings of the NSO Workshop on the Physics of the Low Temperature Flare, in press.
Tandberg-Hanssen, E., Reichmann, E. and Woodgate, B.E., 1983, Solar Phys. 86, 159.
Vernazza, J.E., Avrett, E.H. and Loeser, R., 1976, Ap. J. Suppl. 30, 1.
____________________, 1981, Ap. J. Suppl. 45, 635.
Woodgate, B.E., Shine, R.A., Poland, A.I. and Orwig, L.E., 1983, Ap. J. 265, 530.