SOFT X-RAY LINE EMISSION FROM SOLAR FLARES

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I. Introduction

Soft X-ray line spectrum in the wavelength region of 1.85-1.94A provides a powerful tool for the diagnostics of the 10-20 million degree plasmas produced in the solar flare (Gabriel 1972 : Mewe and Schrijver 1980). Many observations of this spectral region have been performed and currently in progress improving spectral and temporal resolutions (Newpert et al., 1967 ; Doschek et al., 1971 ; Grineva et al., 1973 ; Doschek et al., 1980 ; Gabriel et al., 1980). Observations of the spectrum at the early stages of flare are particularly important to study the heating phase of flares as theoretical studies of transient flare plasma (Mewe and Schrijver, 1980) indicate. To study this phase, however, both high sensitivity and high time resolution are required to the spectrometer since the rapid variations of the spectrum is expected to occur at low flux level. A crystal spetrometer designed on a new conception (Tanaka and Nishi 1978) which satisfies this condition has been flown on the Tansei-IV satellite launched on 17 February 1980 by the Institute of Space and Aeronautical Science, University of Tokyo. It measures spectra in the two wavelength bands of 1.8-2.0A and 3.1-3.25A with variable time resolution of 6-30 seconds. The sensitivity of the specrometer is such that an incident flux of I photons $cm^{-2}s^{-1}$ at 1.85A at the earth orbit produces a count of 0.14-0.7I corresponding to the above time resolution. Spectral resolution of the crystal (LiF) is 0.005A at 1.85A. This spectrometer differs form ordinary ones in that incident angle of X-ray photons to the crystal is varied for a fixed crystal and detector system by the spin of the satellite. For this purpose the satellite's spin axis is pointed always to a fixed direction slightly (0.7-1.7 degrees) away from the sun. The wavelength scan is made automatically twice in one spin period, at different rates depending on the spin period (n=1-5 resolutions per minutes). This allows for variable time resolution, spectral dispersion and sensitivity. During net observation time of 240 hours in the eight months operation of the satellite, the spectrometer recorded 300 flares. Most of these are small flares with X-ray class less than M1. In this letter we report possible detections of two kinds of variation in the spectrum in the heating phase of flare. A slow spectral variation is generally seen in the rising phase of the flare, while rapid spectral changes have been detected only for a short interval at the initial phase of the flare which shows impulsive rise of flux.

II. Observations

The data are sampled in two kinds of rates : 32ms and 250ms which correspond to a scan step of the spectrometer, respectively, of 0.00026nA and 0.0021nA (n:spin rate in r.p.m.). Fig.1 shows a time series of the spectrum 1.8-2.0A obtained with a scan step of 0.0008A for the May 28 flare (X-class M2.8). The time resolution is 10 seconds. Seven peaks recognizable in the spectra are identified with blended lines from FeXXI to FeXXV(cf. Doschek et al., 1980), FeXXV resonance line at 1.850A and Kα emissions at 1.935A. A gradual variation of the spectrum can definetely be seen. In the initial phase the FeXXV resonance line at 1.85A is apparently weaker than the 1.865A peak. Toward the maximum the resonance line becomes most pronounced among the all. Intensity time profiles in seven wavelength bands in Fig.2 shows that the rate of increase and decrease in the intensity is largest for the resonance line, and for the other wavelength regions the rate is nearly the same but slowly decreases to the longer wavelengths. Intensity curve of Kα emission is similar to the total Fe line emission, I(Fe), or the sum of the intensities from 1.84A to 1.95A. This variability may be characterized by a time profile of a single index : R which is defined as the flux ratio of the combined emissions $\lambda<\lambda_o$ to those $\lambda>\lambda_o$. For the dividing wavelength λ_o we chose λ_o =1.88A as this wavelength position can be determined precisely, even in lower dispersion spectra, with the reference to the emission line obtained in the other band (3.2A) of the spectrometer. In the condition of ionization equlibrium R may be converted to an equilibrium temperature as will be discussed later. Time profiles of R for two deifferent flares are plotted in the lower parts of Fig.3. Compared to the total emission I(Fe) shown in the upper part of Fig.3 R is found to attain maximum at the same time as I(Fe). The coincidence of the times of both maxima has been found generally for all the flares with the X-ray class than M3. In contrast the intensity maximum is delayed to the maximum of R by one to two minutes in those flares with the X-ray class greater than M7, although we have observed only four such large flares. For small flares steady increase of R with the ascent of the flux appears to be quite universal. The duration of this phase ranges from one to three minutes depending on the type of flare.

Large instrumental width of our spectrometer may prevent measurement of the line profile. However line profiles definitely broader than the instrumental width

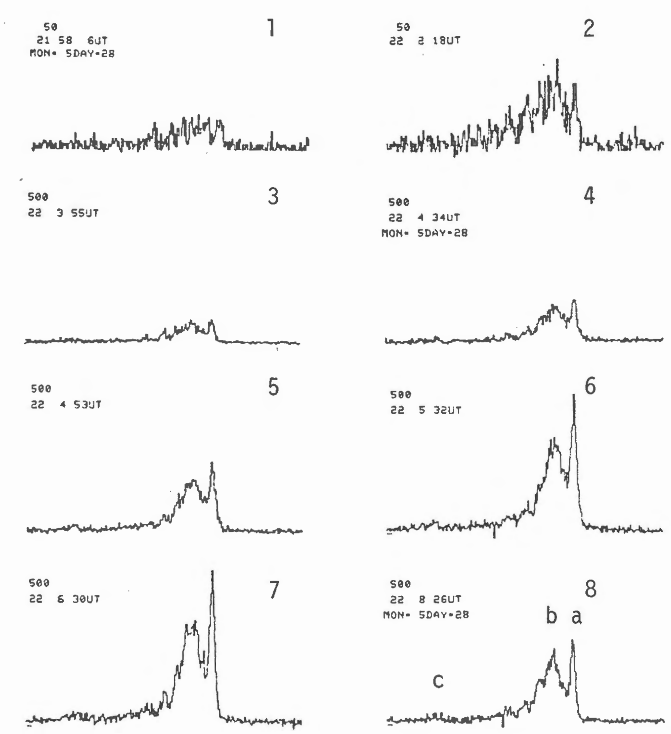

Fig.1

Time sequence of the iron line spectrum:1.80-2.00A. (Ordinate scale for the top two is 1/10 that for the lowers.)

a.1.85A(FeXXV),b.1.865A, c.1.94A(Kα)--frame 8

1.21 58 06 UT
2.22 02 18
3.22 03 55
4.22 04 34
5.22 04 53
6.22 05 32
7.22 06 30
8.22 08 26
(1980 May 28 flare)

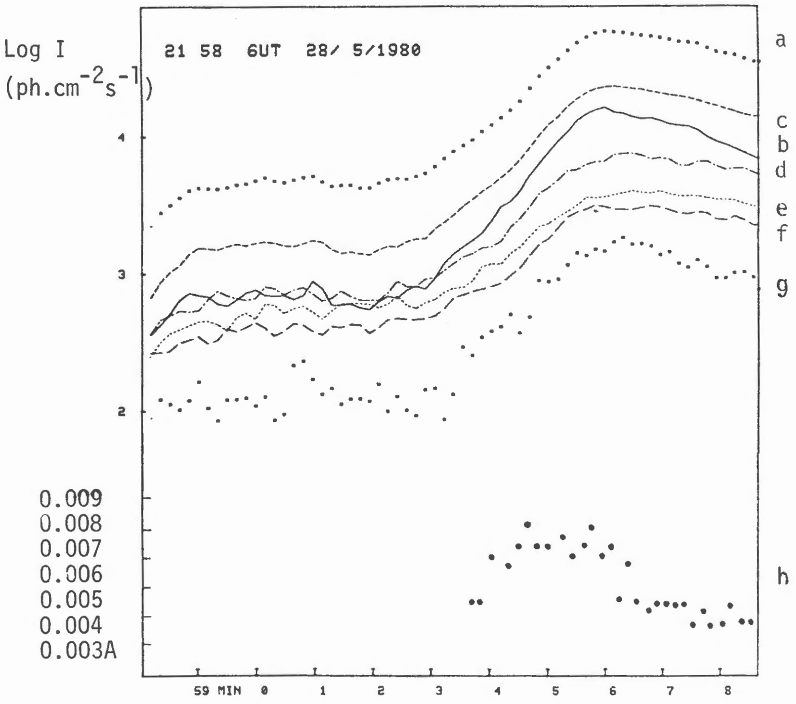

Fig.2

Time variations of the flux in seven bands and of the FeXXV resonance line width(FWHM).

a.1.84-1.96A(total)
b.1.845-1.86A(FeXXV)
c.1.865-1.879A
d.1.879-1.887A
e.1.887-1.896A
f.1.896-1.909A
g.1.92-1.95A(Kα)
h.line width

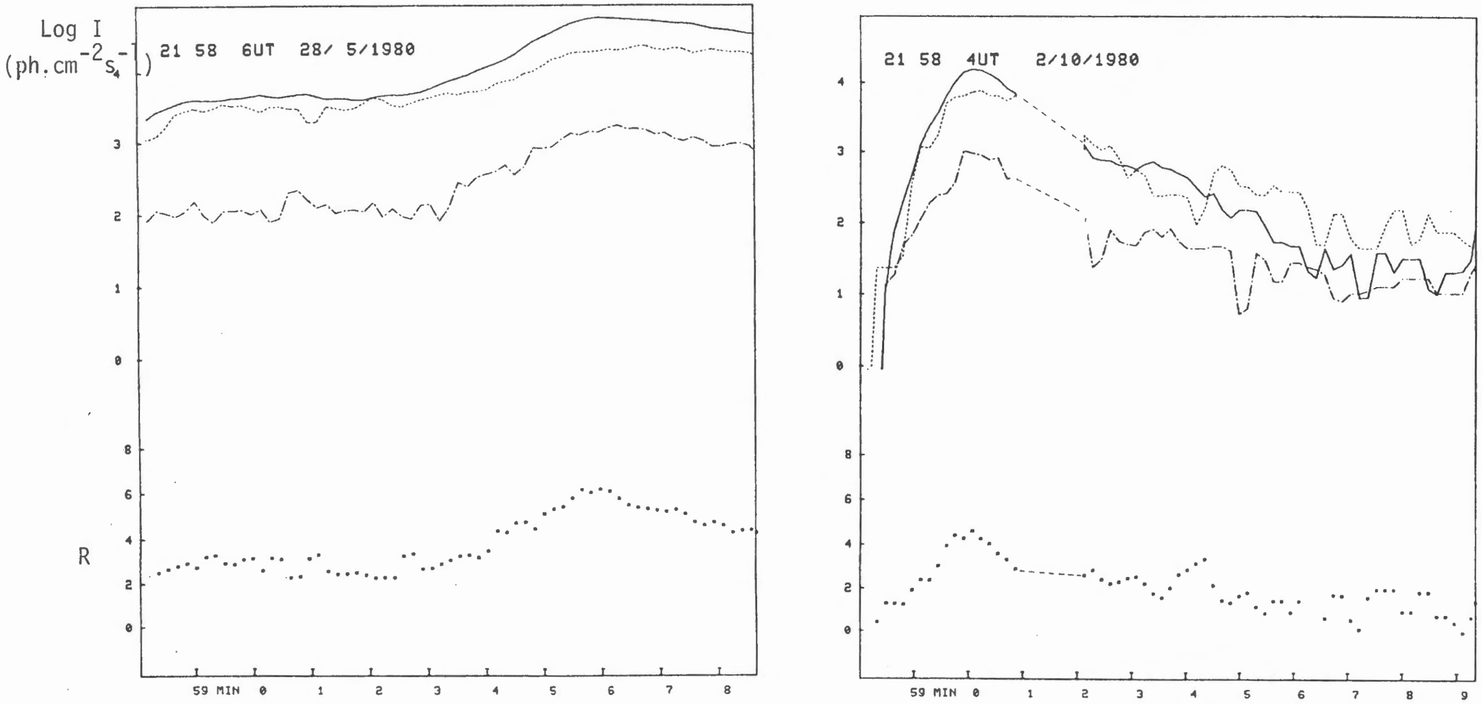

Fig.3 (Top) Time profiles ofthe total fluxof the iron complex(thick line),calcium lines(3.16-3.22A)(dotted line) and K_α line at 1.94A.

(Bottom) Time profile of the flux ratio(R) of combined emission 1.88A to 1.88A.

(Left) 1980 May 28,21 58 06 UT Flare

(Right) 1980 October 2,21 58 04UT Flare

of 0.005A have been recorded in the rising phase of the May 28 flare (Fig.1). The FWHM of the resonance line as plotted at the bottom of Fig.2 shows rapid increase at the time of rapid flux increase, and sudden decrease after the maximum. The intrinsic line width (FWHM) at the peak is estimated to be 0.0056A by deconvoluting the rocking curve width. This value corresponds to the turbulent velocities of about 200kms^{-1}, if the broadenning is due to non-thermal motions.

Rapid spectral variations we present here have been observed only in the fast rise flares.. The rise time of these flares are less than 2 min., and the increase rate of the total flux ($\Delta \log I(Fe)/\Delta t$) is in the range of 1-2 min^{-1}. The rapid changes occur only for a short interval (10-40 sec.) at the initial phase. Time sequences of the spectra in the two flares are shown in Fig.4. The light curves for these flares are shown in Fig.3. Since the spectra were obtained in low dispersion mode with a sampling interval of about 0.005A, fine structure of the spectrum cannot be seen. However it is clear that the increase of the counting rates started around 1.935A and 1.89A. In the March 31 event (Fig.4a) the double peak structure in the spectrum is replaced in six seconds by a pronounced single peak at 1.885A(0050 01UT). The next profile taken at 00 50 07 UT this peak is shifted to 1.865A. The total iron line flux I(Fe) shows significant increase of a factor of ten in only 12 seconds. No detectable change in the position of the maximum intensity is apparent in the subsequent scans. Spectral variation in the October 2 event is more complex. The spectrum taken at 21 58 51UT shows four peaks at 1.94A, 1.895A, 1.865A and 1.850A with the intensity reducing in this order. In subsequent frames the peaks at 1.865A and 1.85 A grow most rapidly with other peaks appearing at 1.920A, 1.90A and 1.885A. The peak of Kα emission is pronounced for 30 seconds during this phase, and then dissappear. After 21 59 29UT the spectral shape remains constant showing double peaks at 1.865A and 1.850. Clear evidence for the rapid shift of the intensity maxima from 1.885A to 1.865A such as have been seen in the May 31 event has been given in other two flares. The shift was accompanied by rapid increase of the flux with the exception of the February 29 event, in which the intensity maxima shifted from 1.885A to 1.86A in 6 seconds without changing the peak intensity. In slow rise flares, too, there can be seen fluctuative changes in the initial sequences of the spectrum, but they are not significant from the count statistics.

In the events shown in Fig.4 microwave bursts at 17GHz have been obtained at the Nobeyama Station. The bursts (Fig.4) show a sharpspike with a short duration coincident with the phase of rapid variation in the X-ray spectrum. Detailed comparisons have revealed that the initial enhancement at Kα and 1.89A occurs at the start of the radio burst, when the flux of the burst is only 3% of the peak flux. The sharp spike of the burst, on the other hands, coincides with the rapid shift of the intensity maximum in the spectrum. In the October 2 event an increase

Fig.4a

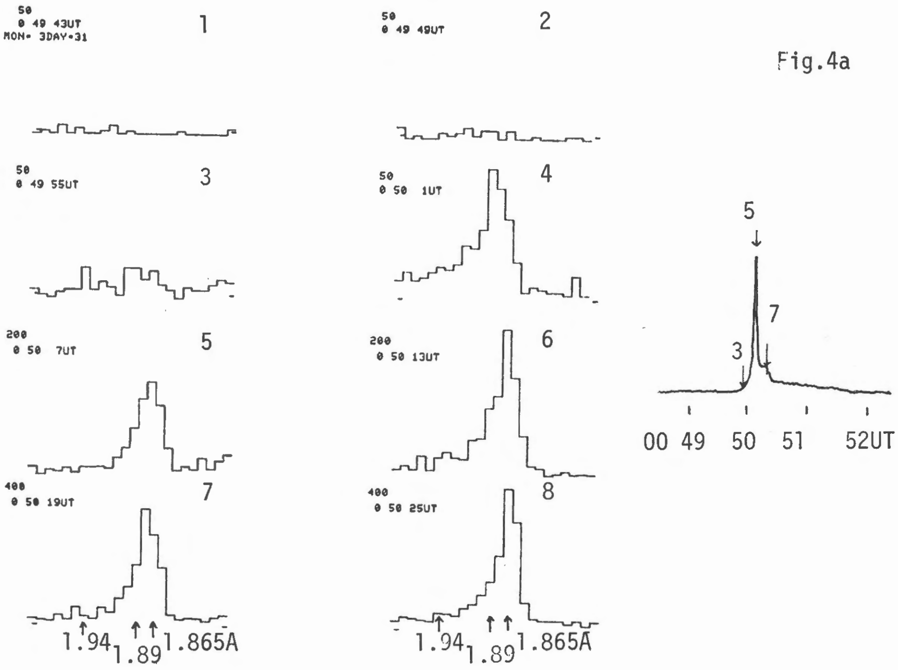

Fig.4b

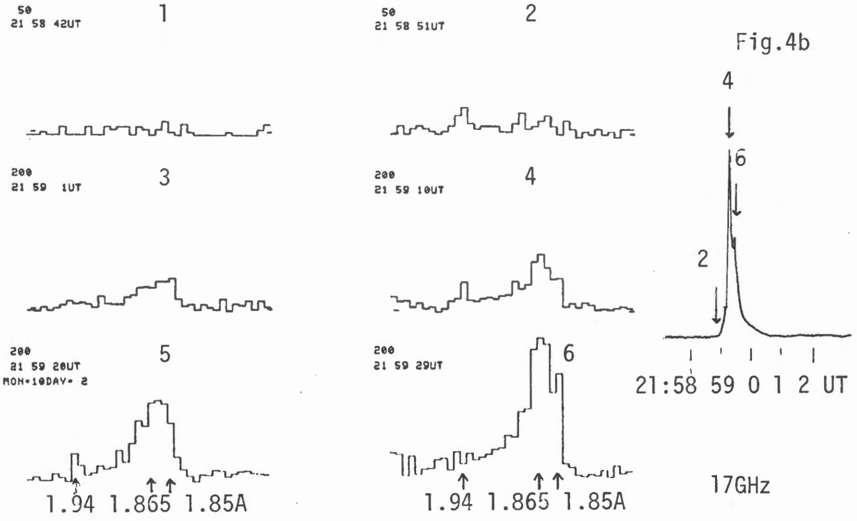

Fig.4 Rapid spectral changes

Fig.4a March 31, 00 49 43UT-00 50 25UT(time resolution 6s)

Fig.4b October 2, 21 58 42UT-21 59 29UT(time resolution 9s)

Time profiles of 17 GHz radio burst obtained at Nobeyama Station (courtesy of Dr.K.Kai) are shown in the right. Numbers indicate the time at which corresponding spectrum was taken of the Kα intensity occurred simultaneously with the sharp rise of the burst. But during a flux increase of the burst by a factor of twenty the Kα emission increased only a factor of four. For the other event no microwave data are avaiable. Preliminary comparison with the hard X-ray burst obtained by SMM indicates coincidence of the sharp spike of the hard X-ray burst with the rapid shift of the intensity maximum in the spectrum (May 31 event).

III. Analysis and Discussions

Rapid spectral changes simultaneous with the microwave burst may be identified with the initial heating of flare plasma. The fact that the changes are seen only at the low intensity level ($I(Fe) \sim 10^{2.5} ph \cdot cm^{-2} s^{-1}$) makes it difficult to observe this phase in the high resolution spectra. To obtain high resolution spectra by means of Ge or SiO_2 crystals to the same intensity level and time resolution as the present observations a large crystal area over $500 cm^2$ would be required. Even in the low resolution spectra like present cases, however, sudden enhancement of emissions at Kα and around 1.89A and subsequent shift of the peak to 1.865A can be safely recognized. Comparing with the theoretical simulations of the iron line spectrum in the transient flare plasma by Mewe and Schrijver (1980), sudden appearance of Kα emission and emissions at longer wavelength region fit the case in which the electron temperature steeply jumps from an initial value of 5×10^6K to a constant higher value of $Te > 14 \times 10^6$K. On the other hand, the shift of the intensity maximum from 1.885A to 1.865A can be reproduced when the temperature rises linearly with time. The speed of this shift determines the electron density if the temperature time profile is known. Among various model calculations by Mewe and Shrijver the observed short time scale (>10 sec.) of the shift appears to be consistent with the case of high density ($ne = 10^{11} cm^{-3}$) in which linear temperature rise to 20×10^6K occurs in one minute. In our observations, however, temperature profile is unknwon and there remains a possibility of non-thermal ionization due to high energy electrons producing the microwave or hard X-ray bursts. The emission peaks at 1.885A and 1.865A are dominantly contributed from FeXXII, and FeXXIV and FeXXV, respectivly. The time required for collisional ionization from FeXXII to FeXXV is equal to $3.3 \times 10^{15} T\ ne^{-1}\ \exp(7.7 \times 10^7/T)$s. Therefore even with high temperature limit of 10^8K, which may be equivalent to the non-thermal ionization, high density of the order of 10" is expected. The strong Kα emission observed at the initial phase is a dominant component of the spectrum. The origin of the Kα emission at the phase may be either due to impact collision of the high energy electrons or due to sudden jump of the electron temperature. The former possibility, however, meets a difficulty by the fact that the Kα emission increase without being proportional to the burst flux. Impact ionization origin of the Kα emission simultaneous with hard x-ray burst is reported in the SMM observation (Gabriel et al., 1980) In contrast the Kα emission visible in later phases is proportional to the total iron line flux. The fluolesence origin is suggested for this case since ionizing of K-shell electron at 7 Kev will vary, more or less, similarly to the toatl iron line flux.

The spectral variation which is observed during the rise of small flares in commom proceeds gradually with a time scale of 1-3 minutes. The high dispersion spectra taken before the rise of the flux and at the maximum in the May 28 flare (Fig.1) show close similarities to the spectra calculated in the ionization equilibrium for 15×10^6K and 20×10^6K, respectively (Mewe and Schrijver, 1980). In a relatively, high electron density close to 10^{11}cm^{-3}, the ionization equilibrium will immediately follow the slow temprature rise if this rise occurs in the above time scale. The quasi-stationary ionization equilibrium has been suggested from the studies of the high resolution spectra (Doschek et al. 1980). We, therfore, assumed ionization equilibrium and calculated theoretical intensities of the 208 lines of FeXIV-FeXXV which are found in the region 1.85-1.94A of the line list of Mewe et al. (1980) to derive the equilibrium emission rates for the total flux I(Fe), combined emissions for $\lambda<1.88$A and for $\lambda>1.88$A as a function of temperature. If the flare region is assumed to be iso-thermal, the ratio R, which is also found to be smooth and monotonic function of temperature, gives an equilibrium temperature, and then the emission measure is determined from the total flux. Time profiles of the temperature and emission measure thus derived are shown in Fig.5. A typical small (<M1) but impulsive flare shows a temperature rise from 13×10^6K to 18×10^6K. In the line ratio analysis using high resolution spectra by Doshek et al.(1980) no increase of the electron temperature has been found in the rise phase of X-class and most of M-class flares. Only for a M3 class flare they have found an increase of temperature from 18 to 20×10^6K. The M2.8 flare in our data shows a rise in the equilibrium temperature from 16 to 20×10^6K, consistent with their result for the electron temperature. Present analysis, combined with their result, suggests that the increase of temperature is found only when the flux is lower than certain level. The critical flux for the FeXXV resonance line appears to be 10^4 ph$\cdot$ cm^{-2}s^{-1}. An interesting aspect commonly observed in small flares is the similarity of time profiles of R and I(Fe). As found from Fig.5 this is converted to the similarities of the temperature and emission measure time profiles. The result appears to contradict with earlier results derived from the continuum analysis (e.g.Horan 1971) However, the large flares (>M7) in the present cases show a time delay of the emission measure maximum behind the temperature maximum as have been found previously. Rather, the effect seems to depend on the size of flares. Presumably basic behavior may be observed in small flares, in which the structure of X-ray emitting loops

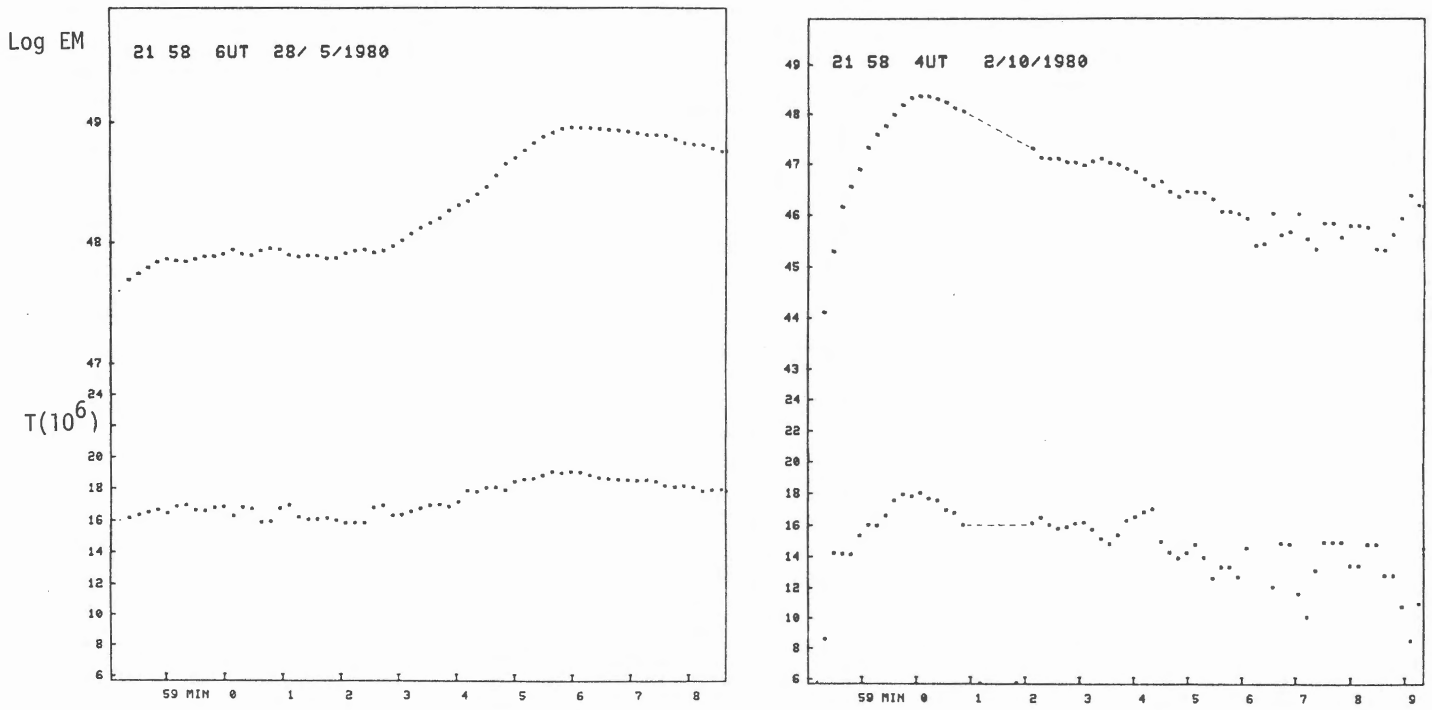

Fig.5 Time profiles of emission measure(upper) and equilibrium temperature(lower)
(Left) 1980 May 28 Flare (cf. Fig.1,2,3)
(Right) 1980 October 2 Flare(cf. Fig.3,4b)

is conidered as simple (Sturrock 1979). Then, an apparent time lag between the two maxima observed in large flares may be caused by complex evolutions which involve many loops. If many X-ray loops develop successively in the large flare and the peak temperature of each loop is lower for the loop developed later, such effect will result. Although finer analysis are needed to the definite answer, we may tentatively, conclude that the temperature and emission measure increase simultaneously in individual loops. With the assumption of constant mass this indicates simultaneous increases of the temperature and density suggesting a plasma compression.

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