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COMPARISON OF SOLAR X-RAY LINE EMISSION WITH MICROWAVE EMISSION DURING FLARES

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ABSTRACT

An analysis of X-ray emission at 1.87 Å observed during three solar flares by OSO-III indicates that maximum line emission is observed to occur 0.5–5 min after impulsive microwave maximum. The time integral of the centimetric radio burst corresponds best to the 1.87 Å line intensity during the rise to maximum X-ray intensity. The constancy of line emission from Fe IX through Fe XV, coupled with strong enhancements in higher ionization stages, suggests that additional material, not originally at coronal temperature, is rapidly heated and elevated to high stages of ionization during the event. Such heating and ionization may be the result of collisional losses by energetic electrons which are also responsible for the impulsive microwave burst.

I. INTRODUCTION

The association between soft X-ray events (photon energies <20 keV) and radio impulsive microwave bursts has not been accurately established in the past since few such X-ray events have been observed in their entirety. For two events reported in the literature (Kreplin, Chubb, and Friedman 1962; Donelly 1967), maximum soft X-ray emission in the spectral range from 1 to 10 Å (12–1.2 keV) occurs after the maximum phase of the impulsive microwave event, the delay being of the order of one to several minutes. Similar results are obtained when flare-associated sudden ionospheric disturbances (SID), produced by excess ionization in the D-layer by an enhanced 1–10 Å X-ray flux, are compared with the associated microwave events (Hachenberg and Kruger 1959; Kawabata 1960; Warwick 1963). We propose in this Letter to reinvestigate these relationships, using OSO-III observations on the strong line emission at 1.87 ± 0.02 Å tentatively identified as the $1s^2$–$1s2p$ transitions of Fe XXV (Neupert *et al.* 1967) as observed during three bursts and to consider possible physical relationships between the two emission processes.

II. OBSERVATIONS

The solar spectrum between 1.3 and 3.1 Å was observed by OSO-III using an uncollimated crystal spectrometer which provided a resolution ($\lambda/\Delta\lambda$) of 200 and a wavelength accuracy of 1 per cent at 2 Å. Either the entire spectrum could be scanned once every 2.5 min, or one wavelength could be monitored continuously with a resolution in time of 0.64 sec. Data are given in Figure 1, *a* and *b*, for the intensity of line emission at 1.87 Å and the accompanying microwave event observed on March 20, 1967, simultaneously with the occurrence of a chromospheric flare of importance 1*N*. The 1–3 Å spectrometer was in scan mode, thus recording the intensity at 1.87 Å once every 2.5 min. However, the integrated X-ray flux between 2 and 8 Å was monitored continuously by an ionization chamber and shows the same smooth rise and fall suggested by the 1.87 Å data points. Emission lines of Fe IX (171 Å), Fe X (174 Å), Fe XIII (193 Å), Fe XIV (257 Å), Fe XV (284 Å), and Fe XVI (335 Å) were monitored once every 3 min with a grazing-incidence grating spectrometer and exhibited less than 3 per cent change in intensity during the event. Strong emission lines of Fe XXIV–Fe XVIII were recorded between 9 and 15 Å by a second crystal spectrometer during the event. The data for these lines have not been fully analyzed and will be presented at a later date.

Similar X-ray data (Fig. 2, *b*) were obtained during a flare of importance 3*B* on March 22, 1967. In this case, emission from Fe IX–Fe XIV changed by less than 5 per cent, Fe XV increased 7 per cent, and Fe XVI increased 16 per cent during the event. During a third event (Fig. 3, *a*) on July 25, 1967, the emission feature at 1.87 Å was monitored continuously. This is the only event of the three which has been classified as an explosive event (by McMath-Hulbert Observatory) in Hα. We have analyzed this event as if it consisted of two separate X-ray and microwave bursts (labeled "I" and "II") since in other instances in which multiple X-ray maxima are observed each maximum can be associated with a different Hα brightening on patrol records.

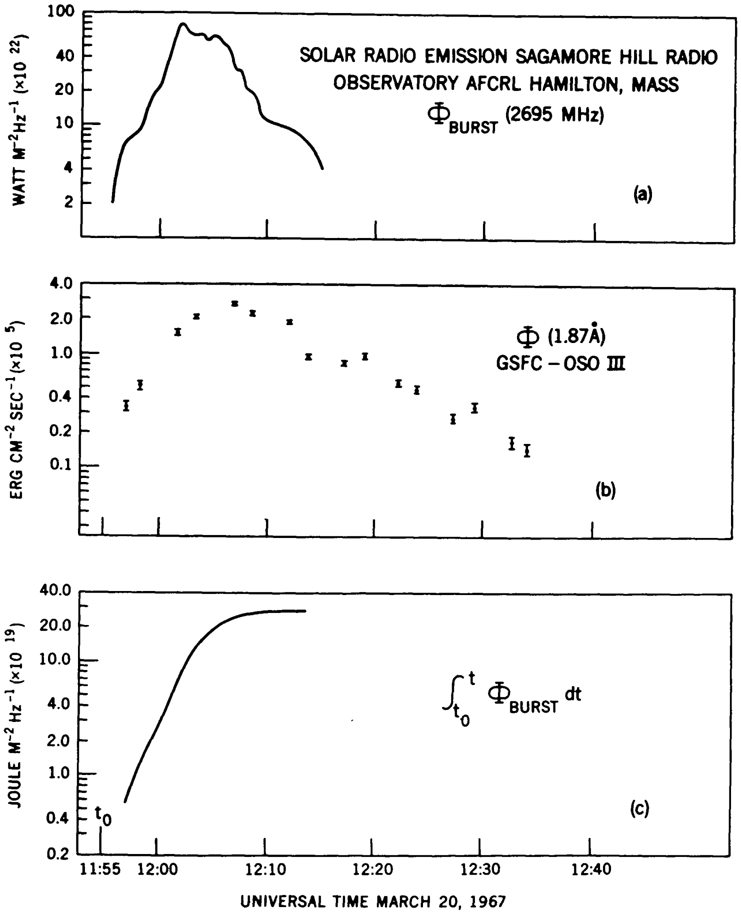

FIG. 1.—(*a*, *b*) Comparison of solar centimetric radio flux at 2695 MHz with X-ray line emission at 1.87 Å associated with a chromospheric flare of importance 1*N* on March 20, 1967. (*c*) Time integral of radio flux shown in Fig. 1, *a*, beginning at time t_0 = 11:55 U.T.

Table 1 gives the times of maximum phase of the Hα event, peak microwave emission (at 2700 or 2695 MHz), peak emission at 1.87 Å, and maximum SID. Also given are times at which the X-ray emission at 1.87 Å was increasing most rapidly.

For all three events we observe the following: (1) Line emission from high stages of ionization of iron (Fe XVIII–Fe XXV) becomes prominent in the soft X-ray spectrum with little or no change in line emission from intermediate stages of ionization (Fe IX–Fe XVI). (2) The maximum X-ray line emission (1.87 Å) occurs 0.5–10 min after peak impulsive microwave emission and remains high even after the end of the impulsive

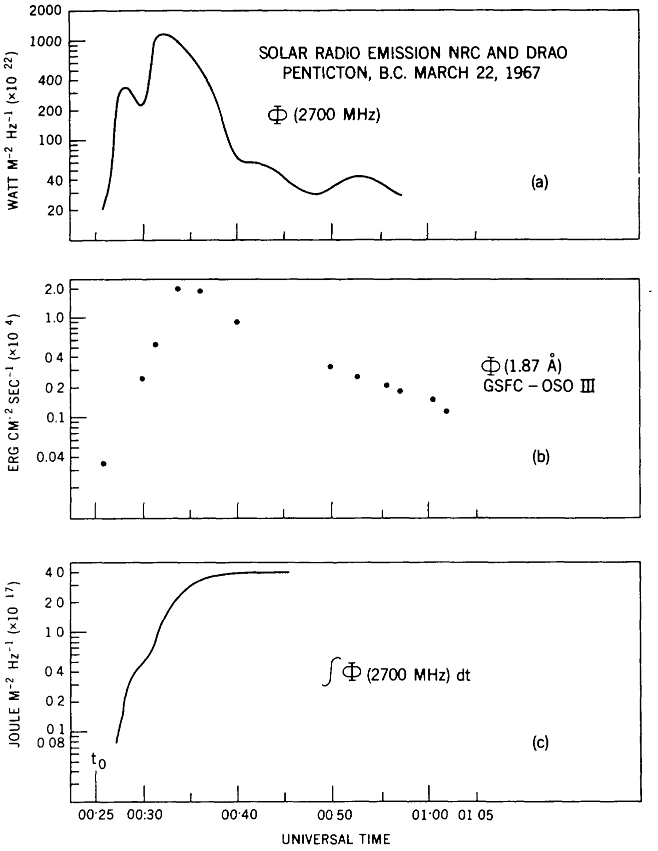

FIG. 2.—(*a*, *b*) Comparison of solar radio flux at 2700 MHz with X-ray line emission at 1.87 Å associated with a flare of importance 3*B* on March 22, 1967. (*c*) Time integral of the 2700 MHz flux, beginning at t_0 = 00:25 U.T.

TABLE 1

OCCURRENCE OF Hα FLARES, CENTIMETER BURSTS, AND X-RAY LINE EMISSION FOR THREE EVENTS OBSERVED BY OSO-III

	MARCH 20 (U.T.)	MARCH 22 (U.T.)	JULY 25 (U.T.)	
			I	II
Hα flare (maximum phase)	....	00:33	14:28	....
Centimeter burst (maximum intensity)	12:02	00:32	14:27:25	14:29:05
X-ray (1.87 Å) (maximum intensity)	12:07	00:35	14:27:50	14:30:50
SID maximum	12:12 (SPA)	00:37 (SCNA) 00:40 (SPA)	14:31 (SCNA) 14:33 (SPA)	
X-ray (1.87 Å) (maximum rate of increase)	12:01	00:33	14:27:25	14:29:20

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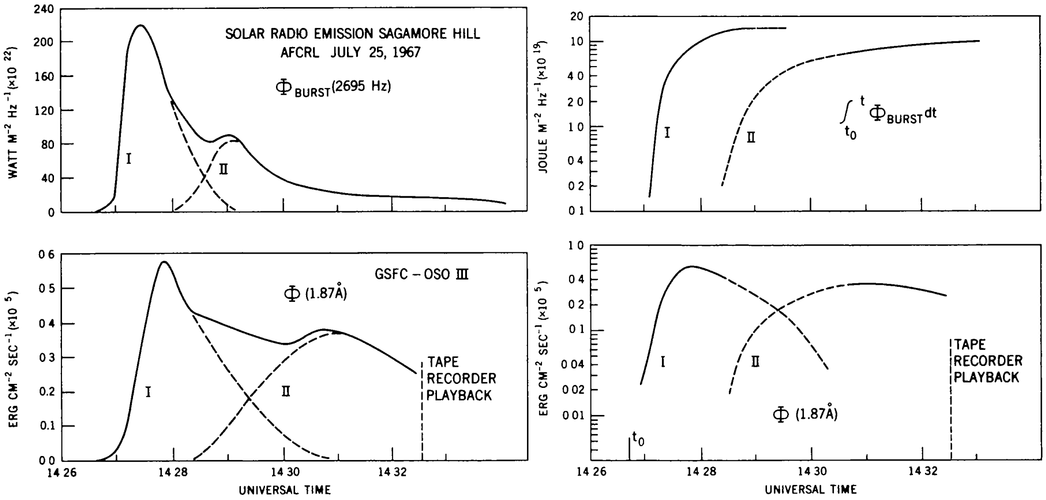
radio burst. The maximum rate of increase in X-ray emission occurs within 2 min of peak microwave emission. (3) The associated microwave burst is most intense at centimetric wavelengths and is weak at metric wavelengths.

III. DISCUSSION OF THE OBSERVATIONS

From the lack of coincidence in time between the impulsive radio emission and the emission at 1.87 Å, it appears unlikely that both can be attributed to the same hot plasma or to the same ensemble of fast electrons. Let us consider the alternative that X-ray line emission originates in a hot plasma which is produced by thermalization of the fast electrons most probably responsible for the impulsive radio burst. Under this hypothesis the total amount of material ionized to high stages of ionization by some time t (and which will remain in such high stages as long as the recombination rate is small compared with the ionization rate) may be related to the energy lost by energetic electrons up to that time. Since microwave emission is the one available measure of the rate at which energy is lost by fast electrons (Takakura 1967), we have evaluated the integral



(a) (b)

FIG. 3.—(*a*) Observations of solar radio and X-ray emission on July 25, 1967. Event is assumed to consist of two consecutive bursts, dashed lines indicating our decomposition of data into two such bursts. (*b*) Comparison of time integral of radio flux, calculated separately for each of the two assumed radio bursts in Fig. 3, *a*, with X-ray line emission (same as in Fig. 3, *a*). Logarithmic scale is used in Fig. 3, *b*, to facilitate comparison between microwave and soft X-ray components of the burst.

$$\int_{t_0}^{t} \Phi dt$$

for each of the three bursts. In this integral, Φ is the microwave flux at a fixed frequency, and t_0 is the assumed beginning time of the burst. The fact that the resulting integral fluxes, shown in Figures 1, *c*, 2, *c*, and 3, *b*, closely match the rising portion of the X-ray emission curves supports this model.

The amount of material which must be ionized during the initial phase of the flare can be estimated from the emission measure, $\int N_e^2 dv$, for the volume which is emitting 1.87 Å radiation (assumed to be the $1s^2$–$1s2p$ transitions of Fe xxv). Assuming that the $1s2p$ level is collisionally excited from the ground state, that this transition has an oscillator strength of 0.75, that iron has an abundance log $N_{\text{Fe}} = 7.7$ on a scale of log $N_{\text{H}} = 12.0$, and that $T_e = 3 \times 10^7$ ° K, we find the emission measure to be about 2×10^{48} cm^{-3} at the peak of the event on March 22. This is smaller than the value of 2–6 $\times 10^{50}$ cm^{-3} suggested by Elwert (1964) for an importance 2+ flare but comparable to that ($\approx 1 \times 10^{48}$ cm^{-3}) attributed (Evans and Pounds 1968) to the corona above active region. Since line emissions of Fe IX–Fe XVII show no decreases during the event, it is likely that additional material, not originally at coronal temperatures, must be brought to high stages of ionization during the initial phase of this event to account for the Fe XXV emission. If the X-ray emitting volume has a base area of 10^{19} cm^2 and height of 2×10^9 cm, then $N_e \approx 10^{10}$ cm^{-3}, the total number of electrons is about 2×10^{38}, and the total mass (protons and electrons) is about 4×10^{14} gm. The kinetic energy of the electrons and protons in this volume, at 3×10^7 ° K, would be about 2×10^{30} ergs.

The total amount of energy originally available in a fast electron stream, postulated by Takakura and Kai (1966) to account for the observed microwave emission, can be estimated from the intensity of the observed microwave burst by considering the relative importance of energy losses via synchrotron and gyroemission and via collisions with ambient thermal electrons (Takakura 1967). Loss by bremsstrahlung is small compared with these terms and will be disregarded. Assuming the plasma frequency and gyrofrequency are both equal to 1000 MHz, radio emission predominates for electron energies greater than 250 keV. At this energy the emission loss per electron is 2×10^{-10} erg sec^{-1} for an electron having a pitch angle of 90°. At the peak of the March 22 event the flux at 3750 MHz was 1650 flux units, implying that, over band width of 2×10^{10} Hz, the peak microwave emission rate at the Sun was about 1×10^{22} ergs sec^{-1}, assuming no gyroabsorption of the emitted radiation. Hence, approximately 5×10^{31} electrons with $E > 250$ keV are required. If these electrons are a part of an original energy distribution $N(\epsilon_0)$ of electrons having the form (Takakura and Kai 1966)

$$N(\epsilon_0) \sim \epsilon_0^{-5}$$

where ϵ_0 = initial kinetic energy/mc^2, we find

$$E_{\text{total}} = \int_{\epsilon_0=0.02}^{\epsilon_0=2} \epsilon_0 N(\epsilon_0)\, d\epsilon_0 \approx 10^{29} \text{ ergs}\,.$$

This result is, of course, critically sensitive to the lower limit of integration, taken here to be 10 keV, and to the initial distributions of pitch angles. If the initial electron velocities are assumed to be isotropic rather than aligned normal to the magnetic field, then drift of electrons along the field and their possible loss from the initial volume are appreciable in times that are short compared with the "deflection" time defined by Spitzer (1962), thereby reducing the total microwave energy emitted per fast electron. Thus 10^{29} ergs should be considered a lower limit for the total kinetic energy in the assumed initial distribution.

In conclusion, our observations to date appear to be consistent with the following highly schematic model of an X-ray emitting region above a flare: Simultaneous with, and perhaps as a result of, the loss of energy carried by fast electrons, a portion of the chromosphere is heated to sufficiently high temperatures (as high as $20\text{–}40 \times 10^6$ ° K) to account for the existence of Fe XX–Fe XXV and is ejected into the lower corona. As the ambient electron density in the lower corona rises, collisional losses rather than gyrosynchrotron emission may become dominant for any remaining energetic electrons and a "quenching" of the impulsive microwave event may occur. Thus the end of the impulsive microwave event coincides with the presence in the corona, at a height of 10000–50000 km (Zirin 1966), of as much as 4×10^{14} gm of hot plasma (for an intense burst, as on March 22). As the plasma cools, recombination of ions with electrons takes place, producing successively lower stages of ionization (Neupert, Swartz, and White 1968). Ultimately a portion of this plasma may fall back toward the Sun, perhaps being visible in the form of loop prominences or "coronal rain," while the remainder may move into the interplanetary space and contribute to the geomagnetic storm often observed at the Earth after large flares.

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