THE ASTROPHYSICAL JOURNAL, Vol. 149, August 1967

OBSERVATION OF THE SOLAR FLARE X-RAY EMISSION LINE SPECTRUM OF IRON FROM 1.3 TO 20 Å

W. M. NEUPERT, W. GATES, M. SWARTZ, AND R. YOUNG
Goddard Space Flight Center, Greenbelt, Maryland
Received June 26, 1967

ABSTRACT

Solar X-ray spectra have been obtained during solar flares by OSO III (Orbiting Solar Observatory). New emission lines are observed in the spectral range from 1.3 to 20 Å and are tentatively identified as transitions in Fe XXVI through Fe XX.

I. INSTRUMENTATION

Solar X-ray spectra have been obtained during solar flares with two uncollimated single-crystal Bragg spectrometers each having a crystal-detector combination optimized for a specific spectral range. In one, a LiF analyzing crystal is coupled with a conventional photomultiplier using a 5-mil Be filter and a Na I conversion phosphor. The spectral resolution of the system is 0.01 Å in the spectral range 1.3–3.1 Å. A similar instrument, with KAP crystal together with a Bendix magnetic electron multiplier using a 2-μ thick filter of polypropylene overcoated with 2000 Å of aluminum, scans the region from 6.3 to 25 Å with a resolution of 0.05 Å at 10 Å. The wavelength calibration of the spectrometers is limited to approximately 0.5 per cent by the finite angular increment through which the crystals are stepped from one observation to the next.

II. OBSERVATIONS

The X-ray spectrometers, part of the scientific payload on OSO III which was launched on March 7, 1967, have to date observed the solar spectrum for more than 1600 hours. Two spectra, obtained with the LiF spectrometer during the build-up of X-ray emission associated with a flare of importance 2b on March 22, 1967, are shown in Figure 1. At this time the detector output has increased from the instrumental background rate of 0.5 count per 0.64 sec observing interval. Superimposed on an apparent continuum we observe emission lines, the most intense of which is 10–15 times more intense than the nearby continuum. Less intense lines which appear consistently in the data are also indicated in Figure 1. Apparent differences in the spectral distribution of the radiation recorded in the two scans is accounted for by the fact that the level of intensity of the X-ray burst was increasing in the 5-min period during which the two spectra were taken.

Spectra for the region 6.3–20.0 Å are given in Figure 2. Spectra similar to our "preflare" spectrum have been obtained in the past from rockets above Earth's atmosphere by Blake, Chubb, Friedman, and Unzicker (1965); Neupert, Muney, and Adelman (1966); Evans, Pounds, and Culhane (1967); and Walker, Rugge, Chater, and Howey (1967). The data presented here are the first observations of the spectrum during a solar flare. In addition to increases in intensity of all lines observed in the preflare spectrum, we observe a new group of lines between 9.0 and 14.0 Å which appear not to have been present prior to the flare.

III. IDENTIFICATION OF NEW EMISSION LINES

Kawabata (1960) has suggested that emission lines from high stages of ionization of iron may be prominent in the spectrum between 1.0 and 20.0 Å during solar flares. Emission lines below 3.0 Å must certainly originate with elements having $Z \geq 18$, since all lighter elements have Lyman limits for their hydrogen-like ions at longer wavelengths. Even for heavier elements, only transitions ending in the ground state of the ion will give rise to lines below 3.0 Å. Consider the Lyman series, $1s$–np, for the hydrogenic ion of a heavy element and equivalent transitions of the form $1s^2 2s^2 2p^n$–$1s 2s^2 2p^{n+1}$ from successively lower stages of ionization of that element. The addition of electrons results in shielding of the nucleus and lowers the energy of the transition. For low stages of ionization the energy of the transition is essentially equal to the energy of the usual characteristic Kα X-ray emission line of the element (Shuvaev and Chechin 1965). In Figure 1 we have indicated the high ionization limit (Lyman-α) and low ionization limit (Kα) for such transitions for the five most abundant elements having $Z \geq 18$. It is

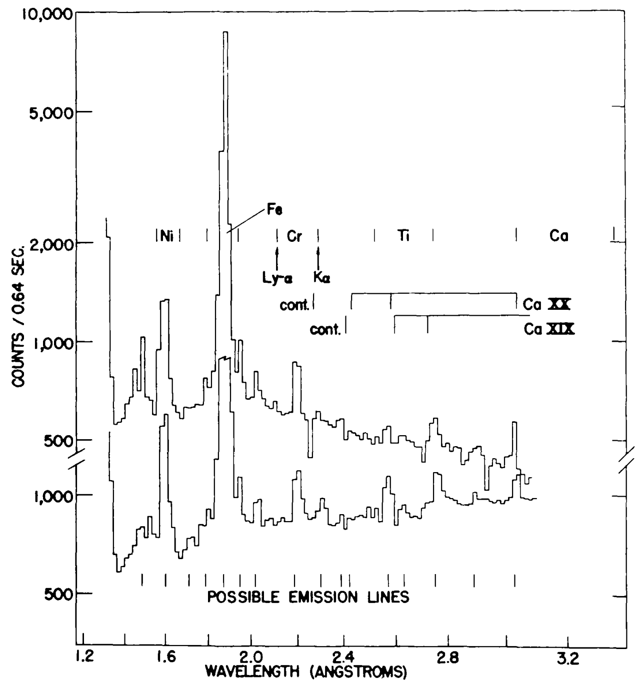

FIG. 1.—Two spectral scans in the region 1.3–3.1 Å obtained during the increasing phase of a solar X-ray burst on March 22, 1967. Apparent differences in spectral distribution are due to the increase in intensity of the X-ray burst in the time (5 min) required to make the two scans. The onset of increased count rate at 1.34 Å coincides with the detector position at which it begins to be illuminated directly by the Sun.

doubtful whether any emission feature can be associated with Ti, but definite structure does appear between the limits indicated for Cr, Fe, and Ni.

Wavelengths for the transition arrays $1s^2 2s^2 2p^n$–$1s 2s^2 2p^{n+1}$, $1s^2 2s^2 2p^n$–$1s 2s^2 2p^n 3p$, and $1s^2 2s^2 2p^n$–$1s 2s^2 2p^n 4p$ have been calculated using screening corrections to hydrogenic energy levels tabulated by Froese (1963). The screening correction, expressed in a power series of $1/Z$, neglects terms of $O(1/Z^3)$ and higher; neither is spin-orbit interaction taken into account. In addition, the splitting between the permitted and intercombination transitions, $^1S^o$–^1P and $^1S^o$–^3P, for Fe XXV has been determined by extrapolation along the He I isoelectronic sequence. Results are indicated in Figure 3. It is immediately evident that the most intense emission peak coincides with the expected position of the first member of the principal series of Fe XXV. Approximately 0.08 Å toward shorter wavelength from the main peak we observe a small but reproducible peak which we identify as the Lyman-α line of Fe XXVI. The apparent long-wavelength tail of the Fe XXV line may be attributed to emission from lower stages of ionization. This tail ends in a statistically significant peak situated at the position of the Fe Kα-emission line where emission attributed to $1s$–$2p$ transitions in low stages of ionization is expected. Since it is unlikely that such low stages of ionization exist in the same region with high-energy electrons and Fe XXV, we suggest that this line may arise through fluorescence in the solar chromosphere produced by that X-ray flux which is emitted downward toward the Sun during the flare event. Transition from higher levels to the ground state are also observed, but definite assignments are difficult because of the probable presence of Ni lines (see Fig. 1). Predictions have also been made for emission lines from Ca XX and Ca XIX, as indicated in Figure 1, and it appears that these ions are also definitely present.

Transitions between quantum levels $n = 3$ and $n = 2$ in Fe are expected to produce lines between 10 and 20 Å, the region observed by the KAP spectrometer. Wavelengths for such transitions have again been calculated, not only for Fe, but also for Si, for which the corresponding transitions in the same isoelectronic series (Li I–Ne I) lie in the region from 40–100 Å and have to a large extent already been observed in the solar corona (Austin, Purcell, Tousey, and Widing 1966; Neupert *et al.* 1966) as well as in the labora-

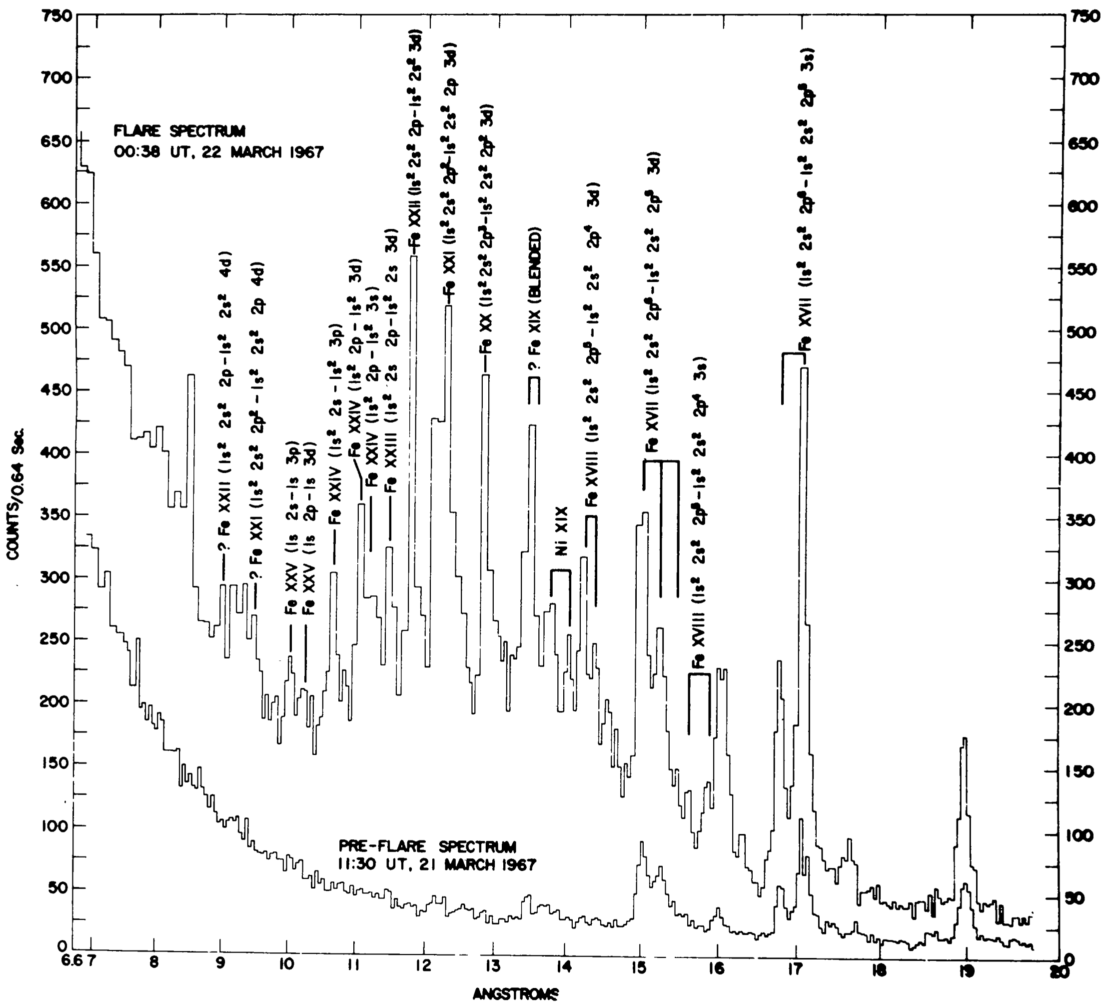

FIG. 2.—Comparison of the solar spectrum between 6.3 and 20.0 Å obtained during a flare on March 22, 1967, with a spectrum obtained on the previous day when no flares were in progress. Tentative identification for new transition arrays of Fe XXV–Fe XX are indicated. Spectral resolution is insufficient to allow resolution of lines within each array. Emission lines of Ni XIX, observed in the laboratory by Feldman, Cohen, and Swartz (1967), are also indicated.

tory (Ferner 1941). A study of the Si spectrum has shown that (1) transitions from 3*d* levels predominate in the coronal spectrum and (2) the most prominent transition from the $1s^22s^22p^n3d$ configuration to the ground state has an energy 2–4 per cent greater than the average energy of the configuration obtained from Froese's tables. For Fe XVII (Tyren 1938) and Fe XVIII (Fawcett, Gabriel, and Saunders 1967), which have been observed in the laboratory, the calculated energy is again lower than the observed energy of the most intense transition by 2 per cent. Predicted wavelengths for the strongest expected lines of Fe XIX–Fe XXV based on these considerations, fall within 1 per cent of the positions of strong unidentified emission lines observed during the solar flare. Our tentative identifications are shown in Figure 2. The Fe XIX lines are probably blended

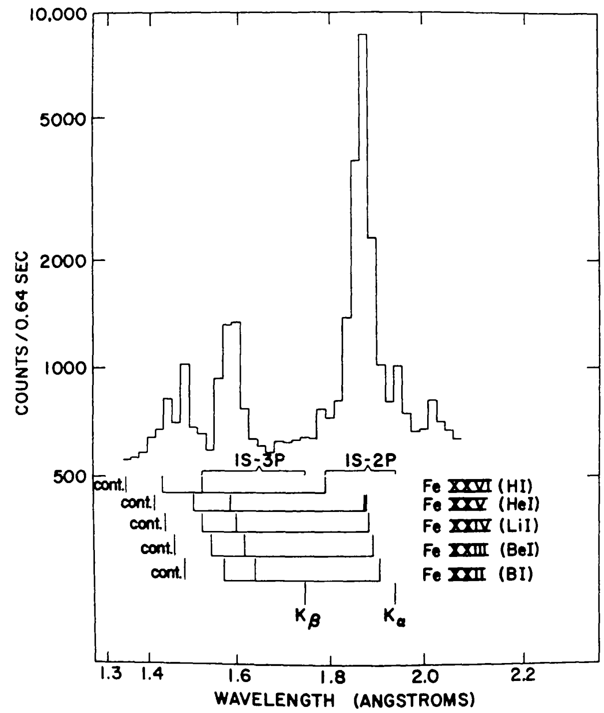

FIG. 3.—Comparison of the spectrum from 1.4 to 2.0 Å with the expected emission lines of highly ionized iron. The isoelectronic sequence corresponding to each stage of ionization of iron is given in parentheses.

with Ne IX lines at 13.44 and 13.55 Å. The line assigned to Fe XX appears adjacent to another strong line at 12.16 Å which may be due to Ne X.

The highest stages of ionization (Fe XXIV–Fe XXV) are found to increase most rapidly at the onset of the flare, while lower stages (Fe XX–Fe XVII) are observed later in the event. These data are consistent with a hypothesis that the initial ionization of iron produces predominantly Fe XXV, as observed at 1.87 Å, and that subsequent recombination of the ions produces successively lower stages of ionization whose spectra can be excited by electron impact. Alternatively, recombination into excited states, followed by cascade to the ground state, may be responsible for the spectral lines observed in the 9–14-Å region.

We wish to acknowledge our indebtedness to the late Dr. John C. Lindsay, Principal Investigator for the Goddard experiment on OSO III and Project Scientist for OSO, who initiated the scientific program reported here. The instrumentation was built by the American Machine and Foundry Company, Alexandria Division. We also wish to thank Mr. William Worrall and the members of the OSO Control Center, Goddard Space Flight Center, for their support in our observing program. We wish to thank Professor L. Goldberg and Drs. A. Dupree and A. H. Gabriel for stimulating discussions on several topics covered in this Letter.

REFERENCES

Austin, W. E., Purcell, J. D., Tousey, R., and Widing, K. G. 1966, *Ap. J.*, **145**, 373.
Blake, R. L., Chubb, T. A., Friedman, H., and Unzicker, A. E. 1965, *Ap. J.*, **142**, 1.
Evans, K., Pounds, K. A., and Culhane, J. L. 1967 (submitted for publication to *Nature*).
Fawcett, B. C., Gabriel, A. H., and Saunders, P. A. H. 1967, *Proc. Phys. Soc.* (in press).
Feldman, U., Cohen, L., and Swartz, M. 1967, *Ap. J.*, **148**, 585.
Ferner, E. 1941, *Ark. Mat. Astr. Fys.* (Stockholm), **28A**, 20.
Froese, C. 1963, *Canadian J. Phys.*, **41**, 50.
Kawabata, K. 1960, *Rept. Ion. Space Res. Japan*, **14**, 405.
Neupert, W. M., Muney, W. S., and Adelman, S. J. 1966, paper presented before the AAS, October, 1966.
Shuvaev, A. T., and Chechin, G. M. 1965, *Bull. Acad. Sci. USSR, Phys. Ser.* (*U.S.A.*), **28**, 838.
Tyren, F. 1938, *Zs. f. Phys.*, **111**, 314.
Walker, A. B. C., Rugge, H. R., Chater, W. T., and Howey, C. K. 1967, *Trans. Am. Geoph. Union*, **48**, 151.