PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Solar Flare X-Ray Spectra

W. M. Neupert

Phil. Trans. R. Soc. Lond. A 1971 **270**, 143-155
doi: 10.1098/rsta.1971.0069

Phil. Trans. Roy. Soc. Lond. A. **270**, 143–155 (1971) [143]
Printed in Great Britain

Solar flare X-ray spectra

By W. M. Neupert
Solar Physics Branch, Laboratory for Space Sciences, Nasa-Goddard Space Flight Center, Greenbelt, Maryland

The solar X-ray spectrum provides a versatile method for determining physical conditions in the lower corona and corona–chromosphere interface which are associated with the chromospheric (Hα) flare phenomenon. Information is contained both in the continuum and line emission which exists at these wavelengths. Continuum emission is predominant below 0.13 nm because of the relatively low solar abundance of heavy elements capable of producing line emission at these wavelengths. During the initial phase of an X-ray event this continuum frequently appears in short, often quasi-periodic bursts whose spectrum is best described by a power law to 100 keV and decreasing more rapidly at high energies. The electron spectrum apparently responsible for these bursts has many similarities to that required for the production of type III radio bursts. The emission of flare-associated soft X-ray radiation (both line and continuum radiation) begins at the time of hard X-ray bursts but reaches maximum one to several minutes later. Line emission from ions up to Ni XXVII in the helium-like ion sequence and up to Fe XXVI in the hydrogen-like ion sequence has been observed during large flares. The evolution of the plasma in which this radiation originates can be studied by comparing emission lines in the same or adjacent stages of ionization of an element. From such observations we conclude that a steady-state condition rarely if ever exists in the X-ray emitting regions associated with a solar flare.

The solar X-ray spectrum between 1 pm and 10 nm, a range of 10000 in photon energy, present an unparalleled opportunity to study physical conditions in the lower corona of the Sun. In the absence of localized regions of enhanced solar activity the 'undisturbed' corona, at electron temperatures of 1 to 2×10^6 K, produces emission lines between 2 and 10 nm. Coronal regions associated with solar activity have higher electron temperatures and consequently contain matter at higher stages of ionization. Such regions, which have lifetimes of several weeks to several months, produce emission lines primarily between 0.5 and 2 nm. The rapid release of large amounts of energy and the acceleration of particles to high energies during solar flares often produce short-lived hard X-ray continuum below 0.1 nm. As the non-thermal electron distribution disappears there remains a hot plasma in which most atoms are stripped of all but one or two of their electrons. These ions emit characteristic lines between 0.1 and 1.5 nm. The physical properties of the plasma are therefore to be studied most effectively at these wavelengths.

The instrumentation chosen to study the spectrum depends on the characteristics of that spectrum: its duration, which defines the temporal resolution to be used; its intensity, which determines the sensitivity required of the instrumentation, and the complexity of the spectrum which defines the spectral resolution that is needed. Finally, there is the requirement for the highest attainable spatial resolution for it appears that the coronal plasma is highly structured and exceedingly complex. Up to the present, X-ray spectra associated with flares have been recorded with little or no spatial resolution. Only when we have such resolution will we be able to produce accurate descriptions of the physical processes in solar flares.

The hard X-ray bursts must be observed with detectors of large effective area (up to 71 cm^2 has been used) which have intrinsically poor spectral resolution. Fortunately, heavy elements which might produce emission lines at such short wavelengths have low solar abundance and can be neglected. On the other hand, iron and lighter elements are sufficiently abundant that their optical spectra cannot be ignored. We therefore must use instruments having good spectral resolution, such as single crystal spectrometers, at wavelengths above 0.1 nm where these lines appear. These soft X-ray fluxes are intense enough, especially for large X-ray bursts, that spectrometers having apertures of only a few square centimetres can record the emission.

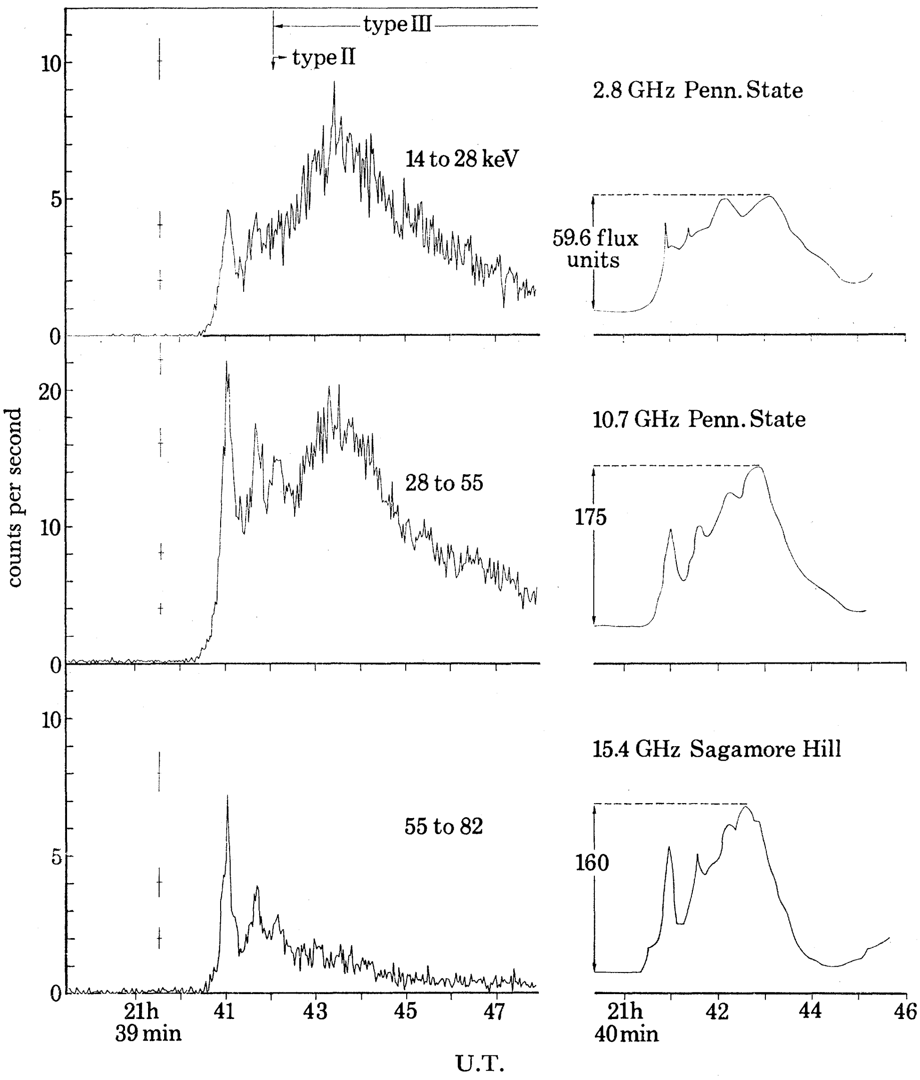

FIGURE 1. A hard X-ray burst observed by Frost on 1 March 1969. Note the equal spacing of the three leading X-ray peaks.

Hard X-ray bursts, observed in the energy range from 20 to 500 keV (60 to 2 pm) are frequently impulsive, i.e. they are short (5 s to 5 min) and highly structured (Peterson & Winckler 1959; Frost 1965, 1969; Kane 1969). They occur simultaneously with impulsive microwave events, and in many cases the correspondence of fine detail in the X-ray and the microwave burst is striking, as in the event recorded by Frost (1969) shown in figure 1. X-ray and microwave bursts sometimes exhibit quasi-periodic structure. In this event three such repetitive bursts occur at 34 s intervals. Such hard X-ray bursts correlate best with microwave bursts which are most intense at the highest radio frequencies (9.4 to 15 GHz). These hard X-ray bursts can be of very short duration.

One burst observed by Frost on OSO–V had a duration measured at half-maximum intensity of only 6 s. Such observations indicate that even the temporal resolution of 2 s available on OSO–V is not enough to define the duration of the subpulses which sometimes comprise an X-ray event. This has strong implications for all flare theories which depend on annihilation of a magnetic field as the source of energy in the flare, for it appears that such annihilation must

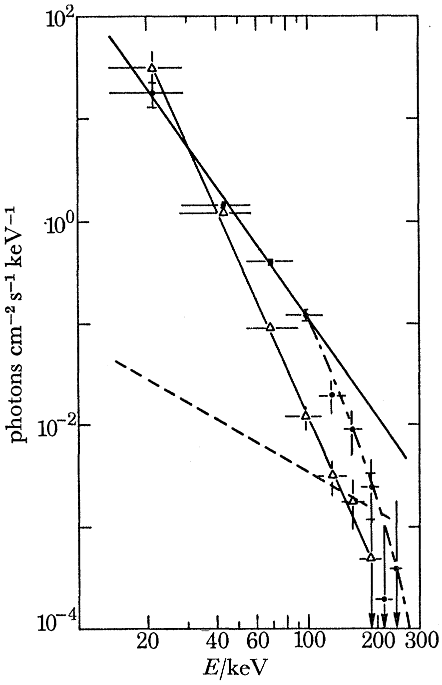

FIGURE 2. X-ray spectra at various times during the event of 1 March 1969. Dashed curve in the lower part of the figure represents the average background spectrum. The spectrum of the first impulsive peak is indicated by the filled circles. This spectrum is fitted to an $E^{-\frac{3}{2}}$ distribution below 100 keV but decreases faster at higher energies.

occur, with the consequent acceleration of electrons to energies of several hundred kiloelectron-volts, in 1 s or less. No annihilation mechanism is known which is sufficiently fast. The spectrum of the burst of figure 1 is shown in figure 2. The data best fit a power law distribution with a sharp cut-off near 100 keV, implying that if the burst is the result of bremsstrahlung from fast electrons the maximum electron energy is near 300 keV. Such a spectrum also appears to satisfy the requirements of the exciter spectrum for type III bursts. Although the correlation between hard X-ray bursts and type III is not good, the strong possibility still exists that the same electron spectrum is capable of producing either phenomenon, depending on the height in the solar atmosphere at which the event takes place (Frost 1969). It is also significant that the hard X-ray burst coincides in time with the explosive phase of the Hα event (Moreton 1964; Valniček 1967) providing further evidence for the rapid dissipation of energy in the lower corona and chromosphere.

Turning now to the flare spectrum at longer wavelengths, we observe, in figure 3, that the flare radiation is composed not only of continuum, as at higher energies, but also of emission lines characteristic of highly ionized (primarily hydrogen-like and helium-like) ions of iron and lighter elements. We will consider each of these components in turn.

The soft X-ray continuum exhibits little of the rapid fluctuation in intensity observed at higher energy. A comparison between microwave radiation and the soft X-ray continuum between 0.1 and 0.3 nm, in figure 4, shows the characteristic tendency for soft X-ray bursts to reach maximum after the microwave maximum and to remain intense after the impulsive radio emission has ceased. The spectral distribution of the continuum emission shown in figure 4

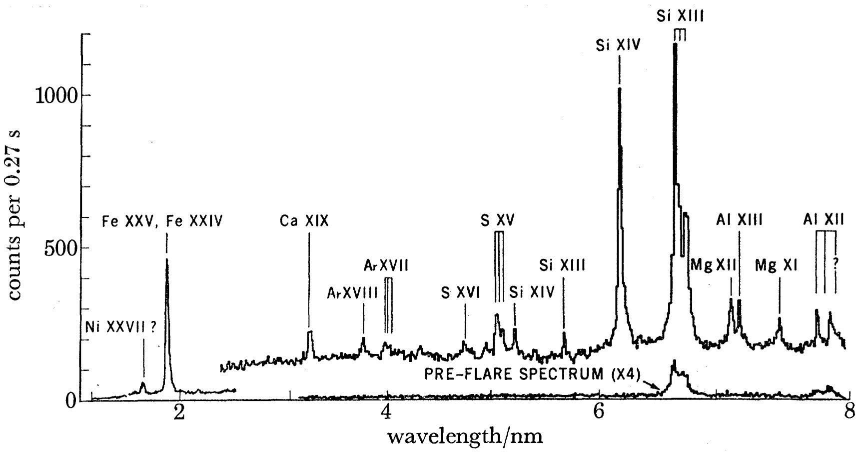

FIGURE 3. Spectral distribution in the 0.1 to 0.8 nm region associated with a flare of importance 2B on 20 February 1969. The solar spectrum before the flare is also indicated. In cases where spectral features consist of a blend of lines from several ions only the predominant ions are indicated.

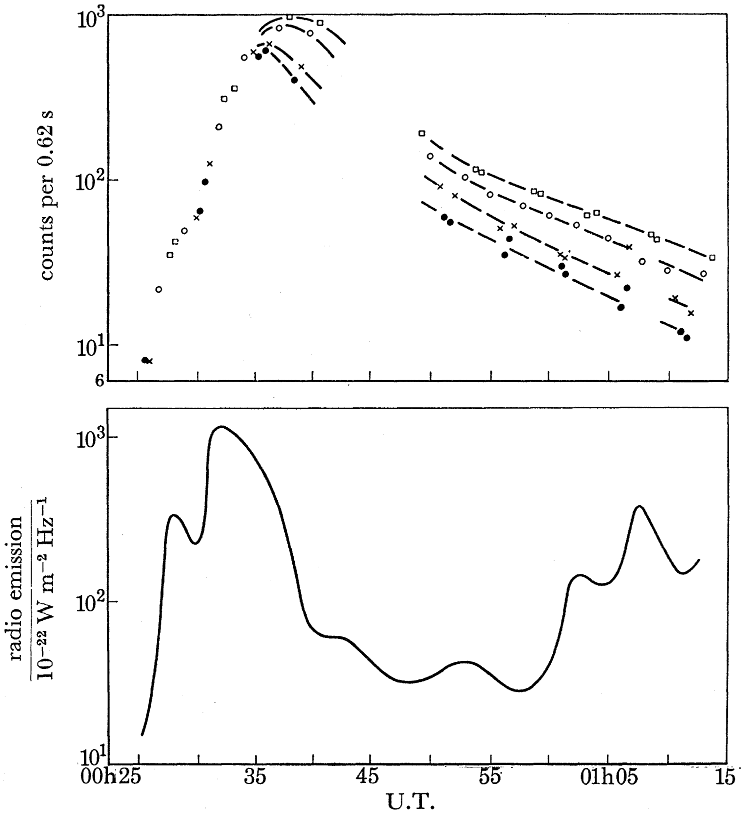

FIGURE 4. Comparison of soft X-ray continuum, measured at specific wavelengths (□, 295 pm; ○, 238 pm; ×, 167 pm; ●, 139 pm) with a single crystal spectrometer, and microwave emission (2.7 GHz) during a flare of importance 2B on 22 March 1967. Note that the soft X-ray flux reaches maximum emission as the impulse microwave component subsides.

varies only slightly with time. During the rising phase of the flare it can be fit by an exponential distribution with $kT_e = 2750\,\text{eV}$ (32×10^6 K). As the X-irradiation reaches a maximum and thereafter, the apparent temperature drops slowly (figure 5). This sequence appears not to depend on the size of the X-ray event. A similar conclusion regarding the spectral distribution can be inferred from broad band X-ray ion chamber data in which the higher energy channels reach maximum output before the low energy channels (Kreplin, Horan, Chubb & Friedman 1970). Such data do not distinguish between line and continuum radiation, thereby making any conclusions uncertain.

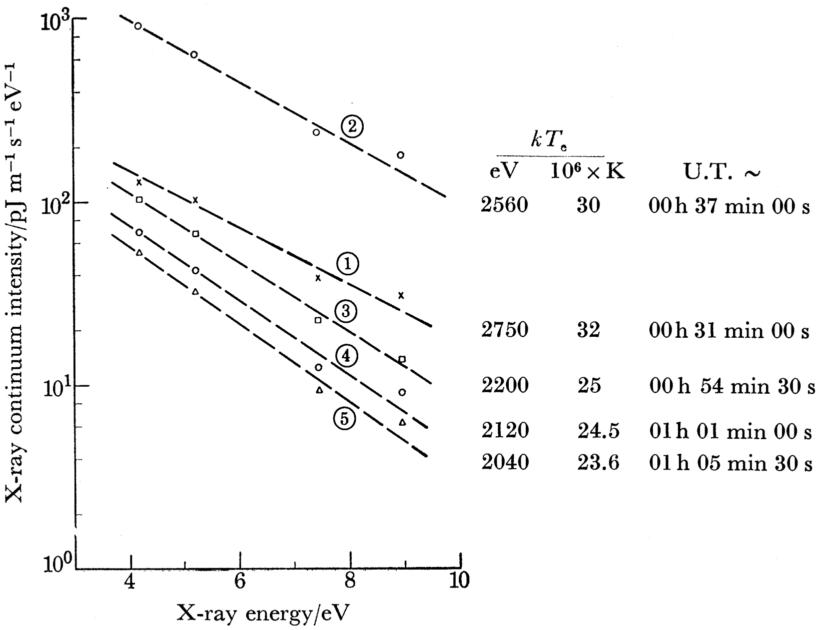

FIGURE 5. Spectra of the 0.1 to 0.3 nm continuum for the event shown in figure 4 at several times in the event. Exponential distributions, approximating free–free emission, are fitted to the data and the appropriate electron temperature indicated. This temperature is a maximum during the build-up of the X-ray flux and declines slowly thereafter.

We turn next to a consideration of the X-ray line emission, and in particular to a prominent emission feature observed near 0.19 nm during many flares (Neupert, Gates, Swartz & Young 1967; Meekins, Kreplin, Chubb & Friedman 1968). Meekins *et al.* have reported that events exist when this line is not present although continuum is observed. Neupert *et al.*, using equipment on OSO–III and OSO–V which gives an apparently higher line to continuum ratio at 0.19 nm than does the N.R.L. equipment, have not observed such a condition. In the OSO–III records the line is normally 10–20 times higher than the count rate on the neighbouring continuum. The exact wavelength and identification of this feature is still subject to question. Meekins *et al.* have reported that the emission peak falls at 0.19 nm and ascribed it to inner shell transitions in Fe XXII and lower stages of ionization. Neupert *et al.* observed the peak at 0.187 nm from OSO–III and proposed that it originates in the $1\,^1S_0$–$2\,^1P_1$ and $1\,^1S_0$–$2\,^3P_1$ transitions of helium-like Fe XXV. In order to determine whether such a difference in wavelength may be a real effect and dependent on conditions on the Sun, we are examining events observed over a wide range of intensities from OSO–V. Two of the extreme cases, differing by a factor of 400 in intensity, are shown in figure 6. The line profiles, the wavelength of maximum emission, and the line to continuum ratio are quite similar in both cases, any differences probably being due to statistical fluctuations in the data for the smaller event. For the larger event we observe quite reliably the emission in the Lyman-α line of Fe XXVI at 0.178 nm and inner-shell transition lines from lower ionization stages of iron at 0.194 nm. If these details are present in the smaller event they are masked by statistical fluctuations. We have observed this emission feature not only in first order diffraction with the LiF crystal, but also in higher orders of diffraction of an ammonium dihydrogen phosphate crystal. These data are shown in figure 7 near 0.56 and 0.74 nm for the same large

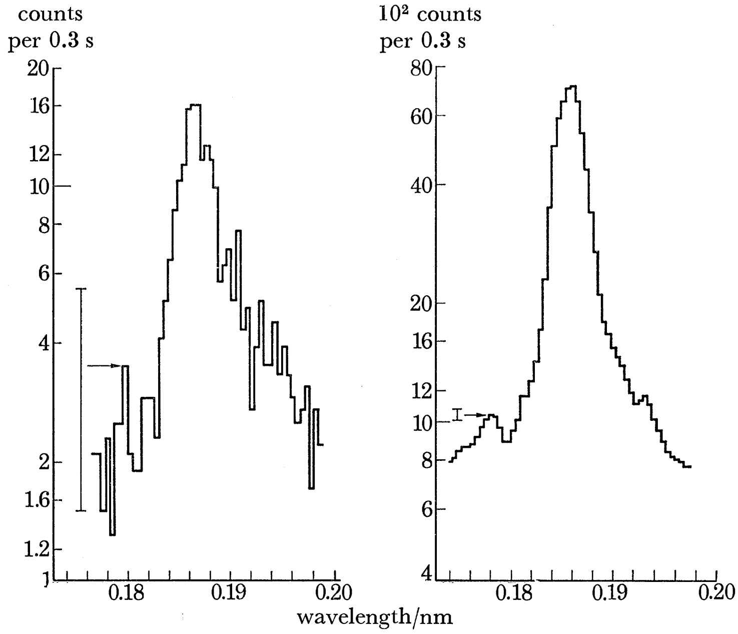

FIGURE 6. Comparison of line emission at 0.19 nm for large and small soft X-ray bursts observed by OSO–V. Statistical fluctuations (note 1σ error bars) are sufficiently small for the large event that the Lyman-α line of Fe XXVI at 0.178 nm and inner-shell transitions (satellite line) of lesser stages of ionization at 0.194 nm are detectable.

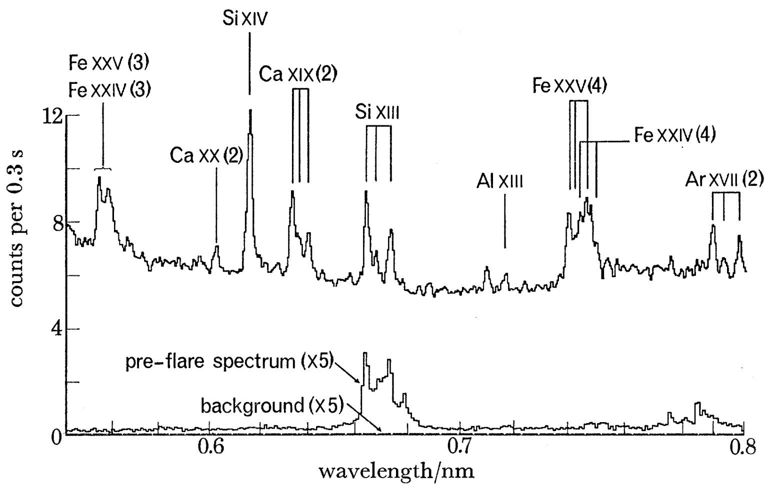

FIGURE 7. The 0.54 to 0.8 nm region of the spectrum during a flare of importance 2B on 27 February 1969. Radiation from argon, calcium and iron was sufficiently intense to be observed in higher orders of diffraction (indicated in parentheses). First-order radiation is attenuated in this spectrum due to an apparent shift in counter sensitivity during this extremely intense X-ray burst. Note the triplet of lines (the $1\,^1S$–$2\,^1P$, $1\,^1S$–$2\,^3P$, and $1\,^1S$–$2\,^3S$ transitions) for each ion of the helium-like isoelectronic sequence up to calcium. For iron, satellite lines of Fe XXIV and lower stages of ionization (not indicated) appear on the long wavelength side of the resonance lines.

event shown in figure 6. In these higher orders the peak at 0.186 nm is resolved into six spectral lines whose wavelength can be accurately measured against neighbouring spectral lines of Si XIV and Ca XX (in second order). In contrast to emission lines from lighter elements such as calcium and silicon, where satellite lines of the lithium-like ion represent less than 5 % of the intensity in the $1\,^1S_0$–$2\,^1P_1$, $1\,^1S_0$–$2\,^3P_1$ and $1\,^1S_0$–$2\,^3S_1$ transitions of the helium-like ion, lithium-like Fe XXIV lines have about 50 % of the intensity of the lines of Fe XXV. Satellite lines of stages of ionization below Fe XXV represent 45 % of the total line emission between 0.185 and 0.194 nm.

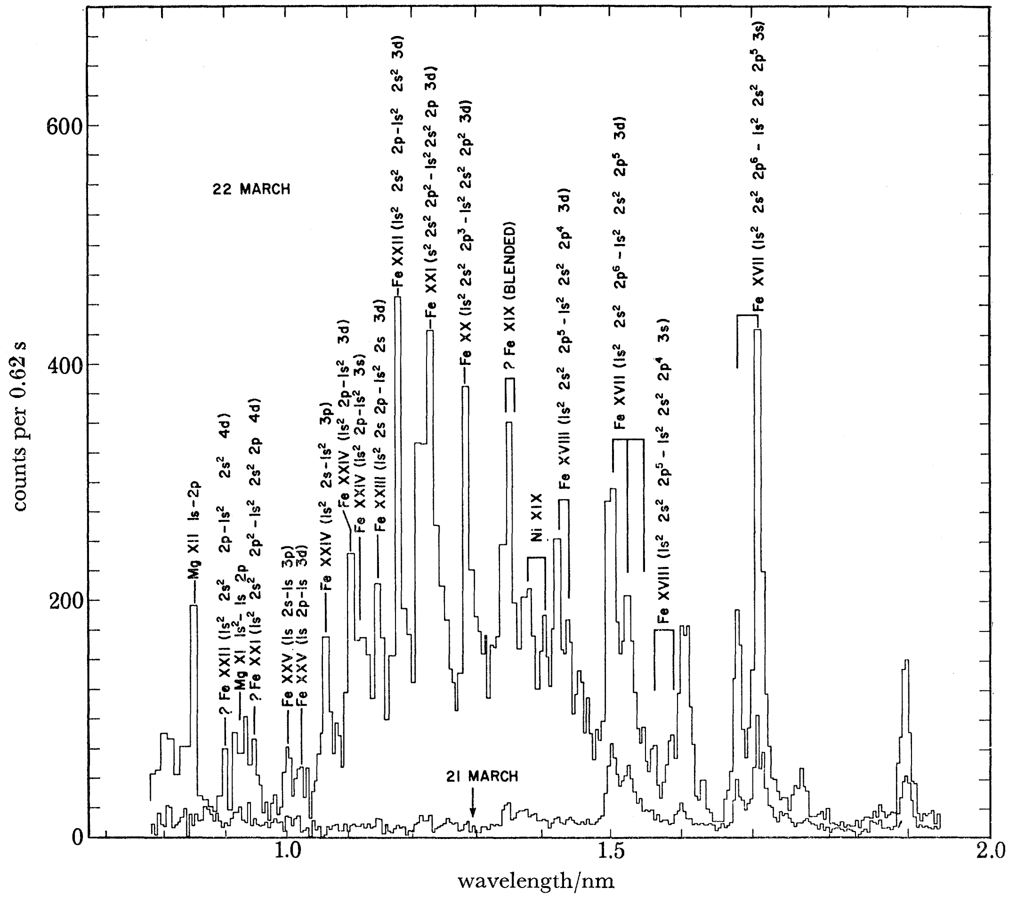

FIGURE 8. Comparison of the solar spectrum between 0.76 and 1.95 nm obtained during a flare on 22 March 1967 at 00h38 U.T., with a spectrum obtained on the previous day at 11h30 U.T. when no flares were in progress. Tentative identification of transition arrays of Fe XXV–Fe XX observed only during the flare are indicated.

Moving toward longer wavelengths from 0.2 nm, we observe the spectra of lighter elements stripped of all but one or two of their electrons. Note that with decreasing atomic number the hydrogen line becomes steadily more intense than the helium-like emission from the same element. This is due to the fact that less energy is required for ionization of the helium-like ion as the atomic number decreases. Since each stage of ionization of an element exists predominantly over a restricted range of electron temperature, the simultaneous appearance of emission lines originating from the hydrogen-like and helium-like ions from neon through iron requires a range of temperatures from 6 to about 50×10^6 K. Each of the emission lines provides a probe with which to study the physical conditions in a limited region of the flare plasma.

Spectra for the region 0.66 to 2 nm observed from OSO–III are given in figure 8 (Neupert

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

et al. 1967). Spectra similar to our 'pre-flare' spectrum have been obtained in the past from rockets and a satellite above the Earth's atmosphere (Blake, Chubb, Friedman & Unzicker 1965; Evans, Pounds & Culhane 1967; Rugge & Walker 1968); the data presented here are the first observations of the spectrum during a solar flare. In addition to increased intensity of all lines observed in the pre-flare spectrum, we observe a new group of lines between 0.9 and 1.4 nm which appear not to have been present before the flare. Optical transitions between quantum levels $n = 3$ and $n = 2$ in highly ionized iron are expected to produce lines between 1 and 2 nm. The most intense lines are apparently transitions from 3d levels to the ground state, being similar in this respect to strong emission lines of silicon from the same iso-electron sequences which appear in the solar spectrum at longer wavelengths (4 to 8 nm). Similar spectra taken from OSO–V with higher resolution and lower background reveal a total of sixty spectral lines between 0.8 and 1.5 nm.

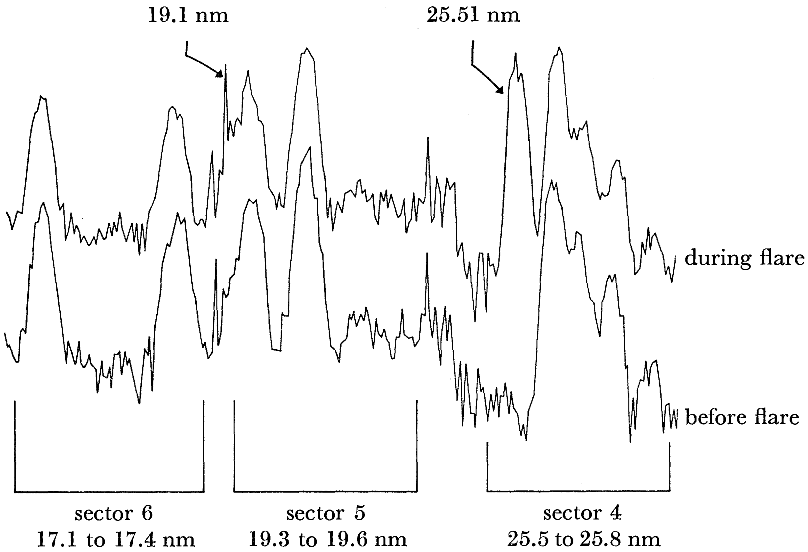

FIGURE 9. Appearance of two emission lines, at 19.1 and 25.5 nm during a flare event on 23 May 1967. These are identified as the resonance doublet ($2s\,^2S_{\frac{1}{2}}$–$2p\,^2P_{\frac{3}{2}}$ and $2s\,^2S_{\frac{1}{2}}$–$2p\,^2P_{\frac{1}{2}}$ transitions) of lithium-like Fe XXIV. The grating spectrometer scanned slowly while in the sectors and rapidly between sectors, causing the apparent difference in line widths. Actual intensities of the two emission lines appear to be in the ratio of 2:1.

Additional emission lines, emitted only during intense X-ray events, appear in the ultraviolet spectrum between 10 and 30 nm. Among them are two lines at 19.1 and 25.5 nm, shown in figure 9. These appear to be the resonance doublet ($1s^2 2s\,^2S_{\frac{1}{2}}$–$1s^2 2p\,^2P_{\frac{3}{2}}$ and $1s^2 2s\,^2S_{\frac{1}{2}}$–$1s^2 2p\,^2P_{\frac{1}{2}}$) of Fe XXIV. After making instrumental corrections, we find that these two lines maintain a constant intensity ratio of 2 to 1, as expected from an optically thin plasma, throughout the events in which they are observed.

The observing programmes carried out with the spectrometers on OSO–III and OSO–V consisted primarily of establishing the temporal relations between lines of differing ionization during X-ray events. An example of such observations is given in figure 10 (Neupert 1969). Three lines, at 0.187, 1.425 and 30.378 nm were observed simultaneously, with data readouts every 0.64 s, during a flare on 26 August 1967. The He II (30.378 nm) enhancement begins simultaneously with the optical flare (observed in Hα) at 00h13 U.T. Maximum emission at this wavelength is nearly coincident in time with the impulsive microwave burst and therefore with the hard X-ray burst which may also have occurred. At the time of the impulsive burst, emission lines at 0.187 and 1.425 nm, originating in Fe XXV and Fe XVIII, respectively, begin to increase rapidly in intensity, the shorter wavelength reaching maximum emission first. Fe XVIII emission continues to increase even after the 0.187 nm emission has reached maximum and begun its decline. This would be the case if the Fe XVIII population were enhanced as a result of recombinations from higher stages of ionization in a slowly cooling plasma. The absence of an Fe XVIII

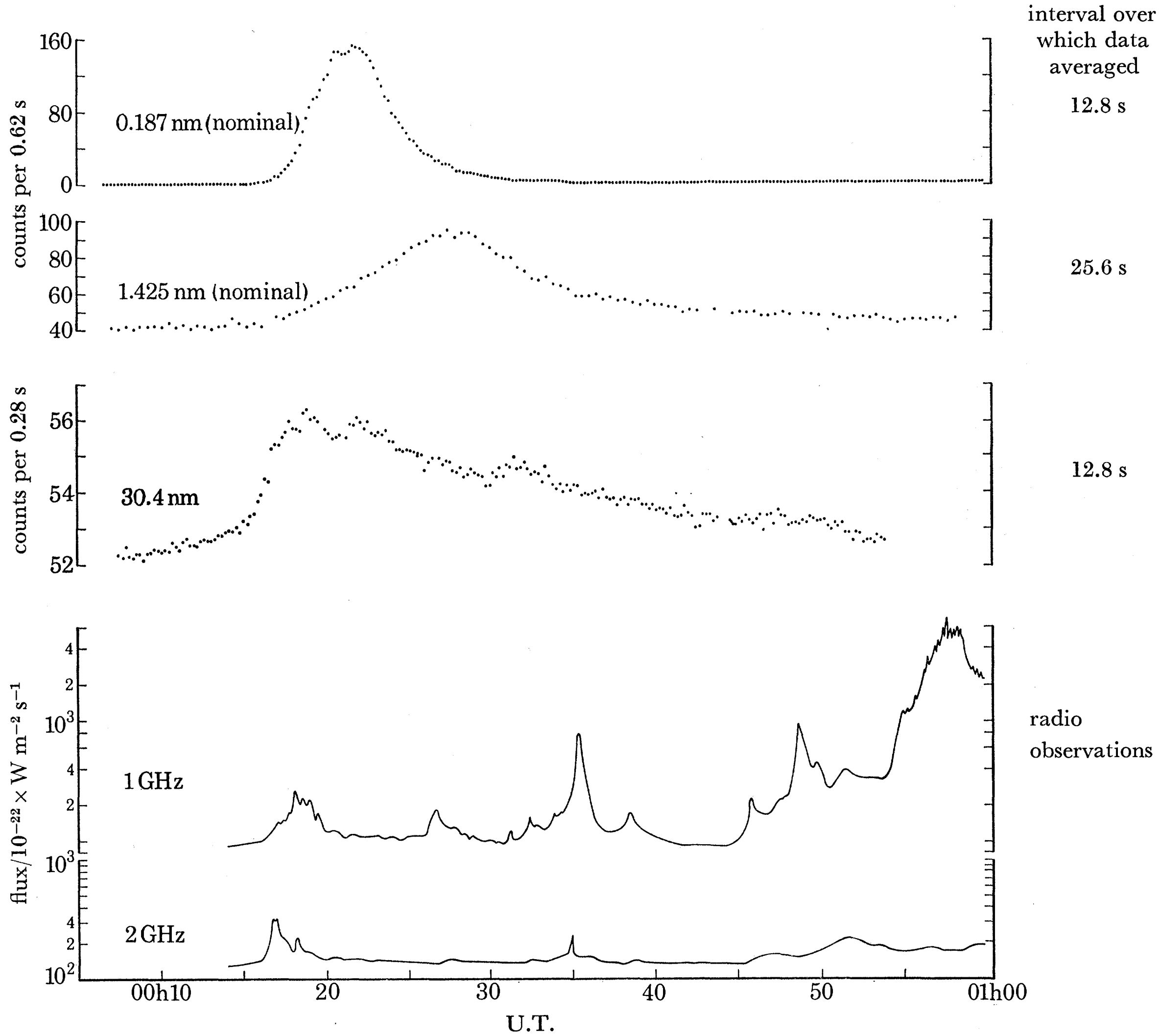

FIGURE 10. Time dependence of X-ray and extreme u.v. emission lines during a flare on 26 August 1967. Data obtained by positioning crystal and grating spectrometers at fixed wavelengths. Radio observations courtesy of Professor Tanaka, Nagoya University, Toyokawa, Japan.

maximum before the Fe XXV maximum indicates that the ionization takes place very rapidly, at high temperature (if this can be considered a meaningful concept) and at high densities in the solar atmosphere. Using collisional excitation and ionization rate equations given by Jordan (1966) we find that an Fe XVIII ion in an electron gas at 20×10^6 K and an electron density of 10^{11} cm^{-3} will have a lifetime against ionization of the order of

$$\tau = 1/N_e q = 1/(10^{11} \times 1.2 \times 10^{-10}) \approx 0.1 \text{ s}.$$

The number density of Fe XVIII ions in a hot plasma becomes vanishingly small very quickly. In addition, ionization becomes more probable than collisional excitation with increasing electron temperature, thus further reducing the possibility of observing the Fe XVIII radiation. Presumably the ion may still be found in regions of steep thermal gradients between the flare plasma and the normal solar corona and chromosphere. A lower limit on the electron density can be found from the rise time to maximum Fe XXV emission. For the event in figure 10, this is

$$N_e = 1/\tau q = 1/120 \times 6.5 \times 10^{-12} \approx 1 \times 10^9 \,\text{cm}^{-3}.$$

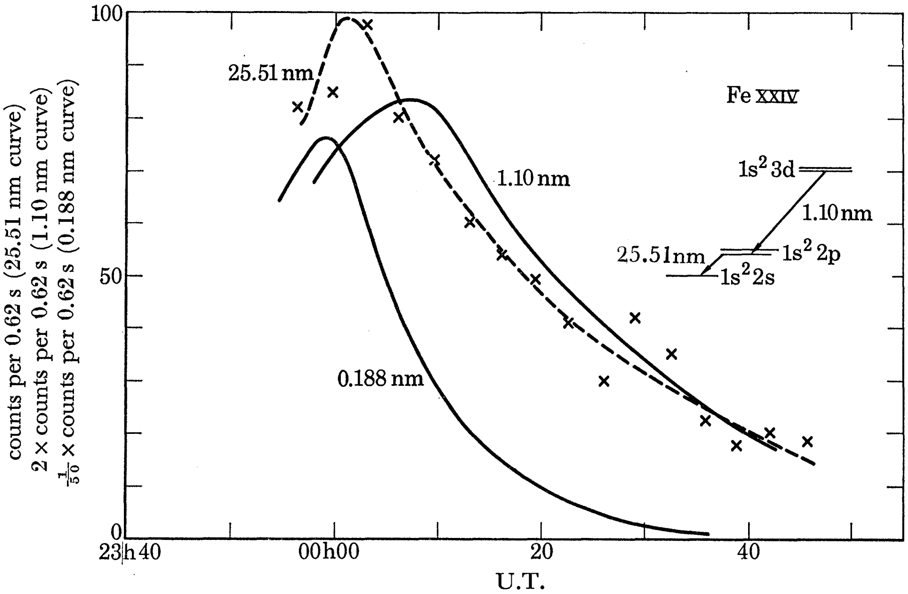

FIGURE 11. Time dependence of emission lines tentatively identified as highly ionized iron during a solar flare. The event began while the OSO–III spacecraft was in the Earth's shadow. Note the difference in time for maximum emission in the two lines tentatively identified as transitions in Fe XXIV. This implies that the populations in the excited states of Fe XXIV do not remain in a fixed ratio during the event. (The 0.188 and 1.10 nm lines are corrected for position of flare.)

From the bursty nature of the hard X-ray bremsstrahlung and from other spectroscopic evidence to be presented it appears that the electron density is several orders of magnitude higher than this estimate. Not evident for the event in figure 10 is the observation, reported by Teske (1969), that soft X-ray emission as observed between 0.8 and 1.2 nm with an ion chamber and the Hα flare often begin together before the explosive phase of the flare and before the beginning of the microwave burst. The X-ray emission lines responsible for this initial X-ray enhancement may be those of Mg XI (0.92 nm) and Mg XII (0.84 nm) which we have not monitored.

A second example of the observations made from OSO–III is given in figure 11. In this case the spectrometers were set to monitor the highest possible stage of ionization in each spectral range as indicated by tentative identifications. Two emission lines of lithium-like iron (Fe XXIV), the $1s^2 2s\,^2S_{\frac{1}{2}}$–$1s^2 2p\,^2P_{\frac{1}{2}}$ transition and the tentatively identified $1s^2 2p$–$1s^2 3d$ transition were monitored simultaneously. Two usable events were recorded, one of which is shown. In both cases the two transitions in Fe XXIV have similar but not identical light curves. If we were to assume that only collisional excitation is important in populating the levels we would deduce that the plasma is heating rather than cooling in the later stages of the event. It is more likely that dielectronic recombination is important near the beginning of the event and that this produces a different population in excited levels via cascades than does collisional excitation.

As a result of the work of Gabriel & Jordan (1969*a*, *b*) it is now possible to infer the electron density in regions where ions in the helium-like isoelectronic sequence are present by comparing the strength of the $1\,^1S_0$–$2\,^3S_1$ and $1\,^1S_0$–$2\,^3P_1$ transitions. Figure 12 shows how this ratio changes during a flare for the lines of Mg XI, an ion which exists predominantly at electron temperatures

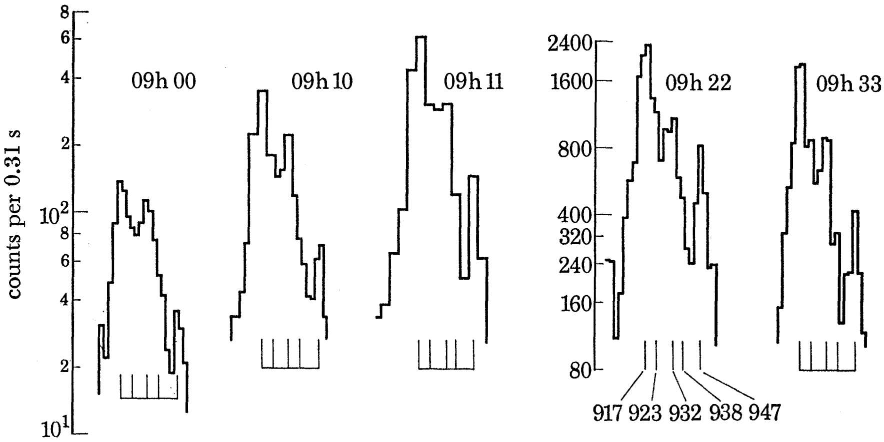

FIGURE 12. Emission in resonance and satellite lines of Mg XI during a flare on 20 February 1969. The forbidden transition ($1\,^1S_0$–$2\,^3S_1$) at 934 pm becomes weaker relative to the intercombination line ($1\,^1S_0$–$2\,^3P_1$) at 923 pm indicating an increase in average electron density to at least 3×10^{11} cm^{-3} in the emitting region.

of 1.3 to 6.3×10^6 K. Before the flare the forbidden line ($1\,^1S_0$–$2\,^3S_1$) is clearly more intense than the intercombination line ($1\,^1S_0$–$2\,^3P_1$) and consistent with an electron density of 5×10^{10} cm^{-3} or less. During the flare the forbidden line declines in intensity relative to the $1\,^1S_0$–$2\,^3P_1$ transition from which we infer that the electron density in the emitting region has increased to about 3×10^{11} cm^{-3}. Using a typical emission measure of 10^{48} cm^{-3}, we infer that the emitting volume is no greater than 10^{25} cm^3. Thus the emitting region must be highly localized (for instance a spherical volume between 2000 and 3000 km in diameter) or composed of extremely fine thread-like structures. This method is most productive for elements having $A \leqslant 16$. For heavier ions the low density limit for observing changes in the line ratios is higher than any electron densities we can reasonably expect in the solar chromosphere and corona.

Finally we return to the problem of the formation of the high temperature plasma during the initial stages of the flare event. We have found that the soft X-ray emission begins with the onset of the hard X-ray and microwave bursts but reaches maximum intensity later. The X-ray flux appears to increase most rapidly at the time of or shortly after the peak in microwave emission (figure 4). Such data suggest that the plasma formation is intimately associated with the thermalization of a non-Maxwellian electron stream which occurs simultaneously with bremsstrahlung losses by these fast electrons as they impinge on the solar chromosphere (Neupert 1968). Since microwave emission is one available measure of the rate at which energy is lost by fast electrons, we have evaluated the integral

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

as a means of estimating the energy lost by fast electrons up to time t (Neupert 1968). In this integral, ϕ is the radio flux observed at a fixed frequency (usually 3750 MHz or higher) and t_0 is the beginning time of the burst. An example of the close match between the resulting curve and the build-up of X-ray line emission at 0.187 nm is shown in figure 13.

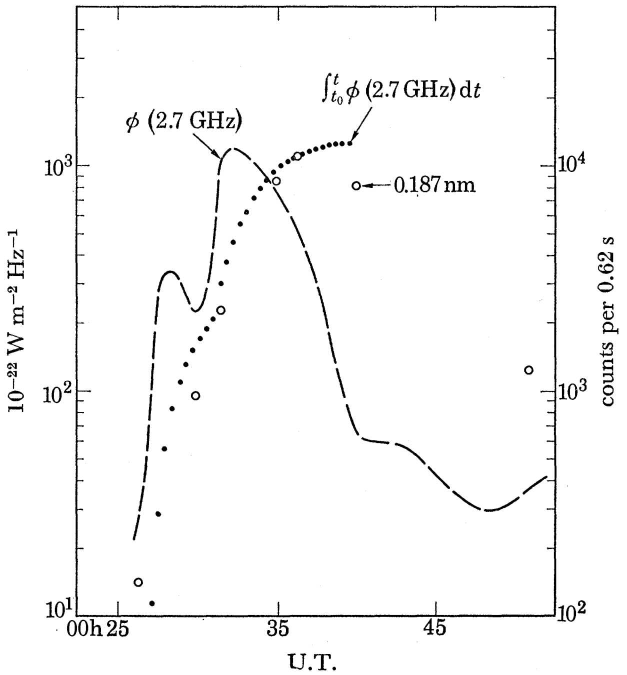

FIGURE 13. Comparison of the time integral of the microwave flux to the flux at 0.187 nm during a flare event. The close correspondence suggests that the build-up of X-ray emitting plasma is related to a form of energy dissipation occurring during the impulsive microwave event. The time integral has been scaled to match the X-ray emission at the peak of the X-ray burst.

It therefore appears that the soft X-ray emitting plasma is formed throughout the duration of the hard X-ray and impulsive microwave bursts. On the other hand, the heating of any one portion of that plasma must take place in a time that is short compared to the duration of the microwave burst since we do not observe emission maxima from intermediate stages of ionization during the rising part of the event (see, for instance, figure 8). The observation that the electron temperature inferred from the 0.1 to 0.3 nm continuum does not increase slowly during the event but appears to be highest throughout the rising portion of an event (figure 11) also supports this hypothesis. We conclude that at any instant of time only a fraction of the eventual amount of flare plasma is being heated and ionized in a highly localized volume and that the ionization takes place nearly instantaneously. The amount of soft X-ray emitting plasma will build up so long as the energy input is greater than energy losses via radiation and conduction. This plasma is produced from cooler material near the interface between corona and chromosphere and, for events investigated to date, remains highly localized in the lower corona during the flare. Eventually a portion of this material may fall back into the Sun while the remainder may escape into interplanetary space.

Discussion

I. PERCIVAL. In view of the short duration of these flares, how do we get inner-shell excitation?

A. H. GABRIEL. The inner-shell excitation arises in Li-like ions by dielectronic recombination from the He-like ion. There is evidence of this from measurements on laboratory plasmas.

I. Percival. In this case, does it occur during recombination?

A. H. Gabriel. Not necessarily. Dielectronic recombination increases with temperature, so that its temperature dependence resembles that of an excitation process.

References (Neupert)

Blake, R. L., Chubb, T. A., Friedman, H. & Unzicker, A. E. 1965 *Astrophys. J.* **142**, 1.
Evans, K., Pounds, K. A. & Culhane, J. L. 1967 *Nature, Lond.* **214**, 41.
Frost, K. J. 1965 *Space Res.* **5**, 513.
Frost, K. J. 1969 *Astrophys. J.* **158**, L159.
Gabriel, A. H. & Jordan, C. 1969*a* *Nature, Lond.* **221**, 947.
Gabriel, A. H. & Jordan, C. 1969*b* *Mon. Not. R. astr. Soc.* **145**, 241.
Jordan, C. 1966 *Mon. Not. R. astr. Soc.* **132**, 515.
Kane, S. R. 1969 *Astrophys. J.* **157**, L139.
Kreplin, R. W., Horan, D., Chubb, T. A. & Friedman, H. 1971 *Space Research* IX. Amsterdam: North-Holland.
Meekins, J. K., Kreplin, R. W., Chubb, T. A. & Friedman, H. 1968 *Science, N.Y.* **162**, 891.
Moreton, G. E. 1964 AAS–NASA *Symposium of the physics of solar flares.* Washington, D.C.: U.S. Government Printing Office.
Neupert, W. M., Gates, W., Swartz, M. & Young, R. 1967 *Astrophys. J.* **149**, L79.
Neupert, W. M. 1968 *Astrophys. J.* **153**, L59.
Neupert, W. M. 1969 *A. Rev. Astr. Astrophys.* **7**, 121.
Peterson, L. W. & Winckler, J. R. 1959 *J. geophys. Res.* **64**, 697.
Rugge, H. & Walker, A. B. C. Jr. 1968 *Space Res.* **8**, 439.
Teske, R. G. 1969 *Solar Phys.* **6**, 193.
Valniček, B. 1967 *Bull. Astr. Inst. Czechoslovakia* **18**, 249.