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New Results of X-Ray Flare Studies

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New results of X-ray flare studies

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Polarization of X-ray emission is found in the wavelength band around 0.1 nm during the rising phase of three X-ray flares. This shows that in the X-ray flare regions directed electron beams are present.

It is established that X-ray flare regions generally have a filamentary structure with bright knots and rapid spatial alterations. Very short X-ray bursts are frequently observed in some flare regions.

The region of an X-ray flare may be considered as a two-component plasma—the main component with a temperature of about 7 to 9×10^6 K, an emission measure of about 0.02 to 0.1 Baumbach and an electron density 1 to 2×10^{10} cm^{-3} containing a dispersed hot (up to $15–30 \times 10^6$ K) small nuclei having an overall emission measure one order of magnitude smaller.

1. Introduction

The mechanism of production of X-ray flares (as well as optical flares) is not yet fully understood. For a better understanding of the X-ray flare origin it is necessary to decide whether the X-ray emission of the flare (continuum and lines) is produced by directed accelerated electron beams or by a process of plasma heating—for example, by fast magnetic compression or other processes. In the case of fast electron beams the question arises as to whether the injection of fast electrons in the flare region or the acceleration of the electrons in these regions is a short-duration process or whether it continues throughout the lifetime of the flare.

The second important problem to be studied is the localization, size and structure of the X-ray flare regions and their connexion with the regions of optical flares. This is, for example, essential in finding out the direction of the electron beams—is it along lines of latitude or does acceleration take place radially?

This paper is based on the latest results of the studies of these two problems performed by our group—I. Beigman, L. Vainštein, B. Vasiliev, I. Zitnick, W. Ivanov, I. Tindo, A. Shuryghin and myself.

2. The polarization of X-ray flare emission

Investigation of the polarization of X-ray emission from solar flares is a good way to establish their nature (Korchak 1967*a*; Elwert 1968). If the X-rays are generated by the bremsstrahlung produced by directed electron beams, then polarization will be expected.† If the X-rays are emitted by bremsstrahlung produced by electrons with a Maxwellian distribution, they will be unpolarized.

The attempt to detect the X-ray polarization in solar flares for the first time was made by us in an experiment on board the satellite Intercosmos-1 and has given a positive result (Tindo *et al.* 1970). The satellite was launched on 14 October 1969, one axis of the satellite was directed toward the Sun with a pointing accuracy of 1 to 2°, and the angular speed of rotation around this axis was slowed down to 0.3 to 0.5°/s. The polarization of the X-ray flare emission was measured using the effect of angular anisotropy of Thomson scattering.

† The synchrotron radiation from directed electron beams in solar magnetic fields is also polarized, but the intensity of this radiation in the X-ray region is negligibly small (Korchak 1967*b*).

In the case of a monoenergetic electron beam the polarization of the bremsstrahlung radiation has values from $+1.0$ to -1.0, depending on the ratio $h\nu/E$, where $h\nu$ is the photon energy and E is the energy of the electrons (Korchak 1967). For most flares the energy of emission does not exceed a few tens of kiloelectronvolts; assuming $E \approx 10^5$ eV there must be a remarkable polarization at wavelengths of hundredths of nanometres. But for most flares the photon flux in this range is very small and thus, as a compromise, we have selected the wavelength band 0.06 to 0.1 nm for our investigation.

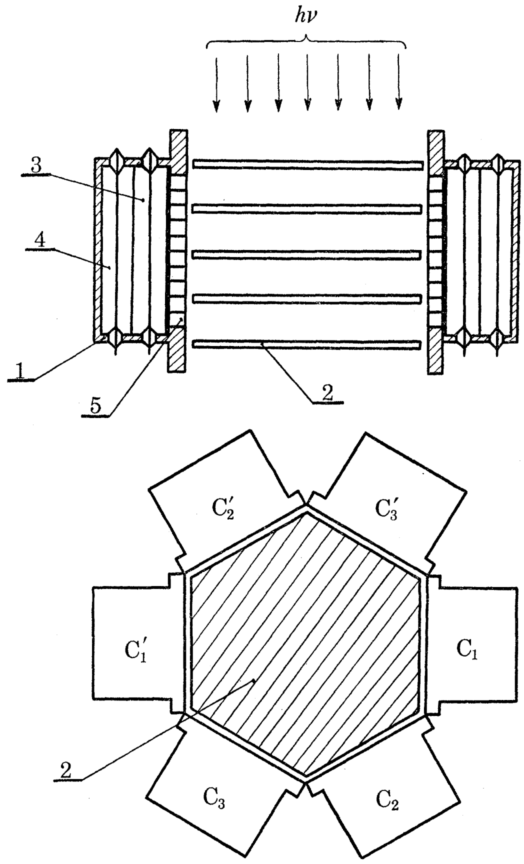

FIGURE 1. Schematic design of the polarimeter. 1, Counters; 2, beryllium plates scatterer; 3, X-ray section of the counter; 4, anticoincidence section; 5, collimating device. Impulses from each pair of counters: C_1-C_1', C_2-C_2' and C_3-C_3' were recorded by one common scaler.

The schematic design of the polarimeter is shown in figure 1. The incident radiation is scattered by beryllium plates, mounted with a free spacing to reduce the average mass density to 0.37. The intensity of the radiation scattered in different directions in the plane perpendicular to the direction of the incident radiation was measured by three pairs of counters mounted symmetrically around the scatterer. To minimize the background counting rate, two-section proportional counters with an anticoincidence connexion were used; an additional lowering of the background rate was achieved by an amplitude discrimination circuit. The impulses from each of the three pairs of counters were counted by independent binary scalers with an accumulation time of 4 or 16 s. The scalers were sampled by a tape recorder at each 10th or 22nd second, respectively. By means of an additional Geiger counter, sensitive to X-rays at about 0.08 nm, we have monitored the X-ray flux of the solar flares; a control counter, insensitive to X-rays, monitored the level of the penetrating radiation (cosmic rays and particles from the radiation belts). A detailed description of the instrumentation and of the experiment performed is given elsewhere (Ivanov *et al.* 1971).

By means of this polarimeter three small X-ray flares were recorded on 20, 23 and 30 October 1969. The recordings of the polarization and X-ray monitoring counters for these flares are shown in figure 2. To eliminate possible differences in the sensitivity of the three pairs of counters with respect to the laboratory preflight calibration we have proceeded as follows: assuming that the polarization vanished at the end of each of the flares we have normalized the readings of each measuring channel during the development of the flare to its reading in the late decay phase of the flare. To reduce the statistical fluctuations, two to eight successive single exposures were averaged.

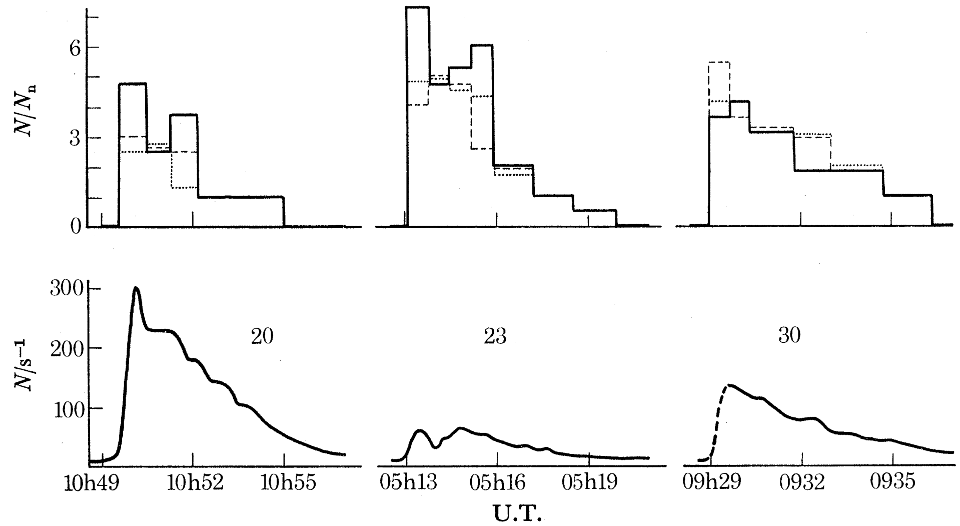

FIGURE 2. Normalized readings of polarization counters and counting rates of X-ray monitoring counter during the flares on 20, 23 and 30 October 1969. —, C_1 and C_1'; – – –, C_2 and C_2'; ········, C_3 and C_3'.

The responses of all three polarization channels differ remarkably at the rising phase of all flares recorded, indicating a substantial polarization. This holds also during the second smoothed intensity maxima seen on the readings of the monitoring counter.† Taking into account the statistical fluctuations, we can state that for all three flares a polarization of $P \approx 0.4$ to 0.2 was observed with a confidence of 90 %.

To check possible errors involved in our treatment of the raw data the same analysis procedure has been performed on the telemetry records corresponding to the parts of the orbit lying in the radiation belts where the counting rates were about the same as during the flares. In this case effects of anisotropy are not expected, and the absence of a spurious instrumental polarization can be checked (Angel, Novick, Wanden Bout & Wolff 1969). We found $P = 0.2 \pm 0.2$ in good accordance with the calculations for unpolarized radiation taking into account the statistical fluctuations.

Thus, the observed X-ray polarization can be considered as a real one for the rising phase and the second maxima of all three flares investigated. This confirms the existence of directed electron beams during these phases. Further X-ray polarization experiments are certainly needed,

† It may be noted that the existence of the second maxima is characteristic for flare emissions with energies $h\nu \geqslant 9.8$ keV (Kane 1969).

especially simultaneous measurements in hard and soft energy ranges. Observations at the solar limb and at the centre of the disk will allow us to establish the direction of the electron beams.

3. The structure of X-ray flare regions

These investigations were carried out with the use of the satellite Cosmos 230 (5 July to 1 October 1968) analogous to the satellite Cosmos-160 (Vasiliev *et al.* 1968). One axis was directed towards the Sun with an accuracy of about 1 to 2°, and this axis carried out scans of the solar disk automatically three times during each revolution and additionally by radio command.

The payload of the Cosmos-230 satellite consisted of an X-ray photometer and X-ray heliograph. The photometer has five photon counters provided with appropriate differential filters,

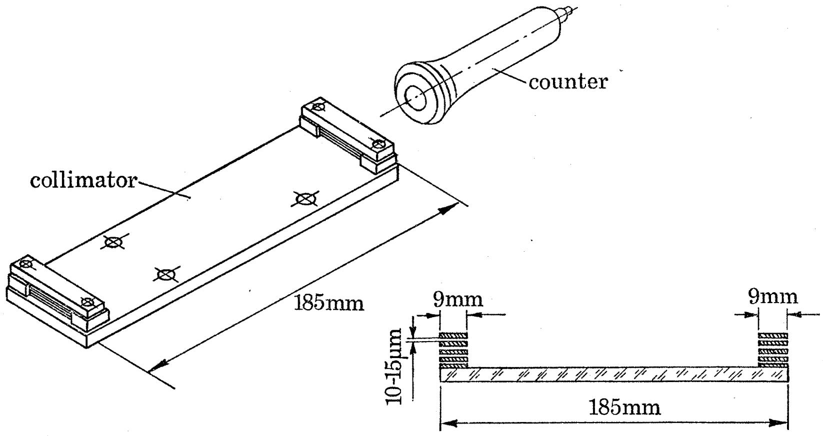

FIGURE 3. Schematic design of the collimator and photon counter of the X-ray heliograph.

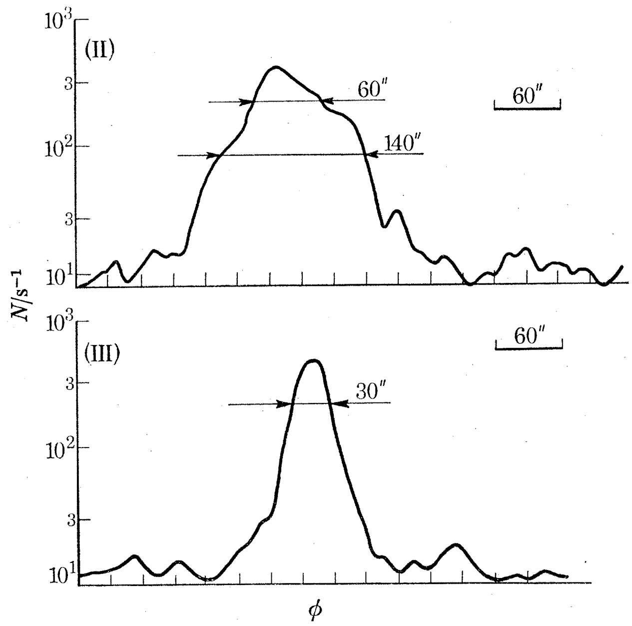

FIGURE 4. Scans of the region of the X-ray flare 31 July 1968. Channel II, X-axis, spectral band 0.2 to 0.8 nm, Channel III—Y axis 0.2 to 0.8 nm band. Arrows show the length and width of the region at half intensity levels.

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isolating spectral bands 0 to 0.22 nm, 0.175 to 0.5 nm, 0.8 to 1.4 nm, and bands containing the recombination continuum and the lines of Fe XXV and Fe XXVI (corresponding differences, however, prove to be too small for a quantitative evaluation); a control counter for monitoring the radiation belt particles was also present.

The heliograph consists of four Soller type slit collimators with photon counters (figure 3). The projection of two slits on the solar disk (*X* axis) was perpendicular to the projection of two other slits (*Y* axis) and the direction of scans was inclined at 45° to both axes. Thus, by performing the scans of the solar disk by the satellite axis, one obtains two one-dimensional scans of the Sun in one direction and two in the perpendicular direction. The data of the channels were on the *X* axis: (I) 0.2 to 0.8 nm band, angular resolution 120″, (II) 0.2 to 0.8 nm band, angular resolution 20″; on the *Y* axis: (III) 0.2 to 0.8 nm band, angular resolution 20″, (IV) 0.8 to 1.2 nm band, angular resolution 15″. The angular velocity of compulsory scans was about 2 to 3′/s, but, after most of these scans, slower spontaneous scans take place. An optical sensor allows one to obtain the actual scan velocity and to fix the beginning of the scans relative to the centre of the solar disk with an uncertainty about 2 to 3′. The rotation speed of the satellite around the axis directed towards the Sun was 0 to 0.05°/s; to determine the scan direction in heliographic coordinates the optical and radio maps of the Sun were used. A detailed description of the instrumentation and of the experiment performed is given elsewhere (Zitnik *et al.* 1971).

The results obtained with the heliograph confirmed preliminary reports (Beigman *et al.* 1969). The region of an X-ray flare has a filamentary structure with bright knots and shows rapid spatial alterations. The length of the filament is about 1 to 2′ and the width 15 to 20″ (the angular resolution limit of our heliograph). Figure 4 shows scans in two orthogonal directions of the region of the X-ray flare at 20h33min U.T. 31 July 1968; the spectral band was 0.2 to 0.8 nm and the angular resolution 20″. The length of the filament is about 140″ with a brighter part about 60″ long; the width is about 30″ (or less if the scan direction is inclined to the direction of the filament). Bright knots are not visible because of the low time resolution of these records—about 1 s. Figure 5 shows five successive one-axis scans of the flare region from 07h50min50s to 07h53min47s U.T. (the end of an optical flare 07h28min–08h02min), on 22 October 1968 in two spectral bands 0.2 to 0.8 nm and 0.8 to 1.2 nm, with angular resolutions of 20 and 15″. These records have a high time resolution—about 0.01 s and show bright knots and rapid structural alterations. Structural elements 5 to 6″ in width, i.e. much smaller than the resolution limit, must be noted. This structure cannot be ascribed to counting rate fluctuations, since these structural elements occur in both channels III and IV, shifted by 1 s. Possibly these structural elements represent fast quasi-periodic X-ray bursts about 0.05 s long, which were not seen before, because the radiation of the full flare region was always recorded.

Figure 6 shows two-axis scans of the region of the X-ray flare 29 August 1968 for 05h06min00s U.T. in comparison with the two-axis densitogram traces of the photograph of the optical flare in Hα.† It is obvious that the X-ray and optical pictures, although differing considerably, have the same shapes—both show three bright knots. It is likely that the regions of X-ray and optical flares, though differing in contrast, have a similar structure. This allows us to suppose that there is a tight connexion between the regions of the X-ray and optical flares. This is supported by the direct measurement of the height of the X-ray flare, which proves to be relatively low—about 20 000 km (Beigman *et al.* 1969).

† We are very much obliged to Professor E. Haradze, Director of the Abastuman Observatory, for his kind communication of the Hα photograph of the flare.

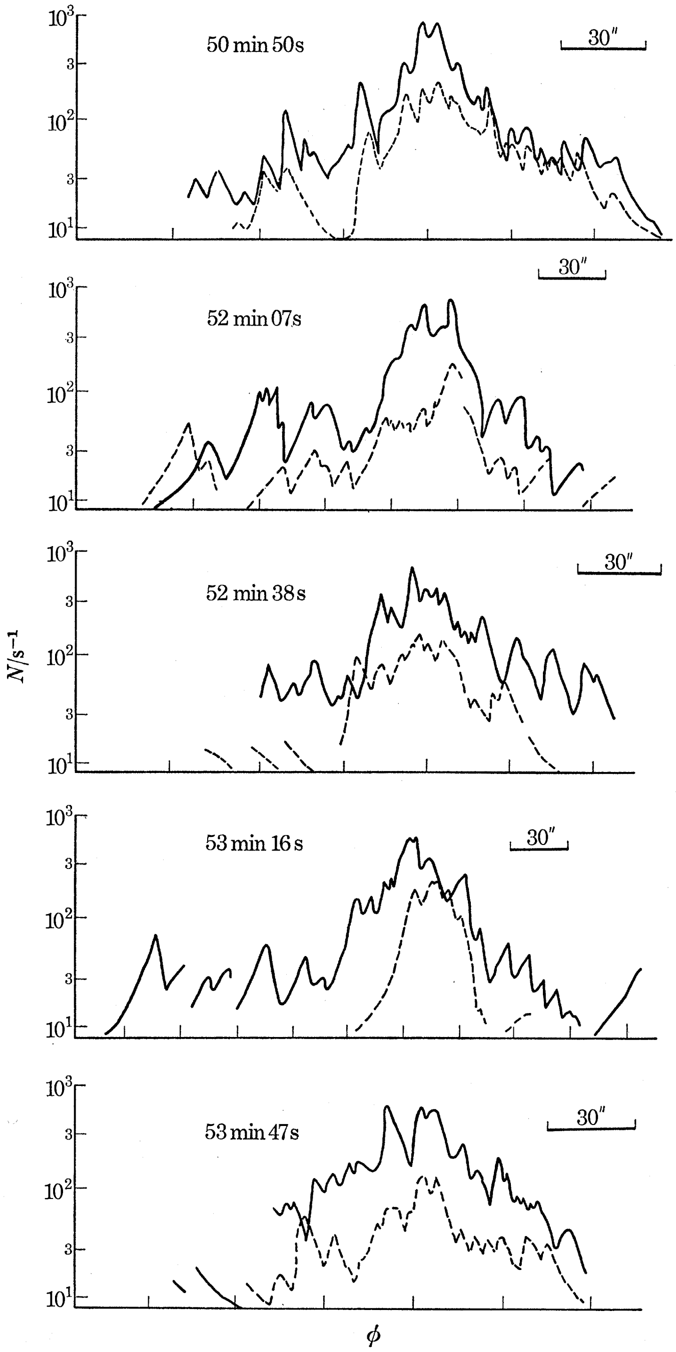

FIGURE 5. Successive one-axis scans of the region of the X-ray flare 22 October 1968 at 07h U.T.; – – –, channel III, 0.2 to 0.8 nm; —, channel IV, 0.8 to 1.2 nm.

4. THE TEMPERATURE AND DENSITY OF THE FLARE REGIONS

As is proved by the polarization experiments in the rising phase of the flare, the X-ray excitation is produced by directed electron beams. In spite of the high electron density of the flare region (see below), the thermalization time for electrons in the energy range $E \approx 10^5$ eV is about 10^2 s or less. It is therefore reasonable to characterize the middle and decay phases of the flares by a definite temperature value. The treatment of records of the X-ray photometer of the Cosmos-230 satellite allows some estimates of the temperature, emission measures and (in connexion with the heliographic data) electron density of the flare regions to be made.

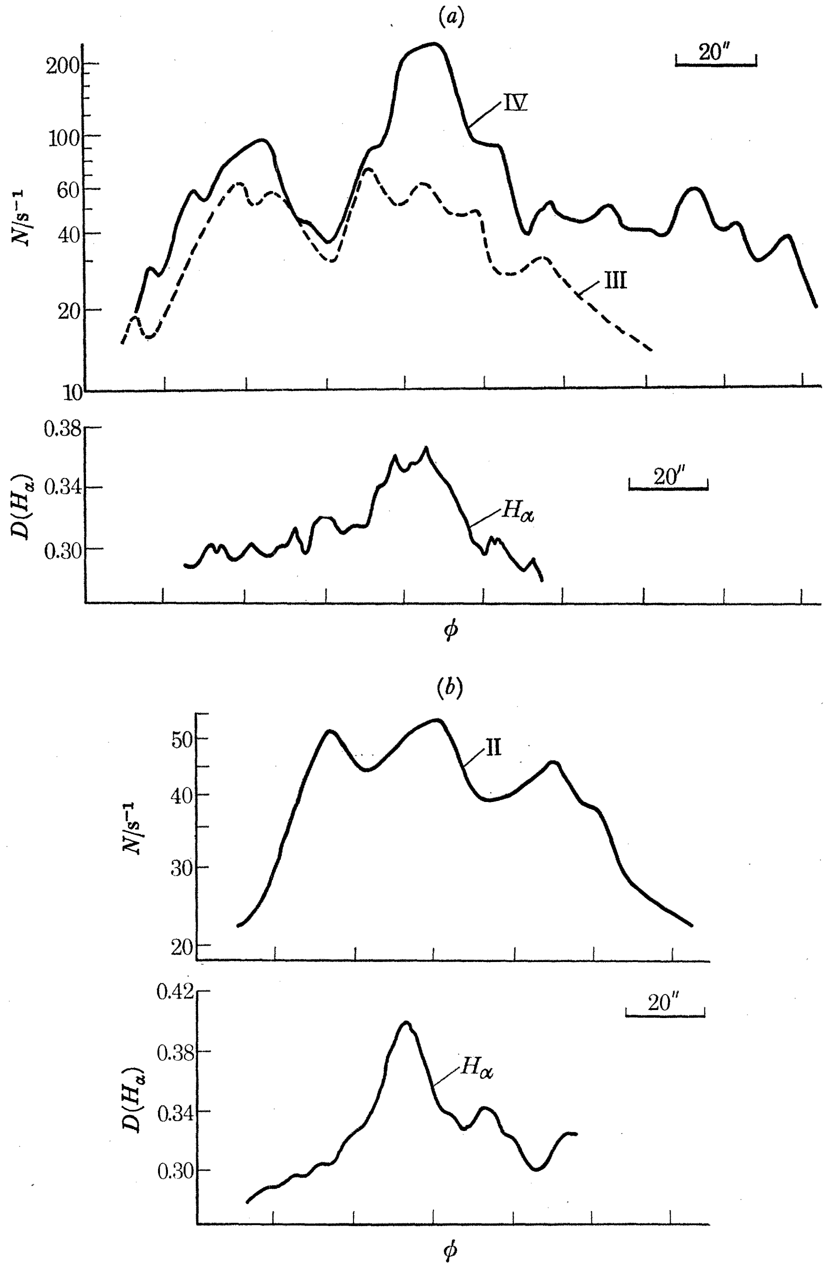

FIGURE 6. Comparison of X-ray scans and densitograph traces of the optical Hα flare photograph for the flare 05h06min00s U.T. 29 August 1968. Channel II, *X* axis, 0.2 to 0.8 nm band; channel III, *Y* axis, 0.2 to 0.8 nm band; channel IV, *Y* axis, 0.8 to 1.2 nm band.

We have used new tables for absolute values of the X-ray flux, recently calculated taking into account coronal abundance data and dielectronic recombination (Beigman & Vainštein 1969).

The analysis of experimental flux values of soft X-rays from small flares shows that for the middle and decay phases the plasma of the flare region consists of two components. The first, cooler component has a temperature $T_1 \approx 7$ to 9×10^6 K and emission measure $y_1 \approx 0.02$ to 0.1 Baumbach unit. Taking, on the basis of heliographic records, the length of the flare region to be about 1′, the width about 30″ and the thickness along the line of sight about 10^4 km, one obtains $N_e \approx 1\text{–}2 \times 10^{10}$ e/cm³. More probably the thickness of the flare region is one or two orders of magnitude less; this gives for the electron density of the X-ray flare region $N_e \approx 10^{13}$ in good accordance with the density of the optical flare regions.

The second, hotter component has a temperature $T_2 \approx 15$ to 30×10^6 K and a small emission measure $y_2 \approx 0.2$ to $0.1 y_1$. It is likely that this hot component is not localized in one nucleus, but consists of small elements dispersed over the flare region. The bright knots are apparently characterized not by a higher temperature value but by higher density. An analogous conclusion as to the dispersed form of hot elements was drawn from the comparison of an X-ray and optical flare behind the limb (Zirin *et al.* 1969). The X-ray emission during the rising phase of flares cannot, as stated above, be described by temperature emission. This is supported by direct measurements of the spectral energy distribution given by photometer records, which cannot be characterized by a temperature model. It is worth noting that also during the middle and decay phases a number of fast electrons exceeding the Maxwellian tail may be present and therefore a surplus of hard emission can exist. In this connexion also it may be noted that the cooling time of the 10×10^6 K plasma is about 30 min, while our measurements show during this time only a small change in flare temperature. This indicates that, in any case for the long flares, a prolonged energy input in the form of fast electrons takes place, but in much lower quantity than at the beginning of the flare.

Note added in proof (*March* 1971)

The polarization of X-ray flare emission was further observed in experiments carried out on board the satellite Intercosmos-4. Measurements of the width of the line Mg XII 0.842 nm reveal a Doppler temperature of the flare of about 30×10^6 K.

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