PRELIMINARY INTERPRETATION OF THE POLARIZATION MEASUREMENTS PERFORMED ON 'INTERCOSMOS-4' DURING THREE X-RAY SOLAR FLARES*

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Abstract. Analysis of the X-ray polarization data at $\lambda \simeq 0.8$ Å for three major chromospheric flares shows that during the 'hard' phase of the flare the X-rays are polarized in the plane, the projection of which on the solar disc is going approximately from the flare region to the center of the disc. Simultaneously performed measurements of the spectral energy distribution have proved that observed X-rays are produced by the bremsstrahlung of the accelerated electrons with the energies in the range 10 – 100 keV. The experimental data are in good agreement with the flare model, which deals with the radial movement of accelerated electrons towards the photosphere, together with the continuous injection of these electrons into the emitting region.

1. Introduction

It is suggested that the X-rays of the solar flares should have measurable polarization, if they are generated by bremsstrahlung of the anisotropic beams of the accelerated electrons (Korchak, 1967; Elwert and Haug, 1970). Thus, the measurements of the polarization give a unique possibility to study the dynamics of the movement of these beams.

The first attempt to detect the polarization was performed at the wavelength of about 0.8 Å on board the satellite 'Intercosmos-1' in 1969 (Tindo *et al.*, 1970a). The experiment was continued in 1970 on the 'Intercosmos-4'. In both cases the instrument was used, based on the polarizational anisotropy of Thomson scattering (Tindo *et al.*, 1970b). Preliminary results of the polarization measurements during three chromospheric flares (importance 2N–3B) observed in October–November, 1970 are reported in the paper (Tindo *et al.*, 1971), from which we take the Figure 1 and following table discussed below.

As well as in measurements on 'Intercosmos-1' at all three flares considered a measurable polarisation persisted rather long (5–10 min). This result could be

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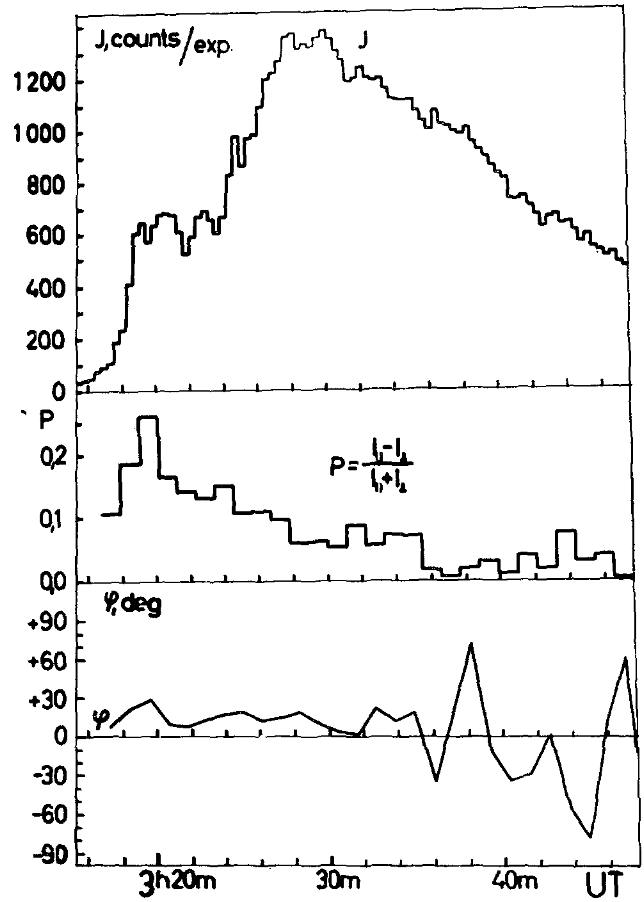


Fig. 1. Polarization P_{exp} and angle of polarization φ_{exp} at the flare November 5, 1970. Top – integral flux at 0.8 Å (measured as average counting rate of the three channels of the polarimeter). Background subtracted. The graph in the middle – absolute values of the polarization degree. Bottom – angle of polarization φ (between the polarization plane and the optical axis of the 1st photon counter).

partially explained by the possible instrumental errors in the obtained values of the polarization, caused mainly by the uncontrolled shifts in the sensitivity of the measuring channels during the flares, if such fast shifts develop in the space conditions*. To take into account the small differences in the sensitivity of the channels, we have normalized the readings on the late stage of each flare, on assumption that the polarization is substantial only at the initial phase of the flare and then diminish to zero at the decay phase. But our results indicate that the polarization decreases rather slowly, making the adopted normalization procedure inaccurate.

Because of the relatively high X-ray fluxes of the flares studied, the errors caused by the statistical fluctuations in the counting rates are insignificant. The temperature shifts in the sensitivity did not cause errors exceeding 0.01–0.03. Conservatively, we

* The preflight calibration performed in laboratory has detected no drifts, greater than ±0.01 in 1 h.

evaluate that possible errrors in the measured values of the polarization P are not more than 0.05–0.08. Thus we shall limit the discussion here to the most reliable part of the experimental data, namely to the relative high and slowly changing degrees of polarization, observed at the beginning of the 'hard' phase of the flares.

2. Spectra of the X-Ray Emission of the Flares and the Energy Distributions of the Electrons

For the comparison of the measured values of polarization with the theoretical predictions, the simultaneous experimental data on the energy distribution of the accelerated electrons are needed. In turn, the latter can be derived from the shape of the X-ray spectral energy distribution. For this purpose we can use the spectral data in the range 5–100 keV, obtained on the 'Intercosmos-4' with the 5-channel scintillation photometer (Valníček, 1972).

The spectral distributions were registered at each 23 sec during the course of the flare. The spectra obtained for some moments of the flare November 5 are shown in the paper published by Livshits *et al.* (1972).

During the X-ray flares investigated the readings of all 5 energetic channels attain their maximal values at about the same moment of the flare development. On the contrary, the marked increase of intensity begins some minutes earlier at low energies, and its decay phase lasts much longer, as it was at the higher energies. It is seen that the part of the flare development, lying in the vicinity of the X-ray maximum has profound resemblance with the so-called 'hard' or 'impulsive' phase of the flare.

The examples of the spectral distributions registered during the 'hard' phase of the flares of October 24 and November 5, 1970 are shown in the Figure 2. The background counting rates are substracted. The boundaries for the energy bins are recalculated taking into account the limited energy resolution of the scintillation detector and using the approximate energy distribution of the flare radiation in the form J (photon $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{keV}^{-1}) \sim (h\nu)^{-4}$.

The integral curves in the Figure 2 allow the power law approximation in the range $E > 10$–15 keV: $I(E > h\nu) \sim (h\nu)^{-\gamma}$ with $\gamma \simeq 3$ for the times indicated on each curve.

Below $E = 10$–15 keV the bend in the curve for flare November 5 is seen*. Possibly, there are some indications for the bend in the curve for the flare at October 24. However these bends need a further analysis concerning the possible non-linearity errors at the registered high counting rates in the channels X-2 and especially X-1.

The discussed X-ray spectra in the range 10–100 keV are clearly indicative for the bremsstrahlung radiation of the accelerated electrons with the energies in the same range and the distribution $N(E)\,\mathrm{d}E = KE^{-\varkappa}$ as it was already shown (for instance Korchak, 1971).

Detailed analysis of the interaction of the electrons with the plasma gives the effec-

* It is worth to mention here another type of anomaly in the spectrum observed by the scintillation photometer during the flare at $00^{\mathrm{h}}50^{\mathrm{m}}$ November 16. In this spectrum unusually high flux is seen in the range 30–100 keV (Livshits *et al.*, 1972).

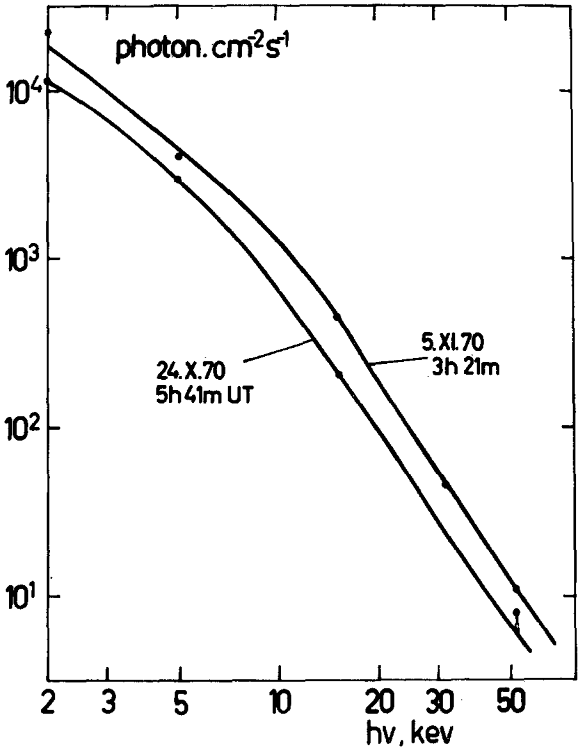


Fig. 2. Integral spectrum of the X-ray emission during the 'hard' phase of the flares October 24 and November 5, 1970.

tive value of $\varkappa = \gamma - \frac{1}{2}$ (for the whole emitting volume) (Gintsburg and Syrovatsky, 1963; Brown, 1971).

Then we should suppose that the change in the slope of the curves at 10–15 keV, if it is a real one, is caused by 'cut-off' in the electron distribution, occurring at this energy.

3. Interpretation of the Polarization Measurements

Now we shall compare the polarization data summarized in the table with theory, using the derived electron distributions and Hα-pictures of the flares. The satellite 'Intercosmos-4' had the two-axial orientation towards the Sun and rotated around the oriented axis with the velocity $\leqslant 0.05° \text{ s}^{-1}$. For the flare at October 24 and November 5 the positions of Y- and Z-axes of the satellite on the solar disc were determined using the orientation data, supplied by the X-ray spectroheliograph* (Vasiljev *et al.*, 1972).

The orientation data were derived using the one-dimensional X-ray scans of the active regions observed on the solar disc and the optical sensor data as described

* Authors are greatly indebted to V. V. Korneev (P. N. Lebedev Physical Institute), who had processed this information.

earlier (Vasiljev *et al.*, 1968). Taking the values of the polarization angle (between the polarization plane and the optical axis of the 1st photon counter of the instrument) from another paper (Tindo *et al.*, 1972), we obtain the position of the polarization plane on the solar disc. In both cases shown in Figures 3 and 4, the polarization plane is so oriented that its projection on the solar disc goes from the flare region towards the center of the disc with deviations of 5–10°. This fact appears to be essential in testing of the different flare models.

The theoretical predictions for the maximal observable degree of polarization

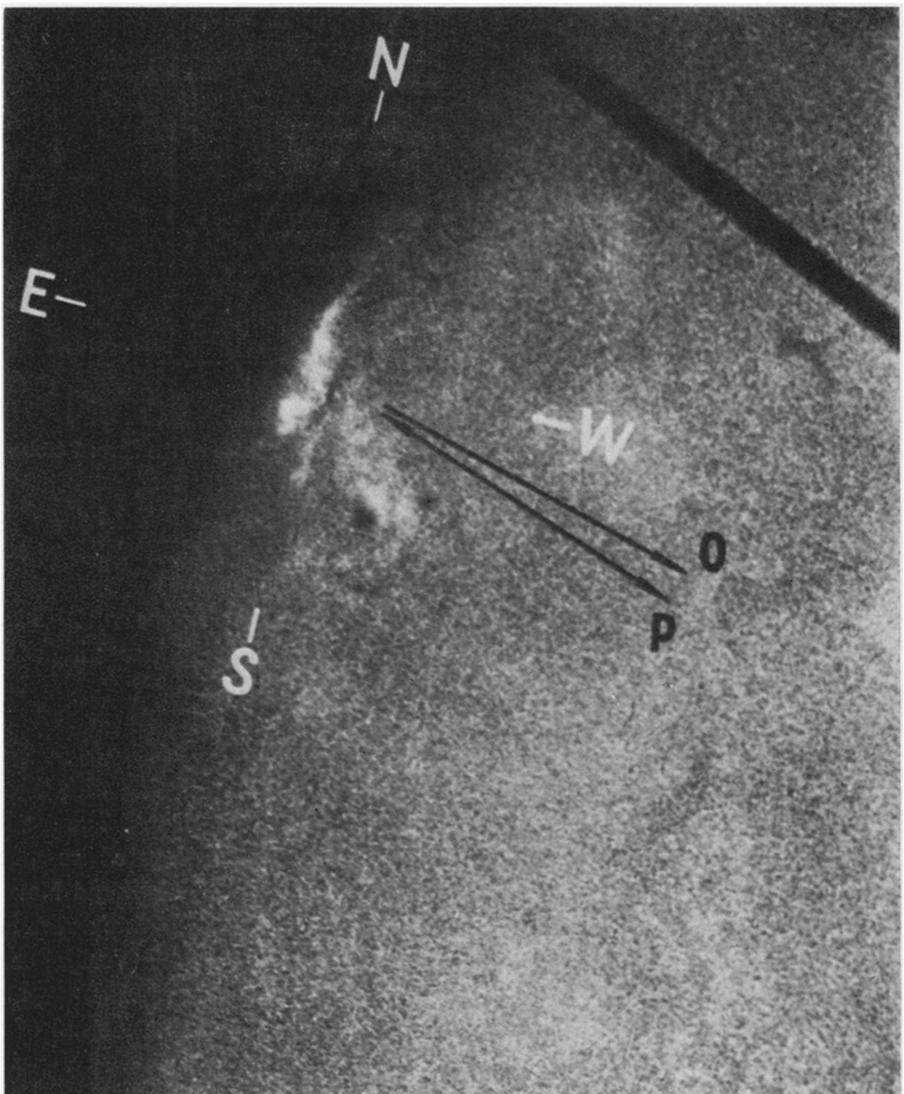
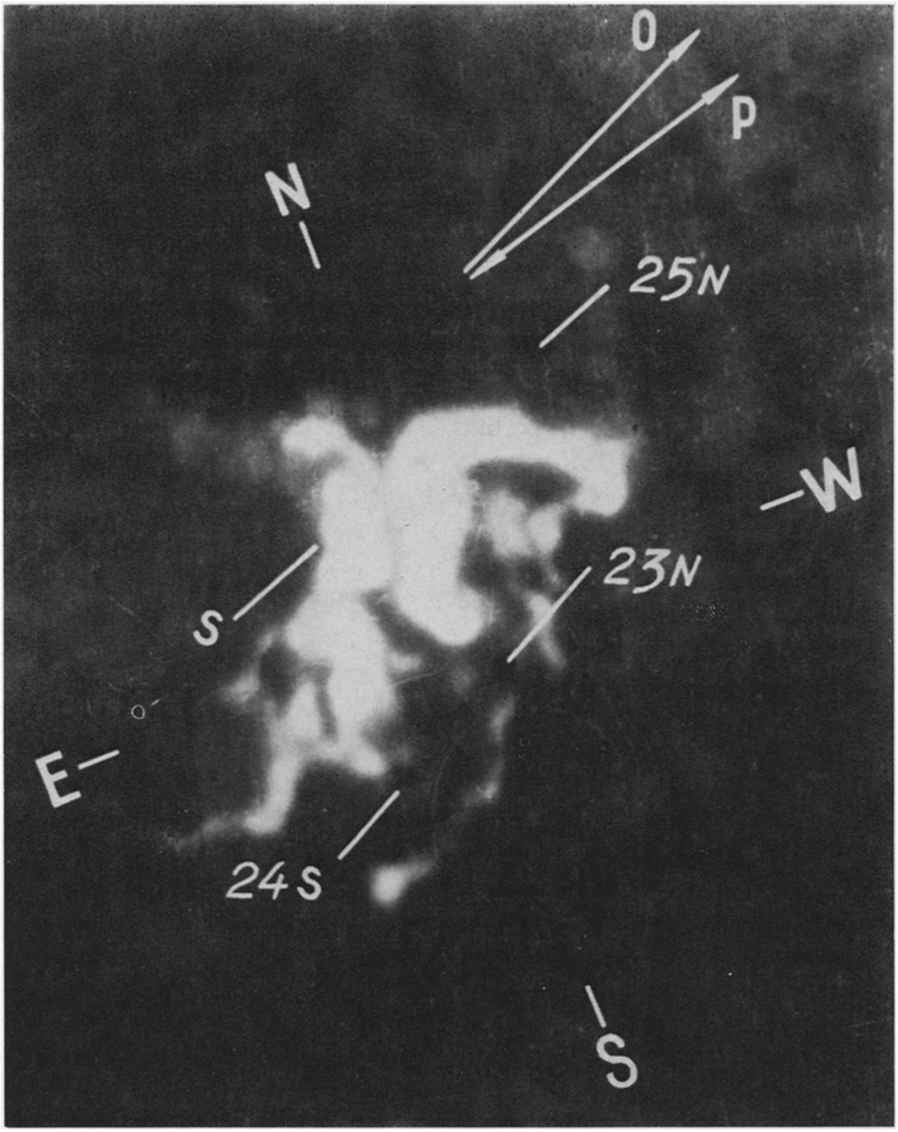


Fig. 3. (For caption see Figure 4.)

$P=(I_{\perp}-I_{\parallel}):(I_{\perp}+I_{\parallel})$ of the bremsstrahlung produced by the accelerated electrons with the power law distribution ($\varkappa>2$) and 'cut-off' at E_{K_0} strongly depends on: (a) the ratio $h\nu/E_{K_0}$, (b) the dynamics of the movement of the electrons, (c) the position of the flare on the solar disc.



Figs. 3 and 4. Hα-pictures of the chromospheric flares at October 24 (05^h20^m UT) and November 5 (03^h25^m UT), respectively. The arrows indicate the direction of the polarization and direction from the flare region towards the center of the disc. At $h\nu/E_{K_0}\geqslant 1$ the projection of the polarization plane should be parallel to the beam propagation line in the model of De Jager and Kundu. In the model of a magnetic tube lying parallel to Sun's surface (Takakura and Kai) the projection of the polarization plane should be perpendicular to the direction of the magnetic field.

Following the idea by Syrovatsky, we assume, that the electrons are accelerated during the impulsive phase of a flare at a 'break' of the current layer, developing in the vicinity of the neutral line of magnetic field (Syrovatsky, 1971). Then according to the conjecture of De Jager and Kundu, a part of the accelerated electrons moves towards the photosphere, where they produce the bremsstrahlung (De Jager and Kundu, 1963). The movement occurs in the ambient magnetic fields which are known to be predominantly radial at the low heights over umbra of the spots. The angular distribution of the 'fresh' electrons should be characterized by rather small pitch-angles α.

Another model proposed by Takakura and Kai deals with the X-ray emission of the trapped electrons moving parallel to the Sun's surface in a magnetic tube situated in the lower corona between bipolar sunspots (Takakura and Kai, 1966). In this case the electrons having large pitch angles will stay longest in the region, where the bremsstrahlung is produced.

In the first model, at $h\nu/E_{K_0} \geqslant 1$, $\alpha \simeq 0$, P is negative (in respect to the direction of the beam) with $P_{\max} \simeq 0.5$. This maximal value can be observed at the position angle $\theta = 90°$, i.e. at the limb. Then P decreases rather slowly till 40–50° and reaches its minimum at the center of the disc. The X-rays are polarized (at shortwave part of the spectrum) in the plane, the projection of which on the disc goes parallel to the projection of the electron beam. In the longwave 'tail' of the emission at $h\nu \ll E_{K_0}$ P diminishes to zero (at $h\nu/E_{K_0} \simeq 0.12$) and then changes its sign (Korchak, 1967).

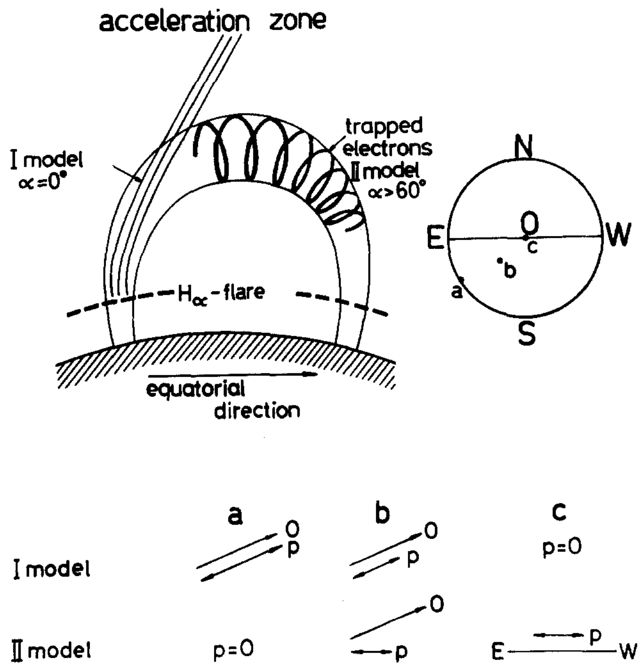


Fig. 5. Geometrical connection between the direction of the movement of the electrons and the polarization plane in the two models of the X-ray flare. The drawing shows magnetic tube lying in the equatorial direction. The length of the vector P qualitatively indicates the expected degree of polarization at three different positions at the disc.

In the model of the trapped electrons in the magnetic tube lying parallel to the Sun's surface, the electrons have the anisotropic angular distribution (say, $N(\alpha) \sim \sin^n \alpha$), the averaged P at $h\nu/E_{K_0} \geqslant 1$ is positive (in respect to the direction of the field) and can reach values of about 0.1–0.2 (Korchak, 1967). The maximal values would be expected at the center of the solar disc. P diminishes towards the limb, by assuming approximately equatorial direction of the magnetic field. Some geometrical characteristics illustrating these considerations are given in the Figure 5.

For flares of October 24 and November 5 and 16 (22^hUT) there are $\theta = 75°$, 45° and 45° respectively, $E_{K_0} = 10$–15 keV. $h\nu_{\text{eff}}$ of the polarimeter used is about 15 keV*.

TABLE I

X-ray polarization measurements ('Intercosmos-4'), optical and radio data for the flares of October 24, November 5 and 16, 1970

		24.X	5.XI	16.XI
X-ray flare	Start (UT h, min)	04 51	03 16	22 13
	1st max (h, min)	05 22	03 20	22 18
	2nd max (h, min)	05 42	03 29	22 23
	Duration (min)	28	32	23
	Max. flux (relat. units)	500	1350	1400
	Polarization (maximal)	0.16	0.21	0.12
	Angle of polarization	−60°	+15°	−20°
Chromospheric flare	Start (UT h, min)	04 47	03 10	21 48
	Max (h, min)	05 17 05 20 05 42	03 23	22 21 22 22
	Duration (min)	89–102	87–249	45–112
	Latitude	N14 19	S12	N16
	Longitude	E74 75	E34 37	W34 35
	Distance from the center of the disc	0.96	0.60	0.60
	Importance	2N	3B	1N
	Type [a]	FDE	UF	DE
	Active region	11002	11010	11029
Radio emission		05 33 impuls. micro-wave burst	0318–0340 cm, dm bursts. In m – types II, IV	2225–2229 in m – types III

[a] D–brilliant point.
E–two or more brilliant points.
F–several eruptive centers.
U–close and somewhat parallel bright filaments (|| or Y shape).

* An additional check of the $(h\nu)_{\text{eff}}$ was made by comparing the time profiles of the flare flux, registered by the polarimeter and by the different energetic channels of the scintillation photometer. It was found that the behavior of the flux, registered by polarimeter, closely resembles that of the third channel of the photometer ($E \simeq 15$ keV). The absolute values of the both fluxes agree within the factor 2.

Thus we should expect measurable P values at the flare on October 24 only for the first model (otherwise for the second model one must assume a rather unusual meridional orientation of the magnetic tube). At the flares November 5 and 16 we should expect the measurable polarization for both models. The ambiguity can be eliminated if the information is available about the direction of P (relative to the Sun's equator and to the axis of the magnetic field in the flare region).

For the flare on October 24 in the group with great number of spots near the limb, the direction of the magnetic field is not clear. For the flare on November 5 the observed angle between the polarization plane and the magnetic field direction (which can be assumed on base of the known polarities of the sunspots) disagrees with the second model, assuming the pitch-angle distribution typical for the trapped electrons ($\alpha_{\rm eff} \geqslant$ $\geqslant 60°$).

On the other hand, for both flares there is full agreement of the observed direction of the polarization with the model of the radial electron beam. These data can be regarded as direct confirmation of the model of De Jager and Kundu, with essentially continuous injection of the electrons in the X-ray emitting region, lasting about 5–10 min. Somewhat smaller measured values of P, as it is predicted for this model, could be caused by the e-e collisions, decreasing the anisotropy of the electron beam (Hudson, 1972; Hurley 1972).

The hypothesis of the magnetically trapped electrons appears rather implausible also on ground of two additional points. First, the duration of the substantial polarization (5–10 min) is much longer as the thermalization time (<1 min) at reasonable density of $n_e \simeq 10^{10}$ cm^{-3}. Second, the observed duration of the 'hard' phase (~ 20 min) is too long as compared with the rate of the collisional energy losses of the trapped electrons (see also (Acton, 1968)).

In conclusion we shall emphasize the need of new improved polarization measurements, possibly at two or more wavelengths, which appears quite fruitful in the investigation of the nature of the flares.

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