Brightness, polarization and electron density of streamers in the solar corona

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BRIGHTNESS, POLARIZATION AND ELECTRON DENSITY OF STREAMERS IN THE SOLAR CORONA

by M. SCHMIDT

Brightness, polarization and electron density of three streamers in the solar corona have been derived from a densitometric investigation of two plates taken by F. K. RICHTMYER during the eclipse of June 8, 1937. Deviations of the direction of linear polarization from the normal direction up to 17° are found. The directions in space of the streamers are derived from the degree of polarization. An attempt is made to identify the filaments associated with these streamers. The intensity gradient in the streamers is definitely higher than in either the K-corona or the combined (K + F)-corona. The gradients of the electron density in the streamers and in the K-corona are about the same. The resulting electron densities indicate that the density in a streamer may be nine times the density in the K-corona.

1. *The plates.*

During the eclipse of June 8, 1937 F. K. RICHTMYER [1]) exposed six plates with a quadruple camera. The camera contained four telescope lenses of 3.5 inches aperture and 48 inches focal length. Polarizing screens (Eastman Kodak Polascreens) could be placed in front of three lenses in such a manner that their polarizing axes made angles of 0°, 45° and 90° with the direction to the north pole. Four simultaneous exposures could thus be made on one 11″ × 14″ plate (Emulsion IB, Eastman, backed).

Due to development under adverse conditions the plates are of moderate photometric quality, but they are exceptional in showing the streamers to a large distance from the sun. A brief description [1]) was published but no further study has been made owing to Dr RICHTMYER's death. With the consent of the National Geographic Society the plates have kindly been put at the disposal of Dr VAN DE HULST by Dr C. W. GARTLEIN of Cornell University, who has taken part in the expedition. They have been studied by the author at Leiden Observatory. Four of the plates had been taken with the polarizing screens in position. The two most suitable ones have been used in the present study to derive data on brightness, degree and direction of polarization, and electron density of streamers in the outer corona.

Three streamers have been investigated, being

number 1 a prominent fairly sharp streamer extending S.W.

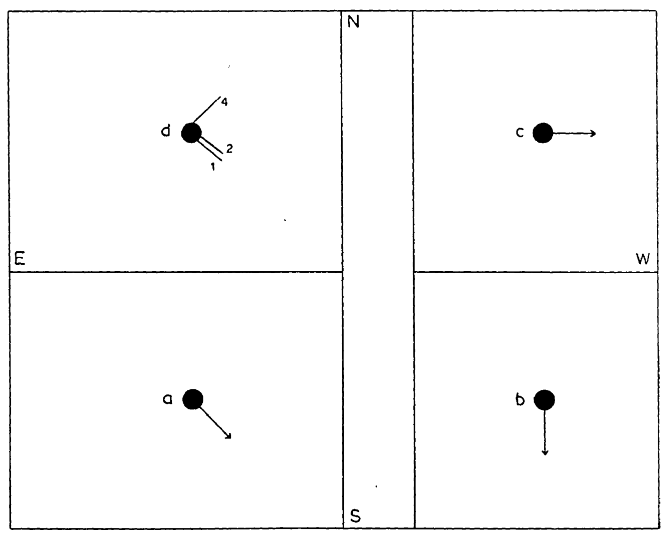
,, 2 a broad diffuse streamer extending W.S.W.

,, 4 a prominent sharp streamer extending N.W.

[1]) *National Geographic Society, Contributed Technical Papers*, Solar Eclipse Series, **1**, 17, 1939.

These streamers are just discernible on reproductions on page 21 and better on page 49 of the N.G.S. publication cited. As usual the reproductions are very much inferior to the original negatives, which show streamers up to a distance of eight solar radii.

FIGURE 1



Orientation of streamers and of polarizing screens.

Figure 1 shows schematically a plate as seen from the glass side. The four images have been given a letter as shown. The positions of the streamers have been marked on image *d*, which was taken without a polarizing screen; the direction of the magnetic vector of the light passing through the polarizing screens has been indicated on the images *a*, *b* and *c*. The light of a 100% radially polarized streamer extending in this direction passes unobstructed through the polarizing screen.

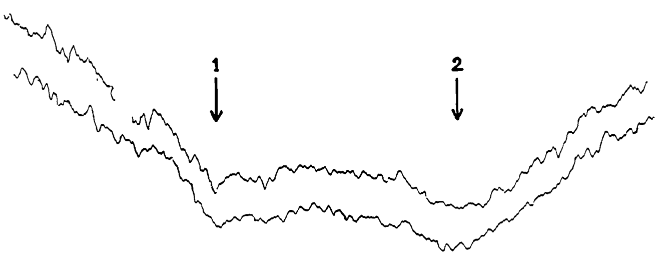
Sensitometer circles are discussed in the next section.

2. *Densitometry.*

Densitometer tracings across the streamers were made on the images *a*, *b* and *c* of the plates with exposure times of 60 and 15 seconds. The dense images *d* exposed without polarizing screen have not been used. The Leiden recording microdensitometer, which produces tracings on photographic paper, was used. The first experiments showed that owing to the graininess of the plates no streamers would be discernible on any tracing. The optical system was then replaced by a very simple one with smaller magnification so that the length of the projected slit could be increased to any value under 1 mm. A slit of 1.00×0.20 mm as projected on the plate was finally used, the short side being in the direction of the motion of the plate, which is the direction across the streamer. This proved to be a great improvement, although the graininess of the plates remained a source of errors.

After every tracing the plate was displaced 1 mm along the streamer, i.e. perpendicularly to the tracing direction, and the tracing repeated with the plate moving in opposite direction. By taking the average the influence of possible changes in the densitometer sensitivity was eliminated. The average minimum distances r to the sun's centre of the double tracings thus obtained were chosen as 7, 6, 5, 4, 3 solar radii on the 60 sec. plate and 4, 3, 2.5, 2 solar radii on the 15 sec. plate, the sun's radius being 5.6 mm. All tracings were at least 12 mm long.

FIGURE 2



Example of tracing across streamers 1 and 2 at $r = 4$.

Figure 2 shows a tracing on image *a* across streamers 1 and 2 at $r = 4$. Before and after every set of at most three tracings, the densities of suitable sensitometer spots were recorded for calibration and check of constancy. In total five series of sensitometer circles had been printed on every plate: one in the clear central region and the other ones near the corners of the plates. The corners have been exposed again during the eclipse and show a heavy fog caused by the corona and scattered light. The densities measured in these series, when reduced to no fog, were very discordant among themselves as well as with those measured in the central series. As the effect of subsequent exposures on the characteristic curve is quantitatively uncertain, it was thought best to use only the series at the centre for the characteristic curve. The stellar magnitudes of the sensitometer circles were sent to us by Dr GARTLEIN and agree with those published by MCNALLY [1]).

3. *Brightness and polarization.*

The tracings across streamer 4 were read on eight places $^1/_2$ mm apart and those across streamers 1 and 2, which appear together on the tracings, on ten places 1 mm apart on the plate. As all tracings were made along straight lines, corrections accounting for the difference of distance to the sun's centre had to be applied to the readings. These corrections were computed from the radial intensity gradient outside a streamer, which was derived from a comparison of tracings at different distances from the sun. All readings were thus reduced to the minimum sun's distance of the tracing. Graphs were then constructed giving the corrected readings as a function of the position measured across the streamer.

It may be useful to specify the meaning of the words intensity and background, as we shall use them in the following discussion. The word intensity will denote what is usually called surface brightness. The background intensity will be the surface brightness outside a streamer, i.e. the combined surface brightness of the K- and F-components of the corona and the scattered light. By streamer intensity we shall understand the surface brightness at the centre of a streamer with the full background intensity subtracted. Further r will denote the projected distance of a point to the centre of the sun's disc, the solar radius being unity.

The graphs mentioned were used to derive, with the characteristic curve, the streamer intensity S. The background intensity near a streamer was derived by reading the graphs at a place, selected carefully by visual inspection of the plates, where no streamers were visible.

In most cases the intensity of the background was virtually the same on both sides of the streamers. The only exception was image *c* on both plates, where a considerable difference of background intensity on both sides of streamers 1 and 2 was observed. Near these streamers only one place showed the background without streamers, so a determination of the angular intensity gradient of the background was difficult. The difference in background intensity per unit tracing length seemed to increase with decreasing sun's distance. This may be understood if the angular gradient is assumed to be constant, because the unit of length is seen under an increasing angle from the

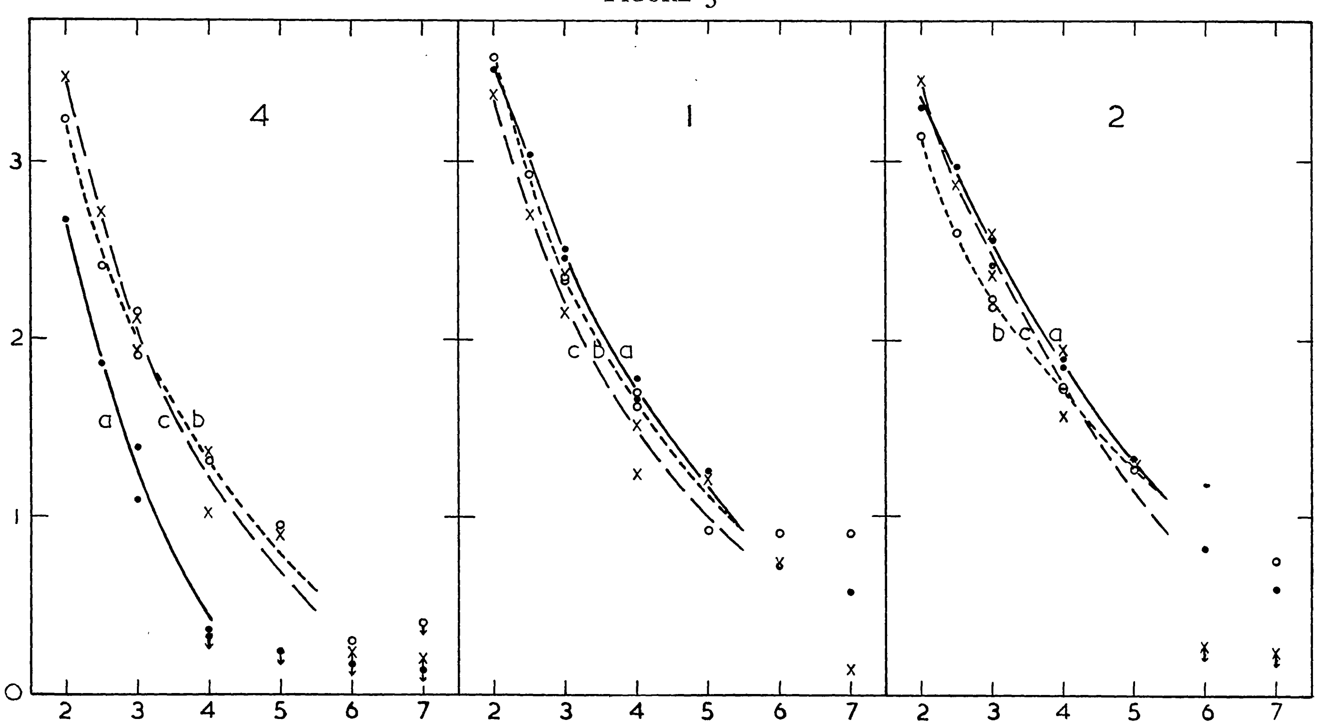
[1]) *National Geographic Society, Contributed Technical Papers,* Solar Eclipse Series, **1**, 59, 1939.

TABLE I

Intensity of the streamers only, in arbitrary units. The table gives log S_a, log S_b and log S_c.

	r	Image a 60^s	Image a 15^s	Image b 60^s	Image b 15^s	Image c 60^s plate	Image c 15^s plate
	2		2.68		3.24:		3.48:
	2.5		1.86		2.41		2.72
	3	1.09	1.38	2.15	1.90	1.94	2.13
Streamer 4	4	<0.36	<0.32	1.31	1.31	1.03	1.37
	5	<0.24		0.95		0.89	
	6	<0.16		0.30		<0.24	
	7	<0.12		<0.40		<0.20	
	2		3.52:		3.58:		3.38 (3.42)
	2.5		3.04		2.93		2.71 (2.76)
	3	2.46	2.50	2.35	2.32	2.36 (2.43)	2.16 (2.25)
Streamer 1	4	1.77	1.65	1.70	1.62	1.52 (1.70)	1.24 (1.53)
	5	1.26		0.92		1.22 (1.40)	
	6	0.72		0.90		0.73 (1.04)	
	7	0.57		0.91		0.14 (0.66)	
	2		3.31:		3.14:		3.48: (3.54:)
	2.5		2.97		2.59		2.88 (2.96)
	3	2.42	2.56	2.18	2.22	2.60 (2.72)	2.37 (2.53)
Streamer 2	4	1.85	1.90	1.72	1.74	1.95 (2.16)	1.58 (2.00)
	5	1.32		1.27		1.28 (1.73)	
	6	0.82		1.16		<0.28 (1.38)	
	7	0.59		0.75		<0.24 (1.20)	

FIGURE 3



Maximum surface brightness of streamers 4, 1 and 2 (from left to right), each in three directions of polarization, as a function of the distance from the sun's centre.

sun's centre with decreasing sun's distance. The change of intensity per degree finally was determined from the tracings at $r = 7$ and $r = 6$, where the influence of other streamers could be neglected. Thus the background intensity on image c was extrapolated to the centres of streamers 1 and 2.

By comparing the background intensity at $r = 3$ and $r = 4$ on both plates, the streamer intensities of the 60 sec. plate have been reduced to the intensity system of the 15 sec. plate. Table 1 and Figure 3 give the resulting streamer intensities, denoted by S_a, S_b and S_c. The values given in parentheses are found if the background intensity in streamers 1 and 2 on image c is assumed to equal the smaller background intensity outside the streamers.

The streamer intensities thus found form the basis for a determination of the polarization. We shall define the polarization axis as the direction of the magnetic vector of the light passing through the polarizing screen. The light of a 100% radially polarized streamer extending in this direction passes unobstructed through the polarizing screen. The following notations are used, all referring to a certain point of a certain streamer:

β the angle between the polarization axis of image b and the direction to the sun's centre;

α the angle between the polarization axis of image b and the direction of linear polarization of the streamer only;

S_o the unpolarized part of the total streamer intensity S;

S_p the fully polarized part of the total streamer intensity S;

p the degree of polarization, so that

$$p = S_p/S = S_p/(S_o + S_p).$$

The intensities on the different images then are

$$S_a = \tfrac{1}{2} S_o + S_p(\tfrac{1}{2} - \tfrac{1}{2}\sin 2\alpha),$$
$$S_b = \tfrac{1}{2} S_o + S_p \cos^2\alpha,$$
$$S_c = \tfrac{1}{2} S_o + S_p \sin^2\alpha.$$

From these equations, in which the intensities S_a, S_b, S_c are known, we can solve the total streamer intensity S, the degree of polarization p and the direction of polarization α. Table 2 shows the results, the total intensity S being given in arbitrary units. The values of β were derived from measurements on the plates. A comparison of α and β, which should be equal for radial polarization, shows for streamer 4 increasing differences with decreasing distance from the sun, up to 17° at $r = 2.5$. The deviations are such that the direction of linear polarization cuts the sun's axis in a point north of the sun's centre. The streamer itself is at high northern latitude ($B = +70°$). It seems difficult to escape the reality of these differences. For $r = 2.5$ for instance we have $S_b = 316$ and $S_c = 525$, from which $\alpha = 53°$ is derived. In order to check the reality of the deviations we take $\alpha = \beta = 36°$ and now calculate S_b and S_c, leaving the total intensity $S = S_b + S_c = 841$. We find $S_b = 572$ and $S_c = 269$. From this example we see that in order to dispute the reality of the deviations found from radial polarization, we must assume errors of more than 50% in the measured streamer intensities. Furthermore, the difference between S_b and S_c should be reversed. All this seems very improbable.

TABLE 2

Polarization and total surface brightness of the streamers only.

	r	β	α	p	$\log S$
Streamer 4	2.5	+ 36°	+ 53°	0.87	2.92
	3	+ 38	+ 46	0.83	2.32
	4	+ 42	+ 41	0.87	1.56
Streamer 1	2.5	− 39°	− 33° (− 34°)	0.59 (0.52)	3.14 (3.15)
	3	− 40	− 40 (− 46)	0.54 (0.38)	2.60 (2.64)
	4	− 40	− 30 (− 44)	0.42 (0.13)	1.88 (1.96)
	5	− 41	− 32 (− 102)	0.30 (0.19)	1.37 (1.50)
Streamer 2	2.5	− 55°	− 61° (− 71°)	0.58 (0.51)	3.06 (3.11)
	3	− 54	− 63 (− 81)	0.53 (0.47)	2.67 (2.76)
	4	− 55	− 49 (− 100)	0.33 (0.41)	2.05 (2.24)
	5	− 54	− 31 (− 110)	0.31 (0.53)	1.51 (1.79)

For streamers 1 and 2 an inspection of Figure 3 shows that while streamer 1 is brightest on image b, streamer 2 is brightest on image c. This suggests opposite deviations from radial polarization as both streamers are very near to each other. The values in parentheses in Table 2 apply when no correction for change of background with direction was made for image c. These serve to give an idea of the uncertainty of the results, which is of the order of the corrections applied. Only for $r = 2.5$ there is some indication of a deviation of α for both streamers but in opposite sense.

4. *Orientation in space.*

The angle θ between the line of sight and the streamer may be computed from the observed degree of polarization. For illumination by a point source $\alpha = \beta$ and $p = \sin^2\theta/(2 - \sin^2\theta)$. The true sun's distance r' then is $r' = r \operatorname{cosec}\theta$. A refined calculation may then be set up, which takes the sun's size and limb darkening into account, e.g. by using the coefficients given by VAN DE HULST[1]). The values of p obtained at $r = 2.5$

[1]) H. C. VAN DE HULST, *B.A.N.* **11**, No 410, 135, 1950.

and $r = 3$ are the most reliable ones; their average value has been used to find the direction of the streamers. The values of p are 0.85 for streamer 4 and 0.56 for streamers 1 and 2. This yields values of θ of 82° and 60° respectively. The position in space of the streamers, as characterized by the heliographic longitude L and latitude B, is determined from the position angle P and the angle θ. The position angle P is related with the angle β defined before by $P = -\beta$. The heliographic co-ordinates of the centre of the solar disc were $L_0 = 297°$ and $B_0 = 0°$; the position angle of the north pole of the solar axis was $P_N = -13°$. An ambiguity in L remains owing to the fact that the sign of sin θ is unknown. The results are tabulated in Table 3.

TABLE 3

Positions of the streamers.

Streamer	P	θ	B	L
4	328°	82° or 98°	+ 70°	4° or 50°
1	218	60 or 120	− 33	350 or 64
2	235	60 or 120	− 19	355 or 59

It is interesting to correlate the positions found with filaments, making use of the Cartes synoptiques[1]). Near one of the possible positions of streamer 1, the western part of filament 8803 (13 appearances) is seen, streamer 2 being 8° further north. In the other possible position there is filament 8781 (5 app.) which coincides very well with streamer 1. No filament is found near the indicated position of streamer 4. It is remarkable however that two sun's revolutions before a very old filament (26 app.) was seen in this position. At the eclipse time its centre, still at $B = +70°$, had shifted to the solar meridian and it extended from $L = 220°$ to $L = 325°$. It is conceivable that streamer 4 belongs to an invisible part of this filament, that is quite exceptional by its high age. If this is true, this streamer would be the same as the one observed at position angle 325° during the 1936 eclipse, when the prominence itself was also visible on eclipse plates[3]) [4]).

5. *Intensity gradients.*

The main purpose of the present investigation is to compare the gradient of the streamers with the general gradient of the corona. It is very important to distinguish between the gradients of the intensity (with or without corrections for the various components of the background intensity) and the gradients of the electron densities. This distinction has not always been made sufficiently clear. In this section we shall confine ourselves to intensity gradients.

Table 4 gives for different distances r the intensity K of the electron part of the corona, the intensity $K + F$ of the total corona and the intensities S of the three streamers investigated. The unit of intensity is in all cases the intensity at $r = 2.5$. It was impossible to derive reliable data of the general intensity of the corona from the plates, as the fog was too irregular, so the intensities K and $K + F$ were taken from a model corona derived by VAN DE HULST[2]).

TABLE 4

Comparison of the intensity of the streamers only and the model corona, all expressed in the intensities at $r = 2.5$.

r	log K	log$(K + F)$	log S_4	log S_1	log S_2
2.5	0.00	0.00	0.00	0.00	0.00
3	− 0.46	− 0.29	− 0.60	− 0.54 (0.51)	− 0.39 (0.35)
4	− 1.04	− 0.67	− 1.36	− 1.26 (1.19)	− 1.01 (0.87)
5	− 1.39	− 0.93		− 1.77 (1.65)	− 1.55 (1.32)

The values in parentheses refer again to no correction for angular background gradient on image c, as discussed before. Only for streamer 2 the gradient is about the same as that in the K-corona; streamers 4 and 1 show a definitely higher gradient. A comparison with the (K + F)-corona shows a higher gradient in all streamers. Thus the results of VON KLÜBER[5]), who found from isophotes in the outer corona a higher gradient inside streamers than outside, are confirmed.

6. *Electron density.*

We shall now compute the electron density in the streamers. Let[2]) J be the source function, H the mean surface brightness of the sun, N the number of electrons per cm³, $\sigma = 0.66 \times 10^{-24}$ cm² the scattering cross-section of one electron, $R = 6.97 \times 10^{10}$ cm the solar

[1]) L. D'AZAMBUJA et R. SERVAJEAN, *Cartes synoptiques de la chromosphère solaire et catalogue des filaments de la couche supérieure*, Vol. I, fasc. VII.

[2]) H. C. VAN DE HULST, *B.A.N.* **11**, No 410, 135, 1950. Cf. also H. C. VAN DE HULST, Vol. I, Ch. V, sec. 14 of 'The Solar System', edited by G. P. KUIPER, Chicago University Press (To appear in 1953).

[3]) *National Geographic Society, Contributed Technical Papers*, Solar Eclipse Series, **1**, 45, 1939.

[4]) E. J. BUGOSLAVSKAYA, *Publ. Sternberg* **19**, 32, 1950.

[5]) H. VON KLÜBER, *Zs. f. Ap.* **2**, 289, 1931.

radius, A and B the coefficients mentioned before, then

$$J = \tfrac{3}{8}\, HN\sigma\{2A - (A-B)\sin^2\theta\}.$$

The length of the line of sight through the streamer is Δy; the half-intensity width of a streamer, as derived from the tracings, is Δx. We shall suppose that the streamer has at any distance from the sun a circular cross-section, that it is homogeneously filled with electrons and that the projected width of the cross section is the half intensity width Δx. The surface brightness of the streamer, which we have called S, is now $S = J.\Delta y$, while $\Delta y = \Delta x$. cosec θ. Introducing numerical values we find the electron density N in the streamer

$$N = 5.81 \times 10^{13} \frac{\sin\theta}{2A - (A-B)\sin^2\theta} \frac{R}{\Delta x} \frac{S}{H}.$$

The streamer intensities S are expressed in arbitrary units, which we have to calibrate in order to compute the electron densities. We shall make use of the background intensities described in section 3. These background intensities are a combination of the intensities of the K-corona, the F-corona, the scattered light and the influence of the general plate fog. If the scattered light and the fog could be determined with sufficient certainty from densities in the corners of the images, it would be possible, by subtracting them from the background intensity, to find the intensity of the (K+F)-corona expressed in the arbitrary units employed in Table 2. This proved to be possible only for image b on both plates. The intensities of the (K+F)-corona thus found had to be corrected for degree of polarization, which was taken from the model corona, to yield total intensities. From a few determinations $\log(K+F) = 3.50$ at $r = 2.75$ was found. The corona model gives at this distance $\log(K+F) = 1.80 - 10$ where the unit is the sun's average surface brightness. The arbitrary unit of surface brightness used is thus seen to be 2.0×10^{-12} times the mean surface brightness of the sun. If we express S in the same unit as before and Δx in mm ($R = 5.6$ mm on the plates), the density is given by

$$N = \frac{650 \sin\theta}{2A - (A-B)\sin^2\theta} \frac{S}{\Delta x}.$$

As S refers to the intensity of the streamer alone, N is the additional electron density in the streamer.

The results are tabulated in Table 5, together with

TABLE 5

Electron density of the streamers.

	r	r'	Δx	log N_e streamer	log N_e corona	difference
Streamer 4	2.5	2.52	1.6 mm	6.59	5.90	0.69
	3	3.03	1.3	6.25	5.48	0.77
	4	4.04	1.7	5.63	4.94	0.69
Streamer 1	2.5	2.88	2.5	6.59	5.60	0.99
	3	3.45	3.4	6.09	5.24	0.85
	4	4.60	2.8	5.69	4.77	0.92
	5	5.75	3.3	5.32	4.51	0.81
Streamer 2	2.5	2.88	4.3	6.28	5.60	0.68
	3	3.45	4.8	6.01	5.24	0.77
	4	4.60	4.4	5.67	4.77	0.90

the electron density of the K-corona at the true sun's distance r'. The density gradient in streamers 4 and 1 is seen to be the same as that in the K-corona. There is some indication of a smaller density gradient in streamer 2, which however may not be real, as all results for this streamer are rather uncertain. The variations in Δx along a streamer are probably not real. If we take for every streamer a mean value of the width, the density gradients are not affected. The total electron density in the streamers 4, 1 and 2 is found to be 6.2, 8.8 and about 7 times the electron density in the K-corona, respectively.

Some authors have suggested that the cross-section of a streamer is not circular but strongly elongated like the filaments, with which they are thought to be associated. The entire streamer would then have the shape of a fan. We shall investigate how the results change if this assumption is correct.

Filaments in low latitude are not, in general, orientated parallel to the equator, so for streamers 1 and 2 the value of Δy used presents a fair estimate. If, however the base of the fan were a line with constant latitude, the line of sight would cut the streamer over a wide range of θ. Assuming that the fan is homogeneously filled over this range of θ and that it has the same density gradient as the K-corona, we can compute what range is compatible with the observed polarization 0.56 ar $r = 2.75$. The fan is found to extend from $\theta = 0°$ to $76°$ or $104°$ to $180°$ at most; the total electron density in streamers 1 and 2 is at least 3.3 and

3 times, respectively, the density in the K-corona. This may be considered to be an absolute minimum.

In the case of streamer 4 the observed polarization 0.85 may be produced by a fan extending at most from $\theta = 76°$ to $104°$. If the base of the fan is strictly a line of constant latitude, its extension over a range of θ produces also an apparent widening of the streamer. If the width of the streamer on a tracing is interpreted as partly due to a true range of latitude and partly due to this extension effect, then the maximum extension of the fan is found to be $\theta = 78°$ to $88°$ or $92°$ to $102°$; the total electron density in streamer 4 is 3.8 times the density in the K-corona. This is again a minimum value.

This short discussion shows that the errors in the electron density derived, owing to a non-circular cross-section of the streamers, will not be more than a factor 2.

It appears from isophotes obtained by WALDMEIER [1]), BRÜCK [2]) and VON KLÜBER [3]), that the intensity gradient in streamers is smaller than in the background in the inner corona and larger in the outer corona [4]). A comparison of the gradients of the intensity in the (K+F)-corona and the electron density in the model corona, shows the latter to be larger up to $r = 1.9$ and smaller at greater distances. Now in the preceding discussion the gradient of the electron density in the streamers and the gradient of the intensity in the (K+F)-corona proved to be about equal. As the intensity of a streamer depends directly on the electron density without any integration effect, it is evident that the intensity gradient in a streamer should be smaller than in the background up to $r = 1.9$ and larger at greater distances. This explains satisfactorily the peculiar behaviour of the intensity gradients as found by the authors quoted.

It is a pleasure to thank Dr C. W. GARTLEIN and the National Geographic Society for permission to study these plates and Professor H. C. VAN DE HULST for his stimulating interest and instructive criticism during all stages of this investigation.

1) M. WALDMEIER, *Zs. f. Ap.* **22**, 18, 1942.
2) H. A. BRÜCK, *M. N.* **104**, 33, 1944.
3) H. VON KLÜBER, *Zs. f. Ap.* **2**, 289, 1931.
4) H. C. VAN DE HULST; to appear in Vol. I, Ch. V, sec. 19.21 of 'The Solar System', edited by G. P. KUIPER.