INTERFEROMETRIC INVESTIGATION OF THE LINE OF SIGHT VELOCITIES IN λ5303 DURING THE ECLIPSE OF 11 SEPTEMBER, 1968

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Abstract. Fabry-Perot interferometric observations of the λ5303 Å corona line on 22 September, 1968 were carried out. There are many elements of the interferometric rings with considerable line of sight velocities. The influence on the results of the changes in the brightness of the monochromatic and white-light corona were discussed.

1. Observations

During the eclipse on 22 September, 1968 we obtained interferograms in λ5303 Å with the help of a Fabry-Perot interferometer and a narrow interference filter in polarized light (Figure 1) (see A. B. Delone and E. A. Makarova, 1969a, b). The instrumental profile of the entire optical system was determined by a photograph of the krypton rings from a gas discharge ball set in the focus of an objective which had been fixed in front of the main objective of the installation. The half width of the profile was found to be 0.21 Å. The diameter of the Moon's image on the interferogram of the eclipse was 15 mm; and the distance between the ring maximums (rings 3–11) was about 1 mm. An A-600 film was used.

We measured two negatives obtained with the polaroid in different positions, the exposure being 4 s. The measurements were made with the help of a recording microphotometer. A slit was cut in the negative 0.025 mm across the ring (this being only half the instrumental half-width) and 0.1 mm along the length of the ring. The center of the ring system was located by coincidence with the system of concentric circumferences. When the measurements were being made, the distance was taken with the help of a micrometer from the centre of the system to the edge of the Moon, the distances from there being measured by recording. Sections were made at every degree of the position angle in the ring system, with the exception of places where line λ5303 had no luminosity. To translate the data into intensities, a calibration made with a tube photometer having a green filter was used.

On the radial sections of corona photographs arranged in a scale of intensities, we traced a continuous background in the form of a smooth curve passing through the minima between the rings (Figure 2). This background was formed by a continuous spectrum of the corona that passed through the interference filter, known as the premonochromator. Thus, the background had a value for each point in the section of the interference pattern. This background value was substracted from the measured total intensity of the monochromatic and white-light corona. The profiles obtained as a result of the substraction of the continuous background value will further be regarded as profiles of line $\lambda 5303$ in the corresponding places of the corona. It is necessary to bear in mind that each abscissa of such a profile corresponds not only to its λ, but also to its place on the corona image in contrast to the profiles of spectrographs. Therefore, the magnitude of the corresponding ordinate may reflect not only

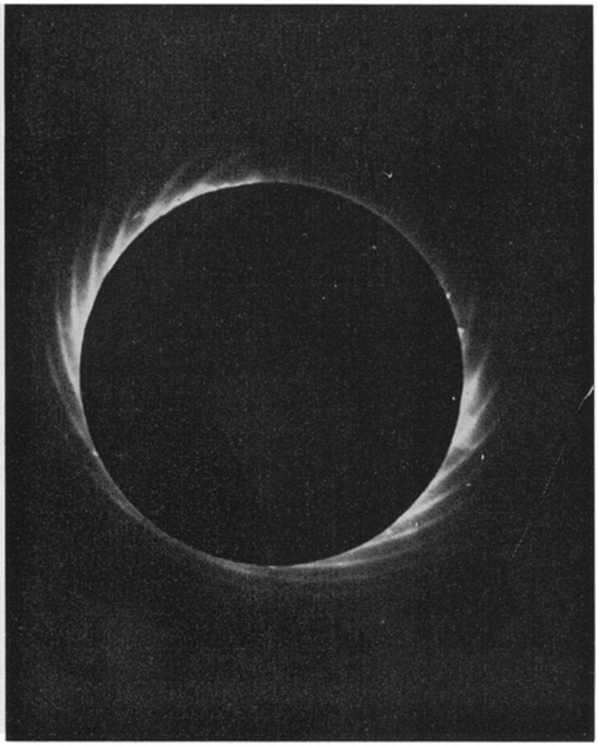

Fig. 1. A photograph of the solar corona in the line $\lambda 5303$ Å, obtained with the Fabry-Perot interferometer. The exposure time is 4^s, September 22, 1968.

the change in the profile of the coronal line, but also the changes in the brightness of (a) the monochromatic corona and (b) the white light corona, if it does not have the form of a smooth curve. But in the case of the interferometric pattern, (a) and (b) will have different influences on the profiles of the line: the deviations of the white light corona brightness from a smooth curve will appear directly in the ordinate of the line profile, but the deviations of the brightness of the monochromatic corona will have different factors, which will depend on the distance from the centre of the line and the half width of the line. We consider both cases below.

To determine more reliably the line of sight displacement, we compiled a large scale map showing the centres of gravity of $\lambda 5303$ Å profiles. At the same time we found the circumferences which the profiles' centres of gravity best fitted. In nine places over the limb, the centres of gravity of the profiles, for a series of successive rings, deviate from the circumferences found as described above. 'Pieces' of rings 3–6° in size of position angle are displaced 1–2 Å. In eight cases out of nine these shifts are situated over the protuberances. It appears that these shifts can be interpreted only as line of sight velocities in the given place of the corona.

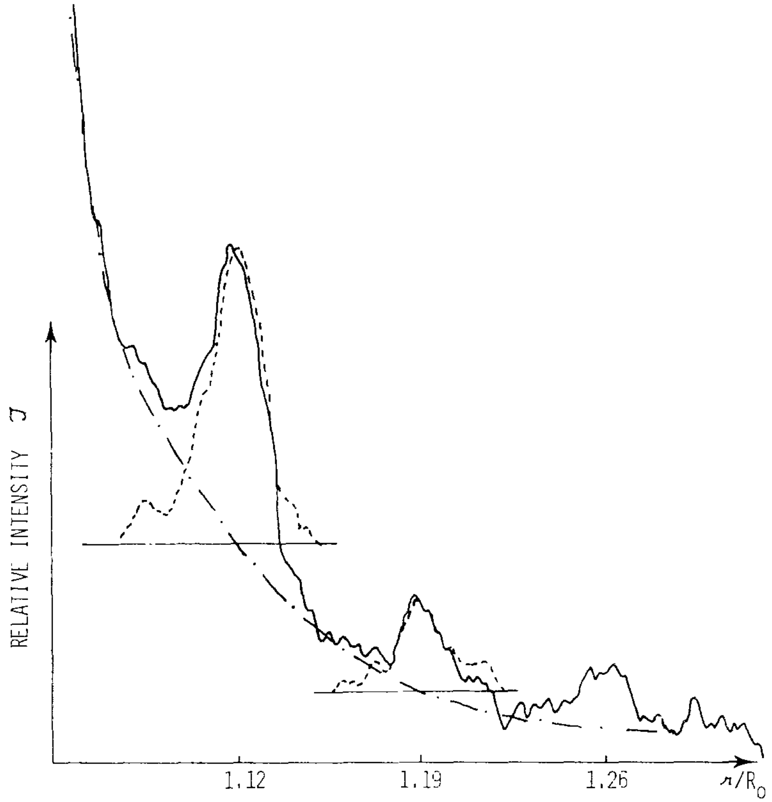

Fig. 2. Photometric section of coronal photographs with Fabry-Perot interferometer in the line λ5303 Å. The dashed line is the contour of the emission in λ5303 Å.

We then selected the Gaussian profiles which best matched the profiles we had obtained through observations. It often happened that the profile of a ring could not be represented by a single Gaussian profile. In some cases it would be well represented by the sum total of such profiles. That these profile elements are real (proceeding from the fact that they do exist, we have divided the profile observed into several components) is confirmed by their recurrence (in approximately half the cases) in adjacent – by the position angle – sections of the interference pattern. We cannot be sure *a priori* that these profile elements are not the result of the non-uniformity of the photographic emulsion. However, that the division really exists can be checked by comparing the profiles obtained on two different negatives (Figure 3). We have found both simple and complicated profiles to 'coincide' on two negatives in 56% of the cases examined.* It should be borne in mind that the centre of the ring system has been determined with an error of $\sim 0.014\ R_{\odot}$, this corresponding at the edge of the disc to 1° of the position angle. It should also be noted that the position angle is determined by the protuber-

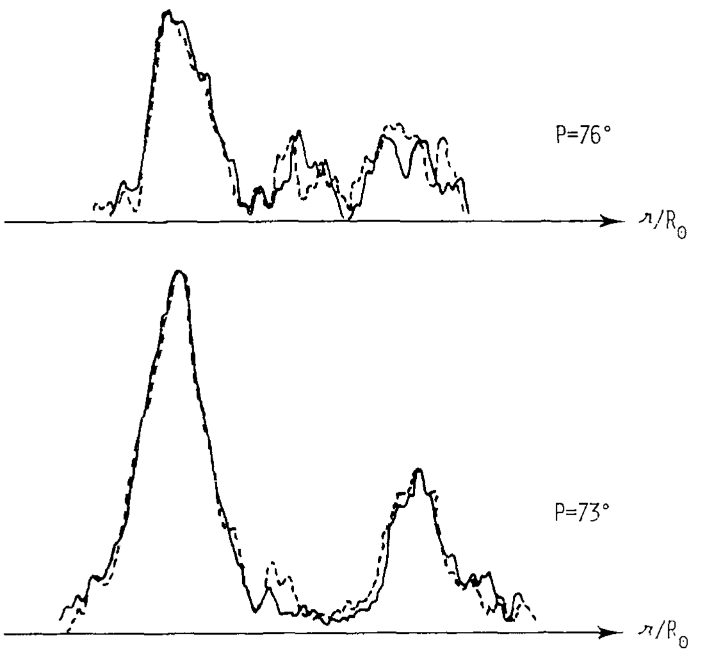

Fig. 3. The concidence of the details with $v \neq 0$ in the section of the frames 1 and 3. p is the position on the limb; - - - - - - - - - frame 1; – – – – – frame 3.

ances and carries the same error. Therefore, when comparing the profiles of formally identical points on two negatives, it should be expected that they will frequently fail to coincide, particularly in places where one of the negatives has registered some rapid change, and a shift has occurred in the position angle. Besides the fact that the two negatives examined were obtained with differently orientated polaroids (a difference of 60°), the non-coincidence of a considerable number of contours may have been due to the effect of polarisation, which will be the subject of our next work.

* We have considered the possibility that a coincidence may be of an accidental nature. If we compare pairs of profiles taken at random from a given ring (normalized by central intensity), the number of coincidences drop to 17%. Out of this 17%, some really do coincide (similar conditions being possible in different parts of the corona), whereas a certain number may be due to the 'play of grain' in the photoemulsion.

TABLE I

Line of sight velocities, km s^{-1}	Number of cases	Line of sight velocities, km s^{-1}	Number of cases	Line of sight velocities, km s^{-1}	Number of cases
0	286	−55	18	+ 95	7
−15	34	+55	39	−105	26
+15	59	−65	18	+105	21
−30	47	+65	15	−120	4
+30	76	−80	22	+120	11
−40	16	+80	33	−135	17
+40	29	−95	7	+135	11

56% of the profiles on one negative having been confirmed by coincidence with profiles on another negative, we maintain that the complex structure of profiles is an established fact, together with the existence of line of sight (radial) velocities, determined by the displacement of separate profiles from the 'zero' position which corresponds to the radius of the ring examined.

In the whole we have made 700 sections of the interferometric pattern on the coronal negative, situated at distances of from 1.02 to 1.39 $R_{\odot}$. Some of these 700 profiles were divided and as a result we had 913 profiles of the corona line λ5303 Å. Many of these profiles were displaced from the centre of the corona line and so line of sight velocities have been registered, the rate of occurrence being shown in Table I. In 10% of the points the velocities are $V_{\gamma} \geqslant 100$ km s^{-1} (we have been unable in principle to register velocities greater than 135 km s^{-1} which correspond to half the distance between the rings of the interference pattern). It is important to note that with the exception of cases when pieces of rings are displaced, high velocities refer to separate weak elements in the corona. There is only one point near a big protuberance on the western edge of the disc ($P = 292°$, $R/R_{\odot} = 1.04$) which is characterised by powerful displacement and strong radiation in the line. In all cases when the profile or its components could be represented with our degree of accuracy* in the form of a Gaussian profile, we produced a corresponding Gaussian half-width of the line in Å.

2. Discussion

Table II gives the distribution of $\Delta\lambda$-full widths at half the level of intensity, against the distance from the edge of the Sun, as expressed in $R_{\odot}$. Here and in Table III we consider only Gaussian profiles out of the whole 913 profiles. The table does not offer any clear cut regularity. Now if one examines the distribution of the line half-widths depending on the line of sight velocities of the corresponding profiles, he will observe a difinite regularity: with an increase in the line of sight velocity the centre of gravity of the distribution is displaced towards the smaller half-widths. This is shown in Table III.

* The degree of accuracy for each intensity is determined by the clearly visible noise in the spots on the film produced by the tube photometer.

TABLE II

Distribution $\Delta\lambda$ depending on distance from the edge of the Sun (number of cases)

Interval by r in $R_\odot$ / $\Delta\lambda$, Å	0.00–0.05	0.06–0.10	0.11–0.15	0.16–0.20	0.21–0.25	0.26–0.30	0.31–0.35	0.36–0.42
0.8	6	29	25	21	23	7	2	1
0.9	6	27	20	15	17	7	1	1
1.0	2	8	10	26	20	9	1	
1.1	5	13	10	7	8	7	4	2
1.2	5	13	15	15	7	6	2	
1.3	4	21	11	12	9	4	1	1
1.4	4	16	6	11	6	5		
1.5		15	23	6	7	3	1	1
1.6		6	10	3	3	2	2	
1.7	3	7	5	4	4	2	1	
1.8		3	6	2	4	1		1
1.9		3	3	2	3	5	1	
2.0			2	3	3			
2.1	1		2	2	3			
2.2			1	3	3			

TABLE III

Rate of occurrence of elements characterised by a definite line of sight velocity, against a given half-width of contour

	Line of sight velocities, km s^{-1}										
$\Delta\lambda$, Å	0	15	30	40	55	65	80	95	105	120	135
0.8	8	7	10	5	7	10	10	11	18	7	7
0.9	8	9	9	6	6	3	11	6	12	3	5
1.0	9	7	6	3	7	11	9	4	4	3	5
1.1	19	5	10	1	7	1	5	1	3	1	2
1.2	15	6	8	3	4		3	1			1
1.3	25	6	9	5	2		2	1	1		2
1.4	21	6	8	2	2		2				1
1.5	24	7	11	2	1		1				
1.6	10	7	3	1	1		1		1		
1.7	12	3	3	1							
1.8	9	3	2		1		1		1		2
1.9	8	3	1								
2.0	11	1	5		1						

It appears as if the true profile of a separate element in the corona is rather narrow, the elements being characterized by relative velocities. If these velocities are low, we observe a composite profile produced by several elements. It is broadened as a result of the superimposition of separate element profiles, which are somewhat displaced by relative movements. If these velocities are large we observe a set of separate profiles displaced on the line of sight, but not one wide profile. The higher the velocities of components in this composite profile, the greater the probability that we are observing profiles that correspond to separate elements.

Generally speaking, a comparison of the profiles obtained on the basis of two negatives has led us to the conclusion that we have 'underdivided' the profiles, rather than 'overdividing' them into parts corresponding to different velocities. This means that the big half-widths given in Table II and Table III have been 'exaggerated', and that we have failed to establish all the elements characterized by velocities even within the degree of accuracy accessible to us.

Quite naturally we have been puzzled by the fact that we have obtained so many rapidly moving elements in the corona, whereas numerous investigations in the past produced no such result. Why is this so?

Displaced ring elements are not the result of an instrumental defect. This is obvious from the method of using the interferometer: it was placed in the exit pupil, therefore the light passed to each point of the image through the same areas in the interferometer. The krypton rings taken in the same working pattern are very distinct. They are not characterized by displacement. We regarded the presence of additional maxima in the interference pattern as a result of the existence of elements characterized by high velocity.

Now we try to estimate the possibility of an influence of the changes in the brightness of the monochromatic and white light corona on the profiles of the λ5303 line.

2.1. The monochromatic corona

Generally speaking the changes in the brightness of the monochromatic corona can cause displaced on irregular, broadened profiles, such that we can divide the profiles of the line into several profiles. As a result, we could get the effect of some line of sight velocities on the one hand and more narrow profiles of the corona line on the other. The comparison of the interferometric pattern with the structure of the monochromatic corona is the best criterion for the reality of the velocities and narrow profiles. Since we did not get a picture of the corona without the interferometer in 1968 we could not compare each point of the interferometric ring with corresponding place of the monochromatic corona. In such a case, our interpretation of the details in the profiles will be based on an estimate of the magnitude of the changes in the monochromatic corona brightness.

We have estimated the magnitudes of changes in the brightness of the monochromatic corona, and the rate of such changes, to compare I_{max} along the rings for 198 points of an arbitrary chosen place in the corona, from 40° to 158° position angle. Let us designate I_p/I_{p+1} – the relative brightness of two neighbouring I_{max} and N – the number of the cases with the given ratio, the result being shown in Figure 4. One can see in only ~17% of cases that I_p/I_{p+1} is more than 1.5; and in only one case that $I_p/I_{p+1}=2$.

Probably the magnitudes of the brightness changes in our case are smoothed by the small spatial resolution of our equipment. Sometimes real magnitudes of the changes I_p/I_{p+1} can amount to 10–20 if the spatial resolution is sufficiently high. But recently

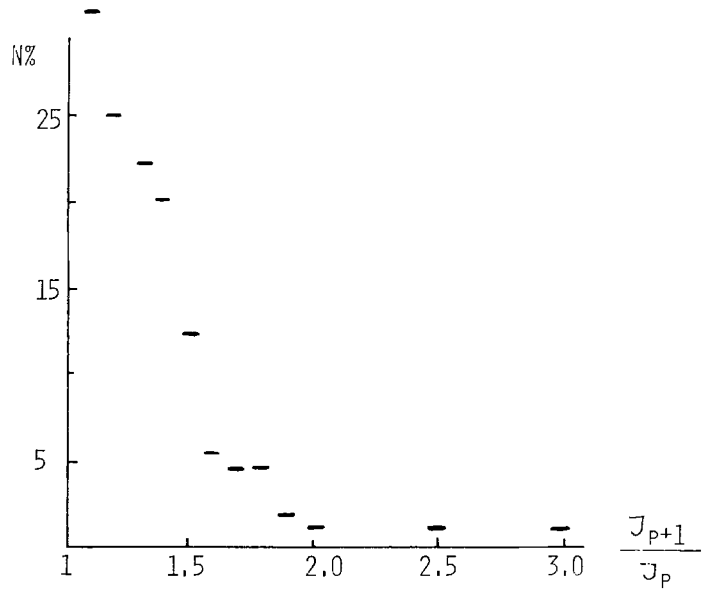

Fig. 4. Rate of change in the brightness of the monochromatic corona along the interferometric rings.

Leroy *et al.* (1973) made estimates like ours. They observed monochromatic corona at Pick du Midi with spatial resolution $\sim 8''$. The magnitude of brightness changes are less than 2.

We have estimated by what factor it is necessary to increase the intensity of $\lambda 5303$ in those places of the corona where there were 'moving elements' of the ring, in order to explain these elements of the profile by monochromatic intensity gradient. The estimate was done only for all displacements having velocities, $V_r \geqslant 40$ km s^{-1}, i.e. for the most interesting and important cases. Only two such elements from the whole 134 could be explained by changes in the brightness by a factor of two. The rest required changes of the brightness by a factor of five or more.

Note that the less the temperature of the corona, the farther in the wing the displaced elements will be located and the more the brightness changes must be in order that we might explain the existence of such elements.

Even if we adopt unreal wide profiles of $\lambda 5303$, $\Delta\lambda_{1/2} = 1.8$ Å, $T \approx 4.5 \times 10^6$ K, we cannot explain the existence of the overwhelming majority of the displaced elements by the brightness changes.

Thus only about 1.5% of the displaced elements with Doppler shifts $\geqslant 40$ km s^{-1} can be explained by the brightness changes of the monochromatic corona.

2.2. White-light corona

We obtained the intensity of the interference pattern from the intensity observed, by subtracting an assumed smoothly changing background value of the white-light corona. Are not these maxima the result of this line of reasoning? Perhaps the background does not change smoothly at all? Failure to take account of the brightness structure of the white-light corona could be the main source of trouble in our work since they could affect any part of the profile. However, we can bring forward two arguments to show that the Doppler velocities observed have not been conditioned by the non-uniformity of the white-light corona:

(a) We carefully examined the characteristics of the whitelight corona at the points for which we have made profiles in λ5303. Having compared our interferograms with the structural chart of the white-light corona compiled by Vsekhsvjatskij *et al.* (1970) on the basis of negatives taken with the help of a ten metre coronograph, we saw that the latter shows absolutely uniform regions of the white-light corona at locations to which line of sight velocities in λ5303 Å correspond.

(b) Of course, several profiles with line of sight velocities that are not equal to zero, correspond to structural regions in the white-light corona. But very often the intensities of these displaced profiles are extremely great as compared to the intensity of the smoothly changing white-light corona; in fact they are too great to be attributed to the changing brightness of the white-light corona.

Let's see whether we can explain the existence of 'moving elements' as a result of the brightness deviations of the white-light corona from the smooth curve which we used at the treatment of our observations. Let's use the same data about the relative brightness of neighbouring points of an interferometric ring. As one can see in Figure 4, 99% of the overwhelming majority of brightness changes of the monochromatic corona are less than two. Consequently, 99% of the brightness changes of white-light corona must be less than 1.4, as the brightness of monochromatic corona is proportional to N_e^2 and that of white-light is proportional to N_e. Certainly this is true only if we suppose that the light of the monochromatic corona and white light came to us from the same volume of the corona. Such an estimate is confirmed independently by Waldmeier and Weber's (1969) data. The changes of brightness as a rule were less than 1.5 in the picture of the corona on September 22, 1968.

Thus, if we suppose that the 'moving elements' are caused by local increases of the brightness of white light corona, these increases must not exceed the smoothed background more than 1.4 times in 99% of all cases. We have made an estimate of the ratio of brightness of such elements to the white light background for the second and the third rings, counting from the edge of the Sun where the photometric measurements have been most reliable. It was found that only in 10–15% of cases were the brightness of 'moving elements' less than 1.4 of the brightness of the white light corona. The brightness of 'moving elements' were more than 1.4 in at least 85% of cases, sometimes being 3–7 times more. Such cases cannot be explained by changes of white light corona.

Summarizing the results of our evaluations of the influence of the changes in monochromatic corona and white light brightness, we can say that the existence of most – about 85% of the 'moving elements' – cannot be explained by such changes of the brigthness. We note that the changes of the white-light corona brightness are more dangerous than monochromatic changes but even these explain the existence of only about 15% of cases.

It seems that the existence of 'moving elements' is a fact. Therefore, although we cannot claim (without careful collation of the profiles with the photometric structure of the white-light corona) that each profile characterized by a line of sight velocity which is not equal to zero is doubtlessly a profile in $\lambda 5303$ and not a burst of brightness of the white-light corona, it is obvious to us that most of these profiles are real. Proceeding from this we must answer the question why earlier investigations did not lead to such results.

Jarret and von Klüber (1955, 1961) using a Fabry-Perot interferometer obtained a large volume of data during the eclipses in 1954 and 1958. They refer to a large distance interval from the edge of the Sun, but give no information about velocities on the basis of their observations. Perhaps, this is the result of caution, the material of 1954 having been over-exposed. However, the authors pointed out that the width of the line appeared to be somewhat greater in some parts of the rings and that this behaviour could be seen from mere visual inspection of the rings (1955). During the eclipse in 1958 they had poorer instrumental resolution – 0.5 Å (1961).

Using a photoelectric interferometer Henderson (1970), and Henderson and Larsen (1971) observed the eclipses in 1966 and 1970 and conducted observations outside the eclipse up to $r = 2 R_{\odot}$ with excellent instrumental resolution (1971). Since no original data were quoted and since the author made no reference to Doppler velocities, we can say nothing about the presence or absence of these velocities proceeding from their data.

During the eclipse in 1970 Hirschberg and Wouters (1970) conducted observations in line $\lambda 5303$ with the help of the Fabry-Perot interferometer. In their observations Hirschberg and Wouters registered considerable velocities in the northwestern part of the corona.

The other work is on observations carried out at times free from eclipses. Most of this refers on the whole to a distance of 30″–2′ from the edge of the Sun.

To establish why observations conducted at times free form eclipses fail to produce data on the high velocities we have expressed – in per cent of full radiation of a non-displaced profile – the full radiation in a profile being displaced in relation to the main ring. We maintain that Figure 5, representing the dependence of the relative brightness characterizing a moving element on the distance from the limb at which it is observed, answers the question we have posed. The closer the object is to the edge of the Sun the lower the relative brightness of the displaced profile is in relation to the main ring. At distances accessible to observations in periods free from eclipses it is $\leqslant 10\%$. It should be pointed out that our material obtained at such distances refers to the weaker places in the corona, because the brighter places at these distances have been over-exposed. It is expected that in the brighter places this ratio is even smaller, and it is precisely these places that are observed on a mass scale during non-eclipse periods.

It appears that the relatively low luminosity of separate elements, as compared to the high background luminosity in $\lambda 5303$ near the limb, result in the fact that in non-eclipse periods velocities are seldom observed by the profiles of coronal lines.

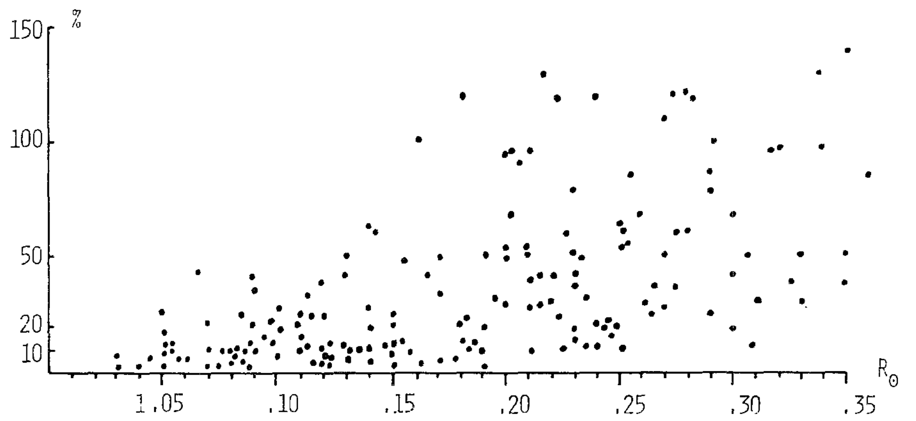

Fig. 5. The dependence of the relative brightness of moving elements, $I_{\nu\neq}$ -/$I_{\nu\neq}$ -(%),)on the distance from the limb.

One cannot observe weak lines of the corona because of the great scattering of light by the sky just as it is difficult to detect moving elements of intensities comparable to those of weak lenses.

Observations with spectrographs that were carried out during eclipses usually have too low a spectral resolution, therefore one can get only half-widths of the lines but not the profiles. Besides, the slits of spectrographs cut very limited regions of the corona in contrast to interferometric patterns.

Coronal structure generally being radial, and structural formations in the corona being nearly always of a durable nature, (see, for instance, Bugoslavskaya (1950), Fisher and Pope (1971)) it should be expected that the motions in the corona will occur in the radial direction too. Since the brightness of the corona drops sharply with the distance, the elements compared by brightness may be separated by considerable distances on the line of sight, only if the point examined on the plane of the sky is adequately remote from the edge of the Sun. Such elements remote from the plane of the sky can produce considerable projections of radial velocity along the line of sight. In our case this will correspond to the division of the ring into several contours displaced by velocity.

Acknowledgement

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