THE SIZES OF LOCAL SOURCES OF SOLAR RADIO EMISSION AT A WAVELENGTH OF 4.5 cm

A. N. Korzhavin and N. G. Peterova

Main Astronomical Observatory, Academy of Sciences of the USSR, Pulkovo
Translated from Astronomicheskii Zhurnal, Vol. 45, No. 1,
pp. 36-44, January-February, 1968
Original article submitted January 20, 1967

The results are given of a statistical treatment of the sizes of local sources of radio emission associated with sunspot groups of small area. The investigation is based on observations of the sun at a wavelength of 4.5 cm with a resolution of about two minutes of arc made with the large Pulkovo radio telescope during 1962-1965. It is found that local sources associated with unipolar sunspot groups are 1.5 times larger than local sources associated with bipolar sunspot groups. For bipolar sunspot groups the local sources have dimensions of the same order as the sizes of the groups in the photosphere: in the unipolar case the local sources are 4-6 times larger than the associated groups. The correlation coefficient of the sizes of the local sources with the areas of the sunspot groups and also with the intensity of the magnetic field in the spots is found to lie between the limits 0.5 and 0.7. The dependence of the sizes of the local sources on their distance from the center of the disk of the sun is close to but a little weaker than a cosine law for the unipolar groups: in the case of bipolar groups practically no dependence at all is found.

The determination of the sizes of local sources of solar radio emission associated with active regions has attracted the attention of many investigators. Christiansen et al. found [1] that the contours of the local sources at a wavelength of 21 cm closely coincided with the contours of the flocculi, having the dimensions 3'-10'. Observations in the range 8 mm to 10.7 cm [2-14], made with radio telescopes of high resolving power, show that the sizes of the local sources are less than at 21 cm and lie within the limits 1' and 3', sometimes up to 5'. It follows from eclipse observations of the sun in the centimeter range [15] that the sizes of the local sources closely coincide with the optical sizes of the associated sunspot groups. The dependence of the sizes of the local sources on the wavelength was specially investigated by a number of authors [16] for ten large sources on the sun, and in [17] was investigated on the basis of observations of the eclipse of the sun on February 15, 1961. It was found that for large sources in the centimeter range their sizes showed practically no dependence on the wavelength and only increase at the wavelength 21 cm. In [14] a case is mentioned in which the sizes of the local sources differed considerably for two neighboring wavelengths. In [8, 9, 11] it was shown that the local sources have the form of a bright region of small dimensions (nucleus) surrounded by a weak aureole, an extended source with dimensions up to 10'. The nucleus is apparently connected with the sunspots and the aureole with the flocculi surrounding the corresponding sunspot group. Such a structure can also be seen in examples of detection of solar radio emission carried out in the investigations [5, 7, 13, 14]. Some observations reveal the presence of fine structure in the composition of the bright part of the local sources. In nonpolarized radiation local sources were observed which consisted of two nuclei, corresponding to the leading and following parts of a bipolar group [2, 7, 11, 27]. Observations in polarized radiation reveal that a local source associated with a bipolar group is also bipolar [18-20]: it also follows from eclipse observations [18, 19] that a local source breaks up into several very small parts, reflecting the structure of the associated sunspot group.

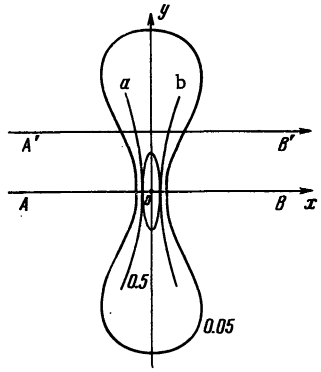

Fig. 1. Cross section of the directional diagram of the large Pulkovo radio telescope on the celestial sphere at levels 0.5 and 0.05 of maximum power. AB is the trajectory of the center of the solar disk through the directional diagram; A'B' is the trajectory of the local source. The curves a and b show the size of the directional diagram at the level 0.5 of maximum power in sections parallel to AB.

In this paper we investigate the dependence of the sizes of the bright regions of the local sources found by observations with high resolution on various optical characteristics of the associated sunspot groups.

The investigation is based on observations made at a wavelength of 4.5 cm by N. G. Peterova with the large Pulkovo radio telescope during 1962-1965. As is known [21, 22], the "beavertail" directional diagram of the large Pulkovo radio telescope has a rather complicated form (see Fig. 1), which changes depending on the angle of the point of observation. The antenna of the radio telescope was directed so that the center of the sun passed through the center of the diagram. The sources situated on the sun could intersect the directional diagram of the antenna at different distances from the central section AB of the diagram, and therefore for these the size of the diagram in these sections differed from that of the central size of the diagram. Thus, in order to take proper account of the influence of the width of the antenna diagram on the determination of the size of the local sources, it was necessary to know, for each local source, at which diagram width it was observed. The sizes of the corresponding diagram sections were determined by calculations from the known field distribution in the antenna aperture. It was found that the sizes of the sections of the antenna directional diagram for different source detections varied within the limits 1'.70 and 3'.30.

The effective size of the local sources was determined by the known formula (assuming a Gaussian form of the antenna diagram and a one-dimensional distribution of the radio brightness of the local sources)

$$B_0 = \sqrt{B^2 - \theta^2(h, y)},$$

where B_0 is the size of the source; B is the size of the source for detection at the half-power level; θ (h, y) is the size of the diagram section at the half-power level in the given section, which depends both on the height h of the sun above the horizon and on the distance y of the source from the diurnal circle of the center of the solar disk.

In Fig. 2 we give the histograms of the sizes of the local radio sources for bipolar and unipolar sunspot groups respectively. In the bipolar groups we included groups of the classes C, D, E, F, and G according to Waldmeier's classification and in the unipolar, groups of the classes A, J, and sometimes H (of simple structure). The mean size of a local radio source for bipolar groups was equal to 1'.4 and for unipolar groups $\overline{B}_0$ = 2'.2. Thus, in the mean, the sizes of local sources associated with unipolar groups are approximately 1.5 times greater than for those associated with bipolar groups. It is clear from the given histograms that the dispersion of the sizes of the radio sources is fairly large (σ = 0'.8). The sizes of the radio sources can attain 4' and at the same time there are also a number of cases when the sizes of the local sources are less than 0'.5 (the error in the determination of the size of a local source is of the order of 0'.5). For bipolar sunspot groups the number of radio sources with dimensions less than 0'.5 attains 15% of the total number of cases, whereas for unipolar sunspot groups only 5%. The unipolar sunspots as-

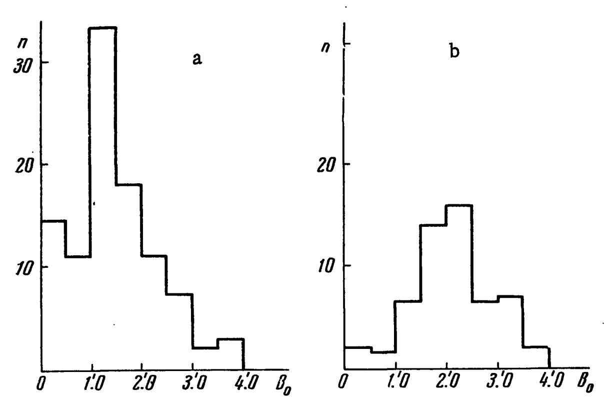

Fig. 2. Histograms of the sizes B_0 of local sources at a wavelength of 4.5 cm associated a) with bipolar sunspot groups, mean size $\overline{B}_0$ = 1'.4, σ = ±0'.8; b) with unipolar sunspot groups, mean size $\overline{B}_0$ = ±2'.2, σ = ±0'.8.

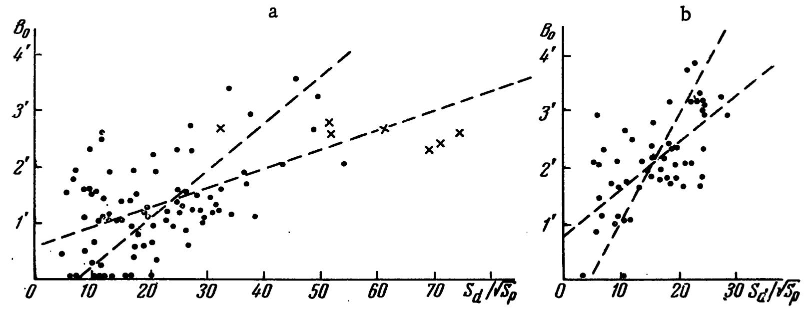

Fig. 3. Correlation diagrams of the relation of the sizes B_0 of the local sources at the wavelength 4.5 cm to the quantity $S_d/(S_p)^{1/2} = 2L\cos\theta$: a) for bipolar sunspot groups (r = 0.62 ± 0.06); b) for unipolar sunspot groups (r = 0.67 ± 0.08). The dashed lines give the regression equations.

sociated with the local sources investigated by us had areas which basically fell within the limits of 100 to 300 millionth parts of the solar hemisphere, whereas the bipolar sunspot groups had areas up to 1000 millionth parts of the solar hemisphere. It is interesting to compare the dimensions of local sources associated with both types of sunspot groups for the same values of the area. The mean size of local sources associated with unipolar spots having areas from 100 to 300 millionth parts of the solar hemisphere was equal to 2'.4. For bipolar sunspots with areas lying in the same interval, the mean size of the local sources was equal to 1'.1, which is 2.2 times less than the first.

In order to find the relation of the sizes of the local radio sources with the optical characteristics of the associated sunspot groups, we constructed the dependence of the sizes B_0 of the local sources on S_p (the area of the group in millionth parts of the solar hemisphere), on S_d (the apparent area of the group in millionth parts of the solar disk), and on the quantity $S_d/(S_p)^{1/2} = 2L\cos\theta$. Here θ is the angle seen from the center of the sun between the directions to the earth and to the sunspot group, and L is a certain effective size of the sunspot group, related to S_d and S_p by the equations

$$S_p = L^2,$$
$$S_d = 2L^2 \cos\theta.$$

The quantity $S_d/(S_p)^{1/2}$ to a certain degree takes account of the perspective contraction of the linear dimensions of the sunspot groups along the radius of the solar disk depending on the angle θ. In Table 1 we give the correlation coefficients of the sizes B_0 of the local sources with the quantities S_p, S_d, $S_d/(S_p)^{1/2}$, and also with H, the maximum intensity of the magnetic field in the sunspot group. The values of S_p, S_d, and H were taken from the bulletin "Solnechnye Dannye."

It is clear from this table that the correlation of B_0 with $S_d/(S_p)^{1/2}$ is the best compared with S_p and S_d both for bipolar sunspot groups and especially for unipolar sunspot groups. Evidently this is related to the dependence of the sizes of the sources on their position on the solar disk. In Fig. 3 we give the dependence of the sizes of the local sources on the quantity $S_d/(S_p)^{1/2}$ for bipolar and unipolar sunspot groups. Apart from our data, we have also marked in Fig. 3 (with crosses) data taken from [16]. These data refer to large sunspot groups (we had only a few such groups): evidently it conforms to the general dependence between B_0 and $S_d/(S_p)^{1/2}$, somewhat amending it. The correlation coefficients in Table 1 were evaluated taking account of these data.

From Table 1 it is clear that the correlation coefficients of the sizes of the local sources with the maximum magnetic field intensity in the sunspot groups are about the same for bipolar and unipolar fields and equal to 0.5. In Fig. 4 we give the correlation diagrams for bipolar and unipolar sunspot groups respectively. Generally speaking the unipolar spots have magnetic field intensities within the limits of 2000-3000 Oe. The mean size

TABLE 1

Correlation of B_0	Correlation coefficient r	
	bipolar groups	unipolar groups
S_p	0.495±0.075	0.275±0.123
S_d	0.513±0.070	0.570±0.090
$S_d/\sqrt{S_p}$	0.623±0.062	0.670±0.077
H	0.510±0.079	0.490±0.110

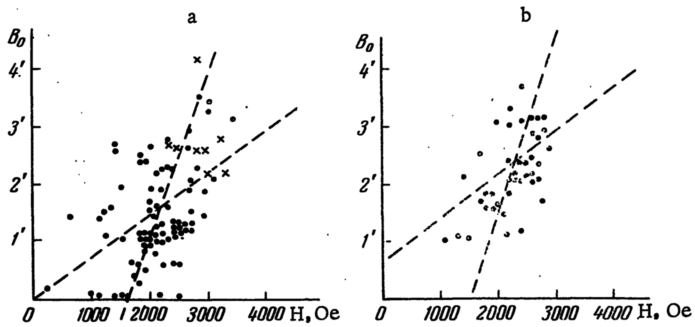

Fig. 4. Correlation diagrams of the relation of the sizes B_0 of the local sources at a wavelength of 4.5 cm to the maximum magnetic field intensity H in the sunspot group: a) for bipolar sunspot groups ($r = 0.51 \pm 0.08$); b) for unipolar sunspot groups ($r = 0.49 \pm 0.11$). The dashed lines give the regression equations.

of the associated local sources is about 2'.4. For bipolar groups with the same values of the magnetic field intensity the mean size of the local sources is approximately 1'.5, which is 1.6 times smaller than the first.

We also carried out a comparison of the sizes of the local sources with the sizes of the associated sunspot groups. The sizes of the sunspot groups were determined from prints from the photo-heliograms made at the mountain station at Kislovodsk. We only had at our disposal photographs of the sun from July 1964 onward, so in view of the lack of data we give here only preliminary results of this comparison. For bipolar sunspot groups the sizes of the local sources proved to be of the same order as the optical dimensions of the associated sunspot groups. This corresponds to the results found previously by various authors [2-15]. For unipolar sunspot groups the sizes of the local sources were approximately 4 to 6 times greater than the size of the associated sunspot group: here one should remember that the distance between the spots is included in the size of a bipolar group, whereas a unipolar group is mostly represented by only one spot.

The data obtained enabled one to estimate the dependence of the sizes of the local sources on their position on the sun. The perspective contraction of a plane source along the radius of the disk of the sun is expressed by the function $\cos\theta$. It is possible to obtain such a dependence for a uniform plane circle also when detecting a one-dimensional brightness distribution at an arbitrary orientation of the radius-vector of the source with respect to the direction of the diurnal motion of the sun. As can be shown (see Fig. 5), the size of a source with coordinates (φ, θ) along the axis OX is equal to the size of a source situated on the axis OX and having the coordinates $(0, \theta')$, whereby $\sin\theta' = \sin\theta\cos\varphi$, and the size of the source is equal to $L\cos\theta'$.

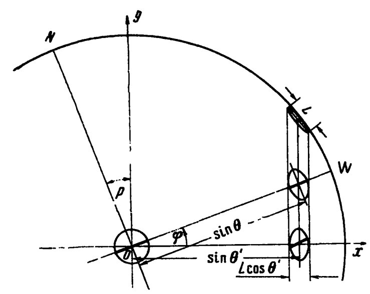

Fig. 5. Explanation of the determination of the size of the local sources. The large circle is the solar limb. The circle and the ellipses are images of a plane circular source with diameter L situated on the sun, projected onto the celestial sphere. It is shown that the size of the source along the axis OX (the direction of the diurnal motion of the sun) depends only on $\sin\theta' = \sin\theta\cos\varphi$ and is equal to $L\cos\theta'$. The heavy line segments are the diameters of the circles, parallel to the solar equator and equal to $L\cos l$.

In the case of a plane source significantly elongated in longitude (or, for example, a source consisting of two parts separated in longitude), the perspective contraction of dimensions is expressed by the function $\cos l$, where l is the longitude of the source from the central meridian. However, since observations of the sun with the large Pulkovo radio telescope are carried out at the meridian, and since the sunspots are situated in the equatorial zone of the sun, it follows that, taking the average over all possible angles P (the position angle of the axis of rotation of the sun, less than 27°) and all possible latitudes of the sunspots, one obtains a dependence analogous to $\cos\theta$.

For all local sources we determined the values of $\rho = R_\odot \sin\theta'$ and $\overline{\cos\theta'}$, and for the intervals of ρ equal to $0-0.3R_\odot$, $0.3-0.6R_\odot$, and $0.6-1.0R_\odot$ we evaluated the mean values of $\overline{B}_0$, $\overline{S}_0$, $\cos\theta'$, and ρ. In order that our data should be more or less uniform we restricted ourselves to sources for which the

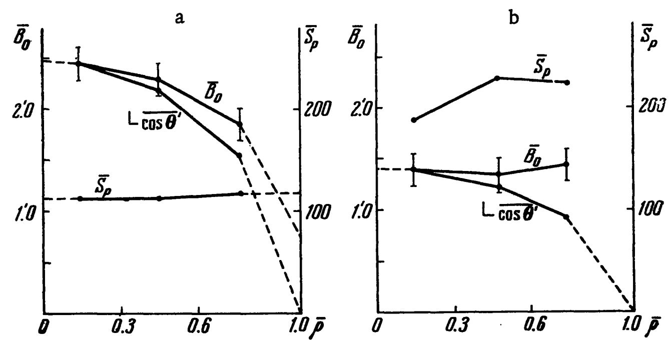

Fig. 6. Dependence of the radio sizes of the local source on their position on the solar disk ("directional" effect). $\bar{B}_0$ is the mean size of the local source for the intervals of ρ from 0 to $0.3R_\odot$, from 0.3 to $0.6R_\odot$, and from 0.6 to $1.0R_\odot$. L $\overline{\cos\theta'}$ is the computed mean size of a plane circular disk with diameter L for the same intervals of ρ. $\bar{S}_p$ is the mean area of the sunspot groups associated with the local sources for the same intervals of ρ. From a comparison of the behavior of $\bar{B}_0$ and L $\overline{\cos\theta'}$ it is clear that: a) the "directionality" of the unipolar local source sizes is close to but a little weaker than a cosine law (at ρ = 0 the size of the local source is equal to 2'.5, and at ρ = 1 the size of the local source is of the order 0'.5 to 1'.0); b) the size of a bipolar local source is practically independent of ρ (at ρ = 0 the size of the local source is equal to 1'.5, and at ρ = 1 the size of the local source is of the order 1'.0 to 1'.5).

areas of the unipolar and bipolar sunspot groups were $S_p < 200$ and $S_p < 400$ millionth parts of the solar hemisphere respectively, rejecting the rare cases during our observations of large areas. It turned out that for unipolar sunspot groups the value of the quantity $\bar{S}_p$ was approximately the same in all three intervals, and that for bipolar sunspot groups the value of $\bar{S}_p$ in the first interval was slightly lower than in the other two (see Fig. 6). The results of the calculation are given in Fig. 6a for unipolar sunspots and in Fig. 6b for bipolar sunspot groups. L has been chosen such that in the first interval $\bar{B}_0$ = L$\overline{\cos\theta'}$. It is clear from these figures that $\bar{B}_0$ does not change as fast as cos θ, but it is not clear how $\bar{B}_0$ varies for ρ close to unity (in the angular limits of θ from 50-90°). Formally, in order to elucidate this, one can make use of determinations of the sizes of local sources at ρ = 1. The separation of a limb source in the detection is difficult, since the local source is situated in the section where there is a rapid fall in brightness from the "quiet" sun; however, with accurate analysis it is still possible to separate a source reliably and to determine its size. We have two determinations of the sizes of local sources for unipolar sunspot groups situated on the limb, giving B_0 = 1'.0, and four determinations of the sizes of local sources for bipolar sunspot groups, giving B_0 within the limits 1'.0 and 1'.5. Taking account of these determinations of the sizes, we found that for local sources associated with unipolar sunspots the size $\bar{B}_0$ does depend on their distance from the center of the solar disk, but weaker than should be the case for plane sources. For local sources associated with bipolar sunspot groups there is practically no dependence of the size $\bar{B}_0$ on their position on the solar disk. Sources associated with sunspot groups can be both circular and also significantly elongated in longitude (these alternatives can be distinguished by two-dimensional observations of the sun), but in both cases they are apparently fairly extended in height.

It is clear from what we have said above that the local radio sources associated with bipolar and unipolar sunspot groups have significantly different characteristics. In Fig. 7 we give schematic representations of the possible form of radio sources based on the geometrical relationships found above.

If one assumes that the height of the layer responsible for the emission at the wavelength 4.5 cm of the "quiet" component of the solar radio emission is about 10 to 15 thousand km, and that the local sources are situated above this layer, then, taking account of the extension in height of the local sources found above, we find that the height of the radio emitting region must be about 30 thousand km for unipolar sunspot groups, and 40 thousand km for bipolar sunspot groups. Local sources situated at the edge of the solar disk and having dimensions of 2' to 3' have also been observed by a number of

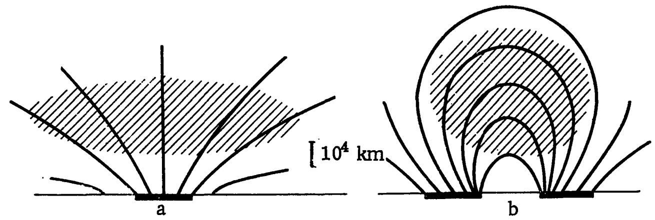

Fig. 7. Schematic representations of the possible form of local sources at a wavelength of 4.5 cm associated with a) unipolar and b) bipolar sunspot groups. The thick line segments represent the sunspots on the photosphere; the dashed areas represent the local sources situated above a level of $15 \cdot 10^3$ km over the surface of the photosphere; the curved lines represent the magnetic lines of force, which penetrate the local sources.

other authors, for example [2, 3]. Thus, on the basis of the sizes of the local sources situated at the solar limb, one can conclude that the heights of the radio emitting regions attain 40 thousand km. One may also mention that such values for the heights are in good agreement with the determinations of the heights of coronal condensations by optical methods, and also with certain height determinations from radio observations of local sources, for example, in [3-5].

In [23] a model of a local source is constructed, based on the assumption that regions with the temperature of the corona descend to just above the sunspots. Although this model explains some characteristics of local sources, it is in disagreement with the relatively large heights of local sources as determined from the observations. However, if one attributes an important role in the radio emission of local sources to coronal condensations, it may be possible to avoid this difficulty. The form and dimensions of a coronal condensation are evidently closely interconnected with the structure of the magnetic field in the corona above the sunspots. Thus, information about the form of local radio sources gives some indication of the form of the magnetic field above the sunspots. The increase in the sizes of local sources on going from bipolar to unipolar sunspot groups would appear to be related to the change in the structure of the magnetic field supporting the coronal condensation. Since the local source associated with a unipolar spot is considerably larger than the spot itself, it is necessary for the lines of force of the magnetic field which penetrate the local sources to diverge considerably to the sides of the sunspot (see Fig. 7a), covering a large area on the photosphere. This conclusion is qualitatively in agreement with the results of investigations made with the help of a magnetograph of the magnetic field structure of unipolar sunspots [24-26]. The lines of force of the magnetic field of a bipolar group must, apparently, form a more compact system in the corona (Fig. 7b).

We mentioned above that a fairly large number (15%) of local sources associated with bipolar sunspots had dimensions less than 0'.5. One might imagine that such small dimensions resulted from the predominant radiation of just one principal sunspot in the group. In order to check this supposition we give in Fig. 8 the dependence of the sizes of the local sources in bipolar groups on the ratio of the area of the principal sunspot S_{pr} to the area of the whole group S_p. From the diagram it is clear that any sort of prevalence of small sizes for groups with a dominating principal sunspot is missing. This makes the above supposition doubtful and shows that the small source size is connected with the complete structure of the group and not with a separate detail of it. However, for a final solution of the problem it is necessary to have a direct comparison of the coordinates of the small

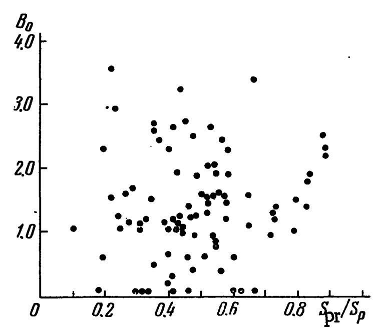

Fig. 8. Dependence of the sizes B_0 of the local sources on the ratio S_{pr}/S_p for bipolar groups. Sources having dimensions less than 1'.0 are associated with groups in which the area of the principal sunspot makes up 0.3 to 0.6 of the area of the whole group.

local sources with the detailed structure of the group.

Thus, from the statistical evaluation of the observations of the sizes of local radio sources at a wavelength of 4.5 cm, carried out during the years of minimum solar activity for sunspot groups of small or medium area, we obtain the following results.

1. The sizes of the local sources associated with bipolar sunspot groups are on the average 1.5 times less than the sizes of the local sources associated with unipolar sunspot groups. The mean size of a bipolar source is equal to 1'.4 and that of a unipolar source to 2'.2. The dispersion in size is in both cases rather large and is ±0'.8. One obtains a more pronounced difference of the sizes of the local sources if one compares local sources for groups of sunspots with the same areas. For areas S_p from 100 to 300 millionth parts of the solar hemisphere, the unipolar radio source is 2.2 times larger than the bipolar source.

2. The sizes of the local sources associated with bipolar groups are of the order of the dimensions of the groups themselves on the photosphere. Local sources associated with unipolar groups are 4 to 6 times larger than the spots themselves.

3. The sizes of the local sources are correlated with the areas of the associated groups of sunspots. The largest correlation coefficient is that for the sizes of the local sources with the quantity $S_d/(S_p)^{1/2} \sim \cos\theta$ and is equal to 0.6 to 0.7.

4. The correlation coefficient of the sizes of the local sources with the maximum value of the magnetic field intensity in the group is equal to ~0.5 for the unipolar and bipolar sunspot groups.

5. A comparison of the sizes of the local sources situated at the center of the solar disk with those at the limb shows that the extension of the local sources associated with unipolar groups along the surface of the sun is 2 to 3 times greater than that in height. Local sources associated with bipolar groups have a form which is nearly spherical.

The authors express their sincere gratitude to G. V. Gel'freikh for suggesting this investigation and for constant interest during its execution and also thank M. N. Gnevyshchev for photographs of the sun.

LITERATURE CITED

1. W. N. Christiansen and D. S. Mathewson, Paris Symposium on Radio Astronomy, Stanford Univ. Press (1959), p. 108.
2. A. E. Covington, Gladys A. Harvey, and H. W. Dodson, Astrophys. J., 135, 531 (1962).
3. G. Swarup, Sci. Report No. 13, Stanford Electronics Laboratories, Stanford Univ. Press (1961).
4. H. Tanaka and T. Kakinuma, Proc. Res. Inst. Atm., 7, 79 (1960).
5. V. N. Ikhsanova, Izv. Gl. Astron. Observ. v Pulkove, 21, 162, 29 (1958).
6. V. N. Ikhsanova, Izv. Gl. Astron. Observ. v Pulkov _, 164, 62 (1960).
7. V. N. Ikhsanova, Izv. Gl. Astron. Observ. v Pulkove, 23, 172, 31 (1964).
8. M. R. Kundu, Ann. Astrophys., 22, 1 (1959).
9. A. E. Salomonovich, Astron. Zh., 39, 260 (1962) [Sov. Astron. – AJ, 6, 202 (1962)].
10. A. G. Kislyakov and A. E. Salomonovich, Astron. Zh., 40, 229 (1963) [Sov. Astron. – AJ, 7, 177 (1963)].
11. U. V. Khangil'din, Astron. Zh., 41, 302 (1964) [Sov. Astron. – AJ, 8, 234 (1964)].
12. G. V. Kuznetsova and N. S. Soboleva, Solnechnye Dannye, No. 3, 70 (1964).
13. V. Ya. Gol'nev, V. N. Ikhsanova, N. G. Peterova, N. S. Soboleva, and N. F. Ryzhkov, Solnechnye Dannye, No. 9 (1964).
14. V. N. Borovik, A. N. Korzhavin, and N. G. Peterova, Solnechnye Dannye, No. 10, 67 (1965).
15. A. P. Molchanov, Izv. Gl. Astron. Observ. v Pulkove, 24, 177, 38 (1964).
16. G. Swarup, T. Kakinuma, A. E. Covington, et al., Astrophys. J., 137, 1251 (1963).
17. A. P. Molchanov, Solnechnye Dannye, No. 2, 53 (1962).
18. V. D. Korol'kov, N. S. Soboleva, and G. B. Gel'freikh, Izv. Gl. Astron. Observ. v Pulkove, 21, 164, 81 (1960).
19. D. V. Korol'kov and N. S. Soboleva, Astron. Zh., 38, 647 (1961) [Sov. Astron. – AJ, 5, 491 (1962)].
20. H. Tanaka and J. L. Steinberg, Ann. Astrophys., 27, 29 (1964).
21. S. É. Khaikin, N. L. Kaidanovskii, N. A. Esepkina, and O. N. Shivris, Izv. Gl. Astron. Observ. v Pulkove, 21, 164, 3 (1960).
22. N. A. Esepkina, N. L. Kaidanovskii, B. G. Kuznetsov, et al., Radiotekhnika i Élektronika, No. 12 (1961).
23. M. A. Lifshits, V. N. Obridko, and S. B. Pikel'ner, Astron. Zh., 43, 1135 (1966) [Sov. Astron. – AJ, 10, 909 (1967)].
24. V. Bumba, Izv. Krymsk. Astrofiz. Observ., 23, 212 (1960).
25. A. B. Severnyi, Izv. Krymsk. Astrofiz. Observ., 33, 34 (1965).

26. B. A. Ioshpa and V. N. Obridko, Solnechnye Dannye, No. 3, 54 (1965).

27. G. B. Gel'freikh, A. F. Dravskikh, et al. Astron. Zh. (in press).