GALACTIC RADIO HALO ACCORDING TO A STUDY OF THE RADIO BACKGROUND AT 38—404 MHz

Slobodan Ninković

Abstract. A high latitude study of the galactic radio background is done. A clear evidence for a weak radio halo is found. An attempt to estimate the strength of the magnetic field in the galactic halo is done. It is found that this quantity is most likely equal to 1.6 μG but it could be as great as 3 μG.

1. INTRODUCTION

The existence of the galactic radio halo was proposed by Shklovskij (1952). This discovery was generally accepted during fifties and even became a starting point for a further research (e. g. Baldwin, 1955; Spitzer, 1956; Mills, 1959).

During late sixties and early seventies the existence of the radio halo was seriously questioned (e. g. Baldwin, 1967; Burke, 1967; Berkhuijsen, 1971; Price, 1974). In some recent papers (e. g. Dogel' et al., 1975; Webster, 1975; Suh, 1976; Milogradov-Turin & Ninković, 1979) a clear evidence in favour of the radio halo on a basis of a thorough analysis of observational data was found.

In the present paper an analysis of an observational material is done. Results of this analysis favour the existence of a weak radio halo around our Galaxy.

2. APPROACH OF THE PRESENT PAPER

„Galactic“ temperatures at a given frequency are plotted against longitude on a fixed latitude and an analysis of these plots is done in the present paper. The „galactic“ temperatures are measured brightness temperatures corrected for the extragalactic contribution.

If the radio halo exists, a galactic temperature at a frequency ν in a direction (l, b) is given by

$$T_G(\nu, l, b) = T_D(\nu, l, b) + T_L(\nu, l, b) + T_H(\nu, l, b), \qquad (1)$$

where T_D is temperature of the radio disc, T_L contribution of the radio loops and T_H halo temperature. The nature of the galactic loops is not known and for this reason it is decided to separate their contribution.

It is assumed for the radio halo if it exists:

1) its shape is spherical or spheroidal;
2) ist volume-emissivity is isotropic.

The first assumption seems the most reasonable one and also it has been assumed by nearly all the scientists dealing on the same subject. The latter is assumed because the magnetic field in the galactic halo is most likely randomised (e. g. Okuda & Tanaka, 1968; Daniel & Stephens, 1970) and the density of cosmic electrons is isotropic. Hence it follows

$$T_H(\nu, l, b) = \varepsilon_H(\nu) L_H(l, b), \tag{2}$$

where ε_H is the volume-emissivity of the radio halo and L_H is the dimension of the radio halo along the line of sight. When a temperature is directly proportional to the dimension of the radiating region at a given frequency, we shall call it uniform.

The structure of the galactic radio disc is a complicated one (e. g. Webster, 1975) thus it may not be assumed for its temperature to be uniform. Here it is assumed that the disc contribution in each direction and at each frequency is composed of some „base disc" contribution whose radiation is uniform and a nonuniform disc component. The base disc is of course a fiction. Its temperature T_D in a direction (l, b) at a frequency ν is given by

$$T_D(\nu, l, b) = \varepsilon_D(\nu) L_D(l, b), \tag{3}$$

where ε_D is the emissivity of the base disc and L_D is the distance between the sun and the edge of the disc. The evidence for the radio halo should be searched on high latitudes thus only latitudes which satisfy a condition $|b| \geqslant 30°$ are used. In such a case we have for the temperature of the base disc

$$T_D(\nu, l, b) = \varepsilon_D(\nu)\, d_{1/2} \operatorname{cosec} |b|, \tag{4}$$

where $d_{1/2}$ is the half-thickness of the disc.

For a radio halo which satisfies the assumptions mentioned above, the dependence of its temperature on longitude on a fixed latitude is described by a curve of a characteristic shape (Fig. 1). This curve will be called below halo-curve. There is no significant difference between a halo-curve for a spherical shape from a halo--curve for a spheroidal shape of the radio halo. A halo-curve for a spheroidal shape is generally shallower.

If the radio halo exists the temperature of the uniform galactic component is a sum of the halo and base disc contributions. In such a case the dependence of the uniform component temperature on longitude on a fixed latitude is represented by a halo-curve (formulae (2) and (4)). In the case of no halo this dependence is represented by a straight line parallel to the l-axis (form. (4)).

If we separate somehow the uniform component we cannot expect to obtain a halo-curve or a straight line parallel to the longitude-axis because of observational and method errors. We can only examine is the obtained curve more similar to a halo-curve or a straight line parallel to the l-axis. Then we can try to find a halo--curve or a straight line which fit the observational points best by the method of trial and error. From the obtained curve it is possible to determine the parameters of the radio halo and base disc.

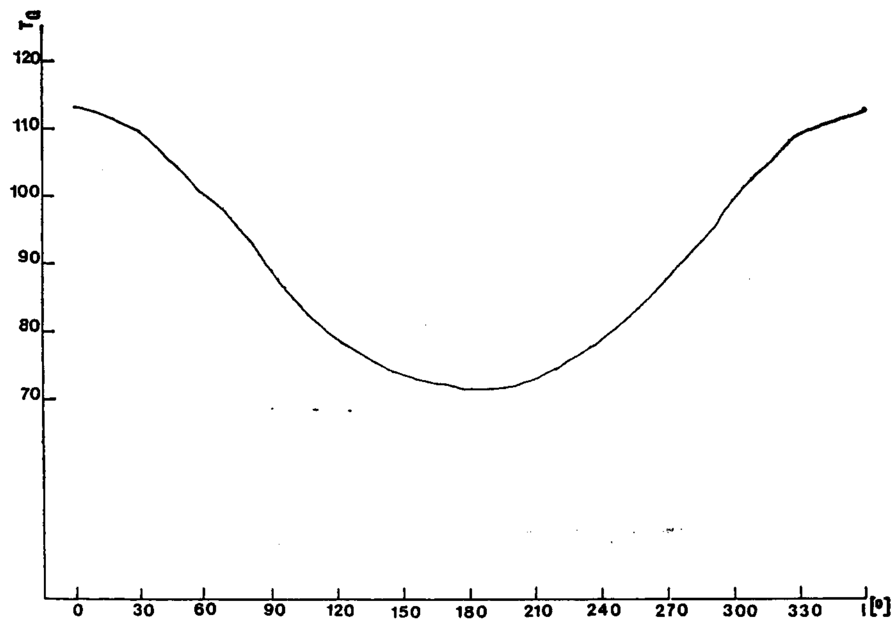

Fig. 1. A halo-curve

3. PROCEDURE AND RESULTS

The extragalactic contribution is removed following Bridle (1967) at all used frequencies. At 404 MHz the contribution of the relict black body radiation of 2.7 K is also taken into account.

Used data

TABLE I

author	year	ν (MHz)	beamwidth	observ.	note
Milogradov-Turin&Smith	1973	38	7°5	Jodrell Bank	corrected for ionospheric absorption
Yates	1968	85	3°5 × 3°8	Parkes	whole sky map
Landecker& Wielebinski	1970	150	3°5 × 3°8 2°2 × 2°2 5° × 1°25	Parkes	whole sky map resolution varies
Pauliny-Toth & Shakeshaft	1962	404	7°5	Mullard	

Contributions of the galactic loops are removed drawing a lower envelope of the observational curve at the places where the loops are present. The residual radiation should be disc+halo radiation. To separate the base disc component we decided to define the base disc in such a manner that at each frequency and in each direction the radiation of the radio disc is an algebraic sum of the base disc and the nonuniform disc component. That means that departures from uniformity in the disc radiation can take both signs. The latter is possible because the base disc is a fiction. Thus the base disc radiation may be considered as some mean disc radiation over longitude and latitude. Thus a smooth curve which represents the radiation of the uniform component is drawn as a lower envelope of the observational curve on some latitudes and as some mean curve with prominent minima below it on other latitudes (Fig. 2 and 3).

When the smooth curve corresponding to the uniform component radiation is drawn it is possible to determine the parameters of the radio halo and base disc. We have for a spherical halo

$$L_H(l, b) = R_\odot \cos l \cos b + \sqrt{R_\odot^2(\cos^2 l \cos^2 b - 1) + R_H^2}, \tag{5}$$

where $R_\odot$ is the distance of the sun from the galactic centre, in the present paper assumed to be 10 kpc and R_H is the radius of the radio halo. It is attempted with a spherical shape as a simpler one and also following the results of the paper by Milogradov-Turin and Ninković (1979). In such a case it is possible to determine the parameters of the uniform component from differences between two temperatures corresponding to different longitudes on a same latitude and at a same frequency. These two temperatures we read from the smooth curve corresponding to the uniform component. In such a manner values for ε_H, R_H and $\varepsilon_D d_1/2$ are obtained. With these values we can construct a model for the uniform component and examine its fit to the observations. When the best fit on some latitude is achieved we change the latitude.

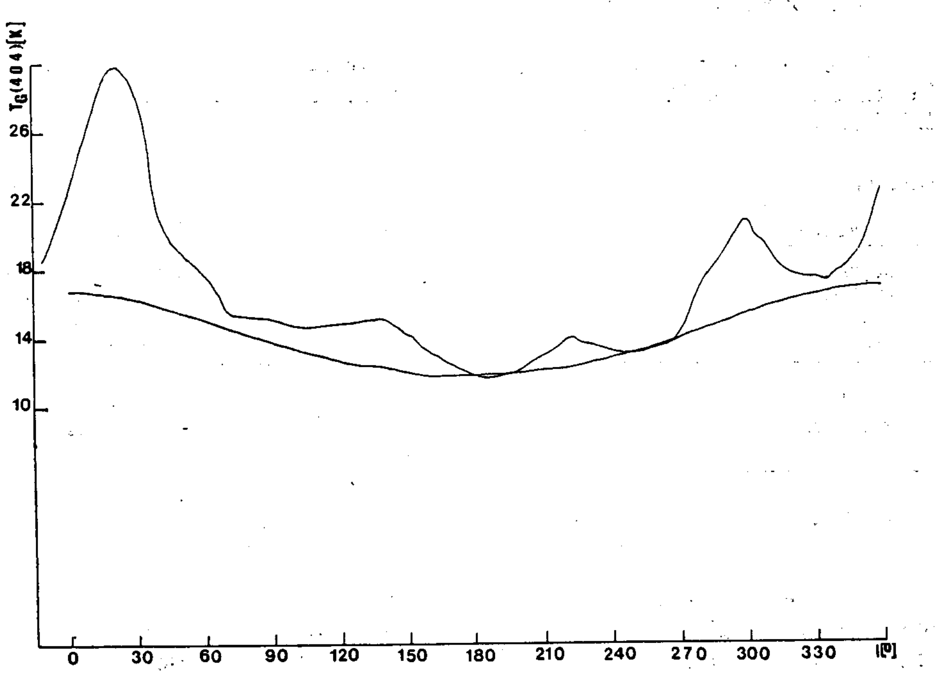

Fig. 2. The observational plot $T_G(l)$ at ν = 404 MHz, b = 62° presented together with the theoretical plot (smooth line), R_H = 16 kpc, ε_H = 0.55 K kpc^{-1}, ε_D = 10 K kpc^{-1}.

In Fig. 2 an observational curve on $b = 62°$ at 404 MHz is presented together with a model curve (best fit). The prominent maxima seen in the figure correspond to Loop I and Loop IV. In the feet of the loops the agreement between the model and observations is satisfactory. Nearly the same may be said about Fig. 3 where

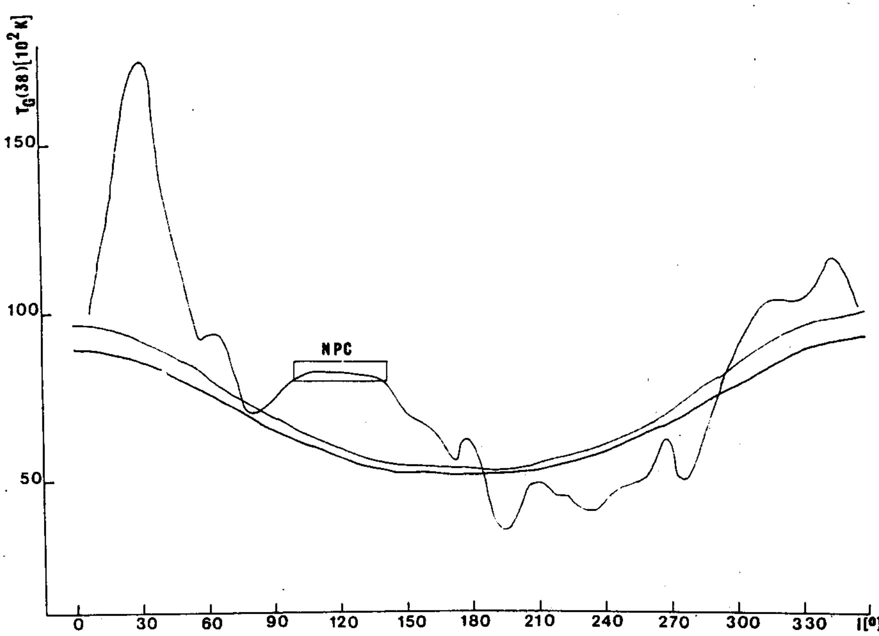

Fig. 3. The observational plot $T_G(l)$ at $\nu = 38$ MHz, $b = 38°$, presented together with theoretical plots: $R_H = 16$ kpc, $\varepsilon_H = 280$ K kpc^{-1}, $\varepsilon_D = 3400$ K kpc^{-1} (thin line) and $\varepsilon_H = 250$ K kpc^{-1}, other same (thick line). The theoretical plots are presented by smooth curves. Points within rectangle marked by NPC are dummy values, because within the circle $\delta = 70°$ there were no measurements at 38 MHz.

an observational curve at $\nu = 38$ MHz and on $b = 38°$ is presented together with two model curves. The minimum seen in the figure about $l \approx 200°$ corresponds to the cold region.

At 85 MHz and 150 MHz it is possible (see Table I) to examine both southern and northern latitudes.

Southern latitudes are not so favourable for an examination because the loops are present in a very wide range of longitudes. Therefore it is difficult to draw a smooth curve corresponding to the uniform galactic component. During the work we were very often obliged to draw at first a smooth curve already obtained on a latitude b and then to examine does it contradict to the observational points on a latitude — b. No contradiction has been found.

The model curve is above the observational curve inside the „cold" region (see Fig. 3). There is also a „cold" region nearly quite symmetrical relative to the galactic plane in the southern hemisphere. The halo temperatures calculated in the present paper are well below the observational temperatures of the „cold" regions. Thus these regions could be explained like regions of a less emissivity of the radio disc.

Results of the described analysis are presented in Table II.

Results of the paper TABLE II

ν (MHz)	ε_H (K kpc^{-1})	ε_D (K kpc^{-1})	$r_{H,D}$
38	280	3400	12.14
85	42	515	12.26
150	8	100	12.50
404	0.55	10	18.18

$R_{\odot}=10$ kpc $R_H=16$ kpc $d_{1/2}=0.6$ kpc

The value $R_H = 16$ kpc fits the results at all used frequencies. By the applied procedure it is possible to determine only the product $\varepsilon_D d_{1/2}$ but none of these quantities separately. It is assumed that $d_{1/2}$ is equal to 600 pc (Sofue, 1976) to find ε_D. The quantity signed as $r_{H,D}$ in Table II is a ratio of the emissivities of the base disc to the radio halo.

An attempt is done to determine the spectrum of the radio halo. Using the data from Table II it is possible to see that the spectral index of the radio halo is not far from 2.6. This value is obtained with a corrected value of 0.6 K kpc^{-1} for ε_H(404) (Milogradov-Turin & Ninković, 1979), the values from Table II for ε_H(38) and ε_H(150) and a value of 35 K kpc^{-1} for ε_H(85) which still satisfies the observations.

The all four surveys used in the present paper are not of the same resolution (Table I). Thus it was necessary to discuss the effect of the miscellaneous antennas. A discussion of this effect showed that in the regions of interest for the present analysis this effect was entirely negligible.

4. DISCUSSION

By the applied procedure it is difficult to form a final judgement between a spherical and a spheroidal shape for the radio halo. Therefore it must be emphasized that a spheroidal halo with an axis ratio as great as 1.5 fits the observational data equally well.

In nearly all the papers on the galactic radio halo a range of 10 kpc $\leqslant R_H \leqslant$ 20 kpc has been found. Some scientists (e. g. Burke, 1967; Webster, 1975) give advantage to a smaller halo. Soviet scientists, on the contrary, tend to favour a large halo (e. g. Ginzburg, 1967; Dogel' et al., 1975). The present paper gives advantage to a middle size halo, near an upper limit for it, i. e. R_H = 15—17 kpc. Baldwin's test (Baldwin, 1967) made the existence of the radio halo questionable on account of small ratios of temperature at 0° to the temperature at 180° on a same latitude and at a same frequency. For a spherical or a spheroidal halo of isotropic emissivity this ratio is less as the radius (semimajor axis) is greater. This is another argument in favour of a larger halo.

Some scientists are very cautious with the estimated values for the extragalactic radiation (e. g. Anand et al., 1968b). It must be emphasized that the estimated extragalactic temperatures do not affect the determined values for the radius and emissivity of the radio halo because the latter quantities are determined from the temperature differences for the different directions and the extragalactic temperature is an isotropic quantity. The estimation of the extragalactic temperature only affects the value for the product $\varepsilon_D d_{1/2}$ which is only a by-product of the present paper.

The emissivity of the base disc ε_D is affected by a value assumed for the half-thickness of the disc $d_{1/2}$. In the present paper it is assumed $d_{1/2} = 0.6$ kpc (Sofue, 1976). This value seems a realistic one according to the results of many authors (e. g. Pooley, 1969; Falgarone & Lequeux, 1973; Pawsey, 1965).

The assumption that the radius of the radio halo is equal to the distance of the sun from the galactic centre (Burke, 1967) is without any observational or theoretical base. This assumption and an unfavourable choice of latitudes may be the main reasons for his doubt towards the radio halo. Price's (1974) conclusion about the radio halo is not based on a thorough analysis of the high latitude radiation but on a statement that the sun is inside the local spiral arm which he deduced by an investigation of the radiation in the galactic plane. The latter fact does not really contradict to the existence of the radio halo (see also Anand et al., 1968b).

Berkhuijsen's (1971) arguments against the radio halo seem rather strong. But after a thorough examination it is seen that a weak halo like that found in the present paper could be reconciled with her results. A weak radio halo found in the present paper can be masked by the errors of her method.

The agreement of the results of the present paper with the results of the papers by Webster (1975) and Suh (1976) is satisfactory.

5. ASTROPHYSICAL IMPLICATIONS

It is clear according to the results up to now, that the radio halo is less emissive than the disc. If both regions radiate by the synchrotron mechanism than either the magnetic field is weaker in the halo, or the density of relavistic electrons is smaller in the halo, or both. By a comparison of the emissivities of the disc and the radio halo it can be infered something about the physical conditions there (magnetic field, cosmic electrons). The comparison is related with a difficulty how to compare these regions of the Galaxy when they are so different.

In the halo the magnetic field is randomised and therefore we assumed that the emissivity of the radio halo is isotropic. On the contrary the structure of the disc is very complicated, so is the magnetic field and we cannot ascribe a unique value to the strength of the magnetic field in the disc. On account of it the induction of the base disc is useful. We have an idealized object which gives expression of the real qualities of the radio disc and its radiation is approximately the mean radiation of the radio disc. Therefore we shall choose some value for the magnetic field of the base disc and we shall compare the emissivity of the base disc with the emissivity of the halo.

It is assumed that the density of cosmic ray electrons is the same in the disc and in the halo. It is also assumed that the strength of the magnetic field in the disc is 8.5 μ G (Daniel & Stephens, 1970; Webster, 1975).

Thus we can write

$$H_D^{\beta_D - 1} \Big/ H_H^{\beta_H - 1} = r_{H,D}, \tag{6}$$

where H_D is the strength of the magnetic field in the disc, H_H the strength of the magnetic field in the halo and β_D and β_H are the spectral indices of the disc and halo, respectively. As we can see from Table II $r_{H, D}$ is equal to 12.5 at 150 MHz. At this frequency the spectral index of the radio disc is approximately 2.56 and the corresponding value for the radio halo is 2.6 (see section 3). With the assumed value for the strength of the magnetic field in the disc we obtain by use of the formula (6) a value of 1.7 μ G for the strength of the magnetic field in the halo.

The strength of the magnetic field in the halo is determined in the present paper in another fashion. This time the obtained value is independent on the magnetic field in the disc, but it depends on the assumed value for K (energy spectrum of cosmic electrons $KE^{-\gamma}$). Again we assume that the density of cosmic electrons is same in the disc and halo. By use of the formula given in Okuda and Tanaka (1968) with an assumed value of 8×10^{-3} CGS units for K (Okuda & Tanaka, 1968) and 2.6 for the spectral index of the radio halo we obtain a value of 1.5 μ G for the magnetic field strength in the halo. We use the same frequency — 404 MHz as Okuda and Tanaka, but with the value of 0.6 K kpc^{-1} which is two times less than a value assumed by Okuda and Tanaka.

It is assumed below a value of 1.6 μ G for the magnetic field strength in the halo.

The value obtained for the magnetic field in the halo gives a value of 10^{-13} erg cm^{-3} for the energy density of the magnetic field which is ten times less compared to the cosmic ray energy density (Parker, 1968). Thus the magnetic field in the halo is too weak for the confinement of cosmic rays. We need a field of at least 5 μ G for the confinement. Thus it is very unlikely that the halo is the confinement region of cosmic rays. In this case the magnetic field in the halo can be stronger than 1.6 μ G because the last value is obtained on the basis of the confinement hypothesis for the halo.

An attempt is done in the present paper to see how much stronger the field can be. If we assume that the energy densities of cosmic rays and of the magnetic field are equal in the halo, with an additional condition that the value of the product $KH_H^{\beta_H - 1}$ is equal to the value which satisfies the equality of the halo emissivity at 404 MHz to 0.6 K kpc^{-1}, we obtain a value of 3 μ G for the magnetic field and then the density of cosmic electrons is approximately three times less in the halo than in the disc.

6. CONCLUSIONS

A study of the galactic background radio emission at a frequency range of 38—404 MHz is done in the present paper. A clear evidence for existence of a weak radio halo is found.

The halo radius (semimajor axis) appears to be equal to 15—17 kpc. The axis ratio may be as great as 1.5. The emissivity of the halo appears to be equal to 200—300 K kpc^{-1} at 38 MHz, 30—45 K kpc^{-1} at 85 MHz, 7—10 K kpc^{-1} at 150 MHz and 0.55—0.65 K kpc^{-1} at 404 MHz.

The spectrum of the radio halo can be roughly approximated by a power law with a value of — 2.6 for the exponent.

On the basis of the cosmic rays confinement hypothesis is found a value of 1.6 μ G for the halo magnetic field. Most likely the density of cosmic rays is not equal in the halo and disc. Thus the strength of the magnetic field in the halo can be greater. If the energy densities of the magnetic field and cosmic rays are equal in the halo, the strength of the magnetic field can achieve a value of 3 μ G.

ACKNOWLEDGEMENT

The author thanks Mrs Milogradov-Turin and Dr Salter for many valuable advices.

REFERENCES

Anand, K. C., Daniel, R. R. & Stephens, S. A. 1968a, *Nature*, **217**, 25.
Anand, K. C., Daniel, R. R. & Stephens, S. A. 1968b, *Proc. Ind. Acad. Sci.*, **68**, 219.
Baldwin, J. E. 1955, *Mon. Not. R. astr. Soc.*, **115**, 690.
Baldwin, J. E. 1967, IAU Symposium No. 31, ed. H. van Woerden, Academic Press, London, p. 337.
Berkhuijsen, E. M. 1971, *Astr. Astrophys.*, **14**, 359.
Bridle, A. H. 1967, *Mon. Not. R. astr. Soc.*, **136**, 219.
Burke, B. F. 1967, IAU Symposium No. 31, ed. H. van Woerden, Academic Press, London, p. 361.
Daniel, R. R. & Stephens, S. A. 1970, *Space Sci. Rev.*, **10**, 599.
Dogel', V. A., Bulanov, S. V. & Syrovatskij, S. I. 1975, Proceedings of Cosmic Rays Conference, Munich.
Falgarone, E. & Lequeux, J. 1973, *Astr. Astrophys.*, **25**, 253.
Ginzburg, V. L. 1967, IAU Symposium No. 31, ed. H. van Woerden, Academic Press, London, p. 365.
Hornby, J. M. 1966, *Mon. Not. R. astr. Soc.*, **133**, 214.
Ilovaisky, S. A. & Lequeux, J. 1972, *Astr. Astrophys.*, **20**, 347.
Landecker, T. L. & Wielebinski, R. 1970, *Australian J. Phys. Astrophys., Suppl.* **16**, 1.
Milogradov-Turin, J. & Ninković, S. 1979, *Publikacije Astronomske opservatorije u Beogradu*, **26**, 133.
Milogradov-Turin, J. & Smith, F. G. 1973, *Mon. Not. R. astr. Soc.*, **161**, 269.
Mills, B. Y. 1959, Paris Symposium on radio Astronomy, ed. R. N. Bracewell, Stanford University Press, p. 431.
Okuda, H. & Tanaka, Y. 1968, *Bull. Astr. Inst. The Netherlands*, **20**, 129.
Parker, E. N. 1968, in Nebulae and Interstellar Matter, ed. B. Middlehurst & L. Aller, volume VII of Stars and Stellar Systems, University of Chicago press, Chicago & London, ch. 14, p. 707.
Pauliny-Toth, I. I. K. & Shakeshaft, J. R. 1962, *Mon. Not. R. astr. Soc.*, **124**, 61.
Pawsey, J. L. 1965, in Galactic Structure, ed. A. Blaauw and M. Schmidt, volume V of Stars and Stellar Systems, University of Chicago Press, Chicago & London, ch. 11, p. 219.
Pooley, G. G. 1969, *Mon. Not. R. astr. Soc.*, **144**, 143.
Pooley, G. G. & Ryle, M. 1968, *Mon. Not. R. astr. Soc.*, **139**, 515.
Price, R. M. 1974, *Astr. Astrophys.*, **33**, 33.
Sofue, Y. 1976, *Astr. Astrophys.*, **48**, 1.
Spitzer, L. 1956, *Astrophys. J.*, **124**, 70.
Suh, P. K. 1972, *Astr. Astrophys.*, **20**, 375.
Suh, P. K. 1974, *Astr. Astrophys.*, **35**, 339.
Suh, P. K. 1976, *Astr. Astrophys.*, **51**, 417.
Shklovskij, I. S. 1952, *Astron. Zh.*, **29**, 418.
Webster, A. S. 1975, *Mon. Not. R. astr. Soc.*, **171**, 243.
Yates, K. W. 1968, *Australian J. Phys.*, **21**, 167.