NASA TECHNICAL MEMORANDUM NASA TM-76209

NEW METHOD FOR DETERMINING THE DISTANCES TO CERTAIN EXTRAGALACTIC RADIO SOURCES

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(NASA-TM-76209) NEW METHOD FOR DETERMINING THE DISTANCES TO CERTAIN EXTRAGALACTIC RADIO SOURCES (National Aeronautics and Space Administration) 15 p HC A02/MF A01 CSCL 03B

N80-28280

Unclas

G3/90 28033

Translation of "Novyy metod operdeleniya rasstoyaniy do nekotorykh vnegalakticheskikh radioistochnikov", Academy of Sciences USSR, Institute of Space Research, Moscow, Report PR-325, 1977, pp.1-15

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 JUNE 1980

STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-76209		

4. Title and Subtitle	5. Report Date
NEW METHOD FOR DETERMINING THE DISTANCES TO CERTAIN EXTRAGALACTIC RADIO SOURCES	JUNE 1980
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Yu A. Kovalev	
	10. Work Unit No.
9. Performing Organization Name and Address	11. Contract or Grant No.
SCITRAN Box 5456 Santa Barbara, CA 93108	NASW-3198
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Translation
National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

Translation of "Novyy metod operdeleniya rasstoyaniy do nekotorykh vnegalakticheskikh radioistochnikov", pp.1-15, Academy of Sciences USSR, Institute of Space Research, Moscow, Report Pr-325, 1977

16. Abstract

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17. Key Words (Selected by Author(s))	18. Distribution Statement
	Unclassified - Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22.
Unclassified	Unclassified	15	

NASA-HQ

The structure evolution of variable radio sources is examined in the "Hedgehog" [1] model, proposed as an explanation for the variation in the stream of quasars and radio galaxies [2-4]. It is shown that the time evolution of the angular separation θ of two components (nucleus and cloud of electrons dissipating along the force lines of the radio magnetic field of this nucleus) is described by the ellipse equation, whose ratio of axes $\tilde{R}_1$ yields the distance $R/c=\tilde{R}_1$ to the source in light time units (c—velocity of light). In addition, if θ' is velocity, θ'' is the acceleration at any point of the ellipse, then

$$R/c = \tilde{R}_2 = [\theta/\theta'' - (\theta')^2]^{-1/2}.$$

If the typical maximum angular separation θ_m and the duration τ of the radio flux flare are known, then an evaluation can be made of the distance from below:

$$R/c = \tilde{R}_3 \geq \tau/(k\theta_m);$$

where k=1 for the scattering components and k=2 for the converging components. The distances R/c were estimated by using observations and $\tilde{R}_3$ for the sources 3C 84, 3C 120, 3C 273, 3C 345, 4C 39.25, as well as $\tilde{R}_1$, $\tilde{R}_2$ for the object VRO 42.22.01. All the model estimates do not contradict the distances obtained from the red shifts in their cosmological interpretation. The conditions

$$\tilde{R}_1 = const, \; \tilde{R}_2 = const, \; \tilde{R}_1 = \tilde{R}_2$$

are criteria for the applicability of the model to the studied object.

NEW METHOD OF DISTANCE DETERMINATION TO CERTAIN EXTRAGALACTIC RADIO SOURCES

By. Yu. A. Kovalev

1. Introduction /5*

Currently almost all the methods for obtaining distances R to extragalactic sources are associated with optic observations. Therefore, distances have mainly been defined only to those radio sources that have been successfully identified with optic objects. It will be shown that the model "Hedgehog" (Yĕzhik), suggested by N. S. Kardashev [1] as a phenomenological model of quasars to explain the variability of their radio emissions permits a determination of R directly from radio astronomical observations, and provides distinct criteria for the applicability of the model, regardless of the observed law of evolution for the source radiation flow.**

*Numbers in margin indicate pagination in original foreign text.

**Synchrotron radiation in certain particular cases and the bases for the model have been analyzed in publications [2, 3]. The structural evolution and spectrum of the source synchrotron radiation have generally been examined in [4]. In contrast, this work, within the framework of the set task, and without being limited to the radiation synchrotron mechanism has obtained a law for the structural evolution of a two-component source with regard for the possible anisotropy of the initial electron distribution according to velocities. Here primary attention was focused on a discussion of those consequences from the obtained law that are important for determining R.

2. Description of Model /6

Assume that from the moment in time t'_0 in the radio magnetic field of a certain nucleus at angle ϑ to the observer a cloud of ultrarelativistic electrons is scattered with isotropic distribution at t'_0 according to the pitch-angles in limits from ψ_{0min} to ψ_{0max}. At the moment t'_0 the cloud is located a distance z_0 from the center of the nucleus with radius z_n; here $z_n / z_0 \ll 1$, while the maximum linear size of the cloud is much smaller than z_0. It is assumed that the energy density of the magnetic field is much greater than the energy density of the electrons, and when the cloud electrons enter the nuclear area they are completely absorbed. Any mechanism of energy loss is permitted that does not result in scattering of the ultrarelativistic electron radiation in directions that differ from the direction of its instantaneous velocity, and which permits a change in the energy electron during the examined time to be ignored. For the radio magnetic field with intensity H and pitch-angles of the electrons ψ, on the condition that the adiabatic invariant of the dependence on z is preserved:

$$H = H_0 \, (z_0/z)^2 \quad , \qquad (1)$$

$$\sin\psi = (z_0/z)\cdot \sin\psi_0 \quad , \qquad (2)$$

where the amounts with zero indices correspond to their values at t'_0.

The time $\Delta t' = t' - t'_0$, necessary for the electron to traverse the distance from z_0 to z (here its pitch-angle ψ' changes from ψ_0 to ψ), can be found by integrating the ratio $dt' = dz / c\cdot\cos\psi'$. After integration we will have:

$$\Delta t' \cdot c/z_0 = (z/z_0)\cdot\cos\psi - \cos\psi_0 . \qquad (3)$$

Assuming further $\psi = \vartheta = const$, and passing to the time interval of the ob- /7
server $\Delta t = t - t_0$, by using the delay factor [5]
$\partial t/\partial t' = \left[1-(\cos\vartheta/c)(\partial z/\partial t')\right]$, and selecting $t_0=0$, we obtain the law for movement of the cloud electron system, "visible" to the observer in the final form:

$$z_n = z\cdot\sin\vartheta = z_0\sqrt{1-\left(\frac{t\cdot c}{z_0}-\cos\vartheta\right)^2} = z_0\sqrt{1-x^2}. \quad (4)$$

This equation was attained on the assumption that the angle ϑ is random, $z_n/z_0 \ll 1$, $\psi_{omin} \leq \vartheta$, $\psi_{omax} = \pi$, and describes the evolution of the separation of two components (nucleus and cloud) with $0 \leq t \leq (1+\cos\vartheta)\cdot z_0/c$. It is easy to be convinced, that during this time all the pitch-angles of the electrons evolve to values that are smaller than the observation angle ϑ, while the cloud that continues to exist will be extinguished for the observer.

One can show that the values of the parameters z_n/z_0, ψ_{omin} and ψ_{omax}, that differ from those indicated, result in the same equation (4); but it is correct in a more limited time interval t, defined from

$$x = \begin{cases} \cos(2\cdot\vartheta - \psi_0) & \text{with } \begin{cases} \pi/2 + \vartheta < \psi_0 \leq \pi, \\ \vartheta \leq \pi/2, \end{cases} \\ -\cos\psi_0 & \text{with any other correlations between } \psi_0 \text{ and } \vartheta, \end{cases} \quad (5)$$

where ψ_0 with a rise in t traverses the subsequent values from ψ_{omin} to ψ^*_{omax}, whereby

$$\psi^*_{omax} = \min \begin{cases} \psi_{omax} \\ \pi - \mathrm{Azc}\,\sin\,(z_n/z_0) \end{cases} \quad (6)$$

In particular, with $z_n < z_o$, $\psi_{omin} < \vartheta < \pi/2$ and $\psi_{omax} = \pi$, "dispersion" of the nucleus and the cloud is observed while $0 < t < t_m = z_o \cdot \cos\vartheta/c$, such that z_k rises from $z_o \times \sin\vartheta$ to z_o. With $t_m < t < t_{on}$ they converge from $z_k = z_o$ to $z_k = z_n$, after this the cloud is extinguished due to the absorption of electrons by the /8 nucleus, and the moment of extinction t_{otc} is defined from (5) by the value $\psi^*_{omax} = \pi - \mathrm{Azc} \sin(z_n/z_o)$. . If in this example $\psi^*_{omax} = \pi/2$, then only dispersion of the cloud and the nucleus up to moment $t_{otc} = t_m$ will be observed (such a case is possible, in particular, with explosion and scattering of the cloud from the surface of the nucleus; then $z_n = z_o$ and the movement occurs on the background of the nucleus).

3. Methods of Obtaining Distance

Several methods for obtaining distance to the source follow from (4). If the world is Euclidean, then $z_k = R \times \Theta$, where Θ is the observed angular distance to the nucleus in the cloud.

1. Taking this into consideration one is easily convinced that (4) in the coordinate system (t, Θ) is an equation of the ellipse:

$$\frac{\Theta^2}{(z_o/R)^2} + \frac{(t - z_o \cdot \cos\vartheta/c)^2}{(z_o/c)^2} = 1 . \qquad (7)$$

It is apparent from here that the ratio $\tilde{R}_1$ of the semiaxes t_m and Θ_m of the ellipse provides the unknown distance R: $R/c = \tilde{R}_1 = t_m/\Theta_m$, where t_m and Θ_m are directly measurable amounts.

2. Equation (4) together with the first Θ' and the second Θ'' derivatives of Θ for t form a system of three equations with three unknowns (z_o, x and R); the left

part of the equations can be obtained from the observations:

$$\begin{cases} \Theta = z_0\sqrt{1-x^2}\,/R , & (8) \\ \Theta' = -c\cdot x\cdot z_0/(\Theta\cdot R^2) , & (9) \\ \Theta'' = -\left[c^2+(R\cdot\Theta')^2\right]/(\Theta\cdot R^2) . & (10) \end{cases}$$

The signs (9) and (10) refer to the direction from the nucleus. It follows from here that the visible movement of the cloud in relation to the nucleus can occur both with sublight, as well as with superlight velocities, as well as with acceleration, and deceleration. From (10) we have:

$$R/c = \tilde{R}_2 \equiv \left[\Theta|\Theta''| - (\Theta')^2\right]^{-1/2} \qquad (11)$$

3. If in the initial distribution for pitch-angles there are electrons with /9
$\psi_0=\pi/2$, then one can also obtain from (4):

$$R/c = \tilde{R}_3 \equiv t_{otc}/\left[(x_{otc}+\cos\vartheta)\cdot\Theta_m\right] , \qquad (12)$$

where t_{otc} is the time from the moment of cloud formation to cutting off of radiation (extinction of the cloud), while the parameter corresponding to it x_{otc} depending on $\psi^*_{\alpha max}$ adopts values from $x_{otc}=0$ with $\psi^*_{\alpha max}=\pi/2$ to $x_{otc}=1$ with $\psi^*_{\alpha max}=\pi$.

We will compare the potentialities of these methods. The value ϑ for $\tilde{R}_3$ can be estimated from an analysis of the relative amplitude of flow time variants F_ν [4] with synchrotron radiation of the cloud. Measurement of t_{otc} is complicated, linked both to the fact that the time up to cutting-off can be greater than the observed lifetime of the cloud (due to the possibility of $\psi_{\alpha min}>\vartheta$), as well as with the fact that it can be considerably greater than the extremely nonstationary phase of radiation, the flare; during this time new clouds can merge that complicate the source structure. To determine R from $\tilde{R}_3$ it is also necessary to have data on the initial distribution function of electrons according to pitch-angles. These difficulties force us to use (12) only as an estimate from below, after replacing t_{otc} for duration of a separate radio flux flare and $(x_{otc}+\cos\vartheta)$ by the coefficient k=1, if "dispersion" or "stopping" of the nucleus and cloud is observed, and k=2 if they converge. Then:

$$\tilde{R}_3\,(\mathrm{Mps}) \gtrsim 60\cdot\tau\,(\mathrm{years})/\left[\kappa\cdot\Theta_m\,(\mathrm{ms})\right], \qquad (13)$$

where $\tilde{R}_3$ is measured in megaparsecs, τ--in years, Θ_m--in angular milliseconds*. One should stress that the dispersion dynamics is such that the angles close to Θ_m are reached comparatively quickly (see (8)-(10)), therefore the main inaccuracy in /10 estimating $\tilde{R}_3$ from (13) is associated with the roughness of replacing t_{otc} by τ.

For $\tilde{R}_1$, in contrast to $\tilde{R}_3$, no knowledge of the distribution according to pitch-angles ϑ and t_{otc} is required (it is "replaced" by extrapolation of the sections of curve (7) up to Θ=0), but numerous measurements of Θ are needed during the entire lifetime of the cloud in order to obtain a reliable curve (7). This method is advantageous because each successive measurement Θ at the moment of time $t\lesssim t_m$ approaches Θ_m and t_m, and the accuracy of the estimate obtained from here

$$\tilde{R}_1 \gtrsim t/\Theta \qquad (14)$$

increases with time, in contrast to the estimate from (13) and it approaches the "true" obtained from the ratio of the ellipse axes.

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*In contrast to the frequently employed estimate $R/c \simeq \tau/\Theta_d$, where Θ_d is the angular diameter of the nonstationary component (in the given case the cloud), (13) requires the angular distance Θ_m between the cloud and the nucleus.

Finally, $\tilde{R}_2$ makes it possible to determine R from an "instantaneous" measurement of a small ellipse section (7), i.e., this method is free to a considerable degree from difficulties of the previous methods (simultaneously from (8)-(10) we obtain z_0 and x, and consequently also ν_*^c if t is known). However, when the accuracy of measuring Θ is insufficient, and the ambiguity of making the curve through the obtained points is great, large errors are possible in determining R.

Thus, if the primary information for estimating R from $\tilde{R}_3$ is contained in the results of systematic measurements for the evolution of the spectral flow F_ν of the source radio emission (besides these data it is sufficient to have Θ_m from observations of previous clouds or to make occasional measurements of Θ at moments in time defined from the dependence of F_ν on t), then in the determination and estimates of R from $\tilde{R}_1$ and $\tilde{R}_2$, on the contrary, the "center of gravity" of the necessary information lies precisely in the systematic interferometric observations.

4. Comparison with Observations /11

Sources 3C 84, 3C 120, 3C 273, 3C 345, 4C 39.25 and VRO 42.22.01 with clearly pronounced long-periodic variability satisfy the condition for dispersion of components with $t \sim 1$ year and $\Theta_m \sim 1$ ms [6-8]. By substituting these values and k=1 in (13) we obtain a rough estimate of the distance to all of these sources: $\tilde{R}_3 > 60$ Mps, which agrees with the values for the distances obtained from red shifts. Of course, such agreement of the estimate cannot serve as proof for the correctness of the examined model for these objects, but at least it is in its favor.

For VRO 42.22.01 one can attempt to correlate the observed evolution Θ [9, 7] with equations (7) and (11). The selection of this source is governed by the fact that its analysis is complicated to a lesser degree by the ambiguous interpretation of interferometric observations with the help of two-component models, than for many other nonstationary objects.* In the limits of measurement accuracy one can approximate the evolution of Θ by curves 1 and 2 in Figure 1. If curve 1 is correct, then the existence of a point with minimal angle $\Theta \approx 0.5$ ms can be interpreted by converging the nucleus and the preceding component. The possibility of such an explanation has been noted previously, however it was considered unreal [11]. By substituting the results of the graphic differentiation of Θ in (11) we obtain the distance $\tilde{R}_2$. For all the experimental points of curves 1 and 2 the values $\tilde{R}_2$ lie in the limits of 20 Mps about $\tilde{R}_2$=100 Mps, which is 3-4 times smaller than the distance from the red shift z=0.07 [12]. /12

Curves 3-6 were obtained by "adjustment" of the observation results of the initial ellipse sections (7) that correspond to the distances 100 Mps, 300 Mps, and 1000 Mps respectively. For comparison with ellipses 3 and 5 curves 4, 7 and 8 were given that characterize their sensitivity to the change in the semiaxes t_m and Θ_m of the ellipse with fixed $\tilde{R}_1 \cong t_m/\Theta_m$. One can also formally adjust to the measured points the ellipses that correspond to the distance $\tilde{R}_1$>1000 Mps, but the "price" is a sharp increase in t_m and Θ_m. Thus, from all the ellipses with $\tilde{R}_1$=3000 Mps it is necessary to select the ellipse with $t_m \approx 1500$ years, $\Theta_m \approx 30$ ms, in order for its initial section to pass through the experimental points. However, $R_1 \gtrsim 3000$ Mps

*In [10] the two-component nature of 3C 345 is stressed, and the linear law of increase in Θ is obtained as the most probable; this contradicts the discussed model, since acceleration (10) always differs from zero. This result can be correlated with the model only after assuming that during the time of observation a measurement was made of a relatively small section of very "elongated" (as a consequence of the great distance of the source $\tilde{R}_1$) ellipse, which can be approximated by a straight line. Further observations and analysis must help to draw the final conclusion.

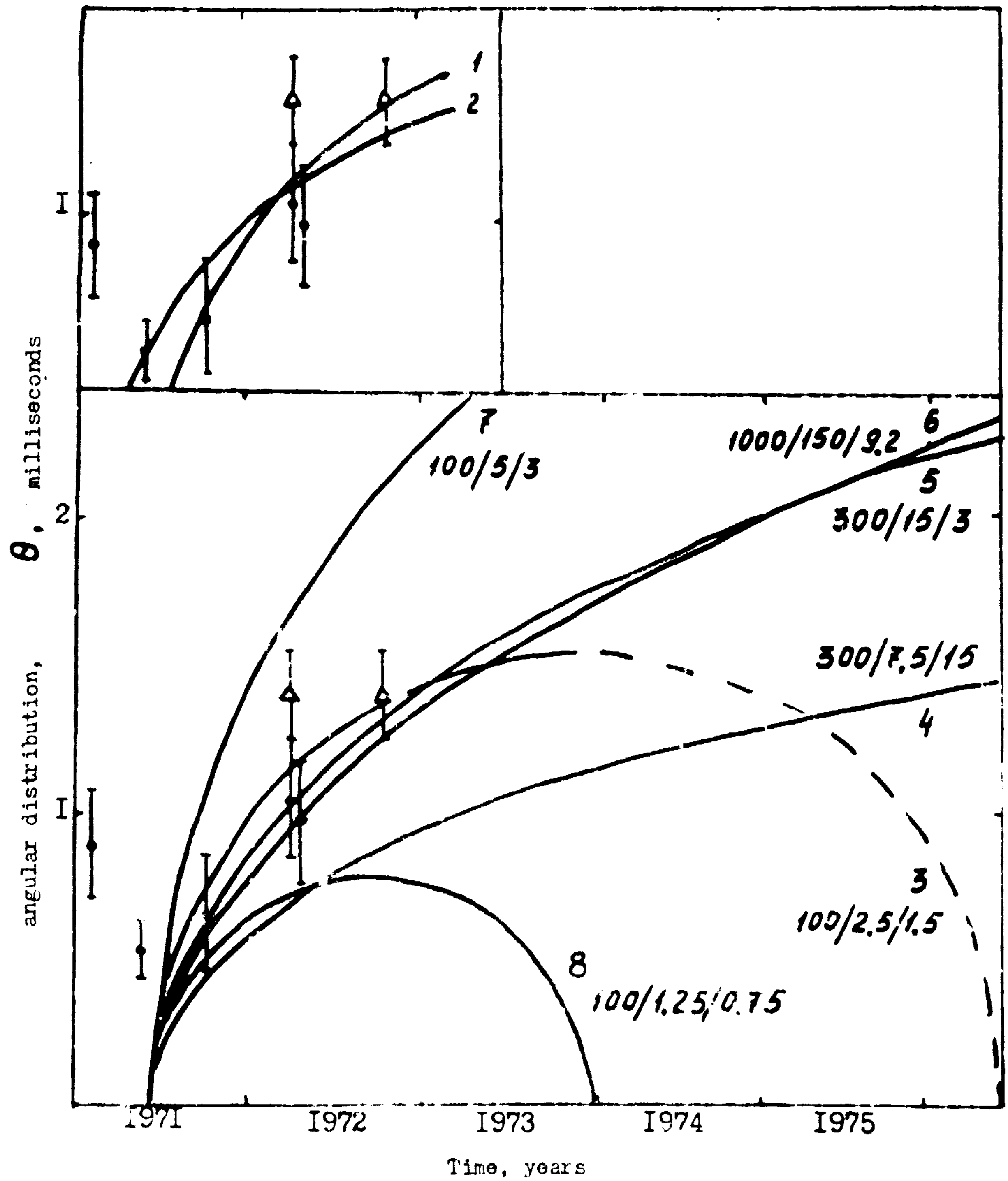

Figure 1. Time Evolution of Angular Separation Θ in Two-Component Model VRO 42.22.01 Experimental points correspond to the data of publications: • —[9], Δ —[7]. Curves 1 and 2 illustrate the determination of the distance from $\tilde{R}_2$, while 3-8—from $\tilde{R}_1$. R_1 (Mps)/t_m(years)/Θ_m(ang. ms) are shown at each of the curves 3-8. The dotted section of curve 3, that characterizes conversion of the components, occurs in the case of $\psi^*_{omax} > \pi/2$ (see text).

(i.e., $t_m \gtrsim 1000$ years), apparently is not very likely if only because $t_m \lesssim 100 \times \tau$ for $\vartheta > 5°$ [4] (with synchrotron mechanism of radiation), while the measured duration of the radio flares is $\tau \lesssim 1$ year [6].

It is apparent from Figure 1 that if the source evolution occurs in accordance with curve 3, then one must observe extinction of one of the components either with $\Theta_m \approx 1.5$ ms at the end of 1973-beginning of 1974 (in the case $\psi^*_{cmax} = \pi/2$--see above), or during conversion of the components from $\Theta_m \approx 1.5$ ms to a certain angle $\Theta < \Theta_m$ during 1974-middle of 1976 (if $\psi^*_{cmax} > \pi/2$) in accordance with the dotted section of curve 3. One should note that the absence of noticeable extinction and possible constancy in the measured Θ during this entire period within the framework of the developed model could occur only in the case of measurements that refer to different clouds that have reached Θ_m at a different time during the examined period. Analysis of the observations does not exclude the fact that in the beginning of 1972 /13
a new component was formed [13]. Its consideration can be useful in the future. If the source evolution is described by curves 6 and 5, then one can expect an increase in the angular separation.

Thus, on the condition of a correct interpretation of employed data as measurements referring to the evolution of a single cloud, from curves 3-5 for the distance up to VRO 42.22.01 we obtain an evaluation $100 \lesssim \check{R}_1$ (Mps) $\lesssim 1000$.

5. Conclusion

Since the distance to the studied source during the observations can be considered unchanged, then the conditions $\check{R}_1$=const, $\check{R}_2$=const, $\check{R}_1 = \check{R}_2$ can serve as criteria for the applicability of the model to the source. In reality, the strict equality in these criteria should be replaced by approximate.

If it is found that the examined model is close to actuality for a fairly broad class of objects, then regular interferometric observation together with the data on the time variations in the radio emission flow of the sources will possibly permit us to obtain from certain nonstationary objects a "radio scale" of extragalactic distances, regardless of the results of optic identification.

I am grateful to M. S. Kardashev for discussions and useful advice, as well as Z. S. Kovaleva for assistance in this work.

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