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RADIO GALAXIES

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1. GENERAL INFORMATION ON DISCRETE SOURCES OF COSMIC RADIO EMISSION

ONE of the greatest astronomical discoveries of the twentieth century was made in 1946. The British radio astronomers Hey, Parsons, and Phillips, in an investigation of the brightness distribution of cosmic 4.7-m radio emission over the sky, observed in the Cygnus constellation an unknown extraterrestrial source, the radiation flux from which varied randomly with time.[1] They concluded that they had observed a discrete source of cosmic radio emission with relatively small angular dimensions. The interference method was not yet widely used in the then recently developed radio astronomy, and the accuracy with which the coordinates of the newly discovered source were determined was very low. According to [1], the approximate coordinates of the source were $\alpha = 20^h$ and $\delta = +43°$. From the fact that the relative fluctuations of the radio emission flux from the source in the Cygnus constellation reached 15%, it was concluded in [1], with allowance for the dimensions of the principal lobe of the antenna employed, that the angular dimensions of the source did not exceed 2°.

In June 1947 Bolton and Stanley in Australia, using a so-called "marine" radio interferometer, determined the coordinates of the Cygnus source with greater accuracy, finding them to be $\alpha = 19^h58^m47^s \pm 10^s$ and $\delta = +41°41' \pm 7'$. In addition, they drew from their measurements the important conclusion that the angular dimensions of the source were in any case less than 8′.

In the next year, 1948, Ryle and Smith in England, using a two-antenna interferometer on 8.5 Mcs with a 500 m base, obtained more precise coordinates for the Cygnus source and, in addition, measured the spectral density of the radio emission flux from this source, finding it to be 1.4×10^{-22} W/m² cps.[3] We note that this is approximately the flux received on this frequency from the sun during the very low period of its activity. In the course of these investigations Ryle and Smith observed in the Cassiopeia constellation another more powerful discrete source of extraterrestrial radio emission.

During the same 1948, Bolton observed with a marine radio interferometer four additional, much weaker sources located in the constellations Taurus, Virgo, Hercules, and Centaurus.[4] The fluxes from these sources turned out to be approximately one order of magnitude lower than from the source in Cygnus. In 1949 Bolton, Stanley, and Slee[4] determined more accurate coordinates for all these sources. They found that the source in Taurus coincides, within the limits of observational errors, with the famous Crab nebula —the remnant of the 1054 supernova. This was the first time in the history of radio astronomy that a source of cosmic radio emission was identified with an optical object, an event that led to important consequences in radioastronomy, astrophysics, and cosmic-ray physics.

The sources in the Virgo and Centaurus constellations have coordinates $\alpha = 12^h28^m \pm 37^s$, $\delta = 12°41' \pm 10'$ and $\alpha = 13^h22^m20^s \pm 10^s$, $\delta = 42°37' \pm 8'$, respectively. These sources were identified with the unusual "peculiar" (as they are referred to in astronomy) galaxies NGC4486 and NGC5128. These rather bright galaxies (with visible stellar magnitudes 9.6^m and 7.6^m respectively) have attracted the attention of astronomers for a long time, owing to their unusual morphological singularities (see below). Once first observations had been made of the most powerful sources, the number of newly discovered relatively weak objects started to increase rapidly. In 1951 Stanley and Slee published in Australia the first catalogue of 18 discrete sources, of which 13 were new.[5] An important feature of this work was that the observations were made at different frequencies in the meter band. These were the first observations of discrete-source spectra. Although a comparison of results made at different frequencies is a rather difficult task (because of the relatively low accuracy of the absolute measurements in radio astronomy), the Australian observers have disclosed the characteristic feature of the spectra of the cosmic radio-emission sources, namely that the spectral density of the flux F_ν decreases with increasing frequency in accordance with a certain power law

$$F_\nu \propto \nu^{-\alpha}. \quad (1)$$

The quantity α has been named the "spectral index." In addition, real differences were observed in [5] between spectra of the different discrete sources of cosmic radio emission. Thus, for example, the source in Taurus, identified with the Crab nebula, has a very "flat" spectrum, i.e., with a small value of α (according to later researches, this source has $\alpha = 0.25$).

An investigation of the spectra of discrete sources of cosmic radio emission is at present one of the most important problems in radio astronomy. We shall return to this question many times.

In 1952 Mills [6] published an important catalogue of 77 discrete sources which he observed with an original type of radio interferometer on a wavelength near 3 m. The main purpose of this work was not so much to obtain the coordinates and radiation fluxes with maximum accuracy, as to analyze statistically their distribution over the sky and to classify them. Mills succeeded in demonstrating for the first time that at least three sources (located in the constellations Parus, Centaurus, and near the galactic center) have measurable angular dimensions amounting to about 30′. Mills subdivided the discrete sources observed by him into two classes. Sources of class I are characterized by relatively large radio-emission fluxes and are all in the Milky Way. Further investigations have shown that their angular dimensions are as a rule relatively large (they reach 1–3°). Sources of class II show no tendency to concentrate near the galactic equator. They include practically all weak sources. The peculiarity in the distribution of class-I sources over the sky signifies that these objects are located within our own stellar system, the galaxy. It was demonstrated subsequently that they are identified with a special type of filamentary nebula formed after a supernova burst. A typical example of such a nebula is the remarkable system of fine filamentary nebulas in the Cygnus constellation. At present there are about 15 known class I sources which are "remnants" of supernova bursts that took place at one time in our galaxy. These include, in particular, the most powerful source in Cassiopeia and the Crab nebula. An investigation of these astonishing objects is of very great significance for physics and astronomy. Closely associated with these investigations are such major problems in modern nature study as the origin of cosmic rays and the origin of the elements. In the present review, however, we shall barely touch upon class-I sources of radio emission.

As already mentioned, class-II sources display no tendency to cluster about the galactic equator. This means that they are either located relatively close to the solar system (for example, at distances of the same order as the nearest stars or less) or, to the contrary, are very far away beyond the limits of the solar system, in the metagalaxy. Attempts were made in 1952 to determine the annual parallactic shift of the most powerful sources. The results proved to be negative,[7] thus leading to the conclusion that the discrete sources are far beyond the limits of the solar system. A similar conclusion follows also from the fact that the sources are not seen to have any motion of their own in the celestial sphere.[7] On the other hand, as long ago as 1949 two rather powerful sources, belonging to class II according to Mills, could be identified with peculiar galaxies (see above). Later on several such identifications were made, and these will be discussed later. It follows therefore that they are all grounds for assuming that class-II sources are very remote objects located in the metagalaxy. The totality of the facts available to modern radio astronomy confirms this important conclusion. The special type of galaxies with which the class-II radio emission sources are connected, are now universally called "radio galaxies." The present review is devoted to an exposition and an analysis of all the data on radio galaxies presently available in radio astronomy and radio physics.

It is interesting to note that the tendency of various objects to concentrate near the galactic plane has different manifestations in optical astronomy and in radio astronomy. In optical astronomy the relatively bright stars (for example those seen with the unaided eye) exhibit no tendency to cluster about the Milky Way, whereas the sufficiently weak stars are highly concentrated near the galactic equator. In the case of sources of cosmic radio emission we observe exactly the opposite. The reason is that the distances from us to the bright stars are as a rule smaller than the thickness of the galactic stellar "disc," about 500 parsec. The galactic sources, which are remnants of supernova explosions, include relatively few galactic objects, which are thousands of parsecs away from us.

The Mills classification of sources was of great importance to the development of radio astronomy, since it disclosed the essential singularity of the nature of discrete sources.

As a result of the research made by the Australian and British radio astronomers, the number of known sources had reached hundreds by 1952, the overwhelming majority not being identifiable with objects known in optical astronomy. This raised the urgent problem of devising a system of designations for both the old and the newly discovered sources. Several such systems were proposed. One still in use for the most powerful sources consists of writing the name of the constellation in which the source is located, followed by a hyphen and a capital Latin letter. The letter A denotes the most powerful source in the given constellation, B the next powerful one, etc. Consequently, historically the first discovered powerful source in the Cygnus constellation is designated Cygnus-A, the Crab nebula is denoted Taurus-A, etc. In another widely used system the Cygnus-A source is designated 19N4A, that in Taurus-A 05N2A, etc. This code denotes in the case of Cygnus-A that the direct ascension of the source lies between 19^h and 20^h, the declination is positive ("N") and lies in the interval between 40° and 50°, and that this is the most powerful source in the designated interval of α and δ. Now, however, when more powerful methods are increasing the number of observed sources very rapidly, a serial number in an appropriate catalogue is usually employed. For example, 3C-295 denotes the 295-th source in the third Cambridge catalogue.

Altogether, the Cambridge group of radio astronomers has published three catalogues of discrete sources. All the observations were carried out by an interference procedure at meter wavelengths. Thus, for example, the second Cambridge catalogue, published in 1955, contains the values of the coordinates and fluxes for 1935 sources registered in the declination range between $+83°$ and $-38°$.[8] The interferometer used for these observations had four elements with centers arranged in a 580 by 52 m rectangle. The observations wavelength was 3.7 m. Each element was a parabolic cylinder about 100 m long and 12 m high. The radiating dipoles were located along the focal line of the mirrors. The use of two bases permitted a rough estimate of the angular dimensions of the sources.

The third Cambridge catalogue, published in 1959, contains only 500 sources.[9] The observations were made with the same interferometer, but at half the wavelength and were much more accurate than in the second Cambridge catalogue. At the present time the third Cambridge catalogue is regarded as one of the best and is widely used in radio astronomy.

Mills proposed an exceedingly clever cruciform antenna system, which possesses two seemingly mutually exclusive properties—very high directivity (and consequently very high resolving power) and relatively low effective reception area (Fig. 1). The resolving power of his antenna was about 50′, the observations being made on 3.5 m. In 1957 Mills and Slee published a catalogue covering the sky region $8^h > \alpha > 0^h$ and $0.10° > \delta > -10°$. A total of 383 sources were observed in this region.[10] This catalogue covers everything down to flux values 2×10^{-25} W/m^2 cps. At the same time, a considerable number of weaker sources were also observed, with flux $\sim (1-2) \times 10^{-26}$ W/m^2 cps. The agreement between the coordinates of the relatively weak sources of the Mills catalogue and the second Cambridge catalogue is not satisfactory, principally because of large errors in the latter. However, the Sydney observations are in good agreement with the third Cambridge catalogue.

Along with interference procedures the principal lobes of large antennas have been extensively used and are still being used for observation of discrete cosmic radio sources. Important results were obtained with the giant 76-meter reflector of the Jodrell Bank Radio Astronomical Observatory near Manchester (Fig. 2). Very valuable radio astronomical observations were made with the large Pulkovo antenna, which has an original design and operates on a relatively short wavelength and with a very narrow directivity pattern in one coordinate. Notice should also be taken of the interesting observations of 9.6 cm sources, recently made by A. D. Kuz'min and others on the 22 m precision reflector of the Physics Institute of the Academy of Sciences near Serpukhov.[11] Figures 3 and 4 show photographs of Pulkovo and Serpukhov antennas.

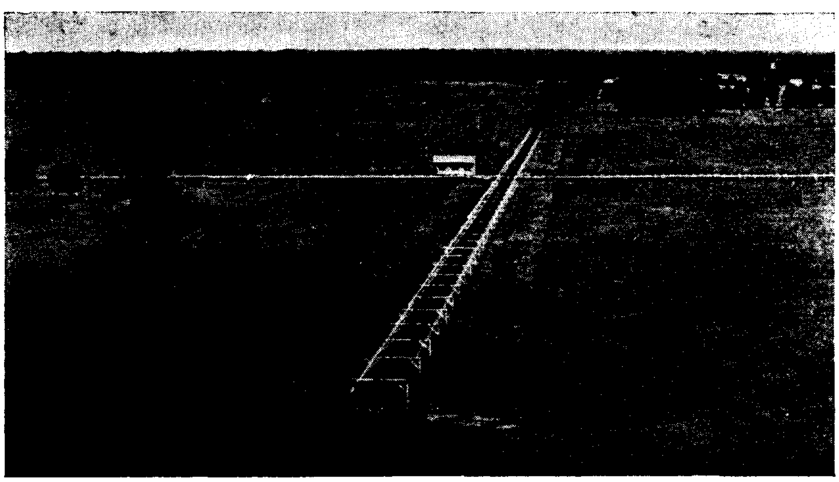

FIG. 1. The Mills cruciform antenna.

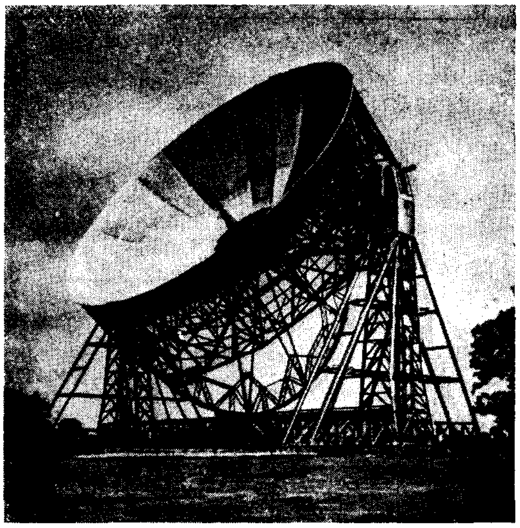

FIG. 2. The 76-meter radio telescope of the Jodrell Bank Observatory.

FIG. 4. 22-meter precision radio telescope of the P. N. Lebedev Physics Institute, U.S.S.R. Academy of Sciences.

Recent observations of a large number of discrete sources were made with the 27 m reflector of the National Radio Astronomical Observatory in Greenbank. Of particular significance are the discrete-source observations carried out under Bolton's guidance with two 30 m reflectors at the California Institute of Technology. These observations were made on 31 cm, with the two large reflectors used in most cases as elements of an interferometer (see Fig. 5).

Mention should also be made of Westerhout's observations in Holland, made on the 25-meter reflector of the Dwingeloo radio astronomical observatory, and Metzger's highly accurate observations on the Bonn (West Germany) 25-meter reflector. Both the Dutch and West-German observations were made in the 21 cm band. The results of all these researches will be discussed below.

Starting with 1959, a large radio interferometer has been in operation in Cambridge on 1.7 m. It consists of two large elements, one stationary and one mobile. The stationary element is a parabolic cylinder more than 20 m high and more than 450 m long. The mobile element is a reflector of the same shape

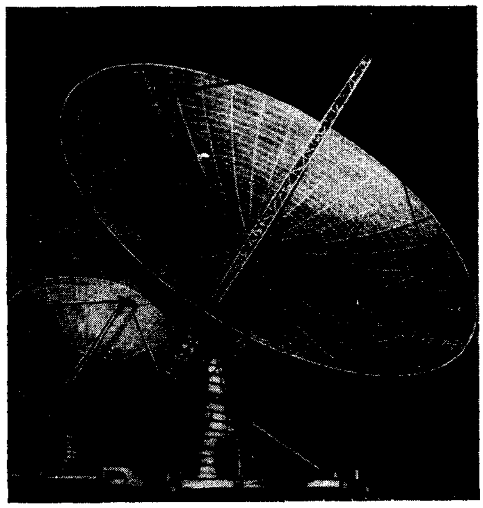

FIG. 5. 30-meter reflectors of the radio interferometer at the California Institute of Technology.

and height, but shorter, only 60 m. The mirrors are perpendicular to each other. The base is approximately 1 kilometer.[12] Figure 6 shows the arrangement of the elements of this giant interferometer.

The capabilities of the new Cambridge interfer-

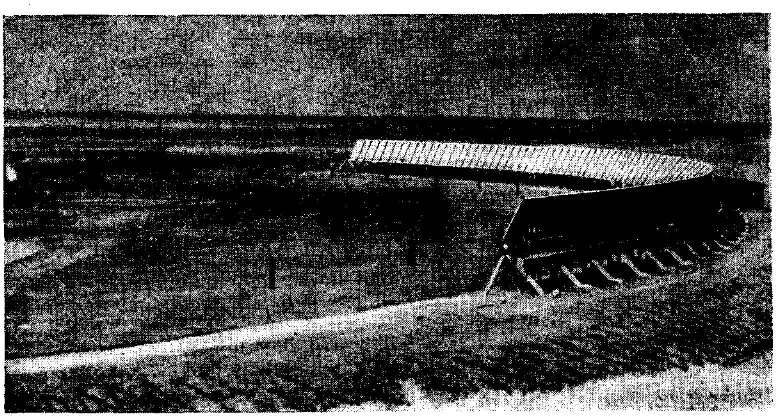

FIG. 3. Pulkovo "fan" antenna.

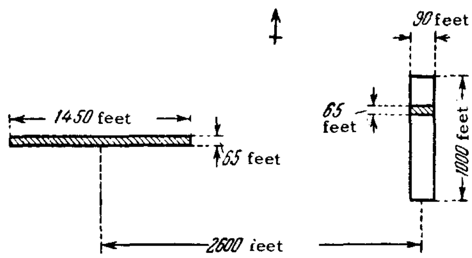

FIG. 6. Arrangement of the elements of the large Cambridge radio interferometer.

ometer are very great, for it can discern about 10,000 sources in the sky. Some important results obtained with this instrument will be discussed later.

Summarizing, we can state that progress in radio astronomical research techniques has made it possible by now to observe reliably in the entire sky about 10,000 sources, most of them radio galaxies. The appreciable increase in the sensitivity of the receivers used on the centimeter and decimeter bands, resulting from the introduction of quantum amplifiers into radio-astronomical research practice, uncovers exceptional possibilities for the nearest future. Recognizing further that many giant telescopes with reflector diameters of several hundred meters are now planned or partially completed in various countries, we can imagine, albeit with difficulty, the number of radio galaxies that will be investigated within 5 or 10 years.

By now the range of observed fluxes from galaxies, ranging from the strongest to the weakest, comprises a factor of about 10,000 or nearly ten stellar magnitudes. A considerable expansion of this range is to be expected in the nearest future.

The circumstance that made it possible to discover the first source of radio emission in the Cygnus constellation was the variability of its flux (see above). By 1950, however, it became already clear that this variability did not describe the nature of the source at all. Observations have shown the source flux fluctuations in the meter band to have periods on the order of seconds and minutes. British researchers have shown, however, that all correlation between the recorded fluxes vanishes if the radio receivers are spaced > 4 km apart.[13-15] Similar results were obtained in Australia. This means that the flux fluctuation is not connected with the nature of the source and is of atmospheric, more accurately ionospheric origin. This is quite analogous to the well known flickering of stars. Special investigations have disclosed diurnal and seasonal variations in these fluctuations, which are well correlated with the variations of the characteristics of the E and F layers of the ionosphere. This "radio flicker" of the sources is due to inhomogeneities in the electron concentration in the ionosphere, which have dimensions of approximately several kilometers and move randomly at approximate speeds of several hundred meters per second. At present investigation of the source flux variations is a useful method of analyzing inhomogeneities in the ionosphere.

Fluxes from cosmic radio sources are constant, within the limits of errors (which reach approximately 5% even for the strongest sources). This result is quite interesting if it is recalled that the optical radiation flux from many stars is variable. In the radio range, the radiation from the star closest to us, the sun, is most variable. The fact that the cosmic radio emission from discrete sources has constant flux means that these objects are hardly likely to be stars. Indeed, further investigations have shown that class-I sources are special galactic nebulas, remnants of supernova bursts, while class-II sources are peculiar extragalactic nebulas.

It is curious, all the same, that the direct cause leading to the discovery of the cosmic radio sources was a fact that had nothing in common with the nature of the sources themselves. This, however, is not an isolated example in the history of science.

Of decisive importance in the understanding of the nature of discrete cosmic radio sources was the measurement of their angular dimensions. The first research in this direction dates back to 1950, when practically nothing was known about the nature of these sources. At that time the question of the possible star-like nature of the sources (the so-called "radio stars") was extensively discussed in the scientific literature. Were this hypothesis to be correct, the angular dimensions of the sources should be negligibly small. Even in the few cases when these sources were identified with peculiar galactic and extragalactic nebulas, the question of the dimensions of the region responsible for the powerful radio emission remained open. Thus, in the case of the Crab nebula, an unanswered question was whether the radiation came from the nebula itself or from a weak 16th-magnitude star located inside this nebula, which by assumption was a supernova in the past. In the first case the angular dimensions of the Taurus-A source should reach about 5′, and in the second case they should be unmeasurably small.

The problem of measuring the angular dimensions of cosmic radio sources is related to the low resolving power of the radio telescopes. Radio astronomy has made outstanding progress towards overcoming this difficulty. Interferometers with very large bases have been built. In addition, observations in the principal lobe of large antennas can also be made in many cases.

The attempts made prior to 1950 to observe finite angular dimensions in the most powerful discrete sources unavoidably yielded negative results. These measurements made it possible only to estimate for the angular dimensions an upper limit, which depended on the resolving power of the interferometers employed.

This problem was solved in 1951, practically simultaneously, by research groups in Manchester,[16] Sydney,[18] and Cambridge.[17] In Manchester, Jennison and Das Gupta used interferometers with different base lengths and different azimuths on 120 Mcs, and the correlation method.[16] The base lengths ranged from 300 m to 4 km. It was shown first that the Cygnus-A source had finite angular dimensions. It was further observed that the source was quite asymmetrical. With varying base azimuth, the source angular dimensions ranged from 2′ 10″ to 35″. Later on the "radio shape" of Cygnus-A was subjected to considerable refinement, as will be described in the next section.

Interference measurements on 100 Mcs were made in Sydney by Mills.[18] The base length ranged from 290 m to 10 km and was varied by displacing one of the elements of a two-antenna interferometer. The amplitude of the interference pattern ("depth of modulation") from the four most powerful sources (Cygnus-A, Taurus-A, Virgo-A, and Centaurus-A) continuously decreased with increasing base length (Table I).

Table I

Source	Depth of modulation			
	Base 0.29 km	Base 1.02 km	Base 5.35 km	Base 10.01 km
Cygnus-A	1	1	0.3	0.05
Taurus-A	1	0.55	0.1	0.1
Virgo-A	1	0.40	0.1	0.1
Centaurus-A	1	0.30	0.1	0.1

It is quite evident from Table I that the angular dimensions of the Cygnus-A source are much smaller than those of the other sources measured by Mills. For example, at a base length of 1.02 km the depth of the modulation in Taurus-A, Virgo-A, and Centaurus-A decreases considerably. This means that at this base length the angular dimensions of these sources are of the same order as the lobes of the interference diagram, i.e., λ/d, where $d \sim 1$ km. Since $\lambda = 3$ km, the angular dimensions are approximately 10′. Yet in the case of Cygnus-A the depth of the modulation remains constant at a base length of 1.02 km. Consequently, its angular dimensions are much smaller than 10′. Only at $d = 10$ km, after the interference pattern from other sources has long disappeared, does the interference pattern due to Cygnus-A vanish. It follows directly from this that the angular dimensions of Cygnus-A are approximately five times smaller than those of other sources measured by Mills.

Similar results were obtained in Cambridge by Smith,[17] who used an interferometer with variable base (up to 400λ) on a wavelength of 1.4 m. The angular dimensions of various sources were subsequently determined many times. The most important of these determinations will be discussed later.

The determination of the angular dimensions of a source is merely a rough estimate of the radio brightness distribution within the confines of the source. This distribution, as shown by observation, can be quite complicated. Modern radio astronomy tends whenever possible to obtain the "radio image" of the source. The source brightness distribution in radio beams is of primary importance, and much attention is now been paid to it. In principle the problem of obtaining the radio image of the source can be solved by two methods. Observation with large single mirrors, using as narrow a lobe of the directivity pattern as possible, is the essence of the first method. Such observations are particularly advantageous at high frequencies. First, for a fixed mirror dimension, the principal lobe of the diagram will be narrower at the higher frequencies. Second, receiver sensitivity at centimeter and decimeter wavelengths has greatly increased of late, in view of the remarkable progress made in quantum radiophysics. Of course, it is essential to satisfy in such observations the condition that the angular dimensions of the source be considerably greater than the dimensions of the principal lobe of the directivity pattern.

Another method of obtaining the radio image of some source is by making interference observations with variable bases placed at different azimuths. From such observations it is possible to calculate the distribution of the radio brightness within the limits of the source. If, for example, the interferometer axis is located in a "west-east" direction, then the theoretical brightness distribution in direct ascension is given by the formula

$$B_t = \int_0^\infty A_\omega \cos(\theta_\omega + \omega t)\, d\omega, \qquad (2)$$

where A_ω and θ_ω are the amplitude and phase of the Fourier component of the recorded curve. If we assume that the source brightness distribution has circular symmetry, then $\theta_\omega = 0$, so that we can calculate the sought brightness distribution B_1 from the observed values of A_ω, using formula (2). This formula yields essentially the "integrated" brightness, where the integration is along a straight line perpendicular to the projection of the interferometer axis on the source. If the intensity distribution within the limits of the source does not have circular symmetry, interference observations must be made, with bases oriented in different azimuths. The number of azimuths can be relatively small if a certain hypothesis is made concerning the type of symmetry of the sources. Thus, for example, if we assume that within the limits of the source the isophots are ellipses with a common center, the brightness distribution can be obtained by means of interference observations (with variable bases) in three azimuths only. This was precisely what Mills did in 1953.[19] The results of his observations will be discussed in the next section.

Recently the most important problem of obtaining more or less rough radio images of individual sources has attracted much attention. We shall report later the most important results of these researches.

2. RADIO GALAXIES

In the preceding section we already mentioned that as long ago as in 1949 two powerful radio emission sources—Virgo-A and Centaurus-A—were identified with the peculiar galaxies NGC4486 and NGC5128. We shall discuss the main results of observations of these galaxies both in the optical region and in the radio region, carried out essentially in recent years. We shall then present an analogous discussion for other galaxies identified with discrete sources. To conclude this section, we shall consider the main properties of the radio galaxies, obtained from an analysis of the observed optical and radio astronomical data.

NGC4486 (M-87). This spheroidal galaxy is among the brightest members of the known galactic cluster in the Virgo constellation. Its visible magnitude is 9.6^m. The angular dimensions of NGC4486 are about 5′, and the brightness is highly concentrated at the center. Incidentally, such a high brightness concentration is common in spheroidal galaxies. At first glance the spheroidal galaxy M-87 does not differ in any way from other spheroidal galaxies which are not powerful sources of radio emission. It has long been known, however, that this galaxy has a remarkable feature, observed long before the advent of radio astronomy, by Curtis in 1918.[20] In the central brightest portion of NGC4486 there is a remarkable "jet" 20″ in length and of average width 2″. The jet itself consists properly of several condensations or "nodes" that lie on one straight line. Figure 7 shows a photograph of the central part of NGC4486, obtained by Baade with the aid of the large Mt. Palomar reflecting telescope (California), with 5 m mirror diameter. The spectrum of the jet is remarkable. It is considerably "bluer" than the integral spectrum of the galaxy itself, and is strictly continuous, i.e., it is completely free of either absorption or emission lines.[21] An investigation of the nature of the radiation in the jet has led to a discovery of fundamental importance, which will be discussed in the next section.

Another feature of NGC4486 is the spectrum of its core. Interesting results were recently obtained by Osterbrock.[22] In the core of NGC4486 one observes a rather intense emission line of ionized oxygen λ3727. This forbidden line is usually the most intense in the galactic diffuse gas nebulas. It is observed quite frequently in the cores of the galaxies, including some elliptic ones. What is unusual in the case of NGC4486 is the high intensity and the profile of this line, shown in Fig. 8. This profile is a superposition of two Gaussian profiles, separated by $\Delta\lambda = 11$ Å, corresponding to $\Delta V = 900$ km/sec. The most intense component is not shifted with respect to the Fraunhofer spectrum of the galaxy. The half-width of the unshifted profile corresponds to a spread of about ± 500 km/sec in the microscopic velocities of the gases emitting the λ3727 line. The angular dimensions of the region emitting the λ3727 line is only 1″. It is very interesting that the emission is concentrated exactly in the core of NGC4486 and does not extend to the region of the jet.

Attention should be called to the tremendous number of spherical clusters contained in NGC4486 (Fig. 9). They number at least several thousand, and only the brightest of these objects are observed. From an analysis of these clusters, Baum estimated the distance to NGC4486 to be 11 megaparsec. From this it follows, in particular, that NGC4486 is a giant galaxy. Its absolute stellar magnitude is about -21^m. The length of the above-described jet (more correctly, its projection on the plane of the figure),

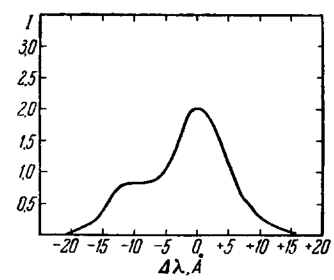

FIG. 8. Profile of the spectral λ3727 emission line in the core of NGC4486.

FIG. 7. Photograph of central part of the NGC4486 radio galaxy.

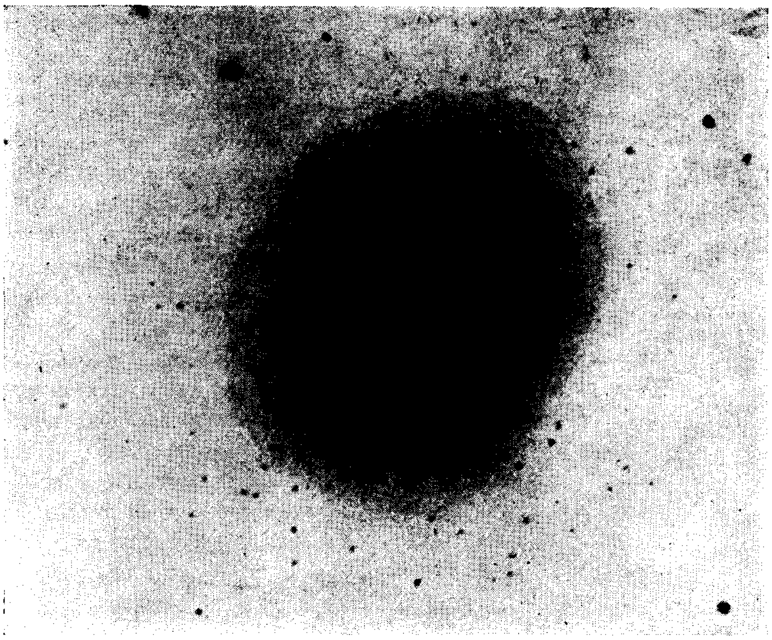

FIG. 9. Photograph of NGC4486 (negative).

reaches about 1000 parsec, with node dimensions of about 100 parsec. The region in the core of NGC4486, which emits the λ3727 line and has angular dimensions of 1″, is quite small, merely about 50 parsec.

It can be assumed that the NGC4486 mass is very large. In fact, in elliptic galaxies the ratio of the mass to luminosity (in solar units) reaches as a rule rather large values of about 50—100 and even more. If NGC4486 is not an exception from this rule, its mass should be greater than 10^{12} solar masses, which is at least one order of magnitude greater than the mass of our galaxy.

Another argument in favor of the large mass of NGC4486 is afforded also by an analysis of the profile of the λ3727 emission line in the core of this galaxy (see above). We shall assume that the line component which is not shifted relative to the Fraunhofer spectrum of the nucleus corresponds to the gas retained in the region of the core by gravitational forces. Then the mean square velocity of the random motions of the gas masses in the core of NGC4486 will be about 500 km/sec. Incidentally, according to observations made by Morgan and Mayall,[23] the absorption lines in the spectrum of the NGC4486 core are broad and smeared out (the "absolute magnitude effect" in galactic spectra, see [23]). This means that the stellar cores that emit a Fraunhofer spectrum are in a state of rapid disorderly motion. Assuming the radius of the λ3727 emitting region to be 25 parsec (see above), and the circular velocity at this distance to be about 10^8 cm/sec, we find that the mass of the core is about 6×10^9 $M_{\odot}$. Recognizing that the core of NGC4486 is weaker than 14^m, i.e., its emission is almost 100 times smaller than that from the entire galaxy (assuming that the stellar composition of the core does not differ from the composition of the entire galaxy), we find that the total mass of NGC4486 should be close to 5×10^{11} $M_{\odot}$. The conditions in the core of this galaxy are quite unusual: the mean stellar density reaches 5×10^4 per cubic parsec, which is approximately 500,000 times greater than the mean stellar density in the vicinity of the sun and about 50 times greater than in the core of our own galaxy. At these high stellar densities, "head on" collisions between stars become quite feasible.

The calculations above are of course tentative in character and must be made more precise in the future by setting up special observations. Nonetheless they give a certain idea of the specific conditions in the NGC4486 core. We shall later return to a discussion of the unusual conditions in the core of this galaxy.

Of great significance are data on the distribution of radio brightness in the vicinity of the source. A comparison of the "radio image" of the galaxy and of its optical image enables us to disclose very interesting regularities, which will be summarized at the end of this section.

A rough radio image of the Virgo-A source was first obtained by Mills on 3 meters by the interference method[19] (see Sec. 1). Figure 10 shows the Mills radio images of the sources Virgo-A and Centaurus-A, identified with the NGC4486 and NGC5128 galaxies. For comparison, the optical images of the galaxies are shown on top. It is seen from Fig. 10 that on radio wavelengths the spheroidal galaxy NGC4486 becomes sharply elliptical. The dimensions of the axes are 6′ and 2.5′. It is interesting that the major axis of this ellipse is almost perpendicular to the direction of the jet. It must be emphasized however, that in the derivation of the intensity distribution from the observational results, Mills used es-

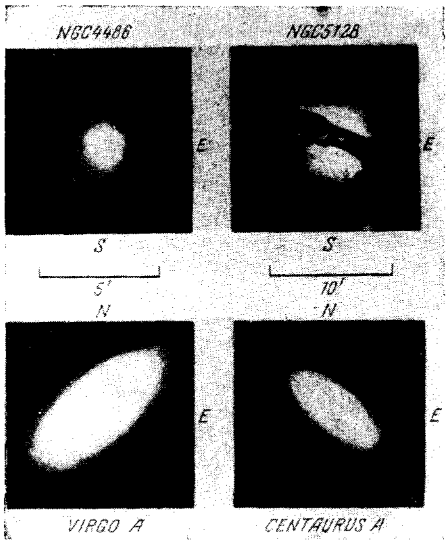

FIG. 10. Optical (above) and radio images (below) of NGC4486 and NGC5128.

sentially the hypothesis that the distribution is elliptical, and having postulated this hypothesis, he obtained the elements of the ellipse. Such a hypothesis, however, is hardly correct, and therefore the true distribution of the radio intensity in NGC4486 may differ considerably from that shown in Fig. 10. In the case of Centaurus-A, the brightness distributions obtained by Mills under the same hypothesis have been found to be totally in error, as shown by later observations (see below).

Nevertheless, it follows from the Mills observations that on a wavelength $\lambda = 3\,\text{m}$ the angular dimensions of the source are quite large, about 5′. Although rather long bases were used, up to $3400\,\lambda$, it was impossible to observe a source with small angular dimensions connected with the jet. Yet observation of such a source, the existence of which was predicted by the theory (see Sec. 3), was of great interest. One can conclude from Mills's observations that the $\lambda = 3\,\text{m}$ emission from the jet does not exceed 10% of the emission from the entire radio galaxy.

In 1960, Biraud, Lequeux, and Le Roux[24] using an interference procedure on 21 cm, and Yu. N. Pariĭskii[25] using the "fan" antenna of the Pulkovo Observatory on 9 cm, observed almost simultaneously a bright source, of small angular dimensions, connected with the jet. For example, it is shown in [24] that at a wavelength of about 21 cm Virgo-A consists of an extensive (~ 10′) source and a very small (~ 40″) elongated source, oriented in the same direction as the jet. The fluxes from the small and "extensive" sources are 112×10^{-26} and 74×10^{-26} W/m^2-cps, respectively. The latter source is identified with the galaxy NGC4486 itself. It was apparently also observed by Mills. The fact that the small source connected with the jet was not observed by Mills can be attributed to its spectral peculiarities.

French investigators have shown quite recently that even the small source connected with the jet is in turn a double source.[26] Both components have practically the same intensity, and their centers are separated by 31″, the angular dimension of each component being 23″.

In 1956 Smith reported that he observed near NGC4486 an extensive (~ 1°) source of low surface brightness.[27] According to Mills's observations this source is shifted away from the center of NGC4486 towards the jet. In 1960 Wade, using the Harvard radiotelescope with 27 m reflector on a wavelength of 21 cm, showed that this weak source (its flux is 25 times smaller than that from Virgo-A) is connected with the M-84 galaxy, which is 1.5° away from M-87, in the same direction as the jet.[28]

NGC5128. As already mentioned in Sec. 1, soon after the discovery of the discrete sources, one of the most powerful sources, Centaurus-A, was identified with the peculiar galaxy NGC5128. Figure 11 shows a photograph of this galaxy. Its angular dimensions are large, about 30′. It could be fully classified as elliptic, were it not crossed by a broad heavy dark band due to light-absorbing material. One should also notice that photographs of this galaxy, taken in red light with a 48-inch Schmidt-system telescope, show a weak projection in the direction of the 45° position angle, approximately perpendicular to the dark band. On the basis of this morphological feature of NGC5128, Minkowski[21] concluded that what is observed in this case is an "end view" of a collision between an elliptic galaxy and a spiral. Such an interpretation, however, as well as other "collisions" of galaxies discussed by the same author, meets with great difficulties and is not shared at present by anyone else. It is hardly doubtful at present that NGC5128 is a single peculiar galaxy.

A spectrogram of NGC5128 discloses bright emission lines of the hydrogen Balmer series and the known λ3727 forbidden line of ionized oxygen, superimposed on the class-G Fraunhofer spectrum which is the usual one for galaxies. The radial velocities of the lines are about 450 km/sec. The profiles of the radiation lines indicate that the emitting gas masses have considerable macroscopic velocities.

E. Burbige and G. Burbige[29] investigated in 1959 the rotation of NGC5128 by spectroscopic means and were able to estimate the mass of this galaxy. They determined the radial velocities from the λ6584 line of the ionized nitrogen. It was shown that NGC5128 rotates about an axis that is approximately perpendicular to the dark band. A rough estimate of the mass leads to a value $2 \times 10^{11}\,M_\odot$, which we believe may be an underestimate. Notice is also taken in [29] of fluctuations of the macroscopic velocities (especially about the center of the dark band), which reach 100–200 km/sec.

According to photoelectric observations made by Sersic[30] the visible photographic magnitude of NGC5128, corrected for the absorption inside this

FIG. 11. Photograph of the radio galaxy NGC5128.

galaxy, is 7.6^m. With the aid of some additional assumptions, which are incidentally quite natural, the distance to NGC5128 is found to be 3.8 ± 0.4 megaparsec.[30] Hence, taking into account the absorption in our own galaxy, the absolute photographic magnitude of NGC5128 is -21.2^m, i.e., this galaxy, like NGC4486, is an object of most gigantic luminosity. It will be shown later on that this tremendous optical luminosity is a common feature of all radio galaxies.

According to de Vanconleurs,[31] the angular dimensions of NGC5128 are 28′ by 20′, which at a distance of 3.8 megaparsec corresponds to linear dimensions of 31 × 22 kiloparsec.

Recent radio astronomical observations have disclosed remarkable properties in the distribution of the intensity of radio emission from the Centaurus-A source, identified with NGC5128. It has been known for a long time that this source consists of two components, one quite extensive (about several degrees), with relatively low brightness, and one bright source with small angular dimensions. According to Mills's interference observations[19] the small bright source was represented by an ellipse with axes 6.5′ × 2.5′ oriented along the dark equatorial band of the galaxy (Fig. 10). It was shown in 1959 by Wade[32] and in 1960 by Bolton and Clark[33] that the extensive component of Centaurus-A is a double one. Figure 12 shows isophots of this source obtained by Wade on a wavelength near 3.5 m. What is striking is that both components of the extensive source are symmetrically situated on both sides of the optically observed galaxy. We shall see below that this unique arrangement of the radio sources relative to the galaxy with which they are identified is a characteristic feature of many if not the majority of radio galaxies.

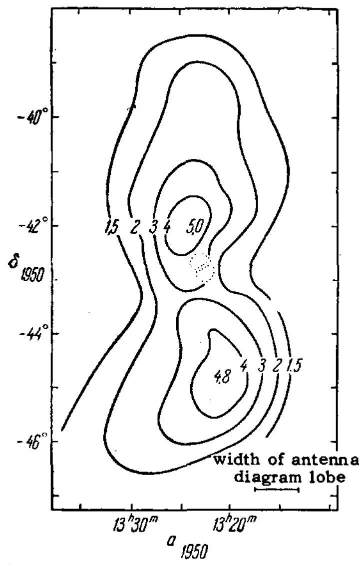

FIG. 12. Isophots of the Centaurus-A source. The dotted line denotes the optically observed galaxy NGC5128.

The dimensions of the extended source are tremendous. The entire radio-wave emitting region has dimensions exceeding 0.5 megaparsec, i.e., more than ten times greater than the dimensions of the optically emitting galaxy. The distance between the center of the two components of the extensive source is about 200 kiloparsec, and the dimensions of each of these (determined from the half-brightness values) are about the same.

In 1960 it was observed on 21 cm that the small bright source situated inside the optically observed galaxy is itself a double source.[34] This was demonstrated finally in 1961 by interference observations made with the large reflectors of the California Institute of Technology (see Fig. 5).[35] Observations were carried out at wavelengths of 31.3 and 21.6 cm with variable bases and different azimuths. Figure 9 shows in suitable scale the positions of both components of the small source relative to NGC5128. It is striking that both small bright sources are situated symmetrically on both sides of the dark equatorial band approximately in the direction of the axis of the radio galaxy. The same feature is seen also in the distribution of the extended components of Centaurus-A (see Fig. 12). Such a remarkable symmetry can hardly be accidental.

Observations made on different frequencies enable us to determine the spectral index of Centaurus-A. According to Heeshen[36] this index is approximately equal to 0.77, i.e., it is approximately the same as in most other radio galaxies.

NGC1316. In 1952 the author and P. N. Kholopov identified the rather strong source in Fornax-A with the spheroidal galaxy NGC1316.[37] In addition to the good agreement in the coordinates, our deduction was based on the similarity in the morphological features of NGC1316 and NGC5128, which at that time was reliably identified with the Centaurus-A source. Our identification was criticized by Minkowski,[21] but was later on fully corroborated.

The photographic magnitude of NGC1316 is 9.8^{m}, which corresponds, for the 15.8 megaparsec distance assumed in [38], to an absolute magnitude 21.2^{m}, i.e., precisely the same as NGC5128. The angular dimensions of NGC1316 are $6' \times 4.2'$, corresponding to linear dimensions of 28×19 kiloparsec—almost the same as NGC5128. Unlike NGC5128, no emission lines were observed in the NGC1316 spectrum. This galaxy discloses a dark band of ragged structure, similar to that observed in NGC5128, but much narrower. This feature, exceedingly rare in spheroidal galaxies, emphasizes the general similarity between NGC1316 and NGC5128.

The latest radio astronomical observations made by Wade in the principal lobe of the 27-meter Harvard radio telescope on 10 cm[38] have shown convincingly that the Fornax-A source has two components. Figure 13 shows the isophots of this source. The distance between the centers of the two components is about 30′. As in Centaurus-A, they are symmetrically situated on both sides of the optically observed NGC1316 galaxy. Again as in Centaurus-A, the distance between the two components and the centers of the corresponding galaxies are not equal. However, while the two components of Centaurus-A are practically identical in size and brightness, one of the components of Fornax-A is almost twice the brightness and the size of the other.

The distance between the centers of the components of Fornax-A is about 140 parsec. Since we are dealing in all cases with the projection of the true distance on the plane of the figure, it can be assumed with full justification that the true distance between the components is about 200 kiloparsec in both Fornax-A and in

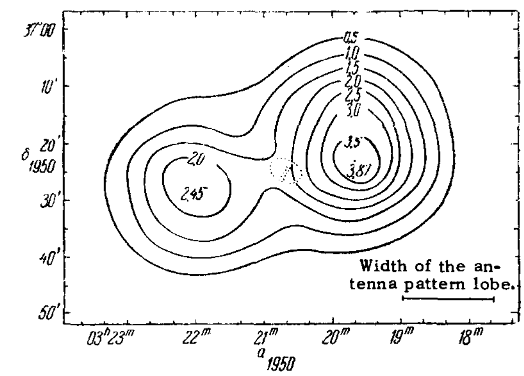

FIG. 13. Isophots of the source Fornax-A. The dotted line designates the optically observed galaxy NGC1316.

Centaurus-A. The spectral index of Fornax-A is 0.77, the same as of Centaurus-A. Recognizing that 25% of the flux from Centaurus-A is produced by the small bright source situated inside NGC5128, it is possible to determine from the known distances to these radio galaxies that the total radio luminosity of Fornax-A is approximately twice that of Centaurus-A.

There is no doubt that future observations will disclose new structural details in Fornax-A. In particular, sources with small angular dimensions may possibly be observed in the region of the galaxy NGC1316 itself.

Summarizing, the radio galaxies NGC5128 and NGC1316 should be regarded as essentially similar objects.

NGC1275. This galaxy is reliably identified with the rather powerful source Perseids-A. It belongs to the rare type of galaxies, investigated by Seyfert,[39] which are characterized by very broad emission lines in the cores. NGC1275 has a magnitude 13.3^{m}. Minkowski believed that what is observed in this case is a collision between two spirals—one of later and one of earlier type.[21] We cannot agree with either this interpretation or with the other "collisions." The NGC1275 spectrum, part of which is shown in Fig. 14, is very interesting. The lines on the photograph can indicate the position of the spectograph slit relative to the galaxy. In many cases the λ3727 line is split. The corresponding radial velocities are 5200 and 8200 km/sec. Minkowski saw in this a confirmation of his collision hypothesis. But we have seen in the case of the NGC4486 core that the difference in the velocities of the two line components reaches 1000 km/sec, although there is no doubt that only one galaxy is observed in this case. The distance to NGC1275, corresponding to a red shift of 5200 km/sec,* is found to be equal to 70 megaparsec (with a Hubble constant H = 75 km/sec-megaparsec), so that the absolute photographic magnitude is -21^{m}, i.e., approximately the same as in other radio galaxies. In addition to λ3727, other

*This is the central radial velocity of the galactic cluster to which NGC1275 belongs.

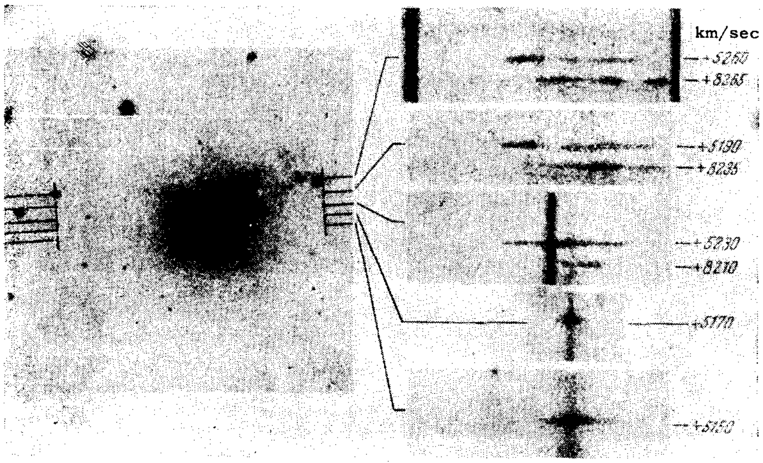

FIG. 14. Spectra of NGC1275, obtained at different orientations of the spectograph slit.

very broad emission lines, as a rule of high degree of excitation, are also observed in the vicinity of the core.

Of great interest is the distribution of radio brightness in the region of NGC1275. According to Bolton[40] there exists in a center of NGC1275 a bright source with small (< 0.8′) angular dimensions, surrounded by an extended (~ 5′) "halo." In such a case the dimensions of the latter should be about 100 kiloparsec. According to recent high-grade interference observations, carried out in Cambridge[41] with a lobe width 13.6′, a bright source with angular dimensions 1′ (i.e., the same as of the optically observed galaxy) is situated precisely at the location of the NGC1275 galaxy, while at a distance ~ 30′ from it there is an extensive source measuring 26′, the fluxes from these sources being practically the same ($\sim 4 \times 10^{-25}$ W/m^2 cps on 178 Mcs). Although this extensive source is within the limits of a rich galactic cluster, the brightest among which is NGC1275, it is apparently not due to the integral effect from all the galaxies in the cluster. If the distribution of the radio brightness of the cluster were to be proportional to the distribution of the optical brightness due to the members of the cluster, this source would have considerably greater dimensions and its brightness would be relatively weakly concentrated towards the center. It is possible that the extensive source in the Perseids-A is genetically related to the radio galaxy NGC1275 (similar to the extensive sources NGC5128, see above). In this case the linear dimensions of the source are about 0.5 megaparsec, i.e., approximately the same as of the extensive sources near NGC5128 and NGC1316. What is striking, however, is the absence of symmetry with respect to NGC1275, i.e., there is no other extensive source on the other side of the galaxy.

Cygnus-A. So far we have considered relatively bright (optically) radio galaxies, which have been known to astronomers for a rather long time and which were identified with the sources of radio emission directly, i.e., essentially from the coincidence of the coordinates. This method was used to identify a few bright galaxies, along with those listed above. In particular, the Seyfert galaxy NGC1068 was reliably identified with a relatively weak source. We recall also the analogous identifications for NGC1218, NGC4261, NGC6166, and a few other objects. However, many sources, including some very powerful ones, could not be identified for a long time. In particular, for five years after its discovery the most powerful source Cygnus-A could not be identified with any optically observed object. All that could be concluded was that there was no bright star or nebula whatever in the location of this source. After the coordinates of Cygnus-A became known with sufficient accuracy, following Smith's interference observations,[42] it became possible, using the most powerful optical telescopes, to attempt to observe some object at the location of this source. This was done by Baade and Minkowski,[43] who used the largest reflector in the world, that in Mount Palomar.[43]

They observed at the location of the Cygnus-A source a weak galaxy, which was quite unusual in many respects. The splendid agreement between the coordinates of the radio source and those of the galaxy makes this identification perfectly reliable. In fact, according to [42] the coordinates of Cygnus-A are $\alpha = 19^h57^m45.3^s \pm 1^s$ and $\delta = +40°35.0' \pm 1'$, whereas the coordinates of the galaxy observed by the American investigators are $\alpha = 19^h57^m44.9^s$ and $\delta = +40°35'\,46.3''$ (all the coordinates are referred to the 1950 equinox). A magnified picture of the galaxy identified with the Cygnus-A source is shown in Fig. 15. It is seen on this photograph that the central part of the galaxy consists of two bright condensations 2″ apart. The position angle of the line joining the centers of these condensations is 115°. The bright central region in which this condensation is located measures 3″ × 5″ and is surrounded by a weaker elliptical nebula with dimensions 18″ × 35″, the major axis of the ellipse having a position angle 150°.

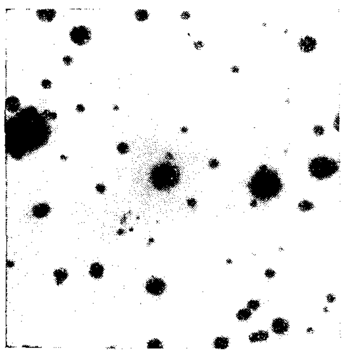

FIG. 15. Photograph of the galaxy Cygnus-A.

The unusual form of this galaxy, and its clearly pronounced duality, have caused Baade and Minkowski to conclude that this is a practically head on collision between galaxies—spirals of the later type. They subsequently assumed that in almost all cases when an extragalactic radio source is identified with an optically observed object, the latter comprises colliding galaxies. Recent research, however, has shown that radio galaxies are not colliding stellar systems (see Sec. 3).

Spectra of the bright central region of the peculiar galaxy identified with Cygnus-A were obtained with the aid of a nebular spectograph with grating, installed in the principal focus of a 5 m reflector and the Newtonian focus of a 2.5 m reflector. Figure 16 shows the spectrum of the Cygnus-A radio galaxy. In the photographic region, the dispersion is 435 Å/mm. These spectra are quite unlike the spectra of "normal" galaxies. More than 50% of the radiation is concentrated in emission lines which as a rule are forbidden and belong to strongly ionized atoms. The lines are quite broad and diffuse. The corresponding Doppler velocities of the radiating gas masses are about 400 km/sec. The λ3727 [OII] line stretches over the entire length of the slit, i.e., 30″. The small inclination of this line indicates rotation of the galaxy.

The red shift of the spectral lines reaches a large value, 16830 km/sec. So large a line shift clearly indicates that this object is extragalactic. Taking the Hubble constant to be H = 75 km/sec-megaparsec (we shall henceforth use only this value of H), we find that the distance to Cygnus-A amounts to 220 megaparsec, i.e., a tremendous value. The visible stellar magnitude of this galaxy, according to photoelectric observations, is approximately 17^m. Taking into account the interstellar absorption, which amounts to about 2^m, we obtain for the Cygnus-A radio galaxy an absolute value -21.5^m, i.e., it has very high luminosity.

The radio galaxy Cygnus-A is unique in its class in that its radio emission flux integrated over the frequencies is 6—7 *times greater than the flux of its* optical radiation. Consequently, its radiation power in the radio band exceeds by as many times its radiation power in the optical band. Moreover, the optical luminosity of this galaxy is approximately one order of magnitude greater than that of our own stellar system, which in itself is a giant spiral of the later type!

The radio spectrum of Cygnus-A was determined many times by analysis of various observations made on different frequencies. The most reliable determination was made by A. D. Kuz'min et al,[44] shown in Fig. 17a. It has a striking "break" at f_0 = 1500 Mcs, whereby the spectral index is $\alpha = 0.75$ for $f < f_0$ and $\alpha = 1.25$, i.e., greater by about one-half, for $f > f_0$. Quite recently Barret, investigating the radio emission from several sources on 1.8 cm with a 27 m radio telescope, plotted the "relative spectrum" of Cygnus-A and Cassiopeia-A.[91] This spectrum (more accurately, the flux ratio of Cygnus-A to Cassiopeia-A at different frequencies) is shown in Fig. 17b. It follows from this figure that there is not so much a "break" as a "slash" in the spectrum (i.e., a reduction in flux that progresses with increasing frequency), starting with $\nu \sim 1500$ Mcs. Such characteristic changes in the spectrum should have a deep physical meaning (see later, Sec. 3).

Quite unexpected results were obtained in radio-interference observations of the brightness distribution within the Cygnus-A source. The first precise

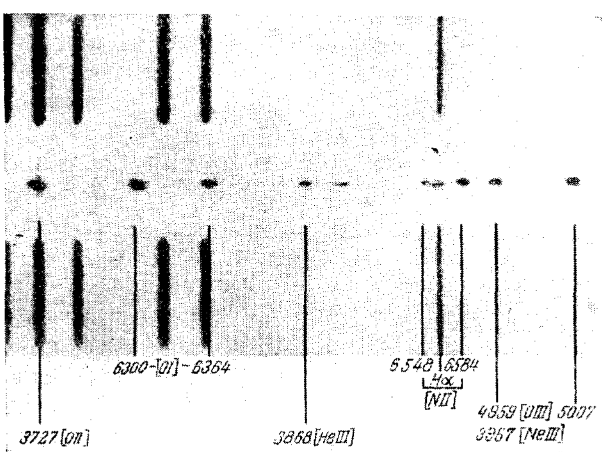

FIG. 16. Optical spectrum of Cygnus-A.

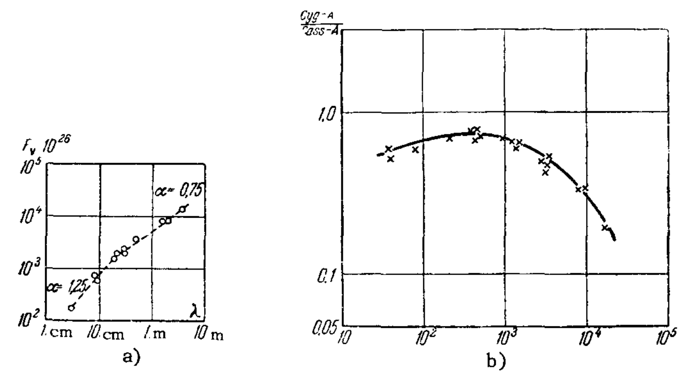

FIG. 17. a) Radio spectrum of Cygnus-A. b) Ratio of Cygnus-A and Cassiopeia-A fluxes at different frequencies.

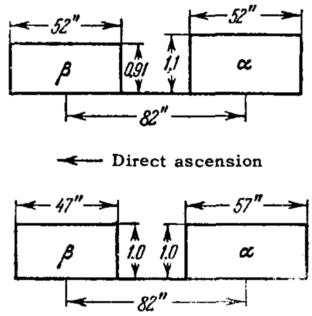

FIG. 18. Models of radio brightness distribution in the Cygnus-A source.

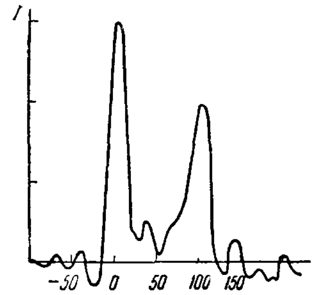

FIG. 19. Distribution of radio brightness of Cygnus-A measured along one coordinate on 21 cm.

observations by Jennison and Das Gupta [45] showed it to be a double source consisting of two components symmetrically situated on both sides of the radio galaxy, at a certain distance from it. Later observations by Jennison, Latham, and Rawson disclosed the following pattern of brightness distribution. From observations on 127 Mcs with a phase-sensitive radio interferometer it follows that the Cygnus-A source consists of two components, the fluxes of which differ by only 20%. The distance between the centers of the components amounts to 82″ at a position angle of 97°. Figure 18 shows two models of the source brightness distribution at a 90° position angle. The angular dimensions on the source along the minor axis are smaller than 30″ on 127 Mcs.

Analogous observations on 3000 Mcs, carried by the same workers, gave similar results. [46] On this frequency the position angle of the major axis of the source is 109°. Both components of Cygnus-A have practically the same angular dimensions as on 127 Mcs, but are separated by somewhat greater angular distance, 101″ (between the centers of the components). The source dimensions in the direction of the minor axis are about 20″.

The tremendous value of the radio flux from Cygnus-A (which is practically the same as from the sun on meter wavelengths), in conjunction with the small angular dimensions, shows that its surface brightness is exceedingly large. On 100 Mcs, the brightness temperature of this source is $T_b \sim 10^8$, some 100 times that of the quiet sun.

Recently Lequeux and Heidmann [26] carried out in the Nancy radio astronomical observatory interference observations of various sources, including Cygnus-A, on 21 cm. The length of the (variable) base reached 6950λ in the east-west direction. According to these observations, the brightness distribution of Cygnus-A in the E-W direction has the form shown in Fig. 19. The distances between components are 100″, the half-width of each being about 25″. What is striking is the very sharp outer boundary of the source. The ratio of the fluxes from the two components is 55/45.

Last year Yu. N. Pariĭskii, using the Pulkovo antenna on 3.5 cm, was able to resolve Cygnus-A into two components. This was possible because on this wavelength the width of the lobe was about 1′. The practical resolving power was about 30″. Thus, Cygnus-A was resolved for the first time into two components by a "direct" and not by an interference method. It is remarkable that the ratio of the intensities of the components of this source is the same on 3 cm as on 127 Mcs (λ = 236 cm). This means that the spectral indices of the components are the same within 1—2%. These observations have disclosed, in particular, that both components are approximately at the same distance from the optically observed bright central part of the Cygnus-A galaxy.

We have stopped to discuss Cygnus-A in detail because this source has been investigated relatively well, owing naturally to its tremendous power. At the same time, objects of this type should constitute an appreciable if not the major part of all the observed class-II sources. Although their spatial density is very small, they can be observed from very large distances, owing to their tremendous radio luminosity, and this is of very great significance to cosmology.

Hercules-A. Until most recently this rather powerful source could not be identified with any optically observed object. This was due to a large extent to errors in the determination of the coordinates of this source. Only quite recently, in 1961, was it possible to identify Hercules-A with a close pair of galaxies of 18th magnitude. The distance between the centers of the galaxies is 3″ at a position angle 130°. This identification was made possible by interference observations on 81.5, 159, 178, and 408 Mcs, performed in Cambridge. [47] These observations have shown that Hercules-A is, like Cygnus-A, a double source.* The distance between the components is 1.95′ ± 0.1′ in the α direction and 0.32 ± 0.60′ in the δ direction. The fluxes from both components of Hercules-A are practically equal. According to [48], the distance between components is 1.82′, the half-width of each component is 47″, and the position angle of the direction joining the components is 98° ± 5°.

Although the galactic latitude of Hercules-A is quite appreciable (b ~ 25°), the interstellar absorption of light in this region is still considerable. It is here that one observes the "tongue" of the zone of disappear-

*The duality of Hercules-A was first observed in 1960 on 21 cm by Boischot,[48] who used an interferometer with variable base.

ance of the galaxies, due to the interstellar absorption of light. In [43] the absorption of light was disregarded, and consequently the values obtained there for the distance of Hercules-A (630 megaparsec) are in error. We shall estimate this distance in the following fashion. We can assume, that, like other radio galaxies, the Hercules-A system has an absolute photographic magnitude close to -21^m. Assuming the absorption of light in the direction of Hercules-A to be $1.0^m - 1.5^m$ (which is quite admissible), we find that the distance to this radio galaxy is about 300 megaparsec, i.e., somewhat greater than to Cygnus-A, but appreciably less than obtained in [47].

The linear dimensions of the Hercules-A system are approximately 1.5 times greater than those of Cygnus-A, and reached about 160 kiloparsec.

Unfortunately, the optical spectrum of the Hercules-A radio galaxy has not yet been found. It would be interesting to verify our conclusion concerning the distance to Hercules-A on the basis of the red shift of the emission lines. The relative position of the two components of the source and of the galaxies is very reminiscent of Cygnus-A. It is curious to note that the position angle of the line joining the two components of the source is quite close to 130°, and consequently close to the direction of the line joining the centers of the two galaxies. The same pattern is observed in Cygnus-A.

In general it can be stated that the Hercules-A source is quite similar to Cygnus-A, except that its dimensions are somewhat greater and its radio luminosity is approximately 20—30 times smaller.

3C-295. According to the third Cambridge catalogue, the flux from this source is 70 times less than from Cygnus-A. Since the angular dimensions are small, there are grounds for assuming that this is an object of the same type as Cygnus-A, but much farther away. In 1960 Minkowski, using the 5-meter reflector of Mount Palomar, found at the location of this source a galaxy cluster containing about 60 objects of 21st magnitude in a region measuring 3′.[49] The center of the cluster had coordinates $\alpha = 14^h 09.6^m$ and $\delta = +52° 27'$ (1950). Spectrograms of two of the brightest galaxies of this cluster were obtained with the aid of a nebular spectrograph. The brightest of these galaxies had a visible magnitude of 18.9^m. Its spectrum, however, disclosed no particular singularities. On the other hand, the galaxy next in brightness, with stellar magnitude 20.5, disclosed an amazing spectrum, a strong $\lambda 5447.8$ emission line seen against the background of weak traces of a continuous spectrum. Analysis shows that is the well known ultraviolet $\lambda 3727$ line, red-shifted into the orange part of the spectrum. Therefore $v/c = 0.4614 \pm 0.0002$. This galaxy moves away at a rate of 147000 km/sec, or almost half the speed of light. This is the largest of the red shifts known to date. The absolute photographic magnitude of the 3C-295 galaxy is $M_p = -20.9^m$, and the distance to it is 1990 megaparsec.

Interference observations were made in Manchester, using very long bases (30000λ), aimed at disclosing discrete radio emission sources with small angular dimensions.[50] In particular, it was found that the angular dimensions of 3C-295 was 4.5″. Thus, this source is four times brighter than Cygnus-A and occupies for the time being first place among all known sources. Its linear dimensions are half those of Cygnus-A, and its radio luminosity is 15—20 greater. The large distance still does not allow us to conclude that this source is a multiple one, as is quite probable. This source is of outstanding interest to radio astronomy, astrophysics, and cosmology.

Hydra-A. After the coordinates of one of the most powerful class-II sources in Hydra-A were measured sufficiently accurately in Sydney and in Cambridge, the source was reliably identified with a peculiar system of spheroidal galaxies.[51] Observations at the California Institute of Technology have finally confirmed this identification.[52] The galactic system with which Hydra-A is identified consists of two galaxies, a considerable distance apart, the brighter component of which consists in turn of two neighboring cores in a common envelope. The spectrum of this peculiar system shows weak broad [OII], [OIII], and also H_β lines. The visible stellar magnitude of the system is 15.9^m, and the measured red shift of the spectral lines corresponds to an outbound speed of 15900 km/sec. Consequently the distance from us to this object is the same as to Cygnus-A. It follows therefore that the absolute magnitude of this radio galaxy (disregarding interstellar absorption of light) is -20.6^m. We note that the absorption can reach as much as 0.5. Thus, this radio galaxy is also a supergiant.

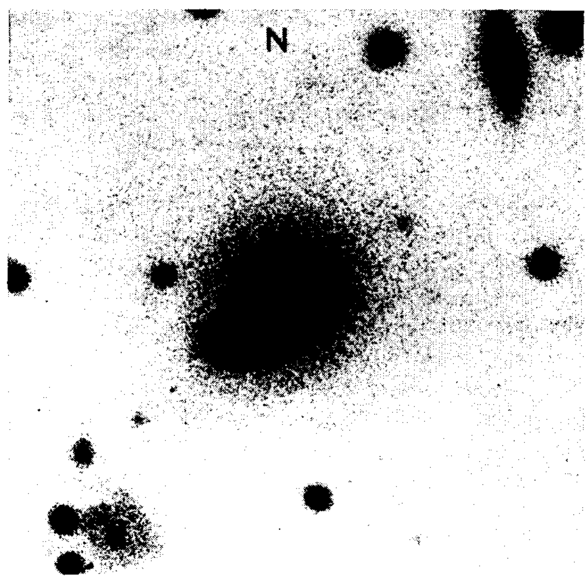

FIG. 20. Photograph of Hydra-A radio galaxy.

Figure 20 shows a magnified photograph of the Hydra-A radio galaxy.

The brightness distribution in the Hydra-A source is quite complicated. Approximately 80% comes from a region measuring 42″, corresponding to about 40000 parsec,[26] and 15% of the radiation comes from a source with very small angular dimensions (< 10″). Finally, from the latest interference observations carried out at the California Institute of Technology it follows that the small bright source is inside a weaker more extensive source (~ 5′), the flux from which amounts to 5—10% of the total flux from Hydra-A (see the corresponding curve on Fig. 22).

We have considered several cases when the sources of radio emission could be identified with peculiar radio galaxies, and analyzed their main characteristics. It must be emphasized that only a small fraction of the Class-II sources have been identified to date. There is no doubt that in the nearest future, as the source coordinates are more precisely determined, some will be identified with peculiar galaxies of 18th—20th magnitude. It is hardly likely, however, that most sources will be identified, since it is quite possible that the corresponding galaxies are too far from us to be observed optically. We have seen, with 3C-295 as an example, that a source which is far from weak is identified with an exceedingly weak peculiar galaxy. If the majority of weak sources are analogous in their radio luminosity to Cygnus-A and 3C-295 (and there are many factors favoring this statement), these will obviously never be identified.

On the other hand, as the number of observed sources increases, some will be identified with ordinary relatively bright (> 12^m) galaxies or with "semi-peculiar," rather bright objects such as NGC1068, NGC4782/3, etc, to which we referred above. In the present review we do not concern ourselves with radio emission from "ordinary galaxies," although at the present time some 20 of these have been identified with late spirals and some with ordinary elliptic galaxies and irregular systems in the Magellanic Clouds (see, for example, [53]).

We shall stop briefly to discuss the "statistical" characteristics of radio galaxies. It must be noted first that the spectra of the sources identified with radio galaxies are quite uniform. This question was investigated by Bolton and his co-workers.[54] Figure 21 shows a histogram of "relative spectral indices," defined as the difference between indices of Virgo-A and the given source. It follows from this histogram that the radio spectra of Class-II sources are quite similar and close to the spectral index of Virgo-A, which is nearly equal to 0.75. Incidentally, there are exceptions. For example, the spectral index of NGC1068 is noticeably smaller, 0.4 according to [40]. It was observed recently that an almost "flat" spectral index is possessed by the source identified with the peculiar galaxy M-82. This galaxy has an anomalously blue-green color, and its integral spectrum is of type A. It is possible that in this case the radiation has a thermal character and is due to a large quantity of ionized gas contained in this stellar system.

Still another important exception is the anomalous spectrum of the eruption of NGC4486, which will be discussed in the next section.

With Cygnus-A, Hercules-A, Centaurus-A, and Fornax-A as examples, we can verify that duality is quite common among Class-II sources. According to [40], approximately 30% of all the sources are double objects, with both components having practically the same intensity. Moffet and Maltby have observed[55] 88 sources with the aid of the large interferometer of the California Institute of Technology. The observations were on 31.3 cm, with variable base up to 1600λ and two mutually-perpendicular azimuths.[55]

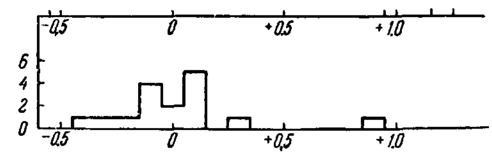

FIG. 21. Histogram of relative spectral indices of radio galaxies.

It was observed that most sources with angular dimensions > 1.5′ have a complicated structure. 3C-75, 3C-111, 3C-134, 3C-219, 3C-210, 3C-270, and 3C-445 are definitely double sources with components of equal intensity. Some 26 sources can be interpreted as double with components of unequal intensity. Ten sources with angular dimensions (along one coordinate) from 1.2′ to 2.5′ are highly prolate with an axis ratio ~ 2 : 1. Four sources have a unique structure consisting of a small bright nucleus and a currounding "halo." No definite conclusions could be drawn for 39 sources with dimensions < 1.2′.

It is quite remarkable that there is no correlation between the duality of the radio-emission source and the duality of the corresponding radio galaxies observed optically. For example, the radio galaxy NGC1316, which is known to be single and spheroidal, corresponds to a double source, while the multiple radio galaxy Hydra-A corresponds to one rather compact source. Incidentally, in the latter case our information concerning the distribution of the radio brightness is still insufficient. It is also necessary to bear in mind the influence of the orientation of the source and of the radio galaxy with respect to a terrestrial observer.

Quite recently the California radio astronomers have completed an extensive program of interference observations, with variable base in two azimuths, on a large number of sources.[56] They published many plots of the depth of modulation of the interference pattern vs. the base length. Some of these curves

Table II. Summary of radio galaxies and class II sources.

Columns: 1—designation of source, 2—direct ascension of source, 3—declination, 4—angular dimensions, 5—flux density on 85 Mcs (if there are no data on the flux at this frequency, A is calculated by extrapolation with spectral index α = 0.7), 6—type of galaxy with which the source is identified, 7—photographic magnitude of this galaxy, 8—radio index, 9—distance to a source in megaparsec, 10—absolute radio magnitude of source, 11—energy of relativistic particles and of magnetic field in the source, 12—average value of magnetic field intensity in source.

Source	α	δ	φ	$F_\nu \cdot 10^{26}$ (W-m^{-2} cps^{-1})	Identification	m_p	$m_r - m_p$	r (Mps)	M_r	E (erg)	H (Oersted)
00+02	$00^h10^m00^s$	+0°37′	~0′,5	20	E+E	18^m+18^m	-9^m	580	—30.5	$2,8\cdot10^{59}$	$5\cdot10^{-5}$
3C-26	00 51 39.5	—03 43	~40″	23	SO+Sb	17 +17	—9	320	—29	$1,6\cdot10^{59}$	$6\cdot10^{-5}$
3C-33	01 06 15,6	13 04,3	1′,3	95	EO	18.5	—11.4	630	—31,9	—	—
NGC545/7	01 23 26,5	—01 36,1	~45″	88	SO+EO	13 +13	—5,7	40	—24.8	$1,9\cdot10^{57}$	$1.4\cdot10^{-4}$
3C-66	02 19 01.7	42 45.8	~15′	33	E	13	—5.3	83	—26,3	$1.8\cdot10^{59}$	$4\cdot10^{-5}$
02-110	02 35 24	—19 43	~30″	44	(d)	18	—10	580	—30,4	$5,0\cdot10^{59}$	$6\cdot10^{-5}$
NGC1068	02 40 07	—00 13,5	~45″	35	SO	10	—1.8	11,8	—22,2	$5,0\cdot10^{56}$	$1.4\cdot10^{-4}$
3C-75	02 55 03	05 49,5	~5′ (d)	51	EO+SO	15,5+15,5	—7	31,6	—24,3	$5,5\cdot10^{59}$	$1,8\cdot10^{-5}$
NGC1218	03 05 50,3	03 55,2	4′+<0′,8	34	E	15	—6,4	125	—29	$1,1\cdot10^{59}$	$1,4\cdot10^{-5}$
Per-*A*	03 15 54	41 00	26′	105	—	—	—	70	—27	$2\cdot10^{59}$	$8\cdot10^{-6}$
NGC1275	03 16 30	41 19	1′	110	Sc_{pec}	13.3	—6,3	70	—27,3	$1,2\cdot10^{58}$	$8\cdot10^{-5}$
NGC1316	03 20 48	—37 24	40′ (d)	950	SO	9,6	—5,2	15,8	—26,8	$1,8\cdot10^{59}$	$1\cdot10^{-5}$
03-03	03 31 44	—01 25	~35″	64	?	18	—11	580	—32	$8,8\cdot10^{59}$	$6\cdot10^{-5}$
3C-98	03 56 10.5	10 17,5	~3′	80	E2	16	—8.7	400	—29,2	$2,6\cdot10^{60}$	$2\cdot10^{-5}$
08+03	08 19 54	06 07	~30″	125	S+S	17,5+17.5	—8.5	440	—29	$4,2\cdot10^{59}$	$9\cdot10^{-5}$
Hyd-*A*	09 15 41	—11 53.1	0′,8	690	E+E	16	—10,5	200	—30.9	$3\cdot10^{59}$	$1,2\cdot10^{-4}$
10-018	10 46 18	—02 33	~30″	20	?	17 +17	—7	320	—28,4	$6,7\cdot10^{58}$	$6,5\cdot10^{-5}$
NGC4261	12 16 50	06 06.2	7′	100	E	11	—5	13,2	—24,6	$2,3\cdot10^{57}$	$2.5\cdot10^{-5}$
NGC4374	12 23 04	+13 05.7	6′×3′	65	E1	10	—2,4	13,2	—23	$1,3\cdot10^{57}$	$2.5\cdot10^{-5}$
NGC4486	12 28 18	12 40	10′+2×20″	1800	EO	10	—6	13.2	—26.6	$1,8\cdot10^{58}$	$4\cdot10^{-5}$
NGC4782/3	12 51 59	—12 17	2′,2	53	SO+EO	13 +13	—5.4	45	—25,8	$7,5\cdot10^{57}$	$4\cdot10^{-5}$
NGC5128	13 22 28	—42 45.6	6×2° (d)	1100	S_{pec}	7.6	—5.6	3.8	—26.0	$2.8\cdot10^{59}$	$5\cdot10^{-6}$
3C-295	14 09 33.4	52 26.5	~4″,5	200	?	20	—13,6	1990	—35,0	$3,1\cdot10^{60}$	$4\cdot10^{-4}$
3C-310	15 02 47.7	26 12.4	~1′,5 (d)	67	E1+EO	18.5+18.5	—10,9	630	—31.4	—	—
3C-315	15 11 30.9	26 18,5	~1′	35	E+E	19 +19	—10.7	800	—31,2	—	—
3C-317	15 14 17	07 12.3	~0′,7	50	SO	12,5	—4,7	40	—25.2	$1,0\cdot10^{57}$	$1,0\cdot10^{-4}$
15+05	15 14 17	07 11	~40″	140	EO	$15^1/_2$	—9	160	—28.7	$1,7\cdot10^{59}$	$1,0\cdot10^{-4}$
Her-*A*	16 48 44	05 04	1′,9 (d)	890	(d)	18	—12.5	300	—31,3	$2,7\cdot10^{60}$	$6\cdot10^{-5}$
3C-327	15 59 55.5	02 06.3	2′,2	65	SO	17	—9,4	320	—29,9	$8,6\cdot10^{59}$	$7\cdot10^{-5}$
NGC6166	16 26 56	39 39,5	1′.5	85	E	14	—6,0	130	—27.3	$6\cdot10^{59}$	$5\cdot10^{-5}$
Cyg-*A*	19 57 44.5	40 35.8	1′,2 (d)	13000	(pec. d)	15,5+15.5	—13,6	220	—34.9	$4,2\cdot10^{60}$	$2\cdot10^{-4}$
3C-433	21 21 30	21 51.4	0′.5	35	E+E	17	—8.7	320	—29,2	—	—
22—09	22 21 23	—02 18	~45″	60	(pec)	17	—9	320	—29.8	$2\cdot10^{58}$	$7\cdot10^{-5}$

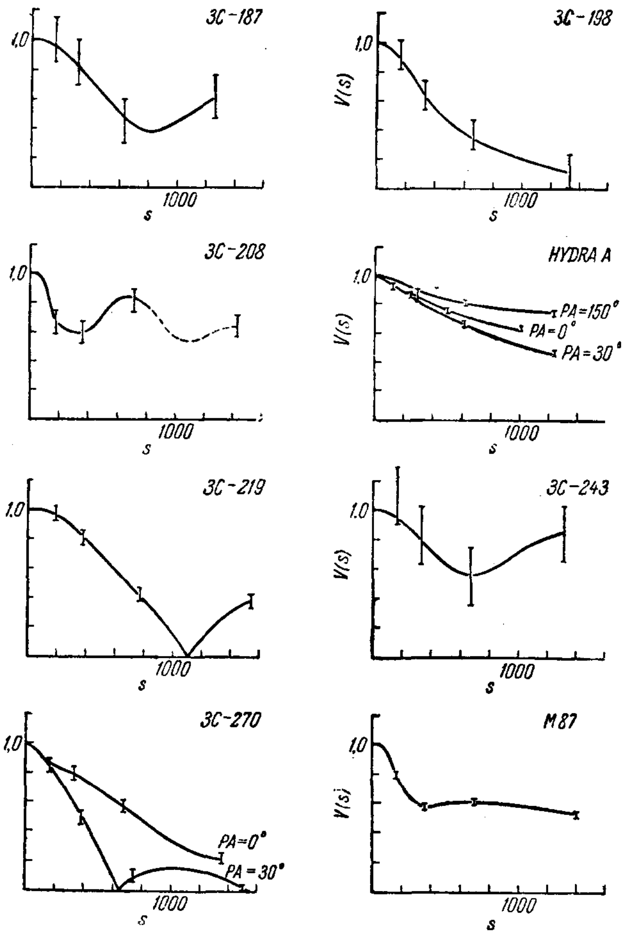

FIG. 22. Dependence of the amplitude of the interference pattern on the base length, for several sources.

are shown in Fig. 22. It follows from these curves that all the sources have a rather complicated intensity distribution. It must be assumed that reduction of these extensive data will soon yield many radio images of the sources. We must remember, however, that the results obtained are not always unequivocal.

Identification of a rather considerable number of sources with radio galaxies the distances to which are known has uncovered a possibility of plotting the "radio luminosity functions" of these objects. The radio luminosity of galaxies varies over a very wide range. For example, the flux from Cygnus-A on 960 Mcs is 1.2 times greater than from the extensive source Centaurus-A. Yet the former is 58 times farther away from us. It follows therefore that on this frequency the luminosity of Cygnus-A is approximately 4000 times that of Centaurus-A. Since the optical spectra of both sources (with the exception of the high-frequency region) are the same, the total luminosity (i.e., integrated over all frequencies) of Cygnus-A will be several thousand times greater than that of Centaurus-A.

In place of the fluxes and luminosities of the sources, "radio stellar magnitudes" are frequently used, in analogy with optical astronomy. The latter are expressed in terms of the radio emission flux from the sources on 160 Mcs in the following fashion:

$$m_r = -53.4 - 2.5 \log F_\nu, \qquad (3)$$

where F is expressed in units of W/m^2 cps^{-1}. The value of m_r so defined is close to the photographic magnitude for "normal" galaxies—late spirals. The difference $m_r - m_p$ between the radio stellar and photographic magnitudes, (called the radio index) characterizes the relative radio luminosity of any galaxy. The radio indices are listed in Table II. The greatest negative radio index (-13.6^m) is possessed by the most powerful radio galaxies Cygnus-A and 3C-295. Knowing the radio stellar magnitude and the distance to the galaxy, we can obtain in the usual manner the absolute radio stellar magnitude, which characterizes its radio luminosity

$$M_r = m_r + 5 - 5 \log r, \qquad (4)$$

where r is in parsec.

By "luminosity function" of a radio galaxy is meant the number of radio galaxies per cubic megaparsec, the absolute radio stellar magnitudes of which lie in a given interval. On the basis of known identifications, Bolton has compiled the luminosity function shown in Fig. 23 (circles). In addition, Bolton obtained the luminosity function by a different method, assuming that the dispersion of the linear dimensions of the sources connected with the radio galaxies is small (there are serious arguments in favor of this hypothesis, see Sec. 3). We can then estimate from the observed angular dimensions the distance to the radio galaxy, and consequently their absolute radio stellar magnitude. Consequently, the luminosity function is obtained in this case from the distribution of the sources over the angular dimensions. The initial material used by Bolton were angular dimensions of the sources, measured in California and in Manchester. The corresponding data are represented by the black circles in Fig. 23.

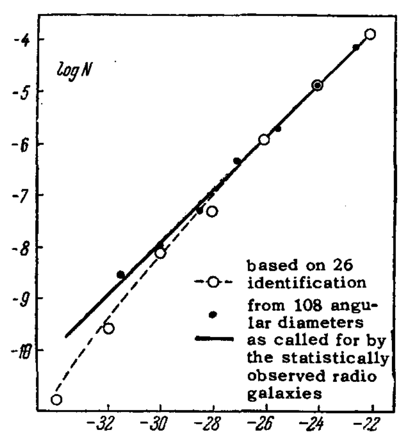

FIG. 23. Luminosity function of radio galaxies.

Both methods give very good agreement at low radio luminosities. At very high luminosities a certain systematic discrepancy is noted. It is also possible to obtain a radio luminosity function by counting the number of radio galaxies in a given interval of radio stellar magnitudes (straight line in Fig. 23). The so derived luminosity function agrees well with the function obtained from the distribution over the angular dimensions. The latter method gives apparently a more reliable result, particularly if we consider the difficulties connected with identifying weak objects that are quite far. We note that an almost analogous luminosity function was obtained by Mills.[57]

A fact worthy of attention is the negligibly small spatial density of the most powerful radio galaxies such as Cygnus-A or 3C-295 ($M_r \sim -34.6$). The densities per cubic megaparsec do not exceed 10^{-10}. This means that the average distance between two similar objects in the metagalaxy is somewhat greater than 1000 megaparsec. From this point of view, we are accidentally located very close to Cygnus-A, the distance to which is "merely" about 200 megaparsec.

The slope of the dotted log N vs. M_r curve is close to 0.5. It turns out in this case that the contribution to the integral brightness of the sky from sources with visible magnitude in the range from m_r to $m_r + 1$, will be larger than the contribution from all the sources that are brighter than m_r. In other words, the surface brightness obtained for the sky in this manner is represented by a divergent expression. The expression for the brightness of the sky converges if the slope of the log N vs. M_r line is ≥ 0.6. This calls for an increase of approximately one order of magnitude in the number of radio galaxies with $M_r = -35$. This is precisely how the straight line of Fig. 23 is obtained as a luminosity function based on calculations of the number of radio galaxies up to a given value of m_r.

Another interesting question is whether at low values of luminosity, $M_r > -22^m$, the luminosity function goes over into the luminosity function for the "normal" galaxies with $M_r \sim -18^m$ or -19^m. Extrapolation of the curve of Fig. 23 to $M = -18.5$ yields $\log N = -2$, a quantity which is apparently smaller than the density of normal spirals. However, the curve can also bend upward, so that the question of the possibility of a continuous connection between the radio galaxies and the normal stellar systems, within the framework of statistical analysis, still remains open. It is important to note that the radio luminosity per unit volume of the metagalaxy, as follows from the luminosity function, is determined predominantly by the radio galaxies with low luminosity. This fact is of great importance in cosmology.

What distinguishes radio galaxies from other galaxies, other than their exceedingly powerful radio emission? First, radio galaxies are objects which as a rule have very high optical luminosity. According to [40], the average absolute photographic magnitude of identified objects with known red shifts is -20.8^m. It is curious that for the radio galaxy NGC4782/3 the absolute photographic magnitude was found to be -17.6^m according to the old data, which so to speak "disturbed the harmony." At Bolton's request, Greenstein obtained the spectrum of this galaxy. From the red shift obtained for the lines in this spectrum it followed that the absolute magnitude of this system was -20.4^m, and everything fell into place.[58] Most radio galaxies are clusters, of which they are usually the brightest member. The clusters contain such objects as Cygnus-A, 3C-295, Virgo-A, Perseids-A, etc. At the same time, objects are encountered which do not belong to clusters, such as Centaurus-A. As a rule, the radio galaxies are gigantic spheroidal systems (E and SO according to Hubble's old classification). Yet objects are encountered with all the attributes of a spiral structure, for example NGC5128. Incidentally, in the latter case the bright spheroidal core is exceedingly large and produces most of the luminosity.

A typical spiral is the Seyfert galaxy NGC1068. In this case, however, the source of radio emission is connected with the bright and extensive core of this stellar system and has no relation at all to its spiral structure. Another spiral of irregular structure with a large core is NGC1275. It must be noted that such rare objects as Cygnus-A and 3C-295, where the greater part of the optical emission is concentrated in spectral lines, do not fit at all into the existing classification systems. On the other hand, most radio galaxies do not have spectral singularities distinguishing them from other analogous objects. Spheroidal galaxies exist with tremendous luminosities, which are not powerful sources of radio emission, for example M-86, which is in line with NGC4486. The remarkable jet, which is the most interesting morphological feature of NGC4486, is a most interesting formation, and may not be observed at all in the case of more remote galaxies. We note in this connection that the radio galaxy 3C-66 has a similar formation with even greater relative dimensions than in NGC4486.

What is striking is the large prevalence of duality, and multiplicity in general, in galaxies identified with sources of radio emission. According to [40], eleven out of the 25 reliably identified systems are dual. As already emphasized above, the duality of a radio source is not necessarily connected with optical duality of the corresponding radio galaxy.

Summarizing, it must be pointed out that so far there are no known reliable optical criteria by which to classify some particular galaxy as a radio galaxy without data on its radio emission.

Of great interest is the classification of radio galaxies. Do they include, for example, sequences, branches, or simple groups? Apparently, these should exist, although the shortage of observation data greatly hinders research in this important direction. We recall that the Herzsprung-Russel diagram has played a tremendous role in the development of astronomy. The empirically established principal sequence, the branch of giants, and other branches and sequences have been shown in the last decades to have significance from the evolutionary point of view. It would be quite desirable to have some analog of such a diagram for radio galaxies. So far, only a first attempt was made in this direction.

Mention should be made first of all of the interesting attempt made by Heeshen,[59] who investigated several sources on 68.2 and 21.4 cm. The ratio of the fluxes from the source to the flux from Cassiopeia-A, used as the standard, was measured. The radio stellar magnitudes were determined from these measurements [using formula (3)] for these wavelengths, after which the "radio color" was obtained

$$C = m_{21.4} - m_{68.2}.$$

If the spectra of the sources can be represented in the interval $21 < \lambda < 68.2$ cm by means of the power law (1), then it is easy to show that "radio color" should be proportional to the spectral index, i.e., $C \propto a$. Knowing the distances to several extragalactic sources, Heeshen was able to determine their absolute radio stellar magnitudes, after which he plotted the C vs. $M_{68.2}$ diagram shown in Fig. 24. It follows first from this diagram that the sources are distributed between two branches. The horizontal branch contains objects of low radio luminosity. These are normal galaxies, which have a great variety of spectral indices which do not correlate with $M_{68.2}$. On the other hand, there is a C-M correlation for radio galaxies in the sense that objects with very high radio-luminosity have the steepest spectrum. We note, however, that the number of points on the diagram is small and that spectral measurements are among the most difficult ones in astronomy. The presence of the horizontal branch may follow from the simple fact that the dispersion of M_r in the branches is small, and C is not reliably determined. We doubt the very existence of a "C-M" dependence for radio galaxies. For example, according to measurements made by Heeshen himself, the spectral index for Fornax-A and Centaurus-A is 0.77, whereas according to [44] it is approximately equal to 0.80 for Cygnus-A at $\lambda > 21$ cm. We note also that in Cygnus-A there is a sharp break in the spectrum in the vicinity of 20 mm (see Sec. 3), whereas in Centaurus-A and Fornax-A

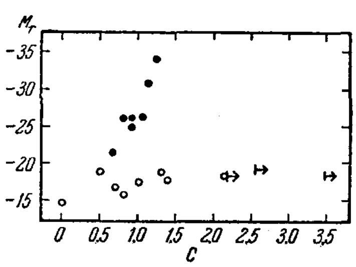

FIG. 24. The Heeshen diagram.

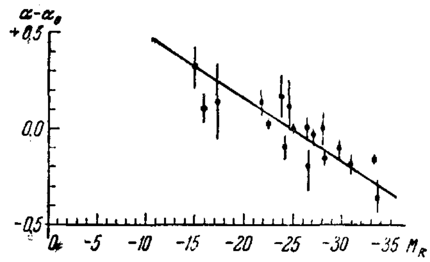

FIG. 25. The Pskovskiĭ diagram.

there are apparently no such breaks. The presence of a break in crude measurements may give rise to an apparent increased slope of the spectrum.

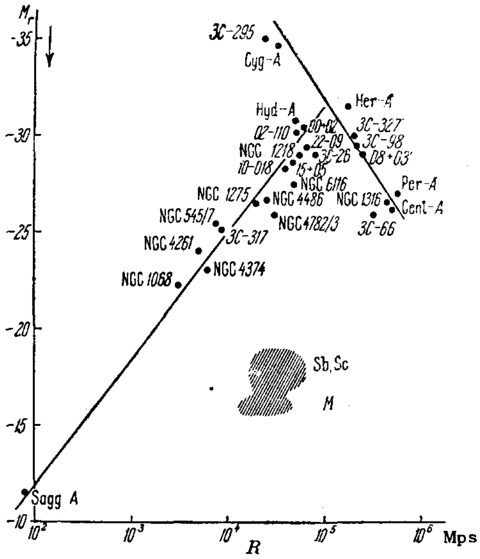

FIG. 26. Dependence of the absolute radio magnitude on the linear dimensions of the metagalacti c sources.

Pskovskii, independently of Heeshen, arrived at nearly the same conclusions, using the known data on the fluxes and spectral indices of the sources.[60] He also obtained the correlation between the spectral index and the absolute radio magnitude. The ordinates of Fig. 25 are the differences $\alpha - \alpha_0$ between the spectral indices of the sources and that of Virgo-A. The dependence obtained is even better than that obtained by Heeshen, and is furthermore based on much more extensive experimental material. Nevertheless, much more knowledge of the spectral indices and of the distances to the radio galaxies is necessary before we can finally accept the Heeshen-Pskovskii diagram.

We have plotted the effective linear dimensions of the sources vs. their absolute radio stellar magnitudes, using all the known observation data on the identification of class-II sources.[61] The results are shown in Fig. 26. We must emphasize that the concept of "effective dimension" has a somewhat arbitrary character, since the sources have complicated structures. It was necessary to treat each source as individually as possible. Figure 26 shows separately the extensive source near NGC1275 (which we call "Per-A"), it being assumed that the distance to this source is the same as to the indicated galaxy.

For several objects there are discrepancies between the different observations, particularly those made in the USA[40] and in Australia.[57] In those cases where there were no additional observations, we used the data of [57]. The black circles on Fig. 26 pertain to different radio galaxies. Their designations in the various systems are indicated alongside.

In spite of the rather large scatter of the points (which is apparently due to the insufficiency and inhomogeneity of the observed data), the correlation between M_r and the linear dimensions of the sources is quite pronounced. We see first of all on this diagram the sequence in which the "radio luminosity" increases statistically with increasing R. This sequence can be called "principal." It is quite curious that the Sagittarius-A source, which is identified with the core of our own galaxy, is situated in this sequence. Further, following this sequence towards the upper right, we encounter galaxies in which the radio emission in the region of the cores has much greater power and comes from considerably larger regions. This includes such objects as NGC1068, M-84, and NGC4261. Further in the sequence are the radio galaxies with rather high luminosity, among them NGC4486, NGC1275, and Hydra-A.

The radio galaxies of the principal sequence lie on a line corresponding to an approximate dependence of the radio luminosity on the linear dimensions R

$$L_r \propto R^{2.5}. \tag{5}$$

Such a dependence denotes that the average radiation from a unit volume decreases very slowly with increasing R. An important feature of the sources of this sequence is that they lie within the limits of the corresponding galaxies.

The second sequence of the radio galaxies can be called "the sequence of giants." It extends from the strongest of the presently known sources, Cygnus-A and 3C-295, through Hercules-A, to objects with large linear dimensions and small surface brightness such as Centaurus-A and Fornax-A. A characteristic of this sequence is the rapid decrease in the radio luminosity with increasing R. Another important feature of this sequence is the sharp disagreement between radio and optical radiations. As a rule, the sources of this sequence consist of two components symmetrically located at a considerable distance from the "optical" galaxy.

Of course, future observations will introduce appreciable corrections to the diagram of Fig. 26. Apparently, however, the main sequences first disclosed by this diagram remain the same as before. In Sec. 3 we shall discuss the possible interpretation of the sequence of giants.

3. THE NATURE OF RADIO GALAXIES

A major accomplishment of theoretical radio astronomy was the determination of the mechanism whereby the radio emission of discrete sources is produced. Knowledge of the mechanism of radio emission enables us to estimate many of the most important characteristics of the sources, and above all the energy consumed in their formation. Of course, we could not attempt to discover the nature of the sources of cosmic radio emission without knowing anything about the mechanism of generation of radio waves in these sources.

During 1946—1950 there was no lack of hypotheses concerning both the emission mechanism and the nature of the sources. All, however, turned out to be inconsistent. One can readily understand the desire of astronomers and physicists to interpret a new phenomenon somehow even when few facts are still available.

In 1950 Alven and Herlofson[62] advanced a new hypothesis concerning the nature of cosmic radio emission. An analogous hypothesis was suggested almost simultaneously by Kiepenheuer.[63] According to this hypothesis, cosmic radio emission is caused by bremsstrahlung of relativistic electrons in interstellar and near-stellar magnetic fields. In those days information on cosmic radio emission was still most scanty. Therefore, for example in [62], use was made of rather strange and absolutely incorrect notions concerning these sources, which were regarded to be singular regions near certain stars.

In the USSR, all the potentialities of this hypothesis were immediately appreciated. The theory (speaking of its physical aspects) received further development in the works of V. L. Ginzburg, G. G. Getmantsev, N. V. Razin, and others, which in turn were based on earlier research by Soviet physicists (see, for example, the review [64]). In particular, a formula was derived relating the spectral index of the source with the energy distribution parameter of the relativistic element. Starting with 1952, the author of the present article applied the new theory to various specific radio astronomical objects (the corona of our galaxy, the Crab nebula, Virgo-A, and others). The theory explained all the main features of the radiation from these sources. It is particularly important that we were able to predict on the basis of this theory a few principally new important phenomena, concerning the existence of which nothing was known at all at that time, and which shortly following the predictions were observed as a result of setting up special observations (polarization of the optical and radio emission from the Crab nebula, the NGC4486 jet, the secular decrease in the flux of radio emission from Cassiopeia-A). By the same token, the theory turned out to be completely correct and has assumed a leading role in many radio astronomical researches. In particular, its greatest success was the creation in our country of a radio astronomical theory of the origin of cosmic rays.

It was only then that the West began to pay attention to the "magnetic-bremsstrahlung" theory of cosmic radio emission, which was then applied to various specific problems. By now this theory has gained full recognition. The mechanism itself has been named the "synchrotron" mechanism, a term we shall use from now on. We give below a brief summary of the main formulas of synchrotron radiation which we shall use henceforth. The derivation of these formulas is contained in the review [64]. The energy radiated by a relativistic electron per second in the frequency from ν to $\nu+\Delta\nu$ is

$$P(E,\ \nu)=16\frac{e^3H_\perp}{mc^2}p\left(\frac{\omega}{\omega_m}\right), \quad (6)$$

where $\omega_m = (eH/mc)(E/mc^2)^2$ and $H_\perp$ is the field component perpendicular to the electron velocity; p is a certain function which reaches a maximum (= 0.10) at $\omega \approx 0.5\ \omega_m$. We have $p \sim (\omega/\omega_m)^{1/3}$ for small ω/ω_m and $p = \exp[-\frac{2}{3}\omega/\omega_m]$ for large ω/ω_m. The intensity of radio emission from a given source is

$$I_\nu \equiv \frac{2kT_b}{\lambda^2}=\frac{1}{4\pi}\int P(E,\ \nu)\,N(E,\ \mathbf{r})\,dE\,d\mathbf{r}, \quad (7)$$

where T_b is the brightness temperature, and $N(E,\mathbf{r}) = K/E_\gamma$ the differential energy spectrum of the relativistic electrons in a small region of the source with coordinates $\mathbf{r}$. Calculations yield (assuming that N is independent of $\mathbf{r}$)

$$I_\nu \equiv \frac{2kT_b}{\lambda^2}=\frac{3}{\pi}(2\pi)^{1-\gamma/2}\frac{e^3H_\perp}{mc^2}\left(\frac{2eH_\perp}{m^3c^5}\right)^{\gamma-1/2}u(\gamma)KR\nu^{1-\gamma/2}$$
$$=1.3\cdot 10^{-22}(2.8\cdot 10^{\gamma})^{\gamma-1/2}u(\gamma)\,KH_\perp^{\gamma+1/2}R\lambda^{\gamma-1/2}, \quad (8)$$

where $u(\gamma)$ is 0.37, 0.16, 0.125, and 0.087 for γ = 1.3, 5, 2, and 3 respectively, while R is the dimension of the source.

Formula (4) leads to an important relation between the spectral index α of the source, defined by formula (1), and the exponent γ in the differential energy spectrum of the relativistic electrons:

$$\alpha=\frac{1-\gamma}{2}. \quad (9)$$

Thus, the power-law character of the spectrum of a radio source is naturally explained by the power-law character of the differential energy spectrum of the relativistic particles. Direct experiments have confirmed that the differential energy spectrum of the primary cosmic rays near the earth indeed follows a power law. This is undoubtedly connected with their acceleration mechanism, and we must assume that the main features of this mechanism have a similar character in different cosmic objects. It is possible that such acceleration is brought about by some modifications of the Fermi classical mechanism.

A major success of the theory was the explanation on the optical emission from the jet of NGC4486 (discussed in Sec. 2) as being due to synchrotron radiation.[67] The radiation is produced in this case by electrons of rather high energy, $\sim 10^{11}-10^{12}$ keV, whereas the low-energy electrons are responsible for the radio emission of NGC4486. On the basis of this theory, we have predicted that the radiation from this jet is linearly polarized, as was soon observed in practice (see below).

The great significance of formula (8) lies in the fact that it enables us to estimate the total energy of relativistic electrons from the measured radio fluxes from the sources, from the measured spectral index, and from the measured distances to the sources; under some natural assumptions it also enables us to estimate the total energy of all relativistic particles, as well as the total magnetic-field intensity in the sources. It goes without saying that this is of exceeding importance for the understanding of the nature of these sources.

The first such estimates were made as long ago as 1953–1955.[66,67]. In 1958 Burbige[68] made similar calculations for several galactic and metagalactic radio sources. Rather detailed calculations were made by A. A. Korchak.[69]

Without going into details of these calculations, we cite only the results. Formula (8) enables us to determine the total energy of relativistic electrons in any source

$$E_e=vK\int_{E_1}^{E_2}E^{1-\gamma}\,dE,$$

where v is the volume of the source (the values of the integration limits are discussed in [69]). The magnetic field is assumed known. Generally speaking, radio astronomical observations do not enable us to determine H, at least at present. There are grounds for assuming, however, that the total energy of all the relativistic particles (essentially heavy nuclei) cannot exceed the magnetic energy of the source. Otherwise the relativistic particles could not be retained in the vicinity of the source.[70] We note, however, that this statement cannot yet be regarded as rigorously proved. We therefore make the simpler assumption that the total energy of all the relativistic particles is proportional to the magnetic energy, i.e.,

$$E_e=k_1E_H=k\frac{H^2}{8\pi}\cdot\frac{4}{3}\pi R^3=\frac{kH^2R^3}{6}, \quad (10)$$

Where R is the radius of the source. It is assumed further that the total energy of the heavy nuclei (predominantly protons) is k_2 times greater than that of the relativistic electrons and positrons responsible for the synchrotron radiation, i.e.,

$$E_p=k_2E_e. \quad (11)$$

We then have

$$H=\left(6\frac{k_2}{k_1}\frac{E_e}{R^3}\right)^{1/2}. \quad (12)$$

The accuracy of these calculations is estimated in [69] at 10%. The radio fluxes from the strong sources are known to the same degree of accuracy. The distances to the sources are known much less accurately (among other reasons, owing to the indeterminacy in Hubble's constant). It seems to us, however, that the complicated distribution of the brightness within the limits of the sources (for example, the duality of the sources) can lead to rather appreciable errors. Later on, when the "radio images" of the sources become more clearly outlined, such calculations can be repeated for specific objects. Let us point out still another circumstance. Equation (8) contains $H_\perp$, whereas (10) contains the total value of H. In order for the calculations to be meaningful, it is necessary to assume that $H_\perp$ is approximately equal to H. This condition is most likely to be satisfied, although in individual cases we can have $H_\perp \ll H$. We note also that when $k = 1$ the value of the summary energy $E_P + E_M$ obtained for any source is a minimum.

We have recalculated $E_P + E_M$ and H for several objects, including those not considered in [68] and [69]. The calculations were made for a model with $k_1 = 1$ and $k_2 = 30$; the limits of the frequency spectrum of the sources were $\nu_1 = 10^7$ and $\nu_2 = 10^{10}$ cps. The assumption that $k_2 = 30$ was made in analogy with the cosmic rays near the earth. This assumption is quite natural if we recognize that the relativistic electrons in the sources are of secondary origin (i.e., they were formed by nuclear collisions between relativistic and semi-relativistic protons), and if we take into account the fact that the relativistic electrons moving in the magnetic field experience considerable losses to synchrotron radiation. Nonetheless, we cannot exclude the possibility that k_2 may be considerably less in individual sources, for example ~ 1; calculations were made for this case, too, but were not listed in Table II.

The total energy of the relativistic particles and of the field will be proportional (approximately) to

$$E_P + E_M \propto F_\nu^{4/7} r^{17/7} \varphi^{-9/7} \left(\frac{k_2}{k_1}\right)^{-3/7}, \quad (13)$$

and the magnetic field intensity is proportional to

$$H \propto F_\nu^{2/7} r^{-2/7} \varphi^{-6/7}, \quad (14)$$

where r is the distance to the source φ —its angular size. The last and next to the last columns in Table II contain the results of these calculations for certain sources of class II.

To make the significance of the numbers in Table II even clearer, we recall that our own galaxy, as well as other large spirals of later types (for example, the Andromeda nebula, M-31) have a radio luminosity $\sim 10^{38}$ erg/sec, i.e., several million times smaller than Cygnus-A. The total energy of the cosmic rays contained in our galaxy can be estimated to be 10^{56} erg. We know that the last quantity can by no means be regarded as small. It is useful to compare the energy of the relativistic and semi-relativistic particles in the radio galaxies, and the magnetic energy of the galaxies with the maximum energy resources of a "normal" giant galaxy (say M-31). For example, the kinetic energy of rotation of such a galaxy is $\sim 10^{58}$ erg, and the gravitational potential energy (i.e., the energy of the gravitational coupling between all the stars and nebulas contained in the galaxy) is only a little greater.

Thus, the energies on the order of 10^{60}—10^{61} erg, which were drawn from some sort of "reservoir" to form a sufficiently large number of relativistic particles and the magnetic field, are exceedingly large. What kind of energy reservoir is this? Under what circumstances does it operate? Theory should be able to answer this basic question. For this purpose it is necessary first to analyze most thoroughly all the known facts on the individual radio galaxies, and only then can we attempt to fit them into a single orderly noncontradictory system. We note that the last problem is exceedingly difficult and so far has no universally accepted solution.

We now consider individual objects, the optical and radio astronomical characteristics of which are known relatively well, and attempt to analyze the physical conditions in these objects.

NGC4486. The use of the "synchrotron" theory in the interpretation of the observations reported in Sec. 2 turns out to be particularly successful in the case of this galaxy. In 1954 we advanced and subsequently proved the hypothesis that the optical radiation of the jet referred to in Sec. 2, is of synchrotron nature. [67] The brightness of the jet was estimated in [67] at 13^m. (This estimate was confirmed by observations reported in [71].) Using the usual calculation procedure, based on formulas (18)—(10), we estimated that $H_\perp \sim 10^{-4}$ and consequently the energy of the relativistic electrons responsible for the optical radiation of the eruption is $E \sim 5 \times 10^{11}$ eV. The values of both $H_\perp$ and E in the jet of NGC4486 are sufficiently close to the corresponding values in the Crab nebula, for the optical radiation of which (with a continuous spectrum) a similar hypothesis was advanced by us as long ago as in 1953. [66] However, the space-time scale in NGC4486 is many orders of magnitude greater than in the Crab nebula.

If the optical radiation is of synchrotron origin, we can expect it to be linearly polarized. This prediction was indeed made in [67]. The following year the expected polarization was observed by Baade with the 5-meter Palomar reflector. [72] He photographed the central part of NGC4486 through a polaroid filter placed in two orientations. These photographs (Fig. 27) show quite clearly the strong polarization of the condensations of the jet. Figure 28 shows the results of electrophotometric polarization observations made by Hiltner.[73]

The polarization of individual consensations reaches about 30%. What is striking is that the polarization has different directions in different jets (the difference almost reaches 90°). An interesting regularity was traced in four condensations, in that the direction of the polarization approximately repeated every other

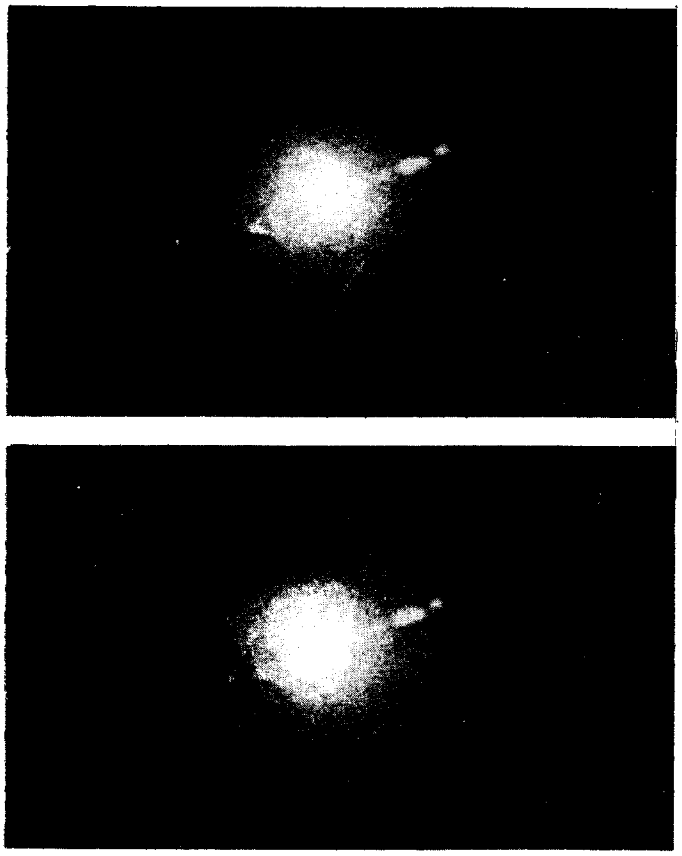

FIG. 27. Photograph of the jet of NGC4486 taken through a polaroid filter.

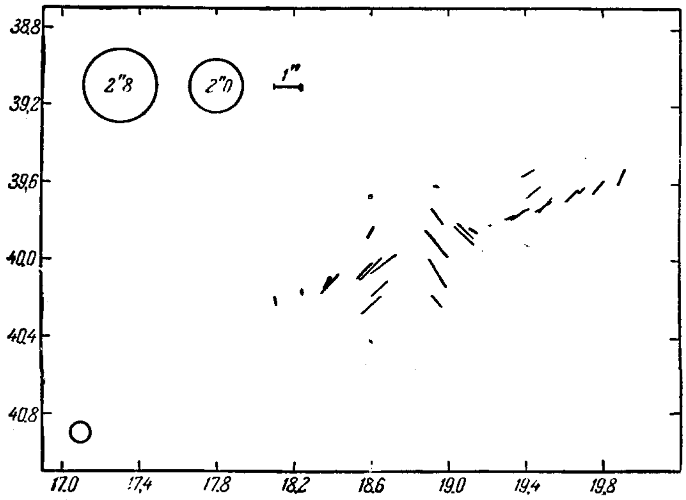

FIG. 28. Polarization of the central portion of NGC4486 in accordance with electrophotometric observations.

condensation. From the theory of synchrotron radiation it is known that the direction of the magnetic field is perpendicular to the direction of the polarization. Therefore a rough scheme of the direction of the magnetic fields has the appearance shown in Fig. 29.

If the optical radiation of the NGC4486 jet is synchrotron radiation, we can also expect radio emission from it; this was predicted in [67]. Such emission was indeed observed five years later on 21 cm (see the figures of Sec. 2). This was followed by observation of a weak ($\sim 3\%$) polarization of the jet on the same wavelength.[74] It is not surprising that the observed degree of polarization of the radio emission of the jet is considerably lower than that of its optical radiation. Since the individual jet condensations cannot be observed and the radio band (their dimensions are $\sim 2''$) and the polarization directions differ greatly, the integral polarization effect will of course be small. V. I. Moroz analyzed the available data on the spectrum of NGC4486 and its jet in the radio and optical bands. From the fact that Mills observed no radio emission on $\lambda = 3$ m from the jet (although the bases he used reached 3400λ, corresponding to an angular resolution $\sim 1'$) it is concluded in [71] that in the $100 < \nu < 1400$ Mcs region the spectral density of the radio flux is practically independent of the frequency (spectral index $\alpha \sim 0$), and becomes steeper at higher frequencies. The "break" in the spectrum occurs somewhere in the 10—20 cm range, and the spectral index increases by approximately 0.5—0.6. According to [71], the total synchrotron radiation power of the jet, integrated over all $\lambda > 3400$ Å, amounts to about 10^{43} erg-sec.*

The "break" in the spectrum can be attributed to the energy consumed in synchrotron radiation of the relativistic electrons moving in the magnetic fields. According to [64], if the relativistic electrons are continuously injected with a spectrum $E^{-\gamma}$, then synchrotron radiation will cause them to have a "steeper" spectrum $E^{-(\gamma+1)}$, starting with an energy

$$E > E_0 = \frac{8.35 \cdot 10^8}{H_\perp^2 t_0}, \qquad (15)$$

where t_0 is the injection time (in years). From (15) it follows that

$$H_\perp \approx 700 \nu_0^{-1/3} t_0^{-2/3}, \qquad (16)$$

where $\nu_0 = 2.9 \times 10^{-11} E_0^2 H_\perp$ is the frequency of the point of inflection in the synchrotron-radiation spectrum. The spectral index α for an $E^{-(\gamma+1)}$ spectrum will be larger by 0.5 then for an $E^{-\gamma}$ spectrum [$\alpha = (\gamma - 1)/2$]. According to [79], this is precisely the "inflection" observed in the spectrum of the NGC4486 jet. Therefore, assuming $t_0 \approx 10^6$ years, $\nu_0 \approx 10^9$ cps, it was found in [71] that $H_\perp \approx 10^{-4}$. In light of Bless's most recent work, this question should be reviewed (see the last footnote).

*Recently Bless [Astrophys. J. 135, 187 (1962)] carried out a spectrophotometric investigation of the optical radiation of the NGC4486 jet. The stellar magnitude of the jet (in blue light) turned out to be 14.1. The color index (λ 4350—6300) is 0.73 ± 0.15, which corresponds to a spectral index $\alpha = 2.56 \pm 0.30$. Consequently $\gamma = 6.2$. Thus, the synchrotron radiation of the jet rapidly "collapses" at optical frequencies. The total radiation power in the frequency interval $2.5 \times 10^{14} < \nu < 10^{16}$ is 0.8×10^{42} erg/sec. We shall use this value of the power below.

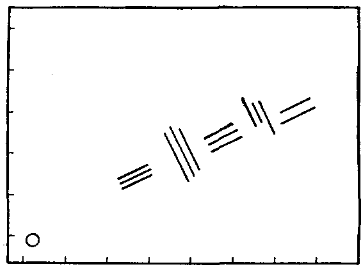

FIG. 29. Diagram of magnetic fields in the center of NGC4486.

We now proceed to estimate the energy of the relativistic particles and of the field in the jet. The jet radiates about 10^{42} erg per second. On the other hand, the time $t_{1/2}$ during which the electron radiating in the magnetic field loses half its energy is

$$t_{1/2} = \frac{0.00835}{H_\perp^2 E} \text{ years,} \tag{17}$$

where E is in units of 10^9 eV. It follows from (17) that when $H_\perp \approx 10^{-4}$ and $E \sim 5 \times 10^2$ BeV, we have $t_{1/2} = 1.5 \times 10^3$ years. On the other hand, the lifetime of the jet is about 3×10^{13} sec, i.e., much longer than $t_{1/2}$. This means that it is reasonable to assume that the electrons are continuously replenished in the jet. Such an injection may be caused by some rather powerful acceleration mechanism, which compensates for the radiation losses. Another source are nuclear collisions, which result in the formation of relativistic electrons and positrons following the pion decay. We shall consider only nuclear collisions here. We can then readily estimate the energy of the relativistic (heavy) particles contained in the jet. Assuming that in each nuclear collision about 5% of the initial energy of the relativistic protons is transferred to the relativistic electrons and positrons, we find that the sought energy is

$$E_p \sim 10^{42} \cdot 3 \cdot 10^{13} \cdot 20 = 6 \cdot 10^{56} \text{ erg}. \tag{18}$$

The length of the jet, within the framework of these concepts, is determined by the nuclear lifetime of the relativistic particles contained in it, $t_{nuc} \gg t_{1/2}$. We denote by n the concentration of the gas in the jet condensations by $\sigma = 2.5 \times 10^{-26}$ cm^2 the effective cross section of nuclear collisions of relativistic protons, by V the velocity of the jet, and by l its length; we then have

$$t_{nuc} = \frac{1}{cn\sigma} = \frac{l}{V}. \tag{19}$$

According to (19), $n = V/cl\sigma$ cm^{-3}. If $V = 3 \times 10^8$ cm/sec and $l = 5 \times 10^{21}$ cm, then $n \sim 30$ cm^{-3} and the density is $\rho \sim 10^{-22}$ g/cm^3. Since the volume of the jet is about 5×10^{61} cm^3, we find its mass to be $M \sim 5 \times 10^{39} \approx 2 \times 10^6 M_\odot$, and the kinetic energy of the moving gas is about 2×10^{55} erg. If the velocity of the jet is about 5×10^8 cm/sec, then the kinetic energy is comparable with the energy of the relativistic particles and magnetic fields contained in the jet. In this case each of these forms of energy amounts to 10^{57} erg, and the lifetime of the jet is 200,000 years. We note that if $V = c$ in this scheme, then $M = 2 \times 10^8 M_\odot$, and the kinetic energy of the jet becomes incommensurably larger ($> 10^{60}$ erg).

The deduction that the jet should contain gas with mass $\sim 10^6 M_\odot$ follows also from other independent considerations. Let us examine the physical conditions in the core of NGC4486. As can be seen from the profile of the λ3727 line observed in the core of this galaxy (see Fig. 8), a considerable portion of the interstellar gas located there has macroscopic velocities close to or exceeding the parabolic velocity. The radial component of this velocity is about 900 km/sec. It can be assumed that the total velocity will be about 1500 km/sec. At such a velocity, obviously, the moving gas masses should leave the core of NGC4486, the dimensions of which are ~50 parsec, within a time $t \sim 5 \times 10^{11}$ sec or 15,000 years. As can be seen from the profile of the λ3727 line in Fig. 8, the total intensity of the "shifted" component is one third that of the "unshifted" one. This means that practically all the ionized interstellar gas contained in the core of NGC4486 should leave it within 50,000 years. On the other hand, the emission from the NGC4486 core, $\int N_e^2 \, dr$, can be estimated in accordance with the available data [22] at roughly $\sim 10^5$. Thus, allowing for the dimensions of the core, we can estimate that $N_e \sim 45$ cm^{-3}, which corresponds to an average interstellar ionized gas density $\rho_{gas} = 10^{-22}$ g/cm^3. Consequently, the total mass of the ionized gas in the core of this galaxy is about 4×10^{38} g or $2 \times 10^5 M_\odot$.

It is quite probable that the "shifted" component of the λ3727 profile, corresponds to the next "condensation" of the jet, now "being formed" in the NGC4486 core. Within about 10^6 years, about 10 "plasmons" will be ejected from the core of this galaxy, with a total gas mass $\sim 10^6 M_\odot$,* in accord with the independent estimate made above.

Two questions arise in connection with the foregoing calculations:

a) What replenishes the gas in the core of NGC4486? To replenish the reserve of interstellar gas in the core of NGC4486 it is necessary to "inject" there $> 10^{34}$ grams or $5 M_\odot$ every year (since the core may still contain a considerable quantity of neutral gas). This gas, generally speaking, may be supplied by the stars (for example, supernova flares, formation of planetary nebulas by stellar collisions, etc). It is most likely, however, that these sources are clearly insufficient. Another possible mechanism is the entry of gas into the core from the surrounding space. The NGC4486 core is a rather deep "potential well" where intergalactic gas can "seep in." Even about ~100 kiloparsec from the NGC4486 core the parabolic velocity is about 400 km/sec. Conse-

*Because the core may also contain neutral gas (see below).

quently if the kinetic temperature of the intergalactic gas is below several million degrees, and its density is about 10^{-29} g/cm^3, then it can be readily shown that the equivalent of many dozens of solar masses will be continuously captured and enter the core (for more details see [61]).

It must be noted that escape of gas from galactic cores is a rather widespread phenomenon. This is observed, in particular, in our own galaxy and in M-31. It is very clearly apparent in Seyfert galaxies. Even in these cases, the question of the mechanism whereby the cores are replenished with gas is quite acute. In all cases the "reservoir" is apparently the intergalactic medium.

b) Why are no emission lines, particularly λ3727, observed in the condensations of the jet, where a considerable amount of interstellar gas can exist?

There are two possible explanations: 1) for some reason or another the gas becomes very hot after leaving the core, 2) the gas becomes cold and neutral. The first possibility is not very likely. The known forbidden coronal lines should be observed even at $T_e = 10^6$. Only at very high temperatures ($\geq 10^7$) will the emission lines be weak. The second possibility is more probable. If there are no sources of ionization, then it can be readily shown that when $N_e \sim 50$ cm^{-3} the hydrogen and oxygen ions should recombine during the time that they move in the core ($\sim 5 \times 10^{11}$ sec). On the other hand, calculations show that even a high concentration of cosmic rays in the jet cannot appreciably ionize the neutral gas contained there.

That the jet should contain very little ionized gas follows from the observed polarization of its radiation on 21 cm.[74] If the amount of ionized gas were sufficient, there would be no polarization at all in the presence of a magnetic field, owing to the Faraday effect. In fact, according to [75], the polarization plane is rotated by an angle

$$\psi = 10^6 \cdot N_e H l \cos\alpha$$

(l — length of the magneto-active medium, α — angle between the vector H and the line of sight). When $H > 10^{-4}$, $l = 2 \times 10^{20}$ cm (thickness of jet), $\cos^2\alpha = 1/2$, $N_e < 0.01$ cm^{-3}, if $\psi < 1$.

If the jet contains considerable amounts of neutral hydrogen, then, recognizing that more than half of the 21 cm radiation from Virgo-A is in the jet,[24] we should expect a weak rather broad absorption line in its radio spectrum (approximately 1 Mcs). It should be shifted by −1.6 Mcs from the standard 1420 Mcs frequency. It would be very interesting to verify this assumption by means of special observation.

If it is assumed that electrons of very high energy are continuously injected into the jet because of nuclear collisions, then NGC4486 should be a powerful source of a very hard radiation. In fact, in the case of nuclear collisions of the type under consideration approximately twice as much energy goes over into γ radiation as into relativistic electrons and positrons. The energy of the produced γ quanta will be of the same order of magnitude as that of the relativistic electrons and positrons, i.e., 3×10^{11}—10^{12} eV. The flux of these quanta on earth will be about 10^{-9} erg/cm^2 sec. Modern physical experimentation techniques permit such radiation fluxes to be detected. Either a positive or a negative result of such observations would be extremely valuable, since it would afford a confirmation or a refutation of the hypothesis of nuclear collisions as injectors of "radiating" relativistic electrons in NGC4486.

We have assumed above that $V \approx (1-5) \times 10^8$ cm/sec. One could start at the very outset from a different point of view. Namely, let us assume that the jet and its condensations result from motion of relativistic particles (generated in the region of the core of NGC4486) in an external almost homogeneous magnetic field. In this case the velocity of the radiating agent is approximately equal to c, and the lifetime of the jet is $t_0 \sim 5 \times 10^3$ years. However, under such an assumption, assuming that a break in the spectrum exists at $\nu = 10^9$, we would get from (16) $H_\perp \sim 3 \times 10^{-3}$, and consequently, according to (17), $t_{1/2} \sim 10$ years $\ll t_0$. It cannot therefore be assumed that the radiating agent that produces the NGC4486 jet moves with velocity c.

The assumption that the condensations of the jets are clouds of magnetized gas and relativistic particles, ejected for some reason from the NGC4486 core (we shall henceforth call such clouds "plasmons") raises a serious difficulty. It is seen from Fig. 7 that the angular dimensions of the condensations ($\sim 2''$), as well as their brightness, are practically independent of their distance to the core of NGC4486. Yet the length of the jet exceeds 1000 parsec. It is utterly impossible to understand why the condensations do not broaden (as the result of magnetic pressure and the pressure of the relativistic particles) and, consequently why their brightness does not decrease rapidly. If the total energy of the relativistic particles in each condensation is $E_p \sim 10^{56}$ erg (see above), then the magnetic field required to confine it to a limited region with volume $\sim 10^{61}$ cm^3 is $H \sim 10^{-2}$ G, a very large quantity. At first glance one might think that the rate of expansion will be of the order of the hydromagnetic velocity $V_H = H/\sqrt{4\pi\rho} \sim 1.5 \times 10^9$ cm/sec, and that within a time $\sim 3 \times 10^{13}$ sec the jet condensations will expand to $\sim 10^4$ parsec, which is a hundred times larger than that observed. One could assume that the jet condensations move in an external rather strong ($\sim 2 \times 10^{-2}$) magnetic field. It is very difficult, however, to understand why this field should be practically homogeneous over about 1000 parsec (otherwise the condensations would spread).

A possible explanation of the lack of a noticeable expansion of the condensations in the jet of NGC4486 is as follows. The plasmons, moving with faster than magnetohydrodynamic velocity, "crush" the force lines of the weak external magnetic field and "draw" them along. At the same time, a unique "boundary layer" is created around the jet, where the external field (parallel to the direction of motion) is greatly reinforced. This field "pinches" the moving plasmon and prevents it from expanding rapidly. The rate of its expansion will in this case be close to the magnetohydrodynamic velocity in the medium surrounding the plasmon. If, for example, $H \sim 10^{-6}$ and $\rho \sim 10^{-26}$ in this medium, then $V_H = H/\sqrt{4\pi\rho} = 3 \times 10^6$ cm/sec, and the plasmon will not expand appreciably after 3×10^{13} sec.

The presence of a preferred direction, in which the ejection of individual plasmons takes place, is also an interesting and difficult problem. It is possible that this direction is close to the axis of rotation of the NGC4486 core. An analogous phenomenon is observed also in NGC5128 (see above).

There is no doubt, apparently, that the relativistic particles located in an extensive source ($\sim 5'$) in the NGC4486 galaxy are due to earlier jets. The total energy of these particles is $\sim 2 \times 10^{58}$ erg (see Table II), i.e., some 40 times greater than in the jet. One must bear in mind, however, that the energy of the particles in the jet has not been estimated with sufficient reliability, since it depends on the assumed lifetime of the jet. Under all conditions we obtain a rather interesting result: the age of the "radio emitting phase" of NGC4486 is $\sim (2-5) \times 10^7$ years. It would be very important to obtain as detailed a picture as possible of the brightness distribution of the extensive source in NGC4486. We can expect some curious and unexpected discoveries, which will help understand the nature of this remarkable radio galaxy.

NGC5128. This radio galaxy has two bright sources of small angular size (see Fig. 11), which apparently are completely analogous to the NGC4486 jet. In both cases ejection of plasmons from the cores of the corresponding galaxies is observed. The only difference is that the synchrotron radiation of the NGC4486 jet is observed also in the optical part of the spectrum, while in NGC5128 it is observed only in the radio band. This, however is not a principal difference. In the case of NGC5128, the plasmons are ejected from the core in a direction close to the axis of rotation of this galaxy. There is no doubt that the two extensive sources, symmetrically situated on both sides of NGC5128, are "replenished" by the plasmons ejected from the core.

From formulas (8) and (10) we can estimate, using the existing observation data, the energy of the relativistic particles contained in each of the two small bright sources located not far from the core of NGC5128. Calculations yield $E_p \sim 10^{57}$ erg, i.e., about 300 times less than in the entire extensive Centaurus-A source (see Table II). It follows from the same calculations that $H \sim 2 \times 10^{-4}$, i.e., 10 times larger than in the extensive source. On the other hand, the small source in NGC5128 has a radio luminosity that is only three times smaller than the extensive source of Centaurus-A. From an examination of the energies of the relativistic particles and the fields in the extensive and small sources of Centaurus-A it follows that for the formation of the extensive source it is necessary to have several hundred "plasmons" of the type that now are small bright sources. We thus arrive at the important conclusion that when the "plasmon" enters the region of the extensive Centaurus-A source its radio emission power decreases by 100 times. This phenomenon must be attributed to the reduced magnetic field intensity in the plasmons. This reduction is a natural explanation for the expansion of the plasmons.

We have developed in [76] a theory of the secular decrease in the radio luminosity of expanding sources and derived there a fundamental formula

$$L_\nu \propto R^{-2(2\alpha+1)}, \qquad (20)$$

where α is the spectral index of the source and R its radius. Formula (20) has been obtained under the assumption that $H \sim R^{-2}$. The secular decrease in the radio emission flux from Cassiopeia-A, predicted in [76], was indeed observed,[77] thus proving the correctness of (20). According to (20), when $\alpha = 0.7$, in order for L to decrease to one-hundredth R should increase approximately threefold. In this case H should decrease to one-tenth, in good agreement with the independent estimate made above.

Thus, the assumption that the extensive Centaurus-A source is made up of several hundred components (plasmons), each of which expands as it moves away from the core of NGC5128, can be regarded as demonstrated.

Cygnus-A. It is seen from Fig. 17a that the spectrum of Cygnus-A experiences a break at $\nu_0 = 1500$ Mcs, wherein the spectral index is $\alpha = 0.75 \pm 0.05$ for $\nu < 1500$ Mcs and $\alpha = 1.25 \pm 0.1$ for $\nu > 1500$ Mcs. Such an increase in α, amounting to 0.5, can signify that an effective "modification" of the energy spectrum of the relativistic electrons is produced in the source, by losses to synchrotron radiation. A similar case is encountered in the jet of NGC4486. The analysis of the "break" in the radio spectrum of Cygnus-A is the subject of an interesting paper by Kardashev, Kuz'min, and Syrovat-skii.[78]

It is shown for the first time in [78] that if the "initial" differential spectrum of the injected electrons has the form $dN(E) = KE^{-\gamma}dE$, then the synchrotron radiation losses give rise to the following changes in the spectrum:

a) the spectrum has the form $dN(E) = K_1E^{-\gamma}dE$ in the low-energy region.

b) the "primary" spectrum $dN(E) = K_2E^{-\gamma}dE$ is retained at intermediate energies.

c) $dN(E) = K_3 E^{-(\gamma+1)}$ in the region of high energies. It follows from (16) that the age of the source is

$$t_0 = 1.9 \cdot 10^4 \cdot H_\perp^{-3/2} \nu_0^{-1/2}. \qquad (21)$$

It is assumed here that the rate of injection remains constant during the entire evolution of the source. The value of $H_\perp$ can be taken from Table II. If the relativistic particles in Cygnus-A are predominantly electrons (i.e., $k_2 = 1$), then $H_\perp = 2.6 \times 10^{-5}$ and at the frequency of the spectrum "break," $\nu_0 = 1500$ Mcs we have $t_0 = 3.3 \times 10^6$ years. On the other hand, if the summary energy of the relativistic electrons in Cygnus-A is 100 times larger than that of the electrons, (i.e., $k_2 = 100$), then $H_\perp = 10^{-4}$ and $t_0 = 5 \times 10^5$ years. If in accord with [91] the spectrum "collapses" starting with $\nu \sim 1500$ Mcs (see Fig. 17b), this means that the effective injection of the relativistic electrons has ceased only several hundred thousand years ago (if $H_\perp \sim 10^{-4}$) or several million years ago (if $H_\perp \sim 2.6 \times 10^{-5}$), and the duration of the "ejection stage" is relatively short.

It follows from the discussion given in [78] that Cygnus-A is an exceedingly young object. Knowing the dimensions of the source (~ 50 kiloparsec) and its lifetime, it is easy to estimate the velocity of the relativistic-particle cloud. If $t_0 \sim 3.3 \times 10^6$ years, then $V \sim 2 \times 10^4$ km/sec, while if $t_0 = 5 \times 10^5$ years, then $V \sim 10^5$ km/sec.

Assuming the rate of expansion to be close to the magneto-hydrodynamic velocity, the density of the medium is estimated in [78] to be about 3×10^{-29} g/cm^2, which may correspond to the density of the intergalactic gas.

According to [78], the development of the Cygnus-A source proceeds in the following fashion. Some 10^6 years ago a tremendous number of relativistic particles was formed in the galaxies identified with this source. These particles could not be confined within the region where they were generated and "broke out" into the surrounding intergalactic space. As they moved, they reinforced the weak intergalactic magnetic field so that the energy of the magnetic field became equal to the energy of the relativistic particles, after which the expansion continued with magnetohydrodynamic velocity.

The short "lifetime" of Cygnus-A causes great difficulties in the interpretation of this radio galaxy. This time can be increased if it is assumed that $H_\perp$ is considerably less than the values given above, with $H \gg H_\perp$. For example, if $H_\perp \sim 5 \times 10^{-6}$ then $t_0 \sim 4 \times 10^7$ years and $V \sim 1000$ km/sec. Assuming $k_2 = 1$, the total energy of the relativistic electrons should then be increased by about 18 times and reaches $\sim 3 \times 10^{60}$ erg. To retain the relativistic electrons in a limited region of space the required field is $H \sim 2 \times 10^{-4}$. Consequently, $H_\perp/H \sim 0.025$. We note that if $k_2 = 100$, the values of the relativistic-particle energies in this model are found to be extraordinarily large.

It is difficult to say at present whether our assumption that the ratio $H_\perp/H$ is small actually corresponds to reality. In any case, we can conclude that the age of the Cygnus-A source does not exceed several times ten million years, and the possibility that this age is $\leq 10^6$ years is not excluded.

An interesting question arises regarding the further evolution of Cygnus-A. It is quite probable that its dimensions will increase. Even if we assume that the injection of relativistic electrons is presently continuing in this source, it will eventually be unable to compensate for the reduction in its radio luminosity and brightness due to the expansion, and described by formula (20). For example, the radiation power decreases by about 30 times if the dimensions of this source are doubled. It is curious that the source Hercules-A has approximately twice the linear dimensions of Cygnus-A but about $1/20$ the power. It is therefore natural to assume that the Hercules-A source is a somewhat later phase in the development of an object similar to Cygnus-A. Favoring this statement is also the near equality of the total energies of the relativistic particles in both sources (see Table II). What will be the final fate of such powerful sources? They will expand more and more, and the power of their radio emission and the brightness will decrease rapidly. At the same time, their characteristics will be close to those of such sources as Centaurus-A and Fornax-A.[79] In fact, the linear dimensions of each of the components of Centaurus-A and Fornax-A (at the half-power level) are ~ 150,000 and ~ 120,000 parsec, respectively, whereas for Cygnus-A the value is ~ 30,000 parsec. With a spectral index $\alpha = 0.75$ we have according to (20)

$$L_\nu \sim R^{-5}.$$

Consequently, if Fornax-A and Centaurus-A were later stages of evolution of sources similar to Cygnus-A, their values of L would be respectively 1000 and 3000 times weaker than for Cygnus-A. Yet it follows from the observational data that L is 2300 times smaller for Fornax than for Cygnus-A, and 3700 times smaller for Centaurus-A. The agreement can be regarded as very good, and this confirms our conclusion.

As was shown in [80], in the adiabatic expansion of nebulas containing relativistic particles, the energy of each such particle decreases as R^{-1}, where R is the radius of the nebula. According to Table II, the energies of the relativistic particles in Centaurus-A and Fornax-A are respectively 2.8×10^{59} and 1.8×10^{59}. If we multiply these quantities by 4 and 5, we obtain the energies of the relativistic particles during the epoch when the dimensions of these sources were the same as those of Cygnus-A. These energies will be

1.1×10^{60} and 9×10^{59} ergs, which is sufficiently close to the energy of the relativistic particles in present-day Cygnus-A.

Figure 30 shows the total energy of the relativistic particles and of the magnetic field vs. the linear dimensions of the sources, compiled from the same observational data as Fig. 26. Both diagrams show the same sequences of radio galaxies—a "main sequence" and a "sequence of giants." All the points on the sequence of giants fit quite well on the straight line $\log E = \text{const} - \log R$.

Thus, during the course of their expansion, sources similar to Cygnus-A will evolve into sources of the type Fornax-A and Centaurus-A. Can we state that in the past the sources of the type Fornax-A and Centaurus-A were without exception objects similar to Cygnus-A? Insistence on such an apparently natural point of view leads to considerable difficulty. The point is that the linear dimensions of Centaurus-A and Fornax-A are merely several times larger than those of Cygnus-A. Therefore, if we assume that the expansion of the sources has the same rate at all times, then the ages of Centaurus-A and Fornax-A should be only several times that of Cygnus-A. But if this were so, then the spatial densities of all these sources would be approximately the same. Yet, as follows from the observation, the spatial density of objects such as Centaurus-A and Fornax-A is at least 1000 times that of Cygnus-A.

If it is assumed that in the past all the sources of the Centaurus-A type passed through the Cygnus-A state, there is the inescapable conclusion that the "age" of the former should be on the order of several million years. But this is difficult to tie in with the fact that the centers of gravity of the radio emitting extended clouds near NGC5128 and NGC1316 are relatively close to the centers of these galaxies [$\sim (3-5) \times 10^{23}$ cm]. The average velocity of the radio emitter away from the core is found to be $\sim (3-5) \times 10^{6}$ cm/sec, which is several times smaller than the parabolic velocity. It is easy to suggest an effective deceleration mechanism for the radio emitting agent moving from the core. Obviously, this deceleration should be due to the intergalactic medium. However, to guarantee effective deceleration it is necessary to ascribe to this medium too high a density.

It can be assumed that the plasmons ejected for some reason or other from the cores of the radio galaxies have initial velocities that are smaller than parabolic and do not go into intergalactic space. After reaching about 100—150 kiloparsec, they are continuously slowed down in the gravitational field of the radio galaxy and then fall back. The falling time is about 10^{8} years, whereas the "activity" of the core continues for several billion years. This hypothesis makes it possible to explain qualitatively (and perhaps even quantitatively) the very presence of two

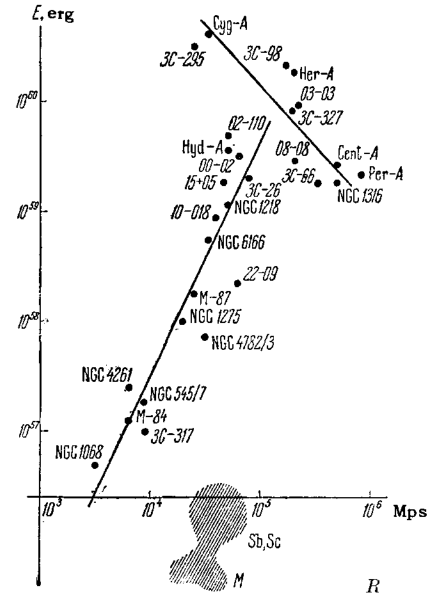

FIG. 30. Dependence of the total energy of relativistic particles and magnetic fields on the linear dimensions of the radio galaxies.

symmetrically situated extended sources. In addition, it enables us to understand why the distances between the components of the sources Cygnus-A, Hercules-A, Centaurus-A, and Fornax-A are so close to each other (100—200 kiloparsec).

Because of the random motions ("rises" and "falls") of the gas condensations in regions of the "apogees" (more accurately, "apogalactees"), the magnetic field will have a random character. The relativistic particles brought into these fields by the plasmons or directly escaping from the cores of the radio galaxies will diffuse in these fields.

It is essential to emphasize that the "spreading" of the extensive sources around Centaurus-A and Fornax-A has the character of diffusion (and not propagation of an explosive shock wave in the intergalactic medium). This follows from the singularity of the isophots of Centaurus-A and Fornax-A. The maximum concentration of the relativistic particles is observed in the central parts of the extended sources, and not on the periphery, as would occur in the case of a strong shock wave. To the contrary, in the case of Cygnus-A, the outer edges of the source are very sharp, indicating the possibility that a strong shock wave is formed there. This can be related with the "youth" of this source.

According to diffusion theory, the displacement of a relativistic particle in a random magnetic field after a time t is

$$L = \sqrt{2Vlt}, \qquad (22)$$

where l is the extent of the quasi-homogeneous field and $V \sim 10^{10}$ cm the velocity of the particle. Putting $L = 5 \times 10^{23}$ cm and $t = 10^{17}$ sec we get $l \sim 10^{20}$ cm or ~ 30 parsec. The smallness of this quantity is a serious difficulty. We cannot, however, exclude the possibility that the field has such a "fine-cellular" structure, particularly if we bear in mind the continuous disturbing action of the rising and falling plasmons.

Attention must also be called to the following fact. It follows from the observations that the "activity" of the core of NGC5128 is continuing even now, since we observe near it two symmetrical small bright sources (see Fig. 11). The lifetime of these plasmons does not exceed several million years (since their velocity should be not less than parabolic). Consequently at the present level of "activity" approximately 10^3 such plasmons should be ejected from the NGC5128 core in 10^{17} seconds. This precisely is the number ejected (see above). But this means that NGC5128 had in the past approximately the same radio luminosity as now (or slightly more). It was therefore unlike present Cygnus-A, where approximately the same number of relativistic particles were ejected in a much shorter time. In this sense the process in Cygnus-A had and perhaps still has an explosive "catastrophic" character.

If the plasmons ejected by the cores of the radio galaxies are not slowed down (either by the gravitational field of the corresponding galaxies, or by the intergalactic medium), the age of an object such as Centaurus-A or Fornax-A should not exceed 10^8 years. To explain the sources symmetrically located away from the cores of the radio galaxies, it must be assumed that the "activity" of the cores was previously several dozens of times greater than now, and that the duration of this phase was $(1-3) \times 10^7$ years. At that time Centaurus-A and Fornax-A had radio stellar magnitudes $M_r \sim -29^m$ or -30^m, and the radio sources had considerably smaller dimensions and were located inside the corresponding galaxies. It is possible that we are observing at present a similar picture in the case of Hydra-A.

It is difficult to say at present which "age scale" is correct for the radio galaxies such as NGC5128 or NGC1316—the "long" one ($\geq 3 \times 10^9$ years) or the "short" one ($\leq 10^8$ years). It is even possible that both cases are realized in nature. This problem can be conclusively resolved only after a thorough analysis of new observations.

This concludes our theoretical analysis of the observations on some relatively well investigated radio galaxies. This analysis will be useful for the critical survey of the hypotheses concerning the nature of radio galaxies, to which we now proceed.

Historically the first attempt to understand the nature of the radio galaxies was the colliding-galaxies hypothesis of Baade and Minkowski.[43] At that time (1951) there was still little information on radio galaxies, not enough to analyze this hypothesis in detail. The colliding-galaxies hypothesis of Baade and Minkowski was undoubtedly suggested by their photograph of Cygnus-A (see Fig. 15), which shows clearly two galaxies very close to each other. Attempting to justify this hypothesis by using more extensive observations, Minkowski saw "collisions of galaxies" in many objects, for example, NGC5128, NGC1275, and others. These attempts were in any case debatable. The colliding-galaxies hypothesis as an explanation of radio emission was subsequently very popular. It had the attractive feature that it apparently offered a natural answer to the most important question of where the energy necessary for the formation of a tremendous amount of relativistic particles came from. It was tacitly assumed that this may be the kinetic energy of the interstellar gas clouds in the colliding galaxies. However, the weaknesses of this hypothesis were soon evident. V. A. Ambartsumyan has already emphasized the very low probability of such collisions, which contradicts the observed number of radio galaxies.[81] The probability becomes even lower if we recall that both components of the radio galaxies (if they are dual) are peculiar objects of very high luminosity and apparently of large mass. Recently some new difficulties were encountered, raising objections to the "collision" hypothesis. We shall list those briefly (see [79]).

1) The number of radio galaxies known to be single is appreciable (for example, Virgo-A, Fornax-A, etc). Consequently, these need a different hypothesis to explain the energy reservoir of the relativistic particles.

2) In the case of Cygnus-A, where $E \sim 10^{61}$ erg, there is clearly not enough interstellar-gas energy even in the giant galaxies. Incidentally, spectroscopic data indicate that the relative radial velocity of the Cygnus-A components does not exceed 100—200 km/sec. In addition, there is very little gas in double elliptic radio galaxies (which are the typical ones).

3) The colliding-galaxies hypothesis is unable to explain the peculiarities of the spatial distribution of the radio emitting clouds relative to the optically observed galaxies (see Sec. 2).

4) By far not all radio galaxies are in galactic clusters, in which case there can be no talk whatever of colliding galaxies.

We have indicated that duality is quite widespread among the radio galaxies. Duality, however, does not mean at all that a collision is observed. One can state with much greater probability that in these cases we observe systems consisting of two (and more) closely-lying components of common origin, in analogy to close pairs of double stars.*

Finally, an analysis of the conditions in specific radio galaxies, as presented in the beginning of the present section, completely excludes the collision hypothesis. The facts speak in favor of clouds of relativistic particles being ejected for some reason or another from the cores of the radio galaxies.

*V. A. Ambartsumyan believes that in the case of multiple radio galaxies we are observing the splitting of a single galaxy,[81] but does not propose a mechanism for this splitting.

Table III

	Solar flare	Formation of radio galaxies
Linear scale	$\sim 10^9$ cm	$\sim 10^{23}$ cm
Characteristic time	~ 10 sec	$\sim 10^{11}$ sec (?)
Total energy	$\sim 10^{32}$ erg	$\gtrsim 10^{58}$ erg

The "collision" hypothesis has by now been refuted by an overwhelming majority of investigators, and replaced by new ideas. There is no unified point of view, however. We shall now discuss the new hypotheses.

a) Recently Hoyle proposed to explain the origin of radio galaxies with a curious hypothesis, which can be called the "galactic flare hypothesis." [82] He advanced an analogous hypothesis earlier to explain solar flares.[82] In Hoyle's opinion, solar flares and "galactic flares" are phenomena of the same order, but of essentially different scales. Table III offers a comparison of these two phenomena.

According to this hypothesis a reservoir of magnetic energy is accumulated over a long time. During some period of time this reservoir is "emptied" at a catastrophic speed and the accumulated energy goes into other forms, particularly into energy of a large number of relativistic particles. It was shown in [82] that under certain conditions the merging of two regions containing magnetic fields with opposite orientations can lead to the annihilation of the magnetic field, and a considerable portion of the magnetic energy goes over into heat and into kinetic energy of matter. The magnetic field diffuses through a gas layer of thickness S between these regions in a time $\sigma S^2/c^2$, where σ is the electric conductivity. In most cases $\sigma \sim 10^8$ sec^{-1} and if $t \sim 10^{11}$ sec then $S < 3 \times 10^9$ cm.

According to Hoyle, such thin "partitions" can actually be formed between regions with oppositely oriented fields under certain conditions. The "compression" of the gas between such regions to the required thickness (when the effective merging of the field begins) continues under solar-flare conditions for one or two days, while in radio galaxies it lasts $\sim 10^9$ years. Upon "annihilation" of the magnetic field, an electric field is formed, which contributes to the conversion of the magnetic energy into other forms. In Hoyle's opinion, the catastrophic character of the "annihilation" of the magnetic field guarantees acceleration of the individual charged particles to very high energies, with the electrons accelerated to the same extent as the ions.

According to [82], suitable magnetic-field configuration can exist in two forms.

1) The reservoir of magnetic energy is concentrated in the cores of radio galaxies, which are quite massive and rotate at high speed. By way of an example (which in our opinion is not too well chosen), Hoyle chooses NGC4486. In this case the mass of the gas should be $\sim 10^{10}$ $M_\odot$. We add that the average magnetic field required there should be about 1 G.

2) The magnetic energy reservoir is contained between the components of the double galaxy, and its mass is $\sim 10^{12}$ $M_\odot$. Since the most massive galaxies are elliptic ones, Hoyle sees a support for his hypothesis in the fact that many of the sources have been identified with double elliptic systems.

However, it is difficult to agree with Hoyle's hypothesis, which is as superficial as it is clever. Hoyle simply disregards the observational data, which patently contradict his hypothesis. For example, in NGC4486 the process of formation of relativistic particles occurs literally in front of our eyes. Yet, according to spectroscopic observations which have been quite unequivocally interpreted, the mass of the interstellar gas in its core can hardly exceed 10^6 $M_\odot$ (were the mass to be 10^{10}, the strongly forbidden line [O II] $\lambda 3727$ would not be observed, owing to the high density).

We note also that the very mechanism proposed by Hoyle raises still another great difficulty. As soon as the field "annihilation" and the release of Joule heat begin, the plasma becomes rapidly heated, the conductivity of the gas increases sharply, and the merging of the fields stops immediately. Thus, this mechanism has an "automatic stop" which makes it quite ineffective.

We shall not dwell here on another attempt by Hoyle to interpret radio galaxies [88] (for a criticism see [85]). Apparently Hoyle himself rejected his earlier hypothesis, since he does not even mention it in [82].

b) Supernova bursts were suggested in [79] as possible energy sources for the formation in the galaxy of a sufficiently large number of relativistic particles and magnetic fields. We started there from the fact that the relativistic particles formed in a supernova burst have a total energy that reaches, according to observations, 10^{49-50} ergs. The initial cause in this case is apparently the release of a large amount of nuclear energy during the flare. There are sufficient grounds for assuming that the supernova bursts are the main source of relativistic particles (i.e., primary cosmic rays) in our own galaxy. In other words, the synchrotron radio emission of the galaxy is due to supernova bursts. However, a difficulty arises immediately. In order to guarantee the release of 10^{60}—10^{61} ergs (and this is the energy observed in Cygnus-A, Hercules-A, 3C-296, and others), one must have at least 10^{10}—10^{11} such bursts. Since the characteristic lifetime of Cygnus-A is 10^6—10^7 years (and perhaps even less, see above), we must of necessity assume that during the time of maximum "activity" up to 10^4 supernovas have burst annually in Cygnus-A (or perhaps still do). In NGC4486 there should burst at present, in the vicinity of the core, several supernovas annually. Taking into account the rate of decrease of the supernova brightness with time, the number of simultaneously observed supernovas should be some 10 times smaller. In the case of the core of NGC4486, this does not contradict the observations.* However, the absolute stellar magnitude of Cygnus-A during its highest activity should reach -26 to -27^m. In view of its short duration, such a phenomenon can with full justification be called a "supernova" or "exploding" galaxy. The fact that the absolute magnitudes of Cygnus-A and 3C-295 are approximately -21^m does not contradict this hypothesis explicitly. It merely denotes that the "active phase" of the radio galaxy has already been passed, although only recently. The reason for so high a frequency of the proposed supernova bursts may be the vigorous star formation process which is going on in these galaxies. This in turn is connected with the high density of interstellar matter. According to present-day notions regarding the rate of formation of massive stars (which can burst as supernovas during the course of their evolution after several million years) [86] is approximately proportional to the cube of the average density of interstellar gas.[87] For example, according to [79], when our galaxy was very young ($\sim 10^9$ years), the number of supernova bursts in it was approximately 100 times larger than now, when this process has "quieted down." On the basis of this it was concluded in [79] that at that time our galaxy had all the characteristics of a "radio galaxy." According to [79] radio galaxies are young objects which have relatively recently condensed out of the intergalactic medium, where there is much gas, and star formation and nuclear genesis proceed vigorously. The latter, according to modern notions, proceeds only during flares of supernovas. Cygnus-A and 3C-295 stand out among other such objects in their large mass and appreciable average density of the interstellar gas.

As already indicated above, this hypothesis does not contradict the observations explicitly. If that rarest of occurrences, the "explosion" of a galaxy (in the sense indicated above) occurs deep in the universe, then, since the distance is $\sim 10^9$ parsec, we should observe a peculiar emitting object, weaker than 14^m. In principle it may be that such objects do exist. They could readily escape observation.

In connection with our hypothesis, let us point out another curious possibility, which was not discussed in [79]. According to [79], the reason for the tremendous brightness of the supernovas of Class I at the maximum of their brilliance is synchrotron radiation. But synchrotron radiation is a rather capricious mechanism. If, for example, for some reasons (as yet unclear) the relativistic electrons produced have an energy only several times smaller than "optimal," or if the magnetic fields are weaker, then the radiation will shift sharply into the far infrared. Such "invisible" supernovas of Class I (with absolute photographic magnitude $> -10^m$) will yield approximately the same number of relativistic particles as the "ordinary" supernovas. At the same time, 10,000 simultaneously radiating objects of this type can produce the same optical effect as a single object of -20^m.

*It was proposed in [79] to observe the core of NGC4486 systematically so as to detect possible changes in its brightness.

Assuming the radio galaxies to be young formations, V. L. Ginzburg attempted to explain the generation of cosmic rays in these galaxies without resorting to the hypothesis that the frequency of the supernova bursts is high.[88] According to [88], such generation can be caused by gravitational compression of the intergalactic medium, from which the galaxy was formed. The presence of inhomogeneities and macroscopic movements in such a contracting system creates, generally speaking, conditions favorable for the acceleration.

As was already emphasized above, the feature of the hypotheses developed in [79] and in [88] is the notion that the radio galaxies are very young systems. At the same time, this notion is the most difficult part of these hypotheses. It is possible that there are very young objects among the radio galaxies. All the same, it is difficult to regard such galaxies as NGC4486 or NGC5128 as young. Many distinguishing features (for example, the integrated spectrum, the presence of a heavy spiral-like band of absorbing matter in NGC5128, and others) indicate that these objects have already passed through a long evolution. Another argument favoring this is the very small amount of gas in the core of NGC4486.

A very interesting development of our notions concerning the decisive role of supernovas in the formation of radio galaxies is a recent hypothesis by Burbige.[89] He, too, rejects the collision hypothesis, regarding it as inconsistent. It is quite natural to attribute the tremendous energies contained in the form of relativistic particles and magnetic fields to nuclear sources. The most effective nuclear energy release mechanism now known in astronomy is the burst of a supernova. Since the overwhelming majority of radio galaxies are elliptical, it is useful to analyze the main properties of such stellar systems and to see which of these properties can potentially contribute to the appearance of radio galaxies. It follows from spectral and colorimetric observations that the luminosity of the central regions of elliptic galaxies is due predominantly to giant stars of Class K, with mass $1-1.5\ M_{\odot}$. During the course of the evolution, some part of the stars contained in such a galaxy burst as supernovas of Class I. If it assumed that the relativistic particles are formed during supernova bursts, then no less than 10^8 bursts are necessary to explain the observed number of such particles in the "average" radio galaxy ($\sim 10^{58}$ erg), which would consume about 10^{10} years under ordinary conditions. Yet the formation of the observed number of relativistic particles in the radio galaxies has occurred apparently within a much shorter time interval and has an almost catastrophic character, so that we can speak of a "burst" or "explosion" of a galaxy, or more accurately of its core. The corresponding time estimates were made above in the analysis of the physical conditions in Cygnus-A and NGC4486.

In order to guarantee a large number of supernova bursts within a relatively short time, we have assumed [79] the radio galaxies to be young objects, where the star formation and nuclear genesis processes proceed with great vigor. In the case of several radio galaxies, however, this meets with the difficulties referred to above. Burbige rejects the idea that radio galaxies are young objects. He assumes that under certain conditions, at a definite stage of evolution, a "chain reaction" consisting of successive supernova bursts can occur in the cores of elliptic galaxies.

The densities in the cores of elliptic galaxies can reach rather high values. In Sec. 2, with NGC4486 as an example, we have seen that in a volume of ~ 25 parsec radius the average stellar density can reach 5×10^4 parsec^{-3}. Burbige assumes that in the innermost regions of such a galaxy, measuring about 1 parsec, the stellar density can be 10^6—10^7 parsec^{-3}. Let us assume that a supernova has burst in such a core. Let the explosion energy be E_1 and let the average distance to the nearest star be D. So long as D is small ($\sim 10^{16}$—3×10^{16} cm), the flux of hard radiation from the exploding star through the surface of its "neighbor" will be rather large. Assuming, for example $E_1 \sim 10^{50}$ erg, we find that the "neighbor" absorbs 10^{16}—10^{17} erg per unit surface.

In order to absorb this radiation (assumed in [88] to be predominantly γ quanta), several g/cm^2 are sufficient. In the case of giant stars, this corresponds to 10^4—10^6 cm, and in the case of stars such as the sun this corresponds to several meters of the stellar atmosphere. It is easy to show that when such a layer absorbs so much energy (disregarding any mechanisms by which heat can leak away) it can become heated to 10^8—10^9 deg K. This is accompanied by nuclear reactions, predominantly with C, N, O, and H. A detonation wave can be produced under certain conditions and propagate inward. This in turn can cause a star located so dangerously close to the supernova to explode. The next star will then explode, etc. Within about 100 years the region of the core (~ 30 parsec) will be enveloped by a catastrophic chain reaction. The chain reaction will stop in the place where the stellar density is appreciably reduced. During the time of this phenomenon, the brightness of the star can increase by 10^{m} or even more. The "induced" stellar explosions will be accompanied by the emission of large amounts of ionized gases. Powerful emission in the lines [OII], [OIII] and [NII] will occur. It must be noted that if a conducting medium ($V \sim 10^8$ cm) is subject to random macroscopic motions, the charged particles can become effectively accelerated by the statistical mechanism.

The radio galaxies in which intense emission is now observed "exploded" relatively recently. It is therefore of interest to search for the peculiar emitting objects (about which we spoke, earlier). Such objects as NGC1068, NGC1275, and the like can have sufficiently dense cores. Strong sources, according to Burbige, are produced in the denser elliptic galaxies, which of necessity must be more massive. Since a considerable number of radio galaxies are multiple systems, it is concluded in [89] that the core densities are higher in such systems.

These are the main outlines of Burbige's hypothesis. One should note, however, that it meets with great difficulties, of which we mention only two.

a) The "induced explosion" mechanism is itself quite unclear. The absorption of hard radiation by the surface layer of the "neighbor stars" can extend over a considerable time interval (> 10 days). It is very probable that the heated layers will have a chance to mix with colder ones, so that the net temperature rise can be relatively insignificant and no nuclear energy is released. Even if we imagine that the temperature in a thin surface layer has risen to 10^8—10^9 it is not clear, without a detailed analysis (which was not carried out in [89]), whether a nuclear explosion of the entire neighbor star will take place.

b) It is not clear why the dense core of the elliptic galaxy did not explode in 10^{10} years, although supernova bursts undoubtedly occurred there (with an approximate frequency of once every 10,000—30,000 years). In order to eliminate this difficulty it is necessary to introduce a possible evolution of the core (in the sense of its becoming denser), which can lead at a certain stage to an "explosive instability." It appears, however, that such an evolution should be too slow.

Nevertheless, one cannot deny that Burbige's hypothesis is attractive. Its undisputed merit is that it raises the question of a qualitatively new phenomenon of unprecedented grandeur in the universe—the explosion of the cores of several galaxies. The possibilities of such an explosion as applied to NGC4486 was pointed out to us as long ago as 1955, [67] although no specific mechanism was proposed in [67]. The same can be said of the hypotheses of V. A. Ambartsumyan. [81] A specific although debatable mechanism is contained in [89].

Burbige's mechanism can be modified in the following fashion. If $D = 3 \times 10^{16}$ cm, then the shell of the bursting supernova will reach the neighboring star in 10 years and "inundate" it. The relativistic particles contained in this shell will enter the outer layers of the star from all sides. It can be shown that the energy flux reaches $\sim 10^{10}$ erg/cm^2 sec, and such "irradiation" will last for several years. Apparently this method of "heating up the neighboring star" is more effective than that proposed by Burbige.

In any case, the very high stellar density in the cores of the radio galaxies is a fact worthy of most persistent attention.

We failed to mention still another hypothesis, according to which the source of the relativistic particles in the radio galaxies is the annihilation of matter and antimatter. [90] Unfortunately, this hypothesis was not supported by any specific calculations. Its main defect is that it is impossible to obtain in the annihilation process an energy greater than 10^9 eV per nucleon. Yet we have already seen that the jet of NGC4486 contains particles with energies 10^{11}–10^{12} eV. Such energies can be attained only through acceleration by some "macroscopic" mechanism of the Fermi type. Further evidence in its favor is also the observed power-law energy spectrum in cosmic-radio emission sources. On the basis of these considerations, the "annihilation" hypothesis cannot be given serious attention.

We now consider a new hypothesis regarding the mechanism whereby relativistic particles are generated in radio galaxy cores. Above, in the analysis of the physical conditions in the NGC4486 core, we have seen that the most probable source by which this core is replenished with interstellar gas is falling intergalactic gas. Since the parabolic velocity in the region of the NGC4486 core (as in the case of other similar objects) is very high, $V_\infty \approx (1-2) \times 10^8$ cm/sec, the intergalactic gas will bring with it a considerable amount of energy. Let us assume that approximately 10 $M_\odot$ or approximately 10^{27} g/sec falls in the core every year.* Then at a velocity of 1.5×10^8 cm/sec the energy flux into the core of the galaxy will be $\sim 10^{43}$ erg/sec. This is sufficiently close to the power necessary to generate relativistic particles in the cores of radio galaxies.

If the gas masses falling in the core carry with them a frozen-in magnetic field (as would be natural to assume), very favorable conditions are created for the acceleration of the charged particles to relativistic energies. In this case a mechanism whereby acceleration is produced between two "magnetic walls" moving towards each other becomes feasible. The Fermi acceleration parameter is $\alpha = V/R$. If the relative velocity is $V \sim 3 \times 10^8$ cm/sec and $R \sim 10^{20}$ cm then $\alpha \sim 3 \times 10^{-12}$ sec^{-1}. Consequently, during the time of formation of the next jet condensation in the core (5×10^{11} sec), the accelerated particles will increase their energy to $Mc^2e^{\alpha t} \sim 10^{11}$–$10^{12}$ eV. Under favorable conditions the number of particles accelerated will be very large. When the pressure of the relativistic particles exceeds a certain limit, they break away from the core together with the magnetic field and the gas. "Plasmons" similar to those now observed in NGC4486 are then expelled from the core.

Naturally, such a "break-away" cannot occur with equal ease in different directions. It can be assumed that it is easiest for the "plasmons" to break away in the direction of the core's axis of rotation, particularly if a regular axially-symmetrical field is present there (which is quite probable). It thus becomes understandable why the "jets" occur in two diametrically opposite directions.

In order for an effective acceleration of the type considered above to occur, it is necessary to satisfy several additional conditions. One such condition is quite obvious: it is necessary that the "lifetime" of the accelerated high-energy particles, determined by the nuclear collisions, be longer than the characteristic acceleration time, i.e.,

$$\frac{1}{n\sigma c} \geqslant \frac{5}{\alpha}, \quad \text{or} \quad n \leqslant \frac{1}{5}\frac{\alpha}{\sigma c} = \frac{1}{5}\frac{V}{R\sigma c}. \tag{23}$$

In the case of the NGC4486 core, $V/5R\sigma c \sim 10^3$ cm^{-3}, and condition (23) is satisfied even if the neutral gas contained in the core is taken into account.

The acceleration mechanism would become inoperative if (in accordance with our hypothesis) the density of the interstellar gas in the NGC4486 core were several times higher. Thus, the effectiveness of the mechanism considered depends quite critically on the conditions in the galactic cores. These conditions can vary during the evolution of the galaxies, and when they become favorable, a large number of relativistic particles begins to be generated in the core. On the other hand, the amount of intergalactic gas falling into the core should depend on the density of the gas in this part of the metagalaxy where the galaxy under consideration is located. This density should also change during the evolution of the galaxy, if it is recognized that during 10^{10} years the galaxy covers a distance of several megaparsec. Periods may occur when the galaxy passes through unique clouds of intergalactic gas with increased density (for example, 10^{-28} g/cm^3 or even higher). During such epochs the mass of gas entering into the cores of the galaxies will be equivalent to many tens or even hundreds of solar masses. The energy flux into the core can reach 10^{44}, and if the conditions in the core are favorable, vigorous generation of relativistic particles will set in.*

*In the case of NGC4486 such an assumption signifies that the amount of neutral gas in its core is approximately twice the amount of ionized gas, which is permissible. Since the jet contains $\sim 5 \times 10^{39}$ g of gas, and since the time of its formation is $\sim 3 \times 10^{13}$ sec, the jet carries away from the core on the average 10^{26} g/sec. In order to prevent accumulation of the gas in the core, it is necessary to assume that the neutral hydrogen continuously flows out of the core without regard to the formation of plasmons in the jet. As is well known, an outflow of hydrogen is observed, albeit on a smaller scale, in the central regions of our own galaxy. If the ideas developed here are correct, the NGC4486 should contain a large amount of neutral hydrogen (10^9–10^{10} $M_\odot$), which should produce a depression in the spectrum of Virgo-A near $\nu = 1475$ Mcs.

*This may explain the tendency of radio galaxies to be located in galactic clusters, where the density of the intergalactic matter should be considerably above average.

In a certain sense this process can be treated as a "collision" of a galaxy with a very extensive and relatively dense cloud of intergalactic gas. In this connection it should be noted that at the present time we know practically nothing concerning the characteristics of intergalactic gas.

It is important to call attention to still another fact. Since the interstellar gas does not accumulate in the cores of the radio galaxies, but is periodically ejected by the pressure of the cosmic rays, the cores of the galaxies and the surrounding intergalactic medium can be regarded as a periodically acting engine—a giant cosmic accelerator. In particular, one cannot exclude the possibility that the gas in the plasmons ejected from the core returns to the core, and is then ejected again. Of course, such a process should have a definite damping decrement, since a noticeable part of the energy of motion of the gas masses is converted into cosmic rays.

The fact that almost all the radio galaxies are spheroidal systems with large masses is naturally explained within the framework of this galaxy by the circumstance that only such galaxies have a deep gravitational potential well in a small region surrounding the core. This hypothesis enables us to understand why in the central regions of such galaxies as NGC1068, NGC4234, NGC4261 and a few others we observe on a more moderate scale the process of generation of relativistic particles. It becomes possible to understand the nature of the "main sequence" radio galaxies, referred to in Sec. 2. Finally, the fact that by far not all Seyfert galaxies or likewise all giant spheroidal systems (for example M-86) are radio galaxies, can be naturally explained by the "capricious" nature of the conditions necessary for effective generation of relativistic particles in galactic cores. Of course, even this new hypothesis raises great difficulties. Thus, for example, it is difficult to visualize how to interpret objects such as Cygnus-A by this method.

It is possible that in such cases there is a certain specific mechanism, connected with the duality of such galaxies. We note in this connection that the potential energy of the close pair of galaxies of Cygnus-A can reach 10^{60}—10^{61} erg. During the process of orbital motion of the galaxies, a considerable intensification of the magnetic field may occur in the surrounding medium, and a certain instability may arise. This important problem calls for additional research, however.

We have discussed in this section the main hypotheses concerning the nature of radio galaxies. We have seen that these hypotheses are quite varied in their premises and frequently contradict one another. This, of course, is quite natural and expected for so difficult and new a problem. There are, however, all grounds for assuming that progress in radio astronomical and optical observations of radio galaxies will soon disclose new important facts, which will enable us to make a final choice between the different hypotheses.

[1] Hey, Parsons, and Phillips, Nature **158**, 234 (1946).

[2] J. G. Bolton and G. J. Stanley, Nature **161**, 312 (1948).

[3] M. Ryle and F. Smith, Nature **162**, 462 (1948).

[4] Bolton, Stanley, and Slee, Nature **164**, 101 (1949); J. G. Bolton, Austr. J. Sci. Res. **A2**, 139 (1949).

[5] G. J. Stanley and O. B. Slee, Austr. J. Sci. Res. **A3**, 234 (1950).

[6] B. Y. Mills, Austr. J. Sci. Res. **A5**, 266 (1952).

[7] F. Smith, Nature **168**, 962 (1951).

[8] Shakeshaft, Ryle, Baldwin, Elsmore, and Thompson, Memoirs of RAS **67**, 106 (1955).

[9] Edge, Shareshaft, McAdam, Baldwin, and Archer, Memoirs of RAS **68**, 37 (1959).

[10] Mills, Slee, and Hill, Austr. J. Phys. **11**, 360 (1958).

[11] Kuz'min, Levchenko, Noskova, and Salomonovich, Astron. zh. **37**, 975 (1960), Soviet Astronomy **4**, 909 (1961).

[12] Scott, Ryle, and Hewish, Monthly Notices of Roy. Astr. Soc. **122**, 95 (1961).

[13] F. Smith, Nature **165**, 422 (1950).

[14] C. Little and A. Lovell, Nature **165**, 423 (1950).

[15] C. Little, Monthly Notices of RAS **111**, 289 (1951).

[16] R. Hanburry Brown and M. Das Gupta, Nature **170**, 1061 (1952).

[17] F. Smith, Nature **170**, 1061 (1952).

[18] B. Mills, Nature **170**, 1061 (1952).

[19] B. Mills, Austr. J. Phys. **6**, 452 (1953).

[20] H. Curtis, Publ. Lick. Obs. **13**, 31 (1918).

[21] R. Minkowski and W. Baade, Astrophys. J. **119**, 215 (1954).

[22] D. Osterbrock, Astrophys. J. **132**, 325 (1960).

[23] W. Morgan and N. Mayall, Publ. Astron. Soc. Pacific **69**, 291 (1957).

[24] Biraud, Legueux, and Le Roux, Observatory **80**, 116 (1960).

[25] Yu. N. Pariiskii, DAN SSSR **137**, 49 (1961), Soviet Phys. Doklady **6**, 185 (1961).

[26] J. Legueux and J. Heidmann, Compt. rend. **235**, 804 (1961).

[27] I. Baldwin and F. Smith, Observatory **76**, 141 (1956).

[28] C. Wade, Observatory **81**, 202 (1961).

[29] E. Burbige and G. Burbige, Astrophys. J. **129**, 271 (1959).

[30] J. Sersic, Z. Astrophys. **51**, 64 (1960).

[31] G. de Vanconleurs, Mem. Commonwealth Observatory, No. 13 (1956).

[32] C. Wade, Austr. J. Phys. **12**, 471 (1959).

[33] J. Bolton and B. Clars, Publ. Astron. Soc. Pacific **72**, 29 (1960).

[34] Twiss, Carter, and Little, Observatory **80**, 153 (1960).

[35] P. Maltby, California Inst. Technology Observatory, Preprint No. 2, 1961.
[36] D. Heeshen, Astrophys. J. **133**, 322 (1961).
[37] I. S. Shklovskii and P. N. Kholopov, Astron. tsirk. No. 131, 2 (1952).
[38] C. Wade, Publ. of the National Radio Astronomy Observatory **1**, 99 (1961).
[39] C. Seyfert, Astrophys. **97**, 28 (1943).
[40] I. Bolton, Calif. Inst. Technology Radio Observatory, Preprint No. 5, 1960.
[41] P. Leslie and B. Elsmore, Observatory **81**, 14 (1961).
[42] F. Smith, Nature **168**, 555 (1951).
[43] W. Baade and R. Minkowski, Astrophys. J. **119**, 206 (1954).
[44] Karachun, Kuz'min, and Salomonovich, Astron. zh. **38**, 83 (1961), Soviet Astronomy **5**, 59 (1961).
[45] R. Lennison and M. Das Gupta, Nature **172**, 996 (1953).
[46] Jennison, Latham, and Rawson, Paris Symposium on Radioastronomy (Russ. Transl.), M., IL, 1961, p. 498.
[47] Williams, Dewhirst, and Leslie, Observatory **81**, 64 (1961).
[48] A. Boischot, URSI, London, 1960.
[49] R. Minkowski, Publ. Astron. Soc. Pacific **72**, 354 (1960).
[50] Allen, Palmer, and Rouson, Nature **188**, 731 (1960).
[51] D. Dewhurst, op cit.[46].
[52] Roberts, Bolton, and Harris, California Inst. Technology Radio Observatory, Preprint No. 3, 1959.
[53] P. Leslie, Observatory **80**, 216 (1960).
[54] D. Harris and J. Roberts, Calif. Inst. Technology Radio Observatory, No. 1 (1960).
[55] A. Moffet and P. Maltby, Calif, Inst. Technology Radio Observatory, Preprint No. 1, 1961.
[56] A. Moffet and P. Maltby, Calif. Inst. Tech. Radio Obs. Preprint No. 4, 5 (1961).
[57] B. Mills, Astr. J. Phys. **13**, 550 (1960).
[58] T. Greenstein, Astrophys. J. **133**, 335 (1961).
[59] D. Heeshen, Pupl. Astr. Soc. Pacific **72**, 368 (1960).
[60] Yu. P. Pskovskii, Astron. zh. **39**, 222 (1962), Soviet Astronomy **6**, 172 (1962).
[61] I. S. Shklovskii, Astron. zh. **39**, 209 (1962), Soviet Astronomy **6**, 162 (1962).
[62] H. Alven and N. Herlofson, Phys. Rev. **78**, 616 (1950).
[63] K. Kiepenheuer, Phys. Rev. **79**, 738 (1950).
[64] V. L. Ginzburg, Usp. Fiz. Nauk **51**, 343 (1953).
[65] G. G. Getmantsev, DAN SSSR **83**, 557 (1952).
[66] I. S. Shklovskii, DAN SSSR **90**, 983 (1953).
[67] I. S. Shklovskii, Astron. zh. **32**, 215 (1955).
[68] G. Burbige, op. cit. [46], p. 527.
[69] A. A. Korchak, Trudy, P. N. Lebedev Physics Inst. vol. 18, 1962.
[70] S. B. Pikel'ner, Astron. zh. **38**, 21 (1961), Soviet Astronomy **5**, 14 (1961).
[71] V. I. Moroz, Astron. zh. **39**, 161 (1962), Soviet Astronomy **6**, 121 (1962).
[72] W. Baade, Astrophys. J. **123**, 550 (1956).
[73] W. Hiltner, Astrophys. J. **130**, 340 (1959).
[74] Barot, Legueux, and Le Roux, Compt. rend. **251**, 2476 (1961).
[75] Mayer, McCullough, and Sloanaker, Astrophys. J. **126**, 468 (1957).
[76] I. S. Shklovskii, Astron. zh. **37**, 256 (1960), Soviet Astronomy **4**, 243 (1960).
[77] J. Högbom and J. Shakeshaft, Nature **190**, 852 (1961).
[78] Kardashev, Kuz'min, and Syrovat-skii, Astron zh. **39**, 216 (1962), Soviet Astronomy **6**, 167 (1962).
[79] I. S. Shklovskii, Astron. zh. **37**, 945 (1960), Soviet Astronomy **4**, 885 (1961).
[80] Ginzburg, Pikel'ner, and Shklovskii, Astron. zh. **32**, 503 (1955).
[81] V. Ambartsumyan, Izvestiya, Armenian Acad. Sci. **11**, 9 (1958).
[82] F. Hoyle, Observatory **81**, 39 (1961).
[83] T. Gold and F. Hoyle, Monthly Notices of Roy. Astr. Soc. **120**, 89 (1960).
[84] F. Hoyle, Monthly Notices of Roy. Astr. Soc. **120**, 338 (1960).
[85] S. B. Pikel'ner and I. S. Shklovskii, Astron. zh. **38**, 196 (1961), Soviet Astronomy **5**, 146 (1961).
[86] E. Salpeter, Astrophys. J. **129**, 608 (1959).
[87] M. Smith, Astrophys. J. **129**, 243 (1959).
[88] V. L. Ginzburg, Astron. zh. **38**, 380 (1961), Soviet Astronomy **5**, 282 (1961).
[89] G. Burbige, Nature **190**, 1053 (1961).
[90] G. Burbige, Astrophys. J. **124**, 416 (1956).
[91] A. Barrett, Astrophys. J. **134**, 944 (1961).

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