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ON THE IDENTIFICATION OF RADIO SOURCES

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ABSTRACT

A discussion of the astronomical evidence concerning objects identified as discrete radio sources shows that the following four types of objects are now recognized: (I) remnants of supernovae; (II) galactic nebulosities of a new type; (III) peculiar extragalactic nebulae; (IV) normal extragalactic nebulae. A discussion of the distribution of the general galactic radiation favors the assumption that this radiation is emitted by objects in population II and therefore probably by stars.

The problem of identification of the discrete radio sources with visible objects has now reached a stage in which a full discussion of the astronomical evidence appears necessary. The low accuracy of the early positions of the sources made their identification a difficult problem. Only very few sources were close to known objects which could be considered seriously, but the two most intense sources were not among them. Only for 7 out of 67 sources known in 1950 [1, 2] were identifications suggested. The objects identified were the Crab Nebula—the remnant of the supernova of 1054—and certain extragalactic nebulae. A survey by Mills[3] increased the number of observed sources considerably but did not add any convincing identifications. Many objects in that part of the sky common to the surveys by Ryle, Smith, and Elsmore and by Mills are in only one of the two lists. This may indicate that neither of the two surveys is approximately complete. Unpublished results by Bolton, however, suggest that some of the positions listed actually refer to blends of objects rather than to individual sources. Since one temporary source is known[4] variability should not be entirely disregarded as a possible explanation of discrepancies. But the percentage of such cases obviously must be exceedingly low. This is shown directly by Ryle's observation[5] that, of about 100 sources, none showed variations greater than about 0.1 mag. over a period of 18 months.

Some of the first objects suggested as radio sources were known to be peculiar astronomically, but the low accuracy of the radio positions admitted considerable doubt as to the validity of the proposed identifications. It seemed definitely established, however, as a result of the surveys, that certain classes of objects were not among the discrete sources: stars brighter than magnitude 4, the nearest stars, stars having a large proper motion, stars with strong magnetic fields, old novae, planetary nebulae, diffuse nebulae, and star clusters. Negative evidence of this kind can be accepted only with reservations. It does not answer the question of whether some stars—other than the sun—are observable radio sources.

When the development of improved techniques led to precise positions and established the fact that many sources have a measurable angular extent, the way was open for an effective search with large telescopes for visible objects. As a result of these searches, the

[1] G. J. Stanley and O. B. Slee, *Australian J. Sci. Res.*, A, **3**, 234, 1950.

[2] M. Ryle, F. G. Smith, and B. Elsmore, *M.N.*, **110**, 508, 1950.

[3] B. Y. Mills, *Australian J. Sci. Res.*, *A*, **5**, 266, 1952.

[4] G. J. Stanley and O. B. Slee, *Australian J. Sci. Res.*, *A*, **3**, 234, 1950.

[5] M. Ryle, *Nature*, **168**, 555, 1951.

two strongest sources—Cygnus A and Cassiopeia—and one fainter source—Puppis A—were identified.[6] Certain more tentative identifications will be included in the present paper. It is now well established that a variety of objects can be strong radio emitters. They will be discussed in the following order: (I) remnants of supernovae, (II) galactic nebulosities of a new type, (III) peculiar extragalactic nebulae, and (IV) normal extragalactic nebulae.

A large part of the published positions of unidentified sources has been inspected by now on plates taken with the 48-inch Schmidt telescope. These attempts to identify more sources are being continued. But little further progress can be expected as long as radio positions have probable errors of the order of a degree or more and as long as marked discrepancies exist between the content of lists of different observers. Even the most precise determinations of positions, however, may not lead to identifications. No visible objects which might be considered as possible radio sources of the required intensity or extent have been found near Hydra A and Fornax A, for which Mills[7] has determined accurate positions. Actually, the identification of the strongest sources entails the conclusion that even relatively strong sources may be objects too faint to be seen or photographed. On the other hand, some objects not in the present lists of sources should be observable in the radio range if certain of the identifications are correct. Radio investigation of such objects is at least as important as attempts to determine more precise positions for all fainter sources.

The close agreement of the position of a radio source with that of an astronomical object is not sufficient for a definite identification. Data on the angular extent of the source are, in general, of equal importance, particularly if the position cannot be determined with high accuracy. Only for one type of source—normal extragalactic nebulae—is a correlation of radio intensity and optical brightness possibly to be expected. To compare intensity and brightness, it is convenient to express the intensity in magnitudes, as has already been done by Ryle, Smith, and Elsmore[2] and by Hanbury Brown and Hazard.[8] The magnitude system of Hanbury Brown and Hazard, which gives comparable radio and photographic magnitudes for normal extragalactic nebulae and almost entirely avoids negative magnitudes, seems more suitable and will be used here. The radio magnitude on this system is

$$m_R = -53.4 - 2.5 \log i \,,$$

where i is the intensity in watts $m^{-2}(c/sec)^{-1}$. If the dependence of the intensity on the frequency f is f^{-n}, the color index between two frequencies f_1 and f_2 is

$$C = m_R(f_1) - m_R(f_2) = 2.5n \log \frac{f_1}{f_2}.$$

The measures of the intensity distribution indicate values of n between 1.3 and 2. Thus the color difference between 100 and 158.5 Mc/sec, for instance, is between 1.0 and 1.5 mag. The intensity of the radio spectrum integrated over all frequencies would be infinite and cannot be determined as long as the true distribution for very low frequencies is not known. But the total energy emitted in the radio region is a datum of some significance, and values will be given based on the assumption that the total energy is

[6] W. Baade and R. Minkowski, *Ap. J.*, **119**, 206, 1954.

[7] *Australian J. Sci. Res.*, *A*, **5**, 456, 1952. The accurate position of Fornax A (Mills 03 − 3)—(1950) $\alpha = 3^h19^m30^s \pm 6^s$, $\delta = -37°18' \pm 3'$—rules out the identification with NGC 1316, $\alpha = 3^h20^m.8$, $\delta = 37°24'$, which has been proposed by I. S. Shklovski, *Astr. J. U.S.S.R.*, **30**, 30, 1953. Moreover, Shklovski's statement that NGC 1316 is similar to NGC 5128 is not correct. NGC 1316 is an SO or Sa nebula with a few faint absorption patches.

Added October, 1953: Mills now admits that Fornax A may be a blend of several sources. Attempts to identify Fornax A should therefore be postponed until the situation is cleared up.

[8] *Phil. Mag.*, **43**, 137, 1952.

equivalent to that contained in a band of 500 Mc/sec width with a constant intensity equal to that at 100 Mc/sec.[9]

The photographic magnitudes quoted for extragalactic nebulae are marked by letters denoting their source, as follows (H) Holmberg,[10] (SW) Stebbins and Whitford,[11] (P) Pettit,[12] (B) Bigay,[13] (SA) Shapley and Ames.[14] According to Holmberg,[10] magnitudes of the Shapley-Ames catalogue are systematically too faint for bright nebulae; where necessary, values corrected for this systematic error are also given.

I. REMNANTS OF SUPERNOVAE

1. THE CRAB NEBULA (RYLE 05.01; MILLS 05 + 2)

The Crab Nebula is the remnant of the supernova of 1054, a supernova of type I. The identification of the source discovered by Bolton[15] with the Crab Nebula was first suggested by Bolton, Stanley, and Slee.[16] Except for the discovery position, all positions given in Table 1 are in excellent agreement with the position of the Crab Nebula. The

TABLE 1

NGC 1952 (RYLE 05.01, MILLS 05 + 2)

α (1950)	δ (1950)	Frequency (Mc/Sec)	m	Observer
5^h13^m	+28°	100	4.0	Bolton*
$5^h31^m20^s \pm 30^s$	+22°02′±8′	....	....	Bolton, Stanley, and Slee; Bolton and Stanley†
$5^h31^m30^s$	+22°01′	100	3.3	Stanley and Slee‡
$5^h31^m37^s \pm 10^s$	+22°10′±20′	81.5	+3.9	Ryle, Smith, and Elsmore§
$5^h31^m34\overset{s}{.}5 \pm 3^s$	+22°4′±5′	....	....	Smith‖
$5^h30^m \pm 2^m$	+22°±20′	100	+3.4	Mills#
$5^h31^m29^s \pm 2\overset{s}{.}5$	+22°00±3′	....	....	Mills**
$5^h31^m30^s$	+21°59′.3	*pg*	9.0††	NGC

* *Nature*, **162**, 141, 1948.

† J. G. Bolton, G. J. Stanley, and O. B. Slee, *Nature*, **164**, 101, 1949; J. G. Bolton and G. J. Stanley, *Australian J. Sci. Res.*, *A*, **2**, 139, 1949.

‡ *Australian J. Sci. Res.*, *A*, **3**, 234, 1950.

§ *M.N.*, **111**, 508, 1950.

‖ *Nature*, **168**, 555, 1951.

J *Australian J. Sci. Res.*, *A*, **5**, 266, 1952.

** *Ibid.*, p. 456.

†† W. Baade, *Ap. J.*, **96**, 188, 1942; *Mt. W. Contr.*, No. 665.

two most precise positions by Smith and by Mills have estimated probable errors which are not larger than the size of the nebula. An effective angular size of 4′ in the east-west direction has recently been determined by Mills.[17] This value agrees well with the size of the nebula. Recent unpublished measures by Mills give an elliptical brightness contour 3′.5 × 5′, with the major axis in position angle 143°, in excellent agreement with the size and orientation of the nebula which are given below. The identification thus is safely established.

The discussion of the structure and the spectrum of the Crab Nebula[18, 19] shows that

[9] See the following paper by Minkowski and Greenstein (pp. 238–242).

[10] *Lund Medd.*, ser. 2, No. 128, 1950.

[11] *Ap. J.*, **115**, 284, 1952.

[12] Personal communication.

[13] *Ann d'ap.*, **14**, 319, 1951.

[14] *Harvard Ann.*, Vol. **88**, No. 2, 1932.

[15] *Nature*, **162**, 141, 1948.

[16] *Nature*, **164**, 101, 1949.

[17] *Nature*, **170**, 1062, 1952.

[18] W. Baade, *Ap. J.*, **96**, 188, 1942; *Mt. W. Contr.*, No. 665.

[19] R. Minkowski, *Ap. J.*, **96**, 199, 1942; *Mt. W. Contr.*, No. 666.

the nebula consists of an envelope of filaments, about 4'.0 × 6'.0, which inclose an inner diffuse mass, about 3'.2 × 5'.9; the major axis is in position angle 130°. The spectrum of the filaments consists of emission lines, that of the central mass is continuous, but the radio emission cannot be considered as the extension of the visible continuous spectrum into the radio region.[20]

If the visible continuous spectrum is interpreted as thermal emission of the ionized gas, the radio emission must be of nonthermal origin. The observational data do not permit us to decide whether the filaments, the diffuse mass, or both are the seat of the radio emission. More detailed investigation of the size and shape of the source, possibly with the aid of an occultation by the moon, may help to settle this question.

The Crab Nebula is at a distance of 1000 psc. The total radio energy emitted by the nebula thus is 7×10^{32} ergs sec^{-1}.

2. B CASSIOPEIAE

The light-curve of B Cassiopeiae, Tycho Brahe's nova of 1572, shows that, like the Crab Nebula, it was a supernova of type I;[21] but no visible remnant of this supernova has been found.

Recently, Hanbury Brown and Hazard[22] have reported a radio source near the position of the supernova. The pertinent data are in Table 2. The positions of radio source and supernova are in satisfactory agreement, but, particularly in view of the uncertainty of the radio position, the identification can be considered as only tentative. An observation of the size of the source may give supporting evidence, since an angular diameter of the same order as that of the Crab Nebula is to be expected.

Data for a comparison of B Cassiopeiae with the supernova of 1054 are in Table 3.

TABLE 2

B CASSIOPEIAE

α (1950)	δ (1950)	Frequency (Mc/Sec)	m	Observer
$0^h21^m49^s \pm 2^m$	$+64°15' \pm 35'$	158.5	6.1	Hanbury Brown and Hazard*
$0^h22^m.0$	+64°52'.2	*pg*	> +15	Tycho Brahe†

* *Nature*, **170**, 364, 1952.
† W. Baade, *Ap. J.*, **102**, 309, 1945; *Mt. W. Contr.*, No. 711.

TABLE 3

COMPARISON OF THE SUPERNOVAE OF 1054 AND 1572

	m_v at Maximum	m_{pg} of Remnant	m_r at 158.5 Mc/Sec
AD 1054	−6.5 to −7.0	+ 9	4.0*
AD 1572	−4.0	> +15	6.0

* From unpublished data of the Radiophysics Laboratory, Sydney, Australia, communicated by Bolton.

[20] J. L. Greenstein and R. Minkowski, *Ap. J.*, **118**, 1, 1953.
[21] W. Baade, *Ap. J.*, **102**, 309, 1945; *Mt. W. Contr.*, No. 711.
[22] *Nature*, **170**, 364, 1952.

In comparing these two objects, the differences in interstellar absorption cannot be disregarded, but no accurate values are available. It is certain that B Cassiopeiae is heavily obscured compared with the Crab Nebula.

The difference between the visual magnitudes at maximum corrected for interstellar absorption may therefore be quite small, almost certainly smaller than the radio differences between the remnants. But the photographic magnitudes of the remnants after correction for absorption would still differ by more than 4 mag. Since radio and optical emissions of the remnants do not seem to be related phenomena,[20] there is no reason why the differences between the radio and between the photographic magnitudes of the remnants should be identical.

3. UNIDENTIFIED AND UNOBSERVED SOURCES

Of the three known galactic supernovae, two have been observed as radio sources, but the third—Kepler's nova of 1604—is not yet observed, although its remnant has been discovered by Baade.[23] Since its position is close to that of the galactic center, high intensity of the general galactic radiation presents certain difficulties for the observation of this source. But, to make the evidence final that the remnants of supernovae of type I are radio sources, a search for a radio source in the position of Kepler's nova and an attempt to measure its size would be of great value.

In a giant stellar system like the Galaxy, supernovae of type I should appear with a frequency of several, perhaps five, supernovae per 1000 years.[24] Since the relatively high radio intensity of the Crab Nebula shows that the radio emission probably will persist for much more than 1000 years, a certain number of unknown supernova remnants must be observable as individual radio sources. This number could be estimated only if it were known how the radio emission decreases with time. But since the emission seems to be nonthermal,[20] its rate of decay cannot be computed. While it is thus impossible to predict how many unidentified sources might be supernova remnants, it is possible to conclude with some confidence that supernova remnants contribute, at most, an insignificant fraction of the general galactic radiation. It is certain that the radio emission of the Crab Nebula must decrease greatly during the next 20,000 years, when its density reaches that of interstellar space. If the radio emission should continue with undiminished intensity until that time, the 100 supernovae appearing within 20,000 years would emit a total radio energy of 5×10^{34} ergs sec^{-1}, not more than a few tenths of 1 per cent of the total emission of the Galaxy. The actual contribution obviously will be even less.

II. PECULIAR EMISSION NEBULOSITIES

The identification of the source in Cassiopeia and of Puppis A has led to the discovery of a new type of galactic nebulosity,[6] filamentary nebulae with large internal motions. Unusual filamentary structures have been found near the positions of one other source. These filaments do not have quite the same character as those in Cassiopeia and in Puppis A, and no data on their velocities are available. The suggestion that they are sources of radio emission is therefore entirely tentative.

Cygnus X, a region of high radio intensity, was initially considered as a feature of the general galactic emission. Measurements at 1210 Mc/sec by Piddington and Minnett[25] have shown, however, that the emission in this region is very probably due to a strong discrete source extending over many square degrees. The region containing this source is

[23] *Ap. J.*, **97**, 119, 1943: *Mt. W. Contr.*, No. 675; see also R. Minkowski, *Ap. J.*, **97**, 128, 1943; *Mt. W. Contr.*, No. 676.

[24] Actually, three supernovae appeared during the last 1000 years. That these are within 1000 psc of the sun, or in a volume of the order of 1 per cent of that of the Galaxy, must be due to a statistical fluctuation in the galactic distribution, since the resulting frequency of the order of one supernova per 3 years in the Galaxy as a whole is clearly contradicted by the evidence from other giant Sb nebulae.

[25] *Australian J. Sci. Res.*, *A*, **5**, 17, 1952.

shown in Figure 1. The position of the center, $20^h27^m \pm 3^m$, $+40^\circ.5 \pm 1^\circ$, is marked by a cross, and the full-drawn curves are contours of equal aerial beam temperature given by Piddington and Minnett. Recent observations by Hanbury Brown and Hazard[26] confirm these results. Their center, 20^h22^m, $+40^\circ 00'$, is marked by a circle, and their curves of equal intensity are drawn as broken curves.

The region near γ Cygni in which this source is located is one of the most complicated parts of the sky, presenting layers of emission nebulosity and heavily absorbing clouds. The following half of Cygnus X is in the most heavily obscured region; obviously, any object in this area would be expected to be hidden from sight. The preceding half is in a more transparent area, and the preceding end may be expected to be affected least by obscuration. Here appear some very unusual filaments. The areas containing these filaments are shown in Figures 2 and 3. The filaments are shown on a larger scale in Figures 4 and 5. Some of these filaments are sharp but longer than those which appear in the Cassiopeia source and in Puppis A; others look like an enlarged picture of the Cassiopeia filaments. Filaments of this type are very rare. Their appearance near that edge of Cygnus X where obscuration is smallest suggests that the radio emission originates in a system of such filaments which is almost entirely hidden by obscuration.[27]

Identification of Cygnus X with thermal radiation from the bright nebulosities surrounding γ Cygni has been suggested by Piddington and Minnett. One obvious objection to this assumption derives from the fact that the Orion Nebula has not been observed as a radio source. This exceptionally dense *H* II region should be barely detectable as a radio source.[20] Compared with it, the Cygnus nebulosities are so much fainter that their thermal radiation cannot be expected to be observable. It is possible, of course, that the heavy obscuration in the galactic plane hides the brightest part of the nebulosity from sight. The nebulosities near γ Cygni and the North America nebula could indeed be the fainter outer parts of an extremely dense *H* II region with observable thermal radio emission, or of several such regions distributed in depth. But, in this case, the radio source should extend in the direction of the galactic equator, not in the direction, inclined about 45°, of Cygnus X. The radio spectrum of Cygnus X can be explained as well by the assumption of nonthermal radio emission combined with the opacity of hydrogen in the low-frequency region[20] as by the assumption of thermal emission from an optically thick *H* II region.

Both the sources in Cassiopeia and Puppis A are near regions in which heavy absorption and diffuse nebulosities appear, and Cygnus X is actually within such a region. It is tempting to assume that they are connected with the interstellar gas, representing regions in which peculiar conditions lead to strong nonthermal emission.

The fact that the only two definitely identified sources of this type seem to have approximately spherical or elliptical outlines suggests some central origin for the peculiar condition, and one might suppose that the nebulosities were formed by an ejection process. But the observed random velocities are so large that they hide so far any expansion which may be present. The largest velocity of expansion admitted by the observations is certainly much smaller than that observed in the Crab Nebula. The conditions in the radio-source nebulosities are thus diametrically opposed to those in the filaments of supernova remnants, where a large velocity of expansion exceeds the relatively small internal random velocities. Moreover, the general appearance of the Cassiopeia nebulosity, with its two distinct kinds of filaments, is entirely different from that of the known remnants of supernovae. Altogether, no observed fact supports the view that the radio-source nebulosities are remnants of supernovae.

[26] *M.N.*, **113**, 109, 1953.

[27] *Added October, 1953:* A spectrogram of one of these filaments has recently been obtained. The composition of the spectrum, which shows $H\alpha$, [N II], and [O II], is normal, and the velocity spread is small. There is therefore no evidence at present that the filamentary structures near Cygnus X are of the same type as the filaments in Cassiopeia source and in Puppis A. Hence the identification of Cygnus X remains an unsolved problem.

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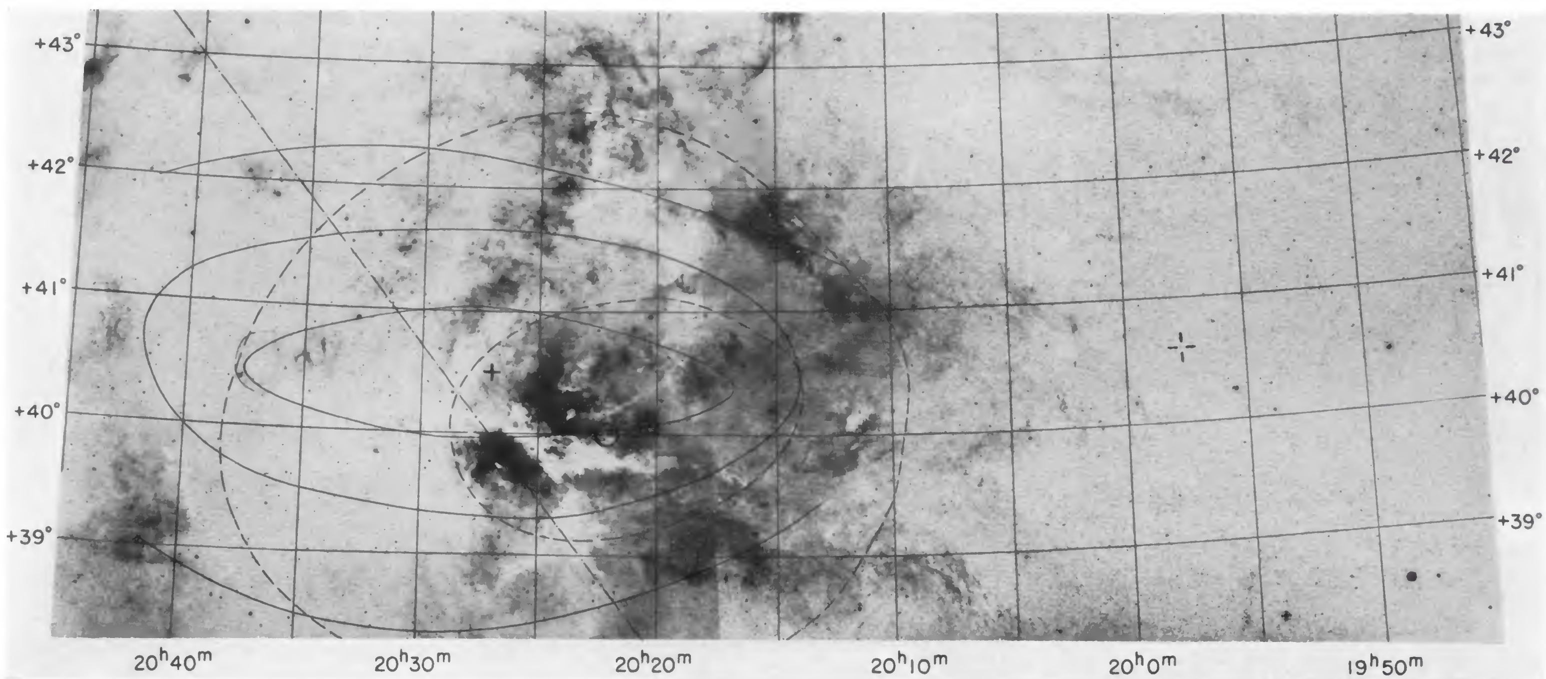

FIG. 1.—Region in Cygnus. Epoch 1950. Galactic equator marked by broken straight line. Cygnus X: Cross at 20^h27^m, $+40\overset{\circ}{.}5$ and solid curves from Piddington and Minnett; circle at 20^h22^m, $+40°$ and broken curves from Hanbury Brown and Hazard. Cygnus A is marked by an open cross at $19^h57^m45^s$, $+40°35'36''$.

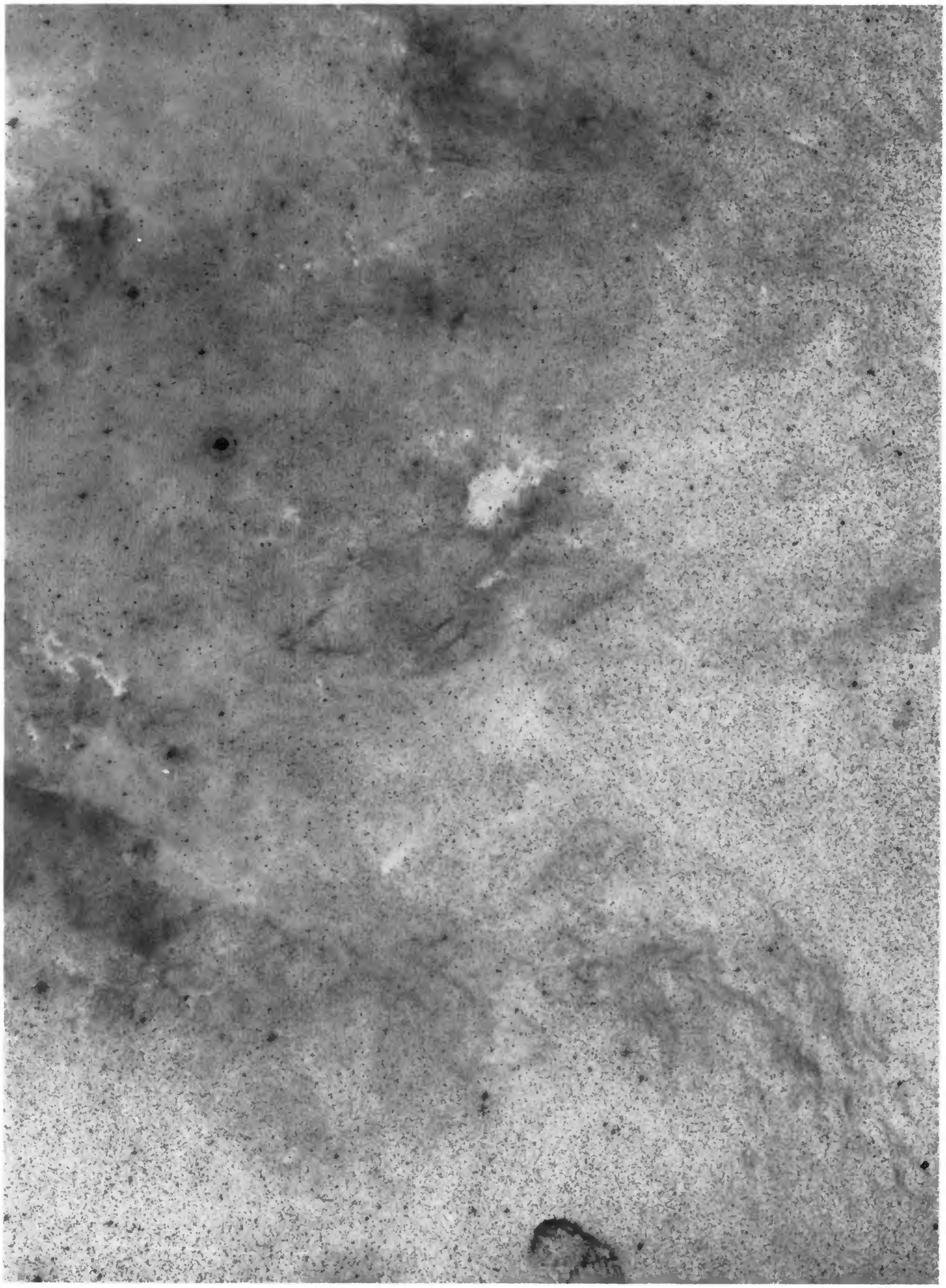

FIG. 2.—Field in Cygnus. Center (1950) 20^h12^m, $+39°42'$; λλ 6300-6700; 48-inch; 1 mm = 67″

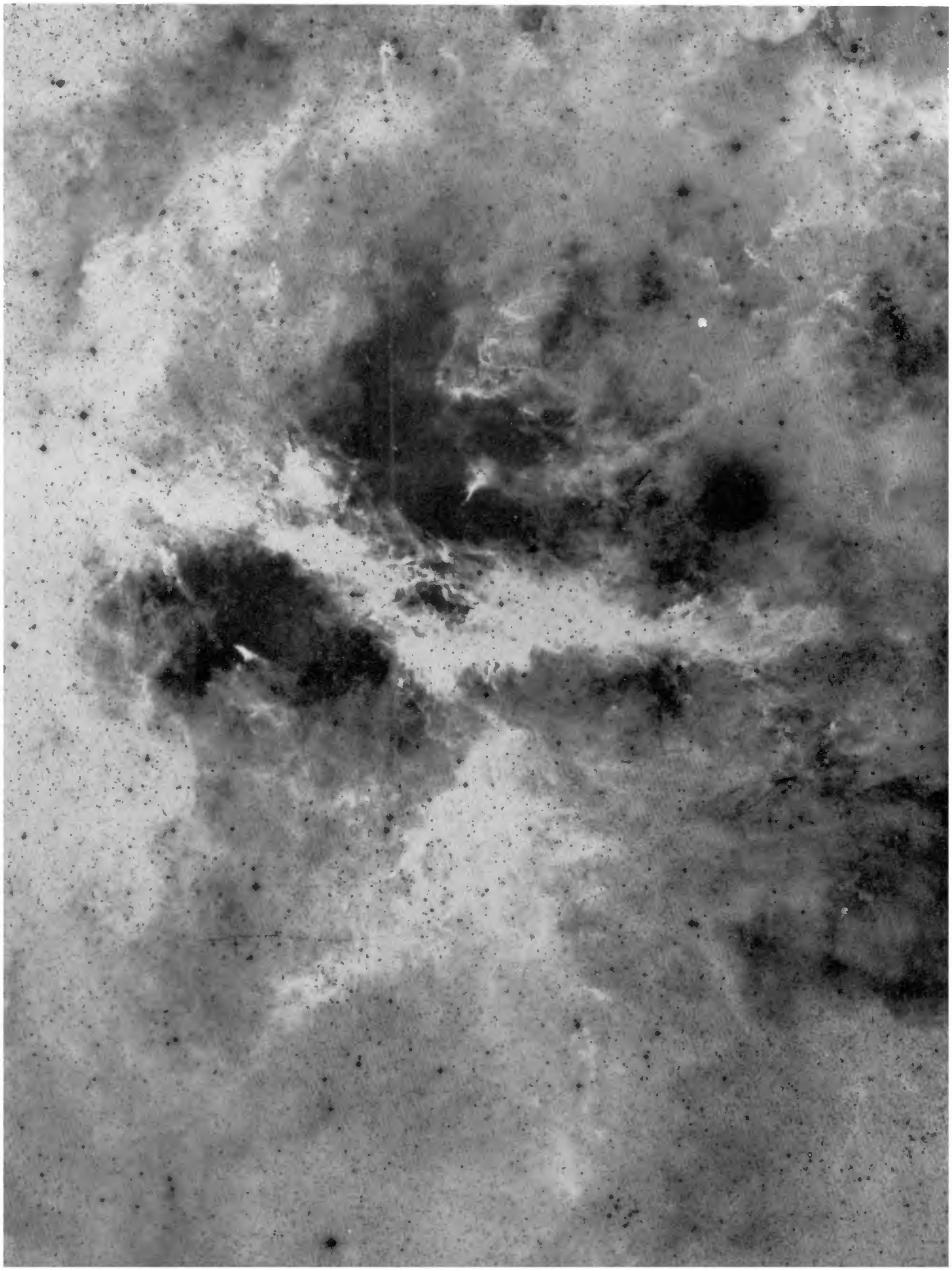

FIG. 3.—Field in Cygnus. Center (1950) $20^h23^m.5$, $+39°47'$; λλ 6300–6700; 48-inch; 1 mm = 67″

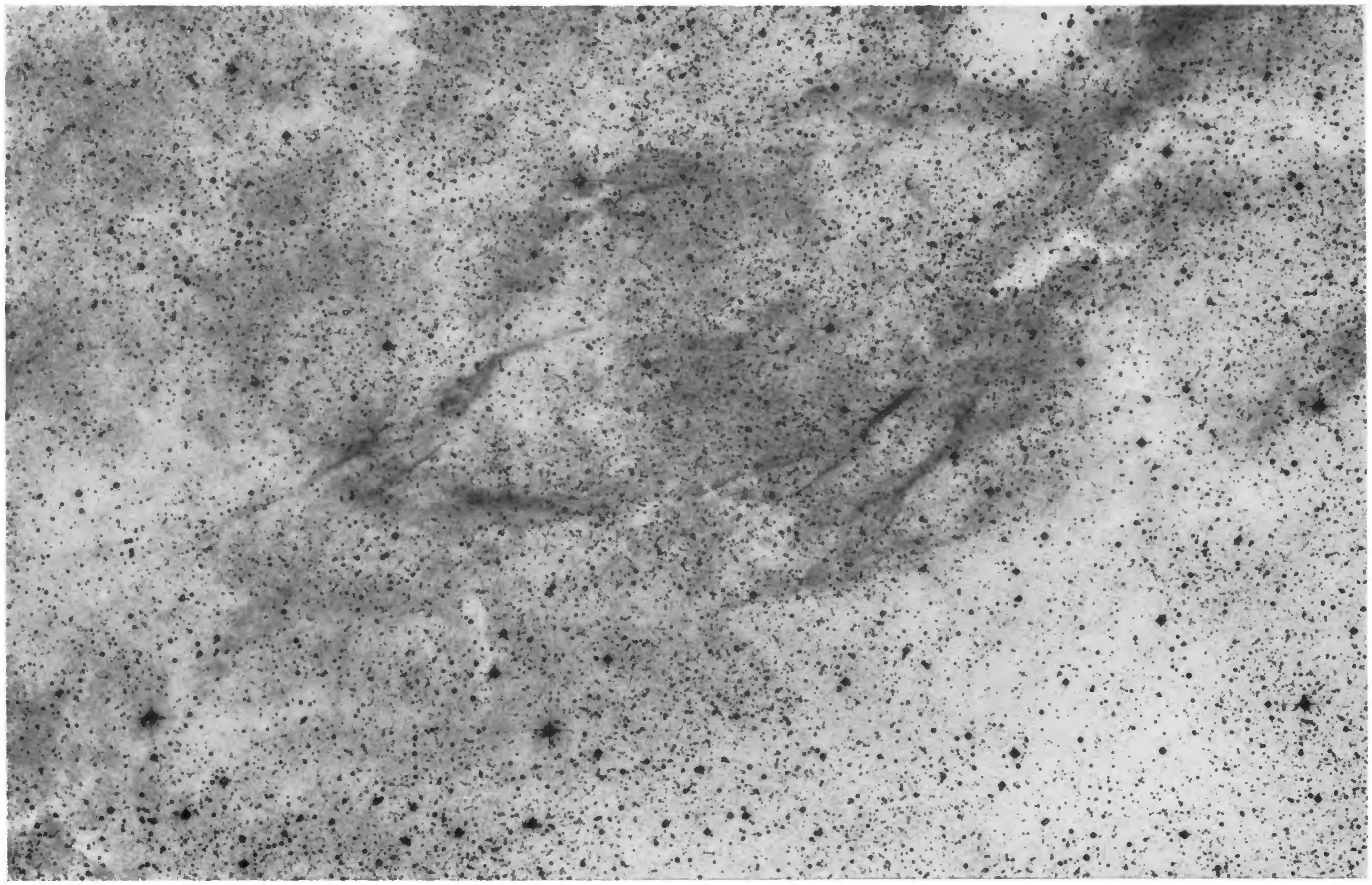

FIG. 4.—Filaments in Cygnus. Center (1950) $20^{h}13^{m}.0$, $+39°38'.7$; λλ 6300–6700; 48-inch; 1 mm = 21″

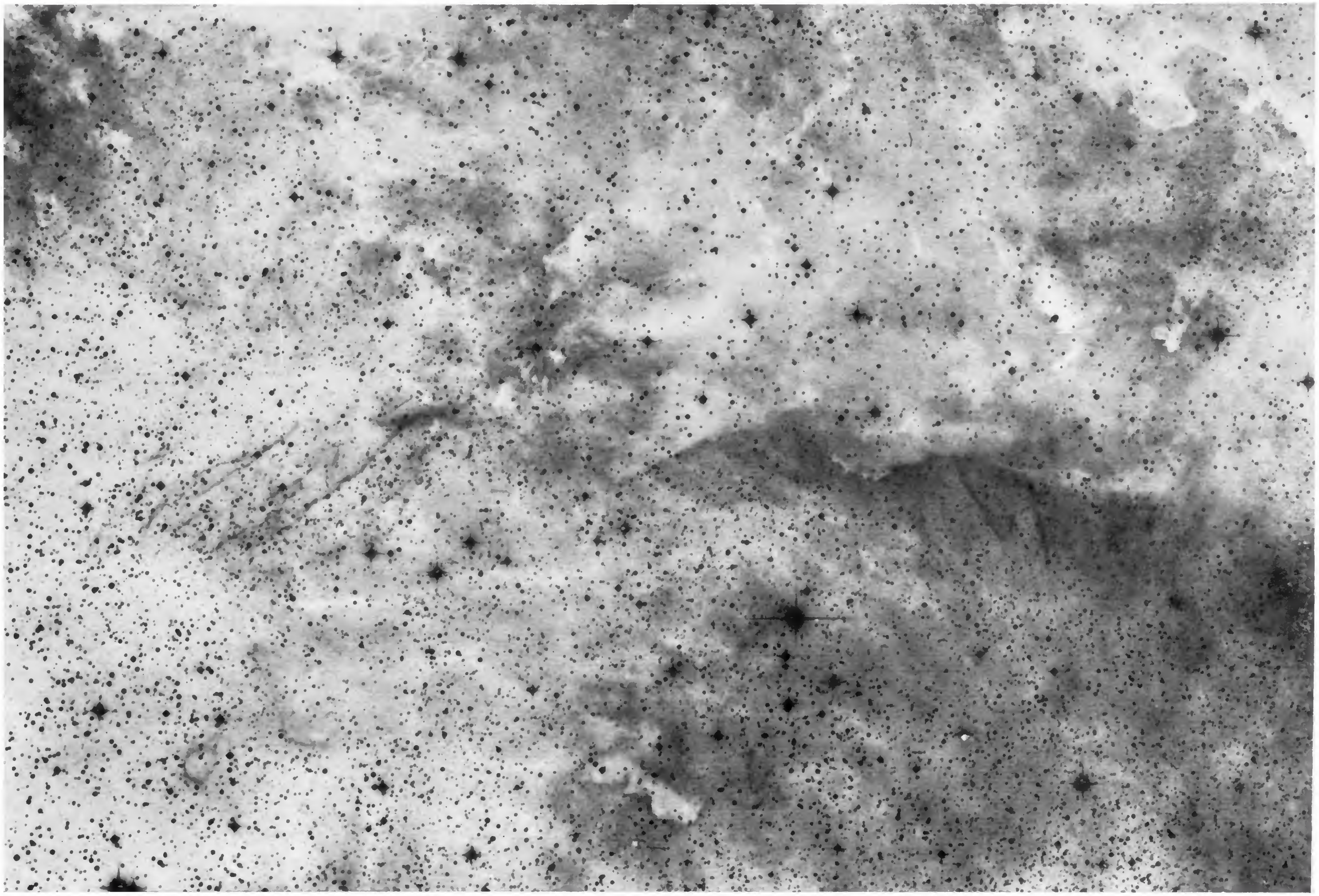

FIG. 5.—Filaments in Cygnus. Center (1950) $20^{h}19^{m}.0$, $+39°22'.6$; λλ 6300–6700; 48-inch; 1 mm = 21″

All three sources are close to the galactic equator, as is to be expected if they are connected with the interstellar gas and thus belong to population I. Sources of this type may not be the only ones which show strong concentration toward the galactic plane. They are certainly only a part of the group of stronger sources with concentration toward the galactic plane which Mills[3] has grouped in his class I of sources. This class does not represent a homogeneous group of objects but contains at least one extragalactic source, Cygnus A, the remnants of the supernovae of type I which are in population II, and the Cassiopeia type nebulosities which are probably in population I. Radio stars, if they exist, would also be in Mills's class I. The attempts to derive distances from statistical analysis of such an inhomogeneous group are, of course, hopeless. In particular, a high degree of galactic concentration is not necessarily an indication of large distances if sources belonging to population I exist.

A certain number of sources found by Mills and by Hanbury Brown are so close to the galactic plane that they might be population I objects. Most of the positions have by now been inspected on 48-inch Schmidt plates. Almost always the positions were found to be in heavily obscured areas, frequently in the neighborhood of large diffuse nebulosities. Near the galactic plane such a result is not surprising.

Since frequency and distances of the peculiar nebulosities are unknown, their absolute emission cannot be determined, and therefore their contribution to the radiation of the Galaxy cannot be estimated. If the distance of the Cassiopeia source is 300 psc, the total radio emission is 11×10^{32} ergs sec^{-1}, less than 10^{-4} of the total emission of the Galaxy. That the peculiar nebulosities contribute more than an insignificant fraction of the galactic emission is therefore very improbable.

III. PECULIAR EXTRAGALACTIC NEBULAE

The identification of two radio sources with the extragalactic nebulae NGC 4486 (M87) and NGC 5128, first suggested as a possibility by Bolton, Stanley, and Slee,[16] is now well established. Neither of the nebulae is of outstanding apparent brightness, but both show outstanding peculiarities. No explanation can be suggested of why and how the peculiarity in NGC 4486 leads to strong radio emission. Another type of peculiarity, in which the basic features of the physical processes seem obvious, is shown by the strong radio source Cygnus A, where the radio emission is due to a collision of two extragalactic nebulae. It is probable that NGC 1275 and NGC 5128 also belong in this class. Thus the group of peculiar extragalactic nebulae whose radio intensity is disproportionate to their luminosity comprises a variety of objects which cannot be assumed to be fully known at this stage.

1. NGC 4486 (RYLE 12.01; MILLS 12 + 1)

The identification of this source with NGC 4486 was first suggested by Bolton, Stanley, and Slee.[16] The agreement of the positions in Table 4 strongly supports the identification.

The field surrounding NGC 4486 is shown in Figure 6. NGC 4486, in the center of the field, is a member of the Virgo cluster of nebulae. At first sight, it is not obvious why this object should be a relatively strong radio source; it does not differ essentially in size or brightness from other bright members of the cluster. It is shown on a larger scale in Figure 7, clearly a nebula of type E0 with a rich envelope of globular clusters; this is not a rare type of nebula. However, NGC 4486 has a unique peculiarity which has been known for a long time.[28] In the center of the nebula, overexposed in Figure 7, is a straight jet, extending from the nucleus in position angle 290°. This feature, relatively much bluer than the nebula itself, is shown from a shorter exposure in the ultraviolet in Figure 8. Several strong condensations are in the outer parts of the jet, which extends

[28] H. D. Curtis, *Pub. Lick Obs.*, **13**, 31, 1918.

about 20″ from the nucleus and has an average width of about 2″. As a member of the Virgo cluster, NGC 4486 is at a distance[29] of 3×10^6 psc. The linear length of the jet therefore is 300 psc, its average width about 30 psc. The total radio emission of the source is 5×10^{39} ergs sec^{-1}.

Spectra obtained by Humason show that the jet has a continuous spectrum, indicating a rather blue color but showing neither absorption nor emission lines. The nebula has a normal spectrum of type G, but superposed on the nucleus appears a strong emission line of [*O* II] λ 3727, which is shifted relative to the nuclear G-type spectrum by -295 ± 100 km/sec. The interpretation which suggests itself is that the jet was formed by ejection from the nucleus and that the [*O* II] line is emitted by a part of the material which forms the jet and is still very close to, if not still inside, the nucleus. The angle between the jet and the line of sight is not known. If it is assumed that this angle is 45°, tangential and radial velocities are equal, and if the velocity of the ejection has remained constant, the formation of the jet has taken place during a time of 10^6 years.

No possibility exists at this time of forming any hypothesis on the formation of the jet, the physical state of its material, and the mechanism which connects the existence of the jet with the observed radio emission.

TABLE 4

NGC 4486 (RYLE 12.01; MILLS 12 + 1)

α	δ	Frequency (Mc/Sec)	m	Observer
$12^h28^m6^s \pm 37^s$	$+12°41' \pm 10'$	100	3.7	Bolton, Stanley, and Slee;* Stanley and Slee*
$12^h28^m25^s \pm 70^s$	$+12°55' \pm 20'$	81.5	4.0	Ryle, Smith, and Elsmore†
$12^h28^m18^s \pm 3^s$	$+12°37' \pm 10'$	....	....	Smith‡
$12^h30^m \pm 2^m$	$+12°30' \pm 20'$	100	3.8	Mills§
$12^h28^m15\overset{s}{.}5 \pm 2\overset{s}{.}5$	$+12°44' \pm 6'$	100	....	Mills‖
$12^h28^m18^s$	$+12°40\overset{'}{.}1$	*pg*	9.9(SW)	NGC

* J. G. Bolton, G. J. Stanley, and O. B. Slee, *Nature*, **164**, 101, 1949; G. J. Stanley and O. B. Slee, *Australian J. Sci. Res.*, *A*, **3**, 234, 1950.

† *M.N.*, **111**, 508, 1950.

‡ *Australian J. Sci. Res.*, *A*, **5**, 266, 1952.

§ *Australian J. Sci. Res.*, *A*, **5**, 266, 1952.

‖ *Ibid.*, p. 456.

Recent measures by Mills[17] give 5′ as the effective size of the radio source in the east-west direction. Unpublished measures by Mills show an elliptical half-brightness contour of $2\overset{'}{.}5 \times 6\overset{'}{.}0$ with the major axis in position angle 45°, almost perpendicular to the direction of the jet. Since the diameters of other radio sources obtained in the same series of observations agree well with their visible sizes, there is no obvious reason to doubt the measure for NGC 4486. However, a diameter of 5′ is of the order of the diameter of the whole system, as can be seen from Figure 7. Therefore, if the measured effective size of the source is correct, the radio emission is not confined to the jet but is distributed through the whole nebula. The jet would then be only the visible sign of a peculiar condition extending over a volume 10^5 times larger than the jet.

2. NGC 1275 (MILLS 03 + 4)

A radio source possibly identical with Ryle 03.02 observed by Hanbury Brown and Hazard[8] and by Mills[3] coincides with the Perseus cluster of extragalactic nebulae shown

[29] All distances for extragalactic objects in this paper are still given on the old scale, and the recent correction to the zero point of the type I cepheids has been disregarded. This correction leads to an increase by a factor of about 2 for all extragalactic distances.

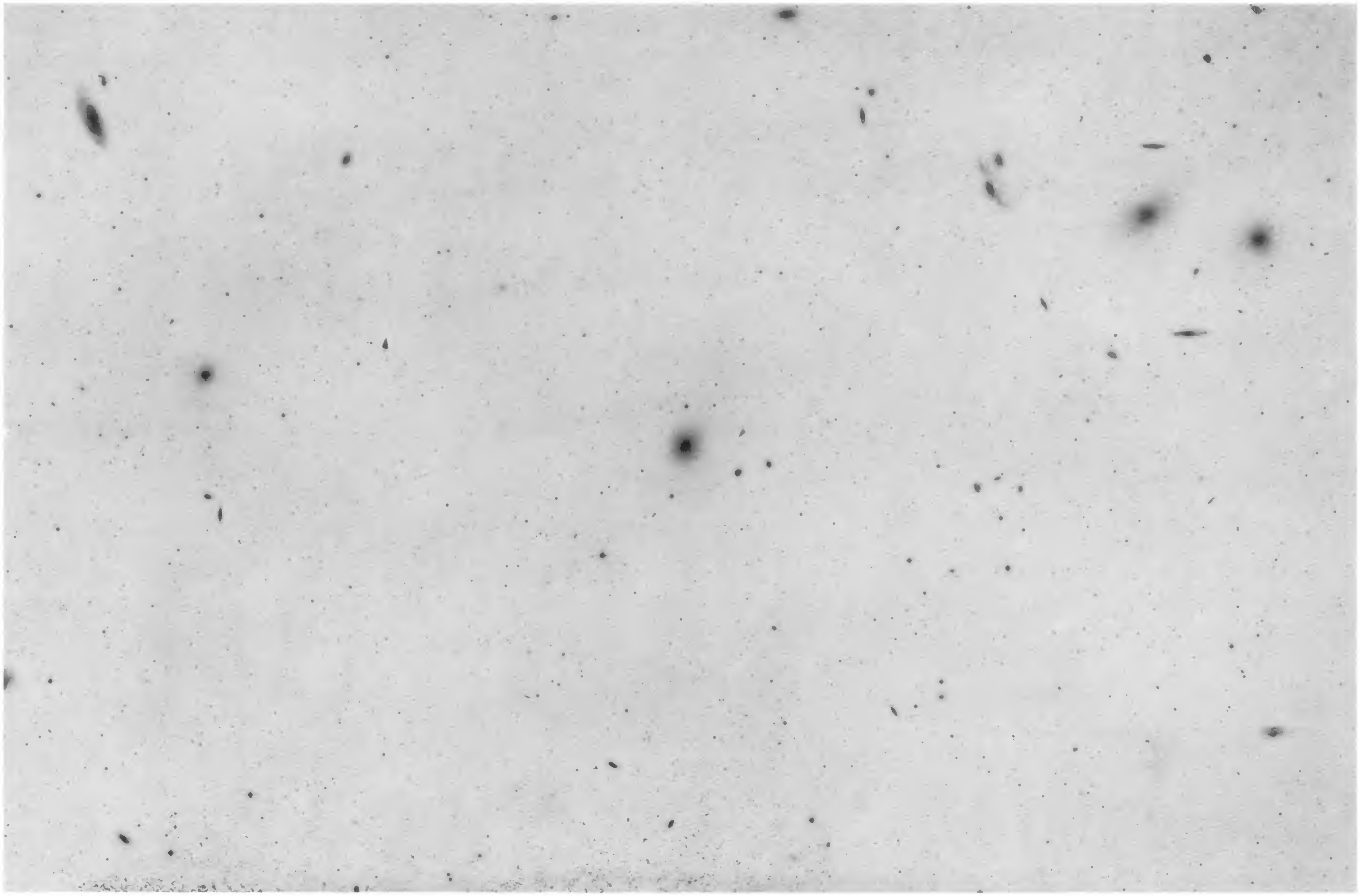

FIG. 6.—Field in Virgo. NGC 4486 in center. λλ 3600–5000; 48-inch; 1 mm = 67″

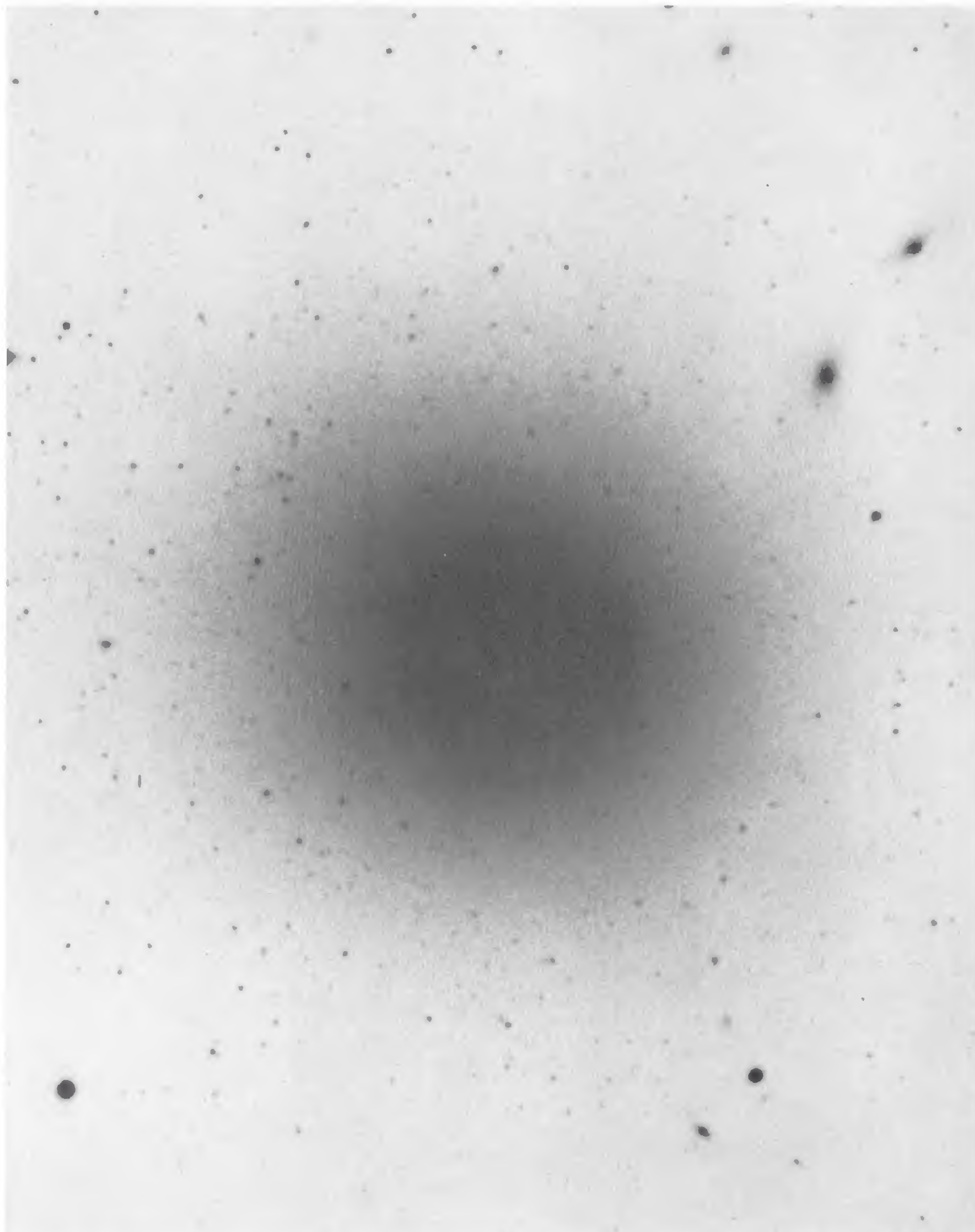

FIG. 7.—NGC 4486. λλ 3600–5000; 200-inch; 1 mm = 2″2

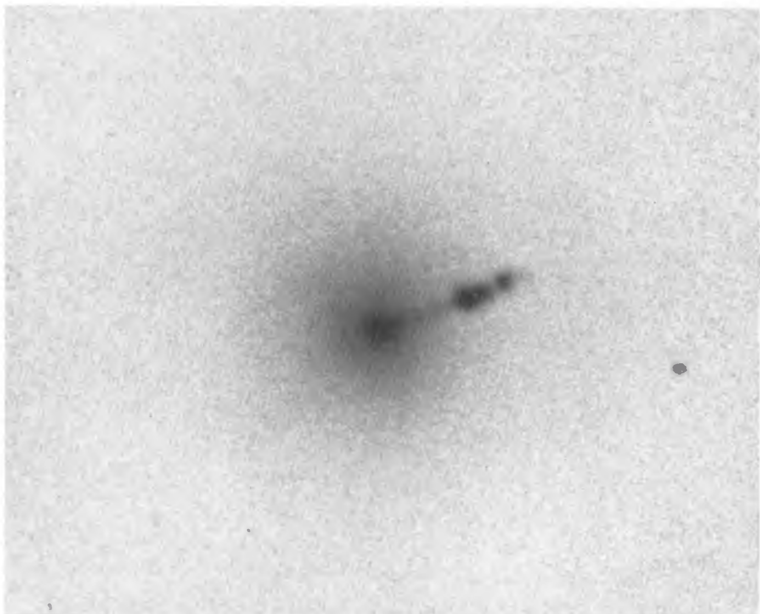

FIG. 8.—Center of NGC 4486. λ < 4000; 100-inch; 1 mm = 0″.8

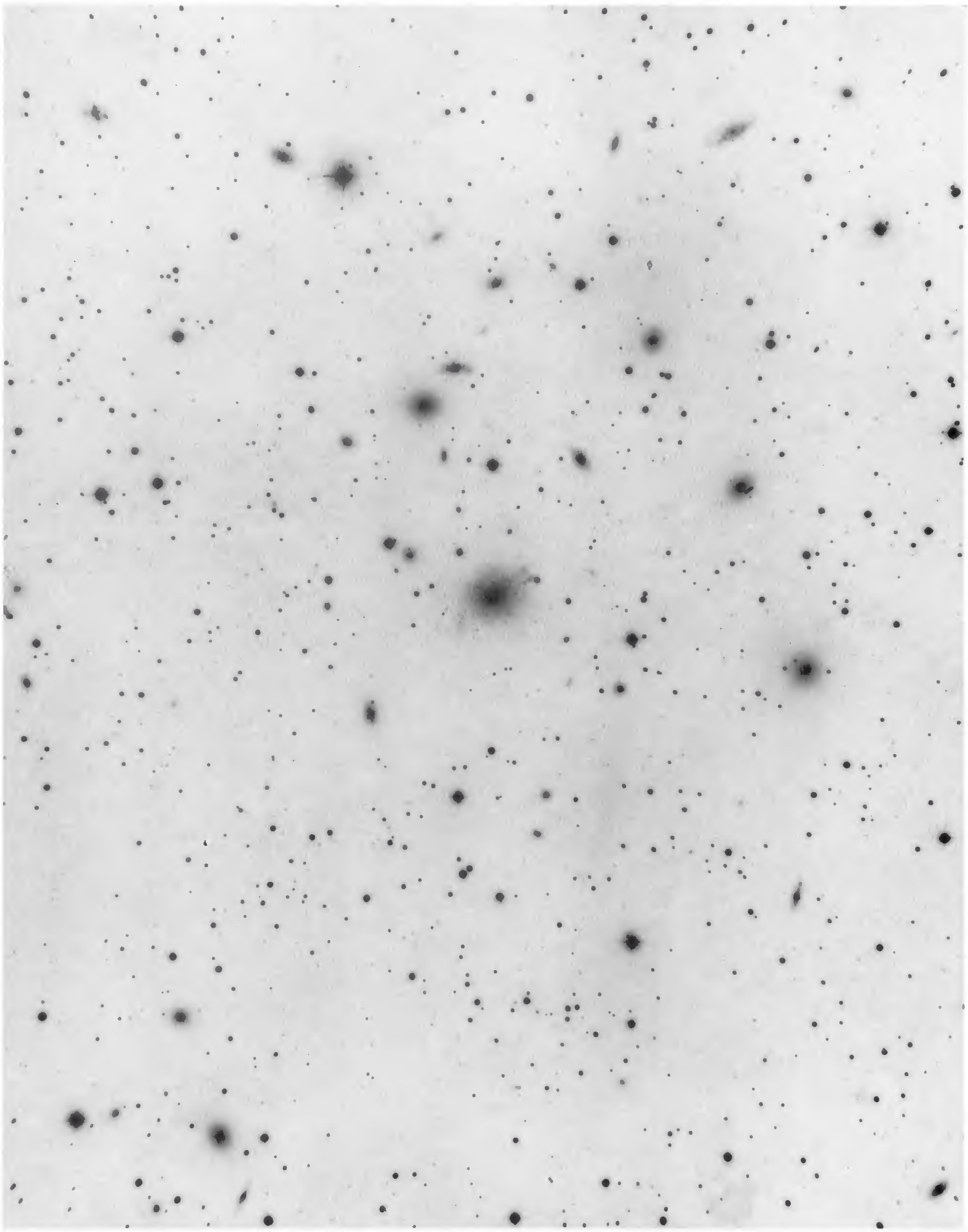

FIG. 9.—Cluster of nebulae in Perseus. λλ 3600–5000; 200-inch; 1 mm = 7″.4

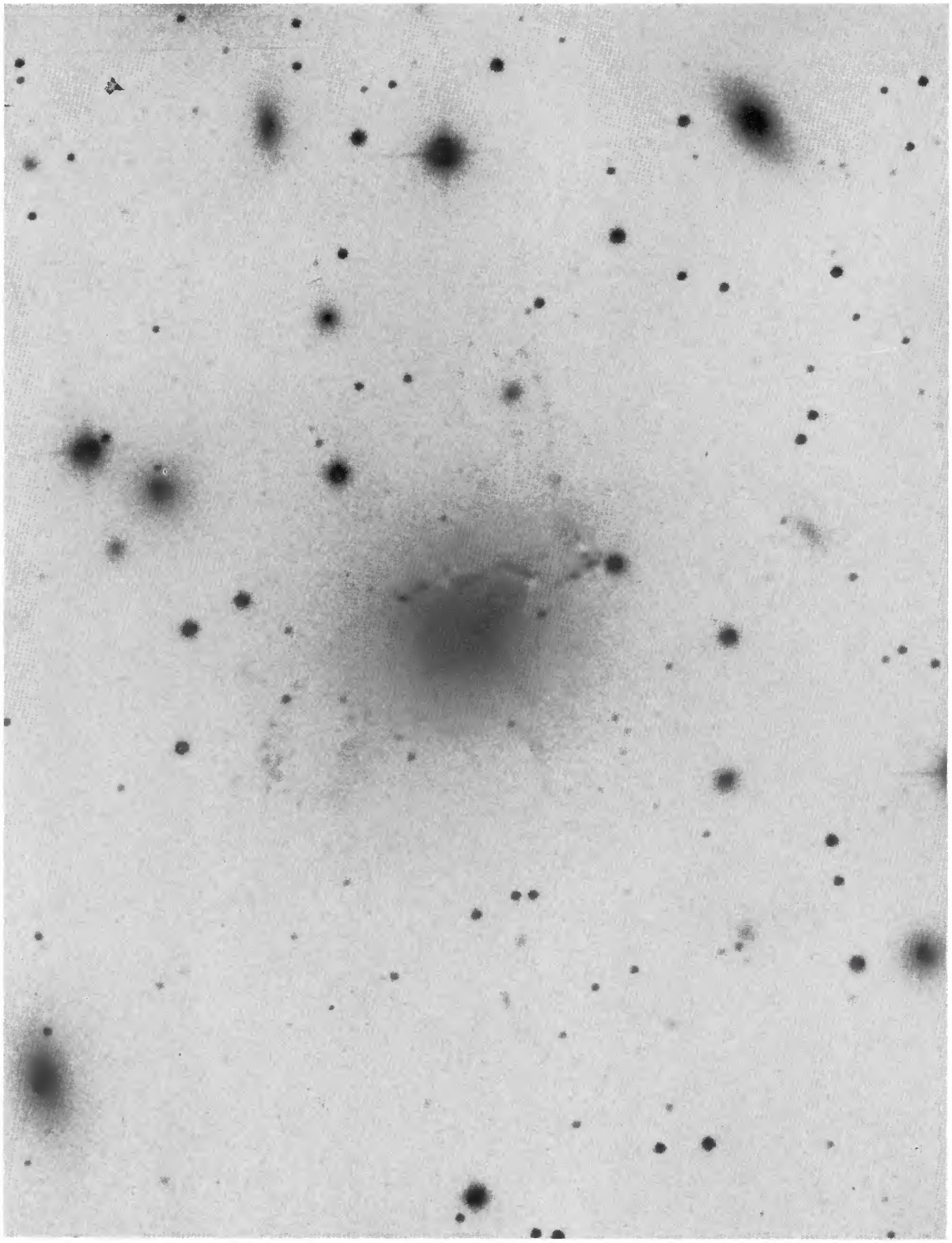

FIG. 10.—NGC 1275. λλ 3600–5000; 200-inch; 1 mm = 2″0

in Figure 9. The identification of this source with the cluster as a whole is not convincing. Not only is the source more intense than one would infer from the integrated brightness of the cluster on the assumption that the cluster contains normal nebulae only, but other clusters which should be observable on the same basis have not yet been found to be radio sources. This suggests that actually not the cluster but a peculiar nebula in the cluster is the radio source. The Perseus cluster, indeed, contains as its brightest member a highly peculiar nebula, NGC 1275, shown enlarged in Figure 10. Since the position of this nebula is usually given for that of the cluster, the coincidence of the positions, in Table 5, remains unchanged.

The structure and the colors of NGC 1275 admit of only one interpretation—that this object shows an apparently tightly wound nebula of the spiral type penetrating from the south a late-type, very loose spiral whose arms are entirely distorted by strong

TABLE 5

POSITIONS OF NGC 1275 (MILLS 03 + 4)

α	δ	Frequency (Mc/Sec)	m	Observer
$3^h15^m15^s \pm 90^s$	$+41°22' \pm 30'$	158.5	7.2	Hanbury Brown and Hazard*
$3^h10^m \pm 4^m$	$+42° \pm 20'$	100	5.6	Mills†
$3^h16^m52^s$	$+40°50'$	....	....	Mills‡
$3^h16^m15^s$	$+41°19'$	*pg*	13.28 (P)	NGC

* *Phil. Mag.*, **43,** 137, 1952.

† *Australian J. Sci. Res.*, *A*, **5,** 266, 1952.

‡ Unpublished. This position has very little random error but considerable uncertainty caused by interfering sources.

tidal forces. Thus NGC 1275 may present a case of radio emission caused by a collision of two nebulae.

Like Cygnus A, NGC 1275 shows emission lines in its spectrum, but superposed on a strong continuous spectrum which contains most of the light.[30] It has been considered as belonging to the group of nebulae whose nuclei show emission lines,[31] but it deviates from the other nebulae of this type in some respects. Exposures with different plate-filter combinations suggest that the emission in NGC 1275 is not restricted to the nuclear region. The width of all emission lines in NGC 1275 seems to be of similar size, corresponding to approximately 4500 km/sec, while pronounced differences are observed in the nebulae with nuclear emission. The hydrogen lines in these objects are very much wider than the forbidden lines, which show individual differences. The forbidden lines in NGC 1275 are unusually wide, but the pronounced asymmetry observed on only one plate for one [O III] line cannot be considered as definitely established. The evidence suggests that NGC 1275 does not belong to the group of nebulae with nuclear emission, none of which has been observed as a radio source.

At a distance of 9×10^6 psc, NGC 1275 emits a total radio energy of 7.5×10^{39} ergs sec^{-1}, roughly 1000 times less than Cygnus A, but still about 300 times more than the Galaxy.

3. NGC 5128 (MILLS 13 − 4)

The identification of the source Centaurus A with NGC 5128, first suggested by Bolton, Stanley, and Slee,[16] appears well supported by the later, more precise positions given in Table 6. Recent measures of the effective size of the source by Mills[17] give a value of 6′, which agrees with the diameter of the bright central part of the nebula

[30] M. L. Humason, *Pub. A.S.P.*, **44,** 267, 1932.

[31] C. K. Seyfert, *AP. J.*, **97,** 28, 1943; *Mt. W. Contr.*, No. 671.

shown in Figure 11. Unpublished measures by Mills show an elliptical half-brightness contour of 1.′3 × 7′ with the major axis in position angle 135°. This contour is shown in Figure 13 superimposed on the image of NGC 5128. There can be no doubt that the radio emission is associated with the absorption band extending across the nebula. Bolton [32] finds that the strong concentration near the center of the source is surrounded by an extended source nearly 2° in diameter. This is definitely larger than the visible size of the nebula, which does not exceed 30′ in any direction.

NGC 5128 is an unresolved E0 nebula with an unusually strong and wide central absorption band, a combination highly anomalous for a spherical nebula. On plates taken with the 48-inch Schmidt telescope (Fig. 12), however, faint outer parts of the nebula become visible, which extend in position angle 45°, a direction almost normal to that of the absorption band. This suggests a new interpretation, that the object actually consists of two nebulae—an elliptical nebula with the major axis in position angle 45°

TABLE 6

NGC 5128 (MILLS 13 − 4)

α	δ	Frequency (Mc/Sec)	m	Observer
$13^h22^m20^s \pm 60^s$	$-42°37' \pm 8'$	100	3.3	Bolton, Stanley, and Slee; Stanley and Slee*
$13^h20^m \pm 2^m$	$-43° \pm 10'$	100	3.6	Mills†
$13^h22^m30^s \pm 4^s$	$-42°46' \pm 2'$	100	2.8	Mills‡
$13^h22^m28^s$	$-42°45.'6$	*pg*	7.2 (SA); 6.1 (corrected)	NGC

* J. G. Bolton, G. J. Stanley, and O. B. Slee, *Nature*, **164**, 101, 1949; G. J. Stanley and O. B. Slee, *Australian J. Sci. Res.*, *A*, **3** 234, 1950.

† *Australian J. Sci. Res.*, *A*, **5**, 266, 1952.

‡ *Ibid.*, p. 456.

and a second nebula of much later type, seen practically edgewise in position angle 135°. This second system, probably a spiral, contains the heavy absorption lanes and lies in front of the E nebula. Near the outer parts of the absorption lanes, the structure typical for beginning resolution of spiral arms can be seen. The curvature of the outer parts of the spiral system and the irregular distribution of absorbing clouds outside the main absorption bands clearly indicate tidal distortion by the E nebula. The two nebulae thus are not merely optically superimposed but form a close pair in a state of strong gravitational interaction, perhaps actually in collision.

Since the E nebula presumably contains little interstellar gas, the strong radio emission may not be caused by the interaction of the gas of one system with that of the other. Differential velocities in the gas of the late-type system, produced by tidal forces, may lead to collisions of gas clouds within this system.

Spectrograms obtained with the nebular spectrographs at the 100-inch telescope by Minkowski and at the 200-inch telescope by Humason show a spectrum of type Gp with λ 3727 [O II] in emission in the brightest part of the spherical mass south of the absorption lane. The brightest patch near the north edge of the absorption lane shows, in addition, $H\beta$ and $H\gamma$ as emission lines. The radial velocity is +450 km/sec. There are indications of velocity differences within the nebula. Both type of spectrum and radial velocity confirm the extragalactic nature of NGC 5128. Hubble's observation[33] of H lines in emission on objective-prism plates is verified; the *He* II line λ 4686 reported by Hubble has not

[32] J. G. Bolton, "Extended Sources of Galactic Noise," Union radio-scientifique internationale Report (1952).

[33] *Ap. J.*, **56**, 162, 1922; *Mt. W. Contr.*, No. 241.

1954ApJ...119..215B

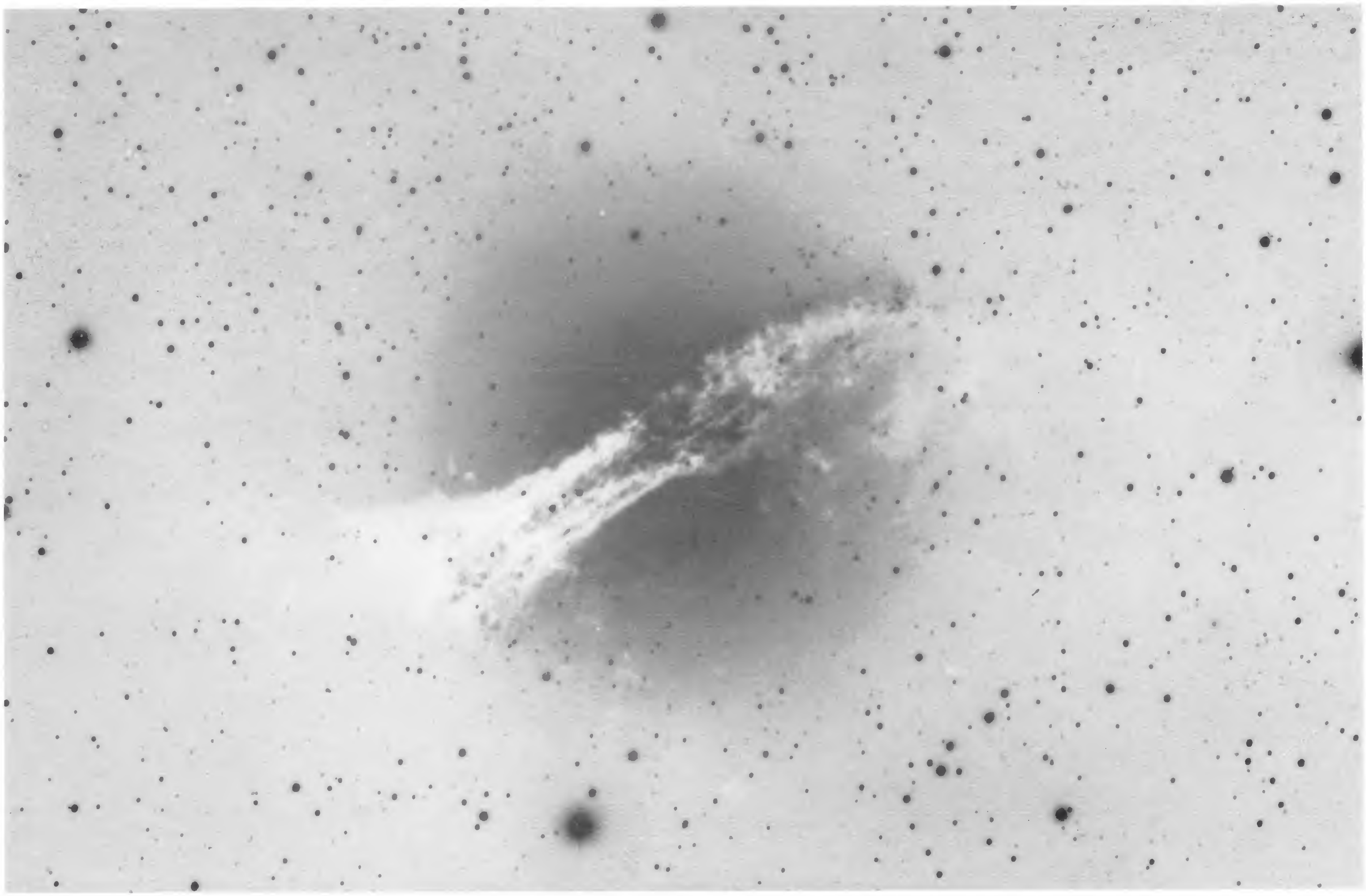

FIG. 11.—NGC 5128. λλ 5500–6300; 200-inch; 1 mm = 5″.5

1954ApJ...119..215B

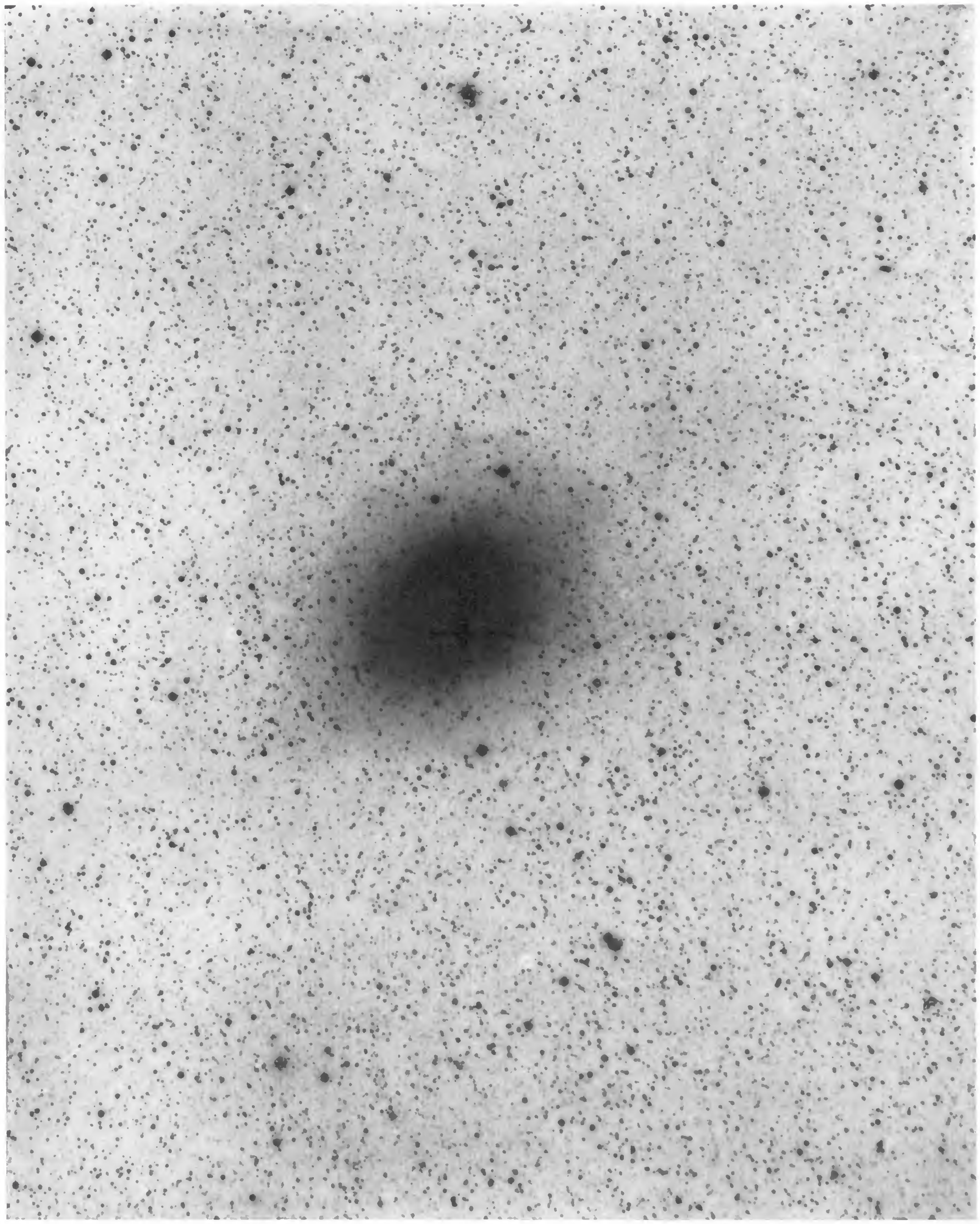

FIG. 12.—NGC 5128. λλ 6300–6700; 48-inch; 1 mm = 37″

1954ApJ...119..215B

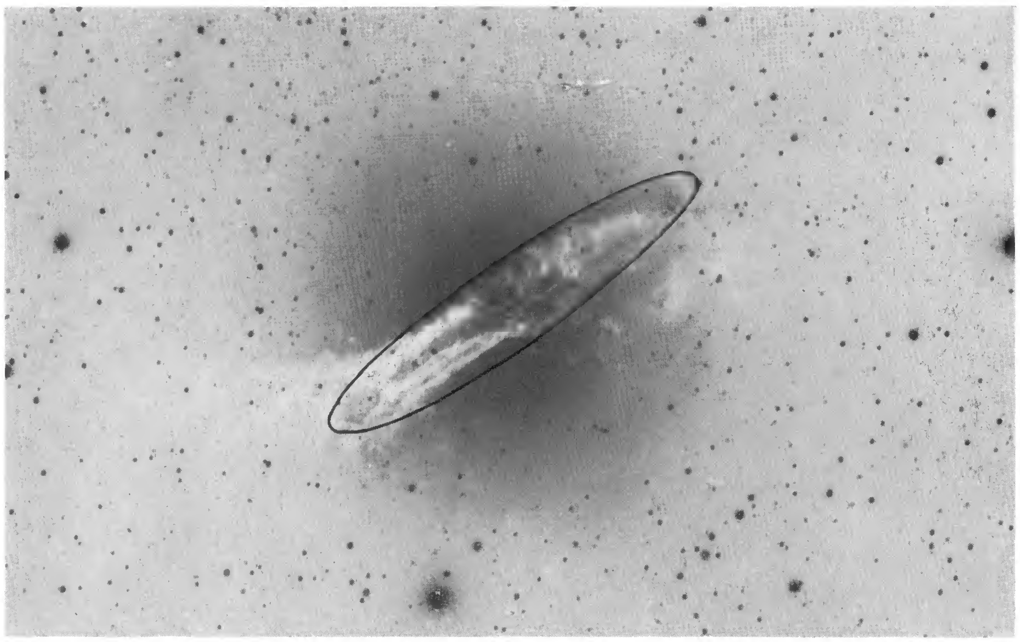

FIG. 13.—NGC 5128. The half-brightness contour by Mills is superimposed. 1 mm = 8″.3

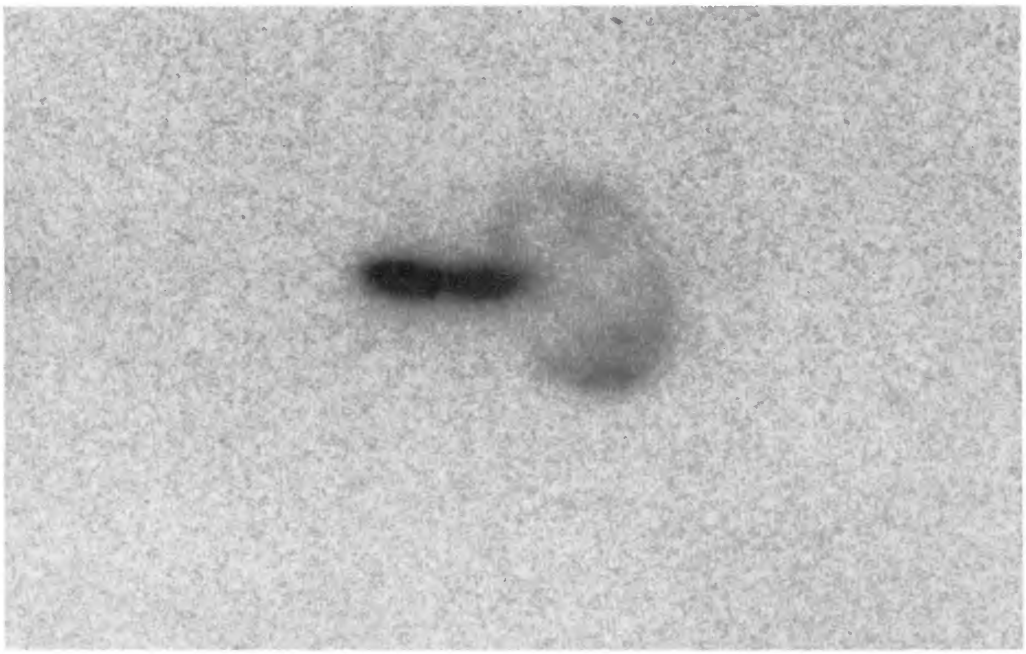

FIG. 14.—Mayall's object. (1950) $11^h1^m\!.2$, $+41°7'$; λλ 3500–5000; 1 mm = 0″.8

been found on the slit spectrograms but could be present in other parts of the object. The system is too far south for extensive work on Mount Wilson or Palomar, but a more detailed spectroscopic investigation would be of great value.

The distance of NGC 5128 is not known but must be greater than that of NGC 224, since the spherical mass remains entirely unresolved with the 200-inch telescope and only beginning resolution can be seen in the spiral system near the outer parts of the absorption lanes. With a distance larger than 5×10^5 psc and $m_{ph} = 6.1$ (see Table 6), the system is brighter than $M_{pg} = -17.5$, without correction for the effects of the heavy absorption in the system and of galactic interstellar obscuration at the relatively low galactic latitude 20°. Most of the light belongs to the E nebula, which thus must be one of the most luminous spheroidal galaxies, near the upper end of the luminosity function. The total radio emission of the source at a distance of more than 5×10^5 psc is larger than 1.3×10^{38} ergs sec^{-1}, or at least about 10 times larger than that of NGC 224. The observed radio emission is probably too strong to consider NGC 5128 as a normal system, as far as radio emission is concerned.

4. UNIDENTIFIED SOURCES

Cygnus A is without doubt an object of exceedingly rare type. But its intensity is so high that at a 10 times larger distance it would still be an easily observable source. At such a distance it would cease to be an optically observable astronomical object; and even at a distance of only twice that of Cygnus A recognition as a peculiar nebula and observation of the spectrum would become very difficult. Thus a large volume of space is easily accessible to radio observations but is practically or entirely beyond the limit of astronomical work, even with the largest telescope. The number of observed or observable sources in this volume cannot be determined. It may be sizable, and it would be no contradiction to any known fact if the majority of the unidentified sources should turn out to be of this type. Whether this is so, only the future can decide.

Less effective collisions than in Cygnus A should be more numerous. But even collisions of the type producing the radio emission of NGC 1275 and NGC 5128 are relatively rare. Certainly, not every close approach or tidal distortion of two nebulae causes enhanced radio emission. We are not yet in a position to predict whether an object representing some kind of collision is likely to be a radio source of enhanced intensity, and some object of this kind can almost always be found in the large area admitted by positions of low accuracy. Occasionally a rather peculiar object can be found, as, for instance, the queer galaxy (Fig. 14) discovered by N. U. Mayall[34] at the Lick Observatory which is near the source 11.01 of Ryle, Smith, and Elsmore. Since other objects of similar character are not observed as radio sources, it does not seem justified to consider such objects even as tentative identifications on the basis of positions of low accuracy.

IV. NORMAL EXTRAGALACTIC NEBULAE

The identification of some faint radio sources with near-by extragalactic nebulae was first suggested by Ryle, Smith, and Elsmore.[2] Any doubt that normal extragalactic nebulae are observable radio sources was removed when Hanbury Brown and Hazard[35] were able to show that the size and shape of the radio source coinciding with the Andromeda Nebula (NGC 224) agree with those of the nebula and that the total intensity of the source is comparable to the integrated intensity of the Galaxy, a system closely similar to NGC 224. The total emission of NGC 224 is 9×10^{36} ergs sec^{-1}, that of the galaxy 24×10^{36} ergs sec^{-1}. The conclusion that normal extragalactic nebulae are radio sources is also supported by the way in which the record of the background radiation obtained by Hanbury Brown and Hazard[8] shows the Ursa Major cloud of nebulae. This

[34] R. T. Smith, *Pub. A.S.P.*, **53**, 187, 1941.

[35] *M.N.*, **111**, 357, 1951.

region, rich in nebulae from the tenth to the thirteenth magnitude, is quite correctly outlined as a broad maximum near right ascension 12^h at declinations 44°–51°.

Data on the radio sources for which identification with normal extragalactic nebulae has been suggested are in Table 7. With the exception of NGC 598, which is outside the region accessible to the Manchester paraboloid, the sources reported first by Ryle, Smith, and Elsmore have been reobserved by Hanbury Brown and Hazard, who have added three sources which may be identified with normal extragalactic nebulae. The radio intensities of the brighter nebulae at 81.5 Mc/sec are somewhat higher, compared to those at 158.5 Mc/sec, than the expected difference, which is between 1.0 and 1.5 mag.; but this obviously is not a significant discrepancy.

The data now available are not sufficient to decide whether there is a fixed ratio between optical and radio intensity for normal extragalactic nebulae. The conclusion by Hanbury Brown and Hazard that the ratio of radio intensity to brightness increases with decreasing apparent brightness was derived by including the source in Perseus, assumed to be the cluster of nebulae. Since it is much more probable that this source is NGC 1275—a peculiar nebula which should be excluded—the question of a possible dependence of observed radio emission on apparent brightness is actually quite open. The data are not inconsistent with the assumption of a fixed ratio between radio and optical intensity. For the following discussion it is adequate to consider the radio magnitudes both at 81.5 Mc/sec and at 158.5 Mc/sec as of the same order as the photographic magnitude.

All the extragalactic nebulae suggested as radio sources are spirals of types Sb and Sc. The general galactic radiation may be included in this statement. It represents the normal radiation of the Galaxy, an Sb spiral. The obvious question arises as to whether there is any significance in the fact that no elliptical nebula has been observed as radio source.

Elliptical nebulae in general are relatively faint. The apparently brightest nebulae of the type are

NGC 205, $m_{pg} = 8.89$ (H)
NGC 221, $m_{pg} = 9.06$ (H)
NGC 3115, $m_{pg} = 9.8$ (SA); corrected, 9
Fornax system, $m_{pg} = 9.1$[36]
Sculptor system, $m_{pg} = 8.8$[36]

These nebulae, all of almost equal apparent brightness, may be expected to be sources with an intensity of the order of 10^{-25} watts m^{-2} $(c/sec)^{-1}$. The companions of the Andromeda Nebula—NGC 205 and NGC 221—are within range and above the limit of detectability for the Manchester paraboloid but are so close to NGC 224, which is almost 5 mag. brighter, that they cannot be expected to be easily observable. The other three nebulae are well isolated, but their expected intensity is well below the limit reached in the survey by Mills.[3] That no elliptical nebula has been observed as a radio source is thus in agreement with expectation, if a fixed ratio between optical and radio intensity exists, and permits no conclusions concerning the contribution of interstellar gas to the galactic radio emission.

Much more serious questions are raised by the fact that no sources have been observed in the positions of certain objects which, on the basis of their brightness, should be observable. Since the discussion of the general galactic radiation suggests that it originates in objects belonging to population II, it is appropriate to discuss separately the unobserved nebulae according to their content of population I and II.

Systems which are rich in population I are nebulae of type Sc and irregular nebulae of the type of the Large Magellanic Cloud.[37] The Large Magellanic Cloud, $m_{pg} = 1.2$, should be a very strong source, with an expected intensity of 10^{-22} watts $m^{-2}(c/sec)^{-1}$, comparable to Cygnus A and Cygnus X but spread over an area in the sky almost 10

[36] W. Baade, *Ap. J*, **100**, 147, 1944; *Mt. W. Contr.*, No. 697.

[37] S. C. B. Gascoigne and G. E. Kron, *Pub. A.S.P.*, **65**, 32, 1952.

TABLE 7

NORMAL EXTRAGALACTIC NEBULAE IDENTIFIED AS RADIO SOURCES

Object	Type	M_{pg}	Position of Nebula (1950) α	Position of Nebula (1950) δ	m_{pg}	Position of Source (1950) α	Position of Source (1950) δ	Frequency (Mc/Sec)	m_R	Observer
NGC 224....	Sb	−18.1	$0^h40^m.0$	+41° 0′	4.33 (H)	$0^h42^m \pm 6^m$	+38° ± 5°	81.5	5.6*	Ryle, Smith, and Elsmore, 00.01†
						$0^h40^m15^s \pm 30^s$	+40°50′ ± 20′	158.5	6.0	Hanbury Brown and Hazard‡
NGC 598§...	Sc	−16.1	1 31.1	+30 24	6.19 (H)	$1^h25^m \pm 5^m$	+30° ± 3°	81.5	6.8	Ryle, Smith, and Elsmore, 01.01†
NGC 891‖...	Sb	....	2 19.3	+42 7	10.85 (H)	$2^h16^m \pm 3^m$	+44°15′ ± 2°	81.5	7.2	Ryle, Smith, and Elsmore, 02.01†
						$2^h19^m \pm 3^m$	+42°10′ ± 30′	158.5	9.3	Hanbury Brown and Hazard#
NGC 3031...	Sb	−16.2	9 51.5	+69 18	7.85 (H)	$9^h51^m20^s \pm 2^m$	+69° ± 1°	158.5	9.3	Hanbury Brown and Hazard**
NGC 4258...	Sb	(−15.6)	12 16.5	+47 35	9.4 (SW)	$2^h15^m.0 \pm 5^m$	+47°30′ ± 1°	158.5	9.8	Hanbury Brown and Hazard#
NGC 5194...	Sc	−15.3	13 27.6	+47 27	8.88 (H)	$13^h26^m \pm 4^m$	+48° ± 3°	81.5	7.8	Ryle, Smith, and Elsmore†
+5195......	Irr	....	....	....	10.47 (H)	$13^h27^m30^s \pm 2^m$	+46°45′ ± 45′	158.5	9.7	Hanbury Brown and Hazard#
NGC 5457...	Sc	−15.8	14 1.4	+54 35	8.20 (H)	$14^h1^m \pm 2^m$	+51° ± 2°	81.5	7.1	Ryle, Smith, and Elsmore†
						††	††	158.5	9.1	Hanbury Brown and Hazard#

* This value is based on Ryle's revised intensity of 2.5×10^{-24} watts m^{-2} $(c/sec)^{-1}$, quoted by G. Westerhout and J. Oort, *B.A.N.*, **11**, 332, n. 3, 1951.

† *M.N.*, **110**, 508, 1950.

‡ *M.N.*, **111**, 357, 1951. The value of M_R is corrected according to a recent letter.

§ Recent unpublished results by J. G. Bolton suggest that the source observed by Ryle is a blend of two sources, one at $1^h38^m \pm 2^m$, $+32° \pm 1°$; the other at $1^h30^m \pm 2^m$, $+28° \pm 2°$. The identification of NGC 598 therefore remains doubtful.

‖ Hanbury Brown and Hazard have suggested identification of this source with the cluster of nebulae centered on NGC 911 ($2^h22^m.7$, +41°43′). Both position and intensity of the source agree better with NGC 891 than with that of the cluster. According to private communication by Hanbury Brown, a second source is 1° north. Possibly the observation by Ryle, Smith, and Elsmore may represent the blend of these two sources.

\# *Phil. Mag.*, **43**, 137, 1952.

** *Nature*, **172**, 853, 1953.

†† The presence of a source separated from the position of NGC 5457 by about 2° made the measurements of the weak source at the position of the nebula unreliable.

times larger than Cygnus X and therefore probably difficult to observe. With $M_{pg} = -15.9$, it is almost as luminous as the most luminous spirals of type Sc. According to a private communication, attempts by the Australian observers recently have succeeded in detecting radio emission from the Large Magellanic Cloud, but the intensity of this radiation is still uncertain. Two unobserved nebulae of type Sc are NGC 253, $m_{pg} = 7.0$ (SA; corrected, 6.0), in the region and probably well above the limit of the survey by Mills; and NGC 2403, $m_{pg} = 8.79$ (H), within reach and presumably above the limit of the Manchester paraboloid. At variance with this negative evidence is the fact that three radio sources have been identified with Sc nebulae. However, the identification of NGC 598 is made doubtful by the new results by J. G. Bolton;[38] and some doubt arises also concerning the identification of NGC 5457, since Hanbury Brown and Hazard found that the presence of a near-by stronger source made the measurements of the weak source in the position of the nebula unreliable. The identification of NGC 5194/5195 seems valid. The fainter component of this double nebula—NGC 5195—is a somewhat irregular E nebula containing population II. Within the uncertainties of the intensities, it is quite possible that a large part of the observed radio emission is due to NGC 5195. Thus there is at present no undebatable evidence that any Sc nebula is observed as a radio source. Altogether, the present evidence seems to suggest that population I contributes little to the radio emission, except the weak contribution of the ionized gas and of individual sources of the Cassiopeia type. Continued attempts to observe the Large Magellanic Cloud and Sc nebulae are of obviously great importance.

No doubt exists that Sb nebulae are observable radio sources, since the identification of NGC 224 is absolutely certain. A search for unobserved nebulae therefore is necessary not to prove that Sb nebulae are observable radio sources but to find out how close the correlation is which seems to exist between apparent brightness and radio intensity. The brightest Sb nebula which is still unobserved is NGC 4736, $m_{pg} = 8.4$ (B), within reach and above the limit of the Manchester paraboloid. This nebula is not bright enough to consider it as significant that it has not yet been observed. More important is the question of whether the Small Magellanic Cloud is an observable source. It clearly contains population I, as indicated by the presence of emission nebulae,[39] but it seems to contain a much higher content of population II than does the Large Magellanic Cloud. The Small Magellanic Cloud, $m_{pg} = 2.8$, should be a strong source of intensity 3×10^{-23} watts m^{-2}(c/sec)$^{-1}$. Its area is roughly half, its surface brightness only little less than, that of the Large Magellanic Cloud. According to private communication, attempts by the Australian observers have not yet definitely established radio emission from the Small Magellanic Cloud. If the Small Magellanic Cloud is really not a radio emitter of the expected order of intensity, the most plausible conclusion would be that the correlation between radio emission and photographic brightness is very loose. It would be premature to draw such a conclusion now, but a more systematic investigation of the correlation between radio intensity and brightness would be of the greatest value for the interpretation of the galactic radiation.

V. RADIO STARS AND THE GENERAL GALACTIC RADIATION

No star, except the sun, has been observed as a radio source. To permit the identification of a stellar source, the accuracy of its position has to be substantially the same as that of good optically determined positions, unless radio stars are spectroscopically highly peculiar. Since radio stars have not been found among the large variety of known peculiar stars, the probability of finding spectroscopic support for an identification is not large. A slim chance may exist of obtaining positions of the required high accuracy from observations of the occultation of sources by the moon.

[38] See Table 7, note to NGC 598.

[39] See, e.g., K. G. Henize and Freeman D. Miller, *Pub. Obs. U. Michigan*, **10**, 75, 1951.

Under the impression of the result that all sources so far identified are extended or of extragalactic origin, the concept of stars as radio sources has dropped into the background. It seems necessary to emphasize that an interpretation of the distribution of the general galactic radiation meets great difficulties without the assumption that radio stars exist.

A comparison of the distribution of the general galactic radiation with the distribution of stars, gas, and dust meets obvious difficulties in the immediate neighborhood of the galactic plane. Within a latitude range of about $\pm 3^\circ$, thermal radio emission from the ionized regions of the interstellar gas should be observable. Results by Ryle and Scheuer[40] show, indeed, a narrow peak in the intensity profile across the galactic equator at longitudes between 338° and 16°, which probably represents the gas emission. A similar contribution from the ionized gas to the intensity profile at the longitude of the galactic center is suggested by unpublished measures by Bolton. Since the radio spectrum of the thermal gas radiation differs from that of the general galactic radiation, it should be possible to separate the two components.[41] But even if the true distribution of the radiation along the galactic equator can thus be established, a valid comparison with astronomical data is made difficult by the effects of heavy obscuration, which permits no more than spotty and incomplete astronomical observations. A discussion of the relation between the distributions of general galactic radiation and astronomical objects must, therefore, be based either on general features of the galactic distribution or on more local information from unobscured regions.

That the galactic radiation cannot be interpreted as thermal radiation of the interstellar gas and is most likely connected with the population II was first pointed out by Unsöld.[42] It is indeed obvious that the general galactic radiation is concentrated much less toward the galactic plane and much more toward the galactic center than the B-type stars[43] and the diffuse nebulae.[44] This is a clear indication that the general galactic radiation does not originate in objects which are part of population I. This conclusion is also suggested by the dissimilarity between the distributions of the continuous galactic radiation and of the 21-cm emission from neutral hydrogen. Christiansen and Hindman[45] emphasize certain similarities between these distributions. These similarities, however, are not conclusive. They arise mainly from the appearance of weak maxima of the continuous radiation near certain positions where the line emission has very strong maxima. A certain similarity of this kind is to be expected as long as the distribution of the continuous radiation is not freed from the possible weak contributions of thermal radiation from the ionized gas and from the effects of unresolved discrete sources, which belong to population I.

A comparison of the intensity distribution of the general galactic radiation with a model of the galactic system by Westerhout and Oort[46] indicates satisfactory agreement of the distribution of the radiation at 100 Mc/sec as measured by Bolton and Westfold[47]

[40] *M.N.*, **113**, 3, 1953.

[41] An attempt to make this separation has been carried out by I. S. Shklovski (*Astr. J. U.S.S.R.*, **29**, 418, 1952). The use of a heterogeneous set of data found by various observers gives this attempt very little weight. The resulting galactic distribution of the nongaseous component has no similarity to the distribution of any known type of galactic object.

Added October, 1953: Hanbury, Brown, and Hazard (*Phil. Mag.*, **44**, 939, 1953) have recently shown that the galactic distribution of the nongaseous component is very similar to the general stellar distribution in the Galaxy. Their method avoids the objections which can be made to Shklovski's discussion.

[42] *Zs. f. Ap.*, **26**, 176, 1949.

[43] R. Minkowski, *Pub. Obs. U. Michigan*, **10**, 25, 1952.

[44] S. Cederblad, *Lund Medd.*, ser. 2, No. 119, Fig. 8, p. 59, 1946.

[45] *Australian J. Sci. Res.*, *A*, **5**, 437, 1952.

[46] *B.A.N.*, **11**, 323, 1951.

[47] *Australian J. Sci. Res.*, *A*, **3**, 19, 1950.

with the distribution of common stars. The excess of the radiation near the galactic poles and in the hemisphere opposite the galactic center was tentatively interpreted by Westerhout and Oort as due to a background of distant extragalactic nebulae. This interpretation is supported by the identification of extragalactic nebulae as strong radio sources. While the general radiation from normal extragalactic nebulae is too small to explain the excess, sources of the Cygnus A type, for example, may provide the required intensity. Since the bulk of the stars in an Sb spiral such as the Galaxy belong to population II, the agreement of the distribution of the galactic radiation with that of the common stars is proof that the radiation originates in objects which are part of population II.

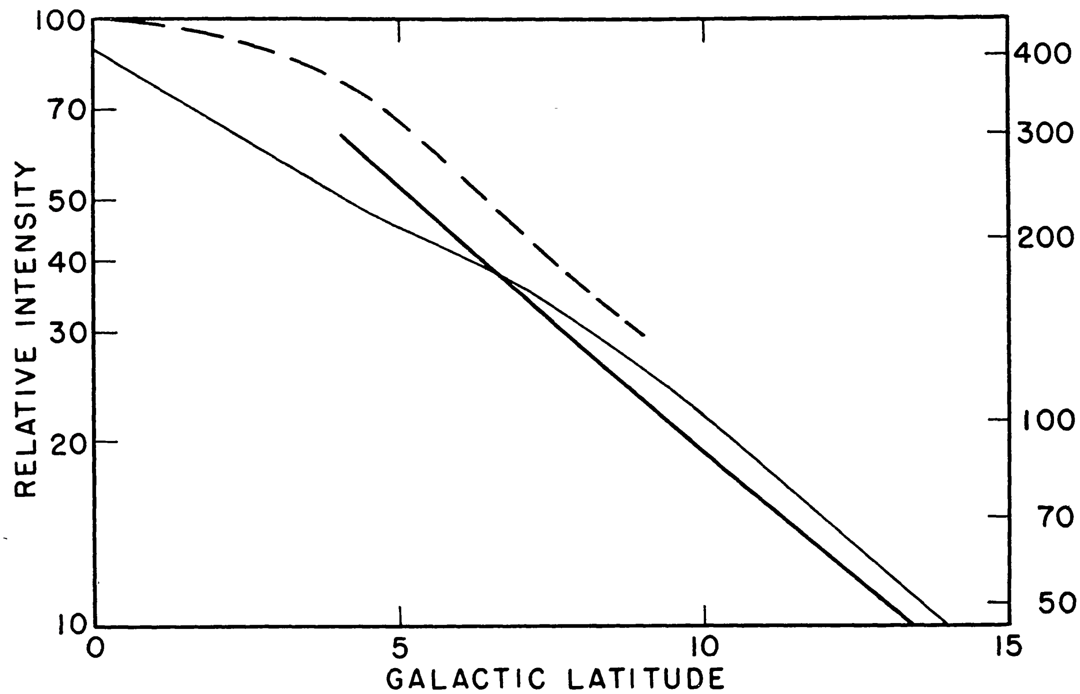

FIG. 15.—Relative radio intensity and number of cluster-type variables as function of galactic latitude at the galactic center. *Broken line:* radio intensity by Bolton and Westfold. *Thin solid line:* radio intensity by Bolton. *Heavy solid line:* number of cluster-type variables.

The same conclusion is reached if profiles of the galactic radiation in latitude across the galactic center are compared directly with the distribution of the cluster-type variables which represent the population II as one of its typical constituents. Owing to the obscuration in the galactic plane, the stellar distribution cannot be determined for the immediate neighborhood of the galactic center. Unpublished results by Baade show that the number of cluster-type variables per 10^6 cubic parsecs as a function of the distance r in kiloparsecs from the galactic center is

$$N = 20.4 \times 10^{-0.765r} \quad \text{for } 0.6 < r < 3.5,$$

$$N = 0.813 \times 10^{-0.361r} \quad \text{for } r < 3.5.$$

From these data, the number of cluster-type variables per square degree may be determined by numerical integration. This number is compared in Figure 15 with the intensity of the galactic radiation as a function of latitude at the galactic center. Starting at latitude 4°, which corresponds to the closest distance reached by the observations of cluster-type variables, the comparison excludes that part of the distribution where radiation from *H* II regions may be observable. The agreement of the distribution of cluster-type variables with that of the galactic radiation is obvious. Similar agreement exists with the profile of Ryle and Scheuer at $l = 340°$.

If the general galactic radiation originates in objects which are part of population II, it is highly probable that these objects are stars. It is true that the presence of gas in population II is shown by the appearance of faint [*O* II] lines in the spectra of elliptical nebulae; but all evidence suggests that the mass of the gas in these systems is small. Consequently, its contribution to the radio emission should be even less important than that of the much larger mass of gas contained in population I.

While it is thus highly probable that radio stars exist, no estimate of their type or luminosity can be made. The attempts by several authors to estimate the number of radio stars on the basis of statistical analysis are completely invalidated by the fact that the strongest sources are now known not to be stellar and that it is completely unknown which, if any, of the known sources belong to the group of objects which emit the general galactic radiation.

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