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CONDENSATIONS IN THE INTERGALACTIC MEDIUM

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ABSTRACT

This paper is concerned with the properties of peculiar galaxies and consideration of the question as to whether some of these galaxies are of recent origin—i.e., whether they have evolutionary ages $\ll H^{-1}$. The steady-state theory requires new galaxies to form. In the cosmological discussion it is shown that, within the framework of the theory, there is no requirement for galaxies to form continuously at a constant average rate, but there must be epochs of condensation of new galaxies. This is a difference between the mathematical form of the steady-state theory and the form based on the perfect cosmological principle of Bondi and Gold.

A discussion is given of all the factors that must be considered—form, internal motions, spectra, colors, and amounts of uncondensed material—when one attempts to determine whether some galaxies have recently condensed. Finally, observational evidence on a small sample of peculiar galaxies within about 100 Mpc is described. The evidence appears to be consistent with the requirements of the steady-state theory in the form described earlier, although we do not believe that it is established beyond doubt that new galaxies are being formed.

I. INTRODUCTION

Extragalactic research has tended to be focused on the regular spiral and elliptical galaxies. Hubble put into the category "irregular" all the galaxies which could not be fitted into his fundamental classification scheme, and the proportion of irregulars among 600 bright galaxies was given by him as 2.5 per cent (Hubble 1936). However, from the point of view of our understanding of the evolution of galaxies, the irregular and peculiar systems are of great importance. Their extreme lack of symmetry, coupled in many cases with the existence of appreciable rotation and sometimes with associated bridges, tails, etc., suggests that they are not in a steady state, and the presence of young, high-luminosity stars and much uncondensed gas in them inevitably suggests that they are at a young evolutionary stage and may indeed have been formed recently. Thus they bring to the fore the fundamental unsolved problem of how galaxies condensed.

A new line of investigation was opened up with the publication by Vorontsov-Velyaminov (1959) of his *Atlas of Interacting Galaxies*. These systems were found by him from a search of the 48-inch Schmidt prints in the Palomar Sky Survey, and he described 355 systems. This *Atlas* contains, as its name implies, systems which are in interaction. It therefore contains doubles and multiples which are extreme in their lack of symmetry but it also contains some systems in which the galaxies are clearly symmetrical, well-organized objects interacting with each other, as, for example, is the case for several double elliptical galaxies in the *Atlas*, with which we shall not be concerned in the present paper. There are also included, however, some objects with which we shall be concerned, i.e., objects which appear to have only one mass concentration in interaction with diffuse intergalactic matter, as well as some single, highly irregular galaxies.

Vorontsov-Velyaminov's *Atlas* does not give a complete listing of peculiar galaxies, since his primary criterion for selection is contained in the word "interacting." If we choose the characteristic of *asymmetry* as of primary importance, then many of the single irregular galaxies, not obviously in interaction with anything else, are of importance. Examples of such objects can be seen in the *Hubble Atlas* (Sandage 1961).

In the last five years a considerable amount of observing time has been spent by two of the authors in investigating some of these systems, mainly with the 82-inch telescope at the McDonald Observatory and also more recently with the 120-inch telescope at the Lick Observatory. The observational studies have so far been restricted to direct photography and to spectroscopic studies, and some preliminary investigations have been published. Related investigations of interacting galaxies have been carried out over a long period by Zwicky, who has reported some of his results in a number of reviews (Zwicky 1956, 1957, 1959).

The arguments for and against the idea that some galaxies are young systems are given in Section III. These questions are of great importance from a cosmological standpoint. In Section II we consider some of these cosmological questions and discuss the conditions under which galaxies may form within the framework of the steady-state cosmology. In Section IV we give a detailed discussion of the observational information available on a sample of the peculiar galaxies so far investigated.

The questions that we pose and attempt to answer in this paper are as follows: (1) What conditions are required to form new galaxies in a steady-state universe? (2) Are some of the peculiar galaxies of recent origin? (3) If they are, then does their existence support the idea that we live in a steady-state universe?

As we shall show, our investigations do not lead to definitive answers (either positive or negative) to any of these questions. Thus it might be argued that to make such an investigation at the present level of our understanding is premature. However, we feel that such an attempt may be worthwhile if only to stimulate other astronomers (who, in many cases, may have different prejudices) on the theoretical side to develop a detailed theory for the formation of galaxies and, on the observational side, to undertake detailed investigations of the peculiar galaxies, with a view to determining their evolutionary history.

II. THEORETICAL CONSIDERATIONS

a) Cosmological Considerations—a Résumé

Undoubtedly, the greatest shortcoming of all cosmological theories lies in their failure to provide a working model of the formation of galaxies. Evolutionary cosmology provides no model at all. Galaxies are supposed to arise from initial fluctuations, every necessary property being inserted into the theory as an initial condition. In short, evolutionary cosmology achieves nothing more than its hypotheses, its deductive successes are nil. The steady-state cosmology is faced by uncertainties at just the point where cosmology and astrophysics should properly be connected—the condensation of the intergalactic medium. However, some progress can be made in the latter cosmology.

A recent investigation by Hogarth (1962) and by Hoyle and Narlikar (1963) has shown that in steady-state cosmology it is possible to work with a time-symmetric electrodynamics in which advanced and retarded potentials enter on an equal footing. The conditions which permit this result are (*a*) the universe expands according to the scale factor exp Ht, and (*b*) the intergalactic density is independent of the time t. These conditions are shown to be sufficient, but, so far as a symmetrized electrodynamics alone is concerned, they are probably not necessary, although none of the evolutionary cosmologies in popular favor yield sufficient conditions. A similar investigation by Narlikar (1962) for the case of neutrinos does establish *a* and *b* as essentially necessary conditions, however.

This new work goes far toward establishing the steady-state theory, especially when taken with a further demonstration by Hoyle and Narlikar (1962) that Mach's principle can be derived from the theory. The basis of the theory is that world lines of particles are half-lines, each possessing one end. To give mathematical expression to this postulate, a scalar field C is introduced, and two terms are added to the normal action function,

$$\tfrac{1}{2} f \int_{V^4} C_i C^i (-g)^{1/2} dV^4 + \Sigma m \int C_i \frac{dx^i}{ds} ds\,, \tag{1}$$

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f being a coupling constant. The first term leads to a modification of Einstein's field equations, in that a new field term depending on the C field appears in the equations. The second term in formula (1) leads to a wave equation for C, with the property that C is generated only by interaction with the ends of world lines. The equations have the remarkable property that the steady-state conditions a and b appear as asymptotic conditions even when initially there is a very wide divergence from a and b. In the asymptotic state the line element becomes

$$ds^2 = c^2 dt^2 - \exp(2Ht)\,[dr^2 + r^2 (d\theta^2 + \sin^2\theta d\phi^2)]\,, \tag{2}$$

where $H = \sqrt{Kf/6}$, $K = 8\pi G/c^4$. That is to say, the Hubble constant, H, is determined by the coupling constant, f. In the asymptotic state the density ρ is constant and is given by

$$\frac{3H^2}{4\pi G}, \tag{3}$$

with $H^{-1} = 4 \times 10^{17}$ sec, $\rho \simeq 2 \times 10^{-29}$ gm cm^{-3}.

Unfortunately, the theory does not specify the nature of created particles—i.e., particles near their end points. Gold and Hoyle (1959) made the postulate that particles were created as neutrons. Decay of the neutrons gave hot ionized hydrogen with an internal energy of $\sim 2.5 \times 10^{17}$ ergs/gm. After allowing for the effects of redshift losses, the "thermal" energy density was $\sim 3 \times 10^{-12}$ erg/cm^3. The coincidence of this value with the cosmic-ray energy density and with energy densities in the Galaxy gave some support to this new postulate. Moreover, the corresponding "velocity of sound" in the hot gas was ~ 3000 km/sec. Pressure variations within the hot gas could lead to the compression of gas over regions of dimensions $\sim 3 \times 10^8\, H^{-1} \simeq 10^{26}$ cm, about 30 or 40 Mpc. This led to a picture of condensation within the gas in three stages, the basic concept being one of constant hydrostatic pressure. The stages are set out in Table 1. The mass values in the last column of Table 1 take account of the effects of fragmentation during condensation, in accordance with the following considerations.

TABLE 1

CONDITIONS IN GAS AT THREE CONDENSATION STAGES

	Density (gm/cm^3)	Temperature (° K)	Distance Scale (Mpc)	Mass ($M_\odot$)
Before primary condensation.	2×10^{-29}	10^9	30	10^{16}
After primary condensation	2×10^{-27}	10^7	3	10^{15}
After secondary condensation .	2×10^{-24}	10^4	0 1	10^{11}

Investigation of radiation by free-free electron-proton collisions showed that, for $\rho \simeq 2 \times 10^{-27}$ gm/cm^3 and $T \simeq 10^7$ ° K, cooling can take place in the characteristic reproduction time $\frac{1}{3}H^{-1}$, of the steady-state theory. Initially, the cooling is slow, the energy of contraction being largely dissipated by radiation. A large measure of dissipation implies that a bound, stable structure will very likely be formed. However, after contraction to about one-third of the initial dimension—i.e., to about 1 Mpc, the density rising meanwhile to $\sim 10^{-26}$ gm/cm^3—the cooling accelerates rapidly, and thereafter only a comparatively small fraction of the energy of contraction is dissipated as radiation. The energy of contraction then appears as dynamical energy, implying a fragmentation into subunits, the subunits being individual galaxies. Cooling within an intergalactic medium of temperature $\sim 10^7$ ° K and density $\sim 2 \times 10^{-27}$ gm/cm^3 would therefore appear to fit the broad requirements of a theory of the formation of galaxies and of clusters. It gives the dimensions, time scales, and fragmentation properties correctly. Moreover, rapid cooling by hydrogen ceases at about 10^4 ° K.

The requirement that the hydrostatic pressure within and without a highly cooled zone be essentially the same thus yields a density $\sim 2 \times 10^{-24}$ gm/cm^3, as shown in the third line of Table 1, and this is just the order of the density required for galaxies (taken before any concentration to a disklike structure). If, further, we ask: What mass of gas at density $\sim 2 \times 10^{-24}$ gm/cm^3 can control dynamical motions of order, 200–300 km/sec, a value given by the speed of sound at temperature $\sim 10^7$ ° K? The answer is $\sim 10^{11}$ $M_\odot$, in agreement with the masses of the main class of galaxy.

The situation concerning primary condensation is less clear, however. Gold and Hoyle argued that, since on the present picture the intergalactic material possesses widely different temperatures in different places, "heat engines" may operate without radiative dissipation needing to be at all appreciable. Such an engine could convert thermal energy almost entirely into the dynamical energy of mass motions of the gas. In such a case, as Hoyle and Narlikar (1961) pointed out, it is most unlikely that the units which later undergo secondary condensation would stay bound together as an aggregate. Primary condensation would be expected to result in a number of clusters of galaxies in motion with respect to each other at speeds that are initially of the order of the speed of sound in a gas of kinetic temperature $\sim 10^9$ ° K, i.e., ~ 3000 km/sec. As the universe continued to expand, such motions would lead to an ultimate separation of most of the clusters, although it would always be possible in special cases for several clusters to have small relative motions and for them to remain within some 20 or 30 Mpc of each other. In this connection it may be noted that initial relative motions of ~ 3000 km/sec imply initial peculiar velocities of order 1500 km/sec. Such motions die away as a cluster ages, according to the factor $\exp(-H\tau)$, where τ is the age. For $\tau = H^{-1}$, the peculiar motions are therefore reduced to ~ 500 km/sec.

b) The Heat Engine—Some New Considerations in the Steady-State Theory

It is an unsatisfactory feature of the theory that the nature of the "heat engine" was not discussed, for it seems unlikely that one can arrive at a detailed understanding of the condensation process as long as the prime agency of condensation is not clearly understood. The description "heat engine" implies some passage of material between cool regions and hot regions, some form of feedback either from the regions of secondary condensation or from the galaxies themselves. Of these, the galaxies appear the more promising. Two possibly important forms of feedback may be mentioned.

Figure 1 shows a remarkable case of a dust cloud entirely enveloping a whole galaxy (NGC 4438). Since this configuration cannot be permanently stable, we argue that the cloud is either being accreted or expelled. Expulsion appears to us the more likely alternative. In general, the expulsion of dust from galaxies into the intergalactic medium could play an important role in the formation of new galaxies, particularly in the effect of dust on star formation. But whether dust could be an effective agent in promoting primary cooling seems more doubtful.

A more drastic form of feedback is observed in radio galaxies. The strongest sources demand minimum energies of $\sim 10^{60}$ ergs, while reasonable allowance for the magnetic intensity not always taking its optimum value and for the presence of protons and other positive ions increases the energy requirement to 10^{61-62} ergs. This represents an energy input into the intergalactic medium capable of supplying a cosmic-ray energy density of $\sim 10^{-12}$ erg/cm^3 throughout a volume of 10^{73-74} cm^3, i.e., a region with dimensions ~ 1 Mpc. Now within, say, 300 Mpc there are some 10^6 galaxies, of which about 300 are radio galaxies. A radio galaxy has a lifetime of 10^6–10^7 years, so that, in a time $H^{-1} \simeq 10^{10}$ years, the number of radio galaxies becomes comparable with the total number of galaxies. These estimates suggest that radio galaxies may well maintain the cosmic-ray energy density throughout space.

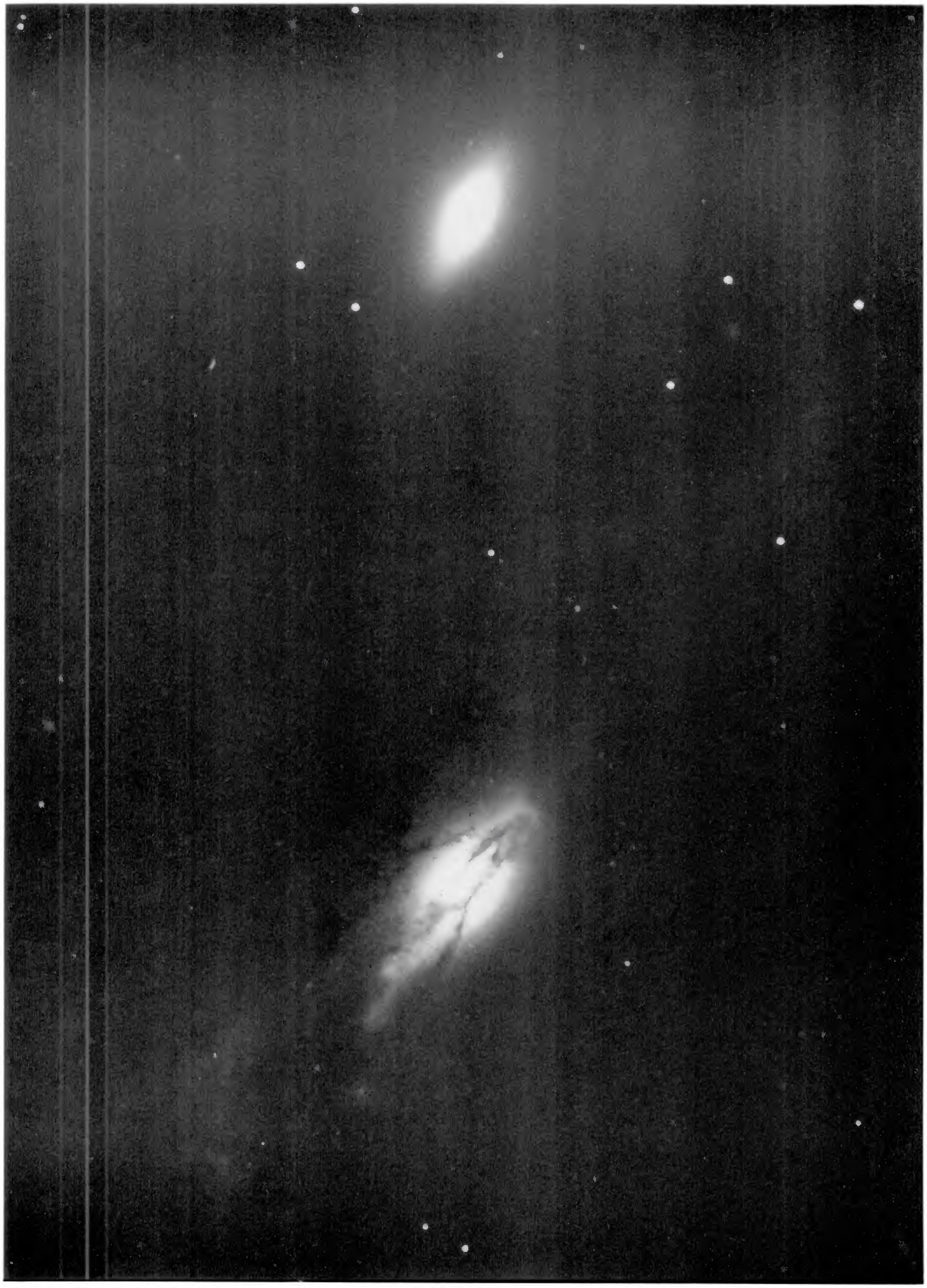

FIG. 1.—NGC 4438, a galaxy in Virgo Cluster enveloped in dust cloud and with intergalactic connections. Galaxy at top is NGC 4435. Plate taken at prime focus of Lick 120-inch telescope on baked Eastman Kodak II*a*-O emulsion. Scale: 1 mm = 2″.7. Northwest at top, northeast at right (vertical edges of print make angle 17° to north-south line).

If the galaxies can themselves supply energy densities of $\sim 10^{-12}$ erg/cm^3, then the galaxies could be responsible for the pressure fluctuations leading to primary condensation. Indeed, there is no longer any need for the neutron decay postulated by Gold and Hoyle. A feedback loop between the intergalactic medium and the galaxies may thus operate as sketched in Figure 2. The time required for the dynamical motions to establish primary condensation is $\sim H^{-1}$ (30 Mpc divided by 3000 km/sec), while the time required for radiative cooling is also of this order. Feedback from the galaxies may require a time $\sim H^{-1}$ to develop if this depends on the evolutionary stage of the galaxies.

The "engine" indicated schematically in Figure 2 occupies a volume with dimension $\sim$30 Mpc at the stage of primary condensation. The secondary condensations (clusters of galaxies) are separated by expansion according to exp Ht, so that the engine may occupy a volume with dimensions exceeding 100 Mpc at the stage of feedback from the galaxies to the intergalactic medium. For the universe on a large scale, we must consider an ensemble of engines, separated initially by perhaps 50–100 Mpc. The important question is: Are the different engines in random phase with respect to each other or not? In all previous work on the steady-state theory it was tacitly assumed that the engines were in random phase, and this led to the condensation model described by Hoyle and Narlikar (1961).

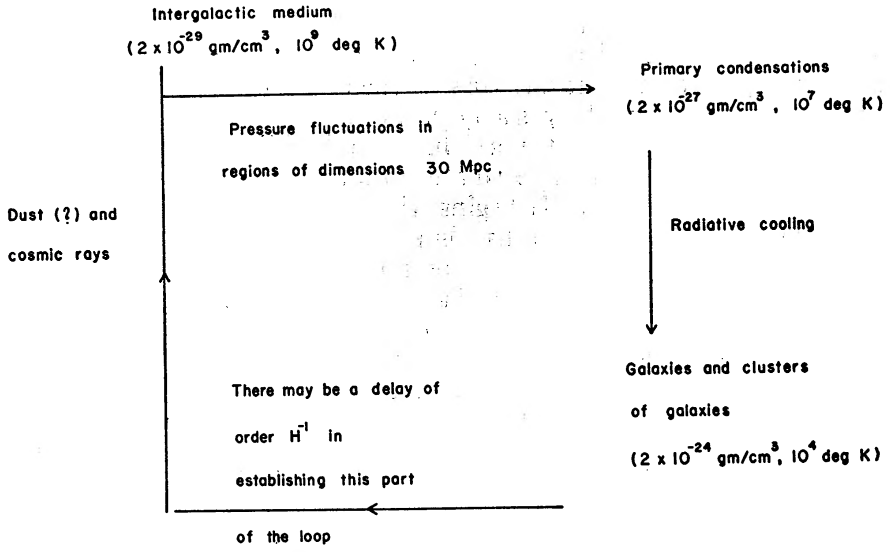

FIG. 2.—Schematic diagram showing feedback loop between galaxies and the intergalactic medium

This assumption may be wrong for engines in any finite volume, however large. Consider an initial situation with engines in random phase with respect to each other and spatially separated. Though each engine expands its own volume, the expansion of the universe insures that all the initial engines stay spatially separated. Consider, now, one particular engine. After this has completed its cycle, new cycles are generated within its interior, and these may all be approximately co-phased. The old engine may now be 150 Mpc in diameter, while the new engines within it are only 30 Mpc in diameter at their inception. Repetition of the argument for a sufficiently large number of generations leads to any finite volume being co-phased, since the universal expansion tends to lock the phases of ever larger regions, provided that the feedback from the galaxies produces further condensation of the intergalactic medium and provided that it occurs at a particular phase in the lives of the galaxies.

This leads to the possibility that the formation of galaxies might be confined to episodes, an episode being the same over the whole (necessarily finite) region of space accessible to an observer. Write T for the average duration of an individual cycle and τ for the time interval that has elapsed since the last episode of galaxy formation. Then the observer will see galaxies of ages $\sim\tau$, $(\tau + T)$, $(\tau + 2T)$, ... If galaxies of age τ have a mean spacing l, then galaxies of age $\tau + nT$ will have a mean spacing $l \exp(-nHT)$. It is particularly emphasized that the ages need bear no relation at all to the mean age $\frac{1}{3}H^{-1}$ of all galaxies taken throughout the universe. The mean age appears only when we go back to the initial situation in which the engines were randomly phased. If, instead of considering one particular engine, we consider the engines as a whole, we see that, while each engine may generate an ever growing co-phased volume, these volumes still remain in random phase. These are the volumes that must be averaged if we are to obtain average properties, particularly if we are to obtain the average age of all galaxies. But, plainly, when the volumes exceed the range of an observer, this becomes an impractical procedure. In fact, it may not be possible at all to determine universal averages by considering finite volumes.

This situation may appear puzzling to readers who have found it easier to think in terms of the "perfect cosmological principle" of Bondi and Gold (1948), rather than in terms of field theory. According to the view of one of the present authors, the "steady" aspect of the steady-state cosmology is a by-product of the theory, not its primary postulate. The primary postulate is that world lines are half-lines, not complete lines. The logical reason for investigating this postulate is that evolutionary cosmology is founded on an absurdity at just this point. It begins with the world lines as complete lines and then proceeds to infer that they are half-lines—i.e., that the universe had an origin. The absurdity of the theory lies in the deliberate exclusion of the mathematical consequences of its own conclusion, namely, the half-lines. To give expression to this property, one must proceed in some such way as that described at the outset. In all mathematical theories that have been investigated the properties *a* and *b* of Section II, *a*, appear as deductions, not as postulates. Although the stationary character of the resulting line element and the constancy of the intergalactic density can be taken as justifying the name "steady-state," the adoption of this name can cause difficulties, particularly in the status of the theory vis-à-vis the perfect cosmological principle. The latter asserts that all average properties of the universe are time-invariant as well as space-invariant. The query already raised by Hoyle (1949) was: What determines the size of the region throughout which one must average? The above considerations suggest that, for some properties, no finite volume of space may be adequate. To the somewhat pallid objection that the theory thereby loses much of its attractive simplicity, we would answer that nothing known to us in physics or astronomy is simple and that we see no reason at all why phenomena on a large scale should be simple.

c) Relation of These Concepts to Observation

To relate these considerations to observation, it is evidently important to know the phase of the cycle of Figure 2 for the present epoch. The activity of radio galaxies suggests that the present epoch may fall on the feedback arm of the loop. Indeed, the steepness of the $\log N - \log S$ radio-source-curve, as obtained by the Cambridge and Australian workers, gives some indication that the maximum of the radio galaxy phase may be slightly past—that we are approaching the phase of primary condensation.

However, we cannot expect that conditions are more than approximately co-phased in different spatial regions. Phase lags or phase advances would be expected in particular zones. Phase differences would affect spatial zones of dimensions $\sim$30 Mpc, so far as the condensation of galaxies is concerned, but zones of $\sim$150 Mpc, so far as radio sources are concerned.

In Section IV of the present paper we shall consider optical evidence taken out to a distance of about 100 Mpc. Our aim is to consider the evidence for the relation of galaxies to a medium surrounding them. Many, but not all, of the objects now to be considered

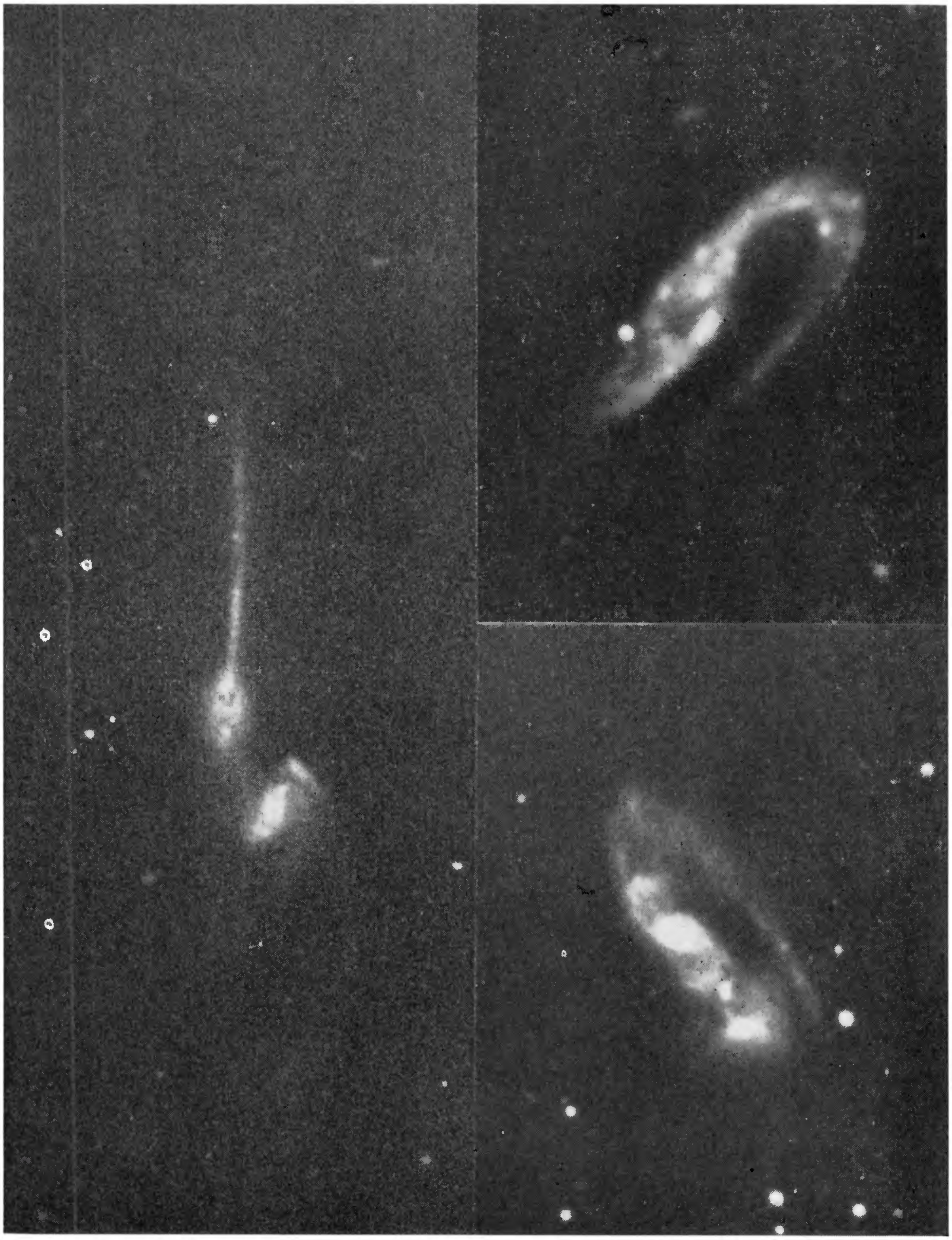

FIG. 3.—Three systems showing tubular forms. *Left:* NGC 4676 (scale: 1 mm = 2″.5). *Upper right:* NGC 3509 (scale: 1 mm = 2″.6). *Lower right:* NGC 6621–2 (scale: 1 mm = 2″.7). North at top, west at left in all. All plates taken at prime focus of McDonald 82-inch telescope on Eastman Kodak emulsion, 103*a*-O for NGC 4676 and baked II*a*-O for the others.

are taken from Vorontsov-Velyaminov's *Atlas*. The objects in this *Atlas* are uncommon. The list is certainly not complete out to 100 Mpc, and its incompleteness, of course, increases with increasing distance. As was discussed in Section I, certain single irregular galaxies not included in the *Atlas* are of interest in the present connection. Thus we may make a rough order-of-magnitude estimate that the kind of galaxy considered in the present paper may comprise about 1 per cent of all galaxies. Since, as will be discussed in Section III, many of the objects must be short-lived in their present forms and may be no more than $\sim 10^8$ years old, it appears possible that if one were to take all the peculiar objects that occurred in a time $\sim H^{-1}$, the number would not differ in order of magnitude from the total number of galaxies.

III. ARE SOME PECULIAR GALAXIES YOUNG?

A galaxy may be said to be "peculiar" because it differs from the majority of galaxies in one or more of the following respects: (1) spectroscopic characteristics; (2) color; (3) amount of uncondensed material (ionized and neutral hydrogen and dust); (4) form; (5) internal motions. The first three criteria bear on the compositions of gas, dust, and stars, and the last two relate to the dynamical characteristics. In practice it has nearly always been the form of a galaxy that first led to its being singled out as peculiar.

Until recently, it was tacitly assumed that all galaxies were old in the sense that the oldest stars present in them had ages comparable with the oldest stars in our Galaxy and that these, in turn, had ages comparable with H^{-1}. However, no proof for this general assumption concerning the ages of galaxies has been given.

Spectroscopic characteristics in relation to composition of galaxies have been discussed by Morgan (1959, 1962; see also Burbidge and Burbidge 1962). Emission features, when seen with the same relative intensities as in H II regions in our Galaxy, indicate H II regions similar to those in our spiral arms. These are presumably illuminated by O and B stars with ages $<10^8$ years. The spectra of many of the peculiar galaxies considered in this paper show only emission features. If underlying continuous spectra can be seen, they are often bluish in color, as compared with continua from normal galaxies. Sometimes no continua are visible, although we cannot say that they are definitely absent because they might show up with longer exposures. Thus all we have *evidence* for in such cases is that ionized gas is present and, if the source of excitation is stars, that these must be O and B stars with ages $<10^8$ years. Of course, we cannot go on from this to deduce that the galaxies themselves must have ages $<10^8$ years, because low-mass stars which may be old could be present in insufficient numbers to be detectable in the integrated spectra and the high-mass stars exciting the gas might be of a late generation. However, it should be stressed that, as long as the only information available is on these emission lines in the spectrum, any assumption that the system is older than 10^8 years will remain unproved from an observational standpoint.

If absorption features are seen and can be shown to come from a stellar population containing giants which have evolved from the main sequence near the sun (see Morgan and Mayall 1957), then the arguments of stellar evolution show that the system has an age $\sim 15 \times 10^9$ years, i.e., an age comparable with H^{-1}. From the spectroscopic evidence, the Hubble sequence from irregular to elliptical galaxies is clearly a sequence of evolutionary age, even if not necessarily a sequence of actual age measured in years.

Criterion 2 is not so useful an indicator of the age of a system because it is ambiguous and because of the confusing effects of interstellar reddening, as pointed out by Morgan (1962). In order to make deductions about the stellar population from many-color observations, it is necessary to assume that the main-sequence luminosity function is smooth and continuously varying. Further, a considerable range of stellar masses evolves into the yellow and red giant regions of the H-R diagram. Also, it is now generally accepted that the initial luminosity function is not universal and constant in all galaxies. The high mass-to-light ratios sometimes found and the variations even among E and

S0 galaxies show that large and variable proportions of low-luminosity stars are present. Also, the spectroscopic investigations of Spinrad (1962) suggest that some galaxies have a greatly increased number of faint main-sequence dwarfs. The initial luminosity function must be determined by the density, temperature, angular momentum per unit mass, magnetic flux, macroscopic motions, and the amounts of dust in a proto-galaxy, and at least the density and angular momentum per unit mass are known to be different in different galaxies. Hoyle and Fowler (1963) have found that the upper and lower mass limits of stars forming in a condensing cloud depend on the opacity conditions, which could be grossly variable from one case to another. It could be a serious mistake to suppose that the most luminous stars formed in a given galaxy—those highest on the main sequence—are always O and B stars. They could be A stars, F stars, or even G stars. Unless we know the opacity conditions in a condensing cloud, we cannot arrive at a definite conclusion. It is just at this point that the initial presence or absence of dust in the gas of a condensing galaxy probably plays a crucial role. There might even be separate major epochs of star formation in one galaxy, in which the opacity conditions (particularly the amount of dust present) were different. Under such conditions it is conceivable that the resulting composite luminosity function of main-sequence stars might not be smooth.

With regard to criterion 3 for the age of a galaxy, in many cases large amounts of uncondensed material in the form of either dust, cold hydrogen, or ionized gas are associated with peculiar galaxies. If the simple assumption is made that the amount of such material relative to that condensed into stars is an indication of age, then it may be concluded that such systems are often younger than well-developed galaxies with little interstellar material such as our own.

We now consider the arguments based on criteria 4 and 5. The criterion of form is the one that is first used to distinguish peculiar galaxies from the rest, since it is the only one that can be used directly from survey photographs. The distinction is clearly between over-all symmetry and lack of symmetry. The majority of all galaxies in the Hubble classification are axisymmetric, while the barred spirals have at least a plane of symmetry. The argument that systems which do not show any symmetry are young in evolutionary terms stems from the observed property of galaxies, that some rotation is associated with the condensed material; in fact, it appears that the angular momentum per unit mass is an important parameter in determining the form that galaxies take. Since spectroscopic investigations of the internal motions (criterion 5) frequently show that the peculiar galaxies have rotation, as will be shown in Section IV, it is clear that, in characteristic time scales of the order of the rotation periods—i.e., times of the order of 10^8 years—their forms will be changed, and symmetrical characteristics will be developed.

Similar arguments apply to the configurations of several galaxies in association where dispersion of the systems is to be expected in times of the order of 10^8–10^9 years. In this case the times are simply estimated from the apparent separations of the systems and the random velocities between them. The only objection to this line of argument lies in the rather special case that is sometimes made that we are seeing chance geometrical configurations in stable groups.

Returning, now, to objections which may be raised to the conclusion that single peculiar galaxies have time scales only of the order of the period of rotation, we can make the following points:

a) We have assumed that no external forces have been in play. Thus another possible explanation of peculiar forms is that the systems have been distorted by gravitational interaction with other galaxies. This is most likely to be important in cases where peculiar galaxies lie in the central regions of rich clusters or are members of compact double or multiple systems. This is sometimes the case, and such galaxies do not provide strong evidence of youth. However, the systems in Vorontsov-Velyaminov's *Atlas* do not, in general, show an obvious concentration to rich clusters. Moreover, little attention has been paid to the magnitude of the tidal effects which can be exerted in such interactions, and observational studies of double galaxies suggest that the distorting forces have little effect in many cases. Also when these effects are seen, as, e.g., in double ellipticals like NGC 4782–3, the resulting configurations are quite different from those in the types of peculiar galaxies being discussed in the present paper.

b) It is conceivable that the distribution of mass is symmetrical but that only some asymmetrical parts are luminous. Whether this is a likely situation may be decided only when a detailed theory of star formation is developed.

c) In some cases a population of old stars may be present, but their contribution to the total light emitted is so small that they cannot be detected. Evidence suggesting that this may sometimes be true is afforded by studies of the Magellanic Clouds. They are the nearest of the irregulars, although they do not fall into the category of extremely unsymmetrical objects that we are discussing, and are also very much smaller. It is known that they contain RR Lyrae stars, thus indicating that there is at least an underlying population of old stars. However, if they were observed at a much greater distance so that individual stars could not be resolved, this population would make a minor contribution to the integrated light, and its presence would be missed. In such cases we may even be seeing new condensations forming about nuclei of old stars.

In this discussion we have tried to describe all the lines of evidence bearing on the ages of peculiar galaxies. We believe that the forms, the rotations, and the presence of uncondensed material all indicate that many of the systems considered in this paper are of recent origin. The ambiguities involved in interpreting colors in terms of stellar populations are considerable, as we have tried to show, and we tend to give greater weight to the other properties listed above as indicators of age.

IV. OBSERVATIONAL CONSIDERATIONS

In this section we give a discussion of part of the information now available on the sample of peculiar galaxies studied by us. More than 50 systems have been investigated in a preliminary fashion, i.e., direct plates have been obtained. Of these, a considerable proportion has been investigated spectroscopically, and many more are on the observing program. For the purposes of this study we have chosen a fraction of these to indicate the variety of forms and spectral characteristics found. Thus it must be remembered that, while the peculiar galaxies are only a small fraction of the total number of galaxies, we are describing here an even smaller sample.

The systems are divided into groups according to their configurations. The physical properties of all of these are collected together in Table 2. The first column of the table gives the name and number in Vorontsov-Velyaminov's *Atlas;* the second and third columns give the 1950 co-ordinates; in the fourth column it is stated whether the object appears to be single or multiple; the fifth and sixth columns give the spectral features seen; the seventh and eighth columns give, respectively, the observed velocity (corrected to the sun) and the velocity corrected to the center of our Galaxy by means of the same formula as that used by Humason, Mayall, and Sandage (1956). The ninth column gives the size in kiloparsecs of the largest dimension (this, of course, is projected on the plane of the sky and the true dimension might be even larger). The distances used in deriving these sizes were obtained from the redshifts in the eighth column and the value of 100 km/sec per Mpc for the Hubble constant. Finally, the tenth column gives the rotation. This is, in general, a minimum figure because the spectrum has usually been recorded only for the brighter parts of these galaxies. Unless otherwise stated, the spectra were obtained with the B spectrograph attached at the prime focus of the 82-inch telescope at McDonald Observatory, with the grating blazed at Hα giving 330 A/mm at that wavelength. We first consider tubular forms.

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a) *Tubular Forms*

In Figures 3, 4, and 5 are shown several galaxies which have tubular structures. The over-all dimensions of these are mostly very large; none are dwarfs in this respect. We describe each galaxy separately.

NGC 3509.—This galaxy is shown in Figure 3. The dimension of 45 kpc is measured from the outside edge of the loop at the northeast end of the edge of the luminosity at the southwest. The spectrograph slit was set in P.A. 49°9 through the elongated knot on the southeast edge of the broadest part of the galaxy; this patch is the brightest part of the object. The recorded spectrum is of this elongated patch with a faint extension from the region southwest of it. The patch has a bluish continuous spectrum. The velocity measures show a small, but apparently real, velocity spread, which we interpret as being due to rotation of the galaxy. Since the measures extend over only 20″, while the over-all diameter of the galaxy is just over 2′, the rotation may well extend over the whole object and be winding up the tubular structure.

TABLE 2

DATA ON PECULIAR GALAXIES

CATALOGUE NO.	$\alpha(1950)$	$\delta(1950)$	MULTIPLICITY	SPECTRAL FEATURES		RECESSION VELOCITY (km/sec)		LARGEST DIMENSION (Kpc)	ROTATION (km sec^{-1} /Extent in ″)
				Emission	Absorption	Observed	Relative to Galactic Center		
Anon. group near NGC 247	0^h45^m0	−20°42′	Quintet	Hα, [N II]	.	+ 6240	+ 6270	152	180/36
VV 117, NGC 2444–5	7 43 6	+39 08	Double	Hα, [NII]	Ca II, Na I	+ 3965	+ 3950	21	. . . . .
VV 75, NGC 3509	11 01 6	+ 5 06	Single	Hα, [N II]	.	+ 7600	+ 7440	45	140/19
NGC 3646	11 19 2	+20 27	Single	Hα, [N II], [S II]	Ca II	+ 4185	+ 4100	45	440/160
VV 172	11 29 2	+71 05	Quintet	[O II]	Ca II, CH	+15580	+15730	48	
VV 31, NGC 3921.	11 48 5	+55 21	Double	[N II]	Ca II, Na I	+ 5930	+ 6020	31	
VV 188, NGC 4438	12 25 3	+13 17	In Virgo Cluster	[N II], [S II]	Ca II, CH, Na I	+ 1207	+ 1136	27	.
						(Cluster)			
VV 224, NGC 4676	12 43 7	+31 01	Double in Coma Cluster	Hα, [N II]		+ 6920	+ 6907	N45	450/17
						(Cluster)		S41	430/26
NGC 4861 .	12 56 7	+35 08	Single	[O III], H, [O II], [Ne III], [S II], [N II], He I		+ 790	+ 830	9	
VV 109	14 43 8	+ 8 42	Single	Hα		+10470	+10490	37	170/10 5
VV 140	14 46 8	− 9 57	Single	Hα		+ 1880	+ 1830	12	180/47
Anon. .	15 16 3	+43 03	Double	Hα, [N II]	. .	+12110	+12270	25	. . . . .
IC 1182	16 03 3	+17 56	In Hercules Cluster	Hα, [O III], [O I], [N II]	Na I	+10652	+10775	72	350/8 0
						(Cluster)			
VV 247, NGC 6621–2	18 13 5	+68 18	Double	Hα, [N II]	.	+ 6230	+ 6490	35	200/4 5

NGC 6621/2.—This object, shown in Figure 3, is at first glance rather similar to NGC 3509, but it has two bright nuclei or condensations and appears to be a double galaxy. One of the nuclei has two fat, short spiral arms at the ends of its major axis. Two spectra were obtained; for the first the slit was set in P.A. 142° through the centers of the two nuclei. This showed emission lines of Hα and [N II] λ 6583 in the larger nucleus, and these were appreciably inclined. The other nucleus showed only a continuous spectrum (less blue than that of the main nucleus) in which no spectral features were visible. For the second spectrum the slit was set in P.A. 111° along the major axis of the larger nucleus. The emission lines were recorded over an extent of only 4″5 or 1400 pc; the rotation measured across this region on the second spectrum was 200 km/sec. The total extent of the object, from the outer edge of the curved tubular structure at the northwest end to the southeast tip, is 35 kpc.

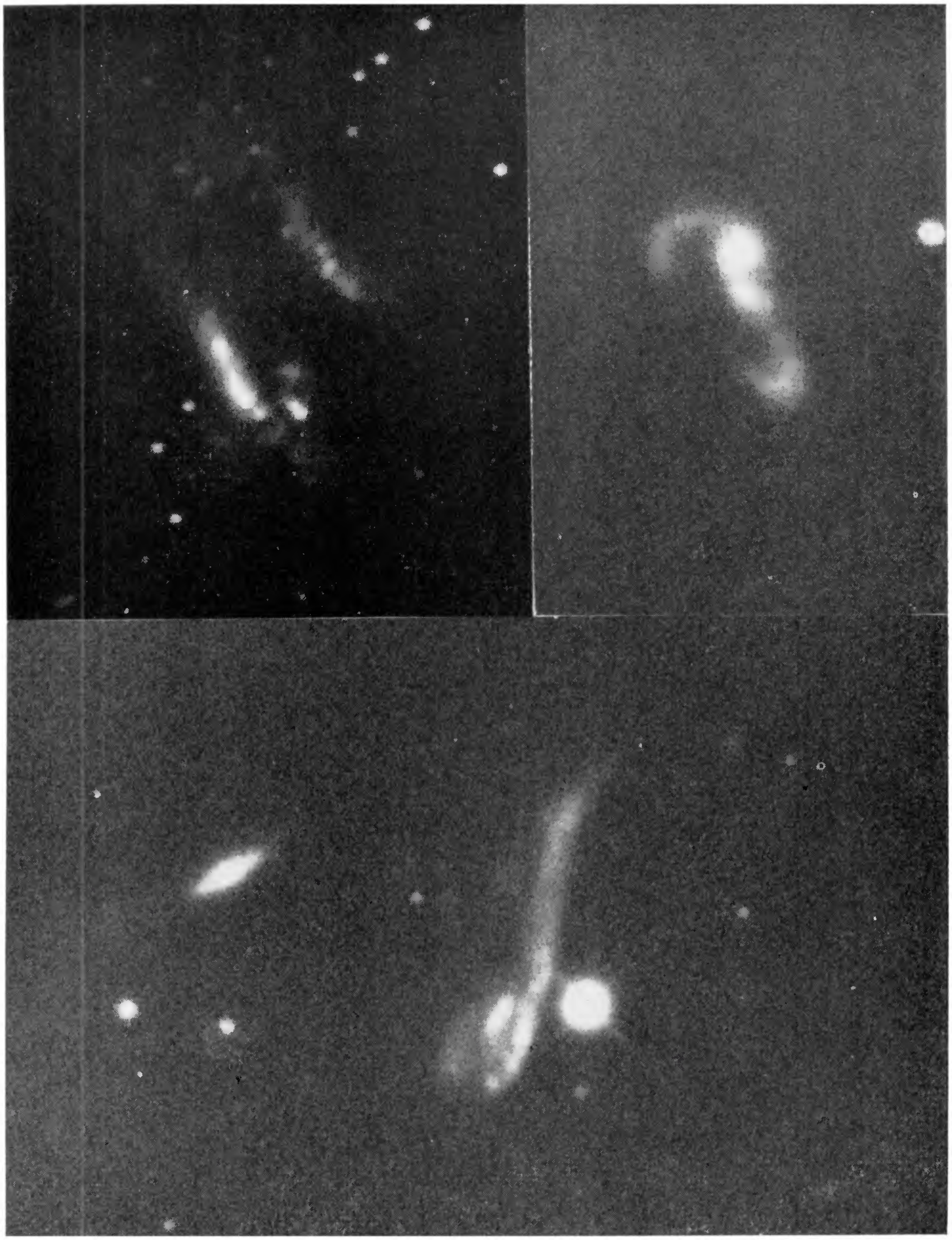

FIG. 4.—Three systems showing tubular forms. *Upper left:* VV 140 (scale: 1 mm = 2″.7). *Upper right:* Anon. 15:16, +43° (scale: 1 mm = 1″.4). *Lower:* VV 109 (scale: 1 mm = 1″.5). North at top, west at left in all. Upper two plates taken at prime focus of McDonald 82-inch, lower at prime focus of Lick 120-inch telescope. Eastman Kodak emulsion, baked IIa-O for upper two and 103a-O for lower.

FIG. 5.—NGC 3921, a galaxy with tubular extensions. Plate taken at prime focus of Lick 120-inch telescope on Eastman Kodak 103*a*-O emulsion. Scale: 1 mm = 1″.4. North at top, west at left.

NGC 4676.—This double galaxy, shown in Figure 3, has long, tubular structures in the form of "tails" and has been described previously (Burbidge and Burbidge 1959*b*, 1961); in the latter paper the results from two spectra are given. The pair is apparently, from its redshift, an outlying member of the Coma Cluster, and each of the elliptical bodies is in rapid rotation. The total length, from the tip of the nearly straight tail from the northern body to the end of the fainter, curved tail from the southern body, is about $3\frac{1}{2}'$, or 70 kpc. The period of rotation of the exterior of the northern component (the component with the long, straight "tail") is 8×10^7 years.

Anon. $15^{\mathrm{h}}16^{\mathrm{m}}$, $+43°03'$.—Of the galaxies discussed here, this (shown in Fig. 4) has the second greatest redshift, and therefore not much structural detail can be seen. It appears to be double, with one nucleus brighter than the other and a curved tube projecting from the opposite ends of each. The object is somewhat similar to NGC 4676, except for the greater curvature and width of the tubular structures. One spectrum in P.A. 160° was obtained and showed strong emission lines of Hα and [N II] in the bright nucleus; at the distance of this object, the scale is not large enough to show whether there is rotation or not.

VV 109.—This object is a striking example of a tubular structure, shown in Figure 4. The bright object south of it is a star. A spectrum was obtained with the prime-focus spectrograph on the Lick 120-inch telescope (red spectral region; dispersion 375 A/mm), with the slit set in P.A. 107°, aligned along the brightest part of the tubular structure. Only the Hα emission line was seen, with a velocity of +10470 km/sec, and no continuum was recorded. The velocities showed a progression along the length of the line, which we interpret as a rotation.

VV 140.—This U-shaped tubular structure is one of the smaller of the galaxies described here. It is shown in Figure 4. The over-all length of the longer side of the U, from the faint southern tip through the brightest part to the faint material at the northwest end, is 12 kpc. One spectrum was obtained, with the slit set in P.A. 157°, along the brightest part on the long side of the U. The measured velocities increase from the northwest toward the southwest end, indicating a rotation, with the northwest end approaching.

NGC 3921.—The final galaxy described in "tubular forms" is NGC 3921, shown in Figure 5, and it is somewhat different from the foregoing galaxies, in that the bright main body shows the absorption lines of Na I and Ca II, due to a big stellar component, and the only emission line visible is [N II] λ 6583 (Hα is not seen). The tubular structure may be gaseous or stellar; its color has not been measured. The greatest dimension, from the free end of the tubular structure at the northeast end to the outer edge of the sharp bend in this structure at the south end, is 31 kpc. One spectrum was obtained, in P.A. $165\frac{1}{2}°$; no rotation was detectable.

We now turn to a general discussion of tubular forms. The bright regions in NGC 3509 and NGC 6621–2 (Fig. 3) and in VV 140 (Fig. 4) presumably contain stars, since their spectra have an underlying continuum, and in these objects, in particular, these brighter regions are so closely related to the tubes as to suggest very strongly that they are condensations formed from material that occupied the interior of the tubes. In NGC 3921, the main bright body, whose spectrum showed it to be chiefly composed of stars, may be older than the tubular structure and have acquired this from the intergalactic medium fairly recently.

The tubes are probably associated with magnetic fields. The importance of a magnetic field is not that it can supply strength against transverse stress but lies in the fact that it will separate different samples of material—e.g., gas at different densities and temperatures. Even a weak field will do this. That is to say, a magnetic field is important because it can make different portions of the intergalactic material immiscible.

It is difficult to believe that the tubes in, e.g., NGC 4676 (Fig. 3) could be so thin and yet so well defined unless they are subject to external pressure. Other examples of such thin, well-defined tubes have been described by Zwicky (1956), who has shown photographs of several.

If we take the external pressure as $\sim 10^{-12}$ dyne/cm^2, it is clear that $H^2/8\pi \ll 10^{-12}$, otherwise the tubes would expand under magnetic pressure. It seems that H cannot be much above 10^{-6} gauss. Since the gas inside the tubes may possess densities $\sim 10^{-24}$ gm/cm^3, it is reasonable to suppose that the original uncompressed magnetic field cannot have been much greater than 10^{-8} gauss.

Rotations in NGC 3509, NGC 6621/2, VV 140, and VV 109 have been measured and range from 140 to 200 km/sec over the brightest parts of the objects (see Table 2). Rotations in NGC 4676 are much larger, amounting to 450 km/sec from one side to the other in each object. The tails associated with these fast-rotating bodies in NGC 4676 and also the curved configurations in the other objects must presumably be young and have short lifetimes. No such short-lived configurations could be defined by stars, although stars can form at any time from the gas. As soon as they formed, stars would not be subject to the magnetic field and the external pressure and would diffuse out of the tubes. As an example, the brightest portion of the tube extending from the northern component of NGC 4676 is about 2″ in width; at the distance of the Coma Cluster, to which the object apparently belongs, this is 670 pc; the time taken for a star with velocity 20 km/sec to cross this dimension is 3×10^7 years.

b) Galaxies Strung along a Tube

Figure 6 shows two examples of "chains" of galaxies. The more extended group (Anon. 0:45, −20°, near NGC 247) is not included in Vorontsov-Velyaminov's catalogue; it was found by chance during examination of NGC 247 on the 48-inch Sky Survey prints. There are four galaxies, three of them Sc objects and one irregular, which seem, from their general appearance, to be at the same distance from us and hence to be a physical group, and there is a fifth more amorphous object at the northern end of the group which may belong to the group or may be a background galaxy. We have succeeded in obtaining spectra of only the two brightest members of the group. The velocity of the northern is +6164 km/sec and that of the southern is +6308 km/sec. Both are somewhat bluish in color, from inspection of their spectral continua, and the only feature visible in either spectrum (exposed about 1½ hour) was Hα in emission. The northernmost bright galaxy in the group showed appreciable rotation, since two spectra, taken in position angles 33° (along its estimated major axis) and 161°4 (through it and the next galaxy to the south of it) both showed Hα to be inclined.

The small inset in Figure 6 shows VV 172, a direct plate of which has been described earlier (Burbidge and Burbidge 1960). Because of the lowered intensity of the night-sky bands in the blue and ultraviolet region, now that solar minimum is approaching, it has finally been possible to obtain the redshift of the two brightest of the galaxies in this closely spaced chain. The B spectrograph and grating blazed at 4000 A (dispersion 390 A/mm) were used on the McDonald 82-inch telescope. Two spectra were obtained in March, 1963, on baked II*a*-O emulsion; only the first (in P.A. 12¼°, through the two brightest galaxies, exposure 3½ hours) was measured, as the night-sky spectrum was again of disturbing strength on the second. Absorption features of Ca II and CH were used; [O II] λ 3727 was also seen but in a region of stronger night-sky bands and therefore not measured. The large redshift is sufficient to shift Hα out of the spectral range accessible on current 103*a*-F emulsion; hence we do not know whether the usual red emission features (looked for on a spectrogram obtained earlier) are present.

Vorontsov-Velyaminov gives magnitudes of 17 and 17½ for the various members of VV 172. Our redshift leads to $m - M = 36.0$, so that the brightest members, at $M = -19$, are by no means dwarfs. The over-all length of the chain (63″) is 48 kpc. The great length of the chain in Anon. 0:45, −20°, amounting to 120 kpc even if the

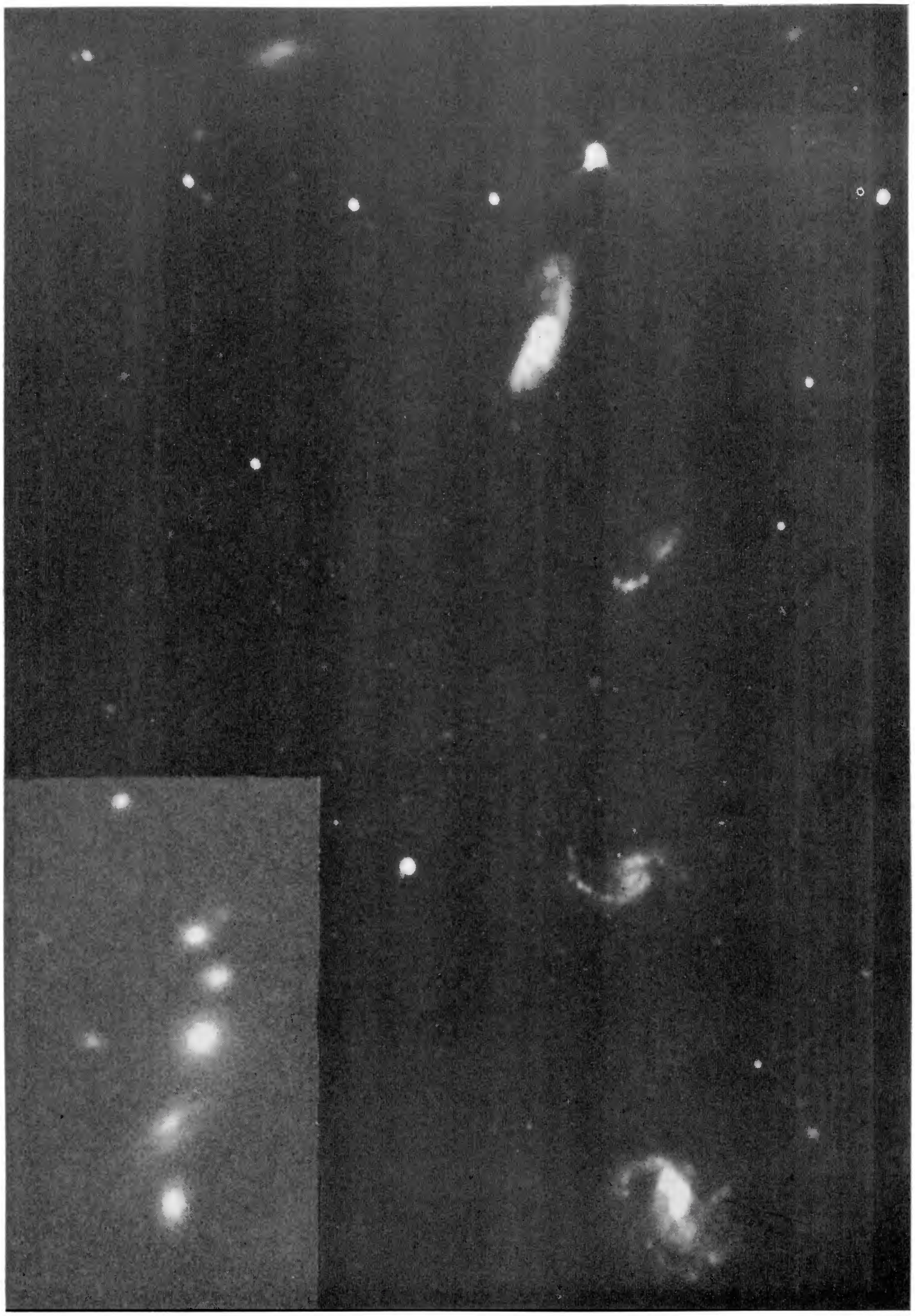

FIG. 6.—Two chains of galaxies. *Main picture:* Anon. 0:45, −20° (scale: 1 mm = 2″.7). *Inset:* VV 172 (scale: 1 mm = 1″.4). North at top, west at left in both. Both plates taken at prime focus of McDonald 82-inch telescope on baked Eastman Kodak II*a*-O emulsion.

FIG. 7.—Highly irregular galaxy NGC 4861. Plate taken at prime focus of Lick 120-inch telescope on Eastman Kodak 103a-O emulsion. Scale: 1 mm = 1$''$.4. North at top, west at left.

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amorphous northernmost object is not a member, shows that this is not a dwarf system, and the estimated minimum mass of the brightest object in this group, from its rotation, is $2.4 \times 10^{10} M_{\odot}$.

The velocity difference between the two measured galaxies in VV 172 is 170 km/sec, and in Anon. 0:45, $-20°$ it is 140 km/sec. For peculiar motions of $\sim$100 km/sec, either of these arrays will be destroyed in less than $\sim 10^9$ years. If their linear arrays then be taken to show a common origin, these systems must be young. We suggest that the galaxies formed as secondary condensations at intervals along a tubular condensation which was more massive than the tubular condensations described in the previous subsection, these latter having sufficient mass for only one or two galaxies. Possibly a tube still connects the arms of the galaxies in Anon. 0:45, $-20°$, although, if this is the case, the tube must be twisted into complicated patterns in the immediate vicinity of each galaxy.

c) Gaseous Emission Objects

Figures 7 and 8 show two remarkable galaxies, which, according to their spectra, contain a large amount of uncondensed gas. The smaller galaxy, NGC 4861, with its curious comet-like form, appears, like the objects described above, to be a tubular condensation. The main concentration is at one end of the object, and a spectrum of this "nucleus" was obtained with the slit in P.A. $20\frac{1}{2}°$. The exposure time was only 40 minutes, so the spectrum of the fainter, elongated part of the galaxy was not recorded. The underlying continuum in the spectrum of the nucleus is rather blue; no absorption lines are seen, but there are numerous strong emission lines, which show that the excitation is high. The spectrum resembles that of the irregular NGC 5253 (Burbidge and Burbidge 1962), but the greater strength of [O III] λ 4363 in NGC 4861 indicates a higher excitation. [S II] and [N II] are much weaker in NGC 4861 than in NGC 5253. Thus the main concentration or nucleus of this galaxy contains much gas and, presumably, high-temperature stars. No rotation was detected on our spectrum.

The total length of NGC 4861 is about 9 kpc, and thus it is of normal galactic dimensions; but if the fainter material (the "tail") were to take up a distribution with circular symmetry about the main condensation, the galaxy would be rather small. The spectroscopic features seen in this galaxy are similar to those in a number of the bright irregular galaxies. We have already mentioned NGC 5253, and other systems which are somewhat similar in this connection are NGC 2188, 4656, and 4449. NGC 4656 and NGC 4449 are shown in the *Hubble Atlas* (Sandage 1961); NGC 4656 also has the appearance of a tubular structure. NGC 2188 is a highly elongated system, which shows a greater degree of symmetry than NGC 4861 or NGC 4656, while NGC 4449 has more of a rectangular form, though with a very uneven brightness distribution. A more detailed discussion of these systems will be given elsewhere.

NGC 2444–5, in Figure 8, is a double galaxy listed in Vorontsov-Velyaminov's catalogue and consists of an elliptical and an irregular, largely gaseous, system. It was described by Burbidge and Burbidge (1959*a*); in that paper the velocities measured on several spectra were published. The excitation of the gaseous emission regions is fairly low. The photograph shown in Figure 8 was obtained with the Lick 120-inch telescope. It shows the structure of the irregular galaxy in much more detail than was visible on the photograph published earlier; in particular, the structure in the large complexes of H II regions can be seen.

The diameter of the irregular is 17 kpc, a normal galactic dimension. It was stated in the earlier paper that the form and high gas content of this irregular suggested that it would be short-lived in its present state; it might indeed be a newly formed condensation that had occurred in the presence of an already existing elliptical galaxy, or, alternatively, we might be seeing the aftermath of a close collision between an elliptical and a spiral in which the spiral had been completely disrupted.

Dr. A. R. Sandage has kindly informed us that the central knot in the irregular (knot d in our earlier paper), whose spectrum showed a fairly strong continuum underlying the Hα and [N II] emission lines, has a color index of about +0.6. Thus, this is the color index of the integrated light from the star group imbedded in the gas in this central knot, or "nucleus." There must be high-temperature stars in the component stellar population, since the Hα/[N II] λ 6583 line intensity ratio in this nucleus is fairly similar to the average value characteristic of diffuse H II regions in spiral arms.

The possibility that a collision has taken place between an Sc galaxy and the elliptical should not be overlooked. However, it not easy to see why the interaction should have taken such an extreme form. The elliptical contains very little gas ([N II] λ 6583, which behaves like [O II] λ 3727 in its appearance in E, S0, and Sa galaxies is absent from the spectrum of the elliptical). While the elliptical might have been swept clean of gas by the collision, this would be possible only if the elliptical were less massive than the original Sc; otherwise the elliptical would have retained more of the gas than the Sc, whereas in fact the nucleus of the irregular galaxy that we see does contain plenty of gas. A simple gravitational interaction does not seem adequate to explain what is observed.

We incline to the view that this is really another tubular phenomenon, in which the elliptical galaxy has acquired sufficient material from the intergalactic medium for a new galaxy to form, for the following reasons. There is a connection between the elliptical and the irregular, which could be magnetic. The sharp edges of the irregular on the west and southwest sides again suggest an external pressure. There is a faint extension on the north side of the elliptical, opposite to the irregular, suggesting a tubular form. In the region south of the elliptical, early-type stars may have condensed in the tube, possibly as a consequence of the ejection of either dust or heavy elements from the elliptical. The large energy supply from the early-type stars could produce a rise of internal pressure within the tube, causing it to become extended in the region we now see. The phenomenon in this respect could be analogous to the simpler case shown in Figure 7 (NGC 4861).

d) The Extensive and Dynamically Unstable Spiral Galaxy, NGC 3646

NGC 3646 is shown in the upper part of Figure 9. The rotation and velocity field in this galaxy were studied earlier (Burbidge, Burbidge, and Prendergast 1961), and it was shown that the velocities in the outer structure surrounding the regular spiral were irreconcilable with circular motion and suggested that this outer ring was in a state of rapid dynamical evolution. The rotation of the inner spiral structure, however, could be interpreted as its being a normal spiral with a mass between 2 and $3 \times 10^{11} M_\odot$.

The diameter of the outer structure is some 45 kpc, i.e., it is large compared with normal galactic dimensions. The emission lines in this outer structure indicate moderately low excitation; they are strong, and the brightest regions have a weak blue continuum that could come from early-type stars. This may be another tubular system that has become wound onto an existing spiral galaxy.

It is important to note that the nature of this remarkable system was discovered only when it was put on the program for observing rotational velocities, and this was done because it appeared to be extremely large and luminous for its class, which was originally given as Sc. It is not in Vorontsov-Velyaminov's catalogue. Such form peculiarities as are visible, i.e., the curious cross-over in the bright tubes at the southwest end and the wave structure in the tube at the north side, would be difficult to detect from direct photographs of such systems seen at much greater distances. An interesting speculation is that many spiral galaxies are continually winding onto themselves more and more of the tubular structures to which they are connected and that NGC 3646 is an extreme example of this behavior.

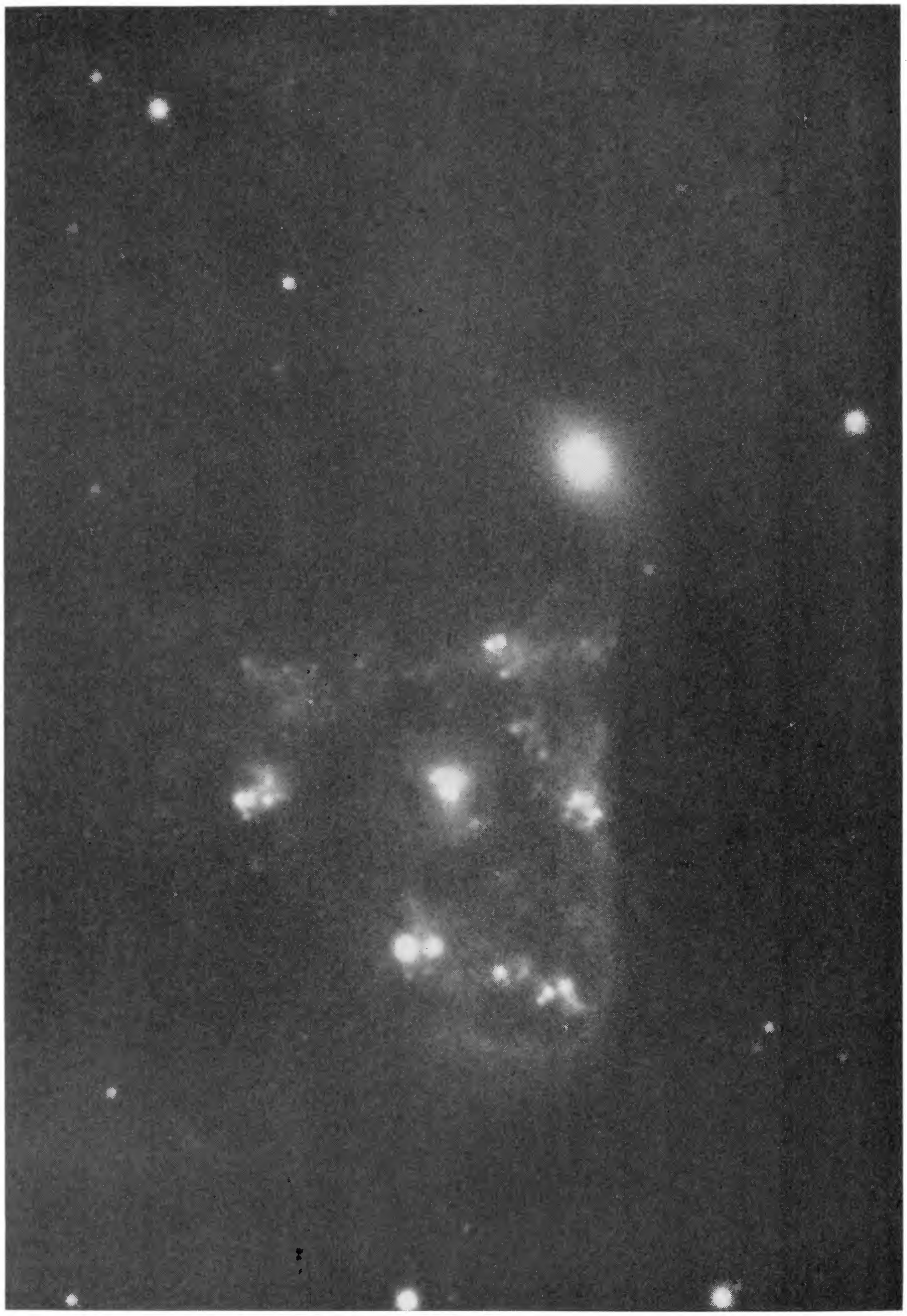

FIG. 8.—NGC 2444–5, a remarkable irregular associated with an elliptical. Plate taken at prime focus of Lick 120-inch telescope on Eastman Kodak 103*a*-O emulsion. Scale: 1 mm = 1″.5. North at top, east at left.

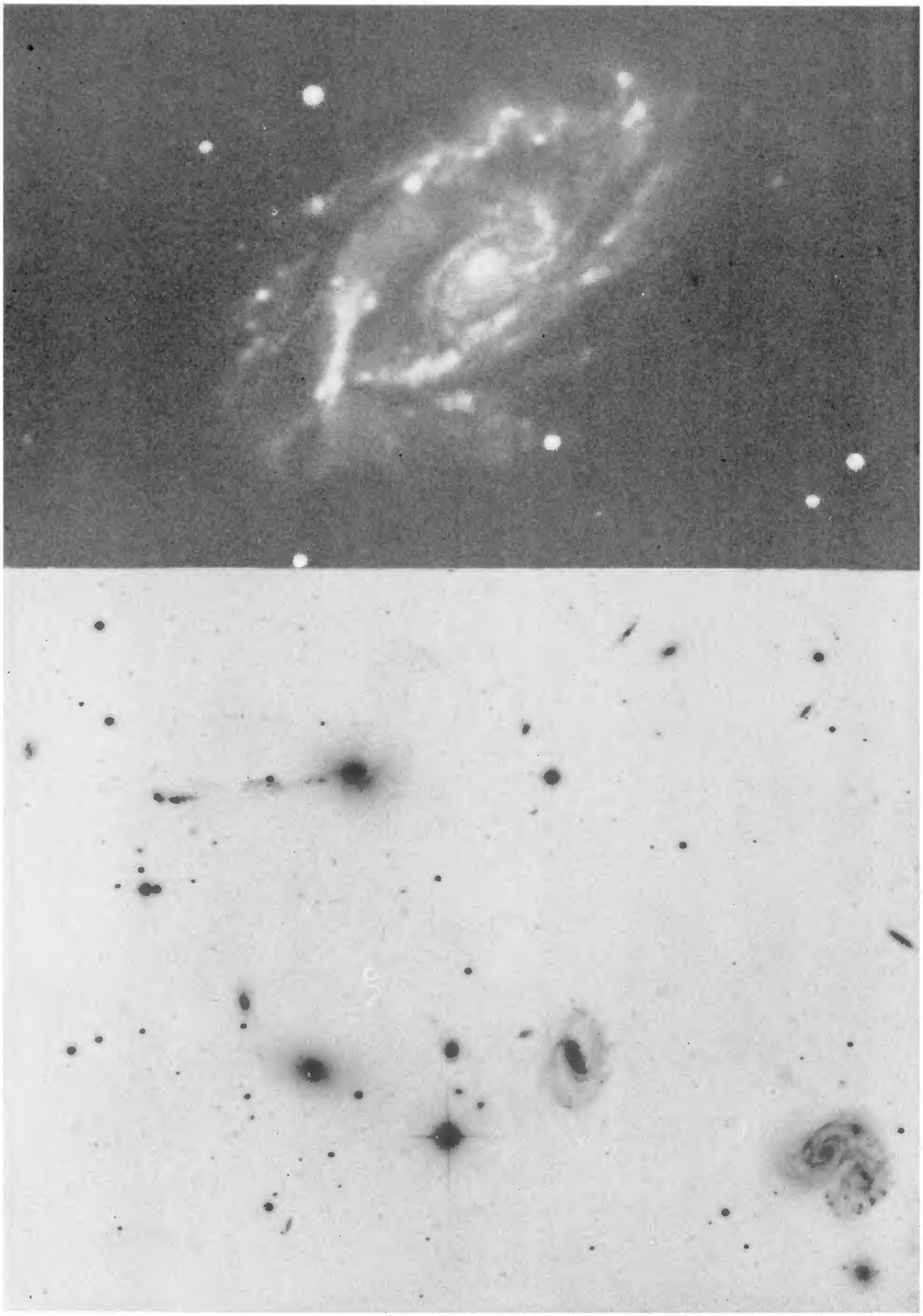

FIG. 9.—*Upper:* NGC 3646, a spiral with extended outer structure not in equilibrium. Plate taken at prime focus of McDonald 82-inch telescope on baked Eastman Kodak II*a*-O emulsion. Scale: 1 mm = 2″.6. North at top, west at left. *Lower:* Part of Hercules Cluster of galaxies, showing peculiar system IC 1182–4 toward upper left of print. Palomar 200-inch plate taken by W. Baade. Scale: 1 mm = 3″.1. North at top, east at left.

e) The Hercules Cluster

The Hercules Cluster is a cluster of galaxies containing only about 75 bright systems. A previous study (Burbidge and Burbidge 1959*c*) showed that either the cluster is disrupting on a comparatively short time scale ($\sim 10^9$ years) or else it contains a large amount of uncondensed material. There are a considerable number of peculiar systems contained in it. It appears to be a site of very strong interaction between the constituent galaxies and a surrounding gaseous medium. One suspects that these galaxies are connected one to another by an intricate tubular network, the tubes being themselves surrounded by a hotter compressing gas. The illustration that we have chosen, reproduced from 200-inch Palomar plates taken by W. Baade and published in the reference given above, includes the very interesting object IC 1182–4, described by Ambartsumian and Schachbazian (1957). The red spectral region of this was photographed with the prime-focus spectrograph on the Lick 120-inch telescope, with the thick Schmidt camera and the grating giving 375 A/mm dispersion (exposure 2^h24^m). A very strong emission line due to Hα was seen; strong [N II] and [O I] were also recorded, and even [O III] could be seen, although it fell well outside the region for which the spectrograph was focused. Quite strong Na I absorption was also seen. The observed velocity given by these features is +10245 km/sec, which agrees well with the mean velocity of the Hercules Cluster.

The spectrum described above revealed a surprise. The strong Hα line, which extended well beyond the continuum, was very appreciably inclined and gave a velocity difference of 350 km/sec over 8″ (corresponding to about 4 kpc). The slit was in P.A. $99\frac{1}{2}°$, i.e., through the main bright body and along the eastern jetlike extension of IC 1182 (but not through the extensions distant 40″–50″ from the main body). However, only the main bright body showed up on the spectrum; the velocity difference was in the sense that the western side of it is receding from, and the eastern side approaching, the observer. This might be interpreted as rotation, infall of material, or ejection. It is planned to try and obtain the spectrum of the eastern appendage of IC 1182.

V. CONCLUSION

In the last section we described some examples of the different kinds of peculiar galaxies that have been found in the region within a distance of order 100 Mpc. As has already been mentioned, many more systems than those described here are being studied, but we can hope to investigate in detail only the nearer objects. Although we cannot claim to have examined anything like a really distant sample, it seems to us that the data are not inconsistent with the point of view we developed in Section II. From many points of view, the evidence might be considered encouraging, although we do not claim to have established with certainty that galaxies are, in fact, forming at the present time. Our opinion is that an interaction between galaxies and a medium surrounding them is certainly present, that some new galaxies are forming, that some new systems condense on to, or in association with, stars condensed at an earlier epoch, but that the rate of galaxy formation is less than we expect to be reached at the maximum phase in the cyclic operation of our feedback loop. This view is consistent with the opinion we expressed at an earlier stage—that perhaps at the present epoch we are somewhat past the phase of maximum radio and cosmic-ray activity.

The question may arise in the reader's mind as to how far the evidence is consistent or inconsistent with evolutionary cosmology. An important difference is that, on the basis of our discussion in Section II, galaxies of ages τ, $\tau + T$, $\tau + 2T$, . . . , are to be expected, whereas in evolutionary cosmology all galaxies are of closely the same age. It may be possible to distinguish between the two theories on this basis, but the evidence discussed in Sections III and IV is not adequate to do this. A second difference is that in the steady-state theory a pressure of $\sim 10^{-12}$ dyne/cm^2 can exist in the intergalactic medium. This pressure would seem to us to be helpful in understanding the apparently sharply defined edges of the tubes and envelopes seen in Figures 3, 4, and 8. In evolutionary cosmology, on the other hand, the pressure in any intergalactic medium is usually supposed small and no such interpretation can be made.

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