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# Multiple Galaxies

By

F. ZWICKY

With 11 Plates and 7 Figures

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## I. Definitions

The meaning of the term multiple galaxies obviously can be clear only if we know what an individual galaxy is. Unfortunately it is not at the present time possible to give an exact definition of a galaxy as a physical stellar system which is in practice operationally useful. Theoretically one might postulate that any agglomeration of stars, gases and solid particles constitutes a galaxy if its various material components cannot escape directly from this agglomeration. A stellar system or galaxy is therefore a cohesive unit of stars, dust and gases within which only a fraction of its components possess velocities high enough to allow them to escape and to make their way to the vast intergalactic spaces. In reality we cannot of course use the criterion just formulated, since for a long time to come the data available on the velocities of the various members of stellar systems will be entirely insufficient. A more modest approach must therefore be chosen. One may for instance attempt to identify the individual galaxies from their structural features as well as from the surface brightness within a given area and from the decline of this brightness as he moves away from the central regions of the system. Using criteria of this somewhat indefinite character, mistakes are naturally inevitable in the sense that some nebulae will be classified as single systems although they may in reality be groups comprising several self contained dynamic units of the type described above. On the other hand, what appears to be a multiple galaxy may actually be a single dynamic unit when judged according to the proper criteria of dynamic statistical stability.

Another conceptual difficulty which begins to loom high on the horizon is related to the recent discovery of both dark and luminous intergalactic matter (*1*). Indeed, extrapolating the results obtained so far it is probable that most if not all galaxies extend indefinitely until their tenuous outskirts meet those of the neighboring galaxies. Stellar systems may therefore not be *island* universes as HERSCHEL called them and as most astronomers assumed until very recently but they are rather concentrations of stars, dust and gases within a tenuous but continuous distribution of matter distributed throughout the whole universe. Without awaiting the solution of these problems we may nevertheless deal fruitfully with certain simplified criteria defining single and multiple galaxies. Using this operational approach the following tentative classification will be adopted.

a) An extragalactic nebula will in general be considered to be a single galaxy if the average surface brightness within circles of ever increasing size and centered on the brightest nucleus decreases monotonely as it approaches the surface brightness of the sky background.

b) As a second more restrictive condition we demand that the appearance of the nebulae in question and of the spectra in its various parts be such that the nebula does not obviously represent two galaxies in a close encounter as is for instance the case of NGC 1275 which we shall discuss further on.

c) Multiple nebulae fall into two classes, namely, line of sight groups and physically related systems. The following criteria will often suffice to distinguish between the two classes. The members of a line of sight double nebula do not show any effects of mutual tidal actions and there will be no visible connection between them of the type to be discussed later in this article. Also, the redshifts in the spectra of the components should in general be different although, statistically there will be rare exceptions to this rule, as we shall see in the course of our study.

Physical double or multiple galaxies can be of several types. For instance, the components of a group may be clearly separated by areas whose brightness is not markedly superior to that of the night sky, and there may or may not be any clear evidence of mutually induced tidal actions and distortions. On the other hand the member galaxies of a group may be actually interconnected by luminous intergalactic filaments, bridge like structure and interwoven long spiral arms, or all of the galaxies may be imbedded in a luminous cloud of matter. For convenience we shall distinguish between close pairs and groups whose members are separated by less than two or three of their "classical" diameters on the one hand and physical associations of galaxies which are farer apart. Many of the close multiple galaxies probably are real dynamic units whose components cannot escape directly, while most of the widely separated galaxies are presumably in the process of departing from each other, in spite of the fact that they may be connected by long filaments.

It was originally thought that the single isolated galaxies are in the majority (*2*) and that only a few percent of the total number are members of large clusters. Work during the past two decades with the Schmidt telescopes on Palomar Mountain however, has led to the conclusion that this estimate is entirely incorrect and that most galaxies belong to clusters which may be virtually regarded as filling cosmic space completely. When discussing the subject of multiple galaxies in this study we shall arbitrarily make a distinction between small groups and large clusters. We shall not deal to any great extent with clusters here but concentrate our attention almost entirely on double galaxies and some small groups not containing more than half a dozen members.

## II. Remarks on the History of the Subject

### A. Small Groups of Galaxies

Astronomers noticed long ago that there exist many close groupings among the extragalactic nebulae. First, the great nebula in Andromeda was seen to possess two companions, NGC 205 and NGC 221. Among the brightest galaxies there are some conspicuously beautiful pairs such as the Whirlpool nebula, Messier 51, with the two companions NGC 5194 and 5195. Soon after the 60-inch reflector became available at the Mount Wilson observatory Dr. F. G. Pease from 1911 until 1919 photographed a great number of individual and of double nebulae describing them in two classical papers (*3*) which preceded the final identification, shortly afterwards, of many of these objects as extragalactic stellar systems by H. D. Curtis (*4*), K. Lundmark (*5*), E. P. Hubble (*2*) and others.

Curiously enough the study of double and multiple galaxies was severely neglected for a long time. Even today the data available are far too scant to allow us to draw any far reaching conclusions as to the intrinsic nature of groups of stellar systems. There are cosmologists who hold that these groups were formed out of large amorphous masses of primordial gases while others, including the author, think it more likely that most multiple galaxies represent the result of inelastic collisions and subsequent mutual capture of galaxies which were formed a long time before the encounters. The luminous intergalactic formations of stars recently found by the author (*1*) to connect many widely separated galaxies have greatly added to the mystery of the formation of a certain class of complexes of stellar systems. On the other hand this discovery, if explored properly, promises to furnish us with a number of entirely new clues about the fundamental problem of the evolution of galaxies and of groups of galaxies.

K. Lundmark who contributed so much toward the consolidation of our views about the realm of the extragalactic nebulae or, the metagalactic system, as he proposed to call it, also was probably the first to point out the unique value of the study of multiple galaxies for the derivation of the physical characteristics of distant stellar systems (*6*). His contributions to the subject were clearly reviewed by E. Holmberg (*7*) who says "Knut Lundmark was the first to recognize the great importance of the double galaxies and to make use of them in obtaining the absolute characteristics of the anagalactic objects (extragalactic nebulae). In several papers (*6*) he calls attention to these problems. Thus Lundmark has investigated about 8000 NGC-objects and has found about 200 double and multiple systems. Furthermore he has made a search for these objects on the Franklin-Adams Plates, on Crossley plates and on plates taken with the great instruments at Mount Wilson."

"Concerning the absolute characteristics of the anagalactic objects Lundmark has pointed out that from the double galaxies we can, among other things, obtain the differences in absolute magnitudes and in absolute dimensions. From these we can derive the dispersions in the corresponding quantities, and through processes of integration, or rather interpolation, numerical expressions for several connections can be derived. Thus the double galaxies are of very great importance for the derivation of absolute quantities and interrelations within the metagalactic system."

Holmberg (*7*) himself in an extensive study published in 1937 continued the investigations started by Lundmark. He determined the apparent properties of 827 double and multiple systems of galaxies by means of the rich collection of Bruce plates of the Heidelberg Observatory. Some of his results and conclusions are as follows.

1. There is an unbroken line of transition: double galaxies — multiple galaxies — metagalactic clusters — metagalactic superclusters or clouds.

2. Holmberg considers as a double galaxy any system in which the apparent distance $\Theta_{12}$ between its components is equal to, or smaller than twice the sum of the largest apparent diameters $a_1$ and $a_2$. Thus

$$\Theta_{12}/(a_1 + a_2) \leqq 2\,. \qquad (1)$$

In a multiple system the condition (1) must be valid for any one of the components taken together with one of the others. Holmberg states that the double galaxies selected according to the definition (1) prove in general to be physical systems, and that the probable number of optical systems should amount to only a few percent.

3. The components of multiple systems may be elliptical, spiral or irregular galaxies. Using HUBBLE's distance scale (*2*) HOLMBERG derives for the members of the systems he investigated an average absolute photographic magnitude $M = -14.35$ and a dispersion in magnitudes $\sigma_M = 1.02$, not very different from what HUBBLE found for individual galaxies (*2*). HOLMBERG also derives absolute diameters $A$ of the member galaxies and a relation between $A$ and $M$.

4. HOLMBERG is of the opinion that the formation of double galaxies is probably due to capture. Starting from this premise he finds that the observed number of double galaxies requires an effective age of the metagalactic system of the order of $4 \times 10^{12}$ years.

5. From the radial velocities determined for the components of double systems HOLMBERG obtains for the selected galaxies an average mass of about $10^{11} M_\odot$.

More work was recently done by TH. PAGE (*8*) who obtained small dispersion spectra (330 Å/mm) of about forty nebulae which are the members of twenty double systems. PAGE comes to the conclusion that "although the observations do not yet permit an accurate determination of the frequency distribution of masses among these nebulae, there is good evidence in these and other data that many individual masses are over twice the mean, and many others are one tenth the mean or less. In fact these limited data indicate a sharp division between heavy weight and light weight galaxies of $1.5 \times 10^{11}$ and $0.5 \times 10^{10}$ solar masses respectively."

In section C we shall discuss recent advances which make it doubtful whether the statistical study made by PAGE on the basis of entirely insufficient material has any degree of reliability. Some of the main objections to this study obviously are a) PAGE did not apply any effective criteria whatever to distinguish between nebulae which are close neighbors in space and optical doubles. The pooling of both of these types of apparent and of real pairs may very well have given rise to the conclusion that there is a sharp division between light weight and heavy weigh galaxies, a result which is most unlikely when analysed theoretically and when compared with other well established data. Indeed, many thousands of double and of multiple galaxies have now been studied as they appear on 48-inch Schmidt plates. From the distribution of types and from the differences in apparent magnitudes of the member nebulae within these groups one must conclude that there is no drastic gap in the number of galaxies either as a function of luminosity or of mass. b) PAGE also did not have at his disposal any criterion to decide if neighboring galaxies actually form dynamic units or if they are escaping from one another. c) In order to determine the masses from the differences in radial velocities one must obviously know the absolute separations of the components in the double nebulae. This separation can be obtained only from reliable data on the absolute distances of the nebulae which are involved. Distance determinations for extragalactic objects have recently undergone severe revisions. For nebulae whose apparent velocities of recession are less than 5000 km./sec. the final results for the distances are still in doubt by factors of the order from two to five.

The recent advances made in the observation of multiple galaxies which will be described in the following will make possible a more rigorous use of the differences in radial velocities for the determination of the masses of the components of double galaxies. For the time being, however, the only reliable dynamic methods for the derivation of the masses of cluster nebulae are based on the procedures originally proposed and applied by the author (*9*). These procedures make use of the Virial theorem and the thermodynamic statistical analysis developed by EMDEN for the study of polytropic gravitational gas spheres (*10*).

## B. Clusters of Galaxies

Clustering among the nebulous objects in high galactic latitudes excited the attention of the early observers, long before it was recognized that these nebulae are extragalactic. The distribution of nebulae was in particular explored by the Herschels who found pronounced concentrations in Virgo, Ursa Major, Pisces-Perseus and other parts of the sky. An interesting review of their results is to be found in Humboldt's "Cosmos" (*11*).

At the beginning of this century M. WOLF (*12*) discovered some of the more distant clusters such as the one in Coma which was to play a most important role in all later investigations on the large scale distribution of matter in the universe. With the advent of the large telescopes in the United States of America a series of beautiful distant clusters was found, including those in Corona Borealis, Ursa Major, Gemini, Bootes and Hydra II. As is well known these clusters served HUMASON and HUBBLE as stepping stones in their explorations with the 100-inch reflector of the universal redshift in dependence on distance (*2*). From the analysis of the apparent magnitudes of the members of the nearer clusters HUBBLE (*2*) also derived the luminosity function of nebulae with a maximum frequency at the absolute photographic magnitude —14.2 and a dispersion of only 0.65 magnitudes. As it was shown later on by ZWICKY'S investigations (*13*) with the Palomar Schmidt telescopes, HUBBLE'S luminosity function which until recently was considered as well established by most investigators is based on a systematically biased selection of objects and is quite erroneous. Actually, because of the discovery of ever increasing numbers of dwarf stellar systems and of swarms of intergalactic stars it now appears that the luminosity function does not possess any maximum at all but is rising monotonely as the absolute brightness of the galaxies decreases (*14*).

Because of the large solid angles subtended by the nearby clusters of galaxies their structural features could not be effectively explored with the large reflectors. Here the invention of the Schmidt telescope twenty five years ago came to the rescue. These instruments have large fields of uniformly excellent image quality in all colour ranges. Because of their large focal ratios, F/2 and F/2.5 respectively for the 18-inch and

48-inch Schmidt telescopes on Palomar Mountain, these instruments possess very high speeds for the photography of extended luminous objects and they are therefore ideally suited for the investigation of agglomerations of galaxies. Twenty years of work with these telescopes have produced numerous significant results on the characteristics of clusters of galaxies. Some of these results are as follows.

1. Contrary to opinions previously held by astronomers (*2*) clusters and clouds of galaxies are the rule, rather than the exception. Isolated galaxies are clearly in the minority.

2. Clusters and clouds of galaxies are virtually space fillers. Some among them are open clouds or medium compact swarms but, a surprisingly large fraction of the rich clusters are spherically symmetrical.

3. If $m_{max}$ is the apparent photographic magnitude of its brightest member, a rich cluster may contain as many as ten thousand galaxies in the magnitude range from $m_{max}$ to $m_{max} + 7$.

4. In many of the large spherical clusters the radial distribution of the brightest members can be closely approximated by the function representing the density distribution of matter as a function of the distance from the center of an isothermal gravitational gas sphere, as originally analyzed by R. EMDEN (*10*).

5. There occurs a radial segregation of the members of a cluster, both as to type and luminosity. Very bright nebulae of the types $S_0$ and E are preponderantly concentrated toward the centers of the large clusters, while faint nebulae of all types are relatively more numerous toward the outskirts, where also most of the spirals are found. The outlying parts of a cluster may therefore also be expected to be the bluest in colour.

6. The large spherical clusters of galaxies are remarkably similar in structure, and their absolute dimensions as well as the absolute luminosity functions for their brightest members are closely the same.

7. The velocity dispersion within the large clusters of galaxies is of the order of 2000 km./sec.

8. Both luminous and dark intergalactic matter have been found to be concentrated with a slight radial gradient toward the centers of the large clusters. The large luminous clouds in which the cluster nebulae appear imbedded show surface brightness corresponding to a range of apparent photographic magnitude $m_p$ per square second of arc lying in the range $+23 < m_p/\text{sq. second of arc} < +25$. In the neighborhood of close multiple nebulae belonging to a large cluster, the surface brightness of the luminous intergalactic matter may be even greater and approach or surpass that of the night sky glow which is of the order of $m_p = +22$ per square second of arc. Such bright local clouds are for instance found near the center of the Coma cluster (R. A. $12^h\ 57^m.5$, Decl. $+28°\ 13'.5$, Epoch 1950.0), of the Corona Borealis cluster (R. A. $15^h\ 20^m\ 21^s$, Decl. $+27°\ 54'$), and the so-called A-cluster (R. A. $1^h\ 6^m\ 17^s$, Decl. $-15°\ 38'\ 40''$). In the latter case the cloud is quite asymmetrical and partly red and partly blue in colour (*15*). In most cases the large intergalactic clouds within clusters appear rather blue, similar in colour to the bridges between galaxies which we shall discuss in the following.

9. Clusters of galaxies appear to be distributed uniformly and randomly throughout an apparently *flat* and *non-expanding universe*. This somewhat surprising result was derived from studies of both the apparent distribution of the centers of clusters in the celestial regions least obscured by interstellar and intergalactic dust as well as from the analysis of the frequency distribution of the angular diameters of nearly one thousand rich clusters (*14*, *16*).

10. From the study mentioned under 9. it also follows that there is no systematic clustering of clusters. Actually it can be shown that, if gravitional interactions are transmitted with a finite velocity $c_g$ assumed to be equal to the speed of light $c$, no statistically well organized cluster of galaxies can be formed with a diameter materially greater than about twenty million light years (*16*). Also, if $c_g = c$, or $c_g$ not materially greater than $c$, a uniform expansion of the universe appears to be theoretically impossible, since local instabilities will lead to avalanching collapses of matter. These processes would give rise to irregular swarm formations of galaxies and to vast lacunae devoid of matter, both of dimensions vastly greater than the observed regular clusters of galaxies (*17*). No swarms or lacunae of the type described seem to exist.

11. The analysis of the large clusters in Coma, Hydra I, Perseus, Cancer and others led to the recognition by Zwicky (*14*) in 1933 that the average masses of the first several hundred brightest member galaxies in these clusters are of the order of $2 \times 10^{11}$ times the mass of the sun, that is two hundred times greater than the average masses originally derived by Hubble (*2*) and others from absolute luminosity criteria. Holmberg in 1937 in his study (*7*) which we discussed in section II a arrived at similarly large values for the average masses of the components of double nebulae. Both the author's and Holmberg's mass determinations must of course be revised as soon as a new more reliable distance scale will become established.

## C. Recent Advances

A number of recent developments have shed important new light on the problems related to the structure and to the formation of multiple galaxies. Some of these developments are as follows.

1. Drs. M. L. Humason and N. U. Mayall have now completed their catalogue of the redshifts in the spectra of over six hundred galaxies. Their data not only refer to the shifts in wave lengths but they also give a great wealth of information on the intrinsic character of the spectra of various types of individual and of multiple stellar systems.

2. With a view to the determination of the absolute characteristics of the components of multiple galaxies reliable knowledge on the absolute extragalactic distance scale is indispensable. In recent years data have come to light concerning the absolute luminosities of certain classes of variable stars which have made it necessary to abandon the old distance scale. Corrections will have to be applied which may change the distances to many nebulae and groups of nebulae by factors as high as four or five.

Large uncertainties must also be kept in mind because of the recent discovery by the writer of obscuring intergalactic matter (*16*).

3. Sky surveys with the 18-inch and the 48-inch Schmidt telescopes on Palomar Mountain revealed the existence of a surprisingly large number of rather *widely separated galaxies which appear connected by luminous intergalactic formations*. Although the absolute distance scale may remain uncertain for some time to come the luminous bridges and filaments make it certain that *two nebulae so connected are at the same distance*, a fact which is of the utmost importance to astrophysical theory. It is estimated that with the 48-inch Schmidt several thousand pairs of widely separated galaxies have been found to be interconnected by faintly luminous formations. The author has only made a cursory search for close double and multiple nebulae as they appear on a few dozen plates taken with the 48-inch Schmidt. On the basis of this search it appears that probably several hundred thousand close doubles could be located with this instrument. A future thorough project along these lines will thus be rewarding.

4. The discovery of extended luminous intergalactic formations was not entirely accidental. Theoretical considerations had previously indicated that the internal viscosity of stellar systems is far greater than had been originally expected (*9, 18*). Because of this high viscosity it was concluded (*19*) that galaxies on close encounter will violently disrupt each other and much of the "debris" may be expected to escape into intergalactic space since the relative kinetic energy of many neighboring galaxies is often equal or even considerably greater than their internal gravitational potential energy. On the basis of these theoretical predictions the author therefore began an intensive search for intergalactic matter in the large clusters of nebulae, where encounters may be expected to occur most often. As a consequence of this search both luminous and dark internebular formations were found (*15, 20*). As an additional result of the theory the existence of many dwarf galaxies was forseen and observationally confirmed (*19, 20*).

5. As a consequence of the studies of widely separated inter-connected galaxies a reexamination of the structures of close pairs and multiples was started. Many of these were found to possess long extensions not previously known. New results were also obtained on the nature of the tidal actions in physical pairs and, with the help of the so-called analytical composite photography (*21*) a most promising exploration of the distribution of colours and of polarisation over the different parts of interacting stellar systems has been started. The statistics of the differences in apparent magnitudes of the member galaxies in multiple systems has confirmed the conclusion originally derived from theory (*19*) that the luminosity function of galaxies has no maximum but is monotonely increasing with decreasing brightness (*14*).

6. A study has been started of the apparent radial velocity differences of the members of interconnected galaxies. The magnitude of some of these differences (up to more than 7000 km./sec.) poses entirely new and unsuspected problems for astrophysical theory.

7. The advent of radio-astronomy begins to be of the greatest importance for the study of multiple galaxies. Indeed two galaxies lying in the same line of sight might be mistaken for a physical double although actually widely separated. If however the objects in question acts as a radio source one can be fairly certain that he deals with a physical double although the apparent radial velocities of the two components may be quite different, as it is the case for NGC 1275, to be discussed later.

Considering all of the new aspects mentioned in the preceding as well as the rapid developments now taking place, it would be clearly premature to attempt a systematic classification and a basic analysis of the properties of multiple galaxies. It will be more satisfactory for the present to retrace the historical development as it was experienced by the writer and to discuss a number of systems which possess particularly characteristic features and for which significant data have been secured. As mentioned before, the whole recent developments were started as an attempt to prove certain phases of astrophysical theory and they led almost immediately to the discovery of certain multiple galaxies whose members are connected by extended luminous intergalactic formations.

## D. Instrumentation

It may appear somewhat surprising that the many thousands of intergalactic luminous formations were not discovered earlier. The reasons for this are treefold. Large reflectors and refractors were mostly built with small focal rations such as F/5 (for instance the 60-inch and 100-inch telescopes on Mount Wilson). Instruments of this sort are little suited for the photography of faint extended surface images. Much progress was therefore made as soon as Schmidt telescopes of large apertures and large focal ratios (F/2) became available. The second reason for possible failure lies in the frequent neglect of the observers to make their telescopes really light tight. How serious the effects of such neglect can be was experienced by the present writer when he attempted to photograph the luminous filaments between IC 3481 and IC 3483. Although these filaments were clearly recorded by the large Schmidts they could not be photographed with the 100-inch reflector until all sources of stray light were eliminated. Surprisingly enough there were about six sources of this kind including light from the night sky hitting parts of the exposed plates directly or by reflection and scattering on various surfaces. Even dust on the mirrors and poor silver or aluminum coats may be fatal. A third phenomenon which must be watched is the night sky glow. This glow, which may considerably change in intensity from night to night, is seldom explored prior to exposing critical plates. Much can be gained by the use of night sky meters measuring the spectral intensity distribution of the general background. In general the sky glow is the least intense in the green between 5100 Å and 5500 Å, in which range the variations from day to day also seem to be the smallest. Unfortunately photographic emulsions are generally quite insensitive in the green. Also, the luminous formation to be photographed may have its maximum surface brightness in another colour range than green, so that up to the present time the problem still remains of how to record luminous intergalactic matter with the optimum conditions of night sky and of instrumentation.

In addition to photography one may attempt photoelectric recording. Along this line the author a few years ago suggested plans to Dr. W. A. Baum and F. E. Roach to determine both the surface brightness and the colours of luminous intergalactic formations between the members of small groups of nebulae and within large clusters. Surprisingly enough results have not been forthcoming as fast as anticipated. On a first attempt Dr. Baum did not succeed to record the photographically very conspicuous filament between the two nebulae shown in Plate IV. With his newer and much more sensitive pickup (*22*) which is supposed to measure surface brightness as faint as the 25th photographic magnitude per square second of arc Dr. Baum in March 1954 has obtained readings on the above mentioned filaments, but has not yet reduced the data. On the other hand, at the meeting of the Astronomical Society of the Pacific in Pasadena of June 1955 he reported observations on distant clusters confirming the writer's photographic results concerning the existence of extended luminous clouds within the large clusters of galaxies (*15*).

In the meantime great progress has been made with the method of composite analytical photography which is particularly suited for enhancing the contrasts of faint objects against the surroundings and which constitutes a unique means for distinguishing between different colours (*21*).

## III. Widely Separated Interconnected Galaxies

### A. The Triple System IC 3481, Anon, IC 3483

These widely separated galaxies which were the first ones to be found interconnected by long luminous filaments of intergalactic matter also turned out to be some of the most remarkable in the sense of presenting astrophysics with some unsuspected and very puzzling problems. Two photographic reprodutions of plates obtained with the 48-inch and the 200-inch telescopes are shown in the Plates I and II. In the Figure 1 drawing is reproduced emphasizing some of the significant details.

Some of the data on the triple system shown on the two plates I and II as well as in the drawing 1 are as follows.

IC 3481, Type $S_0$ peculiar, R. A. $12^h 30^m 21^s$, Decl. $+11° 40'.8$ (Epoch 1950.0). Apparent photographic magnitude $m_p = +15.0$.

Anon = anonymous galaxy, Type $S_{op}$, R. A. $12^h 30^m 26^s$, Decl. $+11° 40'.0$, $m_p = +16.0$

IC 3483, Type $S_c$ peculiar, R. A. $12^h 30^m 38^s$, Decl. $+11° 37'.4$, $m_p = +15.6$.

All three galaxies appear completely unresolved on a series of photographs made with the 200-inch telescope in various colour ranges. From the near equality of their apparent magnitudes and of their angular diameters one would off hand conclude that the two galaxies IC 3481 and IC 3483 are roughly at the same distance. This first evaluation is of course greatly strengthened because of the apparent connection of the two galaxies with the smaller and fainter central nebula by faintly luminous bands of intergalactic matter. The curved connection between IC 3483 and Anon is particulary impressive, since it appears to be an extension of one of the spiral arms of IC 3483 as indicated in the Fig. 1. Also, on close inspection it is seen that the yatagan like formation has filamentary structure and that it is the widest in the middle. The maximum surface brightness of the connecting bridges is presumably of the order of $m_p = +24$ per square second of arc and the colour seems markedly blue.

From the features discussed in the preceding, the writer and his colleagues felt certain that the three galaxies form a physical triple system and that within narrow limits they are located at the same distance. Under these circumstances the results of the spectral studies which Drs. R. Minkowski and M. L. Humason undertook at the request of the writer came as a complete surprise. Dr. Minkowski first in 1952 laid the slit of the prime focus spectrograph of the 100-inch telescope along the connection over the two northern nebulae. Dr. Humason from this spectrogram deduced for both nebulae an apparent symbolic velocity of recession of the order of $V_s = c\Delta\lambda/\lambda = 7250$ km/sec.

It should here be stated that $V_s$ has the dimension of a velocity since $c$ is the speed of light, $\Delta\lambda$ is the measured displacement from their normal position of the characteristic features in the spectrum of a nebula and $\lambda$ is the wave length of these features in their normal unshifted positions. It must be emphasized that $V_s$ is under no circumstance exactly equal to any real velocity. Even if the expansion of the universe were real, $V_s$ would be exactly equal to the relative velocity of recession of a nebula from the observer only when $\Delta\lambda/\lambda$ is very small.

The spectrum of IC 3483 was obtained by Dr. Humason in the spring of 1953 and showed an astoundingly low value of the apparent velocity of recession of the order of $V_s = 100$ km/sec. This completely shocking result made it imperative that all measures be repeated in order to eliminate any possibilities of oversight or gross errors of measurement and of interpretation. Dr. Humason kindly spent considerable time on this problem and arrived at the following result, for the communication of which I am greatly indebted to him. Dr. Humason's final data are as follows.

*IC 3481.* $V_s = 7304$ km/sec. The spectrum shows a strong continuum with the absorption features at the H and K lines and at the G-band normal. There appear to be no conspicuous emission lines.

*Anon.* $V_s = 7278$ km/sec. The continuous spectrum is weak with narrow and weak absorption lines at H and K. The forbidden oxygen line $\lambda$ 3727 is likewise present and also weak and narrow.

*IC 3483.* $V_s = +108$ km/sec. The continuous spectrum is weak, the *H* and *K* lines are normal and the $\lambda$ 3727 emission is strong but spottily distributed, as it is mostly the case in spiral galaxies.

No spectral record of the faint intergalactic links between the three galaxies could be obtained so far. This is most unfortunate since the displacement of the spectral lines along the various parts of the long bridge would give us a clue as to the cause for the low value of $V_s$ of IC 3483. One most important conclusion which can be drawn from the

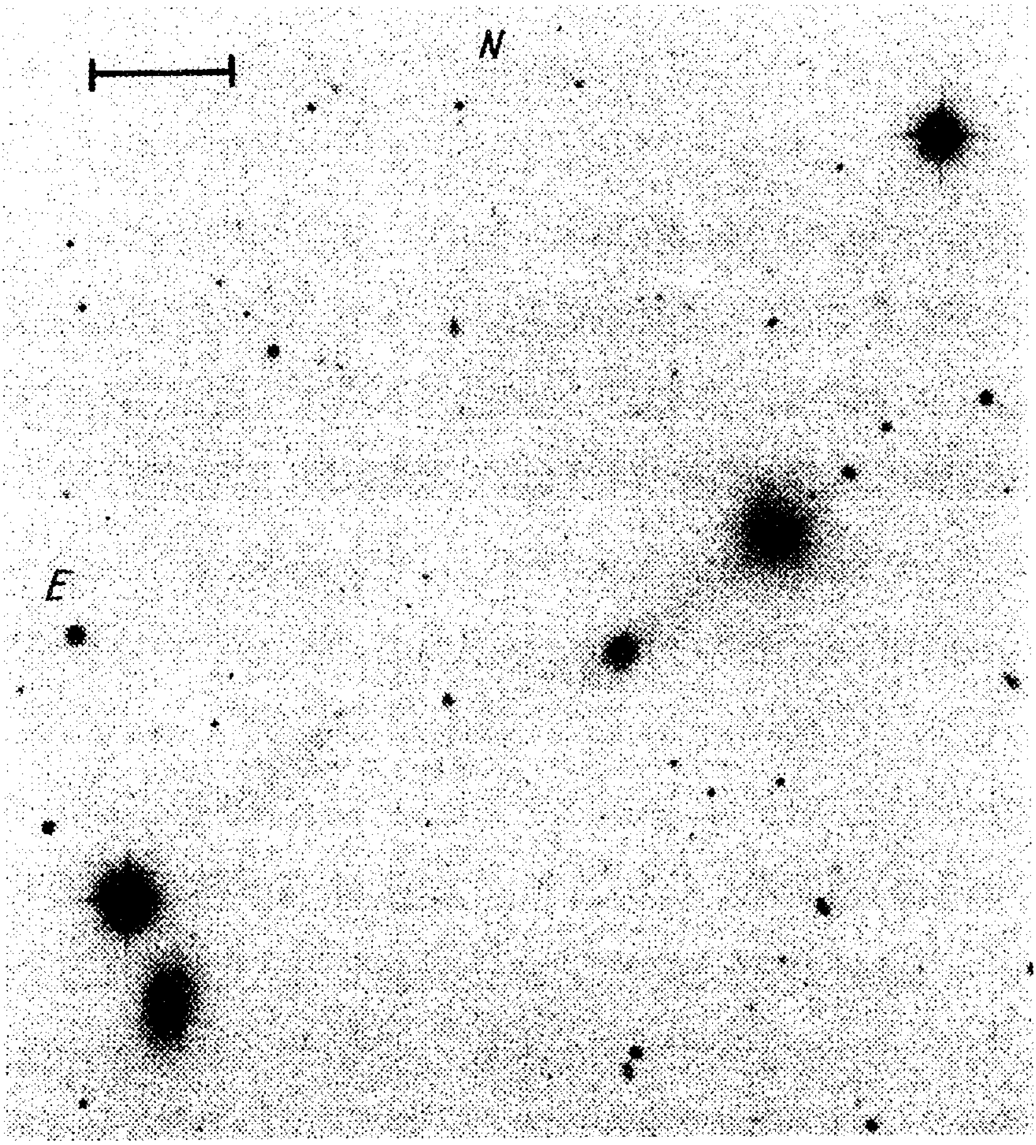


Plate I. Photograph obtained with the 200-inch reflector of the triple galaxy IC 3481, Anon, IC 3483 on an Eastman 103a—0 plate. Scale as indicated on plate equal one minute of arc.

practical unobservability of the spectrum of the bridge is that this intergalactic formation appears luminous because of its stellar content. Indeed, if the observed surface brightness were due in any way to the emission from fluorescent gases, emission lines should be readily observable.

The brightness of IC 3483 was subsequently also determined by Dr. W. E. BAUM. Using a diaphragm 28 sec of arc in diameter he found from his photoelectric measure $m_p = 15.5$ in close agreement with our photographic result. BAUM also obtained $m_{pv}$ (photovisual) $= + 15.0$ corresponding to an international colour index $+ 0.5$. IC 3483 is therefore somewhat redder than the nearer spirals.

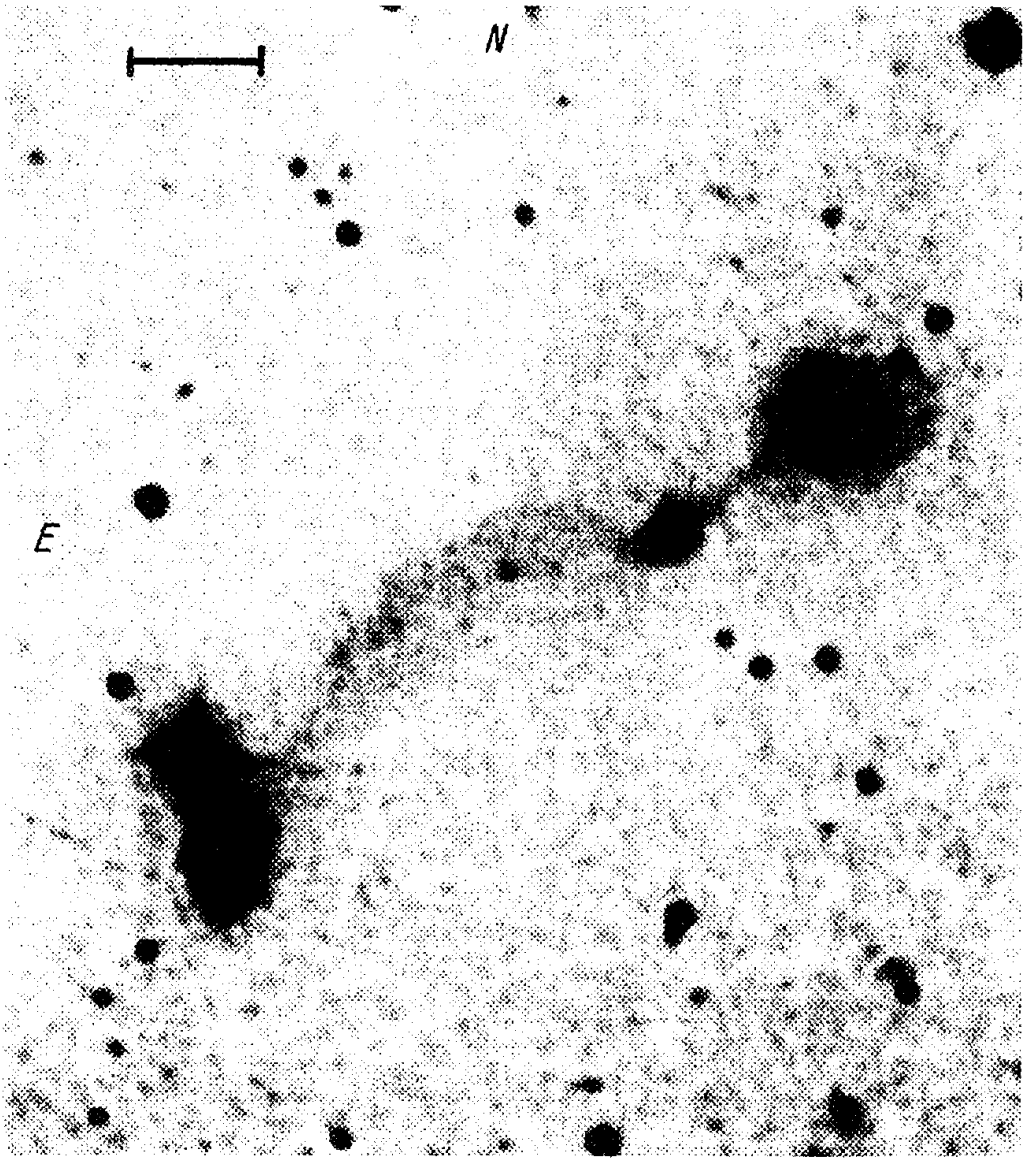


Plate II. Photograph of the triple galaxy IC 3481, Anon, IC 3483 obtained with the 48-inch Schmidt telescope on Eastman 103a—0 blue sensitive emulsion. Scale indicates one minute of arc.

We here mention that whenever we refer in this study to absolute distances these will be given on the old scale corresponding to an average value of the apparent symbolic velocity of recession of $V_s$ equal to 550 km/sec per million parsecs. This scale is certainly wrong. From the newest data it appears that a value of 200 km/sec per million parsecs may be closer to the truth. Until reliable new measures are available we shall use the old scale throughout this article, on the basis of which IC 3481 and Anon will be placed at a distance of 13.2 million parsecs, that is roughly as far away as the Coma cluster of galaxies. Although the spiral IC 3483 from its own appearance and from its connection with the other two nebulae should be located at this same distance, the very low value of $V_s$ introduces some doubts as to the validity of this conclusion. As a matter of fact, as soon as it became known that $V_s$ is equal to 108 km/sec,

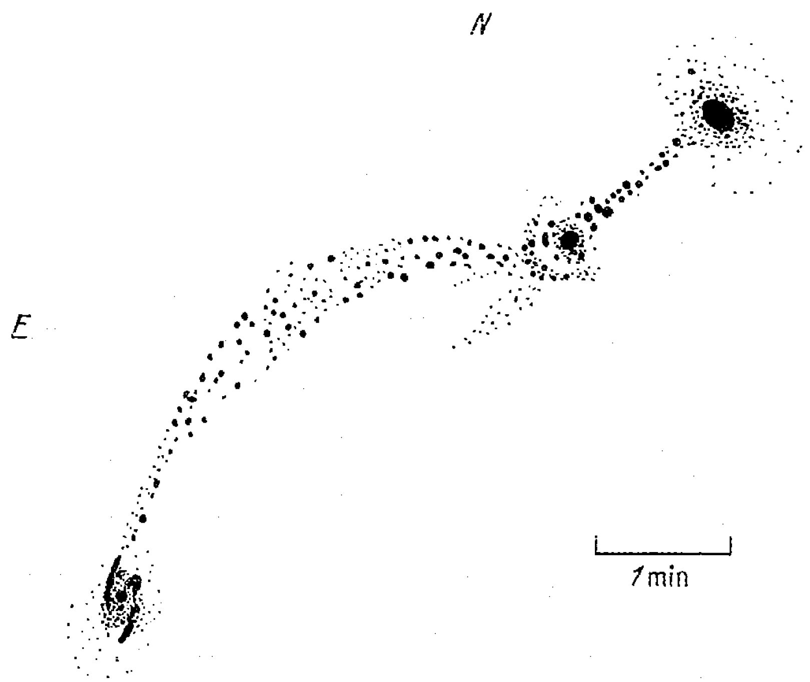


Fig. 1. Drawing of the essential features of the interconnected triple galaxy IC 3481, Anon, IC 3483 as they can be distinguished on a series of good plates taken with the 200-inch reflector and the use of various emulsions behind different colour filters. Scale indicates one minute of arc.

all of the writer's colleagues inclined to the idea that IC 3483 is a foreground nebula. Actually, however, three major possibilities of interpretation remain. These are

1. IC 3483 is a foreground galaxy.

2. IC 3483 is at the same distance as the two other galaxies and its low value of $V_s$ indicates a real radial velocity of about 7000 km/sec relative to the two other members of the triple system.

3. IC 3483 is at the same distance as the two other galaxies, but the large value of $V_s$ between IC 3481 and IC 3483 is caused by some differential effect on the frequency of light quanta travelling cosmic distances. The gravitational drag of light which was discussed by the writer (*23*) long ago as a possibility of explaining the universal redshift of light in a non-expanding universe would in some cases produce large differential shifts in the spectra of little separated galaxies.

In discussing the relative merits of these three interpretations the following considerations may be advanced.

If IC 3483 is a foreground galaxy it most likely belongs to the Virgo cluster which on the old scale lies at an average distance of seven million light years. The values of $V_s$ for all of the members of this cluster lie in the approximate range $-300$ km/sec $< V_s <$ 2500 km/sec. The value $V_s = 108$ km/sec of IC 3481 also lies in this range. If placed at the distance of seven million light years our galaxy would have an absolute photographic magnitude $M_p = -11.0$ and a greatest diameter of the order of 1500 light years. If a member of the Virgo cluster, it therefore follows that IC 3483 is a most unusual dwarf nebula of distinct spiral structure and with a central surface brightness comparable to that of the giant spirals. These conclusions are very uncomfortable when added to the difficulties previously mentioned, which we here reemphasize. Indeed, it is most unlikely that a foreground galaxy should lie at the end point of the yatagan like long extension of the central nebula designated as Anon and that this yatagan should constitute the exact tangential continuation of one of the spiral arms of IC 3483. Also, the colour index $+0.5$ obtained by Baum indicates some reddening as compared with the nearby spirals and therefore greater distance. Finally, if IC 3483 were a foreground nebula, the remaining systems of IC 3481 and Anon would be left as one of the most unusual interconnected galaxies in the sense that among thousands of similar double galaxies not a single one can be found where the "countertide", as we propose to call it, does not constitute the exact tangential continuation of the bridge between the two nebulae in question. It is indeed seen from the plates I and II and from the drawing Fig. 1 that the long extension from Anon which points toward IC 3483 starts out from Anon at a sharp angle relative to the bridge between Anon and IC 3481. This angle on closer analysis can be easily accounted for only if the three nebulae are emerging from a relatively recent triple encounter.

The second possibility of interpretation is that all three galaxies are at the same distance and that the tremendous difference in radial velocities is real. This means that the total velocity of IC 3483 relative to its immediate neighbors is greater than 7200 km/sec, a speed far superior to any known at present for any neighboring bodies with masses comparable to those of regular galaxies. It is of course well known that the velocity dispersion in large clusters may be as high as 2000 km/sec. *(25)*. As the size of a group of galaxies decreases the velocity dispersion decreases likewise and for isolated nebulae it is equal to several hundreds of kilometers per second at the most. Because of these considerations the author originally was inclined to disregard the possibility that a peculiar velocity of the order of 7000 km/sec could be real. Some cogent facts, however, have recently come to light which make the occurrence of very high peculiar velocities more probable or even certain. In the first place there are multiple systems whose members possess relative velocities which are undeniably large compared with the velocities which can be generated by the gravitational interactions of galaxies headed for close encounters or for mutual capture. For instance, in Stephan's Quintet consisting of the galaxies designated as NGC 7317, 7318a, 7318b, 7319 and 7320 the values of $V_s$ for the first four members according to HUMASON are 6736, 6638, 5638 and 6657 km/sec. These nebulae which are inextricably inter-related, and this is particularly true for NGC 7318a and b, have therefore relative peculiar velocities greater than 1100 km/sec. Furthermore a considerable number of galaxies has been observed (*26*) with emission lines in their spectra indicating actual velocities up to 5000 km/sec for internal gas clouds which no doubt constitute a considerable part of the masses of these galaxies. Most significant, however, are the recent combined findings of the radio astronomers and the spectroscopists investigating the nature of the extragalactic radio sources. Perhaps the most important results along this line of attack have been obtained from the observations of NGC 1275, one of the central member galaxies of the rich Perseus cluster. This object is a radio source and on closer inspection by R. MINKOWSKI (*27*) was shown to possess an emission line spectrum due to a close penetrating collision of two galaxies with a relative radial velocity of about 3000 km/sec. Although velocities of this magnitude are rare it does not now seem entirely out of the question that the large difference in the redshift of IC 3481 and IC 3483 might be due to an actual relative motion of the two objects. On this interpretation there nevertheless arises another great difficulty. It is well known from astrophysical theory that two stellar systems devoid of gas and dust passing through each other in the process of a head-on collision hardly disturb each other, unless their relative velocity is very low. Because of the insignificant transfer of momentum and of energy from star to star it is in fact difficult to understand how under any ordinary circumstances stellar systems on close encounters could disrupt each other sufficiently to give rise to the filamentary intergalactic formations of stars shown on the various photographs reproduced in this article. Since the transfer of momentum between stars is inversely proportional to their relative velocity, the physical characteristics related to the internal "viscosity" of the three galaxies of our triple system would have to be of a nature and magnitude quite unknown to us at the present if they had been capable of ejecting the observed stellar intergalactic formations during a close encounter with a relative speed greater than 7000 km/sec.

We add that if the three nebulae just discussed are at a distance of 13.2 million parsecs (HUBBLE's old scale) their absolute photographic magnitudes are $-16.0$, $-15.0$ and $-15.4$ respectively, as one should expect it for objects of this kind. The absolute separation of IC 3481 and IC 3483 in the plane normal to the line of sight would be about 72000 light years and the largest diameters of the two brighter galaxies of the order of 8000 light years.

In view of the fact that there are serious difficulties with both of the interpretations just discussed the third possibility should not be lightly discarded. During the past fifteen years serious difficulties have come to light with respect to the concept of an expanding universe (*14*). If it were found that the universe is not expanding as a whole, the universal redshift will have to be explained on the grounds of long range interaction of light with matter or with other light. It will in this case be quite possible that the redshift is not a function of the distance alone but depends also on the particular constellations of matter surrounding any individual cosmic trajectory of a quantum of light. Relatively large fluctuations in the redshift might occur as a consequence (*28*).

### B. KEENAN's System

Long before the recent development on double galaxies gathered momentum, P. C. KEENAN had noticed the remarkable filament between the peculiar type spiral NGC 5216 and the globular galaxy NGC 5218. His note (*29*) on this system seems to have been overlooked by most of the workers in the field. This fine double galaxy was subsequently "rediscovered" by observers at the Lick and Palomar observatories which resulted in a merry confusion until it was pointed out to us by G. DE VAUCOULEURS, N. U. MAYALL and others that KEENAN fifteen years previously had pointed out its existence. A photograph taken by the author with the 200-inch telescope is reproduced in Plate III.

While there hovers a mass of luminous "debris" around and in between the two galaxies, the most remarkable structures are the concentrated stringlike formation connecting the two stellar systems as well as the fingerlike extension or "countertide" protruding from the globular NGC 5218 and starting on the same tangent as the interconnecting filament, a constellation which as we have mentioned before occurs rather frequently. It is likewise a common feature of many connected double nebulae that only one of them shows a distinct countertide. At my request Dr. N. U. MAYALL at the Lick Observatory this summer photographed the spectrum of KEENAN's system. His preliminary results for whose communication I am indebted to him are as follows.

NGC 5216. $V_s = +2905$ km/sec, as obtained from both absorption and emission lines. Among the latter $\lambda$ 3727 is prominent.

NGC 5218. $V_s = +2883$ km/sec, with no emission lines detectable.

The values of $V_s$ have not been corrected for solar motion. Dr. MAYALL writes further "I see no suggestion on the plate of any nebular emission lines, particularly 3727, in the connecting link. It is possible that a plate taken under better conditions, without having to run to $6^1/_2$ western hour angle, might show something, but I doubt it." Using HUBBLE's old distance scale with an average value of 550 km/sec for $V_s$ per every million parsecs, the distance of KEENAN's system is 17.3 million light years. The separation of the two components follows as about 22000 light years. The photographic apparent magnitude of the spiral galaxy may be estimated as +13.3. With the distance modulus of 28.6 this corresponds to absolute photographic magnitudes $M_p = -15.3$. The globular member is somewhat fainter. No resolution of any kind has so far been detected with the 200-inch telescope a result which is reasonable in view of the fact that KEENAN's system is more than twice as distant as the Virgo cluster. As in all other cases, it will be worthwhile to make further attempts at obtaining spectrograms of the faint luminous

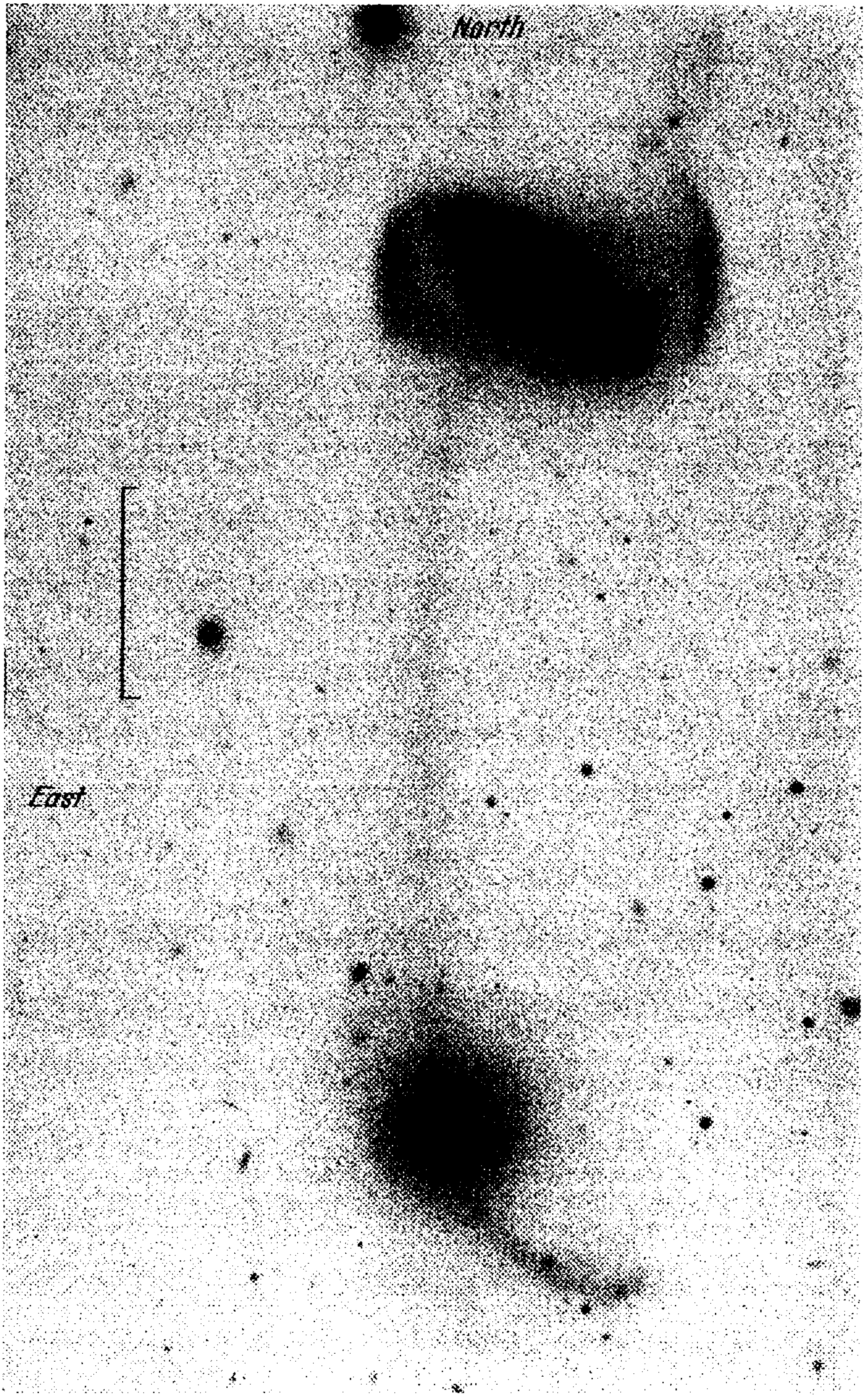


Plate III. Keenan's system, NGC 5216—5218 at R. A. $12^h\ 30^m\ 30^s$ and Decl. $+62°\ 59'$. 200-inch photograph, exposure 30 minutes on blue sensitive Eastman 103a—0 plate. Scale indicates one minute of arc.

intergalactic formations in KEENAN's system. So far it can only be said that these appear blue and show no emission lines, from which fact we conclude that they consist of stars.

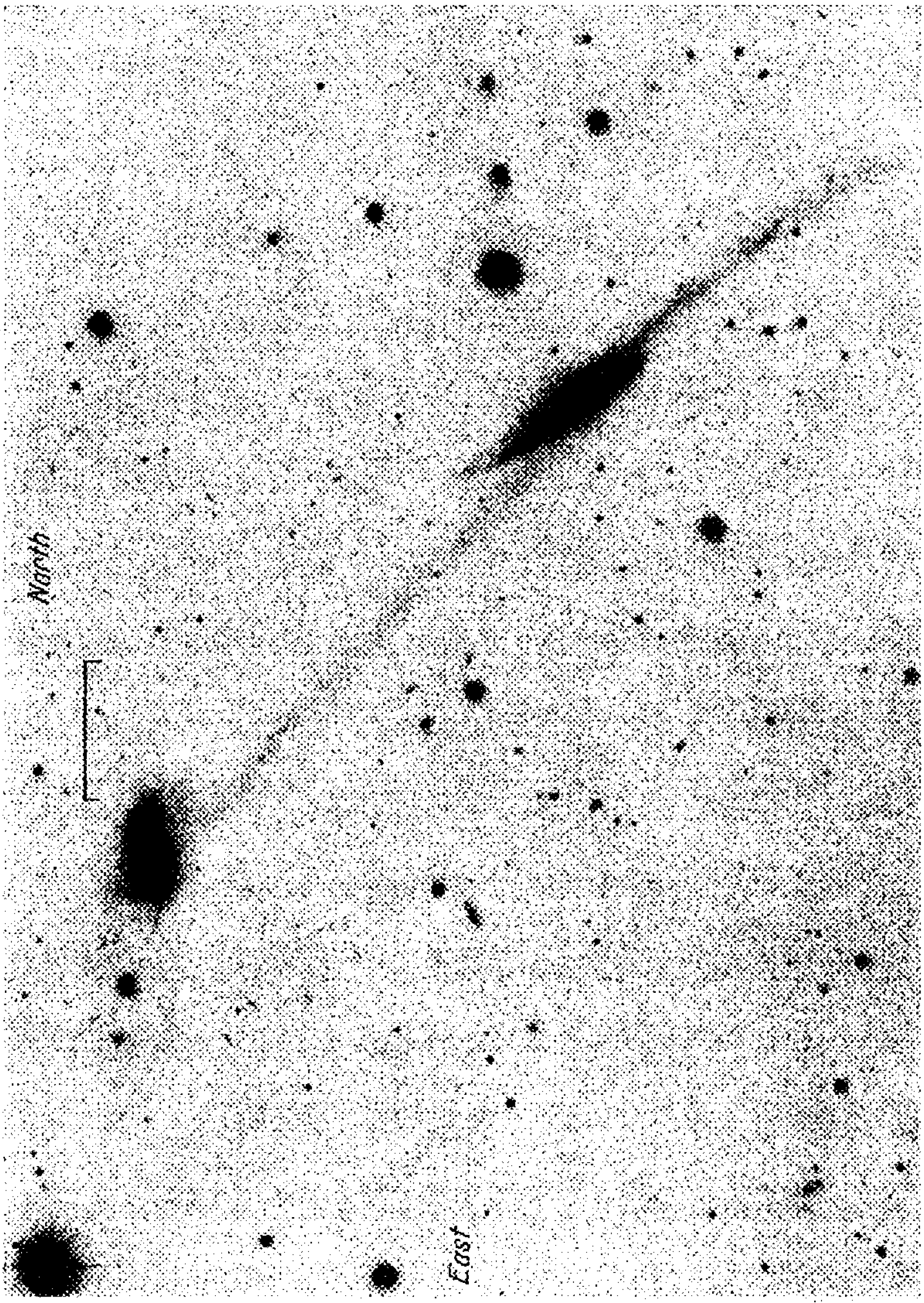


Plate IV. Photograph obtained with the 200-inch telescope on Eastman 103a-O emulsion, exposure time 30 minutes. Coordinates for the center of the system are approximately R. A. $23^h 39^m 16^s$ and Decl. $-3° 49'$ (Epoch, 1950). Scale indicates one minute of arc.

### C. Another Remarkable Filamentary Structure

The interconnected double nebula shown on the Plate IV was discovered by Dr. A. G. WILSON during the sky survey and had also been spotted previously by the author during his systematic search for dwarf galaxies and for intergalactic matter with the 18-inch Schmidt.

The taffy like filament which connects the two galaxies and which on closer inspection of the original appears as the continuation of one of the spiral arms of the southern spiral galaxy is perhaps the most striking example among the intergalactic structures of this type. The "countertide" protruding to the southwest from the southern galaxy seems to be the continuation of its second spiral arm. Lying to the north and west of our system IC 1505 lies at the upper edge of our plate. On original photographs with the 200-inch reflector and with the 48-inch Schmidt it has sometime appeared to the author as if the north following spiral were connected by a wide veil like structure with IC 1505. This observation, however, is so far a mere conjecture.

Dr. HUMASON kindly observed the spectra of the two spirals of our double galaxy with the prime focus spectrograph of the 200-inch telescope (dispersion 370 Å/mm). The results which he obtained are as follows.

Northern Nebula. $V_s = 7016$ km/sec. Rather unexpectedly this galaxy shows pronounced emission lines in its spectrum including $H_\alpha$, $H_\beta$, $H_\gamma$ and strong $\lambda$ 3727.

Southern Nebula. $V_s = 6777$ km/sec. and surprisingly enough, a very washed out spectrum with no trace of any emission lines.

On the old scale the distance of our double galaxy is about 45 million light years and the length of the whole formation projected unto a plane normal to the line of sight is 125000 light years.

A most interesting structural feature is to be found in the geometry of the obscuring regions which, like the bands on some snakes, encircle the southern nebulae crosswise. These bands running at right angles to the axis of the whole formation are suggestive of dust clouds that are being whirled around the nebula in a fashion analogous to the peripheral columnar vortices which are generated in a gas between two rotating cylinders (*30*).

### D. WILD's Triple Galaxy

This system was found by my assistant Mr. P. WILD (*31*) with the 18-inch Schmidt telescope on Palomar Mountain and was subsequently investigated with the 48-inch Schmidt and the 100-inch and 200-inch reflectors. A photograph of these remarkable three nebulae which bear no NGC or IC designation is shown on Plate V.

The two southern preceding objects are the most remarkably similar spirals with a very symmetrically located intergalactic filament and equally symmetrical second spiral arms or countertides. The third most northern component is a barred spiral which is connected with the central spiral by a luminous intergalactic bridge describing a loop on its way from one nebula to the other. The apparent magnitudes given in the following were determined by WILD from films obtained with the 18-inch Schmidt telescope by the "Schraffiermethode". Dr. HUMASON again was kind enough to analyse the spectra of the three galaxies. The data obtained so far are as follows.

*First Spiral.* R. A. $11^h\ 44^m\ 02^s$ and Decl. $-3°\ 34'\ 54''$; apparent photographic magnitude $m_p = +14.5$. Symbolic apparent velocity of recession $V_s = 5108$ km./sec.

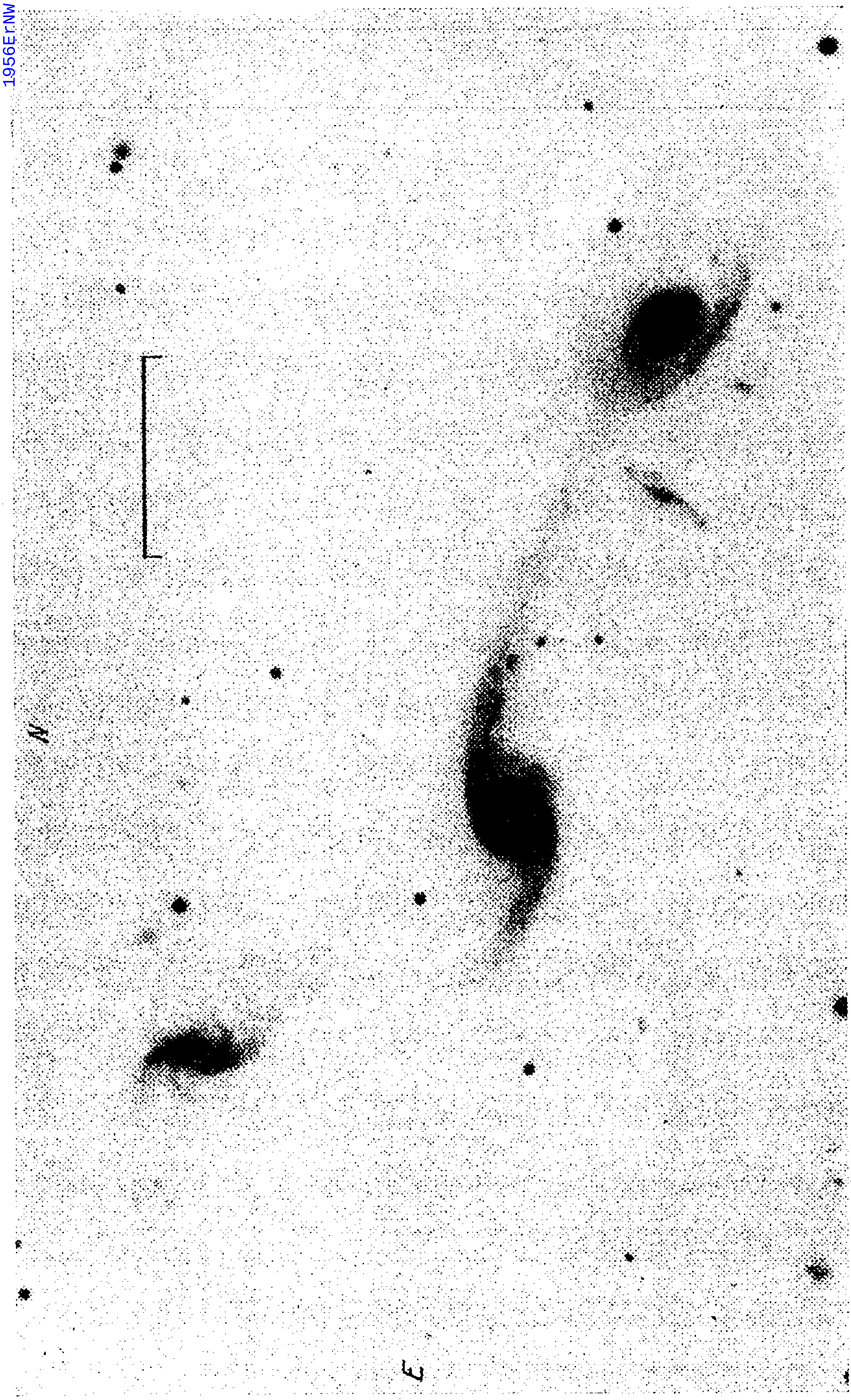


Plate V. Photograph of WILD's triple system obtained with the 200-inch telescope on Eastman 103a—0. Scale = 1′ arc.

*Second Spiral.* R. A. $11^h 44^m 12^s$ and Decl. $-3° 34' 12''$; $m_p = +14.1$; $V_s = 4973$ km./sec. and 5180 km./sec. as determined for two different gaseous emission patches.

*Barred Spiral.* R. A. $11^h 44^m 16^s$ and Decl. $-3° 32' 42''$; $m_p = +15.0$; $V_s = 5224$ km./sec.

Generally it may be stated that all three galaxies show emission lines with $\lambda$ 3727 the strongest and considerably weaker $H_\beta$ and $H\delta$. $H\gamma$ is visible only in the spectrum of the central brightest nebula. The continuous spectra are strong in all cases and extending well into the violet. There is no trace of any absorption lines except in the faintest member, the barred spiral, in which the H and K absorption lines show up very weakly. The differences in the velocities of various emission patches within the same nebula indicate fairly violent internal motions. Using HUBBLE's old scale based on the redshifts the distance of the group is about 9.6 megaparsecs and the whole formation in the plane normal to the line of sight is 50000 light years long. At the distance indicated the absolute photographic magnitudes of the three galaxies are $-15.8$, $-15.4$ and $-15.0$.

## E. The Basic Types of Structures

In the cases observed so far, clouds and patches of luminous matter seem to be strewn about all of the widely separated interconnected galaxies. The actual connections themselves may be of three types, namely

*a*. The connecting bridge or filament is directly related to some distinct structural feature of the galaxies themselves. For instance the filaments may be the extensions of the spiral arms as it is the case with some of the structures shown on the Plates I, II and IV.

*b*. There occur distinct filaments which do not show any direct relation to the structural features of the galaxies. We shall see later on that such an absence of visible relation may have come about because of the rotation of the galaxies having destroyed any which might have existed previously.

*c*. There are no very distinct filaments at all, but all of the member galaxies of a group may be imbedded in a large luminous cloud. Formations of this type are very frequent, but they are difficult to reproduce photographically. A photograph and drawing of one of these groups are shown in Plate VI and Fig 2.

## F. Some Conclusions

From the inspection of widely separated interconnected galaxies we may formulate the following preliminary conclusions.

1. The interconnected galaxies are of all possible types including normal spirals, barred spirals, globular, elliptical and irregular systems. Any of these types may appear tied to a stellar system of the same structural type or to any of the other types.

2. Galaxies with conspicuous extended intergalactic connections seem to be generally absolutely bright or very bright.

3. Speculations as to the mode of formation of interconnected galaxies may follow two lines. A group may have been formed as a whole from a cloud of primordial gas and dust or it may be the result of a

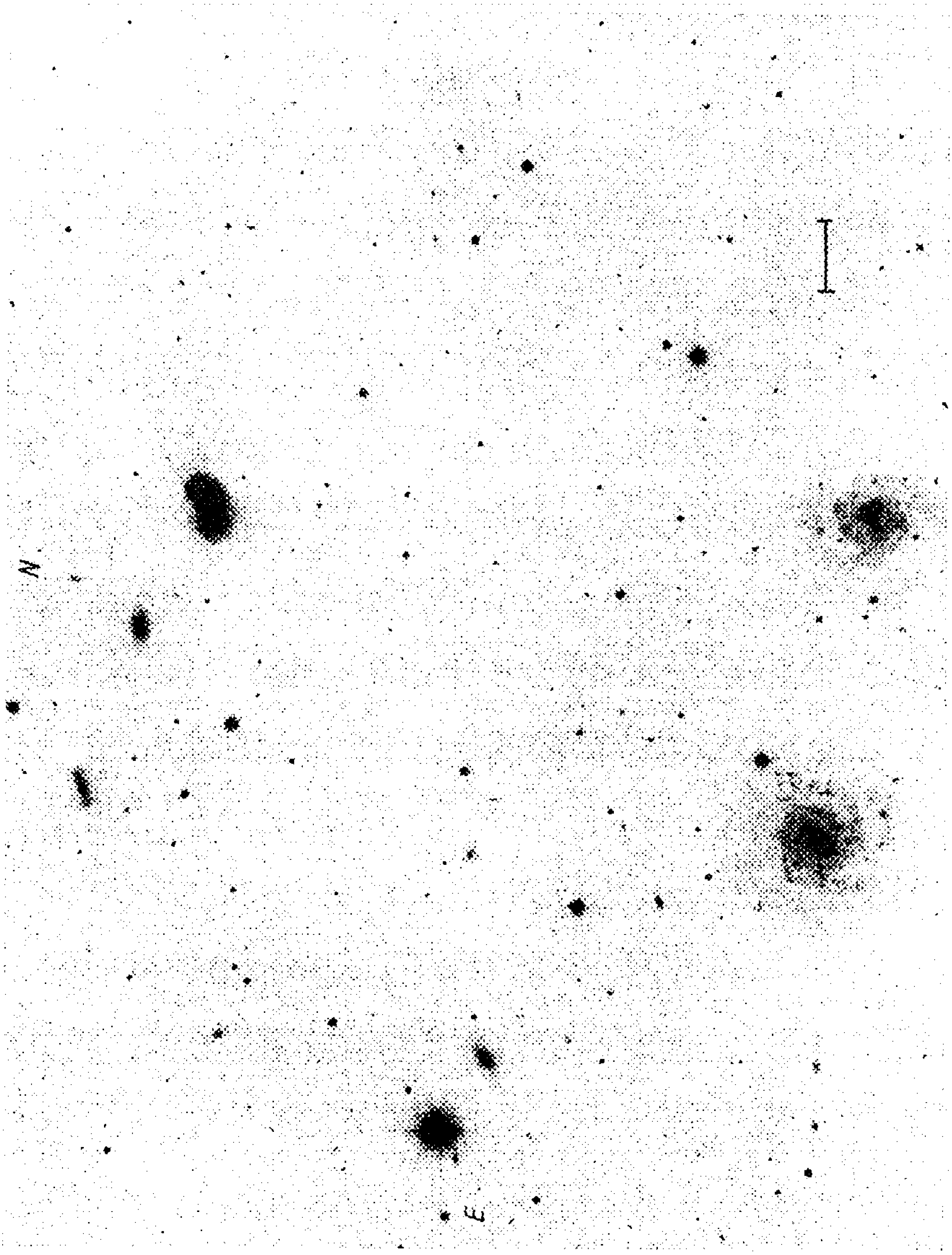


Plate VI. 200-inch telescope photograph of a group of galaxies located at R. A. $12^h\ 24^m\ 11^s$; Decl. $+9°\ 16'\ 50''$. Scale = 1′ arc.

close encounter of galaxies already possessing their normal complements of stars, gases and dust. The structural appearance of the various formations shown in the Plates of this article speaks for the assumption that we here deal with the results of collisions of galaxies. This conclusion is supported by the observation that some of the relative differential radial velocities are so large that the member galaxies of some of our multiple systems are in the process of escaping from one another. As more spectra

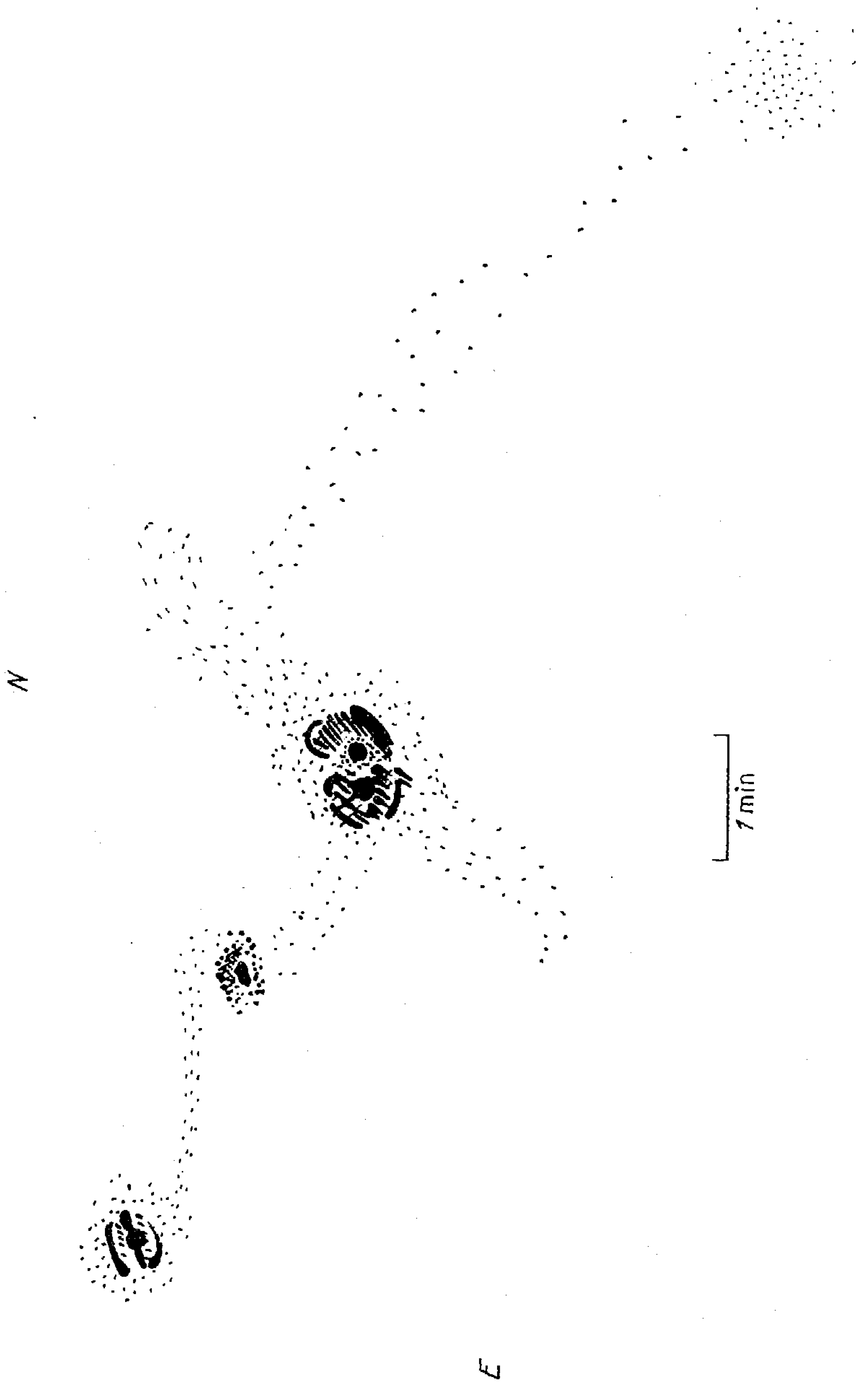


Fig. 2. Drawing of the group of galaxies shown in Plate VI. Perhaps five or six galaxies are interrelated by a complicated cloudy and filamentary structure of luminous matter. Notice in particular the large dwarf galaxy of very faint surface brightness. Scale = 1′ arc.

will be observed in the near future a final decision on this issue should soon be reached. It should be added that with the separations and the relative velocities observed the formations which we have discussed are ten to hundred million years old in order of magnitude.

4. From the structural features of the distribution of matter between widely separated galaxies as well as from the observed kinematic characteristics it is seen that as a result of encounters of galaxies matter is ejected into intergalactic space. Such encounters therefore constitute a direct source of supply for intergalactic matter, in the sense that this matter is not directly related to any specific stellar system but may exist freely until it is eventually swept up by galaxies passing through it. Also because of the observed violent disruptions of galaxies during close encounters dwarf stellar systems can be formed as it was suggested by the writer long ago (*9, 13*). Systems of this type, as they appear on the Plates VI and VIII and in Fig. 5 have in the meantime been found in great numbers in our extragalactic neighborhood. As a consequence of these discoveries drastic revisions had to be made with respect to the shape of the luminosity function of galaxies which according to the original investigators (*2*) had a maximum at an absolute photographic magnitude $M_p = -14.2$ but which from theory was predicted to increase monotonely with decreasing absolute brightness (*13*). As more and more data are being accumulated a luminosity function as it was foreseen by the theory has been emerging ever more distinctly (*14, 16*).

As a far reaching result from the new discoveries on intergalactic formations the former estimates for the average density of matter had to be revised and it now seems most likely that density is at least of the order of $10^{-26}$ grams/cm³. if HUBBLE's old scale for the distances is used.

5. If the luminous filaments and bridges shown in the various Plates of this study are actually ejected during close encounters of galaxies, the "internal viscosity" of these galaxies must be considerably greater than is commonly assumed. Actually, through a quantitative study of oscillatory characteristics of stellar systems as well as of the dynamic interplay of gas and dust clouds with the stars imbedded in them, it can be shown that galaxies encountering each other will lead to the ejection of stars and of dispersed matter into intergalactic space. The occurrence of the taffy like filaments, however, still remains a puzzle which may be related to the still more general problem of the formation of almost stringlike spiral arms in many galaxies.

6. On collision of mechanical systems, internal oscillations within the various components are more readily excited than rotational motion. Indeed, in a head-on collision no moment of momentum is transmitted or generated, while oscillatory motions of more or less great amplitude are always set up. Strangely enough the analysts of the spectra of galaxies and of systems of galaxies have almost exclusively occupied themselves with the translational and rotational properties of nebulae. Oscillatory modes of motions of galaxies are virtually never mentioned in the astronomical literature. From the appearance of the interconnected multiple nebulae shown in this study it is nevertheless certain that oscillations within stellar systems must play a great role since it is obvious that

along the filaments and bridges shown there exist differential motions directed essentially radially to or from the centers of the member galaxies involved.

## IV. Long Extensions and Spurs of Single and of Multiple Galaxies

### A. NGC 4038—4039

One of the best known and most striking formations with very long luminous and filamentary extensions is seen in the double system


Fig. 3. Schematic drawing of NGC 4038—4039 with features as they are discernible on plates taken with the 48-inch Schmidt telescope and the 100-inch reflector. No plates have as yet been obtained with the 200-inch telescope.

NGC 4038—4039, a schematic drawing of which is shown in Fig. 3. NGC 4038 is located at R. A. $11^h\ 59^m\ 18^s$ and Decl. $-18^\circ\ 35'$ (Epoch 1950. 0).

According to HUMASON the apparent symbolic velocity of recession of this system is $V_s = 1673$ km./sec. and its distance (on the old scale) may therefore be estimated at three megaparsecs or ten million light years.

The apparent photographic magnitude is about $m_p = +11.0$ and the absolute magnitude $M_p = -16.4$, if the mentioned distance is used. As expected, the spectrum of the system shows emission lines. It will be of the greatest interest to investigate both the structure of NGC 4038 and its kinematic properties with the 200-inch reflector and to obtain if possible spectra of the long extensions the total length of which from tip to tip is equal to 80000 light years, as projected on the plane normal to the line of sight. NGC 4038 is a weak radio source and therefore probably a system of two galaxies in the process of a close collision.

### B. NGC 750—751

A photographic reproduction of this system, which is located at R. A. $1^h\,54^m\,36^s$ and Decl. $+32°\,58'$, is shown in the Plates VII a, b. The general distribution of luminosity in and around the double galaxy is indicated by the shaded and dotted areas of Fig. 4.

Originally this system was known to be simply a connected dumbell nebula, as shown in Plate VIIa. The author discovered recently that a long spur from the northern component galaxy points toward the north and curves slightly to the west. This spur terminates near a faint spiral which probably, but not certainly, is a distant background galaxy. Spectral observations of this spiral are planned to decide whether or not it is related to NGC 750—751.

Dr. HUMASON has observed the spectra of our two interconnected globular galaxies. These spectra show only continuum with absorption lines, but no discernible emission lines. The values of $V_s$ for NGC 750 and 751 are respectively equal to 5130 and 5126 km/sec. Using Hubble's scale, the distance of the system is estimated to be 9.7 megaparsecs. Since the apparent photographic magnitude of one of the component galaxies is about $m_p = +13$ its absolute photographic magnitude is of the order of $M_p = -17.0$. Using the mentioned distance, the spur may be about 40000 light years long as projected on a plane normal to the line of sight. On the same scale the diameters of the globular galaxies themselves would only be of the order of 6000 light years. This means that the radiation per unit volume emerging from the central parts of these stellar systems must be very high indeed in order to account for an absolute magnitude $M_p = -17.0$ (or $M_p = -19$ to $-20$ on one of the more probable new distance scales).

Dumbell double galaxies are actually very frequent. The two central members of the Corona Borealis cluster at R. A. $15^h\,20^m\,2^s$ and Decl. $+27°\,54'$ (1950) form one of the most beautiful systems of this type. A second dumbell nebula is found on the outskirts of the same cluster.

### C. A System in Leo

On Plate VIII two brighter and several fainter galaxies are shown which are presumably in the state of a mutual encounter. From the structural features of this group and from the jetlike extensions as well as from the enveloping clouds it appears likely that some of the matter ejected during the collision will eventually find its way into intergalactic space where it cannot any more be assigned to any specific galaxy.

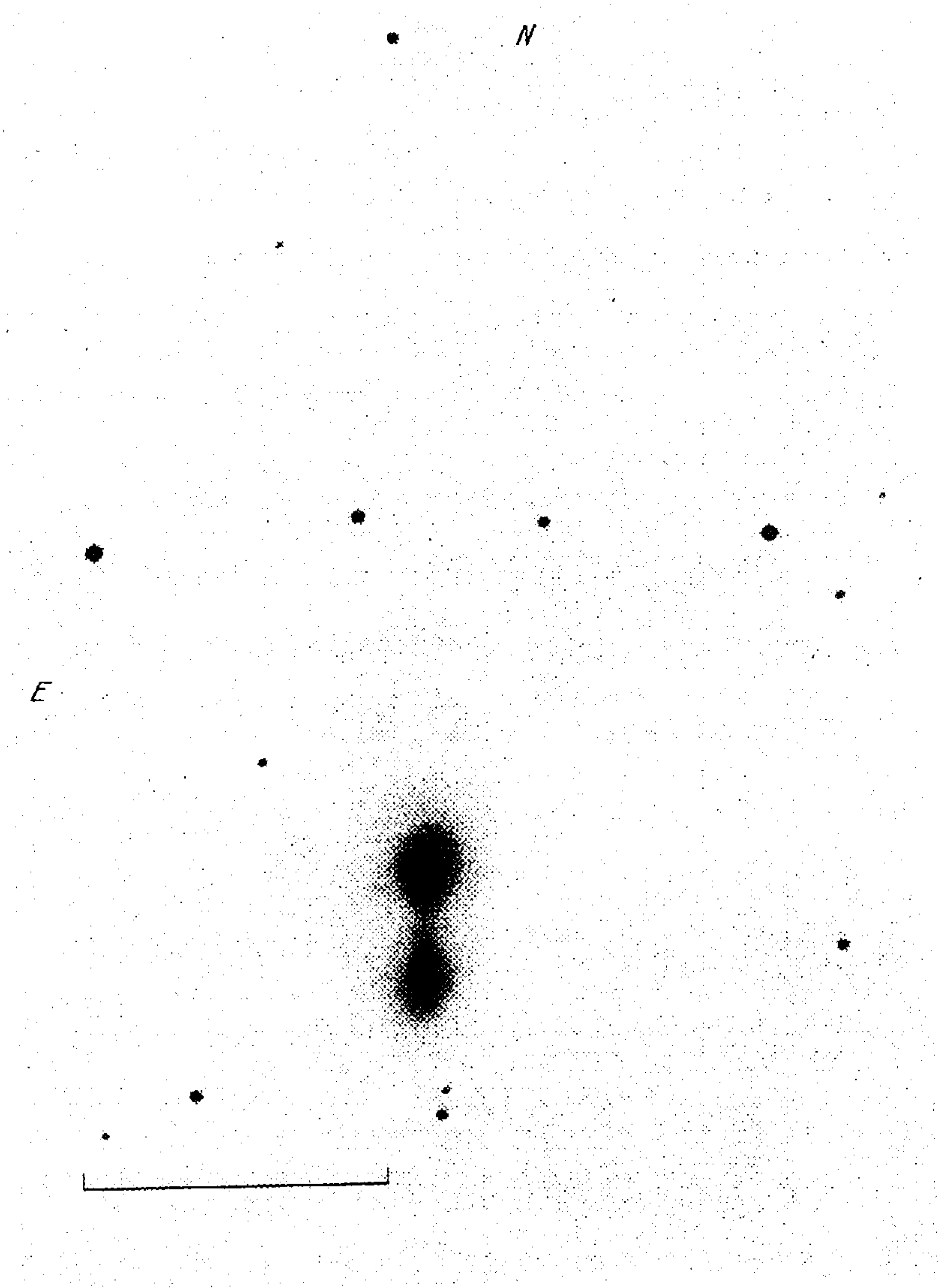


Plate VII a.

The group shown belongs to a fairly large and medium compact cluster of galaxies for which unfortunately no values of $V_s$ have been determined.

### D. NGC 4651 and Dwarf Companion

In Fig. 5 some of the essential structural features of the spiral galaxy NGC 4651 are depicted. The drawing shows in particular an extremely

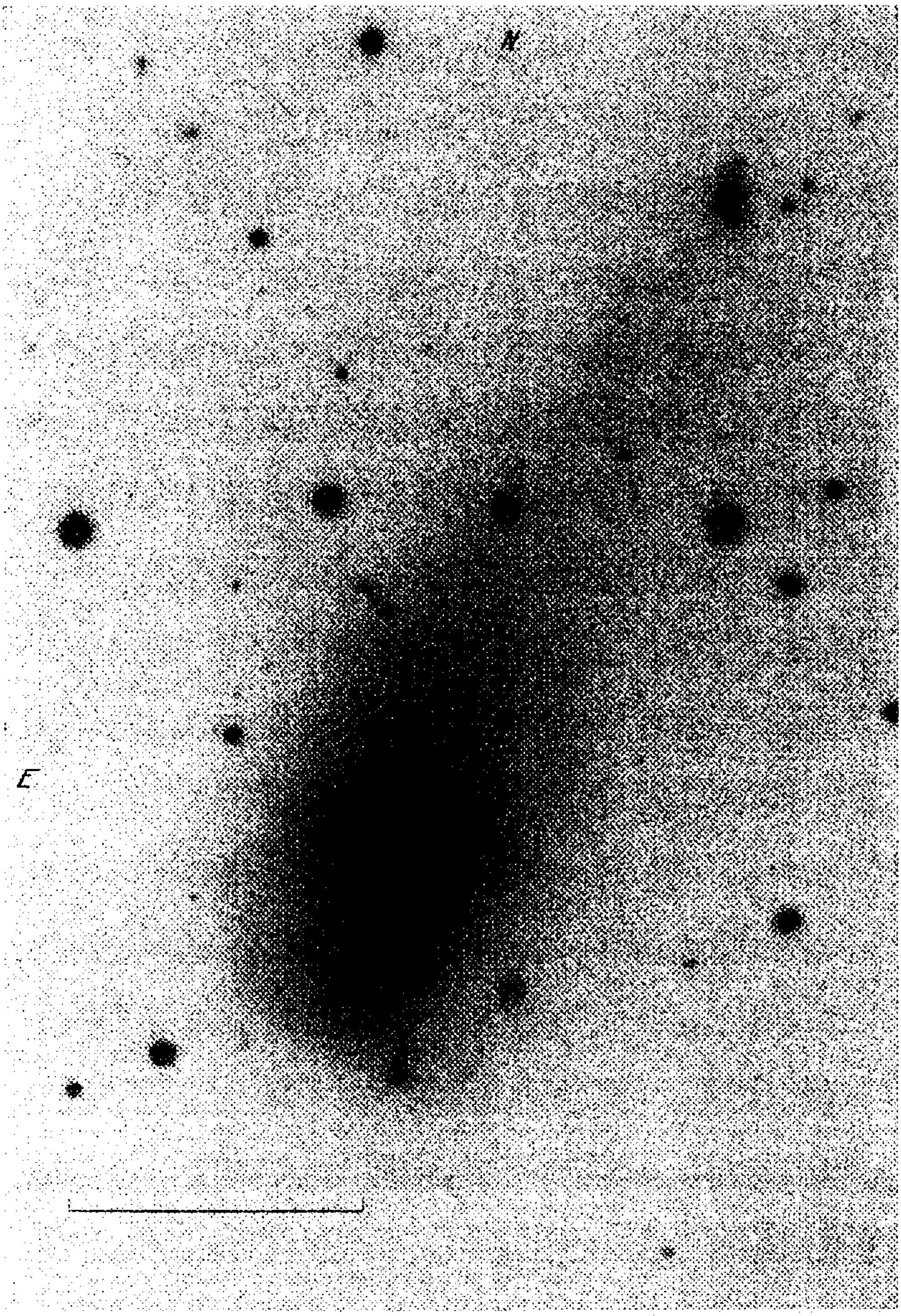


Plate VII b.

Plate VIIa, b. NGC 750—751. Reproduction of a photographic plate obtained with the 200-inch telescope, using Eastman 103a—0 blue sensitive emulsion. Scales = 1′ arc.

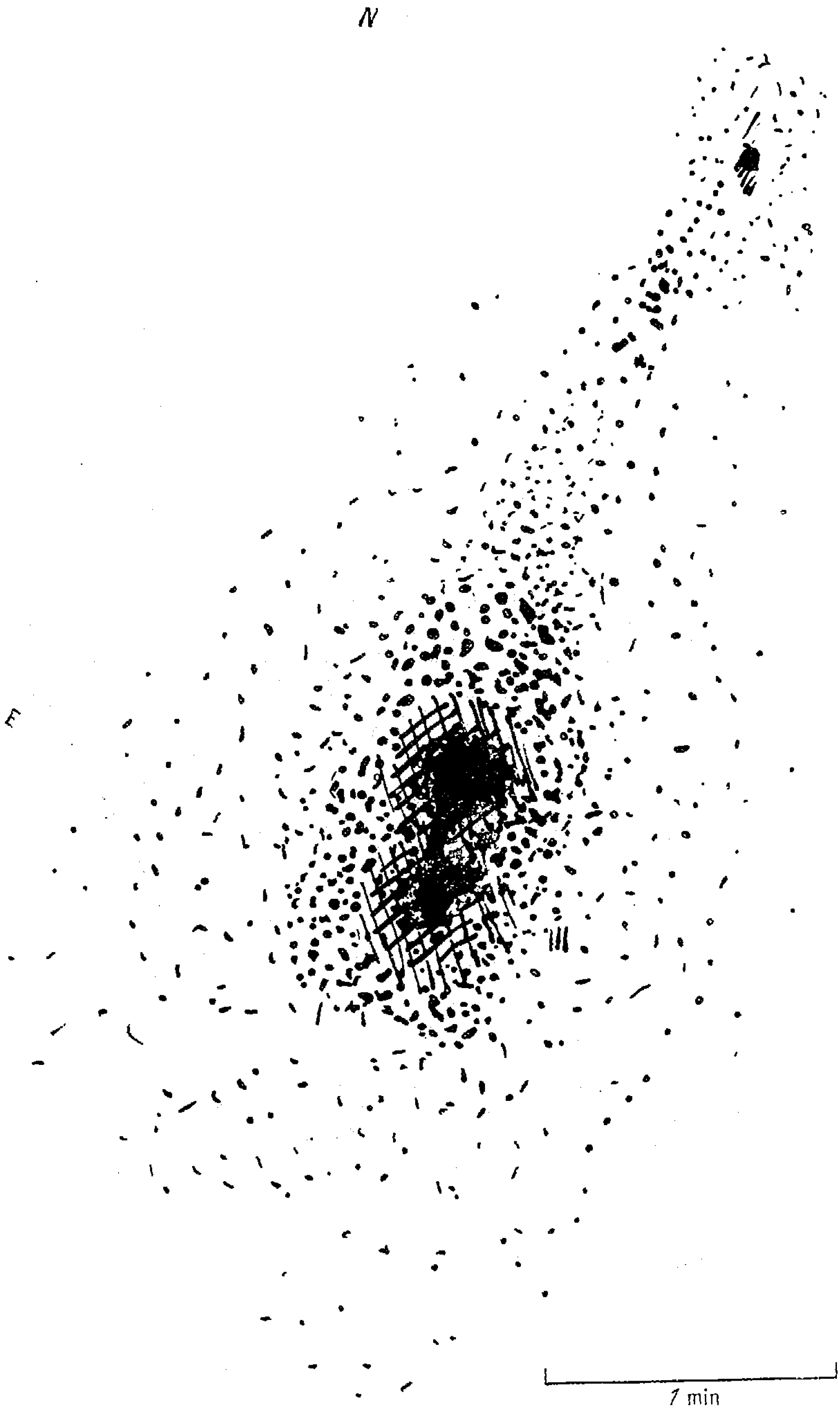


Fig. 4. Distribution of the luminosity in and around NGC 750—751. Scale = 1′ arc.

faint spur with a luminous blob at its end. While the spiral itself has an apparent photographic magnitude $m_p = +11.8$ the magnitude of the blob may be $+20$ or fainter. This means that the blob is a dwarf galaxy

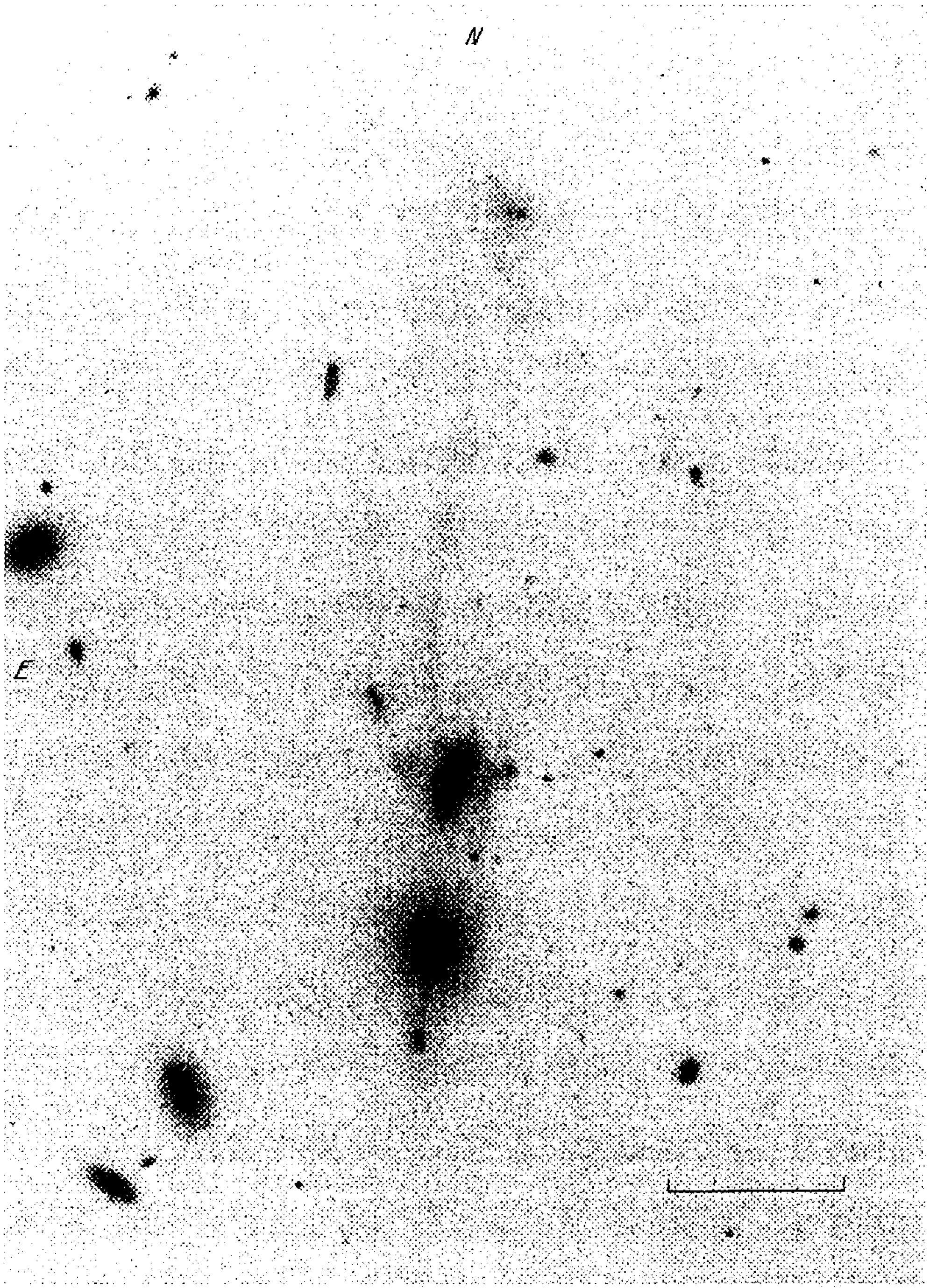


Plate VIII. 200-inch telescope photograph of a colliding group of galaxies located at R.A. $11^h\ 8^m\ 5^s$ and Decl. $+29^\circ\ 2'\ 24''$. Emulsion Eastman 103a—0. Exposure time 30 minutes. Scale = 1′ arc.

of the absolute magnitude $-10$ or fainter (on the old distance scale) and therefore similar to one of the many dwarf stellar systems of very low surface brightness which have been discovered in our immediate extragalactic neighborhood during the past ten years. No values for $V_s$ are available at the present time.

## E. NGC 3628 and Faint Extensions

On close inspection of plates taken with the 48-inch Schmidt telescope and with the 200-inch reflector it is found that very many faint extensions and faint companions of the brighter galaxies have been missed by the early investigators. As one more example of this type we sketch in the Fig. 6 some of the structural features of NGC 3628 and its very faint companion as they appear on the best plates taken with the 48-inch Schmidt telescope on very dark nights.

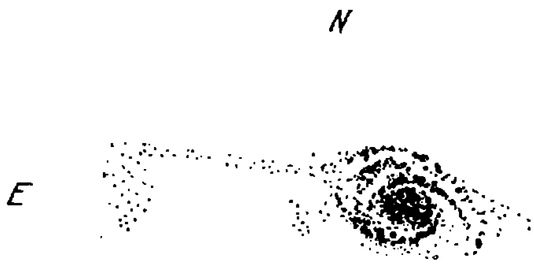


Fig. 5. Drawing of some of the structural features of NGC 4651 and of its faint companion as they can be recognized on good photographs taken with the 200-inch telescope. Coordinates, R. A. $12^h\ 41^m\ 21^s$, Decl. $+16°\ 41'\ 40''$ (1950).

As another striking example of a multiple galaxy with very faint interconnections and still fainter outlying matter we refer to the case of Messier 51 some of whose significant structural features have been described elsewhere (*15, 21*).

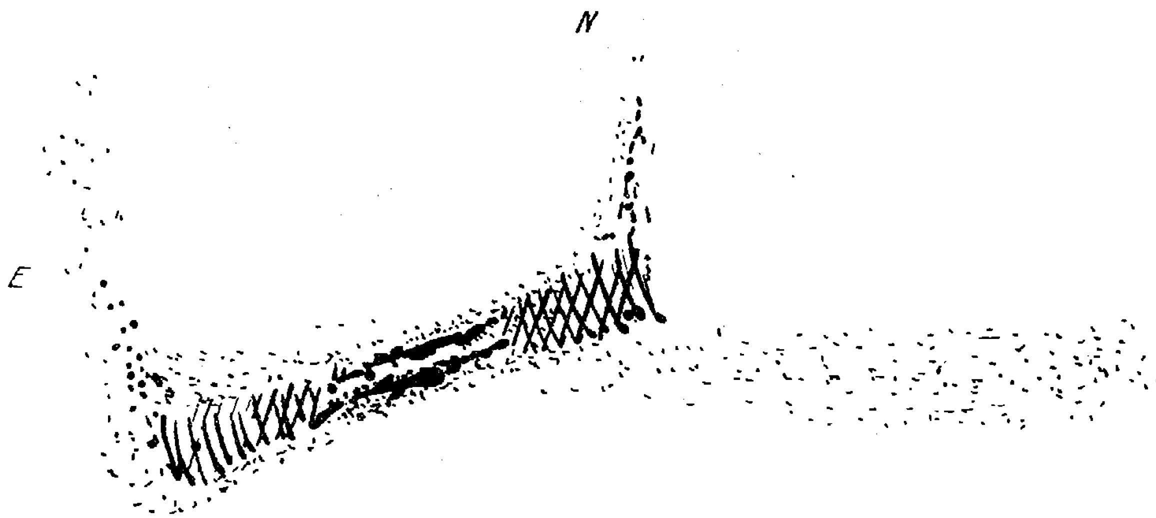


Fig. 6. Sketch of NGC 3628 and of its very faint companion. R. A. $11^h\ 17^m\ 42^s$; Decl. $+13°\ 53'$. $V_s = 842$ km/sec (Value from Dr. N. U. MAYALL; uncorrected for solar motion). $m_p = +11.3$.

## F. Spiral Galaxy with One Long Arm

The system shown on Plate IX obviously has suffered some encounter with other galaxies which, however, cannot be located with certainty at the present time. An exploration of both direct photographs and of the velocity field around the spiral shown will be necessary to retrace the events which have resulted in the long extension of the spiral arm shown on the Plate IX.

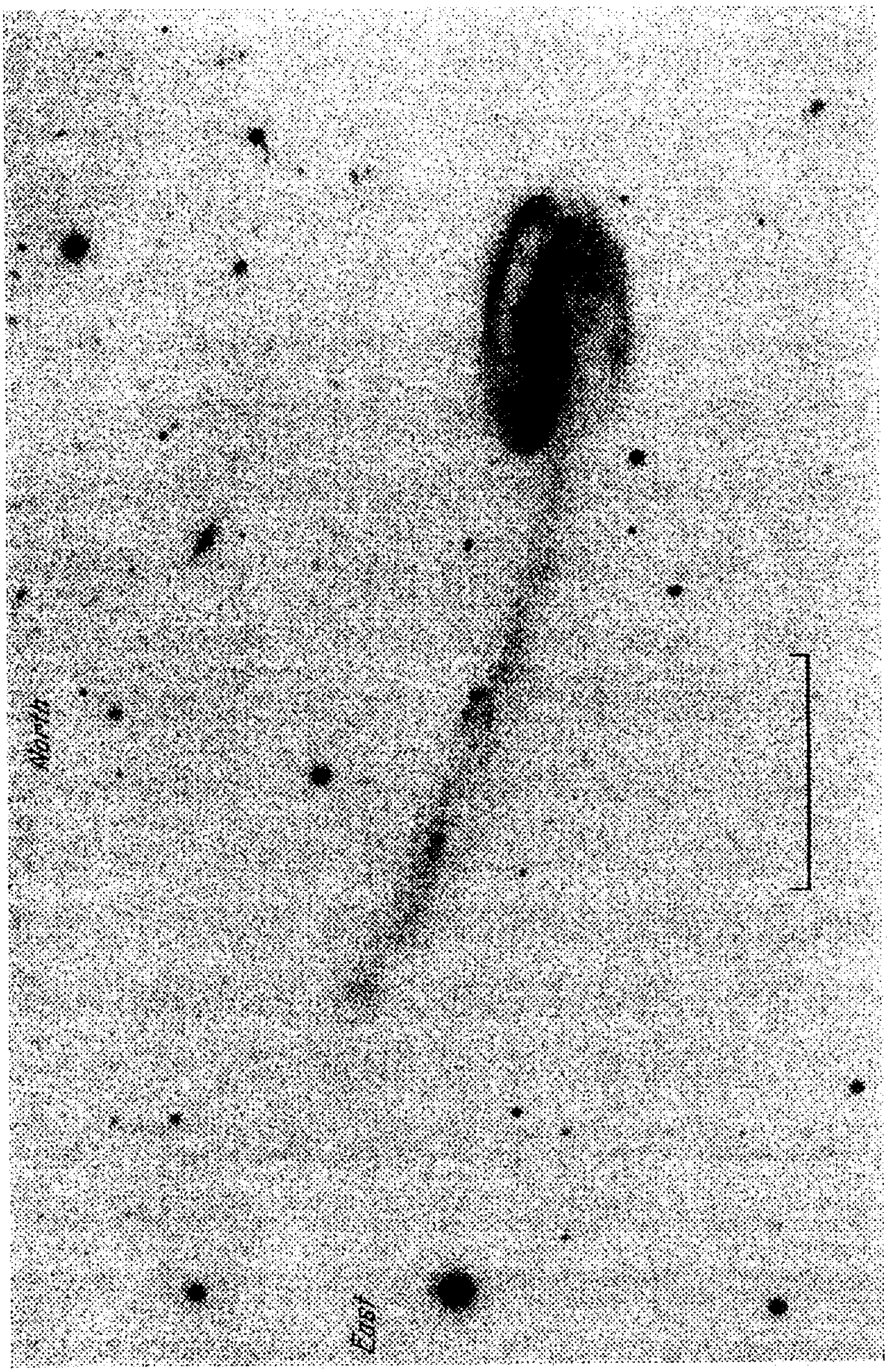


Plate IX. 200-inch telescope photograph on Eastman 103a—0 emulsion of peculiar spiral galaxy at R. A. $16^h\ 4^m\ 35^s$ and Decl. $+55°\ 39'$ (1950). Scale = 1′ arc.

# V. Some Special Problems

## A. The Milky Way System and the Magellanic Clouds

On his visit here in 1952, I discussed some of the problems related to interconnected multiple galaxies with Professor K. LUNDMARK who called my attention to various aspects of the past work in this field. Dr. LUNDMARK suggested in particular that I study the observations which Sir J. F. W. HERSCHEL had made during his stay from 1834 until 1838 in South Africa concerning a possible connection between the Milky Way and the Large Magellanic Cloud. HERSCHEL makes the following significant statement (*32*). —

"Entirely without telescopic aid, when seated at a table in the open air, in the absence of the moon" HERSCHEL scanned the southern skies from a South African Observatory at the Cape of Good Hope and found that no branch of the Milky Way whatsoever forms "any certain and conspicuous junction with the Nubecula Major; though on very clear nights I have sometimes fancied a feeble extension of the nearer portion of the Milky Way in Argo (where it is not above 15° or 20° distinct) in the direction of the nubecula".

The problem of the existence of a possible intergalactic bridge between our own galaxy and the Large Magellanic Cloud was apparently later on forgotten and only revitalized recently after an interval of 120 years. In view of the fact that thousands of faint luminous formations between many neighboring galaxies had been found during the past decade it seemed to me that a reexamination of the surroundings of the Milky Way would be definitely worthwhile. I consequently contacted Dr. R. v. d. R. WOOLLEY, Director of the Observatory at Mount Stromlo as well as Dr. B. Y. MILLS and suggested to them that visual, photographic and photoelectric explorations of the regions between the Milky Way and the Magellanic Clouds should be undertaken to check up on HERSHEL's original attempts. I also felt that in some instances the methods of radio astronomy applying both to the general radiation and the 21 cm waves might give more clean cut results, especially in those regions of the sky where dense formations of foreground stars mar the appearance of faint clouds in the background. All of these suggestions were kindly acted upon and significant preliminary results have been obtained by Dr. G. DE VAUCOULEURS as well as by the Australian radio astronomers. Without going at the present time into any details a few of the aspects of the problem may here be discussed as they were kindly transmitted to the writer by Dr. DE VAUCOULEURS on his visit to Pasadena in August 1955. Some of these aspects are as follows.

Although several indications have been found, the existence of the suspected bridge between the Milky Way and the Large Magellanic Cloud is as yet unproven. On the other hand a long filament-like extension was found by DE VAUCOULEURS to emerge from the Large Cloud on the side opposite to the Milky Way. This filament which is similar to the countertides shown in the Plates III, IV and V seems to be of blue colour. It is entirely unresolved on photographs which reach stars of the apparent photographic magnitude + 17.0 or the absolute magnitude − 1 to − 2. There is no indication that this long spur is a particularly strong emitter of the $H_\alpha$ line or of the 21 cm wave and of the general radio emission (at for instance 3.5 m wave length). The existence of this spur, if it can be interpreted as some sort of a countertide, would of course indicate that a direct tidal connection between the Milky Way and the Large Cloud is also probable.

As far as the space between the Large and the Small Cloud is concerned there exists a spur of the latter pointing toward the former. This spur is well resolved and shows super-giant stars perhaps as bright as $M_p = -7$. It is also relatively strong emitter of the 21 cm wave. According to the information transmitted to me by Dr. DE VAUCOULEURS the total emission in this wave-length from the spur and from a semispherical and apparently empty area surrounding it, is equal to the emission from the main body of the Small Cloud, where the Cloud and the area mentioned are of about the same size but of entirely different material content. As an interesting feature it should be added that if the spur on the Small Cloud is due to tidal action because of the proximity of the Large Cloud, no countertide on the Small Cloud is visible.

The explorations of the whole field surrounding the Magellanic Clouds in terms of the continuous radio waves is not yet completed.

As Dr. DE VAUCOULEURS has suggested, a possible extension of the Milky Way in the constellation of Herculis might be looked for since such an extension would constitute the countertide to the suspected bridge between the Milky Way and the Large Cloud. The writer attempted to approach this problem through relative counts of stars and of distant galaxies in Herculis, but the task proved too herculean indeed. I suggested therefore to the British radio astronomers to explore the regions involved in an attempt to prove or disprove the existence of the looked for extension through the analysis of radio wave intensity contours. In the meantime, during his stay in July 1955 at the Lick Observatory, Dr. DE VAUCOULEURS has photographed the regions involved with lenses of two and of five inches aperture respectively and has not found any evidence for a countertide of surface brightness greater than about + 25/square second of arc.

### B. The Andromeda Nebula and its Companions

Although we do not have at the present anything very new to offer regarding the multiple system whose main member is Messier 31, it is of some importance to describe briefly what information might be obtained from a more thorough investigation of the relationship of M 31 to its companions.

There are two new observations made with the Schmidt telescopes on Palomar Mountain which are of importance in connection with our discussion of multiple galaxies. The first observation is that on long exposures with the 18-inch Schmidt Messier 31 appears to have a diameter of more than 12°, that is two to three times as large as any of the estimates which have recently been given. The 48-inch Schmidt plates revealed clearly that the elliptical companion NGC 205 is really an open barred spiral with very faint symmetrical arms, one of which points exactly at the nucleus of M 31. The extended arms of NGC 205 are possibly due to the tidal effects caused by the inhomogeneous and presumably strong gravitational field surrounding Messier 31. On the other hand it is of great importance to observe that the structure of the globular companion Messier 32 does not seem to be visibly affected by the proximity of the giant Messier 31. Under the circumstances it will be very important to make tests in order to decide whether or not M 31 and M 32 are really close neighbors or if they are components of an optical double separated by a considerable distance in the direction of the line of sight.

The multiple system of galaxies centered on Messier 31 offers perhaps the most important opportunities of any for future explorations of the mutual interactions of stellar systems. The Andromeda nebula and its physical companions constitute indeed the nearest system which is clearly delineated in its entirety. Being the nearest, the interactions of all of the member galaxies involved can be investigated in various independent ways. A first approach will explore the distribution of the individually resolvable stars. Secondly the distribution of gaseous masses can be studied through the use of the characteristics of emission line patches, while the distribution of obscuring matter can be investigated with well known methods. The new methods of radio astronomy should also prove a great tool in the case of the Andromeda nebula and its physical neighbors.

### C. New Clues on the Sense of Rotation of Spiral Galaxies

Many discussions have been published in the astronomical literature concerning the sense of rotation of spiral galaxies. While some astronomers have claimed, both from theory and from observations, that all regular spirals are trailing their arms, others have postulated with equal conviction that the motion is exactly the opposite. To this controversy two remarks must be made. In the first place the problem has so far remained ill formulated because spiral nebulae are not rotating throughout with a constant angular velocity relative to any universal inertial system. Because of this inconstant angular velocity one part of a nebula may well rotate clockwise while the other moves anticlockwise with respect to an inertial system. In order to formulate our problem correctly we must therefore ask if the total angular momentum of a rotating galaxy is parallel or antiparallel to the "structural vector" which has the dimension of an angle. This structural vector is normal to the plane containing the spiral arms and defines the sense in which these arms are curving.

Our second remark is that so far only insufficient data have been gathered to decide in every case what the sense of rotation of a galaxy is. From the theoretical standpoint it would be truly amazing if the spiral arms were either always trailing or always advancing. Indeed, as a mechanical system a spiral galaxy is quite free to rotate either way and in general the moment of momentum vector might even be inclined at any angle relative to the plane of symmetry of a spiral galaxy. Also, since the angular velocity varies in general with the distance from the center of a galaxy, it may be expected that in some cases a part of the system will be found to rotate in one sense while the remaining part turns in the opposite direction, provided that all motions are referred to a universal inertia system*.

The study of the structural features of double galaxies has led the author to some new criteria which might be useful in the investigation of the sense of rotation of normal spirals and of barred spirals. In Fig. 7d we show the essential outlines of an elliptical and of a spiral nebula which are interconnected by a luminous band, the structure of which gives some clues as to the direction of rotation of the spiral.

For purposes of discussion we assume that the globular nebula $A$ in the sketch a) moves with the velocity $V$ toward a passing close encounter with the elliptical nebula $B$ which is rotating in a clockwise direction. Approaching and passing each other in the phases b) and c) the two galaxies will be subjected to the generation of tides and of countertides. The two tides facing each other will eventually join and form the bridge between the two galaxies shown in c). Because of the initial rotation of $B$ this bridge must ultimately be *ruptured*. Obviously the frictional forces within $B$ decrease as we go outward from the center and at a given distance they will be too small to force the remote parts of the bridge to turn with the contiguous spiral arm. The break shown in 7d will therefore occur. As a matter of fact, in our particular case even the spiral arm which remains from the original countertide broke off from the outlying parts of this countertide. The two arms, the two breaks, and the immediate distribution of the luminous matter beyond the breaks form a perfectly symmetrical pattern. Also it would seem obvious from the existence of the clean-cut breaks that most of the matter beyond them will eventually disappear in intergalactic space. The final result in the case shown is an open barred spiral with its two arms advancing. If the initial rotation of the elliptical nebula $B$ had been counterclockwise, the final result of the encounter might have been the formation of a normal spiral rotating in the same sense, and with its arms trailing. It will be profitable to study the effects of encounters starting from all types of nebulae $A$ and $B$ and with various initial boundary conditions as to relative motion and initial moment of momentum. This approach promises to supply us with all of the necessary explanations for all possible forms of normal spirals and of barred spirals. It seems unlikely for the present that we shall have to resort to any processes of evolution starting from primordial masses of gases and of dust to arrive at a satisfactory theory of the structures of galaxies.

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* An inertia system is a system of reference in which Newton's equation $\dot{J} = F$ holds for every particle, where $\dot{J}$ is the time derivative of the momentum vector and $F$ is a real force acting on the particle. The origin of $F$ must be entirely traceable to matter and must not contain any inertial terms which can be transformed away in their entirety by a change to another system of coordinates.

## D. Multiple Galaxies in Clusters and in the General Field

If the formation of interconnected multiple galaxies is mainly due to close encounters resulting in mutual capture we should expect physically

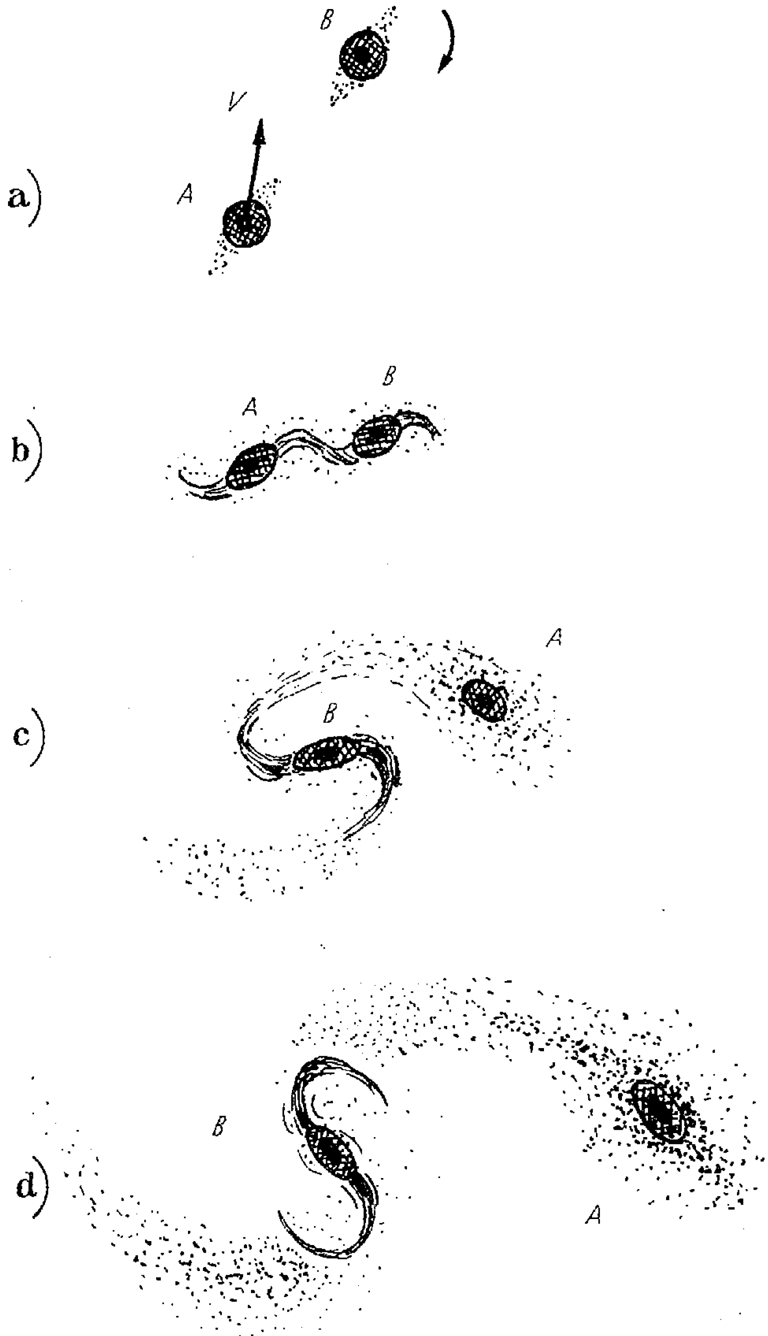


Fig. 7. Schematic drawing of the possible formation of an intergalactic bridge between two galaxies passing each other. The drawing d) represents the essential features discernible on a photograph obtained with the 200-inch telescope of the double galaxy located at R. A. $6^h\ 44^m\ 16^s$ and Decl. $+86°\ 36'\ 0''$ (1950). The total angular extension of the system is only about three minutes of arc and details of the various components can be recognized only with very large telescopes. The sketches *a*, *b* and *c* depict a hypothetical sequence of events.

connected double nebulae should be very much more frequent in clusters than in the general field. This conclusion is correct if the proper reservations are made. Actually we must distinguish between the general field, open clusters and very compact clusters in the centers of which several dozen member galaxies may be in virtual contact and all of them

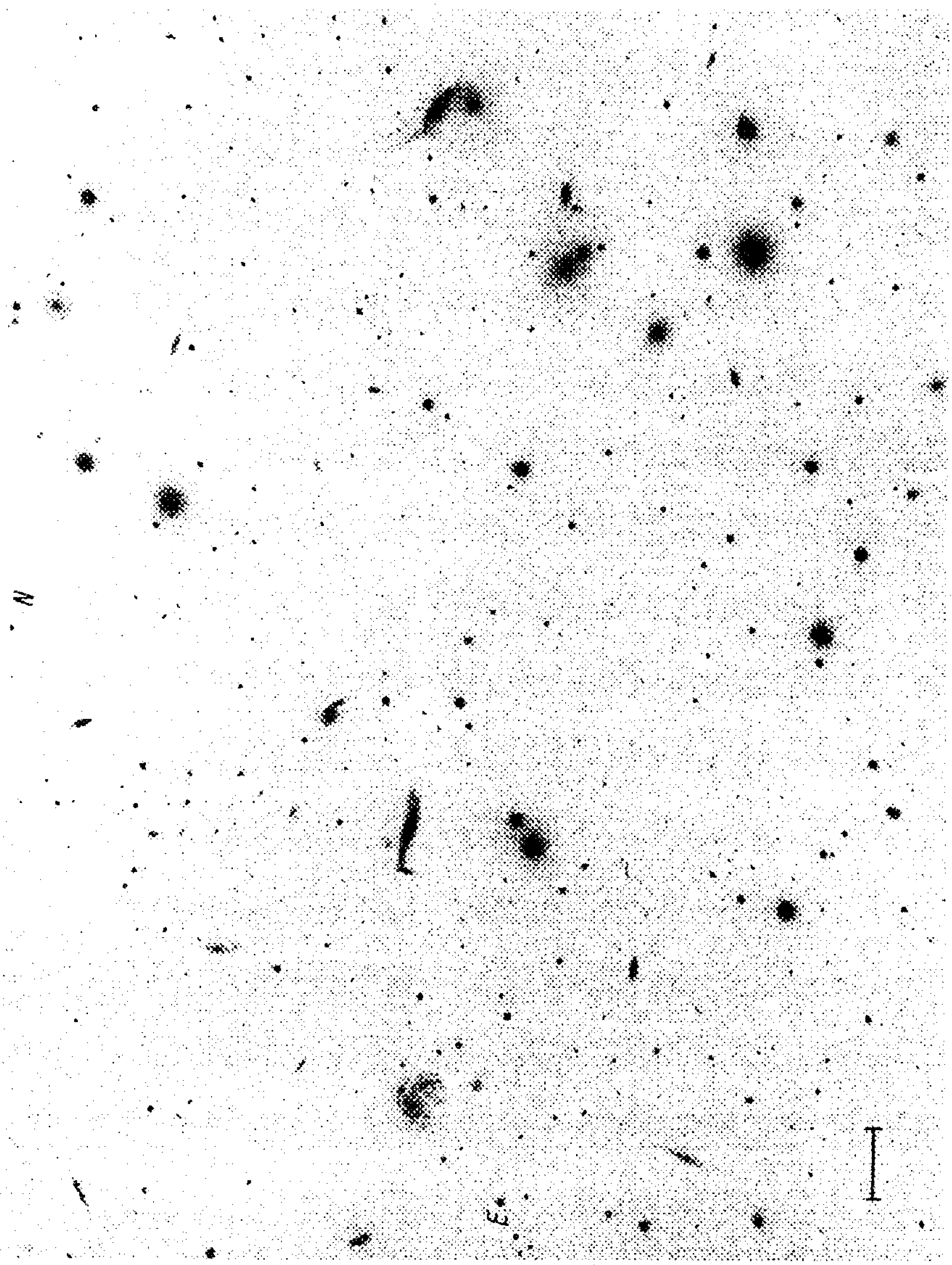

Plate X. Field within the Hercules cluster of galaxies located at R. A. $16^h\ 2^m\ 55^s$ and Decl. $+17°\ 54'$ (Epoch, 1950). Photograph obtained with the 200-inch telescope, exposure time 30 minutes on Eastman 103a—0 emulsion. Scale indicates one minute of arc.

imbedded in a vast luminous cloud of intergalactic stars. In compact clusters it is therefore not any more possible to isolate many double and triple galaxies, just as it is difficult to isolate molecules (multiple atoms) in a liquid or in a crystal. In the open clusters the individual units are separated by several diameters and double and triple nebulae are therefore very conspicuous. Plate X shows a 200-inch photograph of a small part of an open cluster within which half a dozen very beautiful physical double galaxies can be recognized.

Dr. Humason has obtained the following values for the symbolic apparent velocities of recession $V_s$ of seven galaxies in the Herculis cluster. NGC 6041, 6044, 6045, and 6047 have respectively $V_s = 10469$, 9936, 9935 and 9470 km/sec. For IC 1183, 1185 and 1194 it is respectively $V_s = 10038$, 10452 and 11642 km/sec.

## VI. Outlook and Programs

The preliminary study of interconnected galaxies has yielded a few results which promise to be of importance for astrophysical theory. Luminous connections of various types were described in the preceding. These connections occur rather indiscriminately between galaxies of all types. Most, but not all, of the intergalactic bridges are rather blue in colour and they seem to derive their luminosity from stars. So far no emission lines have been found in the spectra of long bridges. The fact that many thousands of extended luminous intergalactic formations have been found on plates taken with 48-inch Schmidt telescope greatly strengthens the theory that because of encounters among galaxies many of them are being disrupted and intergalactic space is continually being supplied with free matter. The fact that galaxies which are obviously connected with one another must be at approximately the same distance will no doubt become a most valuable starting point for the exploration of the true spatial distribution of cosmic matter. On the other hand some very difficult problems have immediately presented themselves in conjunction with the recent observations on interconnected multiple galaxies. These problems refer in particular to the fact that many of the observed filaments and bridges have a taffy-like structure and that they consist of stars. Furthermore, the problem of the unexpectedly large differential velocities of the components in some of the multiple galaxies needs to be explored thoroughly before one may hope to arrive at a satisfactory theory of the kinematic and dynamic characteristics of the large scale aggregates of matter in the universe.

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Prof. Dr. F. ZWICKY, Mount Wilson and Palomar Observatories.
California Institute of Technology, 1201 East California Street,
Pasadena (Calif.) USA.