SPECTRA AND OTHER CHARACTERISTICS OF INTERCONNECTED GALAXIES AND OF GALAXIES IN GROUPS AND IN CLUSTERS. II

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ABSTRACT

In continuation of the work reported in Part I we have analyzed spectra and direct photographs, obtained with the 200-inch Hale telescope, of four additional multiple galaxies whose members are interconnected by luminous filaments, bridges, and clouds. Symbolic velocities of recession for all the galaxies involved were determined, as well as their apparent dimensions and luminosities. Data are also given on the rotation of some of the galaxies. From the mentioned observed quantities indicative absolute distances, dimensions, luminosities, and masses were derived. Finally, some values for the indicative mass-luminosity ratios of the systems discussed in Part II as well as in Part I of this series of articles are given. For purposes of illustration we reproduce one of the spectrograms which shows the spectra of two galaxies and of two knots on the luminous bridge connecting them.

In continuation of Part I of this paper, similar data and discussions are here presented on four additional double and triple galaxies, which are interconnected by pronounced luminous intergalactic formations.

V. THE MULTIPLE INTERCONNECTED GALAXY AT R.A. $11^h8^m5^s$ AND DECL. $+29^\circ2'24''$ (1950)

A photograph of this most interesting system, a sketch of which is shown in Figure 5, may be found in the article by F. Zwicky on "Multiple Galaxies" in the *Ergebnisse der exakten Naturwissenschaften* (Berlin: Springer Verlag 1956), **29**, 375.

Some of the salient structural features of our system are as follows:

1. Galaxy A is of peculiar type Sb or S0, with a very condensed nucleus. Two relatively short extensions point east and west, both of which terminate in luminous condensations. An exceedingly long jetlike extension lies to the north and terminates in a large plume.
2. Galaxy B is of type S0 or E0, showing pronounced patches due to obscuration.
3. A and B are connected by a very faint, curved, luminous bridge.
4. Along a straight line to the south of Galaxy B lie several pointlike blue condensations, with a final very blue knot C (color index about -0.25), which was first found by V. A. Ambartsumian as a result of a comparison of the red and blue plates of the Palomar Sky Survey.
5. The whole system seems to belong to a medium compact cluster of galaxies which contains about 700 members within the range of apparent photographic magnitudes $+14.4 < m_p < +19$ and has a diameter of about $1^\circ.5$, or, according to the distance given by equation (87), an indicative absolute diameter of $2.3/h$ million parsecs. This cluster contains a remarkable number of mutually interacting galaxies.

a) Spectra

i) *Galaxy A*.—The spectrum of this galaxy is judged to be of type G0. It extends remarkably far into the ultraviolet. The positions of the G band, the H and K absorp-

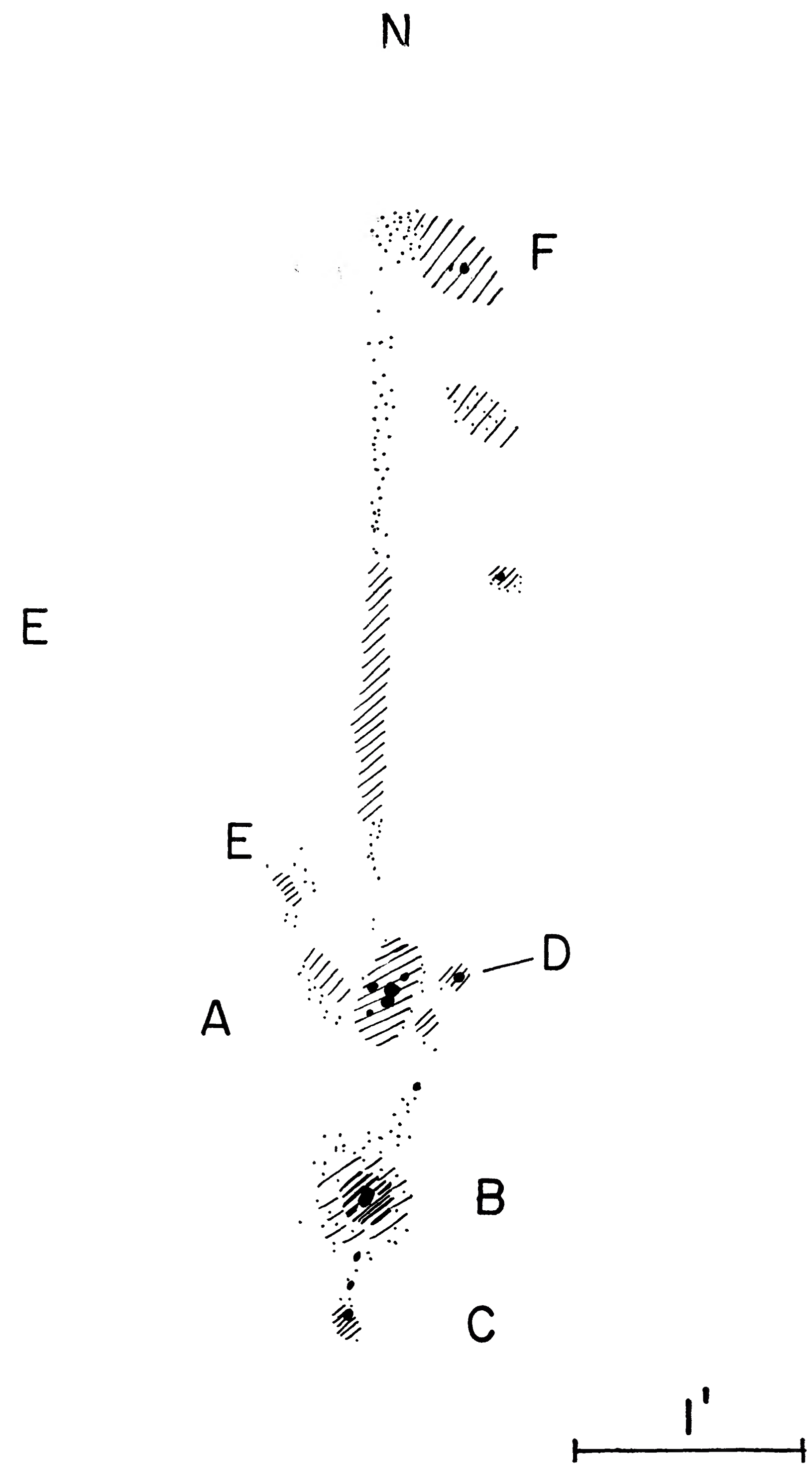

FIG 5.—Sketch from a 200-inch Hale telescope photograph of a multiple galaxy at R A $11^h 8^m 5^s$ and Decl. $+29°2'24''$ (1950) The individual member galaxies are interconnected and surrounded by a great variety of luminous intergalactic formations Scale of 1 minute of arc is indicated.

tion lines, and λ 3727 in emission could be measured. The symbolic velocity of recession, $V_s = c\Delta\lambda/\lambda$, derived from these measures is

$$V_s\,(\mathrm{A}) = +8803 \text{ km/sec}, \tag{79}$$

with a standard deviation of 9.5 km/sec.

With respect to the discussion of the component ω_z of the angular velocity of the three galaxies A, B, C, it must be remembered that the slit was lined up 4°5 from north-south, so as to cover all three galaxies. Therefore, z coincides within 4°5 with the east-west line normal to the line of sight.

The spectral lines show a visible inclination, γ, relative to the comparison lines. It is $tg\,\gamma \cong 1/16$ at λ 3727. This means, according to equation (5) of Part I of this paper, that the component ω_z of the angular velocity ω along the direction normal to both the line of sight and the connecting line between galaxies A, B, and C is equal to

$$\omega_z\,(\mathrm{A}) = 1.68 \times 10^{-15} h \text{ sec}^{-1}, \tag{80}$$

corresponding to a time of revolution

$$\tau\,(\mathrm{A}) = \frac{120}{h} \text{ million years}. \tag{81}$$

The sense of the rotation around the z-axis is such that the south end of galaxy A is approaching the observer.

ii) *Galaxy B.*—The spectrum of this galaxy is of type K0, and the continuum is far redder than that of Galaxy A. Three lines were measured, including the emission line at λ 3727. The resulting value for the symbolic velocity of recession is

$$V_s\,(\mathrm{B}) = +8550 \text{ km/sec}, \tag{82}$$

with a standard deviation of 53 km/sec.

The spectral lines are slightly inclined, with $tg\,\gamma \cong 1/32$ at λ 3727, indicating an angular velocity component,

$$\omega_z\,(\mathrm{B}) = 8 \times 10^{-16} h \text{ sec}^{-1}, \tag{83}$$

corresponding to a time of revolution

$$\tau\,(\mathrm{B}) = \frac{250}{h} \text{ million years}. \tag{84}$$

The sense of the rotation around the z-axis is such that the south end of galaxy B is approaching the observer.

iii) *Galaxy C* (*Ambartsumian Knot*).—Dr. V. A. Ambartsumian, in the course of an examination of the Palomar Sky Survey plates, noticed that the very compact knot C is exceedingly blue. Both he and we estimate its color index to be about −0.25. The spectrogram shows that this blue color is mainly due to the emission line at λ 3727, which, in spite of the relatively much lower total brightness of C, compared with galaxies A and B, is almost as strong as the λ 3727 emission in these systems. Actually, this emission line is visible in our spectrogram along the whole fine connecting filament between B and C.

Only the λ 3727 line could be measured for the knot, no other line showing. The symbolic velocity of recession of the knot is

$$V_s\,(\mathrm{C}) = +8839 \text{ km/sec}. \tag{85}$$

The continuous spectrum for the knot is blue and very weak. There is no measurable inclination of the spectral lines and therefore no determinable rotation around the z-axis. The average of V_s for the system is

$$V_s = \frac{V_s(\mathrm{A}) + V_s(\mathrm{B}) + V_s(\mathrm{C})}{3} = +8731 \text{ km/sec} . \tag{86}$$

The indicative distance of the system, therefore, is

$$D = \frac{87.3}{h} \text{ million parsecs} . \tag{87}$$

It would, of course, be interesting to explore the spectrum of the large plume to the north of the system and particularly of the condensations D, E, and F.

b) Apparent and Absolute Dimensions

All measures of apparent dimensions are from 200-inch plates.

(i) *Galaxy A.*—The major and the minor axes are, in seconds of arc,

$$\alpha(\mathrm{A}) = 29''.7 , \qquad \beta(A) = 13''.3 , \tag{88}$$

and, in absolute measure,

$$a(\mathrm{A}) = \frac{12500}{h} \text{ parsecs} , \qquad b(\mathrm{A}) = \frac{5630}{h} \text{ parsecs} . \tag{89}$$

(ii) *Galaxy B.*—The major and the minor axes are, in seconds of arc,

$$\alpha(\mathrm{B}) = 18''.2 , \qquad \beta(\mathrm{B}) = 17''.6 , \tag{90}$$

and, in absolute measure,

$$a(\mathrm{B}) = \frac{7700}{h} \text{ parsecs} , \qquad b(\mathrm{B}) = \frac{7440}{h} \text{ parsecs} . \tag{91}$$

(iii) *Galaxy C.*—The major and the minor axes are, in seconds of arc,

$$\alpha(\mathrm{C}) = 6''.2 , \qquad \beta(\mathrm{C}) = 3''.7 , \tag{92}$$

or, in absolute measure,

$$a(\mathrm{C}) = \frac{2600}{h} \text{ parsecs} \qquad b(\mathrm{C}) = \frac{1570}{h} \text{ parsecs} . \tag{93}$$

(iv) *Dimensions of the whole system.*—The separation between galaxies A and B is 55″.6 of arc, or, in absolute measure,

$$d_{\mathrm{AB}} = \frac{23500}{h} \text{ parsecs} . \tag{94}$$

The separation between galaxies B and C is 30″.5 of arc, or

$$d_{\mathrm{BC}} = \frac{12900}{h} \text{ parsecs} . \tag{95}$$

The length of the plume from A to F is equal to 205″ of arc, or

$$d_{AF}=\frac{86700}{h}\text{ parsecs},\tag{96}$$

and the over-all length of the system, from C to F, is about 290″ of arc, or

$$L=\frac{123000}{h}\text{ parsecs},\tag{97}$$

while the average width, W, of the whole dispersed intergalactic formation (streamers, bridges, knots, and clouds) is 25″ of arc, or

$$W=\frac{10600}{h}\text{ parsecs}.\tag{98}$$

The intergalactic formations in the whole system, which is one of the largest as yet known, cover about 6500 square seconds of arc.

c) Luminosities

(i) *Galaxy A*.—The apparent photographic magnitude of this galaxy is about $m_p = +14.7$. The absolute photographic magnitude, according to equation (18), Part I, is therefore,

$$M_p(\text{A}) = -20.0+5\log_{10}h-\Delta m .\tag{99}$$

(ii) *Galaxy B*.—The apparent photographic magnitude is $m_p = +14.4$. Therefore,

$$M_p(\text{B}) = -20.3+5\log_{10}h-\Delta m .\tag{100}$$

(iii) *Galaxy C*.—The apparent photographic magnitude is $m_p = +18.5$, and

$$M_p(\text{C}) = -16.2+5\log_{10}h-\Delta m .\tag{101}$$

(iv) *The intergalactic formations (IGF), comprising the luminous bridges, plumes, clouds, and blobs*.—Estimating the average surface brightness at $m_p = 23.0$ per square second of arc, the integrated apparent photographic magnitude of the mentioned luminous formations is of the order of $m_p = +14.0$. The absolute magnitude,

$$M_p(\text{IGF}) = -20.7 ,\tag{102}$$

thus indicates that the corresponding luminosity is about equal to that of A and B together.

d) The Mass-Distance Ratio $\mathfrak{M}_t/D$

From equations (79) and (82) it follows that the differential radial velocity between galaxies A and B is

$$\Delta V=253\text{ km/sec}.\tag{103}$$

According to equation (24), the mass-distance ratio of our system, comprising only galaxies A and B, is

$$\frac{\mathfrak{M}_t}{D}=2.58\times10^{18}f^2\text{ gm cm}^{-1}.\tag{104}$$

For the total mass of galaxies A plus B we may thus write

$$\mathfrak{M}_t(\text{A}+\text{B}) = 7.0\,\frac{10^{44}f^2}{h}\text{ gm},\tag{105}$$

or, in terms of the mass of the sun, $\mathfrak{M}_\odot = 2 \times 10^{33}$ gm,

$$\mathfrak{M}_t\,(\mathrm{A}+\mathrm{B}) = 3.5 \times \frac{10^{11}\mathfrak{M}_\odot f^2}{h}. \tag{106}$$

The combined absolute photographic magnitudes of galaxies A and B, according to equations (99) and (100), is

$$M\,(\mathrm{A}+\mathrm{B}) = -20.9 + 5 \log_{10} h - \Delta m\ . \tag{107}$$

The absolute luminosity $\mathfrak{L}_t$ (A + B) in terms of the luminosity $\mathfrak{L}_\odot$ of the sun, therefore, is

$$\mathfrak{L}_t\,(\mathrm{A}+\mathrm{B}) = 3.3 \times 10^{10}\mathfrak{L}_\odot \times \frac{10^{0.4\,\Delta m}}{h^2}, \tag{108}$$

and the mass-luminosity ratio is

$$\frac{\mathfrak{M}_t}{\mathfrak{L}_t} = 10.6\,\frac{\mathfrak{M}_\odot}{\mathfrak{L}_\odot} \times \frac{f^2 h}{10^{0\ 4\,\Delta m}}. \tag{109}$$

The indicative mass-luminosity ratio ($f = 1$, $h = 1$, $\Delta m = 0$) thus becomes

$$\frac{\mathfrak{M}_t^*}{\mathfrak{L}_t^*} = 10.6\,\frac{\mathfrak{M}_\odot}{\mathfrak{L}_\odot}. \tag{110}$$

Attention should be called to the possibility that, for the determination of a more accurate indicative mass-luminosity ratio, all the components of the system must be considered. This, however, cannot be done at the present time, since additional spectral data are required from which the symbolic radial velocities and velocity dispersions not only of galaxies A, B, and C can be determined but also those of condensations D, E, and F, as well as of the intergalactic plumes and clouds.

VI. THE TRIPLE INTERCONNECTED GALAXY AT R.A. $11^h44^m12^s$, DECL. $-3°34'12''$ (1950)

A photograph obtained for this system with the 200-inch telescope was published in the article "Multiple Galaxies" by F. Zwicky in the *Ergebnisse der exakten Naturwissenschaften* (Berlin: Springer Verlag, 1956), **29**, 344–385. A schematic sketch of the system is shown in Figure 6. The system was discovered by P. Wild (*Pub. A.S.P.*, **65**, 202–203, 1953).

The bridge between A and B is remarkably straight and of uniform width. On the other hand, the filament between B and C seems to form an actual loop.

a) *Spectra*

(i) *Galaxy A: R.A. $11^h44^m02^s$, Decl. $-3°34'54''$ (1950).*—This galaxy, which is an irregular SBb barred spiral, has a spectrum of type F2. The continuous spectrum is strong and extends well into the ultraviolet. Only weak traces of the K lines and the G band are visible. The emission line at λ 3727 is strong, while Hβ and Hδ are considerably weaker. The symbolic velocity of recession derived from these lines is

$$V_s\,(\mathrm{A}) = +5108\ \mathrm{km/sec}\ , \tag{111}$$

and the standard deviation is 61 km/sec.

Rotation: The emission line λ 3727 is inclined relative to the lines of the comparison spectrum by an angle γ, for which $tg\,\gamma = 1/32$ at λ 3727. The slit of the spectrograph was lined up north-south. Therefore, if the z-direction is taken normal to the plane defined by the line of sight to galaxy A and the north-south line, we obtain, according to equation (5) of Part I, for the component ω_z of the average angular velocity of the central parts of galaxy A, the value

$$\omega_z\,(\mathrm{A}) = 1.45 \times 10^{-15} h\ \mathrm{sec}^{-1} \tag{112}$$

and, for the corresponding period of revolution around the z-axis,

$$\tau_z\,(\mathrm{A}) = \frac{137}{h}\ \text{million years}. \tag{113}$$

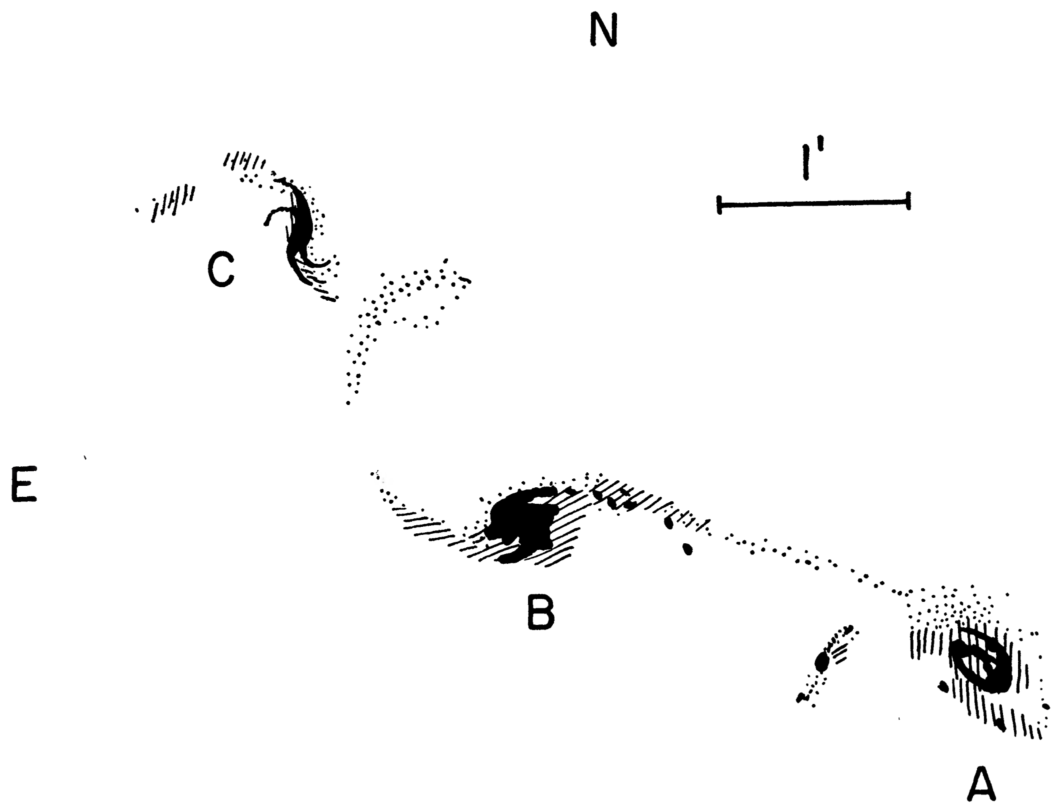

FIG. 6 —Sketch from a Hale telescope photograph of a triple galaxy at R.A. $11^h44^m12^s$ and Decl. $-3°34'12''$ (1950). Scale of 1 minute of arc is indicated

The sense of the component ω_z of the angular velocity is such that the south end of galaxy A is approaching the observer.

(ii) *Galaxy B: R.A. $11^h44^m12^s$, Decl. $-3°34'12''$ (1950).*—The galaxy is also a slightly irregular SBb spiral, and its spectrum is of type A. Again no absorption features show up in the spectrogram, which extends far into the violet. The emission is strong at λ 3727, moderate at Hβ and Hδ, weak at Hγ. From these lines a symbolic velocity of recession of the nucleus,

$$V_s\,(\mathrm{B}) = +5008\ \mathrm{km/sec}\,, \tag{114}$$

was derived, with a standard deviation of 23 km/sec.

Rotation: There are two distinct knots lying north and south, respectively, of the nucleus. The slit of the spectrograph was lined up north-south. The spectrogram shows that the two knots and the nucleus produce distinct emission lines whose differential displacement indicates a rotation around the axis z, which is normal to both the line of sight to the galaxy and the north-south direction. The inclination γ of λ 3727 relative to the lines of the comparison spectrum is given by $tg\ \gamma = 1/30$ and, therefore

$$\omega_z (\mathrm{B}) = 1.55 \times 10^{-15} h \ \mathrm{sec}^{-1} , \tag{115}$$

and, for the period of revolution around the axis z,

$$\tau_z (\mathrm{B}) = \frac{128}{h} \text{ million years} . \tag{116}$$

The sense of the rotation is such that the north end of the galaxy is approaching the observer. The peripheral differential velocity in the line of sight, at the north end and relative to the center of the galaxy, is about 180 km/sec.

The individual symbolic velocities of recession for the northern and southern knots or condensations are, respectively, 4973 and 5180 km/sec.

(iii) *Galaxy C: R.A. $11^h44^m16^s$ and Decl. $-3°32'42''$ (1950).*—This galaxy is a very irregular, open, barred spiral SBc, with apparently two bars in the center and two spiral arms extending in opposite directions from each of the bars. The spectrum is of type F0 and is the only one which shows the H and K absorption lines weakly and well defined. The G band is very weak. From these and the emission lines Hβ, Hγ, and λ 3727, a symbolic velocity,

$$V_s (\mathrm{C}) = +5396 \text{ km/sec} , \tag{117}$$

is derived, with a standard deviation of 55 km/sec.

Rotation: The slit of the spectrograph was again lined up north-south. This is the direction of the long axis of galaxy C, and the spectrogram shows emission lines along a considerable length of this axis. The inclination of λ 3727 is given by $tg\ \gamma = 1/120$. This gives a component ω_z of the angular velocity around the z-axis equal to

$$\omega_z (\mathrm{C}) = 3.8 \times 10^{-16} h \ \mathrm{sec}^{-1} , \tag{118}$$

and a period of rotation around the z-axis

$$\tau_z (\mathrm{C}) = \frac{512}{h} \text{ million years} . \tag{119}$$

The sense of the rotation is such that the south end of the galaxy is approaching the observer.

The average symbolic velocity of recession of the system is

$$V_s = \tfrac{1}{3} [V_s (\mathrm{A}) + V_s (\mathrm{B}) + V_s (\mathrm{C})] = +5171 \text{ km/sec} . \tag{120}$$

The distance of the system, therefore, is

$$D = \frac{51.7}{h} \text{ million parsecs} . \tag{121}$$

(iv) *The intergalactic formations.*—No spectrogram for any of these formations was obtained. Their average color is the same as that of the spiral arms.

b) Apparent and Absolute Dimensions

(i) *Galaxy A.*—The major and the minor axes are, in seconds of arc,

$$\alpha (\mathrm{A}) = 60''.6 , \qquad \beta (\mathrm{A}) = 27''.8 , \tag{122}$$

or, in absolute measure in units of parsecs,

$$a\,(\mathrm{A})=\frac{14900}{h}\text{ parsecs}, \qquad b\,(\mathrm{A})=\frac{6870}{h}\text{ parsecs}. \tag{123}$$

(ii) *Galaxy B.*—The major and the minor axes are

$$\alpha\,(\mathrm{B})=103''.0\,, \qquad \beta\,(\mathrm{B})=30''.4\,, \tag{124}$$

and, in absolute measure in units of parsecs,

$$a\,(\mathrm{B})=\frac{25600}{h}\text{ parsecs}, \qquad b\,(\mathrm{B})=\frac{7550}{h}\text{ parsecs}. \tag{125}$$

(iii) *Galaxy C.*—The major and the minor axes are

$$\alpha\,(\mathrm{C})=44''.0\,, \qquad \beta\,(\mathrm{C})=27''.8\,, \tag{126}$$

and, in absolute measure, in parsecs,

$$a\,(\mathrm{C})=\frac{10900}{h}\text{ parsecs}, \qquad b\,(\mathrm{C})=\frac{6870}{h}\text{ parsecs}. \tag{127}$$

(iv) *Dimension of the whole system.*—The separation from A to B is 153 seconds of arc, or, in absolute measure,

$$d_{\mathrm{AB}}=\frac{38000}{h}\text{ parsecs}. \tag{128}$$

The separation from B to C is 115''.6, or

$$d_{\mathrm{BC}}=\frac{28700}{h}\text{ parsecs}. \tag{129}$$

The over-all length of the system is thus about 180'' of arc, or

$$L=\frac{44700}{h}\text{ parsecs}. \tag{130}$$

The width of the main luminous bridges, on the average, is 14''.5 of arc, or

$$W=\frac{3600}{h}\text{ parsecs}, \tag{131}$$

so that the outlying luminous intergalactic formations cover about 2700 square seconds of arc.

c) *Luminosities*

(i) *Galaxy A.*—The apparent photographic magnitude of this galaxy is $m_p=+14.5$, and the absolute photographic magnitude, according to equation (18) in Part I, is

$$M_p\,(\mathrm{A})=19.0+5\log_{10}h-\Delta m\,. \tag{132}$$

(ii) *Galaxy B.*—The apparent photographic magnitude of this galaxy is $m_p=+14.1$. Therefore,

$$M_p\,(\mathrm{B})=-19.4+5\log_{10}h-\Delta m\,. \tag{133}$$

(iii) *Galaxy C.*—For this galaxy the apparent photographic magnitude is $m_p=15.0$, and

$$M_p\,(\mathrm{C})=-18.5+5\log_{10}h-\Delta m\,. \tag{134}$$

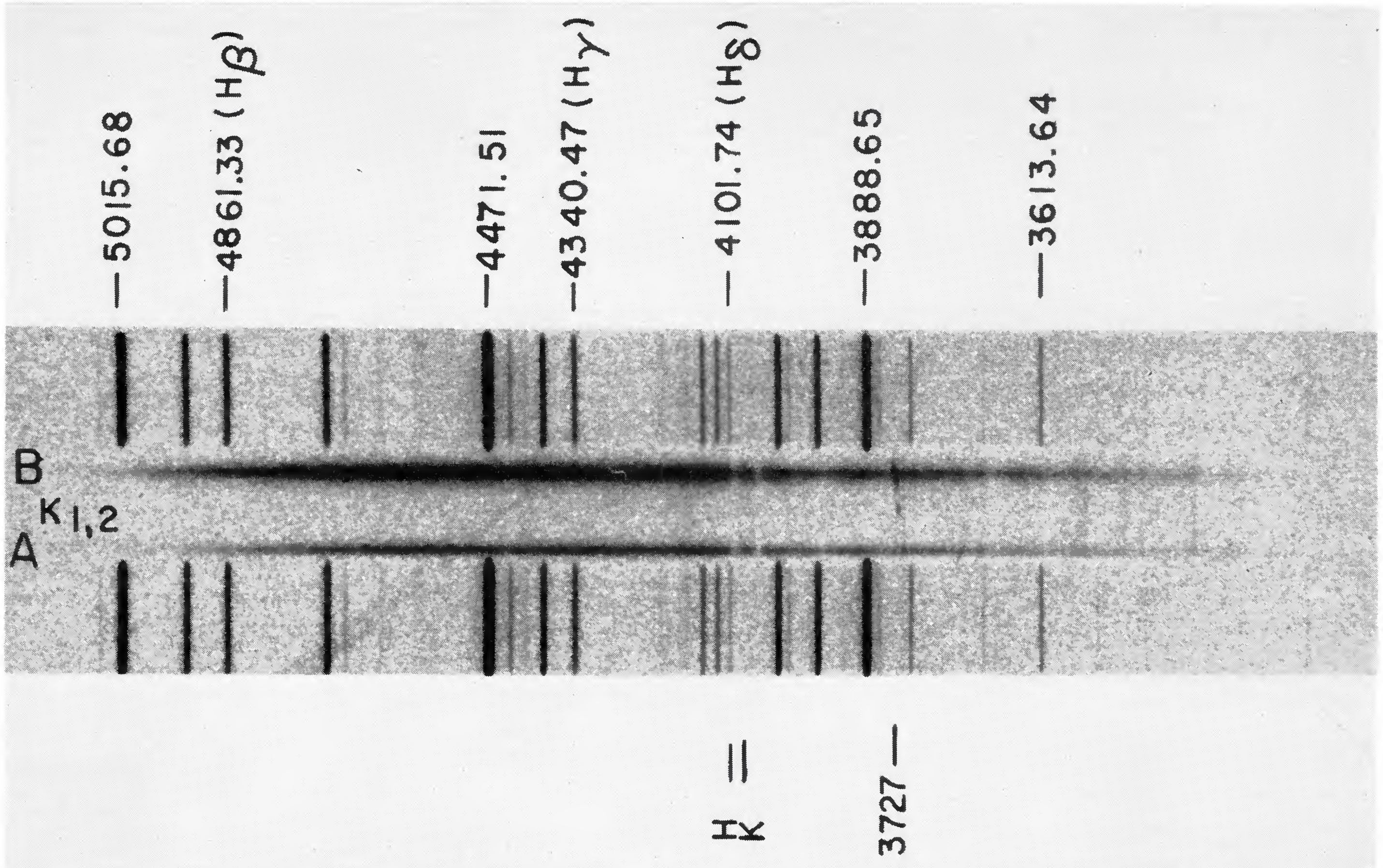

FIG. 8.—Spectrogram obtained with the prime-focus spectrograph of the Hale telescope of galaxies A and B and knots K_1 and K_2 which form part of the triple galaxy at R.A. $16^h48^m0^s$ and Decl. $+45°35'$ (1950). The dispersion of the original spectrogram is 185 A/mm. Comparison spectrum He + H. The λ 3727 and the H and K lines are, of course, displaced from their original positions.

(iv) *The intergalactic formations.*—Estimating the average surface brightness at 23.0 photographic magnitudes per square second of arc, the total apparent brightness of the 2700 square seconds of arc of the recorded luminous formations m_p (IG) = +14.4, and the corresponding absolute magnitude is

$$M_p\,(\mathrm{IG}) = -19.1 + 5 \log_{10} h - \Delta m \,, \tag{135}$$

which is about the same as the absolute magnitude of galaxy A.

d) The Mass-Distance Ratio $\mathfrak{M}_t/D$

The average mass of each one of the three galaxies A, B, and C is $\bar{\mathfrak{M}} = \mathfrak{M}_t/3$. Assuming that the three galaxies, A, B, C, form a *physical* system, we have, from the virial theorem,

$$\bar{\mathfrak{M}} = f^2 \frac{\bar{d}}{G} \langle (\Delta V_s)^2 \rangle \,, \tag{136}$$

where $\langle(\Delta V_s^2)\rangle^{1/2}$ is the dispersion in the three symbolic velocities of recession, f^2 is a numerical constant of the most likely value about 3, while $\bar{d}$ is the average of the three respective distances between A, B, and C.

Numerically, we have $\langle(\Delta V_s)^2\rangle = 27700\ \mathrm{km^2/sec^2}$ and $\bar{d} \simeq 43000/h$ parsecs. Therefore,

$$\bar{\mathfrak{M}} = 5.15 \frac{10^{44} f^2}{h}\ \mathrm{gm}\,, \tag{137}$$

or, in terms of the mass of the sun,

$$\bar{\mathfrak{M}} = 2.6 \frac{10^{11} \mathfrak{M}_\odot f^2}{h}\,, \tag{138}$$

and, for the total mass of the three galaxies,

$$\mathfrak{M}_t = 7.8 \frac{10^{11} \mathfrak{M}_\odot f^2}{h}\,, \tag{139}$$

or, for the mass-distance ratio,

$$\frac{\mathfrak{M}_t}{D} = 9.82 \times 10^{18} f^2\ \mathrm{gm\,cm^{-1}}\,. \tag{140}$$

The combined photographic magnitude of the three galaxies is $M_t = -20.22$, which corresponds to an absolute photographic luminosity,

$$\mathfrak{L}_t = 1.77 \times 10^{10} \mathfrak{L}_\odot \frac{10^{0\,4\Delta m}}{h}\,. \tag{141}$$

The mass-luminosity ratio for the whole triple system of galaxies is, therefore,

$$\frac{\mathfrak{M}_t}{\mathfrak{L}_t} = 44.0 \frac{\mathfrak{M}_\odot}{\mathfrak{L}_\odot} f^2 h 10^{-0\,4\Delta m} \tag{142}$$

and the indicative mass-luminosity ratio is

$$\frac{\mathfrak{M}_t^*}{\mathfrak{L}_t^*} = 44.0 \frac{\mathfrak{M}_\odot}{\mathfrak{L}_\odot}\,. \tag{143}$$

The conclusions drawn are, of course, based on the assumption that our triple galaxy is not violently flying apart. Also there may be considerable intergalactic matter between them which contributes to the mass and to the luminosity of the system in a different relative way than do the three distinct galaxies themselves.

VII. THE TRIPLE INTERCONNECTED GALAXY AT R.A. $16^h48^m0^s$ AND DECL. $+45°35'$ (1950)

This system, of which a photograph taken at the 200-inch telescope was published in the article on "Multiple Galaxies," by F. Zwicky, in the *Handbuch der Physik* (Berlin: Springer Verlag, 1959), **53**, 373–389, is shown in the sketch of Figure 7.

Some of the outstanding features of our multiple system of galaxies are as follows:

1. Galaxy A is of type S0, with a very compact central disk and a fainter ring of uniform surface brightness around it.

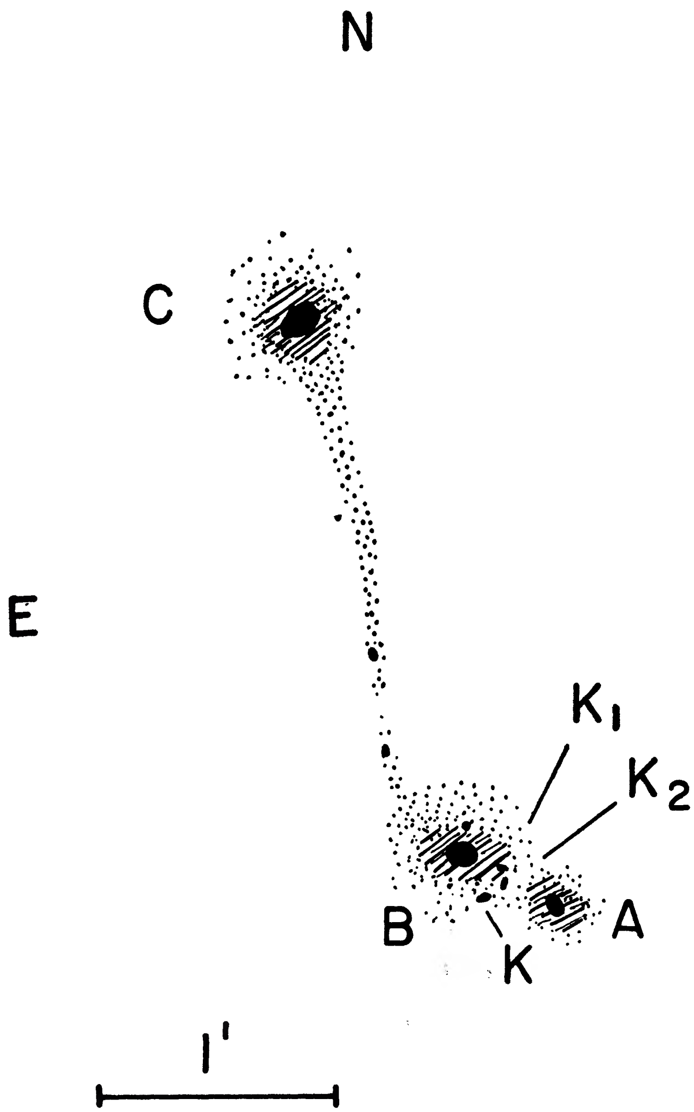

FIG. 7.—Sketch of the interconnected triple galaxy at R.A. $16^h48^m0^s$ and Decl. $+45°35'$ (1950) Scale of 1 minute of arc is indicated.

2. Galaxy B is of type Sa, with a uniform bright central disk and a fairly uniform, ring-shaped suburban structure of much fainter surface brightness than the disk.

3. Galaxy C is an S0 or SB0, with a very bright central body and a much fainter, very uniform ring around it.

4. The outlying formations in which A and B are imbedded are irregular and very faint.

5. The long luminous bridge between B and C is remarkably filament-like and of linear brightness, which decreases irregularly as we go from B to C. On this bridge, as well as between A and B and around B, there are a number of distinct luminous knots which have the appearance of gaseous emission clouds, which are excessively blue. A spectrogram obtained with the slit of the spectrograph covering galaxies A and B confirms this conclusion, inasmuch as the faint knot K^1 strongly emits the line λ 3727.

A considerable number of additional galaxies are located in the field of our triple galaxies and might possibly belong, together with our system, to a small open cluster of galaxies.

a) Spectra

(i) *Galaxy A.*—The spectrum of this galaxy is of type G2. No emission lines show. The measures on the H and K lines give a symbolic velocity of recession, V_s, equal to

$$V_s\,(\mathrm{A}) = +9418\ \mathrm{km/sec}\,, \tag{144}$$

with a dispersion of 20 km/sec.

There is no noticeable rotation of galaxy A around the axis y, as it is defined in the following paragraph.

(ii) *Galaxy B.*—The spectrum is of type G5, with the line λ 3727 very bright and wide, indicating a large velocity dispersion within the central disk of the galaxy. The positions of four lines were measured, including H and K. The symbolic velocity of recession derived from these measures for the nucleus of galaxy B is

$$V_s\,(\mathrm{B}) = +9405\ \mathrm{km/sec}\,, \tag{145}$$

with a standard deviation of 30 km/sec.

Since the spectral lines are inclined through an angle γ relative to the lines of the comparison spectrum, the central disk of galaxy B has a non-vanishing component ω_y of the angular velocity ω, where y is normal to the line of sight and normal to the projection of the connecting line AB unto the celestial sphere. The position angle of AB is 65°. The sense of rotation is such that the parts of galaxy B which lie in the direction of A are approaching, while the parts opposite from A are receding. With $tg\,\gamma = 1/12$ at λ 3727 we have, from equation (5) of Part I and equation (145),

$$\omega_y\,(\mathrm{B}) = 2.10 \times 10^{-15}\, h\ \mathrm{sec}^{-1}\,. \tag{146}$$

This corresponds to a time of revolution of our galaxy B equal to

$$\tau_R\,(\mathrm{B}) = \frac{95.5}{h}\ \text{million years}\,. \tag{147}$$

A photograph of the spectra of galaxies A and B and of the knots on the connecting bridge is shown in Figure 8.

(iii) *Galaxy C.*—The spectrum of this galaxy is of type G0. Nine lines were measured, including a bright λ 3727. The resulting symbolic velocity of recession is

$$V_s = +9449\ \mathrm{km/sec}\,, \tag{148}$$

and the standard deviation is equal to 68 km/sec.

The spectral lines are inclined. At λ 3727 it is $tg\ \gamma = 1/28$. The slit was at a position angle of 33°. The angular velocity ω therefore has a non-vanishing component, ω_x, around an axis x which is normal to the line of sight and normal to the connecting line BC. The sense of rotation is such that the parts of C nearer to B are receding. Quantitatively from equations (5), Part I, and (148) we obtain

$$\omega_x = 9.06 \times 10^{-16} h \text{ sec}^{-1} , \tag{149}$$

and the corresponding time of revolution is

$$\tau_R (\text{C}) = \frac{223}{h} \text{ million years} . \tag{150}$$

The average symbolic velocity of recession of the three galaxies is

$$V_s = \tfrac{1}{3} [V (\text{A}) + V (\text{B}) + V (\text{C})] = +9424 \text{ km/sec} . \tag{151}$$

The distance, according to equation (3), Part I, is

$$D = \frac{94.2}{h} \text{ million parsecs} . \tag{152}$$

(iv) *The intergalactic filaments.*—Two knots, K_1 and K_2, are shown on the connecting bridge from A to B. Both knots emit the λ 3727 line, K_1 weakly and K_2 strongly. From the positions of these lines the following symbolic velocities and recession have been derived:

$$V_s (K_1) = +9187 \text{ km/sec} \tag{153}$$

and

$$V_s (K_2) = +9360 \text{ km/sec} . \tag{154}$$

Since these values of V_s are smaller than those for galaxies A and B, the two knots K_1 and K_2 are therefore in relative approaching motion toward the observer.

From the appearance of some of the knots on the luminous filament which connects B and C it would appear certain that their spectra will also show emission lines. As in the system discussed in Section V, Part II of this paper, we here deal with one of the rarer aspects of long intergalactic filaments between the members of multiple galaxies. The spectra of these filaments, in the majority of cases observed so far, do not exhibit any emission lines.

b) Apparent and Absolute Dimensions

All measures of apparent dimensions are from 200-inch plates, emulsion 103*a*-O.

(i) *Galaxy A.*—The major and the minor axes are, in seconds of arc,

$$\alpha (\text{A}) = 12''.4 , \qquad \beta (\text{A}) = 11''.1 , \tag{155}$$

and the absolute dimensions are, in units of parsecs,

$$a (\text{A}) = \frac{5660}{h} \text{ parsecs} , \qquad b (\text{A}) = \frac{5070}{h} \text{ parsecs} , \tag{156}$$

(ii) *Galaxy B.*—The major and the minor axes are

$$\alpha (\text{B}) = 18''.9 , \qquad \beta (\text{B}) = 17''.9 , \tag{157}$$

and, in absolute units,

$$a (\text{B}) = \frac{8620}{h} \text{ parsecs}, \qquad b (\text{B}) = \frac{8160}{h} \text{ parsecs} . \tag{158}$$

(iii) *Galaxy C.*—The major and the minor axes are

$$\alpha\,(\mathrm{C}) = 19\overset{\prime\prime}{.}6\,, \qquad \beta\,(\mathrm{C}) = 17\overset{\prime\prime}{.}8\,, \tag{159}$$

and, in absolute measure,

$$a\,(\mathrm{C}) = \frac{8940}{h}\ \text{parsecs}\,, \qquad b\,(\mathrm{C}) = \frac{8120}{h}\ \text{parsecs}\,. \tag{160}$$

(iv) *Dimensions of the whole system.*—The distance between galaxies A and B is equal to $26\overset{\prime\prime}{.}3$, or

$$d_{\mathrm{AB}} = \frac{12000}{h}\ \text{parsecs}\,. \tag{161}$$

The distance between galaxies B and C is equal to $151\overset{\prime\prime}{.}5$, or

$$d_{\mathrm{BC}} = \frac{69100}{h}\ \text{parsecs}\,. \tag{162}$$

The over-all length of the system is about 210″ of arc, or

$$L = \frac{95800}{h}\ \text{parsecs}\,. \tag{163}$$

(v) *The bridges and other intergalactic formations.*—These represent an area of about 1000 square seconds of arc.

c) Luminosities

(i) *Galaxy A.*—The apparent photographic magnitude of this galaxy is $m_p = 15.5$. Therefore, from equations (18), Part I, and (152) we obtain, for the absolute magnitude,

$$M_p\,(\mathrm{A}) = -19.4 + 5\log_{10} h - \Delta m\,. \tag{164}$$

(ii) *Galaxy B.*—It is $m_p = 15.1$, and

$$M_p\,(\mathrm{B}) = -19.8 + 5\log_{10} h - \Delta m\,. \tag{165}$$

(iii) *Galaxy C.*—Here it is $m_p = 16.5$, and

$$M_p\,(\mathrm{C}) = -18.4 + 5\log_{10} h - \Delta m\,. \tag{166}$$

The combined apparent photographic magnitude of the three galaxies is $m_p(\mathrm{A}+\mathrm{B}+\mathrm{C}) = +14.4$, and their integrated absolute magnitude is

$$M_p\,(\mathrm{A}+\mathrm{B}+\mathrm{C}) = -20.5 + 5\log_{10} h - \Delta m\,. \tag{167}$$

(iv) *The intergalactic formations.*—Estimating their average surface brightness at $m_p = +23.5$ per square second of arc over an area of 1000 square seconds of arc, the total apparent magnitude of the recorded intergalactic formations is $m_p(\mathrm{IG}) = +16.0$, and

$$M_p\,(\mathrm{IG}) = -18.9 + 5\log_{10} h - \Delta m\,. \tag{168}$$

d) The Mass-Distance Ratio $\mathfrak{M}_t/D$

For the square of the dispersion in the three symbolic velocities of recession we have, from equations (144), (145), (148), and (151), $\langle(\Delta V_s)^2\rangle = 622$ km^2/sec^2 and, therefore, from equation (136) for the average mass of the three galaxies A, B, and C,

$$\overline{\mathfrak{M}} = 1.52 \frac{10^{43} f^2}{h} \text{ gm}, \tag{169}$$

or, in terms of the mass of the sun,

$$\overline{\mathfrak{M}} = 0.76 \frac{10^{10} \mathfrak{M}_\odot f^2}{h}. \tag{170}$$

For the total mass of the three galaxies, it is

$$\mathfrak{M}_t = 2.28 \frac{10^{10} \mathfrak{M}_\odot f^2}{h} \tag{171}$$

and

$$\frac{\mathfrak{M}_t}{D} = 1.58 \times 10^{17} f^2 \text{ gm cm}^{-1}. \tag{172}$$

Since the absolute integrated luminosity of the three galaxies A, B, and C, according to equation (167), in terms of the luminosity of the sun, is

$$\mathfrak{L}_t = 2.30 \times 10^{10} \mathfrak{L}_\odot \frac{10^{0.4 \Delta m}}{h}, \tag{173}$$

and the mass-luminosity ratio

$$\frac{\mathfrak{M}_t}{\mathfrak{L}_t} = 1.00 \frac{\mathfrak{M}_\odot}{\mathfrak{L}_\odot} \frac{f^2 h}{10^{0.4 \Delta m}}, \tag{174}$$

the indicative mass-luminosity ratio, for $f = 1$, $h = 1$, $\Delta m = 0$, thus becomes

$$\frac{\mathfrak{M}_t^*}{\mathfrak{L}_t^*} = 1.00 \frac{\mathfrak{M}_\odot}{\mathfrak{L}_\odot}. \tag{175}$$

VIII. DOUBLE INTERCONNECTED GALAXY AT R.A. $17^h 18^m 6^s$ AND DECL. $+49°7'36''$ (1950)

A photograph of this system, which was obtained with the 200-inch Hale telescope, was published in the article by F. Zwicky on "Multiple Galaxies" in the *Encyclopedia of Physics* (Berlin: Springer Verlag, 1959), **53**, 382. The sketch of this system in Figure 9 shows a long, thin, luminous bridge between galaxies A and B, as well as a long arm from B in the direction opposite to A. As we have pointed out before, this configuration of a bridge between two galaxies and a countertide-like jet from only one of them is a very typical and often encountered configuration.

Structurally, galaxy A is of type E0, while B is an irregular Sb spiral.

a) Spectra

(i) *Galaxy A*.—The spectrum is of type G0 and shows λ 3727 and λ 3868 (Ne III) in emission. The positions of six lines could be measured, from which the symbolic velocity of recession,

$$V_s(\text{A}) = +7250 \text{ km/sec}, \tag{176}$$

is obtained, with a standard deviation of 24 km/sec.

There is no measurable inclination to the various spectral lines, and no value for any component of the angular velocity of galaxy A can be derived. On the other hand, the lines have considerable width. This width, for λ 3727, is equal to about 10 A. This indicates a range of 800 km/sec for radial velocities of the emission nebulae within galaxy A.

(ii) *Galaxy B.*—The spectrum of this galaxy is of type G5:. The bright line at λ 3727 and the result (177) for V_s is

$$V_s\,(\mathrm{B}) = +7182\ \mathrm{km/sec}\,, \tag{177}$$

with a standard deviation of 60 km/sec.

The bright line λ 3727 is inclined through the center of galaxy B such that $tg\,\gamma = 1/11$. It then straightens out on both sides. Since the position of the slit of the spectro-

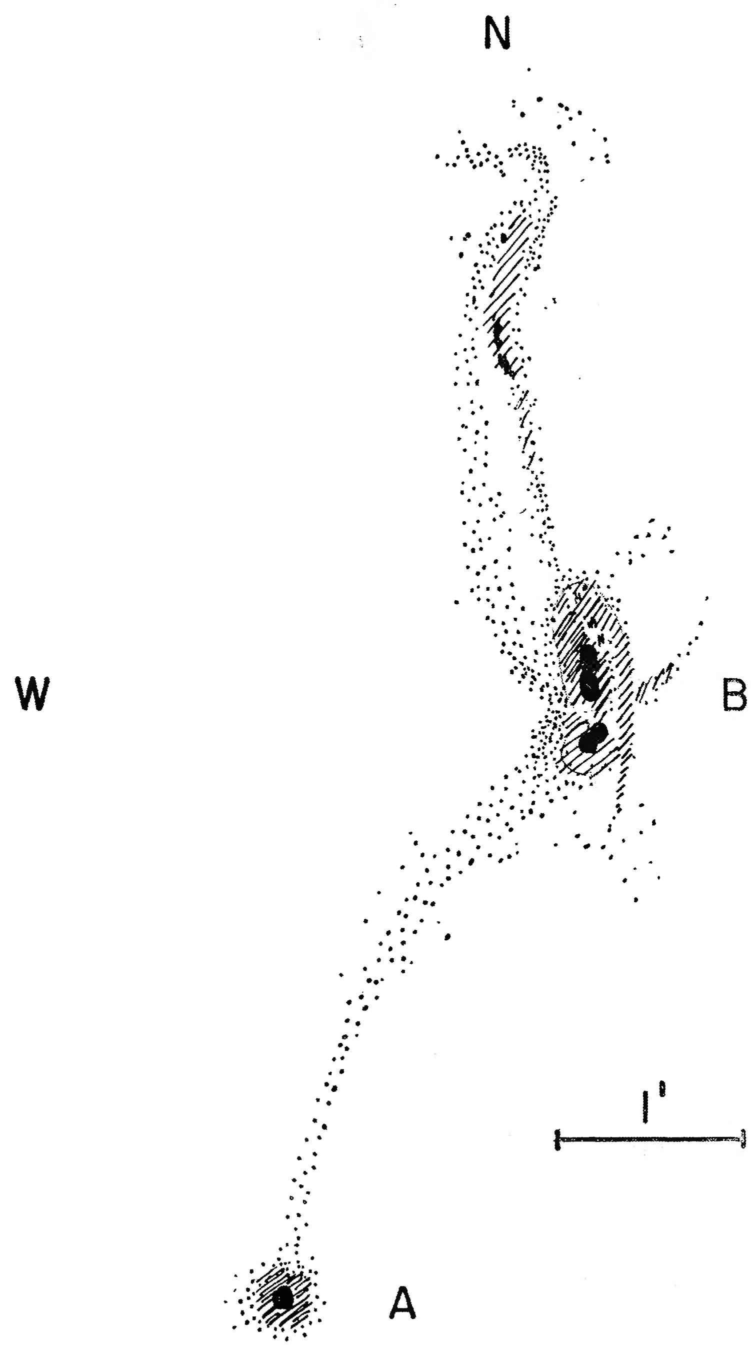

FIG. 9.—Sketch of the interconnected double galaxy at $17^h18^m6^s$ and Decl. $+49°7'36''$ (1950). Scale of 1 minute of arc is indicated.

graph was north-south, the measures show that the northern outskirts of galaxy B have a symbolic velocity of recession that is about 450 km/sec greater than V_s for the southern outskirts.

Designating by z the axis normal to the line of sight and parallel to east-west, the component ω_z of the angular velocity of rotation of the central disk of galaxy B, according to equations (5), Part I, and (181) is

$$\omega_z(\mathrm{B}) = 2.95 \times 10^{-15}\, h \,\mathrm{sec}^{-1}\,, \tag{178}$$

and the corresponding period of rotation is

$$\tau_R(\mathrm{B}) = \frac{67.6}{h} \text{ million years}. \tag{179}$$

The average symbolic velocity of recession of the two galaxies is

$$V_s = \tfrac{1}{2}\left[V_s(\mathrm{A}) + V_s(\mathrm{B}) \right] = +7216 \text{ km/sec}\,, \tag{180}$$

and the distance of the system, therefore, is

$$D = \frac{72.2}{h} \text{ million parsecs}. \tag{181}$$

b) Apparent and Absolute Dimensions

(i) *Galaxy A.*—The major and the minor axes are, in seconds of arc,

$$\alpha(\mathrm{A}) = 20''\!.8\,, \qquad \beta(\mathrm{A}) = 18''\!.5\,, \tag{182}$$

or, in absolute measure,

$$a(\mathrm{A}) = \frac{6800}{h} \text{ parsecs}\,, \qquad b(\mathrm{A}) = \frac{6070}{h} \text{ parsecs}. \tag{183}$$

(ii) *Galaxy B.*—The major and the minor axes are

$$\alpha(\mathrm{B}) = 72''\!.0\,, \qquad \beta(\mathrm{B}) = 27''\!.0\,, \tag{184}$$

or, in absolute measure,

$$a(\mathrm{B}) = \frac{23600}{h} \text{ parsecs}\,, \qquad b(\mathrm{B}) = \frac{8860}{h} \text{ parsecs}. \tag{185}$$

(iii) *Dimensions of the whole system.*—The separation between the two galaxies A and B is 229″ of arc, or

$$d_{\mathrm{AB}} = \frac{75100}{h} \text{ parsecs}. \tag{186}$$

The length of the jet and plume to the north of B is 167″ of arc, or

$$d_j = \frac{54700}{h} \text{ parsecs}. \tag{187}$$

The over-all length of the whole system is about 400″ of arc, or, in absolute measure,

$$L = \frac{131000}{h} \text{ parsecs}. \tag{188}$$

The average width of the bridges is about 20″ of arc, so that they and all the luminous intergalactic formations cover a total area of about 8000 square seconds of arc.

c) *Luminosities*

(i) *Galaxy A*.—The photographic apparent magnitude is $m_p = +14.9$, and the absolute photographic magnitude is

$$M_p\,(\mathrm{A}) = -19.4 + 5\log_{10} - \Delta m\;. \tag{189}$$

(ii) *Galaxy B*.—The apparent photographic magnitude is $m_p = +14.7$, and the absolute magnitude is

$$M_p\,(\mathrm{B}) = -19.2 + 5\log_{10} - \Delta m\;. \tag{190}$$

(iii) *The luminous intergalactic formations*.—The average photographic surface brightness of the luminous intergalactic formations, which cover about 8000 square seconds of arc, may be estimated as corresponding to a photographic magnitude +24.5 per square second of arc. The total apparent brightness thus corresponds to about $m_p = 14.7$, equal to that of galaxy B, and an absolute magnitude of

$$M_p\,(\mathrm{IGF}) = -19.2 + 5\log_{10} h - \Delta m\;. \tag{191}$$

d) *The Mass-Distance Ratio $\mathfrak{M}_t/D$*

According to equations (176) and (177), the difference between the values of V_s for galaxies A and B is 68 km/sec. Therefore, the total mass $\mathfrak{M}_t$ of A + B, according to equations (23), Part I, and (186) is

$$\mathfrak{M}_t = 1.60 \times \frac{10^{44} f^2}{h}\ \mathrm{gm}\,, \tag{192}$$

or, in terms of the mass of the sun,

$$\mathfrak{M}_t = 8 \times \frac{10^{10}\mathfrak{M}_\odot f^2}{h}\,. \tag{193}$$

The mass-distance ratio, which is independent of the Lundmark-Hubble constant, becomes

$$\frac{\mathfrak{M}_t}{D} = 7.20 \times 10^{17} f^2\,. \tag{194}$$

Since the combined absolute magnitude of the galaxies A + B is equal to

$$M_p\,(\mathrm{A}+\mathrm{B}) = -20.1 + 5\log_{10} h - \Delta m\;, \tag{195}$$

their integrated brightness is

$$\mathfrak{L}_t = 1.60 \times 10^{10}\mathfrak{L}_\odot \frac{10^{0.4\Delta m}}{h}\,. \tag{196}$$

The mass-luminosity ratio, therefore, is

$$\frac{\mathfrak{M}_t}{\mathfrak{L}_t} = 5\,\frac{\mathfrak{M}_\odot}{\mathfrak{L}_\odot}\,\frac{f^2 h}{10^{0.4\Delta m}}\,, \tag{197}$$

and the ratio of the indicative total mass $\mathfrak{M}_t{}^*$ of the system to the indicative total luminosity is

$$\frac{\mathfrak{M}_t^*}{\mathfrak{L}_t^*} = 5\,\frac{\mathfrak{M}_\odot}{\mathfrak{L}_\odot}\,. \tag{198}$$

Summary review.—In Table 2 we relist the essential indicative characteristics of the four multiple galaxies which we have discussed in Sections V–VIII. The designations used are as follows: D^* = indicative distance of the system; d^*_{AB} = indicative separation of two galaxies A and B projected onto a plane normal to the line of sight; a^* and b^* = indicative major and minor axes of the individual galaxies; L^* = indicative maximum over-all dimension of the system; M^* = indicative absolute photographic magnitude; $\mathcal{L}^*_t$ and $\mathfrak{M}^*_t$ = respectively, indicative absolute photographic luminosity and indicative sum of the masses of all of the member galaxies of the system; (IG) = luminous intergalactic formation; $\mathcal{R} = (\mathfrak{M}^*_t/\mathcal{L}^*_t)/(\mathfrak{M}_\odot/\mathcal{L}_\odot)$ = relative, indicative mass-luminosity ratio.

TABLE 2

Epoch 1950 0	System			
	V	VI	VII	VIII
R A Decl	$11^h8^m5^s$ $+29°2'24''$	$11^h44^m12^s$ $-3°34'12''$	$16^h48^m0^s$ $+45°35'0''$	$17^h18^m6^s$ $+49°7'36''$
V_s (km/sec)	8731	5171	9424	7216
D^* (10^6 parsecs)	87 3	51.0	94 2	72 2
d_{AB} (parsecs)	23500	38000	12000	75100
d_{BC} (parsecs)	12900	28700	69100	...
a^* (A)	12500	14900	5660	6800
b^* (A)	5630	6870	5070	6070
a^* (B)	7700	25600	8620	23600
b^* (B)	7440	7550	8160	8860
a^* (C)	2600	10900	8940	...
b^* (C)	1570	6870	8120	...
L^*	123000	69400	95800	131000
M^* (A)	−20 0	−19 0	−19.4	−19.4
M^* (B)	−20 3	−19.4	−19 8	−19 2
M^* (C)	−16.2	−18.5	−18 4	...
M^* (IG)	−20 7	−19.1	−18 9	−19 2
$\mathfrak{M}^*_t$ (in $10^{10}\mathfrak{M}_\odot$)	35	78	2.28	8.00
$\mathcal{R}$	10.6	44.0	1 00	5 00

TABLE 3

	System*			
	I	II	III	IV
$\mathcal{R}$	11 2	10 6	0.57	7 66

* Described in Part I of this series of papers.

TABLE 4

	System							
	I	II	III	IV	V	VI	VII	VIII
t^* (10^6 years)	62	208	240	37	82	96	1530	1080

In comparison with the indicative mass-luminosity ratios $\mathcal{R}$ listed in Table 2, the values of $\mathcal{R}$ for the systems discussed in Part I of the present series of papers are given in Table 3.

Assuming that the luminous bridges, filaments, and other intergalactic formations in the systems discussed were formed as a consequence of close encounters of the galaxies involved, it is of interest to estimate the times which have elapsed from the closest approach to the configuration seen at the present. We therefore list in Table 4 as indicative times of formation the values

$$t^* = \frac{d}{\Delta V_s}, \tag{199}$$

where d is the greatest separation between any adjacent member galaxies and ΔV_s is the greatest difference in V_s of any two members of the system.

A statistical evaluation of the absolute luminosity function as well as of the relative frequency of indicative absolute diameters will be postponed until the final part of the present series of papers.