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RING GALAXIES. I.

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ABSTRACT

We propose a classification scheme for ring galaxies, or R galaxies, with three subclasses. RE galaxies have crisp empty rings; RN galaxies are like REs but for an off-center nucleus; RK galaxies have single dominant knots or condensations in their rings. From the projected ellipticities of the rings and the relative positions of their companions we are led to simple three-dimensional models. With the help of these models, we employ photometric and spectroscopic observations made at KPNO to estimate global properties of R galaxies. They have galactic sizes, masses $\sim 10^{11}\ M_\odot$, and kinematical time scales of $\sim 10^8$ yr. Our interpretation of these data suggests that rings are formed when an intruding galaxy passes nearly through the center of a normal disk galaxy.

Subject headings: galaxies: formation — galaxies: structure

I. INTRODUCTION

Arp's (1966) Atlas of Peculiar Galaxies contains two galaxies in the form of elliptical rings with no luminous matter visible in their interiors. A few similar objects (listed below) have been reported by various observers in recent years, and a handful of such "ring galaxies" is now known. These objects invite attention not only because they look unusual but also because they are likely to be unstable (Dyson 1893). The time scale for the instability is $\sim 10^8$ yr, if the objects have normal galactic densities. Indeed, the scant evidence available to us is compatible with such a density estimate, and the conclusion indicated is that the ring configurations are short-lived on the time scale of galactic evolution. These (theoretically) short lifetimes of the ring configurations suggest that the rings are newly formed and that they provide the possibility of observing dynamically significant galactic activity. It therefore seems worthwhile to try to summarize the nature of the ring galaxies on the basis of the available data.

We begin in § II by trying to set up a preliminary classification scheme for ring galaxies, or R galaxies as we shall call them. Our criteria are rather restrictive in delineating the basic class of R galaxies, but we also suggest that there are a number of related ringlike galaxies which may lie along a sequence extending from those which meet our criteria for R galaxies. A number of such related objects can be found in a recent survey by Thompson (1975). Even earlier, discussions of the salient features of ring galaxies were given by Vorontsov-Velyaminov (1960, 1970), who stressed the possible interest of these objects. Photographs of a few R galaxies have been published by Cannon, Lloyd, and Penston (1970).

In § III we try to infer the three-dimensional configuration of ring galaxies on the basis of the available photographic material and adopt a simple model of their structures. Then in §§ IV and V we summarize our limited photometric and spectrographic observations of several R galaxies. These data together with the model proposed in § III lead us to estimates of ring masses and kinematical information for a few rings as discussed in §§ VI and VII. The kinematics also suggest ages of the ring configurations as $\sim 10^8$ yr. In § VIII we propose a model for systems containing ring galaxies which consist of the parts of two galaxies which have recently suffered a direct collision.

II. MORPHOGRAPHY

We shall state the criteria used here for the basic class of ring galaxies, then mention marginal cases and seemingly related objects, which are relatively numerous. The criteria are all photographic, but for the assumption that the objects are extragalactic, which has been confirmed spectroscopically for most cases.

A galaxy which appears photographically as a well-defined approximately elliptical ring without a *central* nucleus we shall call a ring galaxy, or R galaxy. The qualification against a central nucleus is designed to distinguish R galaxies from more normal ones such as the S(r) and (R) classifications of de Vaucouleurs (1959). Examples of R galaxies are shown in Figures 1 and 2 (Plates 6 and 7). Though these galaxies have in common a prominent ring structure, they reveal marked differences. These differences are suggestive of three different morphological subgroups among the known objects which might be classified as R galaxies.

Crisp, elliptical rings with photographically empty interiors, such as Arp 146, Arp 147, and VII Zw 466 (Fig. 1) comprise the first subgroup and will be designated RE galaxies.

The second subgroup, denoted as RN and exemplified by II HZ 4, is characterized by an elliptical ring with an off-center nucleus interior to it. As seen in the 200 inch plate provided by Dr. H. C. Arp, II HZ 4 has a reasonably crisp elliptical ring, as in an RE galaxy, but the ring has an off-center nucleus interior to it. A southern object discovered by Lindsay and Shapley (1960) and recently observed by Graham (1975) has a generically similar appearance. Graham's plate of this object taken with the CTIO 60 inch (1.5 m) telescope reveals that the ring does not close on itself but is roughly a $\frac{3}{2}$-turn tight spiral structure. In fact, there is a hint of similar structure in II HZ 4, and, as it is half the angular size of Graham's object, the marginal detection of spiral form may be simply a question of resolution.

Another possible RN is an object first discovered by Zwicky (1941) and rediscovered by Lü (1971) on the Yale-Columbia proper-motion plates. But a KPNO 4 m plate (shown in Fig. 2) reveals that there is rich and unusual structure in this object. Not only are there spiral filaments between the ring and the nucleus, but the nucleus itself seems to consist of a ring with a nucleus. This object, Lü 0035−34, is classified as an RN here, but whether the three RN's represent physically related objects is moot. The RN classification allows for the possibility of seeing an RE with a foreground (or background) object projected onto its interior.

There are some other objects which have been called ring galaxies in the literature. Two of these are I Zw 45 and II Zw 28 (Sargent 1970) which differ from the R galaxies already discussed in that their large-scale brightness distribution is markedly asymmetrical. We must admit that had it not been for these objects we would probably have regarded large-scale symmetry as a defining characteristic. That we did not, simply reflects our feeling that these objects should be regarded as rings. The ensemble of these cases suggests the possibility of another gestalt. Each of these objects has a single prominent knot that makes it less symmetric. But if asymmetry becomes very pronounced, the ring structure is no longer apparent, and it is difficult to apply the criteria for classification as a ring. In such a grouping of ringlike objects with increasing asymmetry, we feel that a line must be drawn at some point. Too few examples are known to place this cutoff with real objectivity, and we shall identify I Zw 45 and II Zw 28 as primary ring galaxies and list them in Table 1. The marginal cases shall be considered secondary rings, and placed in Table 2 until a more refined classification becomes warranted on the basis of new observations. We suggest that I Zw 45 and II Zw 28 are to be considered as prototypes of a third subclass of R galaxies designated as RK to indicate the existence of a single, very prominent knot in the ring.

Another object which should be mentioned in this discussion is Arp 148 (Mayall's object). This was considered a ring by Burbidge (1964), and its specific location in Arp's catalog indicates that Arp would concur in this classification. However, the part that is ringlike is rather amorphous in its interior, and by our criteria Arp 148 must be considered a borderline case. However, we feel that Arp 148 is likely to be closely related to ring galaxies, and will probably evolve into one.

There are other aspects of the appearances of ring galaxies that should be studied and categorized as more of these objects become known. Though we have alluded to the sharpness of the prototype rings on plates of good definition, we should stress that their brightness distributions are characterized by small-scale detail. All the rings have some knotty structure of which the observed detail depends on the resolution.

TABLE 1

R GALAXIES—PRIMARY GROUP

OBJECT	TYPE	α(1970)		δ(1970)		MAJOR AXIS		REDSHIFT† (km s⁻¹)
		h	m	0	1	arcsec	kpc*	
VII Zw 466.......	RE2	12	31.0	+66	36	22	27	14490 (155)
Arp 146..........	RE3	0	5.0	−6	54	16	...	...
Arp 147..........	RE1	3	9.6	+1	12	17	14	9655 (+5)
II HZ 4..........	RN2	8	56.7	+37	15	29	32	12885 (−25)
Graham..........	RN4	6	43.5	−74	14	95	52	6250‡
Lü 0035−34......	RN2	0	36.2	−33	53	72	...	...
I Zw 44..........	RK4	12	51.7	+37	1	23	17	8345 (+45)
II Zw 28.........	RK0	5	0.1	+3	34	14	10	8580 (−80)
Arp 148..........	R3	11	2.2	+41	0	21	20	10600 (+15) §

* Hubble constant = 55 km s^{-1} mpc^{-1}.

† Uncorrected for solar motion (correction in parentheses).

‡ Graham 1975.

§ Burbidge 1964.

TABLE 2

R GALAXIES—SECONDARY GROUP

OBJECT*	TYPE†	α(1970)		δ(1970)		MAJOR AXIS		REDSHIFT (km s^{-1})
		h	m	0	1	arcsec	kpc	
VV 112	RK4	10	41.3	+13	39	60	5	1070
VV 285	RK4	2	33.1	−8	55	35	40	12950‡
VV 330A §	RK5	10	20.9	+78	47	55	12	2565
2073−72 ‖	RN1	20	23.1	−72	39	30	...	...
Arp 10	RN2	2	16.6	+5	30	40	...	...
Vela #	RN4	10	7.7	−38	13.9	70	...	...
VV 256**	RN5	13	59.7	+41	11	60	20	3600

* VV objects from Vorontsov-Velyaminov 1959.

† Approximate classification.

‡ De Vaucouleurs and de Vaucouleurs 1975.

§ Has companion with faint ring 1:3 to NE with velocity 2545 km s^{-1}.

‖ Arp and Madore 1975.

Sérsic 1968.

** Has companion 1:2 to NE with velocity 3660 km s^{-1}.

The fineness of this structure is an aspect which should ultimately be characterized quantitatively. There are also small-scale loops and filaments in some of the rings (cf. VII Zw 466) as well as diffuse material interior to others (cf. I Zw 45). If these fine details were more prominent they could preclude the object from the R classification, or at least cause a change in subclass.

A final generic feature that we should mention is that the rings are nearly elliptical, a characteristic that we shall deal with quantitatively in § III. Indeed, as the number of known rings increases, it will become useful, as in Tables 1 and 2, to follow the designation R with a number characterizing its ellipticity as is done with elliptical galaxies. But not all ringlike galaxies have such smooth large-scale structure. We consider that objects with pronounced large-scale kinks (such as the Vela object [Graham, private communication]) which are very like rings should be excluded from the primary ring category, but perhaps placed in an adjacent but separate subclass. We shall not do that here though. Instead, with these possible complications pushed into the background for now, let us summarize the properties of the three proposed subclasses of R galaxies.

The RE galaxies we have considered are Arp 146, Arp 147, and VII Zw 466. These are generally sharply defined, nearly elliptical rings, with no detectable emission from their interiors. On a smaller scale they show clearly developed knots and occasional loops or filaments.

The RK galaxies are asymmetric in the large, but some symmetry results from a single, large, luminous knot. We have chosen I Zw 45 and II Zw 28 as the best examples of this group and tentatively excluded the more highly distorted examples.

RN galaxies are ring galaxies which have in their interiors a single galaxy-like object or nucleus which is not at the center of the ring. In practice, all the objects of this type show a fine structure which represents a deviation from the strict ring structure. In descending order of their suitability for the ideal RN category we have designated the following as RNs: II HZ 4, Graham's object, Lü 0035−34, and possibly the Vela object.

Mayall's object, which may eventually tell us the most about the physics of these objects, does not obviously fit into any of these groups. The rings that will be considered in detail are listed in Table 1.

This classification scheme has limited the number of galaxies in it to a few. Yet, our impression is that a whole sequence of objects resembling ring galaxies branch from the RN galaxies. Many such objects are included in a recent survey of ring galaxies by Thompson (preprint) whose criteria for ring classification are broader than ours. The advantage of such a looser grouping is that it makes more objects available for the statistical determination of properties of rings. The danger is that it may introduce spurious rings and therefore admit of spurious theoretical explanations.

With these reservations in mind we have decided to focus attention on the restricted group listed in Table 1. We should mention also that Arp and Madore (1975) have reported some 31 southern rings, which constitute 6 percent of their sample of peculiar galaxies. Dr. Madore has kindly provided photographs of some of these rings, and among them is at least one which fits into our strict RN category. We have too little information on it at present to try to include it in our detailed studies. However, it does seem worthwhile to list this and a number of other galaxies whose appearances commend them as candidates for classification in some (possibly new) subgroup of the R galaxies. These are presented in Table 2, and we shall include these objects in some of our discussion of ring statistics. The objects in Table 2 have been assigned to subclasses for use in the discussion of statistics of R galaxies.

III. GEOMETRY OF R GALAXIES

In order to understand the kinematical observations of ring galaxies, we need some idea of the spatial configuration of these objects. This poses a problem, since it is not immediately clear that the R galaxies are true rings. They might be shells or fortuitously aligned, curved filaments. We consider that the latter possibility may be safely disregarded. To produce the known rings by chance alignments we would need many filamentary galaxies, only a few of which would be seen as rings in projection. This condition does not appear to be met.

The possibility that R galaxies are shells, like planetary nebulae, is more serious. But if R galaxies are shells, we would expect to detect light in their centers; in particular we would expect to see in their geometric interiors the bright knots that are seen in most rings. These knots are all fairly round, and, since they are presumably seen at random orientations, we may assume that they are roughly spheroidal. Moreover, their appearances suggest that they are not the result of chance alignment of lumps and other shapes. Since the knots are clearly visible on the rims, we would expect to see them across the faces of R galaxies if these galaxies were shells.

Furthermore, the smoothed luminosity profiles seem to be incompatible with a simple shell model. With the model of a uniformly emitting spherical shell of optically thin luminous material with radius 1 and thickness β' we calculate that the ratio of emission from the center to that from the brightest part of the apparent ring is $(\beta'/2)^{1/2}$. On the high-resolution plate of VII Zw 466 (Fig. 1), β' is found to be 0.2–0.3, giving the intensity ratios for a spherical shell of this thickness as 0.3–0.4. However, an upper limit on the emission from the center of VII Zw 466 obtained by tracing the plate is smaller by a factor of 5 than that predicted by the spherical shell model. It seems safe then to rule out the shell model.

We tentatively conclude that the R galaxies are truly ring-shaped, but to unravel their kinematics, we need to assume something about the shapes of the rings. We may be guided here by the observation that the R galaxies are roughly elliptical. Since the only curves that project into ellipses for any orientation are ellipses, we assume that the rings are intrinsically elliptical.

We may also ask whether the projection effects in the distribution of observed ellipticities (ratio of minor axis to major axis) of the rings can be statistically removed to allow the determination of the intrinsic ellipticities. In principle this can be done if we know what the probability is that a ring of intrinsic ellipticity E will be seen on the sky with ellipticity between E' and $E' + dE'$ if its orientation is chosen at random. Let us call this probability $P(E', E)dE'$. The distribution P is plotted in Figure 3*a* for a variety of values of E.

Before the observed distributions of ellipticities can be compared with the theoretical curves of Figure 3*a*, corrections must be made for selection effects. One such effect is the evident difficulty in identifying edge-on rings. Given the observed ratio of overall ring diameters to ring thicknesses of about 3–4, and the observation that the rings have angular diameters $\sim 0'.5$, we would not expect to have found R galaxies with $E \lesssim 0.4$. This is consistent with observation.

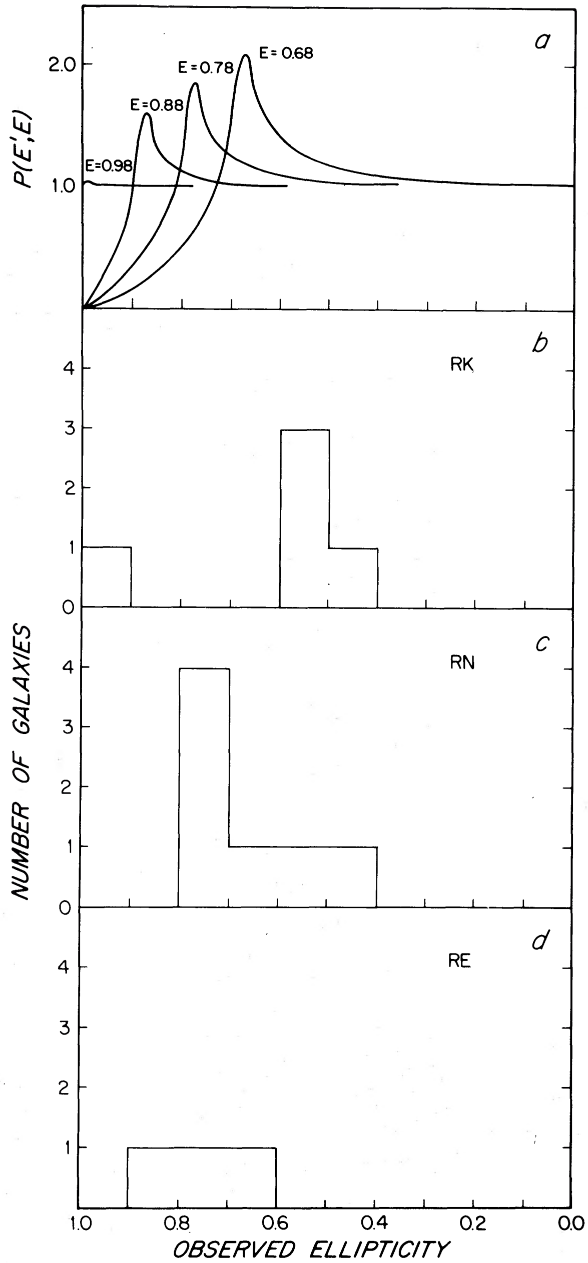

FIG. 3.—(*a*) Distribution of projected ellipticity, E', for randomly oriented ellipses of ellipticity E. (*b*) Distribution of E' for RK galaxies in Tables 1 and 2. (*c*) Distribution of E' for RN galaxies. (*d*) Distribution of E' for RE galaxies.

Another possible selection effect may occur for face-on rings. If the reason for off-centered nuclei were that the nuclei are out of the plane of the rings and are seen off-center because of projection effects, then a nucleus out of the plane but on the axis of symmetry of a ring would be centered for a face-on system. Then what might be seen as an RN galaxy from one viewing angle could be taken as a disk galaxy containing a prominent ring when seen face on. This could lead to false statistics for RN galaxies with $E' \approx 1$. This difficulty will probably be resolvable with additional spectroscopic data. Similarly, a change of viewing angle may cause a change of subclass for some of the rings. With these possible difficulties in mind, we present in Figure 3 the distribution of the ellipticities of the rings in Tables 1 and 2. These data on ellipticities are not sufficient to provide a definite conclusion, but they do indicate certain trends which are suggestive. But before offering an interpretation, we wish to consider another aspect of the appearances of R galaxies which seems relevant.

With one exception, every ring in Tables 1 and 2 has at least one probable, and in most cases spectroscopically confirmed, companion. The exception is II Zw 28, a very round RK which is much thicker on one side than the other. Even in this case, there is a hint from spectroscopic observations that there is a companion obscured by the thickened part of the ring, as discussed in § VII.

A cursory examination of photographs of R galaxies indicates that their companions are not distributed at random with respect to the rings. To be specific, let θ be the angle between a line from the ring center to the companion and the apparent minor axis of the ring. Every R galaxy in Table 1, except possibly II Zw 28, has a companion on or near the minor axis, that is with $\theta < 25°$. The quantitative expression of this fact is shown in Figure 4, a histogram of the frequency of occurrence of θ for companions within three angular diameters of the R galaxies. The stippled portion of Figure 4 is based on the galaxies of Table 1; the outer part of the histogram refers to the totality of objects in Tables 1 and 2. The existence of several companions with $\theta > 25°$ results because many rings have more than one companion, particularly those rings from Table 2. A similar plot of position angles for companions lying between 3 and 6 angular diameters from the ring centers shows no preferred angle. If we subtract a background contribution, we find that the preference of near companions for $\theta = 0$ is very marked. We believe, therefore, that it is a fair working hypothesis to regard the peak around $\theta = 0$ as real and to inquire into its significance, with guidance from Figure 3.

Two extreme interpretations for the minor axis correlation seem possible if we also accept that the rings are well approximated by ellipses: (i) we may suppose that the rings are nearly circular and that the companions lie on the symmetry axes but out of the planes of the rings. In that case, every ring will be seen as an ellipse, and every companion will lie on the projected minor axis. Occasionally there may be no apparent companion, since it will appear in projection on the ring as a knot, or inside as a nucleus. (ii) If, on the other hand, the rings were inherently elliptic, with $E < 0.6$, say, a preference of the companions for the projected minor axes would arise if the companions were in the planes of the rings and on their true minor axes. Figure 5 shows the probability of finding a companion at position angle θ in projection for such a configuration for three inherent ellipticities and for random projection angles. For small enough E, the probability is maximum at $\theta = 0$, but it has a second relative maximum at $\theta = 90°$.

When we began this study, we adopted the first of these idealized possibilities because it seemed to rationalize the data better. But there was an indication of difficulty: the knots of the RK galaxies also

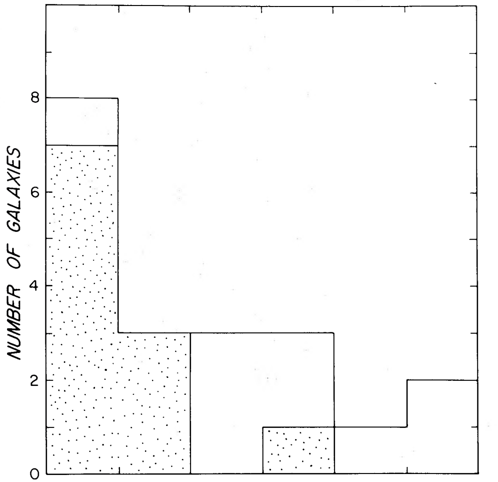

FIG. 4.—Distribution of positions of companions to the rings. The angles are measured from the nearest semiminor axis without regard to sign. The stippled region refers to objects in Table 1. The outer curve is for the totality of objects from Tables 1 and 2.

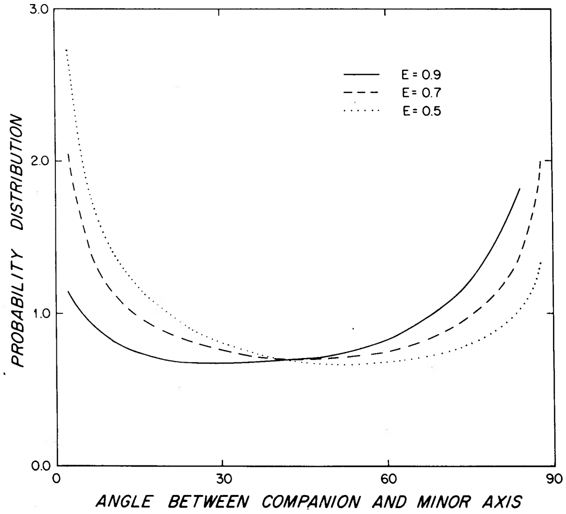

FIG. 5.—Distribution of the angle between the projected minor axis and the projection of the true minor axis for ellipses of inherent ellipticity E and with random orientations.

exhibited a preference for the projected minor axes. When fewer RKs were known, this could have been considered coincidental. But now there are five possible RKs in Tables 1 and 2, all of which have their knots near to their minor axes. Hence, if model (i) is to work for RK galaxies, we would have to assume that the knot as well as the companion is on the axis of symmetry of an intrinsically circular ring. Any deviation from this special configuration would cause displacements of the knot or companion from the minor axis, the displacement being greater the greater the distance from the plane of the ring. But if this were a correct model, there should be almost as many RE galaxies with companions close to the outer edges of the rings as RK galaxies. None of these are seen, and to maintain model (i) we would have to suppose that the objects seen as knots are quite close to the ring planes.

This picture might work, but the ellipticity data make us suspect that it does not. Though the data are not yet adequate for a firm conclusion, they suggest that the ellipticities decrease as we pass from RE to RN to RK. Unless this is a coincidence, the intrinsic ellipticities of RK galaxies are noticeably less than unity. In that case a form of model (ii) becomes more appropriate for RK galaxies in general.

We believe that one should interpret the RK galaxies as being a mix of two kinds, accidental and inherent RK galaxies. The accidental RKs are relatively few and are explained by model (i). The inherent RK galaxies are patterned after model (ii). The knots lie in or near to the planes of the rings and on the true minor axes; indeed it seems likely that they are usually in the rings themselves. In that case, if the masses of the knots were appreciable fractions of the ring masses, the true RKs would be expected to be eccentric, as is required by model (ii). This is supported by the recent discovery of de Vaucouleurs and de Vaucouleurs (1975) that the knot of VV 285 is a Seyfert nucleus. Likewise, the knot of I Zw 45 shows much stronger emission than the rest of this, or indeed of any other, ring. If the mass of the knot is treated as a perturbation and the knot is in the ring, we estimate that $E \approx 1 - 0.6\, M_K/M_R$, where M_K and M_R are the masses of the knot and the ring.

We have then to deal with the preference of the companions for the minor axes in the case of RK galaxies. The available data suggest that this preference may be weaker in RK galaxies than in the other two subclasses, but it is still there. To fit this into model (ii) we must suppose that the companions of RK galaxies also lie reasonably close to the planes and minor axes of the rings, though not as close as the knots, according to the data. Since in every RK listed here the companion is on the same side as the knot (if both exist), we shall suppose that both lie close to the same semiminor axis.

The two models would apply separately to REs and accidental RKs, on the one hand, and inherent RKs, on the other, in the sense that REs are close to model (i) while RKs are close to model (ii) in structure. Perhaps the only accidental RK is II Zw 28, which we believe to be like the REs in having one companion and neither knot nor nucleus. This in fact suggests that we can distinguish between an accidental and true knot spectroscopically, since a very dense region in the ring itself should have powerful emission. But what of the RNs? Their nuclei are too close to their centers to make a determination of position angles as meaningful as for knots and companions. Yet the companions of RNs do show the preferences for the minor axis. We believe that for the present we should describe the RN galaxies as intermediate between models (i) and (ii).

This view of the ring galaxies is constructed to rationalize the data. At present, other ringlike galaxies possibly represent a sequence branching from the R galaxies, and would suggest that as we move along the sequence, the simple model becomes progressively less applicable. Perhaps at this stage, it is also well to inquire whether the definite R galaxies may themselves require refinement of the model, which at best must be considered zeroth order. We would mention here two first order improvements that might be considered.

First, we may ask whether the rings are strictly planar. We do not have enough information to decide such a question, but its answer would help in looking for edge-on rings. Further, a warp in the plane of the ring, with appropriate viewing angle, could provide the appearance of a corner in the projected ring, such as is seen in the Vela object and VV 285 (cf. Fig. 2).

Second, we should inquire into the form of the cross section of the ring when it is cut by a plane containing its axis of symmetry. For purposes of discussion we shall usually take this section to be circular with radius a. But deformations from circularity, again appropriately projected, can lead to large-scale asymmetries in observed rings.

IV. PHOTOMETRY

A visual inspection of the POSS plates reveals that the rings are generally blue objects, similar in color to the disks of spiral galaxies, having a range in integrated magnitudes, m_v, of 14–16. A need for photometry is therefore indicated, since the placement of galaxies in the two-color diagram gives some indication of the distribution of stellar types and hence constraints on the age of the system. With this motivation, we did standard *UBV* photometry for a few of the rings with the No. 2 KPNO 93 cm telescope. For VII Zw 466, I Zw 45, and II Zw 28, a large circular diaphragm was used to encompass the entire ring, while excluding the nearby companions. However, for Arp 148, the west part of the cigar-shaped component and part of the ring fell within the diaphragm. For this reason, magnitudes are not given for Arp 148, and it should be emphasized that the colors given for this object refer to the portion described.

Though the standard star set was repeatable to 0.02 in m_v throughout the night the data were obtained, the large diaphragm used was responsible for the

TABLE 3

PHOTOMETRY

Object	m_v	M_v*	$B - V$	$U - B$
VII Zw 466...	15.7	−21.3	0.41 ± 0.08	−0.24 ± 0.13
VII Zw 466b†	15.31	−21.7	1.08 ± 0.05	+0.66 ± 0.20
I Zw 45......	14.6	−21.2	0.58 ± 0.02	−0.13 ± 0.02
II Zw 28.....	15.35	−20.4	0.30 ± 0.09	−0.15 ± 0.13
Arp 148......	...	...	0.65 ± 0.06	−0.02 ± 0.04

* Hubble constant of 55 km s^{-1} Mpc^{-1}.

† Elliptical companion.

somewhat large error estimates associated with the fainter objects. These would be disquieting in accurate photometry, but we are here trying simply to get some preliminary values for guidance in thinking about these objects. The results obtained are listed in Table 3. These are not corrected for internal or external reddening or redshift. However, for II Zw 28, which is at a galactic latitude of ~20°, an absorption correction of 0.35 mag has been suggested by Sandage (1972).

The rings, as indicated by this sample, have colors that are similar to Magellanic-cloud–type irregulars. Although it is well known that *UBV* colors cannot in themselves uniquely determine the stellar makeup of a galaxy, they can, in conjunction with assumptions about the initial luminosity function and the stellar birthrate, provide some insight into the possible stellar populations in the system. Thus, Searle, Sargent, and Bagnuolo (1973) have calculated the expected *UBV* colors of a variety of model star clusters as a function of time. We may use these to try to obtain some guidance as to the ages of the stellar populations of the ring galaxies.

Let us restrict ourselves to the case of a Salpeter initial mass function (IMF) which is sufficiently representative for our rough purposes. The first three entries in Table 3 are close enough together to be thought of as a point in the color-color plane (Arp 148 is excluded here because of mixture of components observed), and this point lies on or very near most of the temporal sequences given by Searle, Sargent, and Bagnuolo. This leads us to estimate two extreme values for the ages of the stars in the rings. If we take the youngest case compatible with the roughly determined colors, we find that the ring's colors are consistent with a model that had a strong burst of star formation 10^8 years ago. In this model, the young stars dominate the luminosity in the visible and the presence of an older population would be undetectable in all but very sensitive infrared photometry. At the other extreme, for a system with a constant stellar birthrate, its color-color track would pass close to the observed ring when the system is 10^{10} years old.

That these results indicate system ages $\gtrsim 10^8$ yr is not surprising. What will be more interesting in connection with our later discussion is that the colors are consistent with a strong burst of star formation about 10^8 years ago. Though this value is at one end of the range of possible ages, it is also implied by some scanner observations of Sargent and Searle (Sargent, private communication). However, with the burst model, we cannot, with existing observations, rule out the presence of an old population in the rings, and it would seem desirable to attempt wide-band photometry in the infrared.

V. SPECTROSCOPY

We have taken spectra of many of the ring systems of Table 1 and a few from Table 2 with the KPNO 2 m telescope and the Carnegie image tube spectrograph. The primary goal was to obtain basic redshifts for the rings and companions and, where feasible, to begin to unravel the kinematics of the rings themselves. For the purposes of surveying widely in the limited time available we generally aligned the slit along the minor axis of the ring (or nearly so) to pass through the companion. This procedure provided spectra of companion and ring on the same plate. Most of the spectra were of medium dispersion (130 Å mm^{-1}) and were centered either for the [O II] λ3727 doublet and the [O III] lines (blue), or for the [O III] lines and Hα (red).

Typical spectra of the rings themselves show emission lines of low excitation with blue continua. The lines of [O II] λ3727, Hα, [N II] λ6583, Hβ, and [O III] λλ4959, 5007, are normally seen in emission in the rings, while in the knot of II Zw 45, Hγ and Hδ were seen in emission. We detected no absorption lines in any rings, but Sargent and Searle (Sargent, private communication) have found the Balmer lines in absorption in Arp 146, Arp 147, and VII Zw 466 from Oke scanner observations. The companions to the rings often exhibit strong CaH and K in absorption and sometimes show emission lines.

The plates were measured by digitally encoding the spectra onto magnetic tape and determining the line position with a fitting program developed for measuring extragalactic spectra (Theys 1973). For each ring where more than one redshift was measured a mean redshift was calculated by averaging across the minor axis and/or the major axis. These values are listed in Tables 1 and 2, along with the corrections for galactic rotation. (The corrections have not been applied in the velocities quoted herein.) Since many of the measurements were of the unresolved [O II] λ3727 doublet, often with significant night-sky contamination, the velocities from individual plates may contain errors of as much as ~100 km s^{-1}. Kinematic details determined from the spectra are given in § VII.

VI. MASS ESTIMATES

That the rings are extragalactic seems clear from their redshifts, and these imply galactic sizes for the rings. But to estimate masses we have recourse only to indirect arguments.

If we suppose that a, the mean radius of cross section, is approximately the hydrostatic value, or Jeans length, then $a \approx k_J^{-1}$, where $k_J^2 = 4\pi G\rho/c^2$, c is the

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speed of random motions (e.g., turbulence, thermal motion) of the gas or stars, and ρ is total matter density. The mass is approximately $(2\pi R)(\pi a^2)\rho \approx \pi R c^2/(2G)$ where R is the radius of the ring. This expression gives $3.5 R_{10} c_{10}{}^2 \times 10^8\, M_\odot$, where R_{10} is the radius in unit of 10 kpc and c_{10} is the random speed in units of 10 km s^{-1}. Since R_{10} is greater than unity for most rings and probably $c_{10} \approx 10$ if one includes a possible contribution from turbulence, the hydrostatic assumption implies that the masses of the rings range up to $10^{11}\, M_\odot$. If all the mass were in gas, the gas density would be ~ 1 cm^{-3} for $c_{10} = 10$ and $a = 3$ kpc.

Another mass estimate is obtained by assuming an M/L ratio for rings. Magellanic-cloud–type irregulars, which have colors most similar to those of the rings, have estimated M/L ratios of $5\, M_\odot/L_\odot$. A measured absolute V magnitude of -21.3 for VII Zw 466 (Table 3) suggests a mass of $\sim 10^{11}\, M_\odot$.

Finally, a mass estimate for RE galaxies can be made on the basis of large-scale dynamics. Suppose we adopt the model that the rings are roughly circular and are supported against self-gravity by large-scale rotation. If the ring is roughly in rotational equilibrium, it is possible to estimate a mass using equilibrium models of polytropic rings (Ostriker 1964). For the velocity measured across the major axis of VII Zw 466 (cf. § VII) we get $10^{11}\, M_\odot$ which is compatible with the previous estimates. From these estimates we conclude that the rings have masses of order $10^{11}\, M_\odot$.

Upper limits to the masses of gas contained in ring galaxies have been found from 21 cm measurements by Dr. Morton Roberts (private communication) who surveyed three rings, Arp 147, II Zw 28, and I Zw 45. He found an upper limit of $\sim 10^{10}\, M_\odot$ for the mass of H I (assuming $H = 55$ km s^{-1} kpc^{-1} and a velocity dispersion in the rings of 100 km s^{-1}). Even for typical gas-rich early spirals and irregular systems this is not a stringent limit on gas content.

VII. INDIVIDUAL OBJECTS

We have presented in the preceding sections those data which relate to our preliminary study of the colors and redshifts of rings. In addition, we have attempted to obtain a more detailed picture of a few of these objects, particularly with respect to their internal kinematics. In this section we present these additional details together with some qualitative remarks based on direct plates.

a) VII Zw 466

The RE galaxy VII Zw 466 is striking, as much for the proximity (on the sky) of possibly peculiar companions, as for its own structure (cf. Fig. 1; Cannon, Lloyd, and Penston 1970; Freeman and de Vaucouleurs 1974). The ring itself consists of several bright condensations superposed on a faint continuous background which forms a very good ellipse. If we ignore the small loop extending from the ring toward its interior, we may fit the isophotal contours of the ring to an ellipse by least squares. The fit passes through the centers of the knots to within distances comparable to the size of the seeing disk. The ellipticity is 0.75.

A number of spectra at various points around the ring were taken with a bias in favor of the brighter points. The radial velocities measured around the ring are plotted in Figure 6. The position angle, measured counter-clockwise from the minor axis on the side of the nearby elliptical galaxy, is the abscissa in Figure 6. The velocities are referred to a mean velocity over the ring of 14,490 km s^{-1}. If we adopt the model that the ring is a circular toroid, then the only motions that will preserve it are rotation, uniform expansion (or contraction), and translation. The translation is taken care of in the mean redshift of the ring. If we then assume that the rotation is about the axis of symmetry and use the ellipticity to deduce the projection factors we may by a least-squares procedure deduce rotation and expansion velocities. The best fit, shown in Figure 6, results from a rotation velocity of 160 km s^{-1} and an expansion (or contraction) velocity of 8 km s^{-1}. The rms deviations from the curve given by these values is 30 km s^{-1}.

We have measured radial velocities of two of the three galaxies just eastward of the ring, the elliptical and the cigar-shaped ones. Though we have no velocity for the smallest of the three nearby galaxies, we have learned from Dr. C. R. Lynds (private communication) that its redshift is twice that of the ring and will not consider it further. There is also a large elliptical 4′ south of the ring and just out of the field of Figure 1 which is a foreground object with about half the redshift of the ring.

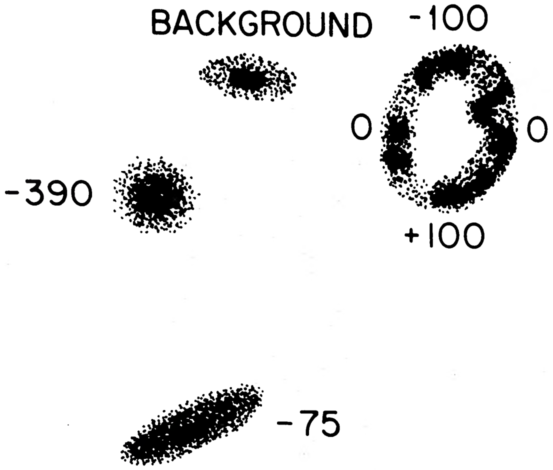

FIG. 6.—Points show distribution of observed radial velocities of VII Zw 466 around the ring. Position angle is measured counterclockwise from the semiminor axis nearest the companion. The zero point is the mean redshift of the ring. The solid curve is the best fit found with an intrinsically circular ring having both expansion and rotation.

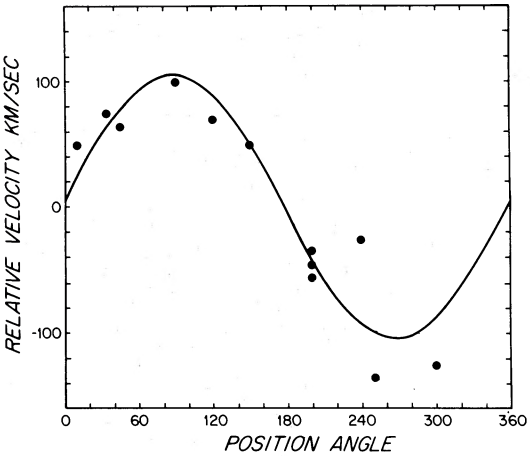

FIG. 7.—Velocity map of VII Zw 466. Zero point is the mean of the ring.

The two galaxies near the ring, for which we have good velocities, are likely to be actual companions of the ring. In the frame of the ring the elliptical and the cigar have redshifts of -390 km s^{-1} and -75 km s^{-1}, respectively. These values are shown in Figure 7, and the signs indicate that the companions have smaller redshifts than the ring. If we adopt the simple view that the elliptical lying near the ring's minor axis is actually on the symmetry axis of the ring, we find by removing the projection factor, a separation of 85 kpc. If the two objects (ring and elliptical) are moving apart, the time required to achieve this separation is 1×10^8 yr, presuming that the elliptical moves along the symmetry axis and has, with the corresponding projection correction, a velocity relative to the ring of 570 km s^{-1}. If the total mass of the ring and elliptical is $\sim 3 \times 10^{12}\ M_\odot$, the pair would be bound. Possibly the presence of the "cigar" alters the likelihood that the triple system is bound, but this would also make the simple configuration on which these estimates are based less likely to be realistic. Both companions have interesting features that are unfortunately only just detectable. Though the elliptical appears to be an ordinary E1 in the blue, on the *V* plate we find a bulge in the faint outer envelope (cf. Fig. 1). The cigar-shaped companion appears nearly uniformly luminous on the blue plate but has a relatively bright linear feature on its NW edge. There is also a hint of a linear filament extending NW from this feature toward a faint, small amorphous condensation about a half a cigar length from the NW tip of the cigar. A red plate shows a bright nucleus in the center of the cigar which, in this case, looks rather like an ordinary disk galaxy seen nearly edge on. Furthermore, there appears some very faint filamentary structure approximately half way between the cigar and the elliptical. The net impression from these various minor quirks is that the three objects in question are (or have been) interacting tidally.

Finally, we note that in the field of VII Zw 466 there are several other galaxies of which four lie within 4′ of the ring. These additional galaxies are all comparable in size with the one nearest to the ring (on the sky) which, following Lynds's result, we have regarded as a background object. On this basis we assume that these other galaxies are also background objects, though eventually one would hope to verify this. Thus, contrary to one's first impression, VII Zw 466 (with its two companions) is apparently not a cluster member. This seems to be true for Arp 146 and 147 as well.

b) *Arp 147*

Arp 147 is a nearly circular RE with about a dozen crisp, nearly circular knots distributed about the ring. Its companion, lying about one ring diameter away looks like an annulus surrounding a slightly off-center central bulge, somewhat reminiscent of Arp 196. If the companion is disklike, its plane is roughly perpendicular to that of the ring.

We took one spectrogram of this object with the slit aligned to intersect both the ring and its companion. Both objects have strong [O II] λ3727, the ring clearly shows [O III], Hβ, and Hγ in emission, but there is only a hint of [O III] and Hβ in the companion; the companion shows H and K absorption as well as some Balmer lines.

For various reasons we measured only [O II]. The mean redshift of the ring is 9655 km s^{-1}. Velocities of two sides of the ring and of the companion with respect to this reference velocity are given in Figure 8. Sargent (1970) reported a velocity of 9424 km s^{-1} for the composite system (including $+5$ km s^{-1} correction for galactic rotation).

The ring has a reasonably large ellipticity, and also is the one in Table 1 which deviates most from an elliptical shape. If we correct the velocity difference across it for projection using the simple model (i) we have tentatively proposed, we find a velocity difference across the ring of 160 km s^{-1}. This result is hard to interpret, not only because we are hesitant to argue from a single spectrum, but also because the locations of the axes are difficult to ascertain. However, the existence of such a high velocity difference across a diameter so close to the minor axis is suggestive of a nonnegligible expansion or contraction velocity. The need for additional spectra of this ring is very clear.

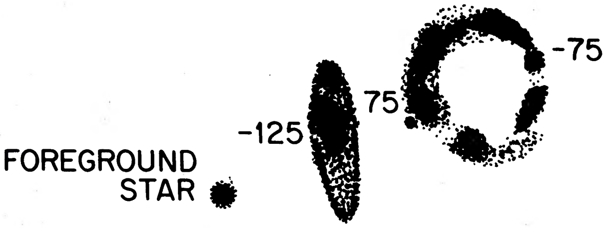

FIG. 8.—Velocity map of Arp 147

Adjusting again for projection we find that the ring and companion are separated by 20 kpc and have a relative velocity of 250 km s^{-1}, which, if interpreted as a velocity separation, gives a separation time of 0.8×10^8 yr. The system is gravitationally bound if the total mass is $\geqslant 2 \times 10^{11} M_\odot$ assuming that the nominal projection factors suggested by the simple model are about right. Implicit in this and the other estimates of separation times is that the objects are moving apart. The model then permits us to decide between expansion or contraction of the ring, given the velocity difference across the minor axis. The evidence for Arp 147, though admittedly very weak, is suggestive of expansion.

c) *I Zw 45*

The RK galaxy I Zw 45 has approximately uniform photographic density around the ring except for a single very bright knot on the end of the minor axis nearest to the companion. On the POSS blue plate one discerns a narrow, very blue filament extending from the knot toward the companion. On a red 4 m plate (shown in Fig. 2) luminous material is seen in the interior of the ring, and this might raise the possibility that the object is a shell. However, as the shape is well described by an ellipse and the companion is on the minor axis, the most plausible model is still a ring.

A spectrogram was taken in the blue with the slit along the minor axis, intersecting the companion. The knot revealed an unusually blue continuum as well as five strong emission lines, [O II] λ3727, [O III] λλ4959, 5007, Hβ, Hγ, Hδ. At the other end of the minor axis the lines and continuum were very much weaker, and only the [O II] doublet could be measured reliably. This measurement indicated no velocity difference across the ring which, on the basis of the simple model we have been using, indicates little or no expansion of the ring, even if the subject is an inherent RK. The redshift of the ring is 8230 km s^{-1}.

The companion to the ring has [O II] emission and weak Ca H and K absorption. Its redshift is 200 km s^{-1} less than that of the ring. With corrections based on the model we find a velocity difference of 250 km s^{-1}, and intrinsic separation of 18 kpc, and a separation time of 0.7×10^8 yr.

d) *II HZ 4*

Figure 1 contains a reproduction of Dr. H. C. Arp's excellent 200 inch Palomar plate of II HZ 4, an RN galaxy whose ring forms a nearly perfect ellipse. The off-centered nucleus of this object appears to be an elliptical galaxy, while the stellar image interior to the ring seems to be a late-type foreground star. The companion outside the ring and just off the minor axis is also an elliptical. At the other end of the minor axis from the ring and just outside is a faint diffuse patch which is also visible on the POSS blue plate but not on the red plate.

The elliptical has a tail extending to the northeast. Moreover, there is a diffuse, faint arc roughly eastward of the ring which is blue (as seen from the POSS plates) and which may be an extension of the tail of the companion. According to Drs. W. W. Sargent and A. Toomre, C. R. Lynds has discovered a companion ring adjacent to the principal ring on its north side. This faint ring can also be discerned on the print recently provided to us by Dr. Arp. The nucleus of the principal ring then becomes a minor axis companion to this secondary ring.

There is, in Dr. Arp's plate, a hint that the principal ring tends to spiral into the nucleus. Perhaps, with better resolution, we would see the same kind of fine structure in the ring as in the object recently discussed by Graham (1975). We should also mention that the interior elliptical has a bulge on its southern edge with a hint of material between the bulge and the ring.

A marginal detection of the O II doublet on the minor axis of the ring plus the H and K lines in absorption for the nucleus and companion provide a mean redshift of 12,885 km s^{-1} for the system. The poor quality of the spectra prevented the extraction of reliable differential velocities but demonstrated that the nucleus, companion, and ring were probably an interacting system. Detailed kinematics for the system have been determined by Lynds (private communication).

e) *II Zw 28*

The only ring in Table 1 without a clearly identifiable companion is II Zw 28. Inspection of Sargent's (1970) 200 inch plate reveals a number of foreground stars in the neighborhood, as expected from the low galactic latitude of the object, but nothing of galactic nature is to be seen. If II Zw 28 had no companion, it would be a unique ring.

On the other hand, the outer contours of II Zw 28 are very nearly circular and if the simple model (i) holds, we would expect the companion to be seen close to the ring in projection. In fact, one side of the ring is very thick and Sargent (1970) has detected Balmer absorption lines (as well as the usual emission lines) in this thickened portion. Strong absorption lines are typically associated with ring companions but not the rings themselves. We suggest the possibility that what appears as a very pronounced thickened portion of the ring hides a companion projected onto the ring. This possibility, which is predicted by the simple model if II Zw 28 is a true ring galaxy, would be testable by a good spectrogram taken with the slit across the minor axis. We would expect to find that the knot has a redshift which is different from that of the ring. If this is borne out, we may consider II Zw 28 to be an accidental RK.

Unfortunately, our only spectrogram of this object has a slit orientation approximately parallel to the major axis of the ring, as in Sargent's spectrum. Even this was contaminated by moonlight, so that absorption lines were not detectable. The redshift of the ring, 8580 km s^{-1}, when corrected for galactic rotation is 50 km s^{-1} smaller than that reported by Sargent. The velocity difference across the major axis is about

80 km s^{-1}. Application of the rather uncertain projection correction indicates a rotation velocity ~ 100 km s^{-1}, which seems reasonable for this object whose diameter is only about 10 kpc.

VIII. CONCLUSION

The objects which we have called R galaxies were selected on the basis of tight criteria in the hope of isolating a single kind of peculiar galaxy. The choice was made as independently as possible of theoretical considerations, and this was fortunate, for once we developed some preference for a model, we were tempted to look favorably on some perhaps less appropriate objects as possibilities. Yet our interpretation of the observations was hampered by this restrictive view, since few statistics were available (Table 1). This situation forced us to include some close seconds (Table 2) in our analysis, but even then, it appears that we were overrestrictive if the broad usage of the term "ring galaxy" in the current literature is any guide.

Even with the relatively small number of R galaxies we have to work with it seems that there is a clear preference for their companions to lie on the minor axes of the rings. Acceptance of this feature as an intrinsic property of the R galaxies has completely shaped our thinking, as has the nearly elliptical form of many rings. This leads us to a model which we wish to summarize briefly here.

The ring itself, R, is an ellipse in first approximation with inherent ellipticity (ratio of minor to major axis) E. It has a companion, C. Some rings may have more than one companion, but we have not attempted to allow for this in the model. One ring (II Zw 28) has no readily detectable companion, but we have postulated one for it. Except for the REs, R galaxies have either an interior off-center nucleus (RN class) or an extremely prominent knot or bulge in the ring itself (RK); let us call either of such objects N.

With O as the center of the ellipse we may draw the lines OC and ON. We believe that the angle between OC and ON is generally reasonably small and *idealize* this belief in the statement that the two lines coincide. Moreover, OC is assumed to lie in (or nearly in) the plane determined by the axis of symmetry and the minor axis of the ring. If the ring is circular, OC lies along the axis of symmetry. Finally, let ψ be the angle between OC and the axis of symmetry. We consider the R galaxies to be approximately described by a sequence of such models lying between two extremes: (i) $\psi = 0$, $E = 1$, (ii) $\psi = 90°$, $E < E_0$, where E_0 is some poorly determined value ~ 0.6. The objects which we called RE galaxies lie near extreme (i), the RKs lie near (ii), and the RN galaxies are in between. The data on ellipticities conform with this picture, but since we are dealing with small number statistics we should be prepared for a rude reversal.

With the help of the model, we were able to interpret the kinematical data. Chiefly, we concluded that the time for the companion to separate from the disk is $\sim 10^8$ yr in all cases where data were available. We reported other data that support this time scale. In Paper II we describe some numerical simulations of self-gravitating rings which suggest that the rings break up in a few times 10^8 yr. This leads us to conclude that the arrival of the companion caused the ring to form.

The qualitative picture that we propose for ring formation is that a disk galaxy, previously consisting mainly of the observed components R and N and perhaps some other debris seen in the vicinity of the ring, was struck by the companion C. The companion passed through the original disk at an angle $\sim\psi$ from its symmetry axis and somewhere near the center. This caused N to be displaced with a resultant reduction in central force. The result is a differential expansion leading to a ring. Originally, component N probably contained much more than just the nucleus of the parent disk galaxy.

In Paper II we shall describe some dynamical calculations bearing on this model. We defer until that time a summary of other theoretical views on the formation of ring galaxies.

Over the years taken to prepare this paper we have benefited from the help of many. Dr. J. Toomre was an equal participant in two of our three spectroscopic runs at KPNO. Many members of the staff at KPNO were very helpful in our initial observing efforts; we thank, among others, A. Hoag, the Stroms, and J. DeVeney. Drs. R. C. Bless, J. Graham, C. R. Lynds, M. V. Penston, M. S. Roberts, and W. W. Sargent provided unpublished material of importance. Dr. H. C. Arp was kind in many ways, especially in permitting us to include here his unpublished 200 inch plate of II HZ 4. We had valuable discussions with L. Woltjer, E. L. Schücking, K. H. Prendergast, and others too numerous to list here. Extensive discussions of spectrographic techniques were held with S. Simkin. We also benefited from the hospitality of several institutions, particularly KPNO, where one of us held a fellowship for two years, and the Goddard Institute for Space Studies, which provided computer support. The photographic assistance of R. Frasel was also appreciated. Finally, we thank the NSF for support under several grants at Columbia, most recently MPS 75-05660, which was essential for the continuance of this work.

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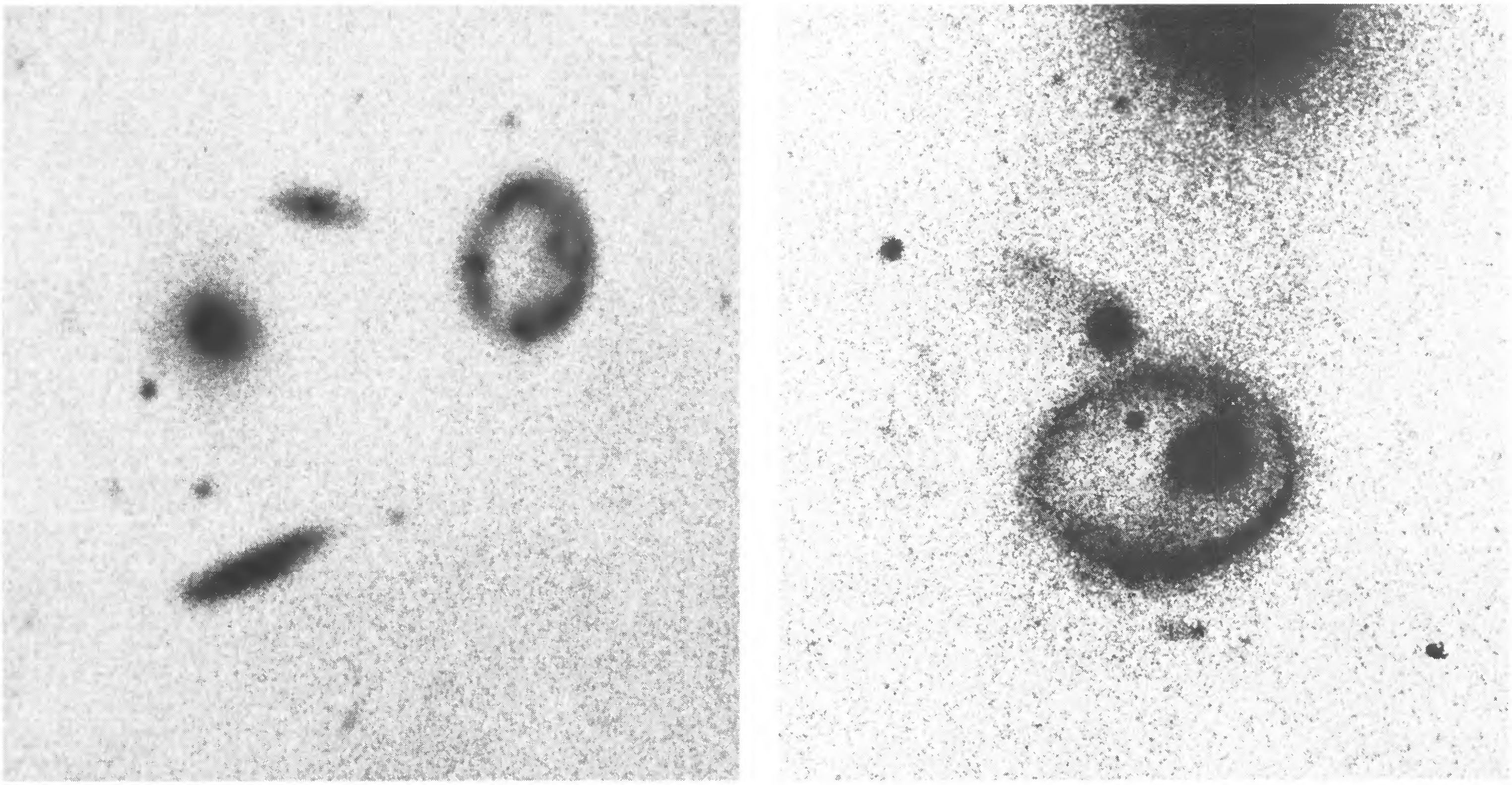

FIG. 1.—(*left*), VII Zw 466 (4 m KPNO *V* Plate); (*right*), II HZ 4 (200 inch Palomar plate provided by Dr. H. C. Arp).

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PLATE 7

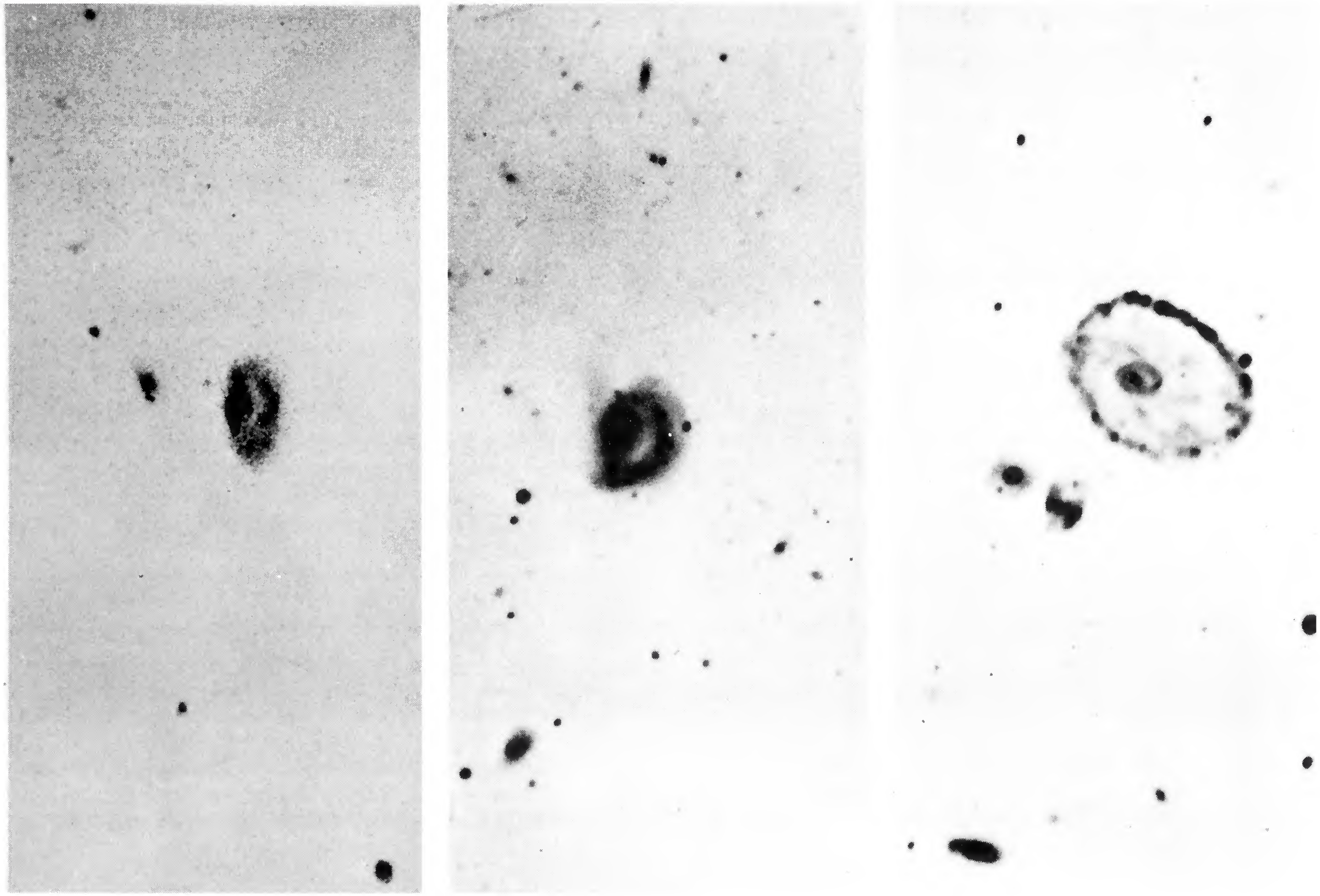

FIG. 2.—(*left to right*), I Zw 45 (two superposed 098−02 plates with RG610 filters), VV 285 (IIIa J), Lü 003−534 (IIIa J). All were taken with KPNO 4 m telescope.

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