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ON THE INTERPRETATION OF RING GALAXIES: THE BINARY RING SYSTEM II Hz 4

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ABSTRACT

It was noticed by one of us that the companion to the ring galaxy II Hz 4 seems embedded in a second and much fainter ring; this discovery supports a simple dynamical mechanism for ring galaxies that had recently occurred to the other.

The present paper displays the new photographs and various spectroscopic data. It also illustrates the proposed mechanism with some computer experiments. In essence, after a companion galaxy has fallen right through a given disk galaxy more or less along the axis, a transient but remarkably severe and ringlike density wave develops as that target disk rebounds from the short-lived extra pull toward its center.

Subject headings: galaxies: internal motions — galaxies: structure

I. INTRODUCTION

A ring galaxy with 1950 coordinates $\alpha = 8^{\mathrm{h}}55^{\mathrm{m}}.3$, $\delta = +37°16'$ was discovered on the Palomar Sky Survey by Emil Herzog in about 1963. As the fourth entry in an informal second list of peculiar galaxies compiled by Herzog, it was designated II Hz 4 by H. C. Arp who in 1965, using the Hale telescope, took the only large-scale photograph of this unusual system that seems to have existed until recently. With Dr. Arp's kind permission, that photograph is here reproduced as Figure 1 (Plate 5).

The large nucleus situated off-center within the ring distinguishes II Hz 4 from such seemingly "purer" ring galaxies (i.e., rings with almost empty interiors) as the well-known objects 146 and 147 in Arp's (1966) *Atlas of Peculiar Galaxies* or the fine example VII Zw 466 illustrated and discussed by Cannon, Lloyd, and Penston (1970), Theys (1973), and Freeman and de Vaucouleurs (1974). On past evidence, indeed, it is valid to ask whether or not these relatively empty ring galaxies are genuinely akin to II Hz 4 and to objects of similar appearance such as the southern ring of Lindsay and Shapley (1960) and Graham (1974) or else another southern ring discovered originally by Zwicky (1941) and reported also by Lü (1971). Theys, who was the first to stress the frequent presence of companions near the apparent minor axes of various ring galaxies, judged them all to be related. However, Freeman and de Vaucouleurs in effect reckoned that any resemblance between the rings with and without obvious interior nuclei is only accidental—before proposing in their recent paper that only the vacant rings (and various "chaotic multinucleated objects, like NGC 2444–5") arise from impacts between galactic gas disks and postulated intergalactic clouds.

In this paper we report the discovery that both kinds of rings appear to be involved in II Hz 4. We believe that this is a crucial observation. Together with the interpretation given below, it should help unify what, until now, has been a puzzling subject.

II. NEW OBSERVATIONS

Three prime-focus photographs of II Hz 4 have been obtained with the recently completed 4 m telescope of Kitt Peak National Observatory. The photographs were made on Eastman IIIaJ emulsion behind a Schott GG385 filter. The reproduction of one of these photographs in Figure 2 (Plate 6) illustrates several features that we deem vital to the present discussion.

First of all, the galaxy-like object within the prominent ring appears to be connected to it by two diametrically situated curved features that resemble spiral arms—suggesting that one is dealing here with a real physical association between a ring and a nuclear mass concentration. Second, there is a clear indication that the system includes a separate but adjacent ringlike feature of low surface brightness, and of a size and aspect nearly identical with those of the principal ring. (Traces of this additional feature to the north can be discerned in the original Arp photograph.) The reality of this second ring was confirmed by the two extra plates. The photographic sum of all three Kitt Peak plates is reproduced in Figure 3 (Plate 7) and certainly portrays a remarkable object. Finally, the galaxy near the north edge of the principal ring seems to be situated within—although just barely within—the faint northern ring, and its curved

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* Operated by AURA, Inc., under contract with the NSF.

luminous extension toward the northeast seems to terminate at the edge of that second ring.

In view of these likely nucleus-to-ring connections, plus the similarities in shape and dimensions of the rings themselves, it seems natural to propose that in II Hz 4 we are observing a real physical association between two ring galaxies, each of which possesses a noncentral nuclear concentration of mass. Apart from the brightness, the only pronounced difference between these two ring galaxies seems to involve the *locations* of their respective nuclei.

Concurrently with the direct photography, a program of slit spectroscopy of II Hz 4 was undertaken with an image-tube spectrograph on the Kitt Peak 2.1 m telescope. With the exception of one widened spectrogram of the north companion galaxy, all spectrograms were obtained without trailing and with the spectrograph slit generally crossing several points in the system. For two of the spectrograms, the slit was placed at a position angle of 1°3; in one case the slit passed through the north companion and through a knot on the southern edge of the principal ring, whereas in the other case it passed through the west edge of the faint northern ring and intersected the principal ring likewise near its west end. For the remaining eight spectrograms, the slit was set at a position angle of 90° and passed, variously, through the north companion, through the nucleus of the principal ring, and through the northern and southern edges of that ring.

The spectra of the nuclei of both ring galaxies show the H and K lines of Ca II, the G and *b* bands, and the D doublet of Na I; no emission lines were detected with certainty in either object. By contrast, the principal ring at various points covered by the observations shows the Balmer lines of hydrogen in emission, as well as the usual forbidden emission lines of N II, O II, O III, and S II. On spectrograms for which the slit crossed the faint northern ring, only a featureless continuum was recorded.

All observed spectral lines were measured to determine radial velocities. Many of these measured features were omitted in the later analysis owing to possible uncertainties introduced by blending with the airglow spectrum and, in the case of the [O II] doublet, owing to uncertainty about the appropriate effective rest wavelength. Corrections were made for the Earth's heliocentric motion, for wavelength-dependent projected-slit curvature, and for the wavelength dependence of the spectrograph velocity system. The results of this analysis are given in Table 1. The first column identifies the features or locations; succeeding columns give the radial velocity relative to 12,840 km s^{-1}, an estimate of probable error, the number of lines contributing to each final velocity, and the number of spectrograms available for each determination. A rather thorough error analysis indicated standard deviations of about 40 and 70 km s^{-1} per line measurement for emission and absorption lines, respectively. Moreover, these standard deviations seemed to correlate well with the weights which were estimated at the time of measurement and which were later employed to establish the probable errors quoted in the table.

Apart from a general agreement that the systemic velocity of II Hz 4 is indeed somewhat larger than 12,500 km s^{-1}, the detailed radial velocities given in Table 1 are, for unknown reasons, almost entirely discordant with those given by Theys (1973). In particular, we have been unable to corroborate that the northern galaxy appears blueshifted relative to the principal nucleus by anything like the 440 or 650 km s^{-1} estimated by Theys. The system as a whole is clearly very nonenergetic in the line of sight; the standard deviation of all final average velocities reported in Table 1 is only 30 km s^{-1}.

This last fact probably removes any lingering suspicion that the apparent proximity of the components of II Hz 4 stems from chance superposition. But otherwise, for anyone who becomes cautious at the 3 σ level, there appears to be not a single velocity difference of assured significance in the entire system. Even that result, though essentially negative, needs to be accommodated by any successful dynamical model.

III. DYNAMICAL MODEL

Obviously, the double structure of II Hz 4 challenges the few theories of ring galaxies that have been proposed. In fact, it seems to us that none of the published

TABLE 1

RADIAL VELOCITIES IN THE II Hz 4 SYSTEM

Feature*	V_r − 12,840 (km s^{-1})	Probable Error	Number of Lines	Number of Spectra
Nucleus.......	+30	20	5	3
Companion....	−20	40	5	3
20°..........	+50	60	2	2
55°..........	+40	(80)	1	1
85°..........	−60	20	2	2
135°..........	−10	10	7	3
160°..........	−20	10	3	2
245°..........	−20	20	3	1
270°..........	−10	10	5	3
295°..........	+10	20	3	1

* Position angles for points on the principal ring have been reckoned from the nucleus.

ideas can be adapted at all easily to account for this new finding. Instead, we favor a symmetrical occurrence of the following simple process which itself seems also capable of explaining the various observed single rings having companions.

Our basic process requires one fairly concentrated galaxy to penetrate a disklike second galaxy of comparable mass at roughly normal incidence and at some spot near its center. In this picture, unlike that of Freeman and de Vaucouleurs (1974) involving a galaxy and a gas cloud, the vital result of such a rare encounter is not any direct impact of the gaseous constituents of the two systems. Nor do we envisage any knocking out of one massive stellar nucleus by some sort of enhanced dynamical friction against the other galaxy, followed at once by centrifugal expansion of the surviving disk owing to its weakened central force of gravity—which is a theme that Spiegel and Theys (private communications 1972–1975) long seemed to favor. We think it unnecessary for the "collision" to expel either the nucleus or any gaseous disk, because it seems to us that already the brief *inward* pull exerted by the galaxy in transit can convert an existing disk into a severely ringlike structure.

To understand that process—and also to appreciate intuitively why such imposed forces should require only a modest fraction of a rotation period to accomplish this conversion—it may be helpful to consider the following analogy. Suppose that another star wanders into the solar system exactly along the axis normal to the Earth's orbit; indeed, pretend that this other star started from rest at infinity and that it now falls unimpeded directly through the Sun and out the other side.

In such a case, one would naturally expect the Earth's distance from the Sun to decrease markedly during the 5 or 6 weeks that the intruder would spend within 1 AU of the Sun. However, such inward motion could clearly not continue for long; soon the extra force would rapidly diminish, and the Earth would "bounce" back centrifugally. These naïve expectations are confirmed with a vengeance by actual calculations such as reported in Figure 4; the heavy curve there shows just how vigorous such a rebound would be if the intruding star had itself contained one solar mass. (Technically, the Earth would still remain bound to the Sun, but the aphelion of its resulting orbit would lie at about 5.5 AU.) Even so, it is not just the vigor of the response that deserves emphasis here; yet more instructive is the addition to this diagram of the mathematically similar time-histories $r(t)$ expected for the planets Mercury, Venus, and Mars. Notice in Figure 4 how all four of these independent trajectories crowd together for several months following the transit. All four inner planets would then find themselves at about the *same, but increasing*, distance from the Sun!

The above crowding stems, of course, from the fact that the Keplerian radial dependence of the dynamical time scales for various planets causes these "oscillators" to drift out of phase. However, a very similar phenomenon must arise even when various stars in the disk of one galaxy are shaken radially by a second galaxy falling nearly through the center. And it is just that analogous kind of transient but severe radial crowding—together with its rapid advance outward—which we now propose as the basic explanation of most ring galaxies including II Hz 4.

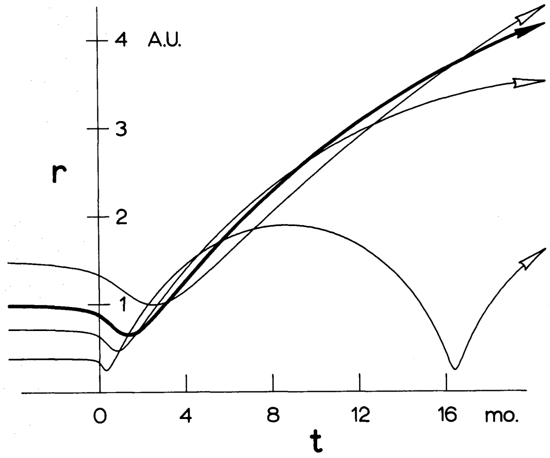

FIG. 4.—Solar system analogy. The computed distance r (in AU) from the axis of symmetry is shown plotted against time t (in months, reckoned from perihelion) for each of the four inner planets in this make-believe deep encounter with another star of 1 $M_{\odot}$.

Figure 5 illustrates the phenomenon more explicitly in a situation where the "victim" disk plays the role of a galaxy consisting no longer of mere test particles. Here the relative mass of the intruder was taken to be two-thirds that of the target galaxy. In the latter galaxy, only one-third of the total mass was ascribed to a central particle (representing a modest spheroidal nucleus); the other two-thirds of the mass was divided equally among 16 discrete rings spaced in radius so as to approximate a smooth Gaussian law of surface density, $\mu(r) \propto \exp(-r^2/2r_0^2)$, where r_0 is a scale length marked in Figure 5. Our choice of exactly 16 rings was of course arbitrary; we adopted that number for graphical convenience only after verifying that the behavior of those 16 rings already resembles closely the behavior of 24 and 32 rings—and hence presumably also that of a continuous disk.

Long before the encounter pictured in Figure 5, these initially coplanar rings were assigned only the circular velocities needed for centrifugal equilibrium. We were careful to ensure that such a "cold" equilibrium disk was stable—at least in an axisymmetric sense. For this purpose we borrowed a trick from Erickson (1974) and Miller (1974) and "softened" the gravitational potential of every mass element dM in the model from an exact $-(G/s)dM$ to an artificial $-G(s^2 + a^2)^{-1/2}dM$, where s denotes distance from that element and a is a fixed length—here set equal to $r_0/3$. The same softened gravity was presumed to govern the interaction between the approaching body and various rings in our disk; however, because that pointlike intruder was itself meant to represent some

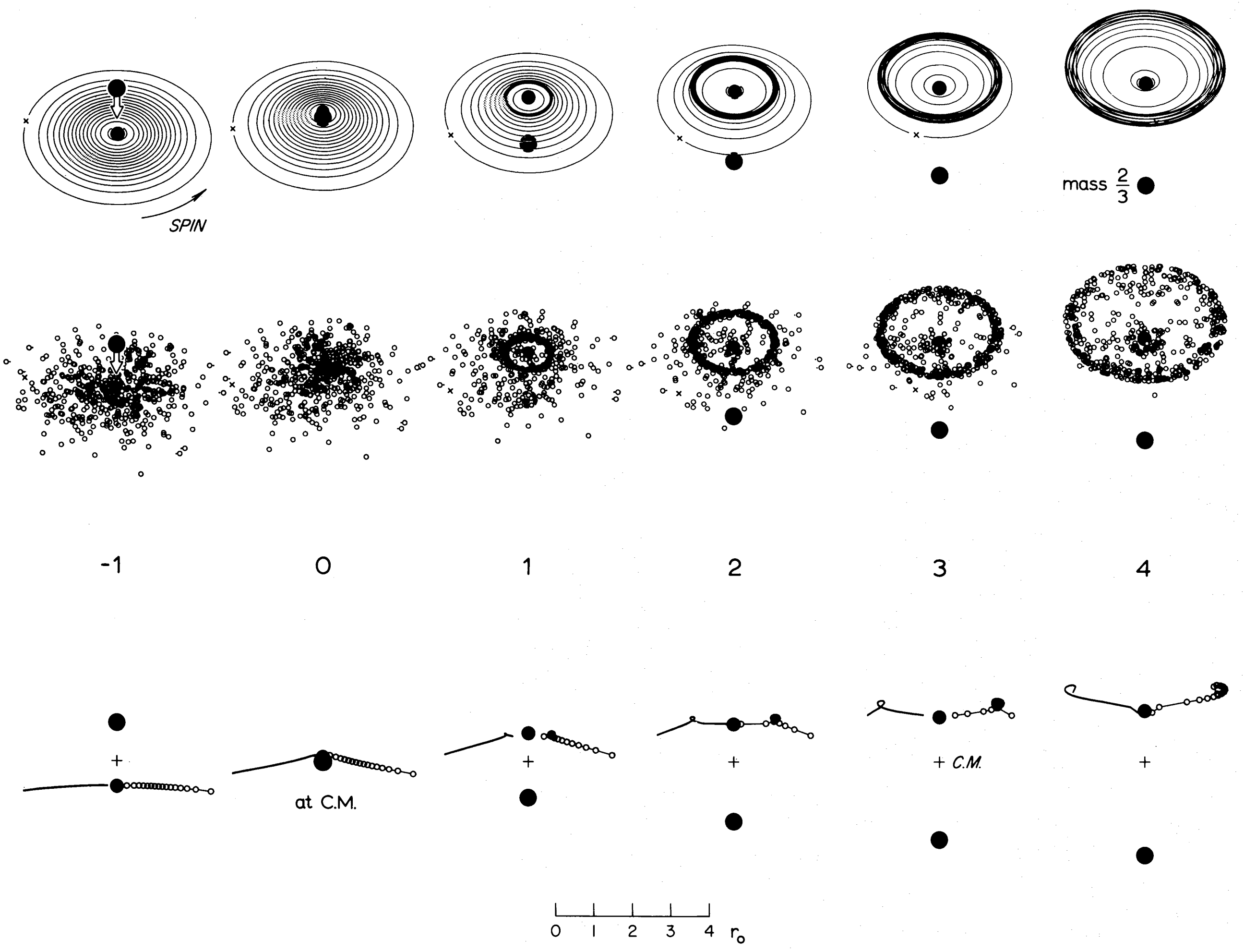

FIG. 5.—Results of an axial penetration of a Gaussian disk galaxy of mass M by another, more pointlike mass $2M/3$; one-third of the former mass resides at the very center of the disk. Time is reckoned in units of $(r_0^3/GM)^{1/2}$ from the instant when the intruder reaches the center of mass of the system. The gravity in this example was somewhat "softened" at close range in the manner described in the text.

small spheroidal galaxy not unlike the central bulge of our target galaxy, the softening length a for the attraction between those spheroidal masses was plausibly increased to $r_0/2$.

The interesting commotion that results from this improbably precise encounter is displayed in three parallel ways in Figure 5. The top row shows the evolving configurations of the 16 elementary rings, viewed from a latitude of 45°. Such a diagram probably exaggerates the importance of the outer rings owing to the greater required amount of ink; hence the first sequence is repeated in the second row as if we had performed our computations with 500 rings and were now exhibiting, from each ring, just one randomly selected particle in its successive positions. (In fact, we were hardly so extravagant; that second set of illustrations actually stems from a 32-ring calculation, followed by linear interpolations.) Finally, for the best view of the three-dimensional nature of the disturbance, the bottom row of illustrations in Figure 5 repeats the 16-ring results in cross section.

As expected, these vertical displacements are not very severe. In essence, therefore, the outward-moving locus of greatly enhanced density in Figure 5 is simply a transient *density wave* of an amplitude much greater than, for instance, the expanding circular ripples obtained by Hohl (1970) from n-body experiments with disks begun not exactly in equilibrium. Evidently the speed of propagation of our wave is such as to maintain, for frames 1 through 4, an approximate equality between the diameter of the expanding ring and the distance to the receding intruder.

At that, our collisionless dynamical demonstration of such a density wave probably underplays the ring-making capabilities of the model. In particular, notice in the cross-sectional views of Figure 5 how various elementary rings in the vibrating disk move past

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each other in a kind of toroidal flow in the vicinity of the density maximum. Any interstellar clouds present could hardly interpenetrate in such an easy manner but would usually collide with each other. For that reason, our density wave should function somewhat like a snowplow in pushing interstellar material before it. In effect, it would produce a circular shock wave. Hence, just as in the usual spiral density-wave picture, we very much *suspect* that such a process would enhance the formation of the bright young stars and H II regions that indeed appear to accentuate many of the observed ring structures (even if not to any dramatic extent those in II Hz 4).

Of vital concern, of course, is the question of whether or not the proposed mechanism requires too much perfection in the symmetry of the encounter. Although a firm answer is not known yet, we can draw some comfort from two preliminary results of Toomre (1976), based on numerical experiments with disks of test particles: (1) It appears that central impacts along trajectories tilted by 30° and often by as much as 45° from the disk axis still yield fairly acceptable ring shapes. (2) Restrictions on the impact parameter are more stringent; in essence, the intruding galaxy needs to pierce the target disk within approximately the central 15 percent of its outer radius.

To put these estimates into perspective, recall that the usual fierce tidal interactions between galaxies require approaches to within about 1.5 radii (assuming parabolic speeds). Hence even with some gravitational focusing of the orbits, the likelihood of producing a ring galaxy in the present manner by chance encounter in small groups of galaxies, or by the falling together of two galaxies from great distance, seems to be very roughly 1/300 that of producing tails, bridges, or some less picturesque aftermath perhaps best described as a mess. Moreover, our comparative chances of observing rings at any given epoch are further reduced by the relatively short lifetimes implied for such objects by Figure 5. On the other hand, fewer than a dozen impressive ring galaxies have been reported thus far, and their redshifts indeed suggest a space density small by a factor of order 10^3 than even that of other *peculiar* galaxies. Needless to say, this rough agreement does not prove anything, but it is at least not disconcerting.

Turning now to II Hz 4 itself, we find that a *slight* miss distance can actually be advantageous. Figure 6 illustrates such a mildly off-center evolution for one of several idealized examples that we have explored. The word "idealized" applies for at least two reasons. One reason is that we were forced to revert to test particles in performing these nonaxisymmetric calculations. The other is that, although the orientation of either disk could have been altered by as much as 30° from normal incidence without seriously degrading the ring-making, we opted here for a simple geometry in which the original spin axes of the disks are parallel not only to each other but also to the relative velocity vector of the two nuclei at their instant of closest approach.

In Figure 6 the upper two rows of illustrations depict the separate evolution of each model galaxy; the bottom row shows the joint evolution, both disks there having begun as Gaussian ensembles of randomly placed particles. The viewing angle remains 45°, even though a slightly more pole-on display seems preferable for the final product in frames 3 and 4.

In defense of our renewed use of test particles to explore a situation where the self-gravity of the real disks might be far from negligible, notice that the length of the major axis of the darker ring in frames 2, 3, and 4 seems to be about 2.0, 2.7, and 3.3 times r_0, respectively. These values are essentially the same as ones obtained in a strictly axisymmetric calculation using the test particles. By contrast, the ring diameters found at identical times in a rerun of the axisymmetric calculations of Figure 5—now using a half-mass intruding galaxy, but the same moderately softened self-gravity as before—were 2.3, 3.1, and 3.9 times r_0, or only about 15 percent larger. We believe that this again illustrates that, although the present ring-making is indeed wavelike, our wave is basically *kinematic* and not indebted much to self-gravitation.

In its geometrical resemblance to II Hz 4, Figure 4 speaks pretty much for itself. The similarity of its frames 2 and 3 to the actual form of II Hz 4 is especially striking. It tempts us to conclude that already our crude model probably contains most of the essential elements of the recent history of this intriguing binary system.

IV. DISCUSSION

Several inferences remain. For one thing, it seems clear that at least one of the two disk galaxies in II Hz 4 must have contained relatively little gas for the two systems to have interpenetrated so cleanly.

A second item is that the coincidence of finding a *double* ring galaxy becomes far less astonishing once we recall that the chief element of luck in the present hypothesis concerns the impact parameter. In fact, once one postulates the good aim needed to produce the principal ring—and also hypothesizes that the second galaxy had a disk of comparable radius—then the experiments cited above imply that perhaps as many as one-quarter of all conceivable *angular* orientations of the lesser disk will permit the development of a noteworthy second ring!

A third topic concerns the expected velocities. Broadly speaking, our model requires a tangential motion for the material in the ring that is comparable to the present speed of the companion, and a degree of expansion that is perhaps smaller by a factor of 2 or 3. More specifically, Figure 6 implies in its frame 4, for instance, that the line-of-sight velocity of the smaller nucleus relative to the larger should be about -0.43 times $(GM/r_0)^{1/2}$; by contrast, the analogous speeds in the principal ring would then be, with considerable scatter, roughly $+0.2$, -0.3, -0.15, and $+0.6$ near the points labeled N, E, S, and W, respectively. The latter numbers are, of course, to be regarded as mere examples. Not only do various

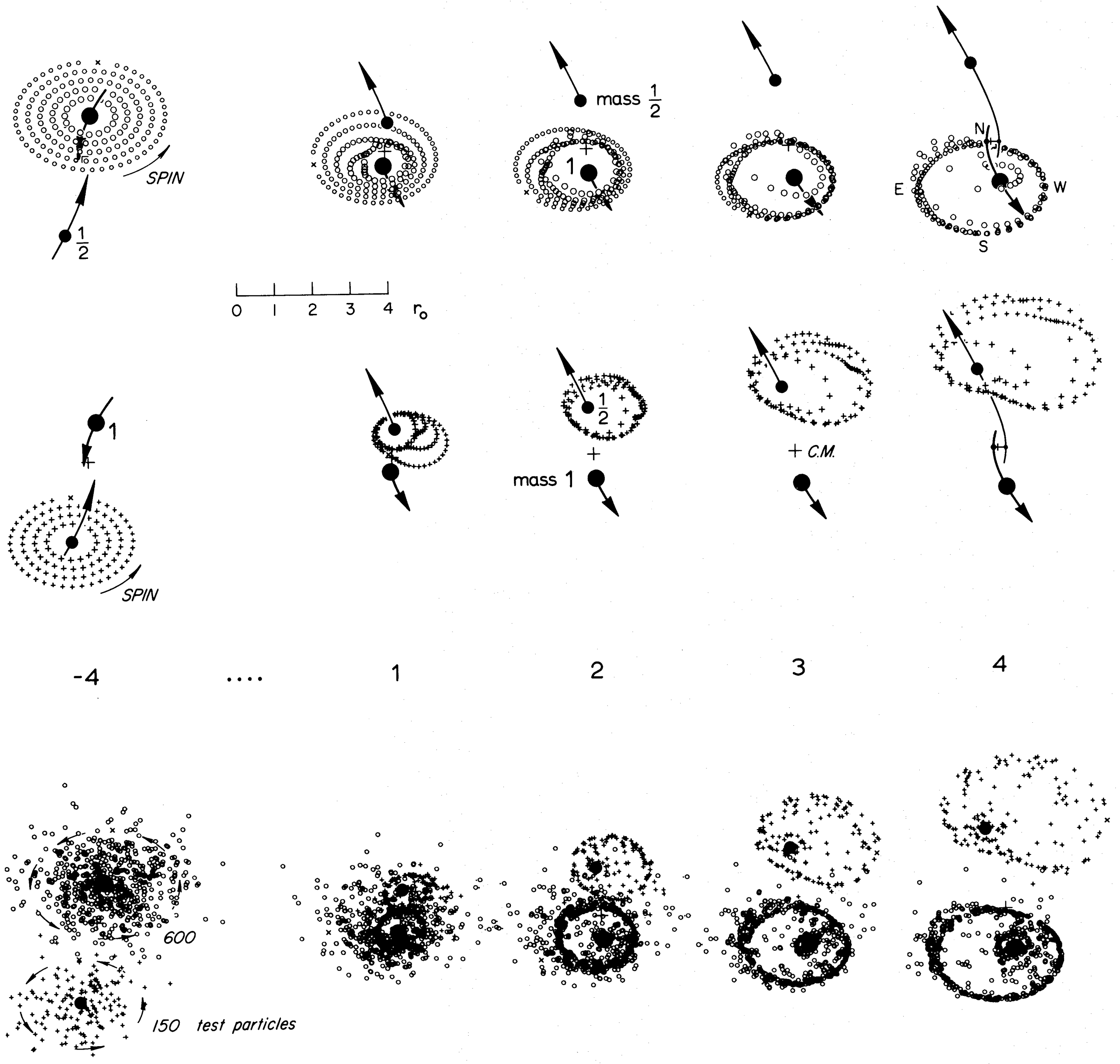

FIG. 6.—An idealized dynamical model of II Hz 4. Used here were two initially parallel disks of test particles surrounding central masses M and $M/2$, each with an appreciably softened close-range gravity. Their interpenetration occurs exactly perpendicular to both disks, at a center-to-center separation $r_0/3$ and with the relative speed developed in free fall from infinity. Time is again reckoned in units of $(r_0^3/GM)^{1/2}$ from the instant 0 of closest approach (itself not pictured here). The top two rows display separately the distortions of the two disks, there composed initially of particles at only the evenly spaced radii 2, 3, 4, ... times $r_0/3$; the bottom row shows the simultaneous evolution of two initially Gaussian distributions of test particles in the same two disks.

angular dependences remain to be determined, but in essence we have merely *assumed* in Figure 6 that both the companion galaxy and the east end of the principal ring are actually approaching us relative to the larger nucleus. As yet, the surprisingly small differences in the actual line-of-sight motions reported in § II only encourage—but cannot certify—even these two assumptions. Fortunately, either or both of these velocity senses can be reversed without serious detriment to the appearance of our model. However, conversely, any significant observational check of the kinematics of this model of II Hz 4 needs to await yet more accurate radial velocities.

Fourth, speaking of observed velocities, if in Table 1 we ignore the two entries of distinctly low weight and accept at face value the remaining V_r determinations in the ring, we see that the east end of that ring might be approaching at about 50 km s^{-1} with respect to the west end. On the assumption that the 45° viewing angle is roughly correct, this implies that the average circular velocity of the material in the ring is perhaps 35 km s^{-1}, or at most, say, 50 km s^{-1}. Even this modest result says something unusual about II Hz 4: Given that the 30″ major axis of the principal ring translates to about 30 kpc in reality, it seems that the total mass of the larger galaxy must be less than 10^{10} $M_\odot$—even though its diameter possibly exceeds that of our Galaxy.

Lastly, but perhaps most important, it is fascinating to observe in Figure 6 how relatively easy it seems for both nuclei—especially the less massive—to get pulled off-center in this not very asymmetric encounter. That effect would have been even more pronounced if our computer simulation had been repeated with a pericenter distance that was twice as large. In such a case, the lesser ring in frames 3 and 4 would not only have appeared slightly more devoid of test particles in its interior, but even its nuclear mass would have seemed almost to have become buried in the "southeast" side of the theoretical ring. We cannot help suspecting that such *lateral* mobility of the former central masses or nuclei has special relevance to other rings heretofore characterized as empty.

Among the colleagues to whom we are indebted, we would especially like to thank Su Shu Huang, Martin Schwarzschild, François Schweizer, and John Theys for valuable discussions, and Chip Arp for his characteristic generosity in providing us with his long-unpublished photograph of II Hz 4. One of us (R. L.) is also grateful to T. D. Kinman for pointing out the early discovery by Zwicky and to Mort Roberts for tracking down the reference; moreover, some of the spectrograms were obtained in collaboration with Jean Goad. The other (A. T.) benefited greatly from a recent six-month visit to Caltech as a Sherman Fairchild Scholar, and both of us appreciate the continued support of the National Science Foundation.

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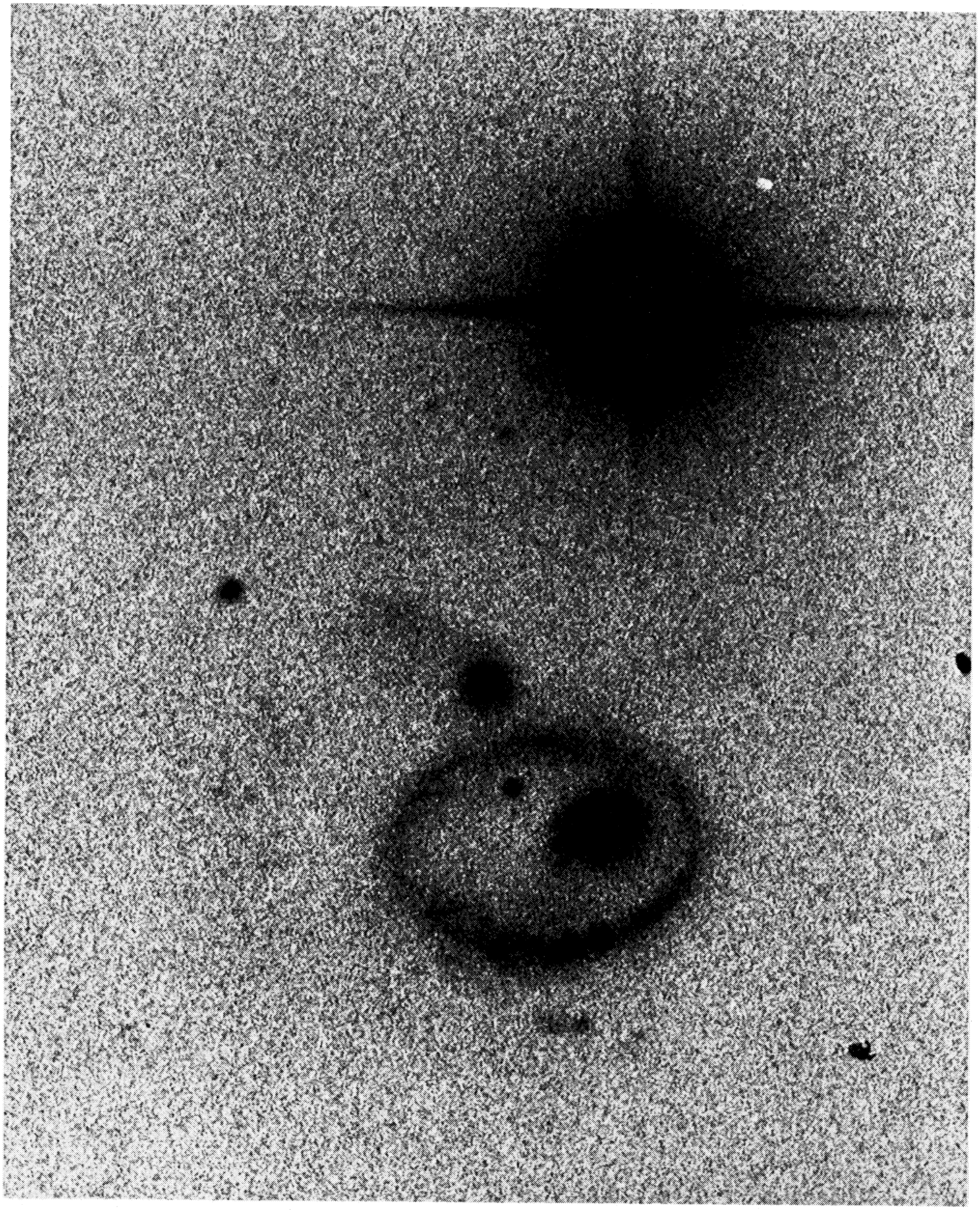

FIG. 1.—Photograph of II Hz 4 obtained by Arp with the Hale Telescope. The exposure was 30 minutes on 103aJ emulsion with no filter. The scale of the illustration is approximately 5 seconds of arc per cm.

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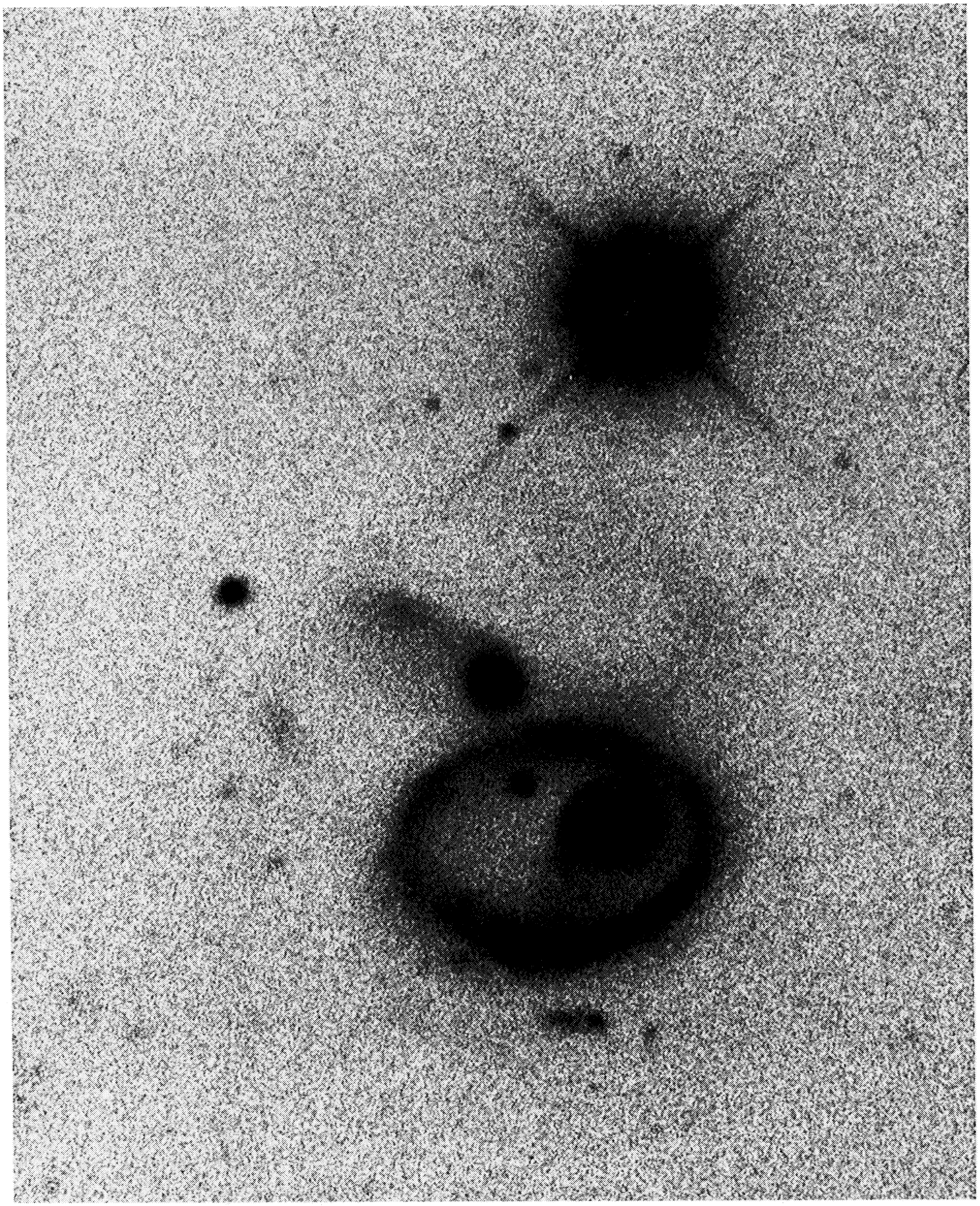

FIG. 2.—Photograph of II Hz 4 obtained with the 4 m telescope of the Kitt Peak National Observatory. The exposure was 45 minutes on IIIaJ emulsion with a GG385 filter. Scale, same as for Fig. 1.

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PLATE 7

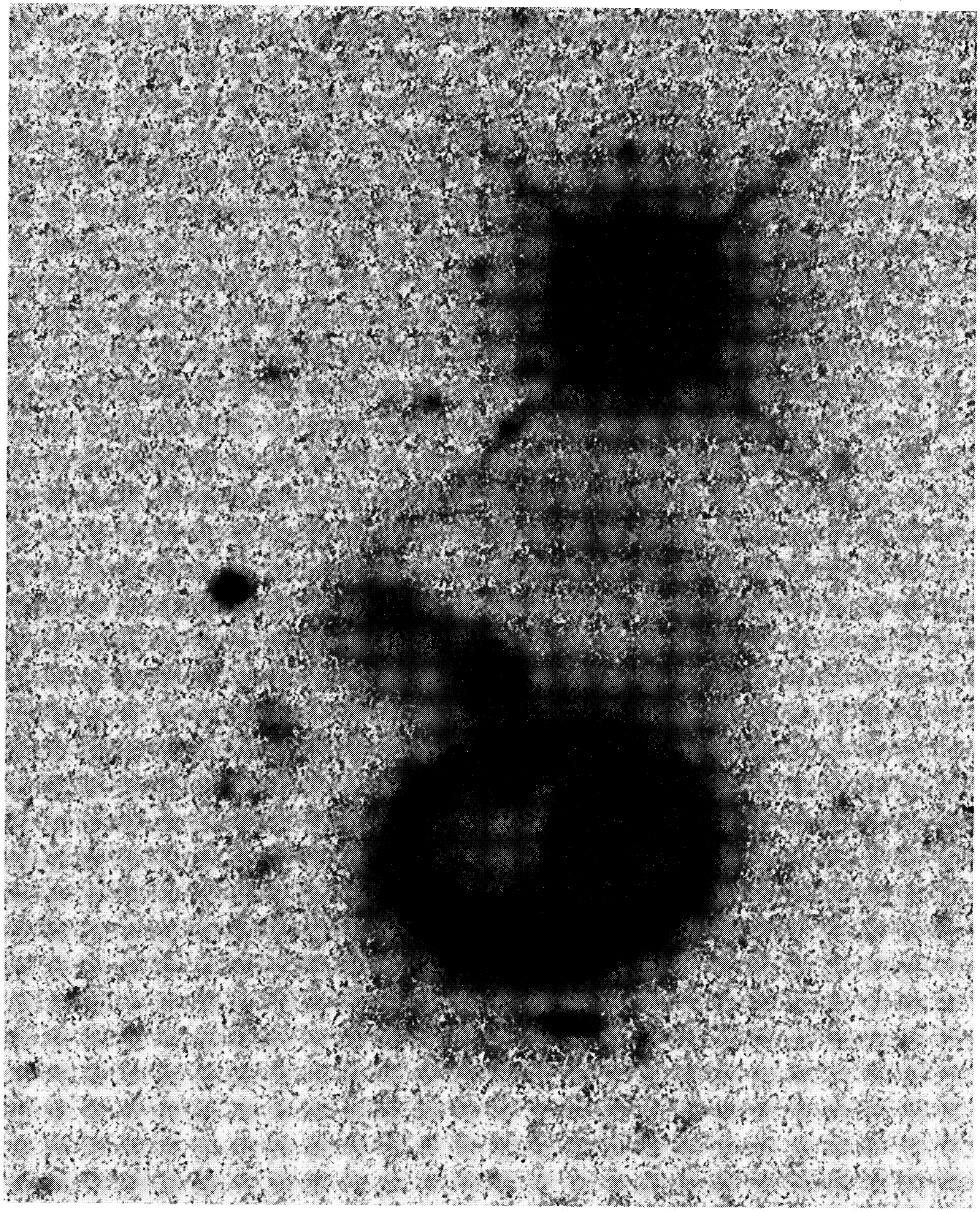

FIG. 3.—Photograph of II Hz 4 made by photographic addition of three plates like the one reproduced in Fig. 2. North is at the top; east is toward the left.

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