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A MODEL FOR RING GALAXIES: ARP 147–LIKE SYSTEMS

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ABSTRACT

The galaxy Arp 147 belongs to a class of objects believed to have formed a ring as a result of a collision with a second galaxy. We have produced a combined stellar and gasdynamical computer model of a pair of interacting galaxies which exhibits many of the features seen in Arp 147. In our model, the ring forms in a disk galaxy following the passage of an equal-mass elliptical galaxy approximately perpendicular through the disk, about two radial scale lengths from the center. Some generic features of this type of collision are that (1) "hot spots" of increased gas density and shocks occur on opposite sides of the ring, away from the nucleus; (2) an incomplete ring forms, with the disk galaxy's remnant nucleus offset from the center and no longer in the plane of the disk; and (3) this nucleus can appear buried in one edge of the ring depending on the orientation relative to the observer.

Subject headings: galaxies: individual: Arp 147 — galaxies: interactions — galaxies: kinematics and dynamics

1. INTRODUCTION

Ring galaxies are of great current interest because they appear to be a unique laboratory for the study of recent star formation. Many ring galaxies exhibit evidence of high levels of recent star formation. For example, Arp 147 has elevated far-infrared emission (Appleton & Struck-Marcell 1987a), bright H II emission (Sargent 1970), and blue spectral colors (Schultz et al. 1990). In the galaxy VII Zw 466, Thompson & Theys (1978) found the ring to be very blue, and Marcum, Appleton, & Higdon (1991) have found a radial color gradient between the ring and the center of the Cartwheel Galaxy that has been interpreted as an indication of progressive star formation. Thus, an understanding of the times for a ring to form and to traverse a region of the galaxy give information about some important time scales for star formation. An understanding of the physical conditions in the ring and the galaxy as a whole will also provide important clues to the process of star formation following the passage of the density wave induced by a collision.

Large-scale ring structures in galaxies can be produced by a collision with a second galaxy. Lynds & Toomre (1976), Toomre (1978), Appleton & James (1990), Appleton & Struck-Marcell (1987a, b), and Struck-Marcell & Lotan (1990) have shown that a collision between an elliptical and a disk galaxy, with the collision taking place approximately perpendicularly to the disk and close to the disk center, leads to the formation of a ring of galactic dimensions. Observational evidence for the collision hypothesis of ring galaxy formation has been provided by, among others, Theys & Spiegel (1976). They found that 15 of 16 bright ring galaxies had nearby companions.

Here we summarize the results from a series of numerical simulations designed to explore the collision mechanism for producing ring galaxies. In these simulations we follow fully three-dimensional collisions between a disk galaxy, including stars and gas, and a spherical, gasless galaxy. Our results show (1) the formation of ring and arc structures for impacts perpendicular to the plane of the disk, in both the stars and the gas; (2) a displacement of the disk galaxy nucleus normal to the plane of the disk; (3) that the outwardly propagating ring or arc of excess density in the gas interacts with outer, infalling material to produce regions of shocks and dense gas, thus providing a region primed for star formation; and (4) that regions of high volume gas densities do not necessarily coincide with regions of high surface gas densities. In many of our models the surface density, integrated along a given line of sight, peaks in the nucleus of the galaxy even though the volume gas density is greatest in the ring or arc. For this reason measured values of gas surface density alone may not be adequate for predicting the occurrence and quantity of star formation. A more complete description of the numerical simulations and the origin of these results is contained in Gerber, Lamb, & Balsara (1992a, b).

One particular subclass of ring galaxies, denoted RE by Theys & Spiegel, has well-developed rings or partial rings, but their interiors are empty, apparently lacking the expected remnant nucleus of the disk galaxy. Lynds & Toomre (1976) speculated that an off-center collision could displace the nucleus and make it appear buried in the ring. Observational support that a remnant nucleus could appear embedded in the ring was provided by photometry of the RE galaxy VII Zw 466 (Thompson & Theys 1978) and *IUE* spectra of the RE galaxy Arp 147 (Schultz et al. 1991). In both cases, the suspected remnant nucleus, distinguished from other knots by its lack of recent star formation, has been found, apparently lying in the ring or very near one side of the ring in the case of VII Zw 466.

Our simulations show that a collision between equal-mass galaxies with the impact perpendicular to the disk results in a displacement of the nucleus normal to the disk. This effect has also been seen in the experiments of Lynds & Toomre (1976) and Huang & Stewart (1988). This displacement allows for the possibility that the nucleus can appear superposed on the ring or arc from certain viewing angles. In order to observe this effect, the disk plane must be tipped to the line of sight, and we expect that a viewing angle near 45° ± 10° would be optimal. A more face-on view would reveal the nucleus to be distinct from the ring or arc, and a more edge-on view makes it hard to identify ring or arc structure in the galaxy. At late times in the ring evolution the ring becomes more diffuse as it expands. In this situation, the nucleus is less likely to be confused as a knot embedded in the ring.

In the remainder of this *Letter*, we present the results of a simulation of an off-center collision between a disk galaxy and

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an elliptical to demonstrate that a ring, with the nucleus apparently buried within it, can be formed. We provide a view of this simulation at a time in the evolution, and from a vantage point in space, when the model closely resembles our view of the Arp 147 system, so that a comparison can be made between the model and observations of star formation in violently disturbed regions.

Our computational method and initial galaxy models are summarized in § 2, and one particular off-center collision simulation is introduced. In § 3 we report the results of this simulation and present it in the context of observations of the Arp 147 system. Section 4 contains a discussion of these results.

2. THE MODEL AND NUMERICAL METHODS

2.1. *Numerical Methods*

Our model disk galaxy consists of an exponential disk of gas and stars surrounded by a massive, almost spherical stellar halo. The elliptical galaxy consists of a spherical distribution of stars only.

The gasdynamics is handled numerically using the method of smoothed particle hydrodynamics (SPH) (Lucy 1977; Gingold & Monaghan 1982; Hernquist & Katz 1989; Balsara 1990). In SPH, particles are used to represent the gas continuum. The density at the position of a particle is obtained by smoothing out the mass of neighboring particles using an analytic smoothing function (we use the M_5 spherical spline kernel of Balsara 1990) and forces are calculated by taking gradients of a smoothed estimate of the pressure. We use Balsara's artificial viscosity formulation to capture shock behavior. We use an ideal gas equation of state and assume that the gas cooling time is less than a typical time step in our calculation so that each gas particle retains its initial temperature.

The gravitational force is calculated by standard particle-mesh (PM) techniques (see Hockney & Eastwood 1988). The gravitational potential is calculated at only a restricted number of points on a three-dimensional grid and the force on an individual particle is determined by interpolation between grid points. Both the stellar and SPH particles contribute to the gravitational potential. In the experiments described in this paper we use a cubic grid with 64 points along each side. More details of the combined code can be found in Balsara (1990), where tests of it are presented.

2.2. *Model Galaxies*

The stellar disk with surrounding halo was constructed in a manner similar to that described in Barnes (1988). A spherical King model (King 1966; Binney & Tremaine 1987) consisting of 2×10^4 particles was allowed to evolve as the force due to an exponential disk, which had a mass $\frac{2}{5}$ that of the halo, was slowly added. The disk was populated with 2×10^4 particles in rotation around the center and Toomre's stability parameter, Q (Toomre 1964), was set to 1.5 everywhere in the disk. The three-dimensional density distribution, ρ, of the disk is

$$\rho(R, z) = \frac{\Sigma(R)}{2H} \operatorname{sech}^2 \frac{z}{H}, \tag{1}$$

where $H = \sigma_z^2(R)/\pi G \Sigma(R)$, and $\Sigma(R) = M_{\rm exp}/2\pi R_d^2 \exp(-R/R_d)$. The scale height, H, was set constant with radius. $\sigma_z^2(R)$ is the velocity dispersion in the z-direction, which is normal to the disk plane. $M_{\rm exp}$ is the total mass of a radially infinite exponential disk with disk radial scale length, R_d. The disk density distribution is cut off at $4.4R_d$, interior to which radius the mass is $0.93M_{\rm exp}$. In the z-direction the density distribution of the disk was cut off after 2 scale heights, where the density is 0.07 of its value at $z = 0$.

Approximately 2×10^4 SPH particles were placed throughout the disk to give a density distribution that followed that of the disk stars with a total mass equal to one-tenth that of the stellar disk. The SPH particles were placed in circular orbits around the center of the disk.

The gasless elliptical galaxy was represented by a spherical King model with 5000 star particles of total mass equal to that of the disk galaxy and was given a radius approximately that of the disk galaxy halo. The initial relative speed of the two centers of mass was chosen to give a mildly hyperbolic orbit. The initial center of mass separation of the two galaxies was about 7 radial disk lengths at the start of the experiment.

As a test of their stability, the models were evolved in isolation for a period longer than the duration of our collision experiments. The disk exhibited a tendency to produce low-amplitude sheared spiral patterns and expanded slightly normal to the plane, but no large-scale changes in the galaxies occurred.

2.3. *An Off-Center Collision Model*

The simulation chosen for comparison with observations of the Arp 147 system is one in which the center of mass of the elliptical intersects the plane about 2 scale lengths, i.e., about $\frac{2}{5}$ of the truncated disk radius, from the center of the disk galaxy. Of the simulations produced by Gerber et al. (1992a, b), this particular model gave the closest fit to the observed parameters of Arp 147. However, it was not constructed to fit the observations explicitly.

When comparing model results to observations it is convenient to assign physical values to the computational parameters. If we assign both galaxies a mass of $1.75 \times 10^{11}\ M_\odot$ and let one exponential disk scale length equal 4 kpc, then one time unit is 2 Myr. With these choices, the disk has a total mass of $5 \times 10^{10}\ M_\odot$, with a gas mass of $5 \times 10^9\ M_\odot$, and the halo mass is $1.25 \times 10^{11}\ M_\odot$. The vertical scale height in the disk becomes 800 pc, a height chosen this large to ensure adequate numerical resolution of otherwise large density gradients. The radial density distribution is truncated at 17.6 kpc. The disk rotation velocity, averaged over the entire disk is 211 km s^{-1}. The gas density in the plane of the disk ranges from about 0.025 amu cm^{-3} at the outer edge to about 2 amu cm^{-3} at the center of the disk. The ratio of temperature to mean molecular weight, T/μ, ranged from 8000 to 6×10^5 K.

In the model reported here, the two galaxies' centers of mass are initially placed 30 kpc apart, and each is given a velocity of 227 km s^{-1}. The elliptical is aimed perpendicularly to the disk and eventually intersects the disk about 7 kpc from the disk's center.

3. RESULTS

Here we report the results of the simulation of the off-center collision described above in § 2.3 and compare the model results to observations of the Arp 147 system.

As the elliptical passes through the disk, the nucleus of the disk galaxy is pulled toward the impact point. Gas and stars flow toward that point, reaching a maximum density there soon after the closest approach of the two systems' centers of mass. As the elliptical recedes, material from the inner part of the disk starts to expand and meets material which is still infalling from the outer part of the disk. This produces an expanding arc of high density on the side of the disk near the impact point. Gas is swept up in this expansion with the greatest initial volume density occurring approximately along the line connecting the disk nucleus and the impact point. However, the outward-moving density enhancement first reaches the edge of the disk on the side where the impact occurred, and thus in this region of the arc there is no longer infalling gas to sweep up, leading to a density decrease as the ring expands. Meanwhile rotation has carried the region of highest gas volume density in the arc to the upper left as seen in Figure 1*b*. A second area of high density occurs at the bottom of Figure 1*b* where the expanding arc meets still infalling gas. There is little evidence in the figures of the caustic edges described by Struck-Marcell & Lotan (1990). This is likely due to the finite initial velocity dispersion present in the disk stars. We have found the transient behavior described in this paragraph to be a generic feature of our simulations of the off-center collision of an elliptical perpendicular to the disk plane.

Figure 1 shows a view of the simulation at a time 74×10^6 yr after close approach from an angle of 51° to the perpendicular to the plane of the disk. The viewing angle of the model has been chosen to give a best match to the observed morphology of the Arp 147 system. The stellar and gaseous surface density distributions in the disk obtained for this model are displayed in Figures 1*a* and 1*b*, respectively. These can be compared with a contour plot of optical emission from Arp 147 (taken from Schultz et al. 1990) shown in Figure 2. From our chosen perspective we see that the remnant nucleus of the model galaxy appears buried in the part of the ring that lies closest to the elliptical. This association is an artifact of the viewing angle, as the nucleus is actually displaced out of the plane defined by the ring by approximately 3 kpc. The orientation is such that the nucleus is lying in front of and obscuring part of the ring. The two-dimensional projection of the position of the center of mass of the elliptical is shown in Figures 1*a* and 1*b* for reference. The true distance between the two centers of mass is larger than appears in the figure as the elliptical lies mostly in front of the disk galaxy.

The ring has an apparent major axis of about 20 kpc. The centers of the two galaxies have a projected separation of 21 kpc (from the "center" of the arc to the center of mass of the elliptical) and a line-of-sight radial velocity difference of 362 km s^{-1}. From our chosen viewing perspective, almost all the velocity differential between the two galaxies is along our line of sight. The side of the arc near the companion is receding; the opposite edge and the elliptical are approaching. The maximum recessional velocities in the model occur in the northwest portion of the arc in Figures 1*a* and 1*b* and the peak velocities towards us are opposite that, along the southeast part of the arc.

The sign of the relative velocities of the companion and the opposite sides of the ring are consistent with observations of the Arp 147 system by Theys & Spiegel (1977) and Jeske (1986). Theys & Spiegel quoted a velocity difference across the ring of 150 km s^{-1} along the line connecting the ring center and the companion, compared to a 220 km s^{-1} difference in our model. Jeske fitted a circular ring model to optical emission data and derived an expansion velocity of 136 km s^{-1} and a rotation velocity of 137 km s^{-1}, compared to deprojected values of approximately 140 km s^{-1} and 150 km s^{-1}, respectively, in our model. The companion is moving towards us at 290 km s^{-1} in our model compared to observed values of 125 km s^{-1} (Theys & Spiegel 1977) and 200 km s^{-1} (Jeske 1986).

The gas surface density contours shown in Figure 1*b* are obtained by projecting particle positions onto the plane of our chosen "sky" and smoothing the mass distribution onto a grid. The maximum surface density of 1.2×10^{22} amu cm^{-2} is found at the location of the nucleus. Secondary peaks occur in two "wings" on opposite sides of the nucleus and have peak gas surface densities of 1.1×10^{22} and 1.0×10^{22} in the north (leading) and south (trailing) wings, respectively.

In contrast to the gas surface density, the gas space density in the model is not greatest in the nucleus. The galaxy disk and nucleus are no longer confined to a plane and the gas contributing to the high gas surface density in the nucleus is spread along the line of sight when displayed in three dimensions. The gas space density is greatest in the "wings" on either side of the nucleus, with the maximum of approximately 0.9 amu cm^{-3} occurring in the north (leading) wing and a secondary maximum of approximately 0.4 amu cm^{-3} occurring in the south (trailing) wing. Strong shocks are also taking place in the high space density regions, with most of the vigorous shocks occurring in the wing on the north.

4. DISCUSSION AND CONCLUSIONS

We take Arp 147 as a prototype of the RE subclass of ring galaxies (see Theys & Spiegel 1976) and compare it to our model. However, several aspects of this system are unknown, such as the mass ratio of the galaxies and the orbital parameters. The model, therefore, cannot be an exact match to this

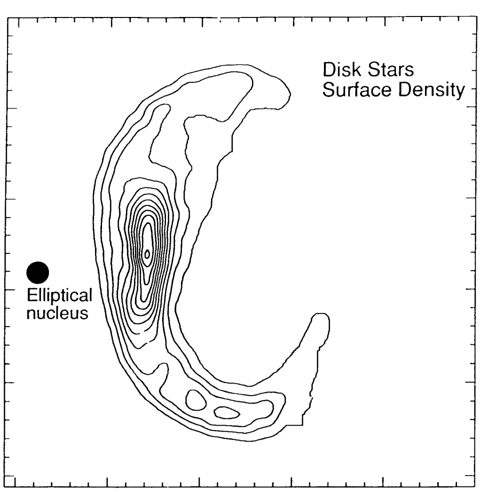

FIG. 1*a*

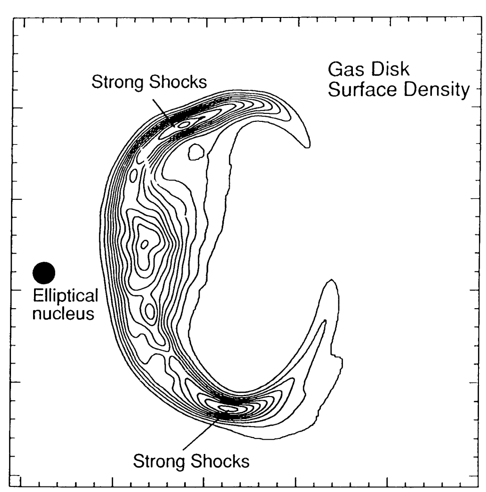

FIG. 1*b*

FIG. 1.—(*a*) A contour plot of the model disk stars' surface density 74×10^6 yr after close approach. The linear size of the incomplete ring is about 20 kpc. The elliptical is 31 kpc away from the disk galaxy, although it appears much closer due to the viewing angle. (*b*) A contour plot of gas surface density (i.e., gas density integrated along the line of sight) for the model disk galaxy at the time corresponding to that in (*a*). The regions of greatest three-dimensional gas density coincide with the regions of strong shocks, which are indicated on the diagram. We note that the overall density distributions of the stars and gas are similar.

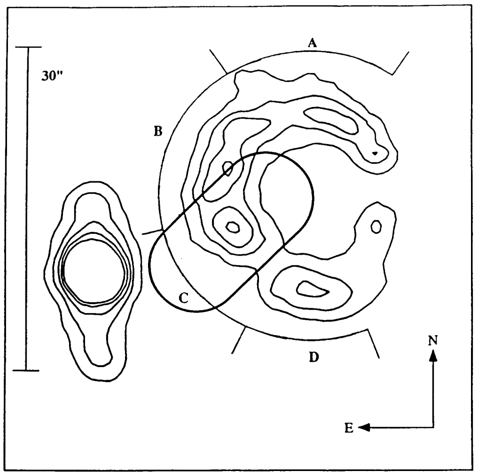

FIG. 2.—A map of optical contours of Arp 147 taken from Shultz et al. (1991). From color-color diagrams, they deduced that active starburst activity is occurring along the northern and southern quadrants of the ring, marked A and D. The oval represents the *IUE* aperture of the data taken by Shultz et al. They found no evidence for recent star formation in this knot.

system, but it is analogous in many ways. Our aim in this paper is to understand some of the generic features of this type of system and of the galaxy collisions which produced it.

The observed aspects of Arp 147 which we wish to emphasize are (1) the arc structure observed in both the stars and the gas; (2) the apparent lack of a nucleus interior to the ring structure; (3) the brightest knot in the ring (near the region labeled C in Fig. 2) has been identified as the nucleus of the disk galaxy by Schultz et al. (1990, 1991) because of a lack of active star formation, as is shown by both *IUE* and photometrically derived color-color diagrams; and (4) that two extended arcs of intense starburst activity have been observed by Schultz et al. (1990) in the regions marked A and D in Figure 2.

In comparing our model to the Arp 147 system, we find that the knot identified as the nucleus in the real galaxy is in almost the same location as the nucleus in our model. Further, both rings have one axis longer than the other with the short axis pointing toward the companion. The ring in Arp 147 is less elongated than that in our model, and a simulation with the collision slightly closer to the disk rotational axis would likely produce a better fit to the observed morphology. Our model gives a reasonable fit to the kinematic data as discussed in the previous section. Thus, in summary, we have found reasonable agreement with the observed morphology and velocity data.

In our model both the stellar and gas surface densities have a strong peak at the location of the remnant nucleus, suggesting that this would appear as the most luminous region. However, we find that the three-dimensional space density of gas is not strongly peaked near the nucleus, nor are strong shocks occurring there. Therefore we would not predict much current star formation in this region. In contrast, our model gives relatively large gas space density enhancements and regions of strong shocks in two arcs on opposite sides of the nucleus. Schultz et al. (1990) interpreted the photometric colors observed in portions of the arc along regions B and C (Fig. 2) as indicating that a starburst had occurred there but has since subsided.

Taken together with the observations, our model is consistent with the hypothesis that star formation is associated with regions of high gas density and strong shocks which form solely as a result of the dynamics of the interaction. The star formation burst sequence in Arp 147, as inferred by Schultz et al. (1990), began along regions B and C (Fig. 2), but has since died out there and is currently occurring in regions A and D. Similarly, in our models, gas density first peaks in an arc near the elliptical and later has maxima in two "wings" as described previously. Observations and models are consistent with the interpretation of the brightest knot in Arp 147 being the old nucleus of a disk galaxy, having an old stellar population with little or no recent burst of star formation.

The model detailed in this *Letter* is one of a limited survey of off-center collisons we have performed. The formation of a full or partial ring with two regions of high density on opposite sides of the nucleus appears to be a generic feature of these collisions. We are now in a position to use these computational techniques to model specific systems, such as Arp 147, II Zw 466, or II Hz 4. From the models, we can obtain the location and magnitude of density enhancements and shocks and then compare these with observed locations of recent and vigorous star formation in the galaxies.

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