MODELS OF THE MORPHOLOGY, KINEMATICS, AND STAR FORMATION HISTORY OF THE
PROTOTYPICAL COLLISIONAL STARBURST SYSTEM NGC 7714/7715 = ARP 284

CURTIS STRUCK
Department of Physics and Astronomy, Iowa State University, Ames, IA 50011

AND

BEVERLY J. SMITH
Department of Physics and Astronomy, East Tennessee State University, Box 70652, Johnson City, TN 37614

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ABSTRACT

We present new N-body, hydrodynamical simulations of the interaction between the starburst galaxy NGC 7714 and its poststarburst companion NGC 7715, focusing on the formation of the collisional features, including (1) the gas-rich star-forming bridge, (2) the large gaseous loop (and stellar tails) to the west of the system, (3) the very extended H i tail to the west and north of NGC 7714, and (4) the partial stellar ring in NGC 7714. Our simulations confirm the results of earlier work that an off-center inclined collision between two disk galaxies is almost certainly responsible for the peculiar morphologies of this system. However, we have explored a wider set of initial galaxy and collisional encounter parameters than previously and have found a relatively narrow range of parameters that reproduce all the major morphologies of this system. The simulations suggest specific mechanisms for the development of several unusual structures. We find that the complex gas bridge has up to four distinct components, with gas contributed from two sides of NGC 7715, as well as from NGC 7714. The observed gas-star offset in this bridge is accounted for in the simulations by the dissipative evolution of the gas. The models suggest that the most recently formed gas bridge component from NGC 7715 is interacting with gas from an older component. This interaction may have stimulated the band of star formation on the north side of the bridge. The models also indicate that the low surface brightness H i tail to the far west of NGC 7714 is the end of the NGC 7715 counter-tail, curved behind the two galaxies. The sensitivity of the tidal structures to collision parameters is demonstrated by comparisons between models with slightly different parameter values. Comparison of model and observational (H i) kinematics provides an important check that the morphological matches are not merely fortuitous. Line-of-sight velocity and dispersion fields from the model are found to match those of the observations reasonably well at current resolutions. Spectral evolutionary models of the NGC 7714 core by Lançon et al. suggest the possibility of multiple starbursts in the last 300 Myr. Our hydrodynamic models suggest that bursts could be triggered by induced ringlike waves and a postcollision buildup of gas in the core of the galaxy.

Subject headings: galaxies: individual (NGC 7714/7715) — galaxies: interactions — galaxies: kinematics and dynamics — galaxies: starburst — methods: n-body simulations

On-line material: color figure

1. INTRODUCTION

Detailed investigations of individual collisional galaxies can provide important information about the physics of the encounter, including enhancement and suppression of star formation (SF) in interacting galaxies and hydrodynamical processes such as shock wave production, heating and cooling, and reaccretion. In practice, however, it has proved very difficult to reconstruct the details of a specific encounter between galaxies and to match precisely the observed properties of an interacting system, particularly when one includes not just the stellar morphology but also the gas distribution and kinematics and the SF morphology.

There are, however, some special circumstances in which such a detailed modeling project is tractable. The first of these is when the galaxies are observed at a time shortly after closest approach and well before a merger. In such cases, there has not been time for phase mixing, and because most encounters are quite impulsive in the early stages, the immediate response is primarily kinematic (see, e.g., Gerber 1993; Dubinski, Mihos, & Hernquist 1999). A second helpful factor is the existence of a special symmetry in the collision.
González Delgado et al. 1995; Paper II; O’Halloran et al. 2000) or an H\textsc{i} counterpart (Paper II), unlike many collisional rings (Appleton & Struck-Marcell 1996). NGC 7714 has three apparent optical tidal tails/arms. The outer southwestern stellar arm may be associated with a large H\textsc{i} loop (feature 2 in Fig. 1; also see Fig. 3). The inner southwestern arm (feature 3 in Fig. 1) is brighter, with a prominent H\textsc{ii} region complex at its base (Paper II). In optical images, the northeastern stellar arm (feature 4 in Fig. 1) is clearly physically separate from the bridge; however, in the H\textsc{i} maps, it is not well resolved (Paper II; see Fig. 3). In addition, low-resolution H\textsc{i} observations reveal a low surface brightness H\textsc{i} tail extending 6$^\circ$ (71 kpc) to the west of NGC 7714, with no observed optical counterpart (Paper I).

The presence of the ring suggests a direct impact on the disk, while the spirals suggest that the collision was somewhat off-center and generated significant tidal torques (Paper I). The ring itself constrains the collision parameters, but the spiral morphologies are so distinctive that they should yield even stronger constraints. The bridge consists of H\textsc{i} gas, old stars, and young stars, with a significant offset between the old stars and the other components (Paper II; see Fig. 3). This offset is clearly evident in Figure 2, where a string of luminous H\textsc{ii} regions lies to the north of an optical continuum bridge. Since models show that connecting bridges are relatively short-lived features (Struck 1997), the presence of one provides strong evidence for a recent encounter. The edge-on shape of NGC 7715 and the stellar countertail of NGC 7715 also constrain the collision parameters. Still more constraints are provided by the map of line-of-sight (LOS) H\textsc{i} velocities (Paper II), which defines the sense of rotation of the two galaxies and kinematic line of nodes.

NGC 7714 has a nuclear starburst (French 1980; Weedman et al. 1981; Keel 1984; González-Delgado et al. 1995; Kotilainen et al. 2001), while the center of NGC 7715 shows a poststarburst spectrum (Bernlörh 1993). The stellar evolutionary timescales associated with these phenomena give additional input on the time since the collision.

In Paper I, we presented a restricted three-body model of the NGC 7714/15 encounter that matched the stellar morphology of the system and the line of nodes and sense of rotation of NGC 7714. This scenario consisted of an off-center, inclined collision between two unequal-mass galaxies, with the encounter being retrograde with respect to the main galaxy NGC 7714 and prograde with respect to the companion. This simulation, however, did not include

### TABLE 1

**Morphological Characteristics of the NGC 7714/15 System**

| Feature                          | Comments                                | References |
|----------------------------------|-----------------------------------------|------------|
| Stellar ring (1)                 | NGC 7714; no gas ring                   | 1, 2       |
| Stellar bar                      | NGC 7714                                | 3          |
| Northeastern stellar arm (4)     | NGC 7714; no gas counterpart            | 1          |
| Inner southwestern stellar tail (3) | NGC 7714                               | 1          |
| Outer southwestern stellar tail (2) | NGC 7714; associated with gas loop     | 1          |
| Large gas loop                   | NGC 7714; northwest-northeast          | 2          |
| Edge-on shape                    | NGC 7715                                | 1          |
| Stellar bridge (5)               | High column density H\textsc{i}, offset to the north of the stellar bridge | 4          |
| Gas bridge (5)                    | In low-resolution H\textsc{i} observations | 4          |
| Stellar countertail (6)          | NGC 7715                                | 1          |
| Gas countertail                   | NGC 7715                                | 2          |
| Far west H\textsc{i} clouds      | In low-resolution H\textsc{i} observations | 4          |
| Southern arc                     | NGC 7714                                | 2          |
| Southern filament                | NGC 7714                                | 2          |

* Number in parentheses is the feature number in Paper I.

**REFERENCES.**—(1) Arp 1966; (2) Paper II; (3) Bushouse & Werner 1990; (4) Paper I.

### TABLE 2

**Other Characteristics of the NGC 7714/15 System**

| Feature                        | Comments                                | References |
|--------------------------------|-----------------------------------------|------------|
| **Kinematic Features**         |                                         |            |
| Mean radial velocities         | Similar in NGC 7714 and NGC 7715        | 1          |
| Bridge radial velocity         | Blueshifted relative to galaxies        | 1          |
| "Spider diagram"               | Line of nodes and rotation sense in NGC 7714, for example | 1          |
| Rotation curve                  | NGC 7715                                | 1          |
| **Star Formation Features**    |                                         |            |
| Central starburst              | NGC 7714                                | 2          |
| Arc of knots in bar            | NGC 7714                                | 2          |
| Inner southwestern arm         | NGC 7714                                | 2          |
| Poststarburst center           | NGC 7715                                | 3          |
| Bridge knots                   | Several dozen                           | 1          |

**REFERENCES.**—(1) Paper II; (2) Bushouse & Werner 1990; (3) Bernlörh 1993.
Fig. 1.—Arp (1966) atlas image of NGC 7714/15. North is up and east to the left. NGC 7714 is the larger galaxy to the west. The field of view is \(50' \times 39'.\) [See the electronic edition of the Journal for a color version of this figure.]

Fig. 2.—Broadband red (F606W filter) Wide Field Planetary Camera 2 (WFPC2) image of NGC 7714 and the NGC 7714/15 bridge, from the HST archives. The field of view is \(2'5 \times 1'5.\) The image has been mosaicked and rotated such that north is up and east is to the left. NGC 7715 lies off the image to the east. Note the prominent H\(\alpha\) regions between the two galaxies, offset to the north of an optical continuum bridge.
hydrodynamical effects. The later acquisition of the high-resolution HI data (Paper II) allowed a stronger test of the collision scenario.

In Paper II, we presented a preliminary hydrodynamical model of the NGC 7714/15 encounter with two gas disks and rigid halos, using parameters similar to those of the Paper I model. This model was not intended to reproduce all the features of the system, but rather to demonstrate two points. First, it showed that the gas loop could be obtained in a collision like that in the model of Paper I with the addition of a gas disk of larger radius than the stellar disk. Second, it demonstrated that the observed offset in the old star bridge versus the young star and gas bridge could be explained as a result of the dissipative impact of the gas disks of the two galaxies. This model did not, however, do a good job in matching the observed location of the gaseous loop or the orientation of the gas-star offset in the bridge.

In this paper we present the results of a more detailed modeling program undertaken to better interpret the features listed in Tables 1 and 2. The new modeling includes fully self-consistent simulations made with the Hydra N-body, adaptive mesh smoothed particle hydrodynamics (SPH) code (version 3.0) of Couchman, Thomas, & Pearce (1995), which includes radiative cooling, and also feedback heating terms in some models (see § 2 for details). These new models are similar to the earlier ones in requiring a direct impact between disks with a moderate impact parameter and a relatively large inclination angle. However, significant changes have been made in the new models in order to better fit the detailed morphology of the system (see § 3.1 and 3.2). Comparisons to observed kinematics (§ 3.3) and SF characteristics (§ 4) have also been made for the first time in this system. The generally good agreement between models and observational kinematics provides strong confirmation of the basic collisional model. The model results on SF are tentative, but they do provide some useful suggestions to be checked in future work. The results are summarized in § 5.

2. NUMERICAL MODELS

As noted above, the general nature of the collision can be immediately deduced from the presence of a few distinctive morphologies. The NGC 7714 ring and the relatively straight bridge connecting the two galaxies provide prima facie evidence for a nearly head-on collision. On the other hand, the offset of the NGC 7714 nucleus from the ring center and the presence of loops and tidal tails suggest some asymmetry in the collision. Tails and rings can be simultaneously produced in collisions of intermediate inclination with closest approach distances somewhat less than the radius of the gas disk of the ring galaxy (see, e.g., Appleton & Struck-Marcell 1996). Tails are more easily produced if the encounter is prograde relative to the tailed galaxy.

2.1. Simulation Codes

We began our modeling work with a large number of exploratory runs with a restricted three-body code (Wallin 1990), in order to refine our estimates of the collision parameters. We do not describe that work any further here. We then used the hydrodynamic code of Paper II (see Struck 1997 for details on this code) to study the gasdynamics of the refined collision and to further adjust it to reproduce the observed HI structure. These runs were also used to study the thermal and star-forming properties of the colliding galaxies in a preliminary way. However, that hydrodynamic code does not include fully self-consistent calculations of the gravitational forces, in particular dynamical friction and
related effects. Thus, one of the most prominent "errors" of typical models (e.g., models in which NGC 7715 begins nearly at rest relative to NGC 7714 at a distance of at least several diameters away) is that NGC 7715 plunges through and well away from NGC 7714, before the H i loop and other tidal structures can develop to the observed degree. Given the limitations of these models, we do not describe their results in any detail.

Fully self-gravitating simulations were then produced with the serial code Hydra, version 3.0 (henceforth simply Hydra), which has been made publicly available. Hydra uses an SPH algorithm, and gravity is calculated with an adaptive particle-particle, particle-mesh (AP3M) algorithm (for details see Couchman et al. 1995; Pearce & Couchman 1997). For a typical time step in our models, adaptive refinements were carried out on about half the gas particles, with about 6–10 submeshes and with the most refinement around the primary center.

The simulations were all run using an adiabatic equation of state. Optically thin radiative cooling was calculated via the tables of Sutherland & Dopita (1993), which were supplied with the Hydra code. The Sutherland & Dopita cooling curves include atomic and ionic line and continuum processes for $T \geq 10^4$ K. Cooling times were not used to limit the size of the computational time step, since the dynamical time is usually longer than the cooling time. Particles evolve adiabatically and are cooled at the end of a given time step, at constant density. No feedback heating was included in most of the Hydra simulations.

2.2. Scalings and Boundary Conditions

The codes used in this project run in dimensionless variables, and many of the graphs below are plotted in those units. The Hydra runs are made on a cubic volume, where $x$, $y$, and $z$-coordinates all run from 0.0 to 1.0 in code units. Most of the computational cube is empty most of the time (see Figs. 1–3). Very few particles reach the boundaries, and when they do they are taken out of the calculation. The adopted scalings for the Hydra model are one computational length unit equals 100 kpc, one time unit equals $10^9$ yr (which implies that the velocity unit is 97.7 km s$^{-1}$), and one mass unit equals $10^{10} M_\odot$.

With these scalings, the model results suggest that closest approach occurred about 100–250 Myr ago; we refine this estimate below.

2.3. Initial Conditions and Model Differences

We ran about a dozen simulations using the Hydra code; in this paper we focus on the results of the best Hydra simulation (henceforth the "model" or "best model"), with only brief mention of the results of other model runs. In the best model the mass ratio of the galaxies was about $\frac{1}{3}$, in accord with the observations (e.g., the optical luminosities). We note, however, that it is possible that the companion has lost a good deal of mass, and thus, its precursor may have been more massive than current observations suggest. A model with equal-mass initial galaxies showed that even with a massive companion it is possible to produce a fairly good model, with only a few disagreements with observations.

In the Hydra simulations, the two model galaxies each contain a collisionless halo, a stellar disk, and a gas disk component, which were added and relaxed sequentially. The halo is approximately isothermal, while the disk components have a nearly constant vertical velocity dispersion with radius and an approximately $1/r$ surface density distribution. The gas fraction of the disks is very high, with equal masses of stars and gas. This may be unrealistic, but it was done to provide adequate particle resolution of the gas dynamics. The gas disk cools somewhat in its relaxation and so is generally thinner than the stellar disk. Many details of the model galaxies are given in Table 3.

In the models we adopted the $x$-$y$ plane as the plane of the sky, and then the model galaxy initial conditions and the orbital trajectories were optimized to match the observations at some later time. Specifically, with the initial orientations given in Table 3, the disk of the primary appears relatively face-on in the $x$-$y$ plane and is edge-on in the $x$-$z$ plane. The companion disk is more nearly face-on in the $x$-$z$ plane. Inner disk orientations are roughly preserved through the collision.

Given the limited number of particles that can be used, we cannot represent an extended halo with great accuracy with the Hydra code. However, we find that the most successful models of this system require relatively compact halos, which can be modeled quite well.

In the following sections, discussions of model results and observational characteristics of the system are highly interwoven. To avoid confusion about which is being referred to, we refer to the model galaxies as galaxies A and B, corresponding to NGC 7714 and NGC 7715, respectively, and reserve the latter names for the real galaxies.

3. MODEL RESULTS: RECONSTRUCTING THE COLLISION

3.1. Overview of the Collision and Formation of the Large-Scale Morphology

In this section, we focus on the morphological and kinematic results, and we briefly discuss thermal effects and SF in § 4. We begin with Figures 4 and 5, which show the evolution of the gas disk of the model in three orthogonal projections. The orbital trajectories of the galaxy centers are also shown in the top row of Figure 4. The appearance of the stellar disk during the last three time steps is shown in Figure 6.

In these figures, we see that galaxy B begins at some distance below galaxy A in the $z$-direction. The galaxies swing around to almost return to their starting positions. Because of the disk tilt in A, the angle of attack of B at closest approach is large (>80°). Both galaxies feel a prograde disturbance.

The tidal tails are the most dramatic structures at the later times shown in Figure 5. The complex bridge is almost as prominent. The same structures are also evident, although more diffuse, in the disk stars in Figure 6.

Figure 7 shows three late-time snapshots of just the gas particles originating in A, while Figure 8 provides the corresponding views of gas particles originating in B. These figures show that there is substantial mass transfer from each galaxy to the other. However, B loses much more mass.

Next we examine individual collision structures in more detail. We note at the outset that the figures illustrating these structures have been chosen at a variety of times in the range 100–220 Myr, although in most cases $t = 120$ Myr.
The latter figure is essentially a default, but if the specific structure is better illustrated by the model output at a different time, we have shown it at that time. In some cases multiple times are shown, to illustrate structure development. The range above approximates our uncertainty in the time since closest approach, and since the lifetime of most structures is longer than this range, all the illustrated features should be visible at the “present.”

### 3.2. Specific Collisional Structures

#### 3.2.1. The NGC 7714 Ring (Feature 1)

The high-inclination orbit of galaxy B relative to the disk plane of galaxy A and the impact of the center of B within or near the A disk should give rise to a substantial \( m = 0 \), ringlike, collisional perturbation of A. In optical images (Fig. 1) a prominent stellar ring is visible. Rings are clear in the A gas disk in Figure 5, but fainter in the stellar disk. The primary reason for this is the fact that the dissipationless star particles have much larger thermal velocities in the model than the gas particles, so stellar waves are heavily smoothed by particle diffusion (also see Fig. 9).

Despite this numerical complication, it remains true that this type of collisional perturbation has strong \( m = 0, 1, \) and 2 Fourier components. The \( m = 0 \) component gives rise to successive rings. The \( m = 2 \) tidal component is largely responsible for the tidal tails and two-armed spirals in the interior, as well as the general barlike appearance of the disk. The \( m = 1 \) and higher odd moments generate asymmetry in these structures. All of these features are apparent in Figure 9, which shows enlarged views of star (left-hand panel) and gas (right-hand panel) particles in the galaxy A disk at a time near the present. The left-hand panel of the figure provides one of the best views of the asymmetric stellar ring. Rings are more evident in the gas disk shown in the right-hand panel, but they are rather complex structures. This is because the rings are also spirals, which are more or less tightly wrapped at different positions. These spirals also smoothly connect successive rings. This is a result of having comparable \( m = 0 \) and 2 perturbations.

In fact, the tidal countercetail (which corresponds to the Hubble loop and feature 2 of NGC 7714) and the companion-side tidal tail are connected at early times. (They are also connected at late times, but the connection is represented by so few particles that it is virtually invisible.) Since these structures developed even before closest approach, we call them the zeroth-order ring. This “ring” is very asymmetric, with the Hubble loop representing the strongly positively torqued side. Each successive ring also has both positively and negatively torqued sides. The former (denoted by a plus sign) moves radially outward earlier and farther than the latter (denoted by a minus sign). At the time shown in Figure 9, ring 0 persists because it is largely a material rather than a phase wave. Much of ring 1 (a phase wave) has propagated through the disk and disappeared. Ring 2 is maturing.

Part of ring 1+ remains visible on optical images as a very faint loop outside the bright east-side ring/loop. It contributes much to the ringlike appearance of the stellar disk in Figure 9. It loops inward more tightly than the corresponding gas feature, which has a wispy appearance. We propose that the strong NGC 7714 stellar ring is equivalent to ring 2 (plus and minus) in the model. The high-resolution HST (WFPC2) partial image in Figure 2 of Lancer et al. (2001) looks very similar to the right-hand panel of Figure 9, except that the ring 2+ arc is not so prominent on the west side. In the HST image there appear to be bubbles and shells on this arc, so SF feedback may have affected its strength and appearance.

To date, the observations do not show a strong gas ring like that visible in Figures 5 and 7. In part, this may be...
the result of limited observational resolution and sensitivity. However, the absence of SF in the ring also suggests that there is not much highly compressed gas. In fact, the gas ring in Figure 9 is weaker on the east (left) side. This is the sector of disk-disk overlap in the collision and also the bridge side. Large-scale shock dissipation is likely to have separated the gas and stars in this region, with the gas being either pushed inward or pulled into the bridge. This accounts for the fact that the east-side ring consists of old stars, with little evidence of compressed gas or young stars.

On the other hand, the west-side gas ring (2+) is strong in Figure 9. We have already noted that HST observations suggest that SF feedback may have heated and scattered the gas on this side. Preliminary models with feedback also support this idea and further show that ring 2+ could be completely disrupted by reasonable amounts feedback.

Observations of the stellar populations in this region would be very desirable.

As we discuss in § 3.3, there is evidence that the northeastern tail (the third entry in Table 1) and the southern filament of Figure 3 are parts of an older ring. These may well be remnants of the gas component of ring 1+.

The ratios of the successive ring radii are closer to unity than in the double-ringed Cartwheel galaxy or most models of double rings. Theory suggests that collisional rings are closer together in galaxies with declining rotation curves (see, e.g., Struck-Marcell & Lotan 1990; Appleton & Struck-Marcell 1996), and so this provides some evidence that the halos of these galaxies are less extensive than most. (Paper I shows that the NGC 7714 rotation curve is flat or slightly declining, but this curve is affected by the collisional disturbances and does not extend much beyond the optical disk.) On the other hand, the asymmetry of the rings and

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**Fig. 4.**—Gas particles in the galaxy disks at three early times in the best-model collision, with three orthogonal views at each time. The top row shows the initial disks ($t = -180$ Myr), the middle row the disks at the onset of the collision ($t = 0$ Myr), and the bottom row the disks at a time just after the closest approach of galaxy centers ($t = 40$ Myr). The labels “A” and “B” in this and the following figures denote the model galaxies representing NGC 7714 and NGC 7715, respectively. For galaxy A every third gas particle is plotted; for galaxy B every particle is plotted. Coordinates are given in dimensionless code units, which can be scaled as described in the text. (Note that we assume that the observer is located at the appropriate distance along the negative $z$-axis.)
the fact that they have been torqued in the interaction complicate this interpretation.

3.2.2. Outer Southwestern Tail and H\textsc{i} Loop of NGC 7714 (Feature 2)

The outer southwestern tail seen in optical images (feature 2 of Fig. 1) appears to be just the base of the great H\textsc{i} loop described in Paper II (see Fig. 3). This stellar feature becomes broader and fainter at a position angle of about 270°, due west of the NGC 7714 nucleus, and at low surface brightness levels traces the H\textsc{i} loop to at least a position angle of 330°.

Our Hydra models (Figs. 5 and 6, bottom left-hand panels) also show a low surface brightness stellar feature coincident with a gaseous loop. As in the observations, the stellar feature is shorter and less prominent than the gaseous feature. This is a common property of tidal tails (see, e.g., Hibbard & van Gorkom 1996; Elmegreen et al. 2000; Mihos 2001); it is the result of the fact that tails are pulled out of the disk like taffy out of a pot, with the outer boundary of the tail derived from the outer edge of the disk, which is typically gas-rich, while the inner base of the tail includes material from deeper within the disk, which has a larger proportion of stars.

To help understand how such a large mass of gas ($\approx 1.1 \times 10^9 M_\odot$) was pulled out into the huge loop, we investigated the history of the particles in the loop in the Hydra models (Fig. 10). In the left-hand panel are shown all gas particles above the plane $y = 0.31 + 0.48x$, i.e., most of the loop material that is not too close to the galaxy A disk.

The right-hand panel of Figure 10 shows the location of the same gas particles at a time shortly before the impact of the two disks. It suggests that most of the outer disk on the south side is pulled out into the loop as the companion swings by.

However, Figures 4 and 5 show that while this loop has characteristics of a classical tidal tail, it also has a strong ringlike aspect. For example, it is always a loop, which connects back to the galaxy A disk, and not a tail with a
detached end point. Thus, this loop may also be regarded as part of the first ring wave.

The fact that most of the material in the loop originates in the outer part of the precollision disk also helps explain the lack of detectable molecular material in the loop, despite the large gas mass it contains (see Smith & Struck 2001). We note that the nucleus of NGC 7714 has moderately low chemical abundances \[12\, + \, \log(O/H) \approx 8.5\] (French 1980; González Delgado et al. 1995), and the material in this loop may be even more metal-poor than that in the nucleus.

Note that the contour levels, while arbitrary, are the same in both panels of Figure 10. However, the area contained within them is much less in the left-hand panel, which highlights the strong compression resulting from the collision.

3.2.3. The Bridge (Feature 5)

The H i maps of Paper II suggested that the bridge between the two galaxies is a complex structure. In particular, there is a measurable offset between the star and H i gas centroids. To begin to understand this, let us consider the origin and development of the bridge. A plot like Figure 10, but for bridge particles (not shown), tells us that most bridge particles originate in the outer parts of their parent disks and on the side that is closest to the other galaxy at closest approach.

The y-z plots of Figure 11 provide good views of the development of several bridge components (which are labeled in the second panel). The figure shows the results of Hydra models at two intermediate times. The first model is the usual “best” model, while the second is one we refer to as the “alternate.” The alternate model differs from the best model by having a different tilt of galaxy B and higher orbital angular momentum (see Table 3). It is representative of a group of models with slight differences from the best model. Comparisons between the best and alternate models help us understand which structures are common to a range of similar models, such as ring waves and the tidal tails, and which depend sensitively on structural and orbital parameters. The bridge contains components of both types.
The first bridge component (labeled “i” in Fig. 11) is the B tidal (counter)tail, which loops back down into projection onto the bridge in this view and especially in the \( x-y \) view. It is not physically associated with the other (true) bridge components. The second component (“ii”) is a strong tidal bridge from B to A. This component, the late or postcollision B bridge, begins as a dark, nearly vertical line on the left-hand side of the gas between the two galaxies in the top left-hand panel. It also dominates the left-hand side of the bridge in the alternate model at this time (top right-hand panel). A third component of the bridge (“iii”) is the tidal stream from A to B. Bridge particles and galaxy contours are shown in Figure 12. This stream generally misses its target initially in three dimensions. In the best model, this component does not even stretch much toward B before it falls back to the A disk plane. However, it remains outside the A disk and projected onto the bridge in the \( x-y \) view through most of the simulation. This can be seen in the top left-hand panel of Figure 11, which provides the remaining two views of the bridge gas at intermediate times. In the alternate model, this A bridge does stretch toward B (see Figs. 12 and 11). At late times it transfers gas directly into the core of B. Figure 11 highlights this difference between these two otherwise very similar models. This difference is mostly due to the different companion tilt angles. In the best model the companion cuts through more sharply, not splashing as much gas, just gravitationally lifting the nearby disk slightly. Because the gas is projected onto the bridge in both cases, observations may not distinguish between the two models in this regard.

There is also a fourth component of the bridge (“iv”), which can be seen as the sharp linear feature stretching from the B center toward the A center in the top right-hand panel of Figure 11. It is also present in the best model, although harder to distinguish in the top left-hand panel of Figure 11. This feature merges with the late bridge by about \( t = 100 \) Myr. Graphs at other times (not shown) reveal that this structure is the remnant of an early or precollision tidal transfer stream from B to A, which appears to transfer a respectable amount of material (see discussion at the end of this section). Thus, B is a remarkable case of a galaxy with a
Fig. 8.—Same as Fig. 5, but including only gas particles that originated in galaxy B (model NGC 7715).

Fig. 9.—Left: Distribution of stars and a (weak) stellar ring in the primary disk at a time near the present in the best model. Right: The same, but for gas particles. The dynamically cooler gas disk shows the ring waves more clearly. Several of these are labeled as described in the text.
Fig. 10.—Left: Gas particles in the best model representing the NGC 7714 H\textsubscript{i} loop or tail (feature 2 of Paper I) at time $t = 120$ Myr, as well as a few representative contours to mark the location of the galaxy disks. Right: The same gas particles, at a time ($t = 0.0$ Myr) just before closest approach, and the sample disk contours. At times between those of the two panels the companion moves clockwise from the right to the left and a bit below the primary.

Fig. 11.—Two $y$-$z$ views at intermediate times that provide a good perspective on the origin of the bridge particles in the best and alternate Hydra models. Gas particles from galaxy B are shown as dots, while the gas distribution of galaxy A is shown by a few representative column density contours. The bridge in the alternate model is made up of four components (labeled i–iv in the top right-hand panel). Components ii and iv are the dense streams that make up the outer edges of the broad bridge from B to A. In the best model the projected B-A bridge is much narrower, although of comparable mass. Component iii is the tidal bridge from A, visible in the contours at the earlier time. Component i includes the top and end portions of the B tail that happen to be projected onto the bridge in the $x$-$y$ view. See Fig. 15 and text for more details.
long tidal tail and two(!) tidal bridges originating on opposite sides of the galaxy. The multifaceted structure of this bridge also helps explain how such a large mass of HI gas can be located outside the disks of the two galaxies.

The different components of the bridge have different degrees of gas-star offset. The B tail has essentially no offset between stars and gas. In Figure 13, we show two views of gas and star particles that originate in A in the best model. It is clear in this figure that the stars are much more broadly distributed than the gas particles. It is also evident from the top panels that the center lines of the star and gas distributions are offset.

Moreover, the bottom two panels of Figure 11 show how the bridge gas particles from B compress into a relatively thin filament in the Hydra models. This compression includes a merger of the “early” and “late” B bridges. In the gas this process is dissipative, but the stars are dissipationless. This also helps explain the offset.

From Figure 11 (and Fig. 15), we deduce that most of the bridge material is contained within tidal structures. In Paper II, we speculated that the bridge might contain a mixture of “splash” and “tidal swing” material. Dissipation in the collision between disks does seem to be an important factor in the development of the A-to-B component, which is important in determining the gas-star offset. However, this splash effect is more indirect than originally envisioned. Dissipation in the later compression of the early and late B-to-A components also plays a role (see also Mihos 2001).

These considerations suggest an unusual explanation for the young star clusters in the bridge. As noted, shortly before the present the late B bridge swings east and overtakes the remnant of the early bridge. The gas in the latter is compressed, and this compression may trigger SF. The Hα observations of Paper II suggest that these clusters are truly young. This is the only dynamical event that occurs in the region within a few times $10^7$ yr of the present, so it is indeed a likely trigger. However, we do not have sufficient particle resolution in the simulation to detect clump compression, so we cannot directly confirm this conjecture.

Another possibility is that these star clusters are formed in the NGC 7715 tail, which experiences compression in the segment projected onto the bridge at about the same time. Delayed strong compression was found to occur in many of the models of Wallin (1990). Kinematic observations might allow this hypothesis to be tested. We describe the kinematic predictions of the simulation below.

3.2.4. The NGC 7715 Tail (Feature 6)

Next we consider the NGC 7715 (stellar and gas) counter-tail. As we have discussed above, our models indicate that
this tail curves around behind NGC 7715 and the bridge (Fig. 8). Actually, in the best model it is located a bit below the bridge in the x-y plane. In the alternate model it is slightly above the bridge (at the same time). The inclination of the companion disk was changed in the best model to give a more edge-on appearance in the x-y view (see Table 3). With a somewhat smaller change it should be possible to obtain a quite edge-on appearance, while also superposing the tail on the line of centers of the two galaxies.

In the models, at \( t \geq 100 \) Myr the gas in this tail extends about 25 kpc to the southwest of NGC 7714 (Figs. 5, 8, and 14). The long H i plume to the southwest of NGC 7714, seen in low-resolution H i maps (Fig. 3b in Paper I) is very likely the observational counterpart to this model tail. This feature does not have an observed optical counterpart, consistent with its being the end of an H i–rich tidal tail. As shown in Figure 14, almost all of this tail material originated in an annulus in the outer part of the NGC 7715 disk, on the side nearest the NGC 7714 disk before closest impact. As discussed below, the observed velocity structure of this tail is also reasonably consistent with the model NGC 7715 tail.

3.2.5. The Bridge Extension

In the Arp atlas photograph (Fig. 1), a small stubby plume is visible on the west side of NGC 7714, exactly in line with the bridge on the east side. This feature lies north of (above) features 2 and 3 in the figure. It seems likely that this plume was formed by bridge material that had fallen through the NGC 7714 disk plane. The model bridges do not have enough particles to confirm this, and the available H i data do not have sufficient resolution to distinguish this feature from the disk.

3.2.6. The Inner Southwestern NGC 7714 Tail (Feature 3)

The inner southwestern tail (feature 3 in Fig. 1) is very unusual in several respects. First, it does not seem to be part of the southern tidal tail of NGC 7714 (which is also the H i loop), but rather an extra inner tail parallel to feature 2. Moreover, it has a high surface brightness and contains knots of recent SF. It also does not appear to be either an extension of the bridge or material accreted out of the bridge.

Figure 15 provides a plausible solution to the mystery. The top left-hand panel shows how mass transfer is well underway at the time of closest approach. Inner southwestern tail particles were first identified in the bottom left-hand panel of Figure 15. That is, all gas particles from galaxy B lying within a rectangular region between the galaxy A disk and the H i loop were selected and marked with plus signs. This somewhat crude procedure misses a number of the...
Fig. 14.—Left: Gas particles in the model NGC 7715 tail ($t = 120$ Myr), with representative contours to mark the location of the galaxy disks. All gas particles with coordinate values $z \geq 0.63$ or $x \geq 0.37$ were included. Most tail particles satisfy these constraints, while particles in the disks and other components do not (see Fig. 7). Right: As in Fig. 11, the same gas particles at a time ($t = 0.0$ Myr) just before closest approach in the $x$-$z$ view. It suggests that a large fraction of the outer NGC 7715 disk is pulled out in the tail (26% of all gas particles). Note that the galaxy B contours at the earlier time primarily show the dense mass transfer stream; the B disk is shown in part by the dots.

Fig. 15.—Four snapshots illustrating the origin of the inner southwestern tail in NGC 7714 as a result of early mass transfer from NGC 7715. Gas particles from the companion are shown as dots, while the gas distribution of the primary is shown by a few density contours. Most of the inner southwestern tail particles are marked with plus signs. These particles were identified on the basis of their position in the bottom left-hand panel. The bottom right-hand panel shows a slightly rotated $x$-$y$ view at a time slightly before the present (see text). The inner southwestern tail is labeled. The $\mathrm{H}\,\upiota$ loop is marked by clumpy contours extending out and upward from the right-hand side of the primary. Most of the particles at the bottom of this panel originate in the galaxy B tidal tail.
inner tail particles and includes some that are not truly part of that structure and travel past it at later times. Nonetheless, the procedure is accurate enough for illustrative purposes. The location of the marked particles in the top left-hand panel confirms that they are part of the earliest mass transfer. Already by the time of the top right-hand panel \((t = 40 \text{ Myr})\) they are part of a plume located behind the nascent Hi loop.

At the time of the top right-hand panel, the point of origin of the early transfer stream is near the top of the companion disk, on the far side relative to A, and this stream has become very thin (just to the left of the label). In the meantime, a second, vigorous transfer stream has developed on the current near side of the companion. The bridge narrows with time, and the streams are merging by the time of the bottom left-hand panel \((t = 70 \text{ Myr})\). In this view the inner southwestern tail is visible as a horizontal set of particles lying below the primary and above the long curved contour of the Hi loop.

The bottom right-hand panel of Figure 15 shows a nearly x-y view at a time near the present, with the feature labeled. In this plot, the plume is offset from the tail/loop, as in the observations. At this time, this structure is in the northwestern quadrant, rather than the southwestern, but it otherwise generally matches the observations well. In the true x-y view the plus signs lie on top of the Hi loop contours. The small rotation (about 5°) about the y-axis used to make the bottom right-hand panel easily separates the two features without greatly changing other characteristics. Thus, the position of this feature seems to be a very sensitive function of viewing angle. The inner southwestern tail is not reproduced as well in the other Hydra models, although it is still present.

3.2.7. The Inner Disks and Mass Transfer

Figure 16 shows, as a function of time, the gas mass contained in a spherical volume of radius 0.03 model grid units (about 3 kpc) normalized to its initial mass centered on the nuclei of the galaxies. The figure also shows the gas fraction in each galaxy transferred from the other galaxy. Note that peaks in the mass transfer at times near closest approach \((t = 0)\) are largely due to the proximity of the two disks and to temporary incursions into the spherical volumes measured.

At times from \(t = 0\) on, ringlike waves have a significant effect on the total gas curves for the primary galaxies in all the Hydra models. As time goes on, there is an increase in the mass of gas in the primary core. This is most likely due to compression resulting from angular momentum transport in the spiral waves. Compression will also result from mixing with low angular momentum mixing gas transferred from the companion.

The delayed central gas buildup after closest approach is interesting and agrees with the observations of delayed starbursts in interacting systems (see, e.g., Bernl"ohr 1993). The delay is long enough that the tidal transfer streams are much reduced before the central buildup gets underway. Most of the gas transferred to galaxy A at the earliest times falls onto the outer parts of the disk. There is some direct transfer from the bridge into the central regions at later times, and some material from the outer parts is transferred inward. The transfer history of galaxy B is more extreme. The bridge from A initially misses B almost entirely in the alternate model and never really leaves the parent galaxy in the best model. In the former case, gas accumulates at the end of this bridge and later falls en masse onto B.

3.2.8. Structure Summary

Tables 4 and 5 provide summary comparisons of the gas masses in different components in the observations and the best model at a time of 170 Myr after closest approach. The comparisons are generally very good. Specifically, the postcollision model disks contain gas fractions that are quite close to those observed. (Note that about 20% of the observed Hi flux is not contained in the identified structures, so the model figures must be renormalized to compare to observation.) The galaxy B disk contains about twice the observed fraction, but this is still much lower than the initial value. That is, it has lost \(\frac{3}{5}\) of its original gas. NGC 7715 is a poststarburst galaxy, so some of its gas may have been lost in a starburst wind, which is not modeled. Alternately, it may simply have had less gas initially than assumed in the model. Even though the galaxy A disk receives a substantial amount of mass transfer, its gas fraction is also greatly reduced by the collision.

The bridge gas fraction of the model appears to be substantially less than that observed, even including the superposed B tail. However, this number is a very sensitive function of time and of the postcollision deceleration. At \(t = 100 \text{ Myr}\) in this model, the gas fraction in the bridge was nearly twice the value shown in Table 5. Between these two times, substantial amounts of gas fall out of the bridge (and mostly onto the A disk). If, for example, the dark halo of A was somewhat less concentrated than in the model, then the galaxies would not have decelerated as quickly after closest approach and would have separated more, stretching the bridge and making for a longer fallback time.

The Hi loop is a little too massive in the model, perhaps indicating that the model A disk is too large. On the other
hand, faint parts of this diffuse structure would not be identified in the observations, so the model result may in fact be more correct than it first appears.

### 3.3. Kinematics

#### 3.3.1. Velocity Maps

In this section we compare the model and observed LOS kinematics. Figure 17 provides the LOS velocity map for the multianary VLA 21 cm observations of this system (presented in Paper II). In Figure 18 we show the corresponding map for the model. More precisely, the figure shows contours of the $z$-component of the velocity across the $x$-$y$ plane, and the contour values have been scaled to be comparable to the observed values as described in the caption. Both Figures 17 and 18 also show the velocity dispersion map in gray scale.

The observational contours in Figure 17 are not calculated at column densities less than a fixed minimum value, and the model contours (and velocity dispersions) are only computed for bins containing at least five particles. The fact that these cutoffs are not identical results in some minor differences; for example, the contours connect across the bridge in the model plot, but not in the observational one. The resolution of the two plots is comparable. The model contours are computed for data binned on a scale of 0.01 grid units, or about 1 kpc. The observational effective beam width is about 6'', or about 1.1 kpc, with the assumed system distance of 37 Mpc.

The limited resolution and signal-to-noise ratio in the observations (and models) of the bridge preclude any detailed kinematic analysis there. However, Figures 17 and 18 do show general agreement between models and observations in the bridge. Specifically, as the contours go from NGC 7714 across the bridge they go from fairly horizontal (constant declination) to mixed vertical and horizontal and, ultimately, more vertical.

Similarly, in the primary galaxy (NGC 7714), the model and observational contours are similar. However, the LOS velocity range of Figure 18 is slightly greater than observed. Also, the model galaxy A contours are more horizontal than the observational contours, but they tilt more toward the vertical, and compress together, at later times.

The agreement in the companion (NGC 7715) is also quite good, with mostly horizontal contours in the bulk of the galaxy that curve upward on the bridge side in both Figures 17 and 18. Figure 18 shows that the velocity range is too large in the model galaxy. This is probably the combined result of several effects. However, because it is common to all the Hydra models, we suspect that the dominant effect is the compact halo distribution.

Figures 17 and 18 also illustrate the spatial distribution of LOS velocity dispersion in both the model and observations. The velocity dispersions range up to about 50 km s$^{-1}$ in the observations and also up to 50 km s$^{-1}$ in the model. However, in the model the largest velocity dispersions come from cells with only 5–10 particles, and the range is reduced by a factor of 3 if these cells are excluded.

In both models and observations the dispersion is larger and less uniform in the primary (NGC 7714) than in the companion. It appears that the distribution of velocity dispersions within the primary is different between the models and the observations. Observationally, the highest dispersions are found in a double cone centered on the NGC 7714 nucleus and oriented 45° from the vertical. In the models the highest dispersions are found on the south side of the galaxy. It is possible that the high dispersion values in the core of NGC 7714 are due to effects of the starburst, or an incipient wind, that are not included in the Hydra models. On the other hand, a significant part of the southern dispersion in the model is due to gas accreted from B or in the tail.

#### 3.3.2. Position-Velocity Maps

Another way to compare model and observational kinematics is by means of position-velocity plots. We consider one example, the velocity–right ascension plot. The model results are shown in Figure 19 and the observational results in Figure 20.

We have made a feature-by-feature comparison between models and observations in Figures 19 and 20, and we briefly summarize the procedure and results. Distinct features were labeled in the observational plot (Fig. 20), and then the corresponding features in the model were located on the model plot (Fig. 19). In most cases the
correspondence was direct; for example, the galaxy A and NGC 7714 disks are very similar. Yet there are some differences. In Figure 19, the disk of galaxy B is a very long and nearly vertical line of gas at $x \approx 0.42$. The prominence of this feature provides yet another indication that the velocity range of the B disk was not quite correct.

Some of the differences between these figures appear to be due to observational sensitivity limits. In particular, the...
long western H\textsc{i} tail (i.e., the western extension of the “eastern tail” from NGC 7715; see Fig. 3b of Paper I) has too low a surface brightness to appear in Figure 20, which is based on the higher resolution H\textsc{i} data of Paper II. The model predicts a slightly higher velocity for this feature (∼3040 km s\(^{-1}\)) than the observed velocity of the H\textsc{i} tail (∼2850 km s\(^{-1}\); Fig. 4 of Paper I); however, the sign of the velocity shift is correct, in that both the model and the observations show that the tail is redshifted relative to NGC 7714 and NGC 7715.

At this time in the model, the inner southwestern tail largely overlaps the base of the H\textsc{i} gas loop, although they were separate at earlier times. In the model plot (Fig. 19), the H\textsc{i} loop and the eastern NGC 7715 tail appear much more extensive than in the observational plot (Fig. 20). This is due to surface brightness limitations in the observations.

The A disk is distorted in both the model and the observations, in the sense that it does not have the form of a typical rotation curve. The model suggests that at large x-values the distortion is the result of the tidal perturbation that is also responsible for the gas loop. At low x-values there is mixing with accreted gas from galaxy B.

The H\textsc{i} maps of Paper II revealed a couple of structures on the southern boundary of the bridge. These are labeled the “southern filament” and “southern arc” in Figure 3 and in Table 1. They do not contain a large amount of gas and so were not discussed above; however, they are notable as distinct features in Figure 20.

The appearance of the southern arc and filament in the H\textsc{i} map suggests the possibility that they are physically connected, or at least connected in their origin. A careful examination of the model results suggests that this is not the case. The models suggest that the southern arc is most likely part of the bridge from NGC 7714 to NGC 7715. In contrast, a close examination of the model results suggests that the southern filament may be an extension of the ring 1+ discussed in § 3.2.1. If so, then the southern filament is a gas structure corresponding to the NGC 7714 optical ring and not, for example, an inner branch of the H\textsc{i} loop.

In conclusion, the model kinematics generally agree with the observations. In addition, dispersion measurements suggest the possibility that the starburst in NGC 7714 has energized the gas.

4. STAR FORMATION HISTORY AND THERMAL PHASES

4.1. Background

One of the primary motivations for making detailed dynamical models of individual collisional systems is to learn to what degree, and how, collisional dynamics orchestrates large-scale SF and nuclear starbursts. By driving galaxy disks far from self-regulated steady states, collisions provide a unique tool for studying these processes. With good dynamical models we can hope to determine how the SF depends on local density and pressure variations, for example. High-resolution observations are required to provide sufficient morphological and kinematic information to constrain the models. Multiband spectral data are needed to determine the stellar populations present and the SF history from observation. At present, only for a few systems do we have sufficient data for a meaningful comparison.
between spectral synthesis models and SF histories derived from dynamical models.

Recently, Lanceron et al. (2001) have published an extensive spectral synthesis model for the nucleus of NGC 7714, based on spectra ranging from the near-IR to the UV. They explored a large range of possible SF histories to achieve a good fit to these spectra, including models with a continuous component of the SF and up to three distinct bursts.

Unfortunately, despite an impressive number of spectral constraints, they found that the model fits were not unique. In particular, they found that two very different SF histories could account for the observations equally well. The first history consisted of three starbursts, with the earliest occurring about 500 Myr ago and the other two occurring at times of about 20 and 5 Myr before the present. The amplitude of these bursts declined with time. The second model consisted of a 5 Myr burst plus a continuous SF component that began about 300 Myr ago and has declined in amplitude since that time. In both these models, a very old stellar component is also assumed to be present. The conundrum emphasized by Lanceron et al. (2001) is that both models require either a burst or the onset of a significant continuous component at a time before the current collision. We take this question up again below, but first we consider what SF histories are suggested by the dynamical models presented above.

4.2. Model Results

We have run versions of the model with feedback heating from SF, and the results of these models are in qualitative agreement with the observational results. For example, the net SF of the system is dominated by that in the central regions of galaxy A; the SF in outer disk waves and tidal structures is generally small or absent. In addition, the SF within the center of A frequently has a burstlike nature, with two or three bursts within the time since closest approach. This is encouraging as far as it goes, but it is beyond the scope of this paper to quantify these results and make more detailed comparisons to observations.

There are two main reasons for this limitation on the results. The first is that feedback models introduce several new parameters, e.g., density and temperature thresholds for the onset of feedback, the amount of energy input per feedback event, timescale for the energy input, and a refractory timescale for the affected gas particles after feedback. The consequences of the feedback depend on timescale ratios involving these and other intrinsic parameters (e.g., cooling times and local dynamic times). To evaluate the validity of specific quantitative results of simulations with feedback, we need a number of runs to explore the region of the parameter space appropriate to the system being modeled. (Moreover, this is an indirect problem because it requires knowledge of the precollision gas distribution in the galaxies.)

A more fundamental difficulty is that feedback models that give postcollision bursts, and in which the gas distribution in the galaxy cores is not greatly changed by the collision (as in this system), are generally also bursty before the collision. The timing and size of the postcollision bursts then depend to some degree on the nature of the last precollision burst(s). As we plan to show in a separate paper, we believe that such models correctly capture the intrinsically recurrent nature of central starbursts in late-time galaxy disks. In isolated galaxies, such recurrent starbursts will ultimately redistribute, heat, or exhaust the cold gas until the core is below a critical (density) threshold (although this latter threshold may simply be one such that below it, the ongoing SF rate is too low to generate significant feedback effects). Mass transfer or collisional compression may push the density above the threshold again and set off a new cycle of recurrent starbursts. The fine tuning of the precollision conditions to simulate this is also beyond the scope of this paper.

If the cores of the precollision galaxies in this system were below a feedback threshold, then their SF behavior will be sensitive to changes in the central gas density and pressure. This conjecture takes us back to Figure 16, which shows central gas density in the model. The figure shows a steady gas density buildup in the core of A, along with small density bursts. The bursts are associated with the formation of asymmetric ring waves. These waves may induce starbursts if the gas is near threshold and not in a refractory period. The monotonic growth of gas density with time would make us expect strong bursts eventually, even without wave triggers. The onset of such bursts is probably strongly influenced by the recovery from feedback effects, assuming that the mass of gas thrown out in burst-driven winds is not too great. If not, waves and recovery processes (such as cooling) probably interact with each other. These processes will be difficult to model in detail.

Figure 16 shows that the companion (B) center experiences a “density” burst at the time of closest approach that is considerably stronger than that experienced by A. This is largely due to the overlap with the A halo at that time and the resulting compression. However, the disk of B also forms rings, even more vigorously than that of A.

Almost all of our models show that a significant amount of gas is removed from the companion disk in the collision and accreted onto A. As discussed above, some of this material probably ends up in the inner southwestern tidal tail (feature 3), perhaps triggering the observed SF. The rest ends up in an accretion disk, which appears only slightly tilted with respect to the original primary gas disk and roughly 2/3 as large.

This may account for some of the diffuse Hα emission observed in the NGC 7714 disk (Paper II and references therein) that extends over a similarly sized part of the disk. The mid-IR emission detected in ISO observations (O’Halloran et al. 2000) also has a similar extent. O’Halloran et al. suggest that the source of this emission is hydrogenated, but not highly ionized, polycyclic aromatic hydrocarbons (PAHs) and, in the case of a 9.6 μm line, molecular hydrogen that could be shock-excited.

The ROSAT X-ray observations of Papaderos & Fricke (1998) show two sources in NGC 7714: the starburst nucleus and a second source that they tentatively identify with either a wind outflow or an accretion stream out of the bridge. If the latter interpretation is correct, the second source may be a hot spot where the stream has hit the more relaxed material in the disk. Our models suggest that this stream would be quite weak and of limited extent by the present time. This is qualitatively consistent with a hot spot, rather than a large hot region. On the other hand, our feedback models also produce a vertical expansion (like a weak wind) following starbursts, so the models favor neither cause.
One important caveat is that the HST imagery and GHRs observations modeled by Lançon et al. (2001) resolve the inner 330 pc of the nucleus, while our simulations do not resolve scales much smaller than about 1.0 kpc. Both the smallness and the incommensurability of these scales are problems. Given the nonlinearity of feedback effects and their dependence on many variables, they can easily induce small-scale bursts that will seem like essentially random occurrences. Thus, data over a larger region are needed before we can compare models and observations with confidence, and so, despite the wealth of data available, we cannot yet do so in this system.

5. SUMMARY AND FURTHER QUESTIONS

Because of its proximity and its rich but not yet relaxed tidal structure, we are able to reconstruct the collisional history of NGC 7714/15 in detail. The models presented here have collisional parameters that are qualitatively similar to those of the earlier models of Papers I and II. The models and the observed morphologies suggest a recent collision (~100–200 Myr ago). Both our new models and previous models require an orbit of at least moderate inclination relative to the primary disk and a center of impact in the outer disk of the primary, but beyond that there are significant differences. The most important of these are the orientation of the companion disk and the fact that for the primary the collision has a significant prograde component to the perturbation (as well as an orthogonal one). In the earlier works, this perturbation component was retrograde. While these earlier models did succeed in producing both ring and tail structures in the primary, these did not match the observed structures nearly as well as the present models.

The models described above do reproduce most of the observed morphological and kinematical structure of the system. Our results include details about a number of specific features (also see Table 5 for a summary of gas masses contained in the collisional components).

1. Rings (feature 1 of Paper I) in the primary disk are naturally accounted for by the near-central impact and the moderately high inclination of the companion’s orbit relative to that disk. The stellar rings are weak in the Hydra models, but this is most probably because the initial stellar velocity dispersion was high. (The NGC 7714 stellar disk is also likely to be more massive than in the models; see § 2.3.) The prominent ring of the optical images consists primarily of old stars, without the numerous young star clusters that characterize other gas-rich collisional rings like the Cartwheel (Higdon 1995). We can suggest a couple of effects that might be responsible. The first is that much of the gas in the outer disk is flung out in tails and the bridge, and so, if the ring is near the outer edge of the remnant disk, there may be little gas left there. A related factor is that the collisional overlap with the companion disk was on this side of the primary disk. Second, the radial perturbation is not as great as in a classical ring galaxy, so gas compression in the wave is less. The models suggest that this strong asymmetric ring may be the second ring wave. Traces of the first may be seen as a faint (east-side) feature on deep optical images, and perhaps in the gas as the southern filament.

2. The H i loop and the optical southwestern tail (feature 2) are parts of the same tidal structure, which is a tidal countertail, produced by the prograde component of the disturbance. Although it originated as a tidal tail, the H i loop is ringlike, and it is described above as a precursor, or zeroth-order, ring.

3. The connecting bridge (feature 5) is predicted to consist of multiple components: early- and late-forming bridges from NGC 7715, a bridge pulled from NGC 7714, and the superposed tidal countertail from NGC 7715. The superposition of these components accounts for the large gas mass of the bridge.

4. The tidal tail originating on the east side of NGC 7715 (feature 6) may curve behind the disk of its parent galaxy and the bridge and appear on the far west side of NGC 7714 as an extended H i tail. The models suggest that this is a long and massive feature, although largely hidden. More generally, they suggest that much of that galaxy’s original disk has been ripped out. This helps explain the low gas mass in NGC 7715.

5. The stubby northwestern plume of NGC 7714 is most likely an extension of the NGC 7715 (late) bridge. This conclusion is based mainly on optical imagery, as this feature is not clearly resolved in the H i maps. This feature is minor, and the models do not have sufficient resolution to confirm it as a bridge extension.

6. The inner southwestern tail (feature 2) of NGC 7714 is one of the most mysterious structures in this system. The Hydra models suggest that it is the result of material transferred at early times from the companion. It was subsequently torqued out into a tail, like other material in the NGC 7714 disk, but at a slightly different location.

7. The models suggest that mass transfer onto the NGC 7714 disk has been prolonged and significant, but that there has been little accretion onto NGC 7715 as yet. (This result should be treated with some caution, since it depends on the specific orientations of the two disks.)

8. There is general agreement between model and observed (H i) kinematics, including the distributions of both LOS velocities and velocity dispersions; however, there are several differences in detail. For example, the western H i tail is somewhat more redshifted in the model than in reality.

9. We achieved better fits to the collisional morphologies with models with a halo potential that yields a flatter rotation curve than the softened point mass potentials used in the earlier models. Nonetheless, these latter halos diminish quickly at radii greater than the initial disk radius, in accord with the criterion of Dubinski et al. (1999) for halo structure in tailed systems.

These comparisons show that the simulations above have provided one of the most successful and detailed collisional models of a disturbed galaxy system to date. This model reconstruction not only provides an example of the power of collisional theory, but it also provides a basis for studying SF on a region-by-region basis within these systems. It makes it possible to test our understanding of the mechanisms of interaction-induced SF, and the role of various gas dynamical processes, with much more precision than would be possible without such information. We obtained the following results related to SF.

10. The SF history in the center of NGC 7714 is driven, in part, by multiple ring compressions. Multiple bursts have also been suggested by the population synthesis models of Lançon et al. (2001). These synthesis models further suggest that an episode of SF began a considerable time before
closest approach (i.e., 100–400 Myr earlier). Our numerical simulations do not resolve the mystery of how this SF might have been caused. They suggest the possibility that compression began somewhat before closest approach. Since the time since closest approach could be quite long (up to 200 Myr) in an encounter like that of the best model, triggering by this early compression might suffice to explain the early burst. Another possibility is triggering by an earlier encounter, even if this encounter was distant and the perturbation small. The relative orbit of the galaxies, at a time much before closest approach, is not well constrained.

11. NGC 7715 is characterized as a poststarburst galaxy. The models yield a compression at the time of closest approach that might be expected to trigger a burst. From that time to the present the loss of disk material and lack of mass input result in the suppression of SF in this disk.

12. The models provide intriguing hints about regional SF. For example, the model result that the bridge consists of multiple, generally nonoverlapping and low-density parts helps us explain the apparent contradiction between the large gas mass and low SF rate in the bridge. At the same time, there is a beautiful filament of SF knots on the north side of the bridge. Our models suggest that this SF was triggered by an interaction between bridge components. Another interesting SF region is the inner southwestern tail. Our models suggest that this is a mixing region between disk and accreted material. Thus, SF may be the result of turbulence and enhanced compression.

Results 10–12 are tentative, because the resolution of compressed regions is limited, and the representation of thermal processes is approximate. Yet the qualitative agreement between the dynamical models and spectral evolutionary models for the recent SF history of this system is encouraging. At the very least, these results yield no contradiction to the proposition that collision-induced compression drives the SF.

To date, there have been few cases in the literature in which the spatial/temporal pattern of compressional disturbances is quantitatively compared to that of its young-to-intermediate-age stellar populations. The extreme case of large amounts of gas dumped into the cores of major merger remnants, followed by superstarbursts, provides one example. Classical collisional ring galaxies like the Cartwheel, with aging burst populations behind the propagating wave, provide another example (see Appleton & Struck-Marcell 1996). Our success with this system offers hope that we can also succeed in other, less simple, systems. We need many such comparisons in order to advance our understanding of how interactions induce SF.

Despite the fact that this system has been observed in almost every wave band from radio to X-ray with a wide variety of ground- and space-based telescopes, it remains true that additional observations would be helpful. Increased resolution of the distributions of gas and stellar populations would be very helpful for answering the remaining questions and guiding more refined models. For example, the H I observations of Paper II barely resolve important structures like the ring and the bridge. As a second example, extensive HST imaging and spectral observations have been made of the starburst core of NGC 7714 (see § 1), with snapshots of various parts of the system. However, no complete HST imaging survey has been undertaken. High-quality spectral observations of SF regions outside the core would also be very useful. When higher resolution observations become available, the simulations presented here could serve as a starting point for a new generation of models with much greater particle and spatial resolution.

This research is based in part on archival 21 cm H I observations made in 1989, 1992, and 1994 with the Very Large Array (VLA) telescope, a facility of the National Radio Astronomy Observatory (NRAO), which is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. We have also made use of the Digitized Sky Survey, a compressed digitized form of the Palomar Observatory Sky Atlas, which was produced at the Space Telescope Science Institute under US Government grant NAG W-2166. The National Geographic Society–Palomar Observatory Sky Atlas (POSS-I) was made by the California Institute of Technology with grants from the National Geographic Society. We thank John Wallin for his restricted three-body code, which we used for preliminary modeling runs.

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