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

Beverly J. Smith
Department of Physics and Astronomy, East Tennessee State Univ., Box 70652, Johnson City, TN 37614

ABSTRACT

We present new N-body, hydrodynamical simulations of the interaction between the starburst galaxy NGC 7714 and its post-starburst 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 HI 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 HI tail to the far west of NGC 7714 is the end of the NGC 7715 countertail, curved behind the two galaxies. The sensitivities of the tidal structures to collision parameters is demonstrated by comparisons between models with slightly different parameter values.

Comparison of model and observational (HI) 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 ring-like waves, and a post-collision buildup of gas in the core of the galaxy.

Subject headings: galaxies: individual (NGC 7714/7715) — galaxies: interactions — galaxies: kinematics and dynamics

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 in interacting galaxies and hydrodynamical processes such as shock wave production, heating and cooling, and re-accretion. In practice, however, it has proven 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 star formation 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 (e.g., Gerber (1993), Dubinski et al. (1999)). A second helpful factor is the existence of a special symmetry in the collision. The symmetric collisional ring galaxies provide a notable example (Appleton & Struck-Marcell 1996). Another example is provided by the ocular galaxies, in which the characteristic eye-like morphology results from a strong prograde disturbance, implying that the companion orbital plane has a small inclination relative to the disk plane of the ocular (Elmegreen et al. (1991), also see Kaufman et al. (1997), Kaufman et al. (1999), and Elmegreen et al. (2000)). Long tidal tails also result from nearly planar prograde interactions (Toomre & Toomre (1972), and review of Struck (1999)), and can provide important clues to the nature of an ongoing interaction.

The interacting system NGC 7714/15 (Arp 284), with a relatively nearby distance of 37 Mpc (assuming $H_0 = 75$ km s^{-1} Mpc^{-1}), has many of these exceptional properties. The most important features of NGC 7714/15 are summarized in Tables 1 and 2, and are visible in the optical Arp (1966) Atlas photograph (Figure 1, with a Hubble Space Telescope archive image in Figure 2), and in the published 21 cm HI and Hα maps (Smith & Wallin (1992), hereafter Paper I, and Smith et al. (1997), hereafter Paper II). NGC 7714 has a prominent stellar ring (Arp 1966) which does not have on-going star formation (Bushouse & Werner (1990); Bernlöhr (1993); González-Delgado et al. (1995); Paper II; O'Halloran et al. (2000)), or an HI 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 HI loop (Feature 2 in Figure 1, also see Figure 3). The inner southwestern arm (Feature 3 in Figure 1) is brighter, with a prominent HII region complex at the base of this arm (Paper II). In optical images, the northeastern stellar arm (Feature 4 in Figure 1) is clearly physically separate from the bridge, however, in the HI maps, it is not well-resolved (Paper II; see Figure 3). In addition, low resolution HI observations reveal a low surface brightness HI tail extending 6′ (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 HI gas, old stars, and young stars, with a significant offset between the old stars and the other components (Paper II; see Figure 3). This offset is clearly evident in Figure 2, where a string of luminous H II regions lies to the north of an optical continuum bridge. Since models show that connecting bridges are relatively short-lived features (Struck 1997), its presence 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 contraints are provided by the map of line-of-sight HI 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); and Kotilainen (2001)), while the center of NGC 7715 shows a post-starburst spectrum (Bernlöhr 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 3-body model of the NGC 7714/5 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 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 7714/5 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' (version 3.0) N-body, adaptive-mesh SPH code of Couchman et al. (1995), which includes radiative cooling, and also feedback heating terms in some models (see the following section 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 section 3.1 and 3.2). Comparisons to observed kinematics (section 3.3) and star formation (SF) characteristics (section 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 section 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 (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 will not describe that work any further. We then used the hydrodynamic code of Paper II (see Struck (1997) for details on this code) to study the gas dynamics 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, and 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 HI loop and other tidal structures can develop to the observed degree. Given the limitations of these models, we will not describe their results in any detail.

Fully self-gravitating simulations were then produced with the serial code Hydra 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 (PP), particle-mesh (AP^3M) algorithm (for details see Couchman et al. (1995), Pearce & Couchman (1997)). For a typical timestep 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 and 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 timestep, since the dynamical time is usually longer than the cooling time. Particles evolve adiabatically and are cooled at the end of a given timestep, 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 Figures 1-3 below). 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), and the mass unit equals $10^{10} M_{\odot}$.

With these scalings, the model results suggest that closest approach occurred about $100 - 250 Myr$ ago; we will 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 will 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 models the mass ratio of the galaxies was about 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 observation.

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 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 adopt the x-y plane as the plane of the sky, and then the model galaxy initial conditions and the orbital 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 will be highly interwoven. To avoid confusion about which is being referred to we will 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 will focus on the morphological and kinematic results, and briefly discuss thermal effects and star formation in the following section. 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 first 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 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, though 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, galaxy B loses much more mass.

Next we will 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 $100 - 220 Myr$, though 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 A, and the impact of the center of B within or near the A disk, should give rise to a substantial m=0, ring-like 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 Figure 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 bar-like 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 panel) and gas (right panel) particles in the galaxy A disk at a time near the present. The left 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 panel, but 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 m=2 perturbations.

In fact, the tidal countertail (which corresponds to the HI 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, it is virtually invisible.) Since these structures developed even before closest approach we call them the 0 order ring. This 'ring' is very asymmetric, with the HI 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 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 ring-like 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(+ and -) in the model. The high resolution HST (WFPC2) partial image in Figure 2 of Lançon et al. (2001) looks very similar to the right panel of Figure 9, except that the 2+ ring 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 effected 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 star formation 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 either being 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 SF feedback may have heated and scattered the gas on this side. Preliminary models with feedback also support this idea, and further show that the 2+ ring could be completely disrupted by reasonable amounts feedback. Observations of the stellar populations in this region would be very desireable.

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

The ratio 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 (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 doesn't extend much beyond the optical disk.) On the other hand, the asymmetry of the ring, and the fact that they have been torqued in the interaction, complicates this interpretation.

3.2.2. Outer Southwest Tail and HI Loop of NGC 7714 (Feature 2)

The 'outer southwest tail' seen in optical images (Feature 2 of Figure 1) appears to be just the base of the great HI loop described in Paper II (see Figure 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 HI loop to at least a position angle of 330°.

Our Hydra models (Figures 5 and 6, lower left 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 ($\simeq 1.1 \times 10^9 M_\odot$) was pulled out into the huge loop, we investigated the history of the particles in the loop in the Hydra models (Figure 10). In the left 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 A disk.

The right-hand panel of Figure 10 shows the location of the same gas particles at a time shortly before the impact 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 ring-like aspect. E.g., it is always a loop, which connects back to the 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 pre-collision 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) $\sim$ 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 panel, which highlights the strong compression resulting from the collision.

3.2.3. The Bridge (Feature 5)

The HI maps of Paper II suggested that the bridge between the two galaxies is a complex structure. In particular, there is a measureable offset between the star and HI 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 will refer to as the 'alternate.' The alternate model differs from the best model by having a different tilt of the B galaxy, 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, like ring waves and the tidal tails, versus those which depend sensitively on structural and orbital parameters. The bridge contains components of both types.

The first bridge component (Labeled i in Figure 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 post-collision B bridge, begins as a dark, nearly vertical line on the left side of the gas between the two galaxies in the upper left panel. It also dominates the left side of the bridge in the alternate model at this time (upper right 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 towards galaxy 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 upper left 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 towards galaxy B (see Figures 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 panel of Figure 11. It is also present in the best model, though harder to distinguish in the top left 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 pre-collision 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 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 last two panels of Figure 12 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 Figure 15 below) 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 star formation. The Hα observations of Paper II suggest that these clusters are truly young, and this is the only dynamical event that occurs in the region within a few times 10^7 $yrs.$ of the present. 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 will describe the kinematic predictions of the simulation below.

3.2.4. The NGC 7715 Tail (Feature 6)

Next we will consider the NGC 7715 (stellar and gas) countertail. As we have already discussed, 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 superimposing the tail on the line-of-centers of the two galaxies.

In the models, at $t \geq 100$ $Myrs.$, the gas in this tail extends about 25 kpc to the southwest of NGC 7714 (Figures 5, 8, and 14). The long HI plume to the southwest of NGC 7714, seen in low resolution HI maps (Figure 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 it being the end of an HI-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 (Figure 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 has fallen through the NGC 7714 disk plane. The model bridges do not have enough particles to confirm this, and the available HI data do not have sufficient resolution to distinguish this feature from the disk.

3.2.6. The Inner Southwest NGC 7714 Tail (Feature 2)

The inner SW tail (Feature 3 in Figure 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 HI loop), but rather an extra inner tail paralleling feature 2. Moreover, it has a high surface brightness, and contains knots of recent star formation. It also does not appear to be an extension of the bridge, nor material accreted out of the bridge.

Figure 15 provides a plausible solution to the mystery. The first panel shows how mass transfer is well underway at the time of closest approach. Inner SW tail particles were first identified in the third panel of Figure 15. That is, all gas particles from B lying within a rectangular region between the A disk and the HI loop were selected and marked with plus signs. This somewhat crude procedure misses a number of the 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 first panel confirms that they are part of the earliest mass transfer. Already by the time of the second panel ($t = 40\ Myr.$) they are part of a plume located behind the nascent HI loop.

At the time of the second 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 third panel ($t = 70\ Myr.$). In this view the inner SW tail is visible as a horizontal set of particles lying below the primary, and above the long curved contour of the HI loop.

The final 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 NW quadrant, rather than the SW, but 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 fourth 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 SW tail is not reproduced as well in the other Hydra models, though 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 temporary incursions into the spherical volumes measured.

At times from t = 0 on, ring-like 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, and angular momentum mixing with transferred gas.

The delayed central gas buildup after closest approach is interesting, and agrees with the observations of delayed starbursts in interacting systems (see e.g., Bernlöhr (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 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 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

Table 4 provides 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 post-collision 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 B disk contains about twice the observed fraction, but this is still much lower than the initial value. That is, it has lost 2/3 of its original gas. NGC 7715 is a post-starburst 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 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 observed, even including the superposed galaxy B tail. However, this number is a very sensitive function of time and of the post-collision deceleration. At $t = 100\ Myr$ in this model, the gas fraction in the bridge was nearly twice the value shown in Table 4. Between these two times, substantial amounts of gas falls 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 fall-back 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 line-of-sight (LOS) kinematics. Figure 17 provides the LOS velocity map for the multi-array 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 5 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 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, which 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 in the observations range up to about 50 km s^{-1}, 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 2/3 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 dispersion 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, which 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 will 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 will briefly summarize the procedure and results. Distinct features were labeled in the observational plot (Figure 20), and then the corresponding features in the model were located on the model plot (Figure 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 B is a very long, and nearly vertical, line of gas at $x \simeq 0.42$. 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 appears to be due to observational sensitivity limits. In particular, the long western HI tail (i.e., the western extension of the "eastern tail" from NGC 7715, see Figure 3b of Paper I) has too a low surface brightness to appear in Figure 20, which is based on the higher resolution HI data of Paper II. The model predicts a slightly higher velocity for this feature (∼3040 km s^{-1}) than the observed velocity of the HI tail (∼2850 km s^{-1}; Figure 4 in 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 SW Tail largely overlaps the base of the HI gas loop, though they were separate at earlier times. In the model plot (Figure 19), the HI loop and the eastern NGC 7715 tail appear much more extensive than in the observational plot (Figure 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 HI 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 HI 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 1+ ring discussed in Section 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 HI 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. Presently, 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, Lançon 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 occuring about 500 Myr. ago, and the other two occuring 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 continous SF component, which began about 300 Myr. ago, and 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 Lancon et al., is that both models require either a burst or the onset of a significant continuous component at a time before the current collision. We shall take this question up again shortly, 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 star formation, and the results of these models are in qualitative agreement with the observational results. E.g., the net star formation of the system is dominated by that in the central regions of galaxy A; the star formation in outer disk waves and tidal structures is generally small or absent. Secondly, the star formation within the center of galaxy A frequently has a burst-like nature, with 2-3 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 observation.

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, time scale for the energy input, and a refractory time scale 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 pre-collision gas distribution in the galaxies.)

A more fundamental difficulty is that feedback models which give post-collision 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 post-collision 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 on-going star formation 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 pre-collision conditions to simulate this is also beyond the scope of this paper.

If the cores of the pre-collision galaxies in this system were below a feedback threshold, then their star formation 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 galaxy A, along with small density bursts. The bursts are associated with the formation of an 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 the mass of gas throw out in burst-driven winds is not too great. If not, waves and recovery processes (like 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, which 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 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 SW tidal tail (Feature 3), perhaps triggering the observed SF. The rest ends up in an accretion disk, which is 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 $H\alpha$ emission observed in the NGC 7714 disk (Paper II and references therein), which extends over a similarly sized part of the disk. The mid-infrared 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, 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. 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 incommenserability of these scales is a problem. Given the nonlinearity of feedback effects, and their dependence on many variables, they can easily induce small scale bursts, which will seem like essentially random occurances. 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 7714/5 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 ($\sim 100 - 200$ 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 orthogonal). 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 kinematic structure of the system, including the following specific features. (Also see Table 4 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 Section 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. Secondly, 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 HI loop and the optical SW 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 HI loop is ringlike, and 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 superimposed 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 HI tail. The models suggest that this is a long and massive feature, though 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 NW 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 HI maps. This feature is minor, and the models do not have sufficient resolution to confirm it as a bridge extension.

6) *The inner SW 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 an slightly different location.

7) The models suggest that *mass transfer* onto the NGC 7714 disk has been prolonged and significant, but 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 (HI) kinematics, including the distributions of both line-of-sight velocities and velocity dispersions, however, there are several differences in detail. E.g., the western HI 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 star formation, and the role of various gas dynamical processes, with much more precision than would be possible without such information. We obtained the following specific results.

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 post-starburst 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 non-overlapping and low density parts, helps us explain the apparent contradiction between the large gas mass but low SFR 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 SW 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.

These results on SF 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 where 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 super-starbursts, 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 waveband 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 HI 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 section 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 HI observations made in 1989, 1992, and 1994 with the National Radio Astronomy Observatory (NRAO) Very Large Array (VLA) telescope, 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 NAGW-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 3-body code, which we used for preliminary modeling runs.

TABLE 1

MORPHOLOGICAL CHARACTERISTICS OF THE NGC 7714/15 SYSTEM.

Feature	Notes	References
1. (1) Stellar Ring[a]	NGC 7714	1
	(No gas ring)	3
2. Stellar Bar	NGC 7714	2
3. (4) NE Stellar Arm	NGC 7714	1
	(No gas counterpart)	
4. (3) Inner SW Stellar Tail	NGC 7714	1
5. (2) Outer SW Stellar Tail	NGC 7714	1
	(Associated with gas loop)	
6. Large Gas Loop	NGC 7714	3
	(NW - NE)	
7. Edge-on Shape	NGC 7715	1
8. (5) Stellar Bridge		1
9. (5) Gas Bridge	High column density HI, offset to the north of the stellar bridge	4
10. (6) Stellar Countertail	NGC 7715	1
11. Gas Countertail	NGC 7715	3
12. Far West HI Clouds	In low resolution HI observations	4
13. Southern Arc	NGC 7714	3
14. Southern Filament	NGC 7714	3

[a] Number in parenthesis is feature number in ref. 4

[1] Arp 1966

[2] Bushouse & Werner 1990

[3] Smith, Struck & Pogge 1997

[4] Smith & Wallin 1992

TABLE 2
OTHER CHARACTERISTICS OF THE NGC 7714/15 SYSTEM.

Feature	Description	References
	Kinematic Features	
15. Mean Radial Velocities[a]	Similar in NGC 7714 & NGC 7715	3
16. Bridge Radial Velocity	Blueshifted relative to galaxies	3
17. "Spider Diagram"	E.g., line of nodes & rotation sense in NGC 7714	3
18. Rotation Curve	NGC 7715	3
	Star Formation Features	
19. Central Starburst	NGC 7714	2
20. Arc of Knots in Bar	NGC 7714	2
21. Inner SW Arm	NGC 7714	2
22. Post-starburst Center	NGC 7715	5
23. Bridge Knots	Several dozen	3

[a] Feature numbering continued from Table 1.

[1] Arp 1966

[2] Bushouse & Werner 1990

[3] Smith, Struck & Pogge 1997

[4] Smith & Wallin 1992

[4] Bernlöhr 1993

Table 3
Model Parameters.[a]

	Primary Galaxy	Companion
Initial Galaxy Parameters		
Masses[b]($M_\odot$):		
Halo	6.0×10^{10}	2.0×10^{10}
Gas Disk	2.9×10^{9}	0.97×10^{9}
Stellar Disk	2.9×10^{9}	0.97×10^{9}
Radii (kpc):		
Halo	12. (core = 2.4)	6.0
Gas Disk	10.	7.5
Stellar Disk	7.5	6.0
Disk Peak Rotation (km/s)	200.	200.
Disk Orientation Angles[c]	30° about y-axis	$-10°$ [30°] about the z-axis, then $-20°$ [40°] about the y-axis
Orbital Parameters		
Initial Center Positions[d] ((x, y, z) in kpc)	(12.6, -5.6, 19.2) [11.5, -7.0, 17.5]	(-12.6, 5.6, -19.2) [-11.5, 7.0, -17.5]
Initial Center Velocities[e] (vx, vy, vz in km/s)	(-78.0, 22.5, –71.1) [-74.2, 19.5, -54.7]	(78.0, -22.5, 71.1) [74.2, -19.5, 54.7]
Gas Disk Center Positions (at Closest Approach)	(-2.2, 0.4, 0.0) [-3.3, -0.2, 0.0]	(1.8, -0.1, 0.0) [3.2, 0.3, 0.0]
Gas Disk Center Velocities [f] (at Closest Approach)	(18.6, 39.1 -229.) [0.0, 88., -180.]	(-112., -107., 234.) [0.0, -78., 166.]

[a] For the best model, with values for the alternate model in square brackets. Physical units used here. Conversion from code units described in text

[b] In the self-consistent Hydra models the number of particles in the primary galaxy halo, gas disk and stellar disk are 10,000, 9550, and 9550, respectively. In the best and alternate models the corresponding numbers in the companion are 3000, 3450, 3450. In all of the model galaxies the mass of a halo particle is $6.0 \times 10^{6} M_\odot$, and the mass of a star or gas particle is $3.0 \times 10^{5} M_\odot$.

[c] The primary galaxy is initialized in the x-y plane, which is taken as the fundamental plane, or the plane of the sky. The disk is then rotated as described. The companion galaxy is initialized in the x-z plane.

[d] The initial separation is 44.2 kpc.

[e] Relative velocity is 188 km/s.

[f] Net relative velocity is 380 km/s, with significant uncertainty due to distorted centers.

Table 4
Gas Fractions in Different Structural Components.

Feature	$HI + H_2$ Mass[a]	Percent of Total Gas
	From Observation	
NGC 7714 Disk	$1.7 + 2.2$	42%
NGC 7715 Disk	$0.31 + (\leq 0.13)$	3.4%
NGC 7714 HI Loop	$1.1 + (\leq 0.26)$	12%
The Bridge (Feature 5)	$1.5 + (\leq 0.094)$	16%
NGC 7715 East Tail (Feature 6)	$0.38 + (\leq 0.061)$	4.1%
Totals	$7.0 + 2.2$	**77.5%**
	From the Hydra Model (With 1:3 Mass Ratio at t = 170 Myr)	
	Gas Mass (No. of particles)	
Pre-Collision Disks: A	9550	73%
B	3450	27(%)
Present Values (t = 170 Myr):		
Galaxy A Disk	6906 (= 6064 + 842)[b]	53%
Galaxy B Disk	1000 (= 5 + 995)	7.7%
Galaxy A Loop	$\simeq 2873$ (= 2747 + 126)	22%
Bridge (From A)	452	3.5%
Bridge (From B)	203	1.6%
Galaxy B Tail	1033	8.0%
B Tail on Bridge[c]	129	1.0%
B Tail East[d]	339	2.8%
Total		**99.6%**

[a] HI data from Smith, Struck & Pogge 1997 and H_2 data from Smith & Struck 2001. All masses in units of $10^9 M_\odot$. The molecular gas masses have been calculated assuming the standard Galactic N_{H_2}/I_{CO} conversion factor (Bloemen et al. 1986).

[b] The numbers in parenthesis indicate contributions from Galaxy A and B, respectively.

[c] That is, the part of the Galaxy B counter-tail superimposed on the bridge in the x-y view.

[d] That part of the B counter-tail that is east of the B disk in the (x-y) projection.

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This 2-column preprint was prepared with the AAS LaTeX macros v5.0.

Captions

Fig. 1.— The Arp Atlas (1966) image of NGC 7714/5. North is up and east to the left. NGC 7714 is the larger galaxy to the west. The field of view is $5\rlap{.}'0 \times 3\rlap{.}'9$.

Fig. 2.— A broadband red (F606W filter) Wide Field Planetary Camera 2 (WFPC2) image of NGC 7714 and the NGC 7714/5 bridge, from the Hubble Space Telescope archives. The field of view is $2\rlap{.}'5 \times 1\rlap{.}'5$. 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 II regions between the two galaxies, offset to the north of an optical continuum bridge.

Fig. 3.— The VLA naturally-weighted HI map from Paper II (greyscale), superposed on the Digitized Sky Survey (DSS) POSS-I red image (contours). The resolution of the HI map is $11\rlap{.}''02 \times 8\rlap{.}''48$ with a position angle of $-36.6°$, while the DSS image has been smoothed to $12''$ resolution. Various features have been marked.

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 first row shows the initial disks ($t = -180\ Myr.$). The second row shows the disks at the onset of the collision ($t = 0.0\ Myr.$), and the last row shows the disks at a time just after the closest approach of galaxy centers ($t = 40.0\ Myr.$). The labels A,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 B every particle is plotted. Coordinates are given in dimensionless code units, which can be scaled as described in the text. (Note: we assume that the observer is located at the appropriate distance along the negative z axis.)

Fig. 5.— Gas particles from the galaxies, as in the previous figure, but at times after closest approach ($t = 120,\ 170,\ and\ 220\ Myr.$). This sequence illustrates the development of tidal tails and the collisional bridge.

Fig. 6.— Three views of collisional distortions of the stellar particles at the same times as in the previous figure for the gas particles. The late time x-z view shows that part of the stellar 'bridge' is essentially a near side tail (at the top) in this model. The absence of an object B counter tail in the late time x-y view (lower left) also shows that it is superimposed on the bridge (see Figure 5).

Fig. 7.— Same as Figure 5, but including only gas particles that originated in object A (model NGC 7714).

Fig. 8.— Same as Figure 5, but including only gas particles that originated in object B (model NGC 7715).

Fig. 9.— *left:* The distribution of stars, and a (weak) stellar ring in the primary disk at a time near the present in the best model. *right:* same for gas particles. The dynamically cooler gas disk shows the ring waves more clearly. Several of these are labelled as described in the text.

Fig. 10.— Gas particles in the best model representing the NGC 7714 'HI loop' or tail (Feature 2 of Paper I) are shown in the left panel at time $t = 120\ Myr.$, as well as a few representative contours to mark the location of the galaxy disks. The right panel shows 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 around from the right to the left and a bit below the primary.

Fig. 11.— Y-Z views at two intermediate times provide a good perspective on the origin of the bridge particles in the best and alternate Hydra models. Gas particles from object B are shown as dots, while the gas distribution of A is shown by a few representative column density contours. The bridge in the alternate model is made up of four contributions (labeled i-iv). Features 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-to-A bridge is much narrower, though of comparable mass. The third (iii) is the tidal bridge from A, visible in the contours at the earlier time. The fourth is 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.

Fig. 12.— Two views of gas particles in the bridges

of the best and alternate models at t = 120 and 100 Myr., respectively. Membership in the bridge is determined primarily by x-z position (because the bridge stretch is large in that view). The x-y views (first column) of the two models are quite similar. The x-z views show that in the best model the gas particles from A promptly fall back to the left hand side of the A disk, while in the alternate model these particles are spread across the bridge.

Fig. 13.— Two orthogonal views each of the stars (first column) and gas (second column) in the best model at a time $t = 140\ Myr$. Gas particles from object A are shown as dots, while the gas distribution of B is shown by a few representative contours. The plots in the first row show that the primary's gas bridge is concentrated on the north (top) side of the tidal bridge, while the old stars are more smoothly distributed. This shows the gas/star offset in this component of the bridge. The gas tail from B (not shown) is located in true thin filaments, stretching between the two galaxies. The panels in the second row show that this is not the case for the gas bridge from A, which remains near the A disk.

Fig. 14.— Gas particles in the model NGC 7715 tail are shown in the left panel ($t = 120\ Myr.$), 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 Figure 7). As in Figure 11 the right panel shows 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 B galaxy 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 illustrate the origin of the inner SW 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 SW tail particles are marked with plus signs. The plus sign particles were identified on the basis of their position in the third panel. The final panel shows a slightly rotated x-y view at a time slightly before the present (see text). The inner SW tail is labeled. The HI loop is marked by clumpy contours extending out and upward from the right side of the primary. Most of the particles at the bottom of this panel originate in the B tidal tail.

Fig. 16.— Gas mass relative to the initial value contained within a spherical volume of radius $r = 0.03$ grid units (about 3 kpc.) about the centers of the Hydra model galaxies as a function of time. The solid curves are for the galaxies in the best model (galaxies A & B labelled). Dotted curves show the fractional gas mass around each center that was transferred from the other galaxy in the model. The curve with plus signs (+) shows mass transferred to galaxy B from A, while the curve with open circles shows transfer to A from B. The vertical dotted line shows the approximate time of closest approach.

Fig. 17.— Observational LOS velocities (contours) and dispersions (greyscale), from the data in Smith et al. 1997, for comparison to the model results. The contour interval is 10 km s^{-1}. Some contours are labeled. The range in dispersion plotted extends from 0 km s^{-1} to 50 km s^{-1}, with darker grey corresponding to higher dispersions.

Fig. 18.— X-Y views of the best model kinematics. Contours show line-of-sight velocities, where model velocities have been scaled to the observed range by multiplying by the scale factor of 100 km/s, and adding 2800 km/s (the approximate systemic velocity). The local velocity dispersion is shown in gray-scale, with regions of high dispersion shown darker, and with a linear scale ranging from about 5 to 50 km/s. The outer perimeter contours of this plot are not significant; this plot was made using Matlab, which requires closed contours.

Fig. 19.— Velocity of model gas particles in the z direction versus x coordinate value for comparison to observational velocity-right ascension plot. Note that we have rotated the model results by -10° in the x-y plane, so that the x-axis of the model more nearly corresponds to right ascension. The model velocities have been scaled as in Figure

18 by multiplying by a factor of 100, and adding a constant systemic velocity of 2800 km/s. The x-axis values are in dimensionless code units. Text labels identify particle sets corresponding to those of the observational plot (Figure 20). See text for details.

Fig. 20.— Observational velocity-right ascension plot. Individual features are marked. The 'southern filament' is a stream of gas extending to the south of the bridge, while the 'southern arc' is gas to the southeast of the NGC 7714 disk (see Paper II and Figure 19). Note that in both of the NGC 7714 and NGC 7715 disks, the velocities tend to increase from east to west, as does the gas in the northwest loop and in the bridge. The velocity of the gas in the inner southwest tail, however, decreases from east to west. As noted in the text, the long southwestern HI tail seen in low resolution HI maps (Smith & Wallin 1992) has too low surface brightness to be visible in this plot. It extends to RA 23^h 33m 15^s with a velocity of $\sim$2850 km s^{-1} (Smith & Wallin 1992).