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The grazing encounter between IC 2163 and NGC 2207: Pushing the limits of observational modeling * †

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ABSTRACT

We present numerical hydrodynamical models of the collision between the galaxies IC 2163 and NGC 2207. These models extend the results of earlier work where the galaxy discs were modeled one at a time. We confirm the general result that the collision is primarily planar, that is, at moderate inclination relative to the two discs, and prograde for IC 2163, but retrograde for NGC 2207. We list 34 specific morphological or kinematic features on a variety of scales, found with multi-waveband observations, which we use to constrain the models. The models are able to reproduce most of these features, with a relative orbit in which the companion (IC 2163) disc first side-swipes the primary (NGC 2207) disc on the west side, then moves around the edge of the primary disc to the north and to its current position on the east side. The models also provide evidence that the dark matter halo of NGC 2207 has only moderate extent. For IC 2163, the prolonged prograde disturbance in the model produces a tidal tail, and an oval or ocular waveform very much like the observed ones, including some fine structure. The retrograde disturbance in the model produces no strong waveforms within the primary galaxy. This suggests that the prominent spiral waves in NGC 2207 were present before the collision, and models with waves imposed in the initial conditions confirm that they would not be disrupted by the collision. With an initial central hole in the gas disc of the primary, and imposed spirals, the model also reproduces the broad ring seen in HI observations. Model gas disc kinematics compare well to the observed (HI) kinematics, providing further confirmation of its validity. An algorithm for feedback heating from young stars is included, and the feedback models suggest the occurence of a moderate starburst in IC 2163 about 250 Myr ago.

We believe that this is now one of the best modeled systems of colliding galaxies, though the model could still be improved by including full disc self-gravity. The confrontation between observations and models of so many individual features provides one of the strongest tests of collision theory. The success of the models affirms this theory, but the effort required to achieve this, and the sensitivity of models to initial conditions, suggests that it will be difficult to model specific structures on scales smaller than about a kiloparsec in any collisional system.

Key words: galaxies: individual: (NGC 2207, IC 2163) –galaxies: interactions – galaxies: dynamics.

* Based in part on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Insti-

1 INTRODUCTION

Collisions and interactions between galaxies in groups almost inevitably lead to mergers, with orbital energy converted into random motions of the constituents, and into the kinetic energy of tidal tail ejecta. However, this process is not direct; the initial and final relaxed states are separated by a period in which energy is also used to generate and maintain large-scale coherent structures.

Unless the collision involves special symmetries, the complexity of the tidal structures (and the diversity of galaxy morphology) increases for a time of order several dynamical times (e.g., review by Struck 1999). Ultimately, phase mixing and thermalization erase these structures. The form of the waves generated before this erasure is a function of both the precollision morphology of the individual galaxies and the collision parameters. Dynamical modeling can be used to derive the initial conditions and collision parameters from observations of the tidal structure, a kind of galaxy tomography.

One obvious difficulty in such a program is that we only see colliding galaxies in projection in both coordinate and velocity space. However, we can hope to compensate for the loss of 50% of phase space coordinate information with increasingly detailed, high resolution observations and similarly high resolution models. New instrument and computer technology are providing rapid improvements in both models and observations. On the observational side, HST observations of collisional systems like NGC 2207/IC 2163 (see Figure 1) provide a prime example of the results of improved resolution.

Another fundamental problem is that colliding galaxies have a wide range of dynamical timescales. Orbital and epicyclic periods may range from 3×10^6 yr in the central regions to more than 10^9 yr for the orbits of stars and gas clouds flung out in long tidal tails. Similarly, the duration of the strong interaction in a first encounter may be short compared to the time between encounters.

A third difficulty is that the timescale of the tidal driving is comparable to that of the internal dynamical timescales. For example, waves in the inner-to-middle discs from a first disturbance may have begun to phase mix at the onset of a renewed disturbance, which will generate a new set of waves. The multiple sets of waves generated by multiple impulsive disturbances will interfere with each other in ways that depend on the degree to which the waves are material or phase phenomena. Secondary disturbances result from time-delayed effects like the slow fall-back of material pulled out in long tidal structures, and the different response times of different galaxy components (bulge, disc, and halo).

These difficulties make it nearly impossible to reconstruct the collisional history of systems in an advanced state of merger. Reconstruction is much more feasible in recent collisions (i.e., "young" systems in a relative sense), or collisions with special symmetries, where there are additional constraints on the collision parameters. Two special cases with both these attributes are the collisional ring galaxies (see review by Appleton & Struck-Marcell 1996, and e.g., Struck & Smith 2003, Hearn & Lamb 2001), and the ocular or eye-shaped galaxies, like IC 2163 (see Fig. 1).

In the case of the ocular galaxies, models show that the ocular caustic wave persists for only a relatively short time, and the caustic is only produced in near-planar, prograde encounters, as seen from the ocular (see Elmegreen, Sundin, Elmegreen, & Sundelius 1991, Sundin 1989, Donner, et al. 1991). We use the term "caustic" here to denote a region of stellar orbital overlap or crossing (Struck-Marcell 1990). The structure of the ocular caustic also depends on the overall matter distribution of the galaxy containing it. Thus, the presence and shape of the ocular put strong constraints on the orbital parameters and the global structure of the ocular galaxy.

In the NGC 2207/IC 2163 system there are additional constraints. The two galaxies appear to be very close, at least in projection (see Fig. 1), and have the same (l.o.s.) systemic velocity, within the uncertainties (see Table 1 and Elmegreen et al. 1995a (Paper 1)). We will show below that there are reasons to believe that IC 2163 is physically close to the disc of NGC 2207. The HI kinematics presented in Paper 1 also suggest that we are looking at NGC 2207 somewhat close to face-on, so the plane of the sky nearly coincides with the disc plane. With this information, and the fact that the ocular caustic takes some time to develop, we conclude that the relative orbit is probably well bound at present. If it were not, and the high relative velocities were confined to the plane of the sky (since no high velocities are found in the observations, see Paper 1), then the two galaxies would not stay near the point of closest approach for long, but quickly move apart. The relative orbit of IC 2163 must have kept it close to NGC 2207 for the time needed to form the ocular. Thus, in this case we can also constrain orbital velocity components which are not normally observable.

These additional constraints lead to the expectation that we may be able to model this system with unusual accuracy. A number of these constraints were already used in the earlier papers of this series to produce preliminary models (see Elmegreen et al. 1995b (Paper 2) and Elmegreen et al. 2000a (Paper 3)). In the previous encounter models, the response of only one component (stars or gas) of one galaxy was modeled and the other galaxy was represented by a softened point mass. In the new models the responses of stars and gas particles in both galaxies are modelled in three dimensions. This provides a more realistic treatment of the encounter, and explains many observed features not accounted for by the older models.

In fact, the wealth of spatial structure in this system, observed in a variety of wavebands, presents a modeling challenge. The individual structures, seen on a wide range of scales, depend on the distributions of matter within the galaxies (at present and in the recent past), and the collision parameters. A model that was successful in fitting most or all of these features would yield much information about these quantities. Thus, we can hope to achieve more than the usual modeling goal of accounting for the observed properties of a few major tidal features.

We will see below that the best models do indeed succeed in reproducing almost all of the major features of this system, and provide us with a much improved understand-

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Figure 1. Grey-scale HST B-band image of NGC 2207 (right) and IC 2163 (left), from Paper 4. Rectangles and labels show peculiar emission features described in that paper.

ing of it. We begin in the next section with a survey of the major structures observed in this system.

2 OVERVIEW OF THE NGC 2207/IC 2163 SYSTEM

This system is relatively nearby (the mean recession velocity is about 2750 km s^{-1}, see Table 1 and Paper 1), so we are able to resolve a great deal of detailed structure within it using HST. The major structural features, as well as some finer structures, are listed in Tables 1 and 2. We briefly review them in this section, emphasizing their role in constraining the models. Details on the observations can be found in Paper 1, Paper 3, and Elmegreen et al. (2001 (Paper 4)).

First of all, we note that although NGC 2207 has larger optical and HI diameters than IC 2163, it is not proportionately more luminous. Estimates of the luminosity ratio suggest that the masses of the two are not greatly different, assuming that their mass-to-light ratios are comparable, though the luminosity of IC 2163 is somewhat less than that of NGC 2207.

Paper 1 and Paper 2 discussed the orientations of the optical discs, based on the HI line-of-sight velocity fields and the optical images. Because of the tidal distortions, accurate values of the orientation parameters could not be obtained by using only the apparent axis ratio. Presently, IC 2163 has an intrinsically oval disc, which results in a 63° offset between its photometric and kinematic major axes. Paper 1 and Paper 2 chose the projection line-of-nodes of IC 2163 (the intersection of the plane of the disc with the plane of the sky) to be the kinematic major axis, position angle = 65°, and estimated the inclination i (where $i = 0$ for face-on) as 40°. They interpreted the S-shaped velocity field of NGC 2207 and the 40° offset between the photometric and kinematic major axes of its central disc in terms of a warp that is increasing with time; this gave an inclination for the central disc of about 35° with the projection line-of-nodes at PA = 140°. These values derived from preliminary models formed a starting point for our study. In our simulations, we take the initial discs of these galaxies as unwarped.

As noted above, the presence of an ocular morphology in IC 2163 provides a strong constraint on the encounter dynamics. Similarly, both the global structure of the tidal tail (e.g., length and width), as well as its detailed morphology, constrain both the relative orbit and the halo structure of IC 2163. These features will be the focus of much discussion below.

The spectacular visual impression made by this system owes much to the spiral arms of NGC 2207, seen as emission structures over the bulk of the galaxy, but also as backlit absorption features in front of IC 2163. Although in the former case they are not entirely regular in appearance, we believe that they are generally well accounted for as a simple two-armed (m=2) density wave. As discussed below (also see Paper 2), they would not be produced in otherwise plausible models in which IC 2163 orbits in a retrograde sense relative to NGC 2207. (The absence of prominent tidal tails or a bridge from NGC 2207 also supports the idea that the encounter is retrograde for it.) Thus, we believe that the m=2 density wave predates the current encounter, and we can test its persistence through the encounter. This is an unusual experiment in the field of colliding galaxy models, though the superposition of induced and pre-existing waves is probably a common occurence in nature.

The large-scale distribution of HI in NGC 2207 differs both in shape, and by its significant southern extension, from the global stellar distribution (see Figures 2 and 3). Although faint optical filaments are visible in the southern extension (see Paper 3), the large southern extension is predominantly an HI feature. In the main disc of NGC 2207 the HI distribution forms a broad clumpy ring, broken in the south. The ring contains massive (10^8 $M_\odot$) clouds, which do not always coincide with the stellar arms. The ring-like distribution may be largely a result of a gas hole in the central regions. This hole is not entirely filled by molecular gas either, since the molecules in NGC 2207 are concentrated on the western side of the disc (see Table 1). The gas hole in the central region may be the result of the weak central bar as noted in Paper I. We have not attempted to model the bar. The models also suggest that a mild collisional ring (m=0) component to the collisional perturbation may play a role in generating the HI ring.

Both the optical (Paper 3) and HI observations (Paper 1) suggest the presence of a tidal bridge from IC 2163 to NGC 2207. (E.g., see Fig. 3, where the cloud labeled I4 is on the tidal bridge.) We use the models below to argue that development of the bridge may be related to the mysterious radio continuum ridge found in the NE quadrant of NGC 2207, lying nearly on a tangent to NGC 2207, and connecting to IC 2163.

Region i (see Fig. 1) on the outer western arm of NGC 2207 is also unusually luminous in the radio continuum and Hα. It contains a dark dust cone and arcs of star clusters, and is associated with CO 1-0 emission. This is one of the most mysterious features in the system, though the modelling below does suggest some possible explanations. In general, it is also remarkable that most of the radio continuum emission comes from the outer parts of the NGC 2207 disc, rather than the nuclei of the two galaxies.

Paper 1 displays the kinematical information from a VLA HI cube as channel maps, velocity distributions, velocity fields, and velocity dispersion maps. In that paper, the HI contributions of the two galaxies were separated by inspection of the channel maps in a movie-mode. At some locations with overlap in projection, the kinematic distinction between the gas in each was clear. If not, then in overlap areas, 80% of the gas was attributed to NGC 2207, the same as the global HI ratio. That paper interprets these data in terms of streaming motions, widespread high velocity dispersions ($30 - 50$ km s^{-1}) in the HI gas, warping and z-motions. There are 11 massive (10^8 $M_\odot$) clouds in the discs and tidal arms of these galaxies. For comparison below with the kinematic results of our new models, we have constructed summed position-velocity diagrams from this HI cube (see Figure 9).

Table 1. Observed Properties That Constrain the Models: I. Large Scale Structures.

A. Both Galaxies [a]

1.	Distance = 35 Mpc. [b]
2.	Luminosity ratio (IC 2163/NGC 2207): 0.6 in NIR and 0.3 in the B-band.
3.	Optical, isophotal major radius (R_{25}): 91" (IC 2163) and 130" (NGC 2207). [c]
4.	V$_{sys}$ = 2765 ± 20 km s^{-1} for IC 2163 and 2745 ± 15 km s^{-1} for NGC 2207. [d]
5.	Side nearest us: N by NW for IC 2163, and between N and NE for NGC 2207.
6.	Separation between centers: 85". [e]
7.	Global SFR/(HI mass) - typical of noninteracting spirals.
8.	Widespread, high velocity dispersion ($30 - 50$ km s^{-1}) HI gas.
9.	Molecular gas (traced by CO) in both discs, with more in IC 2163 and no concentration on massive HI clouds (see 28 in Table 2). [f]
B. IC 2163	
10.	Central eye-shaped oval with projected major axis length = 43".
11.	Enhanced emission from ocular rim. [g]
12.	Position angle of the major axis: a) Photometric PA of eye-shaped oval: $128° \pm 3°$. b) HI kinematic $65° \pm 10°$.
13.	Two tidal arms located symmetrically on opposite sides of the nucleus. [h]
14.	100 km s^{-1} streaming motions on tidal tail and around the eye-shaped oval.
15.	Mean velocity is nearly constant along the outer extension of the tidal tail.
16.	Stellar arm contrast of the tidal tail is large compared to normal spiral arms.
17.	The nearly-circular shape and orientation of the spiral arms inside the eye-shaped oval. [i]
18.	Long parallel dust filaments on the tidal tail. [j]
19.	Brightest CO emission from the centre position, also bright emission from oval rim. [k]
C. NGC 2207	
20.	Two long grand-design spirals dominate much of the disc.
21.	HI in the main disc forms a broad, clumpy ring, broken in the S.
22.	A large, elliptically-shaped HI feature extends 220" S/SE of the nucleus. [l]
23.	Position angle of the major axis: a) Photometric PA (optical and HI) of main disc: $110° \pm 7°$. b) HI kinematic PA: varies over range $150° - 177°$ as R increases. c) Isophotal on scale of S/SE extended HI pool: $160° \pm 5°$.
24.	Global S-shaped distortion of the HI velocity field. [m]
25.	Radio continuum emission is enhanced on the companion side along the outer part of the disc.
26.	CO emission not concentrated on the nucleus. Mainly found about halfway between the centre and HI ring, at least on western half of the disc. Brightest emission at about 24" NW of the nucleus.

[a] Properties derived from data presented in Paper 1, Paper 3, and Paper 4
[b] 1.0 arcsec = 170 pc, for $H_o = 75$ km s^{-1} Mpc^{-1}
[c] Note: the IC 2163 value includes part of the tail.
[d] Heliocentric, optical definition.
[e] The western half of IC 2163 is partially obscured by NGC 2207.
[f] See Thomasson (2004).
[g] This includes emission in radio continuum, HI, optical and the near infrared.
[h] In the sky plane, bright HI emission from the tidal tail extends to a distance of 110" NE from the nucleus, which is about 2.5 times the major axis of the eye-shaped oval. Faint HI emission from the tail extends to $R = 190$". Optically, the tidal tail extends out to at least $R = 90$".
[i] Their structure suggests that they may have been produced by inner Lindblad resonances in the tidal potential that formed the oval (see Paper 3).
[j] These may have originated as normal flocculent spiral arms present before the encounter, which were stretched into parallel filaments as the tidal tail formed.
[k] The resolution is 43" (HPBW), so emission centre is uncertain. Spectrum is double-peaked, hinting that some emission is from the oval rim rather than the nucleus.
[l] This feature also contains optical filaments.
[m] This plus the large misalignment between photometric and kinetic major axes imply that the disc is warped, and there are large amplitude z-motions producing the warp.

Table 2. Observed Properties That Constrain the Models: II. Small Scale Structures.

A. Both Galaxies [a]	
27.	SF regions have a normal luminosity-size distribution and luminosity function, except with the SSC distribution weighted towards more massive clusters.
28.	Massive ($10^8 M_\odot$) HI clouds in the disc, not associated with major stellar clumps.
29.	Widely distributed young star clusters and super star clusters. [b]
B. IC 2163	
30.	The nucleus is not detected in radio continuum to a rather faint level.
C. NGC 2207	
31.	Chaotic network of dust spirals in nuclear region.
32.	Parallel, knotty dust filaments span full width of spiral arm that is backlit by IC 2163.
33.	There is an unusually luminous SF region on the outer western arm (Region i, on the anti-companion side). [c]
34.	The nucleus is not the brightest radio continuum source in the galaxy.

[a] Properties derived from data presented in Paper 1, Paper 3, and Paper 4. Numbering continued from Table 1.
[b] The SSCs seem to be confined to a few segments of the spiral arms of NGC 2207 or to the rim of the eye-shaped oval in IC 2163.
[c] This region is very bright in the radio continuum and in Hα. It coincides with a very dark dust cone, and is detected in CO J = 1-0 emission.

Figure 2. Contours of the total HI emission, which is kinematically associated with NGC 2207, on a grey scale image of the system from the digital sky survey. The line-of-sight column density contour levels are 6.4, 13, 19, 25, 32, 38 and 44 atoms cm^{-2}, and the massive HI clouds in NGC 2207 are labeled.

Table 2 contains a list of relatively small-scale features. First, the star-forming properties of this system are not spectacular. The global SFR is modest, and the young cluster luminosity functions of both galaxies do not differ significantly from those of typical late-type disc galaxies (Paper 4). A relatively small number of super star clusters (SSCs), like those in other interacting systems, has been found. Interestingly, these are found in the outer regions of the two discs, rather than concentrated in the central or nuclear regions.

Besides the star clusters, there are also a number of other peculiar emission features found asymmetrically distributed in the outer parts of NGC 2207 (mostly in the southern and western half of the disc, see Fig. 1). Collectively, the set of these emission features is unique to the best of our knowledge (see Sec. 7 in Paper 3). However, this may be partly the result of the superb HST resolution of this nearby system. Alternately, they may involve either mass transfer from an earlier encounter, or continuous interaction between the two discs for some time before the present. Either of these alternatives may help understand the concentration of peculiar features opposite the current locus of interaction.

Other features include the numerous, long, thin, and highly contrasted filaments seen in both the tidal tail of IC 2163, and in the NGC 2207 spiral segments projected onto the face of IC 2163. They also include the massive HI clouds (Figs. 2 and 3) and the inner spirals and turbulent appearance of the nuclear regions of both galaxies.

3 MODEL DESCRIPTION

Previous models of this system captured a number of important features, but were more approximate than our new models. Paper 2 used an N-body two-dimensional (modeling the primary disc plane) simulation of the effect of the encounter on the stellar disc of IC 2163 with NGC 2207 represented by a point mass; the gas disc was not treated. This paper also presented a two-dimensional (azimuthal θ, z) model for NGC 2207 in which the disc of NGC 2207 was divided into segments, no radial motions were allowed, and IC 2163 was represented by a point mass. Paper 3 presented a three-dimensional SPH simulation of the gaseous disc of IC 2163, not the stellar disc, with NGC 2207 represented by a softened point mass.

The new models in this paper use two-disc, gas-star, three-dimensional SPH codes to model the discs of both galaxies simultaneously throughout the encounter. We can thus see if the present more sophisticated models reproduce the same types of unusual features as the more approximate early models, and if the new models can explain observed features not accounted for by the older models. For this purpose, we carried out several dozen new simulations with two different gas-star SPH codes to model the detailed morphology and kinematics of the system. We present the most successful of these models in the following sections. In this section we briefly describe the simulation codes, scale factors, and initial conditions used in these models.

3.1 The S97 Code

The S97 code, used here and in Paper 3 (and described in detail in Struck 1997) is designed for three-dimensional sim-

Figure 3. Contours of the total HI emission kinematically associated with IC 2163. The HI contour levels and the grey scale image are the same as in Fig. 2. Labels identify massive HI clouds in IC 2163. Region i, marked here and in Fig. 1, is unusually luminous in Hα and in the radio continuum. It is not associated with a massive HI cloud (cf. Fig.2).

ulations of gas and star particles in rigid halo gravitational potentials. This code uses an SPH algorithm for the gas dynamics, with hydrodynamic forces computed with a spline kernel on a grid. The grid has a fixed unit cell size, but varying extent. A standard artificial viscosity formulation is used for modeling shocks. The halos of both galaxies in these models are represented by rigid, softened potentials. Specifically, the halo acceleration of a particle is of the form,

$$a = \frac{GM_h}{\epsilon^2} \frac{r/\epsilon}{(1 + r^2/\epsilon^2)^{n_h}}, \qquad (1)$$

where M_h is a halo mass scale, ϵ is a core radius, and the index n_h specifies the compactness of the halo. When $n_h = 3/2$ the potential is like a Plummer potential, and when $n_h = 1$ the rotation curve is flat at large radii. The value of n_h was varied, and a value of about $n_h = 1$ was found (by experimentation with several other values) to give the best model results for both galaxies. This implies flat rotation curves. This is consistent with the nearly flat rotation curves found for IC 2163 in Paper 1.

An adiabatic equation of state is used for the gas particles, with the addition of a simple approximation to the standard cooling curve for a diffuse interstellar gas of solar metallicity. Individual particles are heated when the local gas density exceeds a fixed threshold density and the particle temperature is below another threshold, so that star formation feedback is assumed to occur. The density and temperature thresholds are arbitrary, since the code cannot resolve the high densities and low temperatures of real star-forming clouds. They have been normalized to give realistic rates of star formation in the isolated galaxies.

An approximate treatment of dynamical friction between the galaxy halos was added to this code, because it appears that no reasonable model of the system can be made without frictional effects. Specifically, the Chandrasekhar formula was applied to the rigid companion halo only, not to other particles or density enhancements in either model galaxy. This will result in different accelerations on particles at different radii from the companion center and other errors, but since the frictional accelerations are modest through most of the run, the effects are small. We take the companion to be the galaxy corresponding to IC 2163. (To avoid confusion about which is being discussed we will henceforth refer to the model galaxies as galaxies A and B, corresponding to NGC 2207 and IC 2163 respectively, and reserve the latter names for the real galaxies.)

Specifically, we use equation 7-23 of Binney & Tremaine (1987) for the frictional force on the companion halo, treated as a point source, moving through the primary halo, treated as an extended source. This formula is based on several additional simplifying approximations. First, it assumes that $v_c/\sigma = \sqrt{2}$, where v_c is the circular speed relative to the fixed primary center, and σ is the velocity dispersion of particles in the primary halo. Both speeds are nearly constant at large radius in an isothermal halo. In using this formula we assume that the halo is approximately an isothermal sphere, and that $v \simeq v_c$, where v is the speed of the companion halo (relative to the primary halo). This approximation is used only in the friction formula, though the companion's orbital velocity over most of the orbital segment modeled here is quite close to circular, so it is not a bad approximation in this particular system. Thirdly, we assume that the Coulomb logarithm term $ln\Lambda = 10$. The effect of this approximate frictional force is discussed further in Section 4.2.

There are several advantages in using this code, even though the halo is assumed to be rigid. The first is that it requires a small amount of computer time and memory to run, so improvements to preliminary models can be tested efficiently. A second is that the galaxy discs remain dynamically cold. This is in contrast to N-body codes using modest particle numbers, where the stellar, and to some degree the gas, discs tend to heat artificially. This is an important point in the present case, where we need a good deal of spatial resolution in the discs, and where we are looking at a sufficiently small part of the system's evolution that neglect of most self-gravitational processes (except dynamical friction) is justified. Thus, in this paper we will focus on the results of the S97 code.

3.2 The HYDRA Code

Fully self-gravitating simulations were produced with the serial SPH code Hydra 3.0 (henceforth simply Hydra), which has been made publicly available by H. Couchman, P. Thomas, and F. Pearce. In Hydra, gravity is calculated with an adaptive particle-particle, particle-mesh (AP^3M) algorithm (for details see Couchman et al. 1995, and Pearce & Couchman 1997).

The Hydra simulations were all run using an adiabatic equation of state, and with optically thin radiative cooling calculated via the tables of Sutherland & Dopita (1993). These were supplied with the Hydra code. No feedback heating was included in the Hydra simulations. Given the limited number of particles that can be used, we cannot represent a very extended halo with the Hydra code (unlike those in the S97 code). In any case, the Hydra models have been used primarily as a check that the dynamical friction formulation in the S97 code gives reasonable results for the relative orbit. This was found to be true, in the sense that a very similar orbit was produced by the Hydra model, with only modest changes of the initial conditions (see Sec. 3.4).

3.3 Scalings and Boundary Conditions

The codes described in the previous section use dimensionless variables. For reference, in this section we describe conversion to physical units.

To scale the S97 code, we choose a velocity unit of 5.0 km s^{-1}. In the code all lengths are scaled to the core radius (ϵ in Eq. 1) in the primary halo potential, which we set to 2.0 kpc to scale the results presented below. (While the halo core radius of the primary is 1.0 code unit, that of the

Table 3. Parameters of the Best Model

	Primary Galaxy (Galaxy A)	Companion (Galaxy B)
Initial Galaxy Parameters [a]		
Masses ($M_\odot$):		
Halo[b]	1.5×10^{11}	1.1×10^{11}
Radii (kpc):		
Gas Disc [c]	19.6	6.8
Stellar Disc	9.0	4.8
Disc Peak Rotation (km s^{-1})	160	140
Disc Orientations[d]	25° about x-axis	55° about y-axis
		then
	70° about z-axis	−40° about z-axis
Orbital Parameters		
Initial Center Positions[e] ((x,y,z) in kpc)	At origin	(23.0, 0.0, 4.0)
Initial Center Velocities[f] ((vx,vy,vz) in km s^{-1})	(0.0, 0.0, 0.0)	(-25., 210., -25.)
Center Positions when z=0	At origin	(11.0, 19.2, 0.0)
Center Velocities at z=0[g]	(0.0, 0.0, 0.0)	(-170., 21. -40.)
Gas Major Axis PA at Present Time	≃ 145°	≃ 100°

[a] Physical units used in this table are derived from the scalings: 1 code length unit = 2.0 kpc, 1 time unit = 4.0×10^8 yr, and 1 mass unit = 1.3×10^{10} $M_\odot$, see text

[b] The given halo mass is that contained within a radius equal to that of the initial primary disc. Gas and star disc masses are negligible in this model, see text.

[c] There is no halo cut-off radius in the model. Particle numbers in the best model were: A gas disc - 37200, A star disc - 5640, B gas disc - 18090, and B star disc - 2490.

[d] Both galaxy discs are initialized in the x-y plane. The discs are then rotated as described. More precisely, a statement like "70° about z-axis" means 70° counter-clockwise as viewed from a location at large positive z (above the x-y plane), and analogously in all cases.

[e] Coordinates defined in a conventional, right-handed frame, with the origin fixed at the center of the primary. The initial separation is 23.4 kpc

[f] Relative velocity between the galaxies is 210 km s^{-1}. Positive z velocities are towards the observer. All disc particles were given an initial velocity dispersion of 10 km s^{-1}

[g] Net relative velocity is 176 km s^{-1}. The effects of dynamical friction have reduced this to less than the initial relative velocity. The z=0 plane crossing of Galaxy B occurs at about the same time as closest approach early in the simulation. This is at a time of about 100 Myr after the start of the model and about 280 Myr before the present.

companion is 2.0 units.) The time unit is then about 4.0×10^8 yr. The mass contained within a sphere of unit radius around the primary can also be specified, and was chosen to equal $1.3 \times 10^{10} M_\odot$ here. This gives a peak rotation rate of about 170 km s^{-1} in the primary disc, which is of the same order as in the HI observations for both galaxies in Paper 1. However, the comparison is difficult since IC 2163 is strongly affected by the tidal perturbation, and there is evidence that the NGC 2207 disc is warped. The peak velocity is reached at about 3.0 kpc in both models and at comparable radii in the observations.

The S97 code dynamically extends its computational grid out to a size large enough to include the most distant particles, or out to a fixed maximum distance from the center of the primary. In the present runs this radius was set to 30 units or 60 kpc. Few particles reached this radius over the course of the runs; those that did were reflected back. The timestep was also dynamically adjusted to satisfy the usual stability requirements, but had a mean value of about 3×10^{-4} units.

Hydra runs are made on a unit cube, where x, y, and z coordinates run from 0.0 to 1.0 in code units. 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 results of both models suggest an interaction time of roughly 200-400 Myr, which is measured from the time closest approach between the two discs to the present. The large range of this timescale reflects a liberal estimate of the range in the size of the initial discs and the orbital separation. Shortly after the start of the model, this first interaction takes place on the west side of the galaxy A disc when B moves from the near side to the far side of the A disc relative to us (see Fig. 6). A similar timescale was deduced from the models of Paper 2, and in fact, is likely in any model that matches the observed rotation speeds, and has IC 2163 orbiting through about 180° (west to north to east) near the edge of the NGC 2207 disc.

3.4 Initial Conditions and Model Differences

We choose the x-y plane to be equivalent to the plane of the sky in all models. In both codes, star and gas discs were initialized by putting a fixed number of particles in successive circular annuli, yielding a 1/r surface density profile. The exception to this generalization is that most models initially had a small gas hole at their center, and then a region of constant gas/star surface density.

The initial conditions used in the S97 model are summarized in Table 3. The initial galaxy mass ratio was set to about 3/4, where NCG 2207 is represented by the larger (primary) galaxy. The observed near infrared luminosity ratio of about 0.6 is similar to the model here. The peak rotation velocities are roughly comparable within the uncertainties due to the collisional disturbances, so the observational mass ratio constraints are not tight.

The initial midplane of the A disc is tilted by 25° around the x-axis, and then by 70° around the z axis (see Table 3), so that the near side relative to us is in the east-northeast. The B disc is initialized with the particles first distributed smoothly in the x-y plane, and then the disc is tilted as described in Table 3, putting the near side relative to us in the northwest. These angles are constrained by the HI kinematics. The kinematic constraints are examined in detail in Sec. 4.3.

In the Hydra simulations, the two model galaxies are identical (for simplicity, and to get a maximal estimate of the dynamical friction) and in both, the collisionless halo, stellar disc, and gas disc components were added one at a time, and allowed to relax after each addition. The halos are approximately isothermal, while the disc components have a nearly constant vertical velocity dispersion with radius. The discs have equal masses of stars and gas. The initial position and velocity component values of the galaxies were assigned such that the center of mass would remain fixed at the grid center (in contrast to the S97 models where galaxy A is fixed), see Table 3. The galaxies were initialized in the x-y plane after which their orientations were adjusted exactly as in the S97 model. Initial velocities did need to be decreased in the best Hydra models, relative to those in the corresponding S97 model. This is to offset the effect of the smaller halos in the Hydra models, which have less overlap, and reduced dynamical friction relative to the S97 models.

The initial galaxies in both models were run in isolation to verify the stability of the initial conditions. They were indeed found to be stable, except that the gas density in the companion in the S97 model is about equal to the feedback threshold density, so it experienced a brief wave of star formation before settling into quiescence.

4 RESULTS I: THE EVOLUTION OF LARGE SCALE STRUCTURE

In this section we will describe model results on how the large- scale structural features of IC 2163/NGC 2207 system were formed. For present purposes, we define large-scale structures as those that are comparable in size to the discs of the galaxies, for example, the ocular caustic and the tidal tail of IC 2163. We will begin with a general overview of the collision evolution common to the most successful models. In the second subsection we examine the development of some specific structures and what constraints the comparison of models and observation put on the galaxy structural and collision parameters.

4.1 General Evolution through the Collision

4.1.1 Evolution of the Fiducial Model

In this subsection we describe the evolution of the most successful model (henceforth the fiducial model) of a grid of more than 60 (S97 code) models. We also compare to another model, referred to as Sm1. Most of the models in this grid differ only slightly from the best ones in some orbital or structural parameters. That is, except for a dozen or so early models this is a fairly fine grid in parameter space located near the best models. Many of the models are essentially the same, except for slight differences in the initial relative position and velocity of the companion. These parameters were fine-tuned to match the observed companion disc and tail shape and orientation, and other bulk characteristics, such as the degree of overlap of the two gas discs in the early encounter. Galaxy mass ratios, disc sizes, disc orientations, and halo potential structures were also varied.

Figures 4-7 each provide 6 snapshots each of the evolution of the two discs in the fiducial model. Specifically, Figures 4, 5 and 6 show only the gas particles in the discs, projected onto the x-y and x-z planes. Figure 7 shows the corresponding snapshots of the x-y projection of the stellar disc. Figure 8 shows the x-y projection of the gas disc in Model Sm1 for comparison. Model Sm1 was initialized with smooth, azimuthally symmetric initial gas/star discs. In the fiducial model a two-armed density wave was imposed on both the star and gas discs in the initial conditions of the primary galaxy. More precisely, gas/star particle positions and velocities were perturbed from their initial circular orbit values by putting each particle on an epicycle with phases that varied from 0 to 2π in azimuth. Epicyclic velocity amplitudes were set to a constant times the circular velocities, and times an $(r/\epsilon)^{-1/3}$ fall-off with radius. An arbitrary phase factor, varying with the inverse radius, was also added to give the initial spiral form. Differences in the initial positions and velocities of the companions in the two models with and without a spiral wave were small.

Figure 4. Six snapshots from the fiducial model of gas particles from galaxy B projected onto the x-y plane (i.e., plane of the sky). Galaxy A is shown by a few representative contours of gas particle density. In Galaxy B every sixth gas particle is plotted. In the upper left panel, the companion trajectory through the whole simulation is indicated by a dashed line, with a the present position marked by a cross. Times given in Myr from the start of the simulation; one code unit equals 400 Myr in the adopted scaling. The axes are marked in code length units. One code length unit is 2 kpc or about 12 arcsec in the plane of the sky in the adopted scaling.

Figure 5. Six snapshots from the fiducial model of the x-y plane, like the previous figure, but with gas particles from galaxy A, and with galaxy B shown by a few representative contours of gas particle density. In Galaxy A every sixth gas particle is plotted. More contours are also used in the later panels to outline the tail.

The fiducial simulation begins with the center of galaxy B located at a distance of about 23 kpc away from A, and with a relative velocity of 210 km s^{-1}. That is, they are on a bound relative orbit at this point (see Sec. 4.4). The coordinate system used for the simulations moves with the halo center of galaxy A, so that the galaxy appears fixed at the origin throughout. The initial relative velocity of B has a large positive y component, and relatively small, negative x and z components. The subsequent orbit is shown in the first panel of Figures 4 and 6.

As noted above the x-y plane is defined as the plane of the sky. The A and B discs are initialized with the particles first distributed in the x-y plane, and then each disc is tilted as described in Table 3. The tilt angles are constrained by the HI kinematics, and these constraints apply directly because the models show *a posteriori* that the fundamental planes of the discs are not greatly perturbed over the duration of the encounter. We will see below that these choices are quite satisfactory, but detailed kinematic comparisons suggest some improvements (See Sec. 4.3).

The first panels in Figures 4, 5, and 6 show the system at a time of about 61 Myr from the start of the run in the representative scaling, when the outer edge of galaxy B is just about to impact that of A from the near side (relative to us, i.e., at positive z). Closest approach is at a time of about $t = 0.25$ units or 100 Myr; see the second frame in the figures. This disc collision on the north and western side of A continues through the time of the third frame in these figures. During this time the two discs scrape against each other across a strong shock front. This scraping radially compresses the effected portions of the two discs. Another effect is that some gas from B is transferred to the A disc (see Fig. 4).

Note that we are not completely certain that this disc collision does in fact occur. A slight change in the initial conditions could lead to either no impact between the gas discs or greater overlap and a much more widespread and destructive impact. We have run models of both situations. As a result of those runs we believe that encounters with much greater overlap lead to NGC 2207 disc morphologies at the present time in the south and west that are very different from those observed. The possibility of a complete miss is harder to rule out, but several observations support the idea of an early disc collision like that shown here. The primary one is that the NGC 2207 disc does appear disturbed in the south and west. For example, as we will see in the next section, most of the small scale peculiar emission regions are located in this area. This issue is discussed further in Sec. 4.3.

The last four panels of Figures 4 and 5 show the companion swinging roughly another 90° in a counterclockwise direction around galaxy A as time advances from 180 Myr to 380 Myr. That is, it takes about 380 Myr for the companion to move from the west to east side of the A disc. The specific ocular and tailed morphology of IC 2163 are relatively short-lived (see discussion in Sec. 6 for specifics). If the disc collision did occur, then it is likely that the x-y part of this model trajectory is reasonably correct. A very different trajectory would not get the companion to its present position at the time when these morphologies are present.

For example, if the galaxy B orbit had substantially less momentum or angular momentum, then it would travel under (below), but closer to the center of the A disc. There would have been more interaction between discs, and more dynamical friction between the haloes. As a result the B disc would be unlikely to emerge on the east side; it would complete the merger promptly. On the other hand, in many of our early runs the B orbit had more angular momentum, and B moved much farther from the A disc after the disc collision. Specifically, the separation between discs was much greater than observed when a distinct ocular/tail morphology was present.

It is possible that the z-motion was greater, and that the galaxies have a greater separation along the line of sight. This would require that the two galaxies be near apoapse at present, to reduce the line of sight velocity to the observed low level. However, if that were the case, the total velocity (and its x, y components) could not be much reduced, or the collision would be more direct, with more damage to both galaxies, and there would be a ring galaxy remnant in place of NGC 2207. We believe that both the disc collision and the relative orbit of Figures 4-6 are quite well constrained, and will discuss these constraints more quantitatively in Section 4.2 below.

The fiducial model was run another 200 Myr beyond the present. In that time the companion moves down and inward a bit, and then spirals in to begin the final merger with the primary disc.

Figure 7 shows the distribution of disc stars from both galaxies in the x-y plane, but on a magnified scale relative to that of Figures 4 and 5. Comparison shows some significant differences in the evolution of the gas and star discs. First of all, the stellar oculars in the panels of Fig. 7 are much sharper and more prominent than the gaseous oculars in Fig. 4. In general, the star discs are less disrupted by the encounter than the gas discs, which explains many of the differences in the wave structure in the gas and stars (though the initial stellar velocity dispersion also determines stellar wave sharpness). A related difference is that there is minimal mass transfer between the stellar discs, while there is a good

Figure 6. Six snapshots from the fiducial model of the x-z plane, like the previous figures, but with gas particles from both model galaxies. In Galaxy A every twelfth gas particle is plotted, and in Galaxy B every sixth. In the upper left panel, the companion trajectory through the whole simulation is indicated by a dashed line, with the present position marked by a cross.

Figure 7. Six snapshots from the fiducial model of the distribution of disc stars in the x-y plane. All star particles from both model galaxies are shown. Note we use a magnified scale relative to previous figures in order to show the development of the ocular structure in galaxy B and the density wave structure in galaxy A.

deal of gas transfer. The gas discs also experience strong shock waves, and transfer is helped by the fact that the initial gas discs are larger than the star discs. Indeed the stellar disc of the primary looks hardly disturbed at the last time shown in Figure 7.

This concludes our overview of the fiducial model. Next we consider the origin of the spiral structure in NGC 2207.

4.1.2 Initial Spirals Versus Induced Waves

Figure 8 displays the evolution of the system in model Sm1, which has very similar initial parameters as the fiducial model, but without the initial spiral. The figure shows that the gas disc of galaxy A appears only moderately disturbed by the interaction with B, and specifically, there is no evidence that the beautiful two-armed spiral of NGC 2207 can be produced in such a collision. The many other models we computed affirm this conclusion. The basic reason for this is clear; the companion orbits in a retrograde sense relative to the A disc rotation. It has been known since Toomre & Toomre (1972) that prograde collisions produce strong M51 type two-armed spirals, but retrograde generally do not. Thus, we believe that the spirals predated the current interaction in this system.

This hypothesis raises the questions of whether preexisting spirals would survive the interaction, and if so, how would they be affected? The last frames of Figures 5 and 7 suggest that they are not greatly affected, which is consistent with the impression from Figure 8 that the A disc as a whole is not highly disturbed. (Note that the imposed kinematic spiral persists for several rotation periods in isolation, so it is not amplified by the collision either. We should caution, however, these conclusions may be modified by models with full disc self-gravity (rather than the local self-gravity of the S97 code).)

Similarly, in Paper 3 we suggested that some of the filamentary structure in the IC 2163 tail might have originated in flocculent spiral arms before the collision. The present result seems to support the idea that flocculent arms would persist in some form.

4.2 Timing and Orbital Constraints From Large Scale Structure

In this section we describe how the presence of several short-lived tidal structures that are sensitive to the details of the time-dependent perturbation, and thus the relative orbit and other collision parameters, allow us to constrain these latter parameters unusually well. The strongest constraints are provided by the structure of the IC 2163 tail, the presence and orientation of the IC 2163 ocular feature, and the structure of the extended HI disc in NGC 2207. We will consider each of these in turn, and then briefly consider the accuracy of the dynamical friction approximation used in the S97 models.

In contrast to many galaxies with tidal tails in the Arp (1966) and Arp & Madore (1987) atlases, the IC 2163 stellar tail is not very much longer than the mean disc diameter of that galaxy. This stellar tail also has an unusually large width to length ratio. Both gas and stellar tails get longer and narrower as they develop (see Figs. 4 and 8). Thus, the tail structure argues for a relatively young age.

In fact the gas tail in the last panel of Fig. 4 looks a bit too long and narrow to match the observations of Figs. 1 and 3. However, Figure 8 in Paper 1 shows that the gas tail is longer than shown in Fig. 3. Moreover, the last panel of Fig. 7 (and other larger scale views) shows a stellar tail that is generally like that observed, though it looks more like the observation at a slightly earlier time.

The difference between gas and star tails also shows that tail structure is sensitive to the initial size of the disc, with larger discs developing tails earlier. On the other hand, the size of the IC 2163 disc relative to that of NGC 2207 is constrained by observation. Taking these factors into account we estimate that the "tail age" of this model is in the range 220-260 Myr after closest approach, or 320-360 Myr from the start of the model. Note, however, that time estimates in this section could be increased slightly and decreased by as much as 100 Myr if the model galaxy sizes and orbit sizes were varied over the maximal range allowed by observation.

Next we consider the ocular structure, which is best seen in the star particles shown in Fig. 7. Specifically, if we use the rather liberal definition of an ocular as a pointed oval, we get a time range of about 60-260 Myr since closest approach (the early disc collision). However, at the beginning of this time range the ocular is not in the correct position. At the end of this range, it is developing a rather different appearance as the primary stellar ocular disappears and a second ring-like wave appears. In the middle of this range, the ocular looks quite like what is observed, with sharp (bright) rims on the top and bottom. Also at these times the angle between the upper tail and the upper rim is like that observed.

The IC2163 ocular and tail are two parts of a single tidal distortion; to get a different timing estimate we must look at the NGC 2207 disc. Since we have argued that the prominent spirals in this disc are not a result of the current interaction, neither these spirals, nor any other large-scale optical structure, provides such information. However, comparison of the elongated oval HI distribution in Figure 2 to the model gas distribution of Figure 5 suggests that the shape and position angle of the major axis of the gas distribution can give an age estimate.

Specifically, the observed angle between the HI major axis of NGC 2207 and the line connecting the galaxy cen-

Figure 8. Four snapshots of the distribution of gas particles in the x-y plane for model Sm1 without an initially imposed spiral, for comparison with Figs. 4 and 5.

tres is about 45°. This angle is approximately matched in the models at times in the range 240-280 Myr (since closest approach, or 340-380 in Fig. 4 or 5), like the previous estimates. It appears that the gas in the models does not extend as far to the south of the center of galaxy A, as in the observations. However, we note that the existence of this oval distortion, and the time taken to form it, strongly suggests a prolonged encounter, like that in the model. Finally, the last panel of Figure 4 shows that some gas transferred from the companion is found in the southern extension.

Because of the approximate treatment of dynamical friction in the S97 code we should emphasize again that the observational constraints do not seem to allow a great deal of deviation. Secondly, though important, the effects of friction up to this point in the system's evolution are modest. The models suggest much stronger effects in the immediate future. Thirdly, because the encounter is retrograde relative to the rotation of NGC 2207, and because the halo of the companion is more massive than the disc of NGC 2207, we do not expect strong couplings between the companion and resonant disc orbits, which could modify dynamical friction relative to the Chandrasekhar approximation (Tremaine & Weinberg 1984). Fourthly, we have produced similiar orbits to the best S97 models with the fully self-consistent Hydra code. However, because of the different halo structures in the two models, we have not attempted to produce a detailed match with the two codes.

4.3 Kinematics

Models for this system are quite well constrained by the various tidal morphologies. However, comparison of models to the line-of-sight kinematics provides important checks, and additional input on collision parameter values to which kinematic structures are especially sensitive. These latter include disc orientations and warps.

The observed HI kinematics are summarized in the two observational position-velocity diagrams of Figure 9. Figure 10 shows gas and stellar distributions for comparison, and for reference in the following discussion. In the top left panel the emission summed over all relevant values of right ascension is displayed; in the top right panel, the emission is summed over all relevant values of declination. These diagrams reveal the extent to which the two galaxies overlap in line-of-sight velocity.

We consider first the summed P-V diagrams for IC 2163. The large velocity range in IC 2163 results from velocity streaming along the ocular oval and along the tidal tail and tidal bridge. In the top left panel, the two sides of the rim of the ocular oval are distinct, and the tidal tail of IC 2163 appears as a constant velocity feature at the highest velocity ($v = 3000$ km s^{-1}) extending farthest to the north. In the top right panel, the tidal tail is the wide, constant velocity feature ($v =$ 2900-3000 km s^{-1}) extending farthest to the east; its 100 km s^{-1} velocity width in the RA-V diagram is a result of gas streaming outwards along the inside edge of the tail and inwards along the outside edge of the tail (see Paper 3). The IC 2163 gas at $v < 2640$ km s^{-1} is mainly tidal bridge gas. The brightest features in these P-V diagrams of IC 2163 are produced by the massive HI clouds.

In the summed P-V diagrams of NGC 2207, the HI southern extension is clearly seen as the nearly constant velocity ($v = 2600 - 2680$ km s^{-1}) feature extending farthest to the south in the top left panel of Fig. 9 and as the eastern low-velocity clump in the top right panel. Much of the emission in the far north at a velocity of 2875 km s^{-1} is associated with HI cloud N1 (Figure 2). The encounter model in Paper 2 suggested that a strong warp and perpendicular motions set in at about the distance of cloud N1.

The kinematics of the fiducial model are summarized by the four summed position-velocity diagrams in the lower four panels of Figure 9, which show the Z component (line-of-sight) of the velocity versus X and Y coordinates for the gas particles in each of the two galaxies. We have attempted to facilitate the comparison of these plots to the observational plots by using the arcsec-to-pc conversion of note b) of Table 1 and the model scalings of Section 3.3 to transform code units to right ascension and declination. The specific scaling values are given in the caption.

Comparison of the observational and model figures reveals that most of the large-scale kinematic structures are similar, with a few exceptions. We first consider the right ascension plots. In both the model and observation plots the companion is located to the east of the primary, with some overlap. The primary is generally oval-shaped in these plots. Both model and observation plots show emission peaks on the high and low velocity sides of the oval. In top right panel of Fig. 9 the companion emission has a faint, thin, tilted distribution, with a strong extension to the east at large velocity ($2900 - 3000$ km s^{-1}) due to the tail. The strongest emission in the model plot has the same general characteristics, with a couple of differences.

The first is that the model disc B itself has a few gas particles extending to higher velocities (> 2900 km s^{-1}) on the west side (r.a. $> \ -5.0$), and also much more diffuse gas at intermediate velocities. The intermediate velocity gas is found to be material accreted onto the primary disc. A significant fraction of this gas is in warm phase. We should also point out that much of this gas is probably counted as part of the primary galaxy in the observations. Merging it with the primary in the model declination plot would make that plot look more like the observations. The higher velocity gas is located, on average, slightly above the mean disc plane (in the positive z direction). These high velocity particles were scattered in the scraping interaction between the two discs, but not accreted. The absence of the material in the observational plot may indicate that this gas was accreted onto the primary in the real system, or that this material is below the observational sensitivity.

Next we consider the declination plots. In these plots the centres of the two discs generally overlap and the extent of each is much less than in right ascension. For the primary, most of the model particles and much of the observed emission are located on a nearly linearly rising velocity curve. This feature rises slightly more steeply in the model than in the data. At low declination in the observations, there is a

Figure 9. Observational (top two panels) and model (lower four panels) position-velocity diagrams. In the observational panels the emission is summed over all relevant values of right ascension (top left) and declination (top right) using data from Paper 1. The emission from the two galaxies has been separated, with that from NGC 2207 shown as contours, and that from IC 2163 shown as gray-scale. In the model gas particle position-velocity diagrams Galaxies A and B are shown separately in the middle and bottom rows, respectively. Coordinates like declination and right ascension are derived from code units by using the adopted scale length and distance. Specifically, we take 1 length unit (2 kpc) = 0.2 arcmin. (12") of declination = 0.84 seconds of right ascension. Note that negative numbers are used for offsets to the east (left). For explanation of the labeled features, see text.

Figure 10. Gas and star distributions from the observations (left column) and the fiducial model (right column) at about the present time (t = 380 Myr) are shown for reference. Specifially, the upper left panel is an optical image (from the Digital Sky Survey), the lower left panel is a greyscale total HI image (data from Paper 1), the upper right pamel shows model stars (in the inner disc of Galaxy A) and star-forming gas particles (i.e., young star clusters often located in spiral arm segments), and the lower right panel shows every second gas particle. All figures are shown on comparable scales. Model coordinates with units like declination and right ascension are derived from code units as in the previous figure, observational coordinates are offsets from the nucleus of NGC 2207.

nearly constant velocity extension to the south. On the sky this corresponds to the southern HI extension seen in Fig. 2. This feature (marked as the southern extension "Sp" (for spiral) in Fig. 9) is weak in the model. It consists entirely of particles in the spiral arm that extends to the southeast in the last panel of Figure 5.

The middle left hand plot of Fig. 9 shows that the model primary has two extraplanar plumes that are not seen in the observations. The first of these is labeled 'NArm' in that plot and the corresponding right ascension plot. This material is located in scattered parts of the northeast quadrant of the primary, and much of it is extraplanar. The disturbed velocities of these particles originated from the turn-on of feedback effects in the southern spiral arm at the beginning of the run. Since this initial transient SF and feedback is unrealistic, they are a numerical artifact.

Particles at velocities less than about 2600 km s^{-1} in the middle left plot of Fig. 9 (marked "Scrape") make up a kind of diffuse extension of the southernmost part of the primary disc. These particles, and the diffuse particles between the "Sp" and "Scrape" loci, come from three sources. First, some are products of spiral arm feedback, and thus, are artifacts of initial transient effects in the model, like the NArm. Second, some are primary disc particles that were located in the northwest at the start of the simulation, and were perturbed as a result of a scraping interaction with particles in the companion gas disc. The third group of particles come from the companion, and were on the other side (east side) of the scraping interaction. These particles were removed from the companion and orbited under the primary disc to their present location.

In the real system, as shown in Fig. 9, there is essentially no primary gas at velocities of less than 2570 km s^{-1}. The most likely explanation for the difference is that the scraping interaction between discs may be too strong in the model.

Next we consider the companion declination-velocity plot. Observationally, the companion looks like a thin, nearly vertical oval, with a faint horizontal plume attached in Fig. 9. The model image, in the lower left plot of Fig. 9, is very similar, though compressed (appearing skinny). The shape and orientation of this oval are sensitive functions of the B disc orientation. The initial B disc orientation is close to correct, but not perfect.

In the model, particles making up the horizontal plume are found in two distinct regions. Most of the particles come from the companion tail. The remainder are scattered through a region in the northern part of the primary galaxy, though they originated in the companion. They were accreted in the first encounter between the two discs. They have never had any real association with the tail particles.

In sum, the model can account for all the major kinematic features in this system, except for warps in the gas disc of NGC 2207, and the detailed structure of the southern HI extension of that disc. In the latter case, the model does in fact have particle features corresponding to that structure, but because of the effects of particle resolution and spiral arm parameters they do not match the observed kinematics especially well. The model also makes predictions about the kinematics of accreted gas, but these will be hard to test observationally.

4.4 Before the Present Encounter

Before leaving the topic of overall evolution to discuss finer structural details, we should consider the question of what might have happened before the beginning of the fiducial model. Recall that the fiducial model begins with the companion located a short distance out from the initial closest approach point to the primary, and that after the close approach the companion continues around on a nearly circular orbit. It is natural to infer that this orbit is the continuation of a prolonged nearly circular orbit or one which brings the companion slowly spiraling inward. If so, the tidal interaction would be more prolonged than indicated by the fiducial model, and this, together with previous close encounters, could have a strong effect on the system not accounted for by the fiducial model. (E.g., see the models of prolonged interaction in the M51 system by Salo & Laurikainen 2000a,b)

To test this possibility we ran the fiducial model 'backwards' from its starting point by reversing the initial velocity of the companion's relative orbit, and reversing the sign of the dynamical friction term. We found that, indeed, the relative orbit of the companion is qualitatively like a precessing ellipse with modest eccentricity. It's furthest radial excursion was only about 50% farther out than its closest approach radius.

Given the companion's relative position and velocity at a time about equal to one orbital period before the beginning of the fiducial model, we ran the model forward from that time to judge the effects. The primary was little affected by the prolonged, but still retrograde encounter. However, as would be expected, the effect on the prograde companion was strong. The tidal tail (and bridge) developed immediately, and the tail was very long by the time when the fiducial model was started. By the present time this tail would bear no resemblance to the much less mature observed tail. Thus, there is strong evidence against a prolonged encounter, and the "pre-history" of the fiducial model must be modified from the simplest time reversed extension.

Of the many possible changes we could make to the relative orbit in the fiducial model to avoid the prolonged encounter, a great many can be eliminated because they would lead to a model result that does not match the observations nearly as well. In fact, we don't really want to change the orbit of the fiducial model itself, but only the orbit before the starting point of that model. To match the observations we want the companion to move well away from the primary as we go back in time, and to be well away for a long time before the present.

This scenario plays out very naturally if the nearly flat rotation curve halo of the primary does not extend much farther out than the radius of the companion at the start of the fiducial model. We set up a model with the primary halo density declining beyond this radius, such that the circular velocity fell off as $r^{-0.25}$ (i.e., midway between a flat rotation curve and a Keplerian curve). When this model is run backwards from the fiducial start conditions, the companion flys off to large distances. This example, and the observational constraints, suggest that the companion was initially on a more nearly parabolic orbit of relatively low angular momentum, so that it was able to move into the outer parts of a modest-sized primary halo and be captured onto an orbit like that of the fiducial model.

It may seem that we have to fine-tune the structure of the primary halo to get this solution, but it seems to be required to match the observations. Moreover, the precise density drop in the outer halo is not strongly constrained, and thus, not finely tuned. Finally, this fall-off can help account for the southern gas extension, which is not reproduced well in the fiducial model. Gas that is swung out to the radius where the halo density declines more rapidly, will not fall back as quickly, and may in fact travel farther out than in the fiducial model with no halo cut-off.

5 RESULTS II: DEVELOPMENT OF FINE STRUCTURE

In this section we look somewhat more carefully at a few of the collisional structures of this system, and their origin. Both the high quality of the multi-wavelength observations of this nearby system, and the detailed reproduction of its major features by the models, argue that it is worth pushing the comparison of them to a higher level of detail than usual. In fact, we find that we can give a plausible account of the development of the features considered, and also provide predictions to be checked by future observations.

The overall structure of the IC 2163 bridge and tail are generally what we would expect for a prolonged prograde encounter at an intermediate stage of development. However, there are some peculiarities (see Tables 1 and 2). The bridge, lying behind the NGC 2207 disc, is difficult to discern in the optical beyond the western cusp of the ocular feature. A longer bridge is seen in the HI (see Fig. 3). At later times the models show a good deal of gas has been or is being transferred to A (Fig. 4). Cloud I4 in Fig. 3 may be a result of such ongoing transfer. This gas is connected to the B disc by a very broad, diffuse gas bridge (Figs. 4, 6), which would be hard to identify in the HI observations aside from its contribution to the observed high velocity dispersion in the HI gas. The fiducial model has a substantial gas bridge (Fig. 4 or 5), which looks rather similar to the observed HI bridge. Most of our other models do not reproduce this feature, but the fiducial model has the largest initial gas disc. The fiducial model stellar bridge is significantly offset from the gas bridge and has at best a faint counterpart in the observations. This may mean that the initial model star disc is too large.

The observed stellar tail is rather short and wide compared to many in, for example, the Arp (1966) atlas. However, the models suggest that this is mainly a result of its youth. The tail has a great deal of internal structure, including a number of dark dust and bright stellar filaments.

Figures 4 and 6-8 provide a good view of the overall development of the model tail. However, they provide only rather general information on the origin of tail and its fine structure. Figure 11 provides more details, with snapshots of the evolution of two rings of gas particles in the initial Galaxy B. By the second time shown we can already see the effects of tidal stretching in one direction, and compression in the orthogonal direction. There also appear to be overall compressions and expansions of Galaxy B associated with the ocular waves and the angular momentum perturbations.

The gas particles in these rings are also affected by hydrodynamic shocks. For example, shocks in the disc-disc interactions probably give rise to some of the jagged structure in Fig. 11. In fact, some of the "bridge" particles in the lowermost part of the last three snapshots have likely been captured by galaxy A.

While all the particles in each ring were initially on near circular orbits with nearly the same period, the tidal forces change the orbits to ellipses with phase and period gradients. As a result, ring segments cross other segments in both the same and other rings, as is evident in the final two snapshots of Fig. 11. Many of these crossings occur in parts of the ring that have been pulled out into the tail. To the extent that gas in the tail remains coplanar, shocks will result from attempted orbit crossings (in contrast to the stars). The sizes of ring self-crossings in the last three snapshots of Fig. 11 are similar to those of the dust segments in the HST imagery of the IC 2163 tail (see Fig. 1 and Paper 3, Paper 3 (erratum), Paper 4). Thus, these segments may be explained by the relatively small scale shocks produced by such crossings (also see the model of Paper 3 and the discussion in Salo & Laurikainen 1993 related to their Fig. 8).

Assuming particles at different initial radii have different metallicities, this process would mix stars and gas clouds of different metallicities, especially in the inner tail. The outer parts of the tail would consist mostly of metal-poor gas from the outer parts of the initial disc.

Figure 12 provides a more detailed view of the mass transfer of gas from Galaxy B to A. The upper right panel of this figure shows a sample of gas particles (plus signs) at about the present time, which originated in B and which have been captured by A. Specifically, the plus signs mark 10% of the B particles with $x > -3.0$. This is not a rigorous

Figure 11. Four snapshots of the evolution of two circles (ellipses in projection) of gas particles in Galaxy B. In these plots the origin of the coordinate system has been moved to the potential center of Galaxy B, which is marked by a cross. The positions of groups of 4 particles were averaged in order to smooth distortions due to single particle scattering. See text for details.

Figure 12. Two x-y snapshots of selected gas particles (shown as crosses in the top row) apparently transferred from Galaxy B to Galaxy A. The top right-hand plot corresponds to about the present time ($t = 380$ Myr). The left-hand plot of the first row shows the same particles at the beginning of the run, illustrating where the captured particles originated. The second row shows two views, x-y and x-z, of the trajectories of 10 captured gas particles. 10% of all the gas particles are shown as small dots in all panels for reference, except for the first panel where every fourth particle is plotted.

capture criterion, but since it generally requires the particles to be closer to the potential center of the more massive Galaxy A than to B, it is generally an effective one.

The upper left panel shows the same particles at the onset of the simulation. The plus signs are all clumped in the upper half of the B disc, which is the region that interacts most strongly with the disc of A (see Fig. 6).

The lower two panels of Fig. 12 show x-y and x-z views of the trajectories of 10 representative captured particles, from the start of the simulation up to the present time. These panels make clear that the disc-disc interaction scatters affected gas particles quite widely. Some generally continue to orbit between the two galaxies, though now apparently perturbed out of the plane of the B disc. Others are stopped and have the sign of their angular momentum reversed, so that they orbit in the same sense as particles in the A disc (though again in different planes).

Because of their different orbital planes, these particles pierce the gas disc of A, probably inducing strong cloud collisions, and local heating. At the present time, their distribution is weighted towards the southeast quadrant of the A disc. Apparently, there has only been sufficient time for the accreted material to orbit to that part of the potential.

Paper 3 noted about 20 peculiar emission features in the HST observations of this system (see Fig. 1). Of those that appear to originate in NGC 2207, most are located in the southern half of that disc. It seems quite possible that a number of these were produced by gas clouds from IC 2163 with trajectories like those in the lower panels of Fig. 12. That is, trajectories that are perturbed by interactions with gas clouds in the northern part of the NGC 2207 disc, pierce that disc, and subsequently return to collide with it again in the southern half. (We caution, however, that this depends sensitively on the companion's trajectory.) The wide dispersion of the model trajectories is certainly in accord with the dispersed locations of the emission regions. Several of the emission regions have linear or arc-like forms that could be produced by cloud collision bow shocks.

The far western emission region i is also coincident with a strong radio continuum source, and two candidate superstar clusters. This region may have been directly excited, or driven into vigorous star formation, by the disc-disc interaction. In the fiducial model, the disc-disc interaction occurs most strongly in the northwest, and by the present time, the affected material has rotated to the southeast. If the disc-disc interaction either occurred at a later time along the orbit, or continued longer, so that it was still underway when the companion passed from the north to the northeast of the primary disc, then that part of the primary disc would now be located on the western side of the NGC 2207 disc, near region i.

Alternatively, the activity of region i could be stimulated by a milder interaction than the disc-disc encounter that captured so much material from the companion. The models show that after this strong interaction, the near side of the companion disc continues to press the passing spiral arm of NGC 2207 inward.

Either this prolonged scraping interaction, or continued mass transfer from the bridge, may be responsible for producing the ridge of radio continuum emission on the northeast side of the NGC 2207, described in Paper 1. Additional observations and analysis (to be published elsewhere) have shown that the continuum ridge is in fact coincident with the middle spiral arm in the northeast of NGC 2207. This result would seem to favor interaction between that arm and IC 2163 as the cause of the emission. Changes in the spectral index along the ridge, indicative of an aging, cooling population of radiating electrons, would provide some confirmation for this hypothesis, as opposed to the possibility of a random collection of local point sources.

6 SPATIAL/TEMPORAL PATTERNS OF STAR FORMATION AND ISM PHASES

The S97 code contains a simple SF and feedback algorithm as noted in Section 3.1 and described in more detail in Struck (1997). SF is not particularly strong in this system, and our treatment of it in the simulation code is very approximate, so we should expect that the information provided by the models on this topic will be limited. Nonetheless, the large scale spatial pattern of SF in these two galaxies is interesting, and it is of interest to see how well the models can match it, and what they have to say about its origin and history.

Figure 13 provides four snapshots of the pattern of SF in the fiducial model at various times, with the last at close to the present time. The upper left panel of Fig. 13 shows a time near closest approach, when the two gas discs have begun to scrape against each other. The resulting compression induces a small and brief SF enhancement in the adjacent part of the Galaxy B disc in some of our models. In the fiducial model the scraping involves a spiral arm segment which experiences enhanced SF as a result of the compression. Other parts of the spiral are not particularly active, and Fig. 14 shows little excess SF in the A disc at this time. A core SF burst is beginning in the B disc as the first ocular wave begins to develop. The spiral arms are created in the initial conditions with relatively high gas densities, which generate strong star formation at the beginning of the simulation. This transient

Figure 13. x-y snapshots of star-forming gas particles (shown as plus signs), with 10% of all the gas particles shown as small dots for reference (except in the lower right panel where 20% of the particles are shown). The upper left-hand panel shows an early time near the beginning of the run. The lower left-hand plot shows SF in the developing first ocular wave of Galaxy B at a later time. By the time shown in the upper right panel, the ocular wave has nearly propagated out of B, and a new wave is forming and triggering SF. The lower right panel shows a time near the present, with a magnified scale, focussing on the companion; for more details see discussion in text.

effect has largely damped by the time shown in the first panel. It is responsible for the burst at early times shown by the solid curve in Fig. 14.

The SF in the Galaxy A disc has damped to a more typical level by the time shown in the second panel. By this time the ocular wave has begun to develop in the (displaced) center of Galaxy B, and the resultant compression drives stronger SF. Up to this time, the Galaxy B disc had generated very little SF (except in an early transient ring wave), since it was initialized with gas densities below the threshold. Scattered SF particles are also seen in the nascent tidal tail at this time. There are too few particles involved to attach much significance to this. However, the general pattern is typical of all timesteps after the onset of tail formation, and reasonable, since we expect local gas compressions in the tail. The absence of SF in bridge gas is also interesting. A large fraction of these gas particles have relatively high temperatures (due to the disc-disc interaction) at this time.

The third panel of Fig. 13 shows a time when the ocular wave has nearly propagated through the B disc. Compare this to Fig. 7, which provides better views of wave evolution in the companion. At about this time, a second oval wave appears in the center of the companion and begins to propagate outward (see Fig. 7). As in collisional ring galaxies, this second wave is primarily a product of continuing coherent radial motions resulting from the earlier perturbation, not any new disturbance. This coherence is somewhat less in the gas than in the stellar disc.

The fourth panel shows a time near the present, where the second ring-like wave has propagated well out in the remaining companion disc. The view in this panel is magnified to show the SF in the companion, which is relatively strong and concentrated in the wave. The SF is strong in the upper rim of the oval, as observed. However, examination of many other previous timesteps shows that the SF moves around the oval waves as they propagate, so the location of SF in the last panel is a short-lived situation, and the coincidence with observation is somewhat fortuitous.

The first three panels of Fig. 13 show that SF in Galaxy A is concentrated in the spiral arms. This is in qualitative agreement with the observational results of Paper 4, in which the most luminous young star clusters in NGC 2207, and candidate super star clusters, were found in various parts of the spiral arms.

Figure 14 shows the total amount of SF in each of the model discs as a function of time in the fiducial and for the companion in other models. The SF history in the B disc is qualitatively similar in the models shown. The first peak is associated with the first ocular wave, and exceeds the SF at all other times in either disc (excluding the first, artificial peak in disc A). The time interval between the burst and the present is about 260 Myr (see Figs. 4 and 5). This suggests that a post-starburst population might be present in IC 2163. If observed, this population would provide some circumstantial evidence for the early compression associated with the formation of the ocular waves. The rapid rise in SF at the latest times (i.e., in the future) is due to the onset of merging.

7 DISCUSSION AND SUMMARY

Motivated by the proximity of the NGC 2207/IC 2163 system, and the high quality and resolution of the multi-waveband observations, we have attempted to model its morphological and kinematic structure in considerable detail. The collisional models described above have successfully accounted for the major, large scale structures in this system. In this section we review Tables 1 and 2, in order to see which of the 34 features listed there are accounted for by the models. We also want to consider which features might be so sensitive to specific model parameters that, while they may, accidently, appear in a particular model, they are unlikely to be produced in a generic model. In striving for accurate models, can we begin to perceive the limits of such modeling?

We begin with items 1 and 4 of Table 1. The distance and mean redshift are not relevant to the models, though the difference between the LOS velocities constrains the relative orbit. Item 2 gives luminosity ratios. Table 3 shows that the halo mass ratio (0.7) is quite similar to the observed NIR luminosity ratio (0.6). This similarity may be fortuitous unless the halo mass ratio of the two galaxies is the same as their old star mass ratio. If the mass ratio were much lower the perturbation would not be strong enough to perturb the Galaxy A gas (HI) disc, as observed. If it were much higher, the Galaxy A disc would be more disturbed.

The young star luminosity ratio is quite different (0.3), though more young stars may be obscurred in IC 2163 than in NGC 2207, since in the latter case the SF regions are generally well outside the core. Fig. 14 shows that the ratio of SF particles in the two galaxies varies greatly with time. At the present time it is roughly unity. Simple feedback formalisms can only be expected to give qualitative information about the SFR.

Items 3, 6, and 10 concern radii and separations. First of all, we note that the radius of IC 2163 in item 3, from the RC3 catalog, seems to include the tidal tail. The initial radii of the old star discs in the model galaxies are not as well constrained as gas disc radii are by the need to match tidal morphologies. They can be changed over a modest range with little effect on the collisional or spiral arm morphology. A third caveat is that the ocular diameter of item 10 is time-dependent, as the ocular waves evolve. Despite these caveats the sizes and separations of the fiducial model seem about right (Figs. 4, 5, 7 and 10).

Item 5 describes the observational (HI) estimate of the orientation of the two discs. In the case of IC 2163 the models agree with this estimate. In the case of NGC 2207, the nearest side in the models is in the east, while the observa-

Figure 14. Total number of star-forming particles versus time within the model galaxy discs. The solid curve shows the SF in Galaxy A of the fiducial model. The dashed curve shows the SF in Galaxy B of that model. The dotted and dash-dot curves show the SF in companion Galaxy B in two different, but quite similar models. Comparison of these Galaxy B curves allows a determination of which features are generic; see text.

tions suggest it is in the NE to N. However, the models have little of the disc warp indicated in the observations (item 24). Moreover, the observed HI velocity field could not be fit by a static, tilted ring model; extra z-motions had to be included. Cold gas accreting onto NGC 2207 could contribute to these extra z-motions, as well as tidal forces.

Item 7 notes the typical HI mass to SFR ratio. The SF terms in the model yield qualitative agreement with the observations on the distribution of SF. Item 11 notes enhanced emission in the ocular rim, and the SF model also produces this (Fig. 13).

Item 8 notes widespread, high velocity dispersion HI gas. We have not examined the model gas velocity dispersion in detail. However, Fig. 9 shows the presence of a good deal of warm gas with a large velocity dispersion (e.g., accreting gas in the eastern half of the lower right panel of Fig. 9). This gas also has a large range of temperatures, and is probably only partially ionized, so may correspond to some of the observed high dispersion gas.

Item 12 describes the major axis orientations of IC 2163. In the models the Galaxy B orientation is time-dependent, but at the present time (t = 270 Myr), Fig. 7 shows the photometric orientation of the morphological major axis is about right. The major axis of the gas in the model is also close to that observed for the two galaxies.

Item 13 notes that the bridge and tail of IC 2163 are nearly symmetrical in HI. In the models, the bridge arm is more diffuse, but still extensive.

Item 14 notes 100 km s^{-1} streaming motions in the IC 2163 tail. A similar velocity spread is found in the model tail: see Fig. 9. Item 15 notes that the mean velocity is nearly constant along the tail. It has a shallow gradient in the models as well; see Fig. 9.

The stellar arm contrast is large in both models and observations (item 16).

The spiral arms evident inside the IC 2163 oval (item 17) are not obvious in the model, but our model may not have sufficient angular resolution for discerning these thin arms. In the models, pre-existing flocculent arms and small scale shocks both apparently contribute to producing the dust filaments (item 18) in the tail of IC 2163 (see Sec. 4.1.2). Paper 1 point out an S-shaped wiggle of HI emission from the tidal tails, which might be the result of a small scale shock.

The spiral arms in NGC 2207 (item 20) are also not produced in any of our models. Given the prominence and extent of these arms in NGC 2207, and their complete absence in models like Sm1 (Fig. 8), it appears that they must have been present before the collision. Thus, they must be input into the models.

Item 21 (see also 26) reminds us that the HI distribution in the NGC 2207 disc is dominated by a large partial ring (see Fig. 5). To reproduce this the initial condition for galaxy A requires a large gas hole in its centre. The observed ring is then the disturbed remnant of the initial annular gas distribution.

NGC 2207 is embedded in a large elliptically-shaped pool of HI gas that extends a considerable distance to the southeast of the main disc (item 22, Fig. 2). The model A disc is similarly distorted, but to a lesser degree (Figs. 5, 8). Much of the southeastern extension in the fiducial model is due to the spiral arm extension there. The adopted gravitational potential may produce a force that is too strong in the outer disc, preventing more gas from moving out there.

Inspection of Fig. 7 shows that the photometric PA (item 23) of the model is close to that observed at a slightly earlier time if we assume that both are dominated by the spiral arm morphology. Table 3 shows that the gas kinematic PA in the model is also a reasonable fit to the observation.

The radio continuum ridge in the NE quadrant of NGC 2207 (see Paper 1) is recalled in item 25. The fiducial model does not exactly reproduce this feature. At earlier times the interaction between the bridge and the outer spiral arm in the north is very strong and would produce a "continuum ridge" (e.g., see panel 4 of Fig. 5). Before and at the present time there is a similar, but weaker, interaction between the bridge particles and the middle NE spiral arm, which could be responsible.

This completes our review of Table 1, and we turn to the smaller-scale features of Table 2, which begins with the luminosity and size distributions of young star clusters in the system (item 27). The study of star cluster structure is beyond the scope of our present models. Item 29 notes the widespread distribution of star clusters in the system. This is also seen in the fiducial model, see Sec. 6. The model suggests an explanation in terms of widespread distribution of compressed regions, especially in spiral arms and tidal structures.

Item 28 describes massive gas clumps without young star clusters. It is true that such clumps can also be found in the spirals of Galaxy A and the tail of Galaxy B. However, comparing the model and observational clumps is problematic. The size of the observed clumps is close to the effective beam size, so they are not well-resolved. The scale of the model clumps is close to that over which local self-gravity is computed in the disc. Moreover, they do not contain a large number of particles, so they too are not well resolved. On the other hand, the structure of the model clumps is more reminiscent of knotty dust filaments seen in the spiral arms overlying IC 2163 (item 32).

The lack of nuclear activity in this system is noted in items 30 and 34. This is replicated, at the present time, in the model SF. The models suggest strong central compressions and enhanced SF in the core of IC 2163 at earlier times (Sec. 6). They suggest that no large compressions have occurred in the primary, and that most of the mass transfer was initially into the outer disc.

The dust spirals in the center of NGC 2207 (item 31) are not seen in the models. However, the models do suggest the passage of a number of complex waves over the course of the encounter, and these would be a plausible cause of the dust compression, along with some mass transfer.

Finally, item 33 describes the luminous SF region on the far western arm of NGC 2207. This intense emission source could be an effect of an earlier mass transfer interaction. However, we can only speculate about this; it is extremely difficult to produce such small-scale features in models at the present time.

We should emphasize that the models are generally very successful at reproducing the large-scale collisional morphology and kinematics, as well as the qualitative SF history. The shortcomings of the models can be grouped into several categories. The first category includes structures that are well beyond the resolutions of current models, like the young cluster luminosity functions, or very-small-scale structures like item 33. The latter example falls in a subcategory mentioned at the beginning of this section, features that might be produced rarely in a model grid, but essentially by accident. The second category includes quantities that can be very time-dependent in the models, like the SF ratio of the two galaxies. A third category includes features that are prominent, but do not seem to appear in any of the models of a grid that is otherwise generally successful at producing the observed collisional structure. We have suggested that the spiral arms in these two galaxies, and possibly the warp of NGC 2207, may fall in this category. They apparently predate the collision and must be added to the initial conditions by hand.

The final category, which includes most of the discrepancies cited above, is the set of things that appear 'fixable' if we tune the model finely enough. In the present case, many of these relate to effects of the detailed structure of the rigid gravitational potentials adopted, and also to the dynamical friction treatment. There are two major difficulties in making such fixes: 1) the precise change needed is not clear *a priori*, and 2) such changes generally affect other structures in a way that requires additional fixes. This can lead to a cascade of 'fixes' that does not readily converge.

8 CONCLUSIONS

The discussion of the previous section illustrates the mounting complexity involved in producing successful models of finer scale features or more dynamically evolved systems. To significantly refine some of the category 4 defects, while maintaining good fits to other structures, would take considerably more runs. This is a good procedure for the improvement of early runs where the experienced modeler can fairly quickly identify the source of major defects resulting from particular initial orbital or structural parameters. After several dozen simulations have been run the resulting models are usually quite good, but further improvements must overcome the problems cited in the previous paragraph.

An automated procedure for producing and selecting the best of hundreds of models would be desireable (e.g., like the N-body, genetic algorithmic modeling of M51 by Wahde & Donner 2001). However, a procedure that selects initial conditions that are distributed evenly in parameter space is unlikely to be very efficient, since there are many parameters, and the set of model initial conditions that yield a sufficiently accurate result will generally have a very small volume in parameter space. At the least, the parameter selection algorithm will have to be guided in a nonlinear way by the results of previous, and perhaps, some expert "rules of thumb." To date, attempts at automated modeling have been very limited.

On the positive side, it is not clear that modeling of specific systems needs to be much more accurate than the best, current, by-hand efforts. To reconstruct the complete dynamical history of an evolved merger would require a great deal more, but there is not yet much motivation for such an exercise. The present case shows that by-hand modeling, with sequential improvements, can produce a result that accounts for most of the morphology and kinematics in a pre-merger collisional system. The present case and other detailed studies of relatively symmetric pre-merger systems indicate that most of the collision-induced SF can also be accounted for by such models (see references in the introduction). Thus, we can use such systems as laboratories for the study of some types of induced SF, while other types, such as those found in merger remnants, require statistical studies of samples of galaxies and models.

Finally, we note one unexpected result of the present modeling effort is an indication that NGC 2207 has a rather smaller halo than the Milky Way. Whereas the Milky Way halo may extend to 100 kpc or more (Ivezic, et al. 2004), our models suggest that the halo density of NGC 2207 may begin to tail off at roughly its optical isophotal radius. Models of binary encounters between galaxies such as the one presented here may eventually be useful for constraining the extent of dark matter halos (see also Salo & Laurikainen 2000a)

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