

COMPUTER GENERATED MODELING OF INTERACTING GALAXIES

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ABSTRACT

Substantial evidence shows galaxy evolution is directly influenced by gravitational interactions between galaxies. To further the understanding of this process, we have constructed an ‘automatic galaxy collision’ code, which merges a restricted 3-body galaxy interaction code with a genetic algorithm and a pattern matching routine. Using the interacting pair NGC 7714/7715 (Arp 284) to test our program, we have identified several different methods of interaction, as well as estimates of the uncertainties in the interaction parameters. The results of these test runs and the effectiveness of the automatic code are compared to two previous non-automated interaction models.

Subject headings: galaxies: individual (NGC 7714/7715) - galaxies: interactions - methods: restricted 3-body simulations - galaxies: kinematics and dynamics

1. INTRODUCTION

There is considerable evidence to show that galaxy evolution is directly influenced by galaxy interactions. Computer simulations show that interactions can produce tidal tails and bridges (Toomre & Toomre 1972), increase star formation rates (Kennicutt et al. 1987; Bushouse et al. 1988; Barton Gillespie et al. 2003), and trigger the formation of young super-star clusters (Holtzman et al. 1992, 1996; Whitmore et al. 1993). Consequently, dynamic modeling of the interacting galaxies has become basic to understanding these processes. Detailed models of galaxy interactions can provide reliable information on the interaction parameters of the two galaxies, the time since closest approach, and the history of gas compression in different regions. Computer simulations can also provide predictions of the distribution of star formation, which can be compared to observational results to estimate the effects of compression strength, duration, and other factors (e.g., Struck & Smith 2003).

The first models by Toomre & Toomre (1972) used a simple restricted 3-body code. These were followed by full N-body codes (Noguchi 1987; Barnes 1988), and, more recently, models including gas hydrodynamics, star formation, and heating of the interstellar gas (e.g., Struck 1997). However, a major problem remains. In order to find a likely model for a particular system, a series of runs must be done. Each run, however, contains parameters that must be varied by hand until a model is produced that matches the observed appearance of the galaxies, with a good match being determined by eye. Not only is this a very subjective process, but the requirement of human intervention in selecting new parameters for a single system is very time-consuming. In addition, this method provides little information about the uncertainty in the parameters or the uniqueness of the model, as more than one set of parameters may yield models that match the real system equally well.

In response, we created the Automatic Galaxy Collision (AGC) code (Smith et al. 2008). Details of the code are given in that paper; we briefly summarize here. This code combines a standard restricted 3-body interaction code (Wallin 1990), the publicly-available genetic algorithm code PIKAIA (Char-

bonneau & Knapp 1995), and our own pattern-matching fitness code to determine how a model and the actual interaction compare. The AGC code runs a large number of galaxy interaction simulations with randomly selected interaction parameters. It then uses the pattern-matching routine to determine how well each model fits the observations of the galaxy system. This comparison between the model and the actual interaction is returned to the user as the ‘fitness,’ a measure of how well the model fits the data. Based on the fitnesses calculated for the first generation of models, it then runs a second generation of models using parameters from the first generation as a guide, except with slight changes that will make the parameters closer to those of the real system. Over a set number of generations, this process produces a group of models with parameters and characteristics much closer to those of the observed system than the ones originally chosen at random in the first generation.

As a genetic algorithm, PIKAIA employs the principle of natural selection whereby ‘fitter’ individuals are more likely to pass on their characteristics to succeeding generations. When two individuals (galaxies) are ‘bred,’ their genetic material (interaction parameters) is combined and sometimes mutated, resulting in a new generation with characteristics similar but not identical to their ‘parents.’ When repeated over successive generations, this process virtually ensures improvement in the level of ‘fitness,’ although it does not guarantee absolute maximization of this fitness level (Charbonneau & Knapp 1995). By using multiple runs with different initial conditions, the question of uniqueness can be investigated.

The original PIKAIA code was converted to a parallel code by Metcalfe (2001). The Computer Science Department at East Tennessee State University then re-engineered Parallel PIKAIA as a library of Fortran 90 routines that can be accessed by a separately compiled, user-supplied program. This allows for the ability to execute more simulations in a shorter time period, and the option to increase the number of parameters being evolved.

The Wallin galaxy interaction code is a restricted 3-body program. In general, to find a detailed fit to a particular galaxy system, it is best to first narrow down parameter space by initially fitting with a restricted 3-body code to get approximate parameters. These parameters can then be used as initial best guesses for a more complex N-body code, a method that was

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TABLE 1
BEST FIT PARAMETERS FROM AGC RUNS

| Run | θ ($^{\circ}$) | ϕ ($^{\circ}$) | i ($^{\circ}$) | ω ($^{\circ}$) | r_{min} | α ($^{\circ}$) | β ($^{\circ}$) | Best Step | Fitness |
|----------------------|----------------------------|--------------------------|-----------------------|----------------------------|-----------|----------------------------|---------------------------|-----------|---------|
| 5-23-07 | 41 | 228 | 53 | 273 | 0.189 | 22.5 | 91.6 | 39 | 0.677 |
| 6-11-07 | 38 | 196 | 77 | 280 | 0.382 | 20.3 | 83.0 | 47 | 0.770 |
| 6-21-07 | 327 | 236 | 46 | 77 | 0.566 | 14.5 | 295.9 | 39 | 0.692 |
| 7-16-07 | 166 | 178 | 164 | 115 | 0.158 | 22.3 | 371.6 | 34 | 0.681 |
| 7-25-07 ^a | 17 | 49 | 67 | 55 | 0.617 | 27.0 | 316.5 | 41 | 0.689 |

^a r_{min} was limited from 0 to 2, whereas it is normally 0 to 10

used by Struck & Smith (2003). Typically, N-body codes run much slower than restricted 3-body codes, making it impossible to explore much of parameter space with them. Thus, for automatic galaxy interaction modeling, using a restricted 3-body code for initial parameter space estimation is more feasible for a first trial.

The Parallel Automatic Galaxy Collision (PAGC) code contains a total of 44 variable parameters - 24 from the Wallin interaction code, 11 from the PIKAIA routine, and another 9 from our pattern-matching routine. Some of these parameters, such as the number of generations and the number of individuals per generation, are set by the user at the beginning of each run and are not changed.

2. CURRENT WORK

In the current work, we test the PAGC code by varying 7 of the parameters and keeping the others fixed. These seven parameters include: r_{min} , the radius of minimum approach; i , the inclination of the encounter; ω , the argument of periapse of the encounter; θ and ϕ , the orientation of the companion galaxy's disk with respect to that of the main galaxy; and α and β , the viewing angles of the simulation (Smith & Wallin 1992). We investigate the results from a series of 5 runs using the interacting galaxy pair NCG 7714/7715 (Arp 284) shown in Figure 1. This well-studied system has been previously modeled with a restricted 3-body code (Smith & Wallin 1992) as well as by an SPH code and an N-body code (Struck & Smith 2003). Some important aspects of this interaction that will be compared to the model results are the bridge connecting NGC 7714 and 7715, the three NGC 7714 tails, the NGC 7715 tail, and the NGC 7714 ring on the eastern side of the galaxy. In §3 we present the results of the five PAGC runs that have been completed, and in §4 we analyze the peculiarities of the models and compare our results to the previous models (Smith & Wallin 1992; Struck & Smith 2003). §5 provides a brief summary and analyzes ways that we can make these models better in terms of future work.

3. MODEL RESULTS

Each of the runs done with the PAGC code consisted of 192 generations with 120 individuals per generation, which produces a total of 23,040 actual models. Also, each of these models consists of 47 time steps corresponding to the progression of the interaction. Only the initial random seed that is supplied by the user is changed from one run to the next, as well as the last run (7-25-07) having a more restricted r_{min} ²: 0-2 instead of the usual 0-10. The primary disk (NGC 7714) consisted of 14,000 particles while the companion (NGC 7715) had 7,000 particles. These runs were done on

² r_{min} is in units of the primary disk's diameter

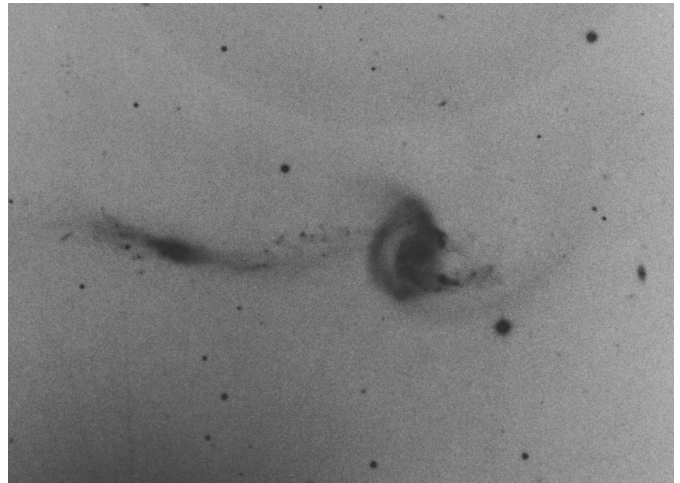


FIG. 1.— Arp (1966) Atlas photograph of NGC 7714/7715. Up is north while east is to the left. NGC 7714 is the larger galaxy to the west, while NGC 7715 is the elongated galaxy to the east. The field of view is $5'.0 \times 3'.9$.

a cluster of 3 Dell Linux computers, where each computer had a single dual-core 3.6 GHz processor; with this 6-core setup, these runs took ≈ 10 full days to complete.

In Table 1, one can see the results of the five runs that have been done. The fitness value is calculated from our pattern-matching routine and indicates how well a model fits the actual interacting pair. Run 2 - with a fitness of 0.770 - is the highest fitness of any run that has been done. Most noticeable is the variation between parameters, but while still being able to produce good models.

In Figure 2, we see the Generation vs. Fitness graphs produced from the PIKAIA algorithm. Each generation is run in consecutive order, with the parameters from one generation serving as a foundation for the parameters in the next. As we would then expect, the first generation has the lowest average fitness of all the generations. And as the run progresses, the fitness increases. However, as the run continues, the models seem to stop evolving - an indication that either the code has reached the best-fit model possible, or has reached a local minimum. Alternatively, the code may be inefficient in finding better fit models. This trend is shown in the long, dark bars at the top of each plot. These plots are discussed further in §4.6.

In Figure 3, we see the actual plots for each run, where the perspective is looking at the two galaxies from Earth; these plots should be comparable to the Arp image in Figure 1.

We can see from Table 1 that runs 5-23-07 and 6-11-07 share rather similar interaction angles. Yet when we look at their plots in Figure 3, several differences become obvious, such as the NGC 7715 tail. This comparison shows how a slight variation in the parameters can produce a model visibly

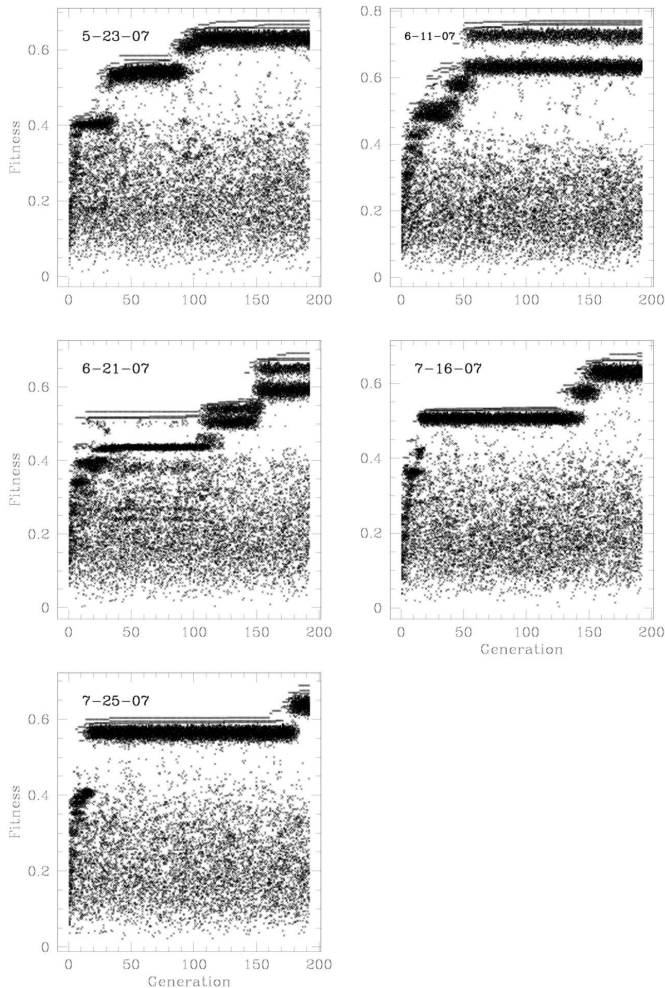


FIG. 2.— Here we present the Generation v. Fitness plot for each of the 5 PAGC runs. The long, dark bars at the top of each plot are representative of the program obtaining the best fit model possible, or has reached a local minimum.

different from another. Also of interest is that even though each model looks different from the others, the program all thought these were the best models from each of their respective runs.

4. DISCUSSION

4.1. Possibility of Mirror Images

When we look at the plots produced in Figure 3, we see that they all resemble the actual collision seen in Figure 1, especially given some expected variation among parameters. But the results in Table 1 seem to tell a different story. Runs 5-23-07 and 6-11-07 both have similar parameters; however, the next run, 6-21-07, shows some significant differences, particularly in θ , ω , and β . The last run, 7-25-07, has parameters similar to those of 6-21-07, except that θ and ϕ are different.

In Figure 4 we see a comparison between 5-23-07 and 6-21-07, from the perspective of looking at the interaction from the side (assuming a face on view from Earth).

With these plots, we can see that in 5-23-07 the companion galaxy (NGC 7715) is farther away from us compared to the main galaxy; however, in 6-21-07, the companion lies closer. Also, when a run is done with the 6-21-07 parameters - except with $\beta - 180^\circ$, $\omega + 180^\circ$, and $\theta - 180^\circ$ - we produce a model very similar to 5-23-07. Since these three angles translate into viewing angles, we show that 6-21-07 is really a mirror image

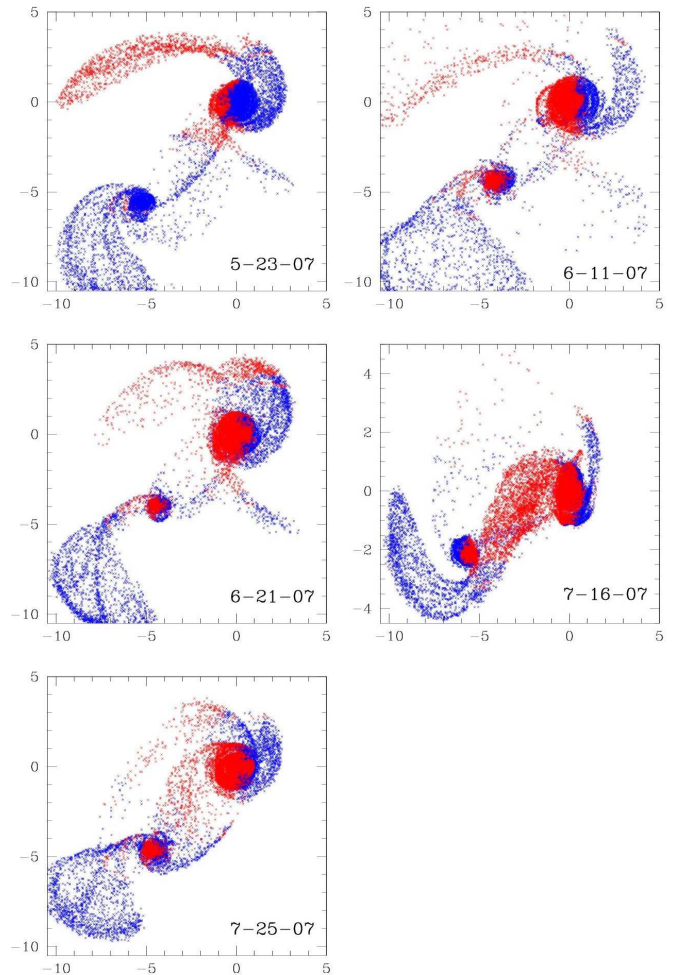


FIG. 3.— These are the plots for each of the five runs. Perspective is looking at the galaxies from Earth. The blue particles are blue shifted, whereas the red particles are red shifted. Each of the plots presented here represents the best of the 23,040 models for each of their respective runs.

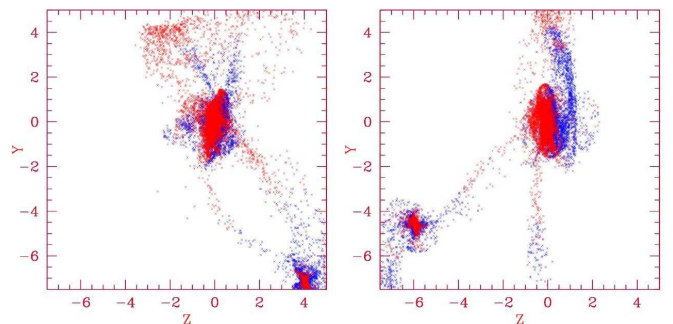


FIG. 4.— Here is a side view comparison with 5-23-07 on the left and 6-21-07 on the right. If we were to see this interaction from Earth, we would be on the left side of the page looking to the right. Both plots are of time step 47 from their respective runs. We can see that in 5-23-07, NGC 7715 is farther away from us than in 6-21-07, and vice versa. However, this cannot be determined from the face on view in Figure 3.

of 5-23-07 (and 6-11-07)³. However, we are unable to determine observationally which image is the actual image. According to PIKAIA, they are both equally plausible models.

³ This mirror ‘imageness’ relates only to the general location of the two galaxies; fine tuning of the parameters can be done to give models that more closely resemble each other

These two models are not perfect reflections, however. Note the differences in the 3-dimensional locations of the tails and the different inclinations of the disks. Perhaps if we can better constrain some of the angle parameters, change some of the parameters such as the star count, or increase the number of generations per run, the models will converge on just one of the images.

4.2. A Third Distinct Model

The 7-16-07 model differs significantly from both the first model and the ‘mirror’ model in both its interaction parameters and its overall appearance. However, its fitness is quite similar. It has a very strong bridge between the two galaxies, but a weaker tail to the west. Further, the eastern tail of the companion curves in the opposite direction. Unlike in the other 4 models, the inclination is greater than 90° . An inclination less than 90° means the orbit of the companion is in the same direction as the spin of the companion galaxy (a prograde encounter). The 7-16-07 model is retrograde, with the orbital motion being in the opposite sense from the spin of the companion.

This model shows that multiple models are possible with PIKAIA. To distinguish between retrograde and prograde encounters, more information is necessary. In the case of NGC 7714/5, the existence of a very long gaseous tail to the west looping back to the bridge (Smith et al. 1997) is more consistent with the other models, and indicates this was likely a prograde encounter. This was previously found by Struck & Smith (2003) with the SPH and N-body codes.

4.3. A Closer Look at the Bridge

Figure 3 shows red and blueshift plots of the 5 runs; in these plots, we can clearly see a bridge that is formed between the two galaxies. To determine where this bridge originates, look at Figure 5. At time step 30, we see the beginning of the bridge between the two galaxies. When we color-code the particles based on galaxy of origin rather than velocity, we see that the bridge is entirely made of particles from NGC 7715; looking at time step 47, this mass of particles is pulled into NGC 7714 as the interaction progresses. Also, we see a nice even distribution of particles from NGC 7715 in the center of NGC 7714 that are being rotated with the galaxy itself. Even though we are using a restricted 3-body code, these findings agree well with an SPH and an N-body simulation (Struck & Smith 2003) that shows the bridge originates from the companion and that these particles are being pulled into the main galaxy.

4.4. Restricting r_{min}

For the 7-25-07 run, we decided to put a limit on the parameter r_{min} . For the first 4 runs, r_{min} could take any value 0 - 10 (units of the primary disk’s [NGC 7714] diameter). However, test runs showed that as r_{min} increased beyond 1.5, little interaction takes place between the two galaxies, which in turn leads to very poor models. To assist PIKAIA when choosing initial parameters, and to not waste time on models that had the galaxies too far apart to interact strongly, we did the 7-25-07 run while limiting r_{min} from 0 - 2. As expected, we can look at Figure 2 and see that the 7-25-07 run initially evolved quicker than any of the others. Limiting this parameter is meant to increase the rate of initial evolution of the models by keeping the two galaxies in close proximity. However, this restriction can only be used on a galaxy pair

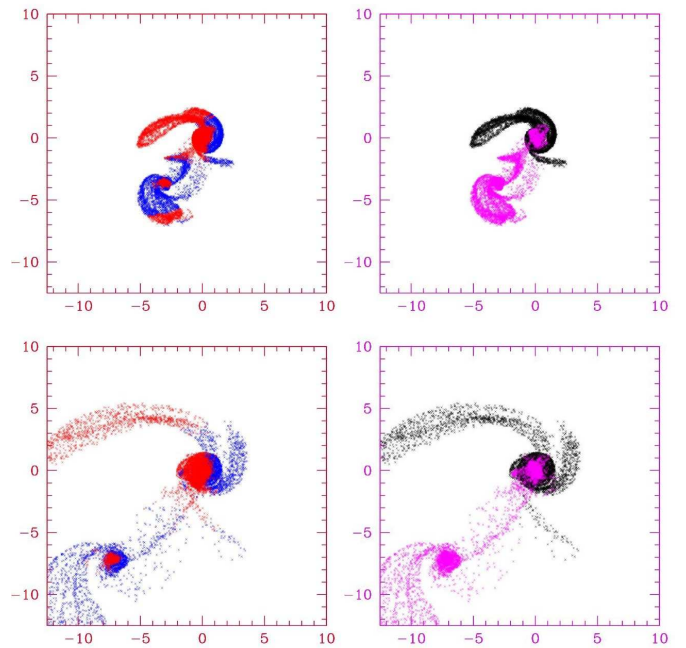


FIG. 5.— These four plots show particle origin vs. red and blueshift. All four plots are from 5-23-07, with the top row being time step 30 whereas the bottom row is time step 47. The left column shows the red/blueshift plots, but the right column is colored based on particle origin. For the right column, the magenta particles belong to NGC 7715 and the black particles belong to NGC 7714.

after enough tests have been run in order to determine how much interaction needs to take place. A smaller r_{min} will produce more profound collisional effects (i.e., larger and more defined tails), whereas too large of an r_{min} will show too little interactional effects between the two galaxies.

4.5. The Uncertainties in the Parameters

In order to make certain that the PAGC and PIKAIA codes are giving us the best possible parameters, we set up a series of runs that would vary each parameter while at the same time keeping the rest of the parameters at their ‘best fit’ values. Therefore, each parameter was varied over its full range in 360 increments. The results of this test are shown in Figure 6. These plots provide an estimate of the uncertainties in the parameters. For example, the peak for α is fairly broad, with $\approx 10^\circ - 40^\circ$ giving good fitnesses. For inclination, good fitnesses are found between $\approx 40^\circ - 60^\circ$.

One of the most interesting plots in Figure 6 is of ω . We can clearly see the maximum around 80° ; however, there is also another, albeit smaller, maximum around 280° . When comparing this with Table 1, we can see that for the 5-23-07 and 6-11-07 runs, their best ω was $\approx 280^\circ$. This same connection can also be seen with θ . For the 6-21-07 run, the best θ was 327° ; however, Figure 6 shows good fitness for θ below 40° , assuming a model with a fitness above 0.4 to be a good model. For 5-23-07 and 6-11-07, θ was approximately 40° . Some of the other parameters, such as r_{min} and α , retain the same relative maxima for all runs regardless of the other parameters.

4.6. Evolution in the Code

Figure 2 shows that for the 6-11-07 run, the models quickly evolve to a ‘good’ fitness. At this point a better model is not produced; we end up ‘running in place’ with the same parameters. In contrast, for the 7-16-07 and 7-25-07 runs, signifi-

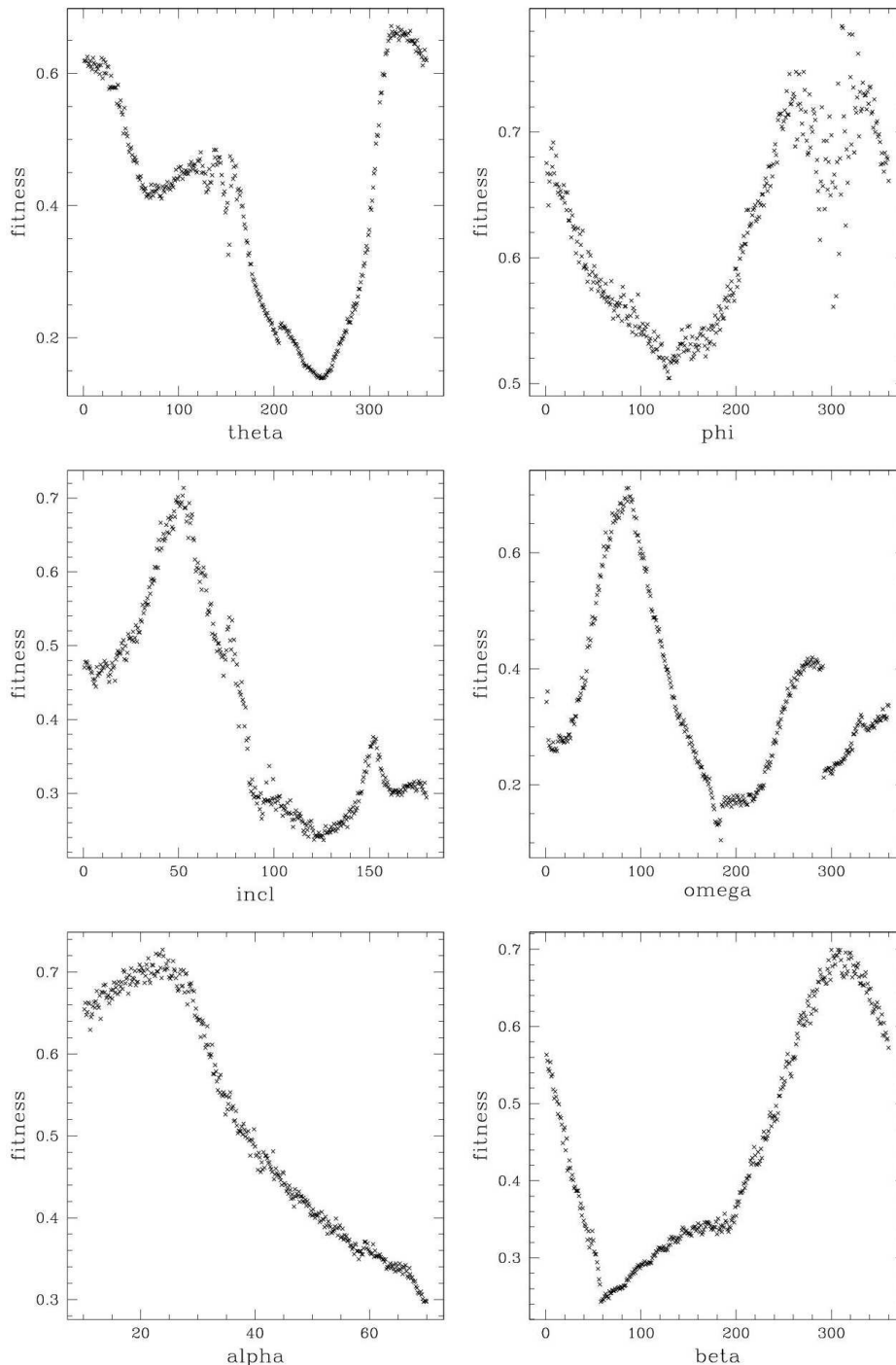


FIG. 6.— In these plots, each parameter was varied over its full range in 360 increments while each of the other 6 parameters were held constant to the best-fit values from 6-21-07. The plot of r_{min} was left out since its variable effects were discussed in §4.4

cant evolution happens near the end of the run. If we were to shorten the length of these runs - say 96 generations instead of 192 - they would produce poor results. Had the 6-21-07 run only been 96 generations, our results would have had a fitness around 0.54 instead of the 0.68 that the longer run gave - quite a significant difference. When looking at Figure 2 we see the fitness plot from each run is characteristic of long, dark bars at the maximum fitness level. If we were to compare the parameters of all 23,040 models from each run, we see that when a model lies in a long dark bar, it will have the same 7 parameters as the other models that also lie in that bar. We can see

from Figure 2 that these long dark bars have an obvious thickness to them (a fitness spread of ≈ 0.05 per bar). One must keep in mind that we are using a star count much lower than the actual interaction; consequently, even though two models might have the same parameters, the random distribution of stars for one model may produce a better fitness in relation to the other. This is the likely origin of the thickness of the bar.

5. SUMMARY AND FUTURE WORK

The interacting galaxy pair NGC 7714/5 (Arp 284) has been used to study models produced from an automated restricted

3-body interaction simulation. When comparing the models to Figure 1, we see that they both share many similarities in the locations of the tails and the bridges. Our automated restricted 3-body code also gives similar results as the SPH or an N-body code, especially when we look at the movement of particles in the bridge. In addition, our code has shown that models with different parameters can produce equally fit models - models that may resemble mirror images of each other. We have also shown that there is some distribution of fitness based on the random distribution of particles for each model.

East Tennessee State University has recently purchased a super-cluster consisting of 240 cores. Using just half of this cluster, our runs will only take ≈ 10 hours instead of 10 days on our current system. This new cluster will provide us with the opportunity to produce more models than before, which will help to further investigate the parameters.

We are still working on improving the PAGC code to make it more efficient at finding better parameters so that it will evolve more quickly. For example, is it more important to increase the star count, or should we be increasing the number of generations that we run? In theory, we would like to do both. This has long been impractical due to the time required for such changes. Indeed, the 21,000 total star count we are using is much lower than the actual number of stars in a pair of galaxies. However, if we were to increase this number, the total time for each run would increase significantly. In one test, a 50 model run with 21,000 particles took 2 hours whereas the same 50 model run with 42,000 particles took 2 hours, 45 mins. This means that if we double the star count for a 192 generation run, it would take just under 14 full days to complete - a 30% increase in time. However, the full benefit of increasing the star count has yet to be determined. Since the number of stars used in the model will never be close to the actual galaxies, the extra time needed for such a run might not be offset by the better results.

Another of the changes to be implemented is the incorporation of an SPH or N-body code. Again, the additional time and CPU's needed for an N-body simulation has made this impractical. With the use of the new cluster, however, this could lead to many possibilities. In theory, a two-step approach would be best: first, use the restricted 3-body code for initial fits, then running the Struck (1997) Smooth Particle Hydrodynamics code for a more accurate match to both the morphology and kinematics. This may help distinguish between the multiple sets of interaction parameters we are currently getting with PAGC.

Also, during this 'testing' stage, we have limited ourselves to producing models only of NGC 7714/5; we plan to eventually model a large subset of the interacting systems in the Arp (1966) Atlas. We will start with well-studied systems of high symmetry for which the solutions are fairly well-known. Other planar encounters also have some symmetry, but the waveforms that develop are quite sensitive to collision parameters (e.g., Struck 1999), which pose a challenge to the restricted 3-body code.

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