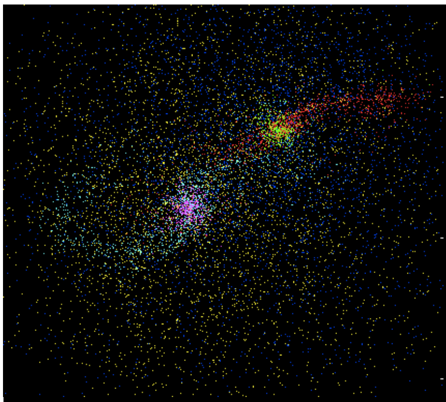


The Fate of Arp 271

Brett Hall

ABSTRACT

Using data obtained from observational studies made predominantly by Fuentes-Carrera et al (2004) which constrain the masses and systemic velocities of NGC 5426 and NGC 5427, I provide a possible scenario for the evolution of Arp 271 using the collisionless N-body simulation code GalactICs to simulate the interaction of this pair. Using the best estimates for the masses and velocities of the galaxies involved I find that merging and the subsequent formation of an elliptical is unavoidable. Exploring inputs to the limits of observational error, I find that even extreme choices for the parameters affecting the interaction results in an eventual merging. A lower limit for the relative systematic velocity required to ensure a merging of NGC 5426 and NGC 5427 does not occur is provided. This generates an answer to the question posed on the websites of some professional astronomical communities: "What will become of these galaxies?"

Background and Motivation

Public interest in science broadly is often mediated through the lens of astronomy and there are perhaps few things more immediately engaging to the casual consumer than some of the spectacular images of the cosmos captured by professionals and amateurs using the most advanced telescopes available. Yet even some of the most widely published and distributed images can be poorly understood and explained by professional astronomy organisations.

Astronomy Picture of the Day (APOD) is a NASA website that acts as a portal through which many people who might otherwise not contemplate the universe on its larger scales engage with astronomy. On July 21st, 2008, NASA's 'APOD' was the interacting pair Arp 271 http://apod.nasa.gov/apod/ap080721.html. This image was taken by the Gemini Observatory http://www.gemini.edu/twinspiral. It is this picture that appears in the top right panel of this page.

The caption to the picture reads "*What will become of these galaxies? Spiral galaxies NGC 5426 and NGC 5427 are passing dangerously close to each other, but each is likely to survive this collision*." It is the primary aim of the present study to both test this claim and answer the question: What will become of these galaxies?

The European Southern Observatory (ESA) also maintains a website which includes a "Picture of the Week" section. Among their spectacular images is to be found a picture of Arp 271 taken by the 3.58 m New Technology telescope at the La Silla observatory in Chile. The caption to their photograph, found at http://www.eso.org/public/images/potw1035a/ (see following page) reads, "*It is not certain that this interaction will end in a collision and ultimately a merging of the two galaxies, although the galaxies have already been affected. Together known as Arp 271, this dance will last for tens of millions of years.*"

NASA, the Gemini Observatory and the ESO are in furious agreement upon Arp 271: it is not known what will happen. Will they merge? How long will it take? It is this uncertainty that is the motivation for the present study.

Fortuitously some recent observational work has helped constrain some key parameters integral to

Figure 1:

Arp 271. Credit: European Southern Observatory (ESO). This image taken by the New Technology Telescope, Chile. Even the ESO is unwilling to wager whether or not the interaction "will end in a collision and ultimately a merging of

Pedro Martir in Mexico to take detailed measurements of the velocity and masses of each galaxy. To date, however, this data has not been used to produce any published simulations of this pair.

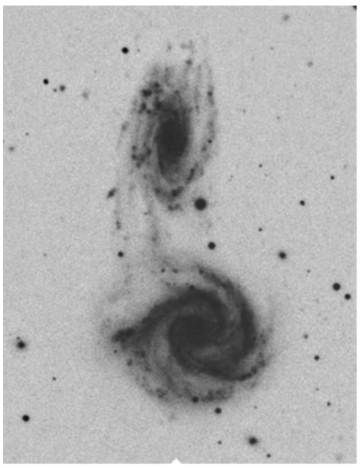


Figure 2: Halton Arp's Original 1966 catalogue image of NGC 5426/27 taken using his 200 inch telescope (credit http://arpgalaxy.com/)

Other studies have been completed on this pair before 2004, most notably by Blackman (1982) whose results sometimes differ from the more recent study.

In this project I will use the data gained by both Blackman and Fuentes-Carrera et al (2004) in order to simulate the interaction between NGC 5426 and NGC 5427. I will determine the effect of the angle of interaction, the total masses of each galaxy, the effect of a more massive halo and also the velocity of interaction.

In the first section of this project I provide a brief overview of the theoretical basis of N-Body simulations of galaxy interactions and the code used for the present study.

In the second section, I provide a summary of the observational limits I am working within and provide some of the calculations I have performed in order to determine the appropriate parameters used within the simulation. The overall ratio of luminous to dark matter (and hence the ratio of halo: disk+bulge) particles is justified as this is not provided directly by Fuentes-Carrera et al (2004). The length scales of each galaxy are derived and estimates for the overall velocity of each galaxy are made and justified.

In the third section I provide the results of varying each of these parameters under various headings including "Angle of Interaction" , "Mass" and "Velocity of Interaction" within the limits either theory of gravity used to make the predictions of this paper is Newtonian and, as explained by Barnes and Hernquist (1992), there are broadly speaking two ways of calculating the potential of N particles undergoing a gravitational interaction; the “action-at-a-distance” or the “field method”. This present study uses an action-at-a-distance N-Body Galaxy Interactions code known as GalactICs (Kuijken & Dubinski, 1995). A common expression for the strength of gravity, Φ, at the location of some particle *i,* is given by:

$$\Phi(\mathbf{r}_i) = -G \sum_{j \neq i} \frac{m_j}{[|\mathbf{r}_i - \mathbf{r}_j|^2 + \varepsilon^2]^{1/2}},$$

Where ε is a softening factor. GalactICs, being a collisionless code, uses a softening factor, (in kpc) of $0.1 \leq \varepsilon \leq 10$ to ensure that the force between particles does not rise without limit as the distance between any two particles approaches zero. Although small ε provides greater accuracy, it is also more computationally expensive.

GalactICs allows a number of parameters to be varied in the construction of a galaxy. Galaxies can be constructed out of up to 3 ‘bulk’ components: the disc, bulge and halo permitting the number of particles in each to be varied from 100 up to a maximum of 3000 in the case of the bulge and 5000 in the case of the disc and halo. Importantly, in a dark matter dominated galaxy, the halo potential well depth, Ψ_0, which is a factor in constraining the overall halo radius, can be set from -3.8 to -5.6. More negative values suggesting a more tightly bound halo and the precise mathematical formulation of which is provided by Kuijken & Dubinski (1995).

GalactICs creates virtual galaxies that are self-gravitating - an improvement over many of the earliest attempts at N-body simulations of interacting pairs. However even without self gravitation, studies involving N-body simulations have been able to demonstrate that galactic morphology such as bridges and tails can be attributed to tidal interactions (Toomre & Toomre, 1972) and thus what we cannot observe in real time can nonetheless be accurately modeled in a simulator.

Barnes and Hernquist (1992) provide strong evidence that the morphologies and features of interacting galaxies created in numerical simulations can be confirmed observationally. This provides a basis for confidence in the output of computational simulations of galaxy interactions.

Of relevance to the present project, the survey by Barnes and Hernquist includes a study of major mergers between systems of comparable mass. They point out that despite N-body simulations being performed as early as 1941 by Holmberg demonstrating the possibility of galaxy mergers occurring, this idea was generally rejected until 1959 when work by Zwicky demonstrated that total mutual capture was possible. Barnes and Hernquist also note that merging which is not too violent “only partly erases the original ordering of material in binding energy; the centers and outskirts of merger remnants remain dominated by particles from the respective centers and outskirts of the victim galaxies. Thus radial population gradients present in the progenitors may well survive the merging process”. It is an ancillary aim of the present project to test for this claim during the interaction of Arp 271.

The simulation of galaxy interactions has improved inline with advances in both hardware and software (for example, self gravity can now be simulated, gas included and the number of particles increased) but the basic principles have been understood since at least 1972 when brothers Alar and Juri Toomre demonstrated that galactic bridges, tails and other morphology found in spiral galaxies were produced by gravitational interactions (Toomre and Toomre, 1972). The theory of tidal interactions between pairs of interacting galaxies is thus well established.

It is under the well established theory embodied in the algorithms which underpin the code which simulates galaxy interactions in GalactICs that I make a prediction about the future evolution and morphology of Arp 271.

The simulations for this project were run upon the Swinburne Centre for Astrophysics and Supercomputing “Green Machine” located in Melbourne and consisting of 145 nodes each comprising of two quad-core 2.33 GHz processors, 16 GB of RAM and two 500 GB Hard Drives (SwinWeb, 2011).

galaxies very great. Blackman observes that 'adjacent halves of the galaxies have been dimmed, apparently by the interaction, contributing only 38% of the total flux". He observes that this phenomena is observed in other interacting pairs (Arp 1966 for example) and might be due to the timescale of the interaction process which may not be long enough to permit the averaging of density of perturbed material and the following star formation.

Parameter	NGC 5426	NGC 5427	Relative Value
Mass ($M_\odot$)	3.5 ± 0.1 x 10^{10}	3.1 ± 0.4 x 10^{10}	NA
Systemic Velocity (km s^{-1})	2516 ± 5	2703 ± 20	187 ± 25
Inclination (°)	59 ± 2	32 ± 2	27 ± 4

Summary of Blackman's Observations

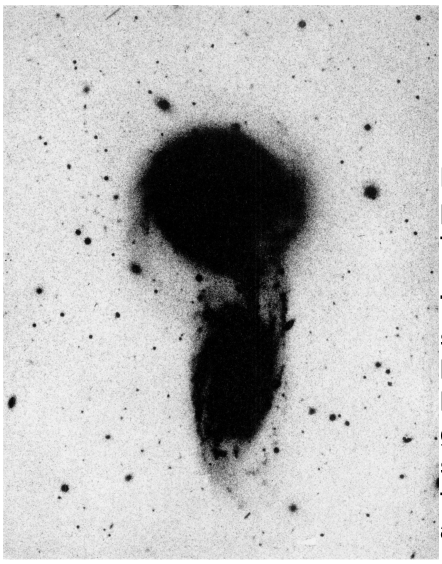


Figure 3: An ultra-high contrast picture of Arp 271 taken from Blackman (1982). This picture shows an obvious bridge of material between the two galaxies that is strong evidence for the interaction already occurring.

Blackman (1982) made observations to the limit of the photometry available at the time, suggesting that NGC 5426 and 5427 had flat rotation curves outside the nucleus but lacked 'massive haloes'. He also inferred that no 'missing mass' is required for them to form a bound system. These conclusions might be an artifact of the era prior to the almost-universal acceptance of dark matter as being the dominant source of gravity in the universe, as more recent studies do suggest massive haloes (see for example Fuentes-Carrera et al, 2004. Fuentes-Carrera et al, apparently in direct response to Blackman state that "The overall rotation curves of these galaxies cannot be considered as flat" (page 464). Blackman for his part had written in the abstract to his paper "Both galaxies have flat rotation curves").

Blackman's masses for NGC 5426 and NGC 5427 are
$3.5 \times 10^{10} M_\odot$ and $2.9 \times 10^{10} M_\odot$ respectively. I present results for simulations run which use some of the parameters determined by Blackman as his masses are substantially lower than the more recent study and provide an opportunity to reduce the potential energy of the system and provide a greater chance to avoid merging. Blackman provides a measurement of the separation of the two galaxies (18.17 kpc) and the difference in the systematic values of the two galaxies (187 km s^{-1}) to come up with an estimation of the time scale of the interaction (10^8 years). This is under the assumption that there are no major additional components to the velocity of the interaction other than this difference between the systematic velocities. This predicted timescale is tested throughout simulations in the present project.

Overview of observations by Fuentes-Carrera et al (2004)

Fuentes-Carrera et al made Hα observations of Arp 271 using 'PUMA' - a scanning Fabry-Perot interferometer - and constrained a variety of parameters for the pair including masses, rotation curves and kinematics. To date these observations are the most comprehensive to be found in the literature for NGC 5426 and NGC 5427. Their analysis includes evidence for the interaction taking place - importantly "a bridge-like feature between both galaxies" in addition to a 'small bar-like structure' in NGC 5426 and a distorted velocity field for NGC 5427. The rotation curves were determined by Fuentes-Carrera et al for both galaxies and moreover the orbital masses derived "from the relative motion of the participants". It is their analysis which allows them to produce a possible 3D scenario for the interaction and this, coupled with my own calculations, provides the impetus for the present study.

Fuentes-Carrera et al (2004) note that NGC 5426 and NGC 5427 have the same morphological type, I turn now to a more detailed analysis justifying the choice of parameters used as input for this GalactICs simulation.

Velocity Considerations

My goal is to model the interaction between NGC 5426 and NGC 5427 by using the best available observational data. Mainly that is drawn from the Fuentes-Carrera et al (2004) study. I am going to vary the velocity of the interaction within reasonable limits to determine if an interaction is likely to occur and under what conditions it will not.

Fuentes-Carrera et al (2004) determined that the systematic velocity of NGC 5426 is 2575 ± 3 km s^{-1}. For NGC 5427, the systemic velocity is 2722.5 ± 1 km s^{-1}. This means that the relative velocity of NGC 5427 with respect to NGC 5426 is 147.5 ± 4 km s^{-1}. These velocities, along with the velocities of other regions (most especially the approaching and receding spiral arms in each galaxy) are determined through the measurement of radial velocity fields from the redshift of the Hα lines.

The systemic velocity is along the line of sight and so is the velocity in one dimension, however there are hints that this is the most significant component of the relative velocity between the two members of this pair. If there was a significant component of velocity for either galaxy in other dimensions, we would likely see evidence of this in the distortion of the galaxies.

At least two other studies also provide information on velocity for this pair, with Blackman (1982) providing the greatest difference from Fuentes-Carrera et al (2004). His values for the systematics velocities of NGC 5426 and NGC 5427 are 2516 km s^{-1} and 2703 km s^{-1} respectively with larger absolute errors. This gives 187 km s^{-1} as his relative velocity between the two galaxies.

Fuentes-Carrera et al argue that the tilt and spin of the galaxies "as well as the position of one with respect to the other" coupled with "The fact that NGC 5427 is a two-arm grand spiral suggests the encounter with NGC 5426 is a direct one." As Fuentes-Carrera et al rightly point out, features of Arp 271 like the bridge between them is exactly what is predicted by Toomre & Toomre (1972) of a flat direct parabolic passage of a companion of equal mass (see below). Fuentes-Carrera suggest that "this first analysis can help as a starting point for future numerical simulations of this particular encounter."

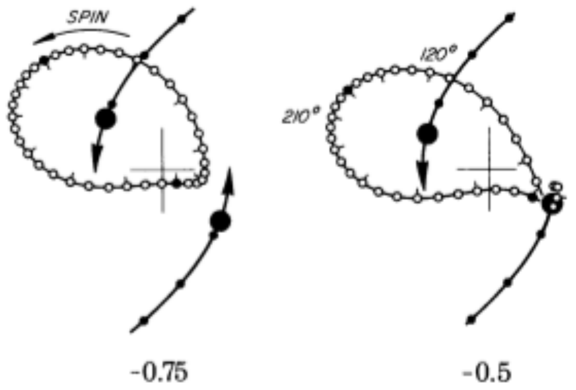


Figure 4: Taken from Toomre & Toomre's (1972) figure 3 in which a companion of equal mass makes a direct parabolic passage. The elongation presented here in the -0.5 frame (0.5 x 10^8 years before perigalactic instant) resembles the bridge of material between the galaxies in Arp 271.

Indeed it is the fact that the separation between both galaxies (18.17 kpc) and the difference between the systematic velocities already mentioned (147.5 km s^{-1}) to give a timescale (around 10^8 yrs) very similar to that of the Toomre and Toomre simulation that Fuentes-Carrera et al conclude - on the basis of a lack of distortion between the galaxies - that the interaction is not a very strong one. As they say "The fact the systematic velocities differ by almost 150 km s^{-1} and that the galaxies seem to be connected by a bridge of material suggests we are actually measuring an important component of the peculiar velocities between these two galaxies. This relative radial velocity difference might represent a significant component of the total velocity difference." It is in this spirit that the majority of the simulations run for the pair in this project concentrate upon values for the velocity which do not deviate substantially from a total velocity in which 147 km s^{-1} is at least one of the largest components and directed to recreating a parabolic passage. In the simulations to come I report upon variations of the velocity parameters and such that the chosen values for the velocity of galaxy 2 (NGC 5427) with respect to galaxy 1 (NGC 5426) include the following:

- 147 km s^{-1} in one spatial dimension only (for example x) with the others left at 0 km s^{-1}. This

this and the 147 km s^{-1} figure for the difference between the systematic velocities of the two galaxies would cease to be one of the “significant” components of the overall velocity.

For completion I also present the results of simulations designed to determine exactly what *minimum* velocity would be required for a direct hit between NGC 5426 and NGC 5427 to result in no merger.

A note on the positions chosen for each galaxy

Fuentes-Carrera et al (2004) provide justification of the distances used in this project. They agree with Blackman (1972) that the reduced luminosity (lack of emission) on adjacent halves of the galaxies was due in large part to “obscuration of dust in NGC 5426’s disk whose inclination is larger than that of NGC 5427’s. This would imply NGC 5426 is in front of NGC 5427.” The figure provided by both Blackman (1972) and Fuentes-Carrera et al is 18.17 kpc as the separation between the galaxies. As this is the current separation and NGC 5427 is closing in on NGC 5427 we can extrapolate back and infer greater separation in the past. Although some simulations have been run with a separation of only 18 kpc, the interaction has already begun at this distance in reality. That it has not begun in the simulator means there is a disconnect between reality and simulation and so for this reason, the distances chosen are significantly different to a separation of only18 kpc. In many simulations, the original distance chosen has been between approximately 30 kpc to 100 kpc in all 3 spatial dimensions to ensure that by the time the galaxies have closed in to a distance of 18 kpc the interaction has already begun and appears as close to what we see Arp 271 as in our epoch with the general principle that the passage should be parabolic of the type suggested by Toomre and Toomre (1972) for a companion of equal mass. As Fuentes-Carrera et al suggest: this is the most likely scenario given the bridge of material that exists between NGC 5426 and NGC 5427. In summary: because the two galaxies are separated by a distance of around 18 kpc and the radius of each galaxy is around 5.5 kpc, the total distance between their nuclei is approximately 30 kpc. However, in some of the simulations that follow I have chosen a separation greater than this (and up to around 100 kpc) for two reasons:

1. The interaction has a history. By beginning the simulation up to 1 Gyr (but in most cases around 0.2 Gyr) before the present day, I can test the validity of the chosen parameters. If, after 1 Gyr I get an interaction roughly similar to the situation we now observe in Arp 271, there is more reason to trust that the subsequent evolution of the pair will more faithfully represent reality.
2. The fixed orientation of galaxy 1 (NGC 5426) that GalactICs imposes upon the simulation means that some features can be obscured when both galaxies begin in close proximity. A greater initial separation helps permit the formation of (and subsequently reveal) tidal structures such as tails, bridges and flow.

Mass Considerations

Fuentes-Carrera et al (2004) find a mass of 11.2 × 10^{10} M⊙ for NGC 5426 and 7.5 × 10^{10} M⊙ for NGC 5427. These figures differ substantially from Blackman’s 1982 figures of 3.39 × 10^{10} M⊙ and 3.1 × 10^{10} M⊙ respectively. These differences are due in large part to the different rotation curves the two papers derived. Blackman concluded there was no massive halo yet Fuentes-Carrera et al did find a massive halo. Fuentes-Carrera et al state that Blackman’s curve was in error as he did not fully account for the inclination of the disc of the galaxies. In the case of NGC 5426 they say “We had to correct Blackman’s curve by the inclination of the disk in order to superpose both curves”.

It is worth a brief note of explanation here as to how the masses of each galaxy are calculated by Fuentes-Carrera et al. They use a method proposed by Leqeux (1983) where two extreme cases are considered: the first that the galaxy is a flat rotating disc where the mass inside some radius is given by

$$M(R) = 0.6 \times \frac{RV^2(R)}{G}$$

$$M(R) = \frac{RV^2(R)}{G}$$

and the second is to consider that the galaxy is spherical where the mass inside the radius is given by

For real galaxies the mass should always lie between these two extremes and the more massive the halo

$$M_{orbital} = \frac{32}{3\pi}\left(\frac{\Delta V^2 \times X_{12}}{G}\right)$$

Here ΔV = the difference between the systematic velocities of the galaxies, X_{12} = the projected separation from one nucleus to the other, G is the gravitational constant. This formula they take from Karachentsev and Mineva (1984) and they find a total orbital mass of Arp 271 of $3.01 \times 10^{11} M_{\odot}$. As the sum of NGC 5426 + NGC 5427 comes to $1.87 \times 10^{11} M_{\odot}$ we find that the actual value is quite lower. Fuentes-Carrera et al explain that this is because the lower mass limit for a parabolic orbit is smaller than 1/3 of this value. That the combined masses were not *above* this estimate from orbital considerations is good evidence in favor of the accuracy of their numbers.

As we now have in hand values for the total mass of each galaxy and high confidence that the errors are small, we must now determine how the mass is distributed throughout each galaxy. As GalactICs allows for a 3 component galaxy to be created - I need relative proportions for the bulge, disk and halo. Although Fuentes-Carrera do provide their own method and subsequent results for the mass-to-light ratio, I provide here my own calculation and estimate based upon the Tully-Fisher relationship.

The Tully-Fisher relationship relates the luminosity of a spiral galaxy to its maximum rotation velocity. The precise form of the Tully-Fisher depends upon the type of galaxy. Now as Fuentes Carrera et al report, both galaxies in Arp 271 are of morphological type Sa to first approximation.

According to Carroll and Ostlie (2007) this means that

$$M_B = -9.95 \log_{10} V_{max} + 3.15$$

$$M = M_{Sun} - 2.5\log_{10}\left(\frac{L}{L_{Sun}}\right)$$

$$-20.567 = 4.74 - 2.5\log_{10}\left(\frac{L}{3.839\times10^{26}}\right)$$

$$i.e: L = 5.09\times10^{36} W$$

Using the Fuentes-Carerra et al value of V_{max} = 209 km/s for NGC 5426 I get a theoretical value for M_B as -19.94 in good agreement with observation of -20.567.

Using the observed value of M_B = -20.567 I can use:

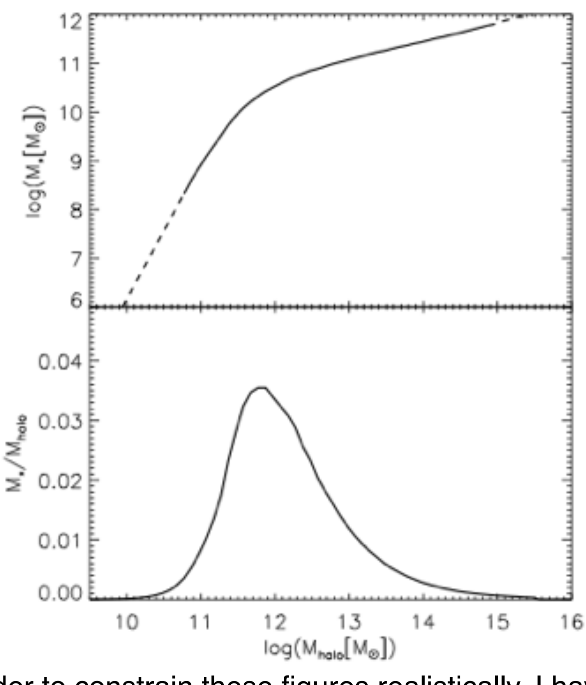
$$\frac{M}{L} = \frac{11.2\times10^{10}}{1.33\times10^{10}} = 8.45$$

If each star has a luminosity of approximately $L_{\odot}$ then I find that:

Fuentes-Carrera et al compute a value of 11.15 using a “maximum disc and pseudo-isothermal sphere for the dark halo.”

These are the upper limits I use for determining the ratio of particles in GalactICs.

It is now clear that the majority of the mass in any galaxy is in a form other than luminous material. Indeed much of the mass can be found in the halo around a spiral galaxy extending out up to a factor of 10 beyond the disc radius. GalactICs permits a number of parameters of importance to the mass of a galaxy to be varied. These include the number of bulge, disc and halo particles as well as the disc mass factor and the halo potential well depth. In



order to constrain these figures realistically, I have used the Milky Way as a model - both NGC 5426 and NGC 5427 are grand spirals and though smaller than the Milky Way will have similar properties - and consulted work by Guo et al (2011) in order to constrain the size and depth of the halo. Guo et al (2011) combines a statistical analysis of the Millenium Simulation (I and II) and compares

Table 1

Galaxy Inputs											
Row	B	D	M	H	Ψ	L (6/7)	x,y,z	v(x)	Θ	5426	5427
1	500	1000	0.6	5000	-5.6	2.45/2	100	-147	25	1.12	0.75
2	500	2000	0.6	3000	-5	**1.2**	17.5	-147	25	1.12	0.75
3	500	1000	0.6	**5000**	-5.6	2.45/2	50	-147	**19**	1.12	0.75
4	500	1000	0.6	5000	-5.6	2.45/2	50	-147	**31**	1.12	0.75
5	500	1000	0.6	5000	-4.8	2.45/2	50	-147	25	0.39	0.31

B = Bulge Particles
D = Disc Particles
M = Disc Mass Factor
H = Halo Particles
Ψ = Halo potential well depth
L = Length Scale (of NGC542**6**/NGC542**7** respectively)

Note that NGC 5426 and NGC 5427 are twin galaxies and it is reasonable to assume that the numbers of particles and length scales are roughly identical for both. Masses are slightly different as indicated in the final two columns.

The table above provides a selection of the key parameters involved in the simulation of Arp 271. Although this is by no means a comprehensive list of the simulations performed, it is provided here as an overview of the most fruitful simulations and, importantly those discussed in this paper.

Using a total mass of $\log(M_{halo}) = 11.2$ for NGC 5426, I find that Guo et al determine that the fraction of luminous matter in a galaxy of this size is very close to 0.015 (see below).

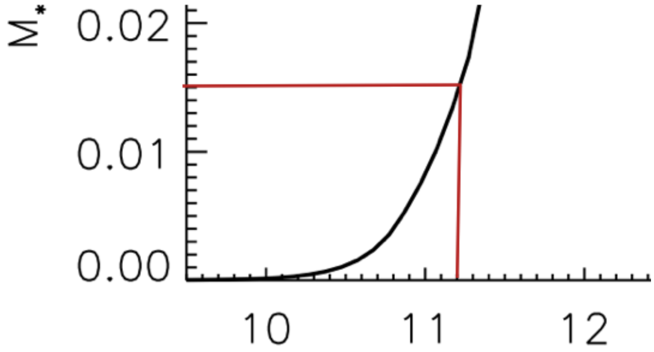


Figure 6: For a halo mass of 11.2, the mass of stars as a function of the halo mass is approximately 0.015.

That is, 1.5% of the total mass of NGC 5426 consists of stars. Such a small number justifies the largest possible halo with the deepest possible gravitational potential well.

In many of the simulations to follow the most common set of inputs therefore which realistically modeled the masses and mass distributions of each galaxy are those found in table 1 (as entered into GalactICs). The disc mass factor is set to 0.6 while the halo potential well depth is set to a maximum of -5.6. This means that although the number of "stars" in the disc and bulge are more than 1.5% of the total *number* of particles, the overall *mass* contribution of the halo to the interaction is much closer to that expected given the Guo et al (2011) figure above.

Masses were explored with a number of extremes and some median values and results are presented which consider a slow passage, a medium velocity passage and a fast passage representing the minimum velocity required in order for NGC 5427 to 'escape' the gravitational well and not merge with NGC 5426.

These simulations are carried out under the assumption that the cold dark matter paradigm is true - that the largest contribution to the mass of each galaxy being simulated here is dark matter. Guo et al and Xue et al provides evidence for a 100:1 ratio of dark to luminous matter for the Milky Way and for smaller galaxies.

As we will now see, given their masses and lengths, NGC 5426 and NGC 5427 are small galaxies by the standards of the Milky Way..

Length Scale Considerations

$M = \frac{V_{\max}^2 R}{G}$ The mass contained within some radius for a galaxy is given by a formula which if evaluated for an entire galaxy of radius R, (assuming spherical symmetry) becomes:

I thought it instructive to use this formula to calculate "R" for both galaxies and thus constrain the

$$11.2 \times 10^{10} \times 1.99 \times 10^{30} = \frac{(209 \times 10^3)^2 \times R}{6.673 \times 10^{-11}}$$

$$\therefore R = 3.4 \times 10^{20} m = 11019 pc = 2.45 \times 4.5 kpc$$

length scales of both galaxies (something I had not accomplished before!)

$$7.5 \times 10^{10} \times 1.99 \times 10^{30} = \frac{(172 \times 10^3)^2 \times R}{6.673 \times 10^{-11}}$$

$$\therefore R = 3.36 \times 10^{20} m = 10894 pc = 2.42 \times 4.5 kpc$$

Hence, using data from Fuentes-Carrera et al, I get:

NGC5426: in the 4.5 kpc are the units required by the simulator.

NGC 5427:

Which means both galaxies are very close in size to each other. Again these numbers are placed into table 2 and are the numbers used in 'Merge Galaxies'.

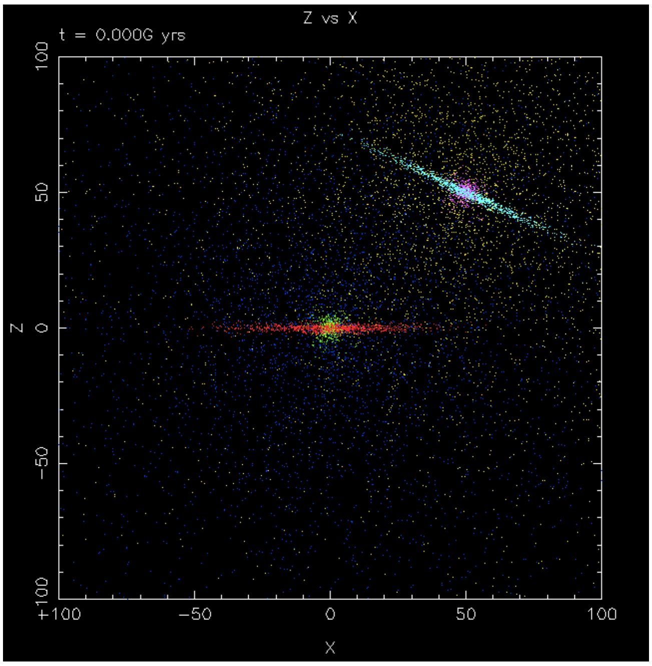
Angular Considerations

Fuentes-Carrera et al (2004) find that the inclination of NGC 5426 is (59 ± 3)° and NGC 5427 is (34 ± 2.5)°. This provides for a relative inclination of NGC 5427 with respect to NGC 5426 of (25 ± 5.5)°. I report upon the resulting morphology for cases where the angle of inclination is varied from a minimum of 19° through

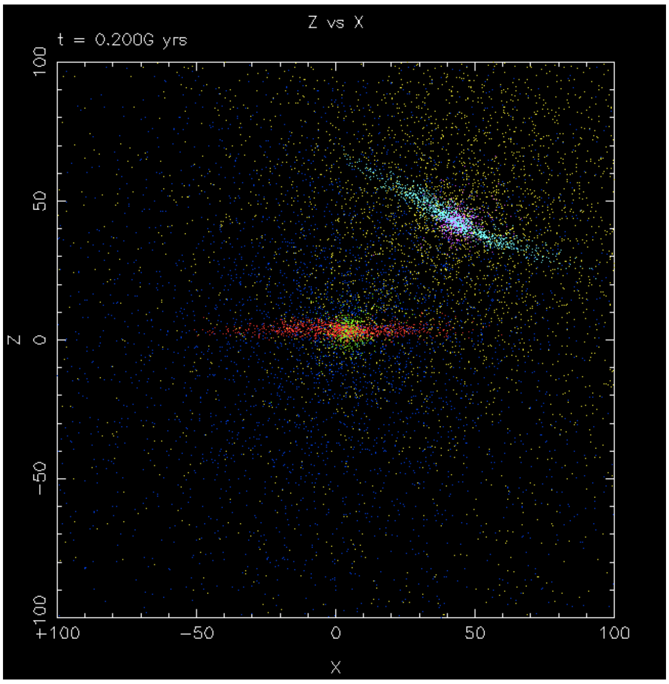
Results

Case of Low Velocity Interaction

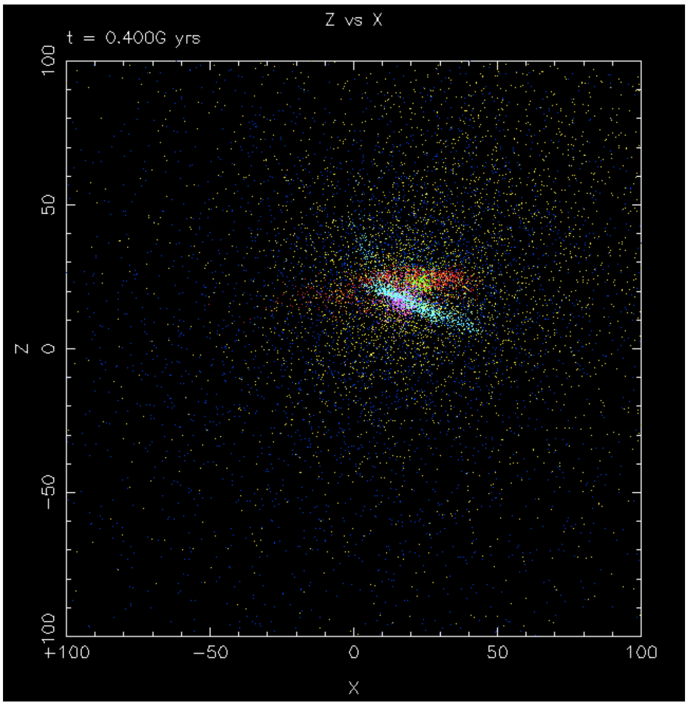
Here I consider the case where the velocity of the interaction between NGC 5426 and NGC 5427 occurs at a relative speed of 147 km s^{-1} in the x-direction only. This is, to use Toomre & Toomre's terminology, a 'parabolic passage of an equal mass companion'. As stated previously, this is, according to Fuentes-Carrera the most likely scenario for the interaction. I begin the simulation at around 200 Myr before the present day. This means that at t = 0.2



Gyr in the following simulation, we should have evidence of the interaction beginning and we do.



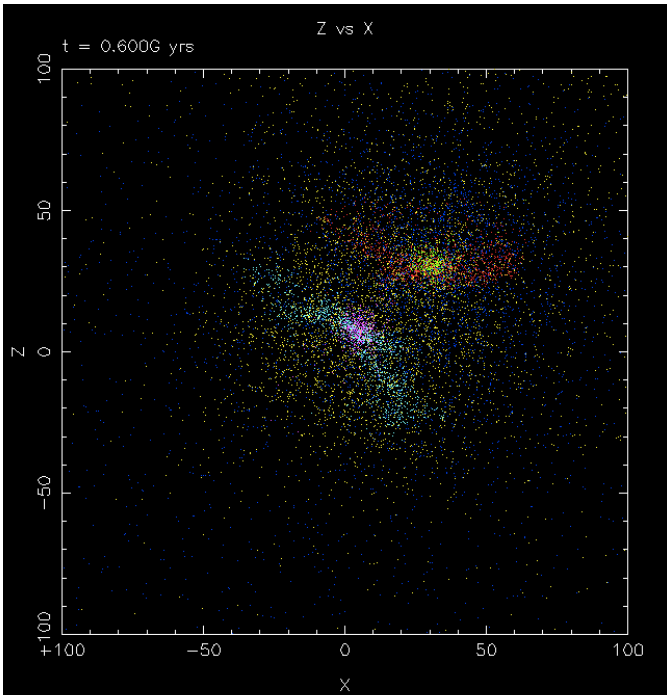
At t = 0.2 Gyr, evidence of the disc of NGC 5427



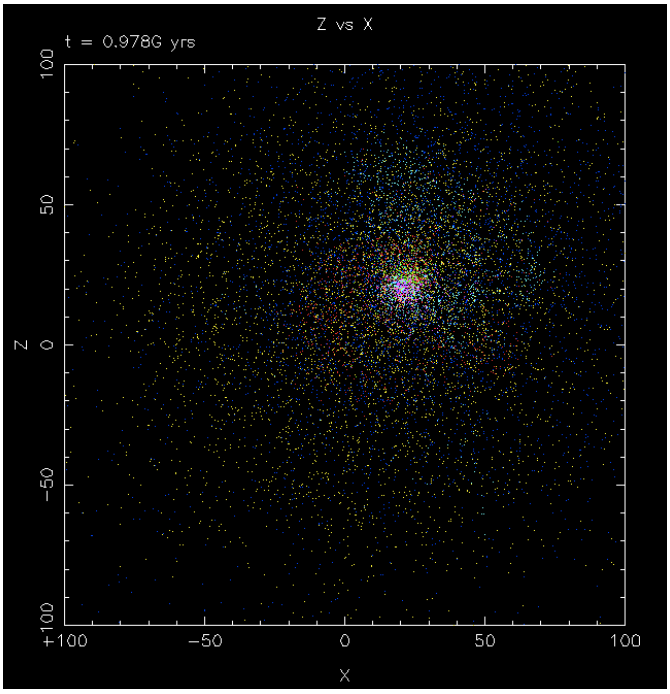
(represented by the blue galaxy here) beginning to undergo some distortion. This is the situation we find Arp 271 in at the present day.

The galaxies pass by each other at t = 0.4 Gyr suffering obvious tidal disruption to all components

And after 200 Million more years their bulge and disc, although still intact, have undergone severe disruption.

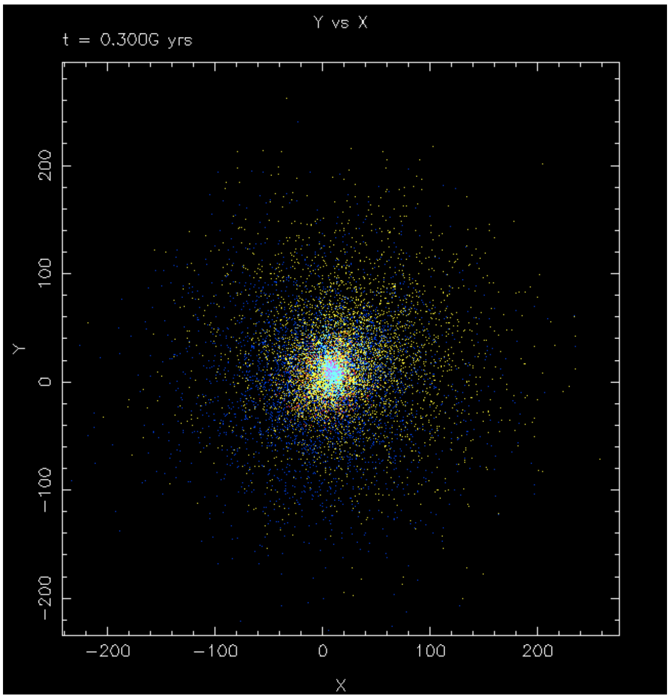


However the eventual result is a merging of the nuclei and this occurs before 1.0 Gyr has passed.



My conclusion here is that given the most reasonable assumptions about the masses of each galaxy involved: for a parabolic passage of 147 km s^{-1} (in galactics this is the case where x, y, z = -147, 0, 0) I find that a merger is inevitable. All similar simulations carried out at velocities up to triple this value (i.e: -147, -150, -150) likewise result in a merger.

The result of colliding the galaxies head-on with velocity components of (vx, vy, vz) = (-85, -85, -85) such that the vector sum of the total velocity was the required 147 km s^{-1} likewise results in a swift merger. In the x-y plot below it is clear that the nuclei have merged sooner than 0.3 Gyr.



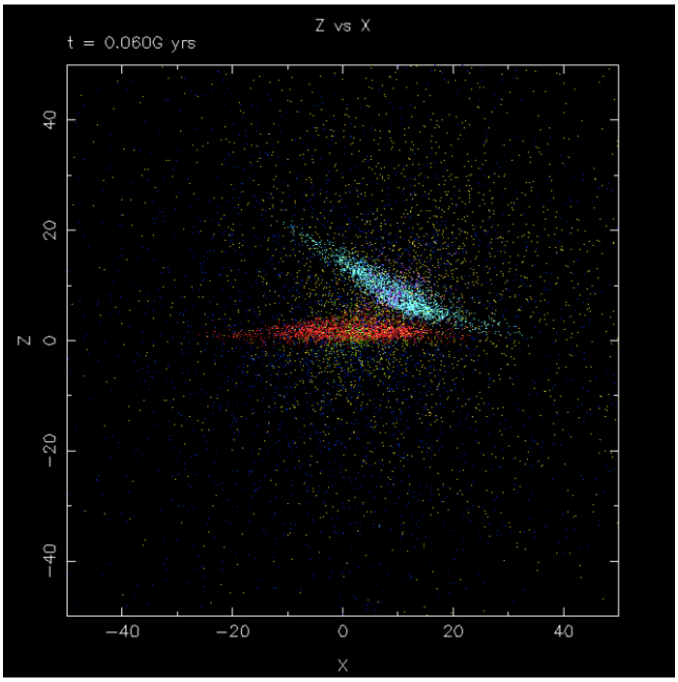
From this it is reasonable to conclude that if the velocity vectors are directed towards a direct hit rather than a parabolic passage this serves only to accelerate the rate at which a merging will occur.

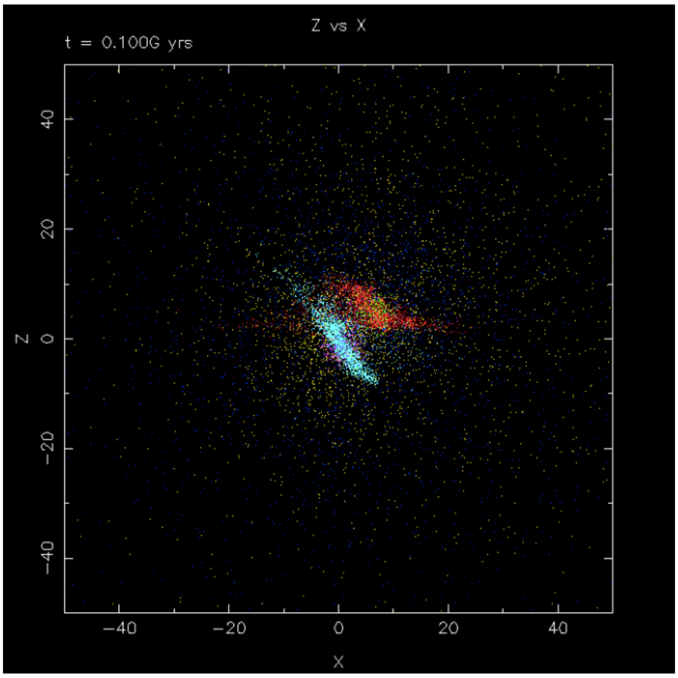
Case of Medium Velocity Result

For the purpose of this study I define a medium velocity of interaction as one in which the 147 km s^{-1} relative systematic velocity is just one third of the total relative velocity between NGC 5426 and NGC 5427.

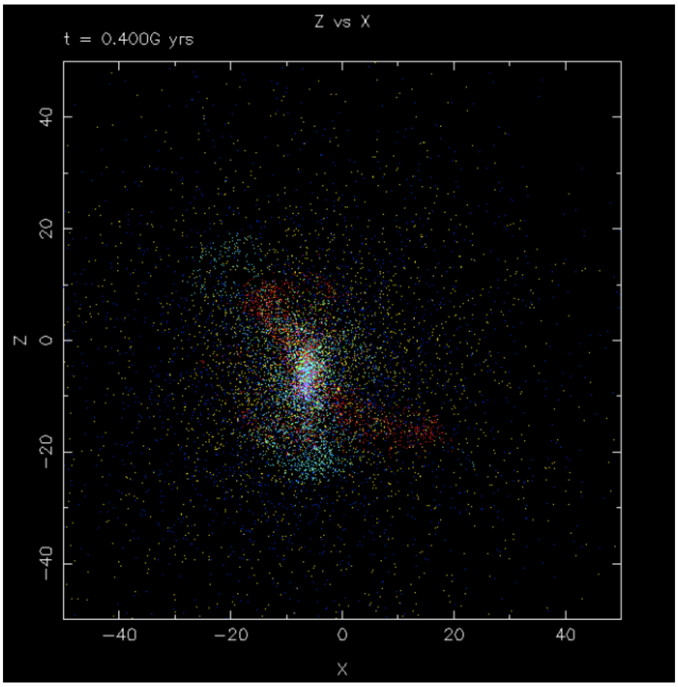
As expected, at a higher velocity the distortion begins much more quickly...

At t = 0.06 Gyr, there is obvious distortion of both galaxies



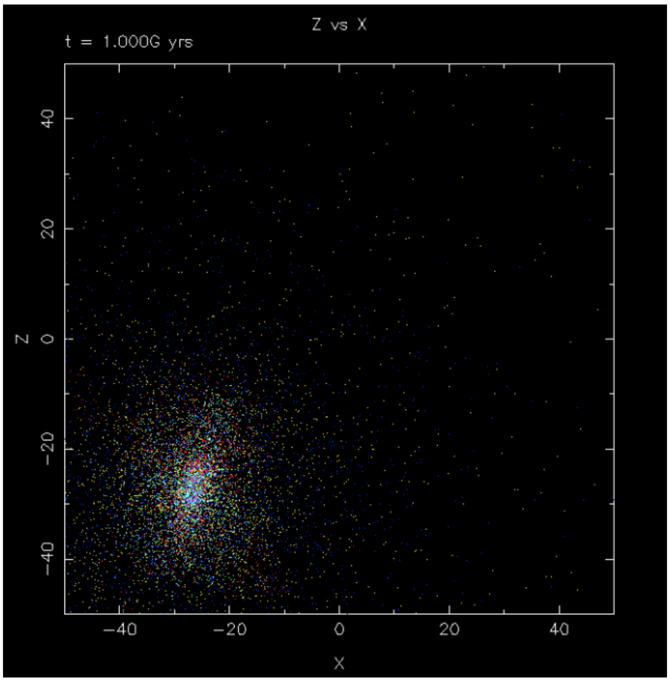


At 0.1 Gyr, both galaxies lose most of their disc-bulge integrity and the merging of their nuclei has begun:

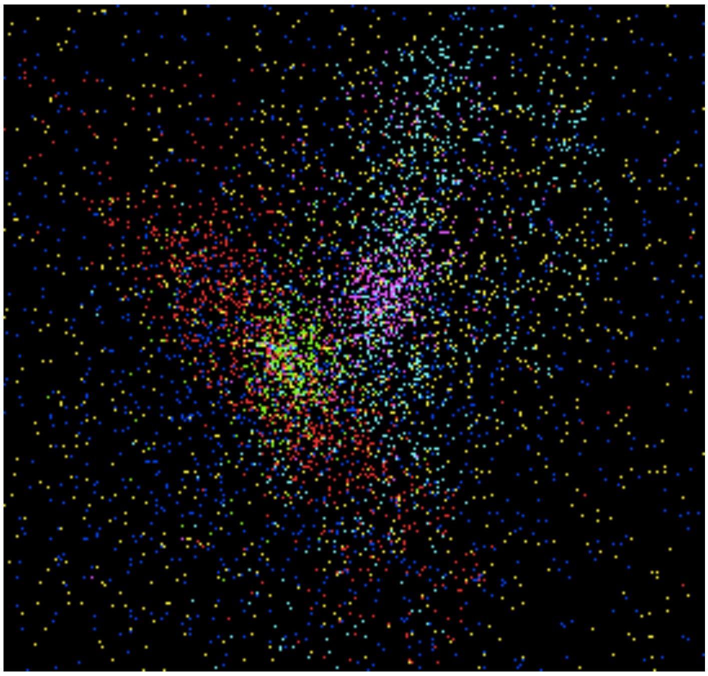


Evidence of tails and bridges can be seen over the

By 1.0 Gyr, the process of merging is once again complete and the morphology viewed from any angle is that of a large elliptical with few if any remaining traces of arms, bridges, bars or tails. This confirms the prediction by Blackman (1982) that the timescale for the interaction is on the order of 10^8 years.



It might also be noted here that we can visually confirm the claim of Barnes and Hernquist (1992) that particles near the core and edge of each galaxy (namely particles in the bulge and disc) remain near the core and edge respectively even after the interaction. The following sequence more clearly shows how purple bulge particles of NGC 5426 and green bulge particles of NGC 5427 predominate the core of the resulting merged galaxy.



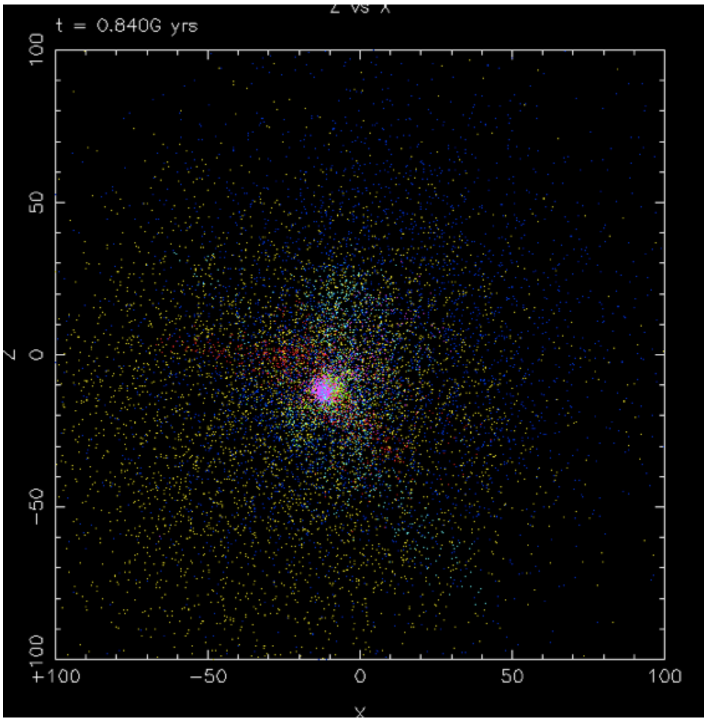
We see below in a zoomed frame that although the distortion of both galaxies is well underway, the cores remain relatively tightly bound.

Subsequently (this frame is from t = 0.78 Gyr - the merger is complete at 1.0 Gyr) we find that there has been an almost complete merging of the green and purple bulge particles while the vast bulk of the red disk particles of NGC 5426 predominate towards the extremities.

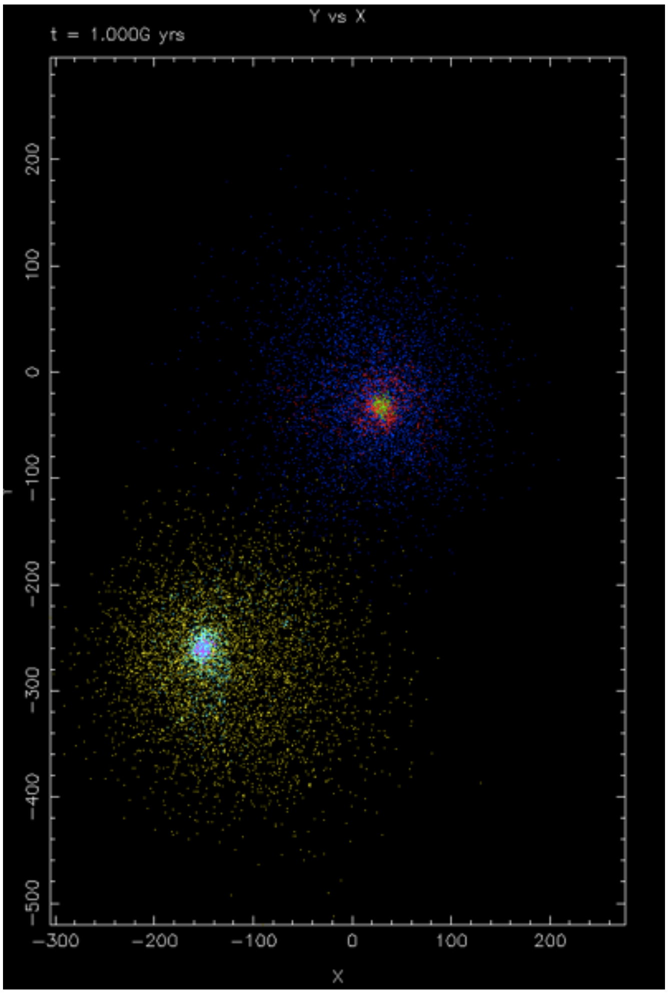
High Velocity Result

In this section I seek to determine the minimum velocity at which a merger will not take place due to the kinetic energy of the interaction exceeding the potential energy which binds the galaxies together. Much trial and error testing was required in order to narrow down the values for the velocity components. I provide here results for the rather broad range of 250 km s^{-1} in the y and z dimensions.

The image below shows the result of velocities in the directions (x,y,z) = (-147, -250, -250) it takes only a little longer for the merger to occur. In this example I check the simulation with two runs over shorter timeframes with smaller softening factors (ε = 0.5 and ε = 0.1 - the minimum possible softening factor).



Using these values produced results which were indistinguishable from the ε = 1.0 case.

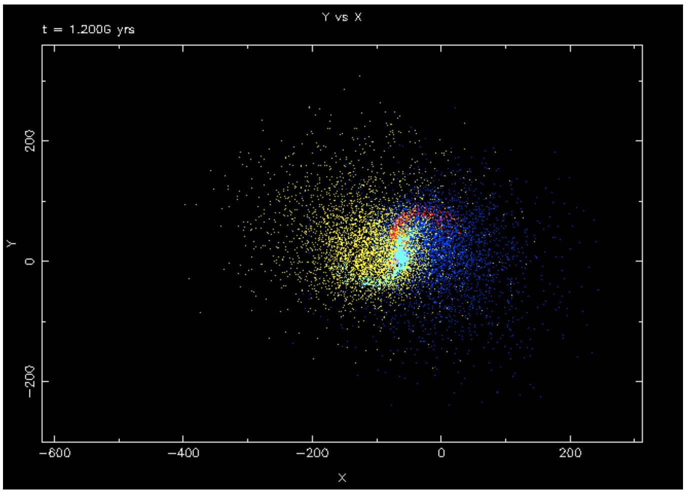


Increasing the velocity to (x,y,z) = (-147, -350, -350) provides the system with sufficient Kinetic Energy to ensure there is no merger. The two galaxies below begin with the same initial conditions as previous experiments but never come back together.

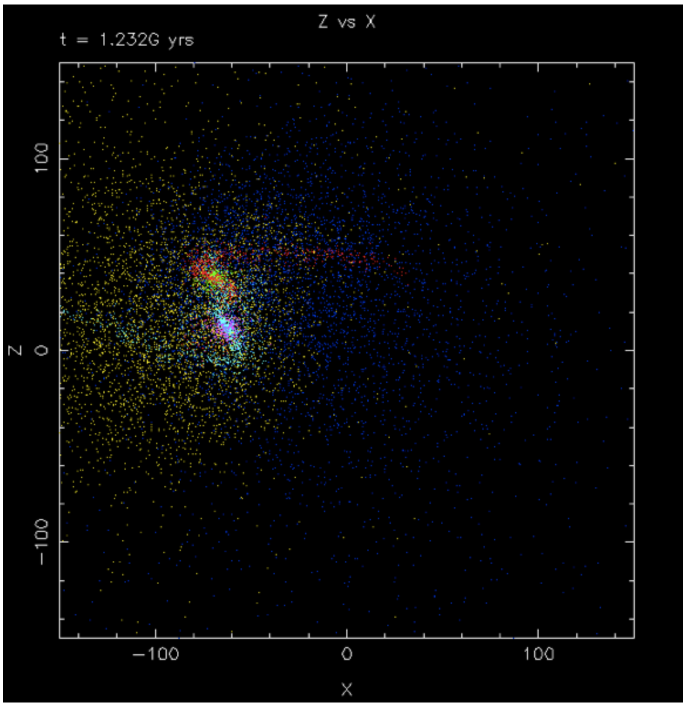
At approximately (-147, 300, 300) the situation is more complex. Here at t = 1.0 Gyr, the scene is much the same as it is above, however NGC 5426 trails NGC 5427 and follows it off screen even after 10 Gyr have passed. This suggests that at velocities very close to this, the system is bound but perhaps unlikely

Results for Mass

Given that Fuentes-Carrera et al (2004) quote a negligible error, scope to vary the masses of either galaxy are restricted. I do however report results for simulations of a parabolic passage using values for mass given by Blackman (1982). The parameters are found in row 5 of table 1. Although Fuentes-Carrera et al claim these are in error, it was instructive to use these values in order to establish that even with lower masses, the kinetic energy of the interaction is insufficient to allow this system to climb out of its potential well. The system is bound and a merger still results as shown below although the time taken for the nuclei to merge takes much longer (around a factor of 3 longer). Perhaps worthy of note is the more spectacular formation of barred spiral structure at these lower masses.



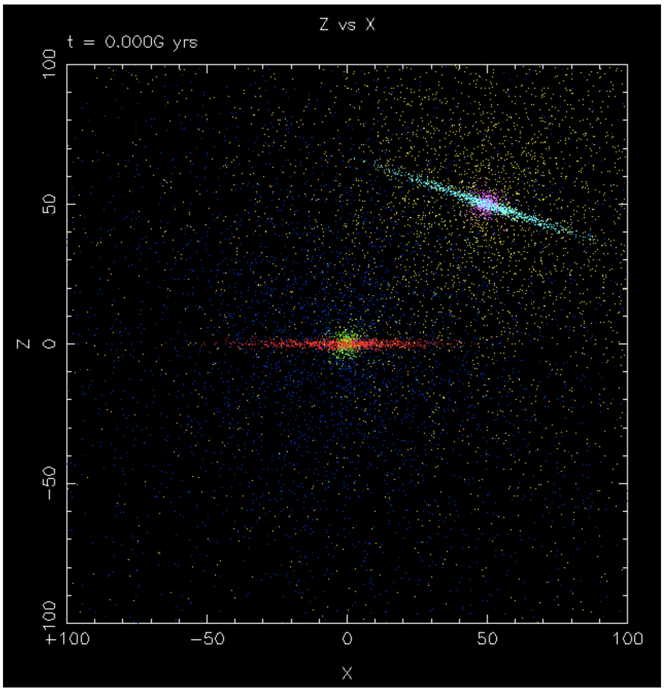
In x and y we see the bar forming



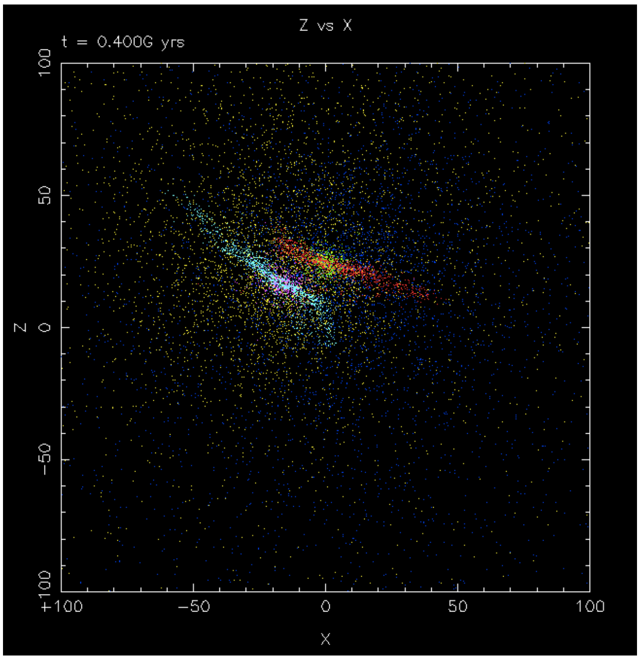
And in the following figure (x vs z plot and zoomed) we see long tails trailing both galaxies.

Results for Angle of Interaction

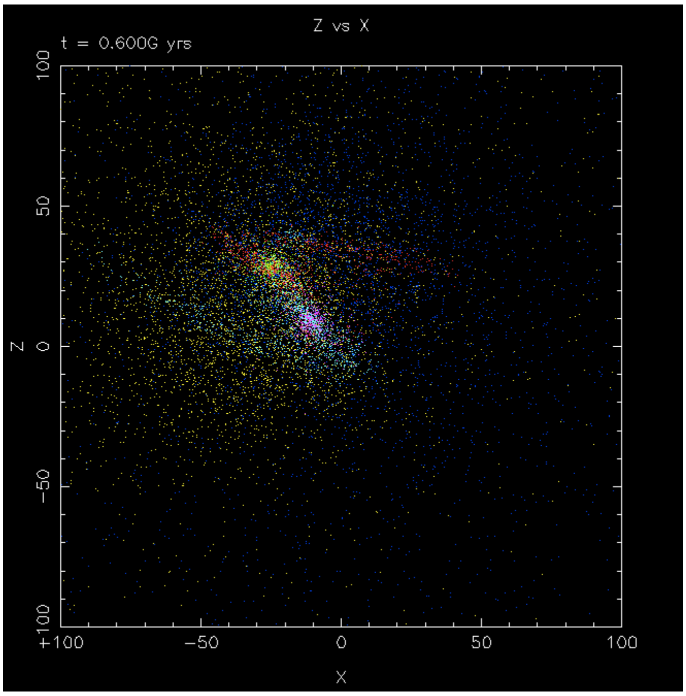
The angle of the interaction has no bearing on whether the system ultimately merges or not. I present here results on the extremes of the angle of interaction. The input parameters are found in rows 3 and 4 of table 1. Most interactions discussed so far occur when the angle is set to 25°, but the two simulations below are for the cases where the angle is equal to 19° and 31° respectively. The resulting morphology is similar but the location of bridges and tails shifts.



This is the initial set-up at 19 degrees.

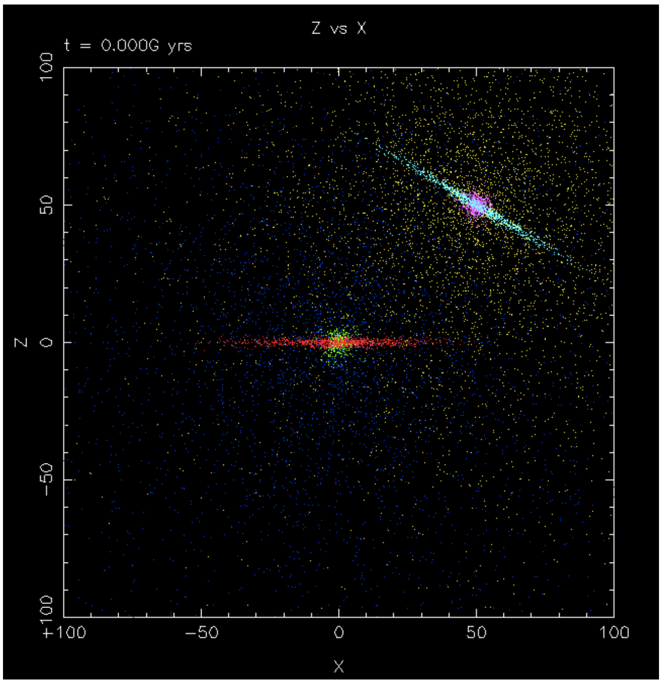


After 0.4 Gyr, the galaxies transit each other

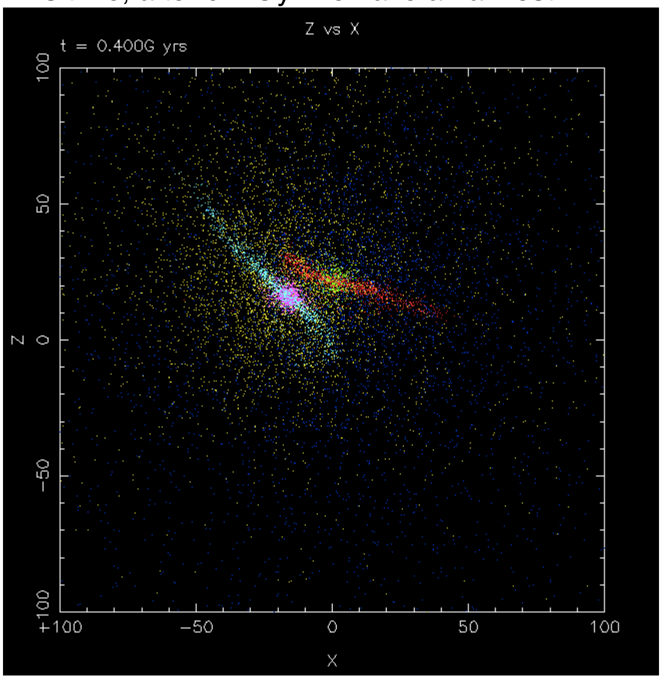


At t = 0.6 Gyr the nuclei are engaged in an orbit around a common centre of mass forming a bar like structure where material is flowing between them prior to their eventual merging which is complete by

For the case of 31 degrees initially we have:

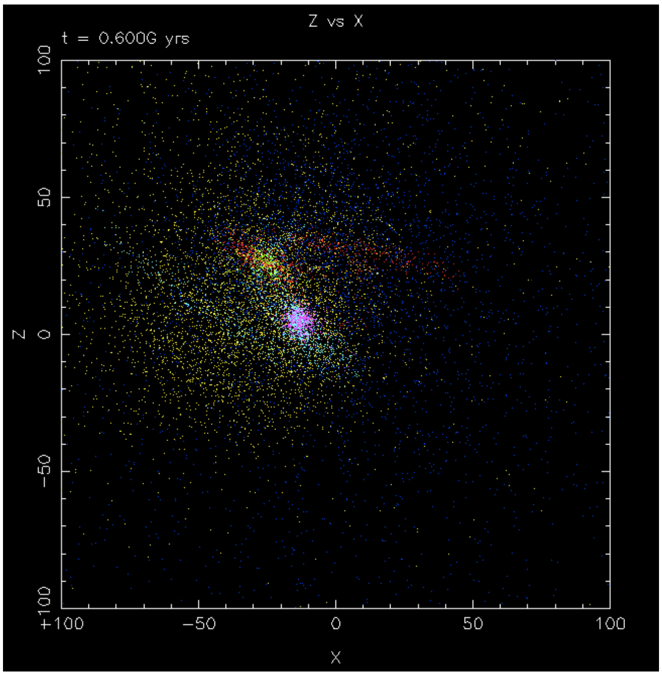


This time, after 0.4 Gyr we have an almost

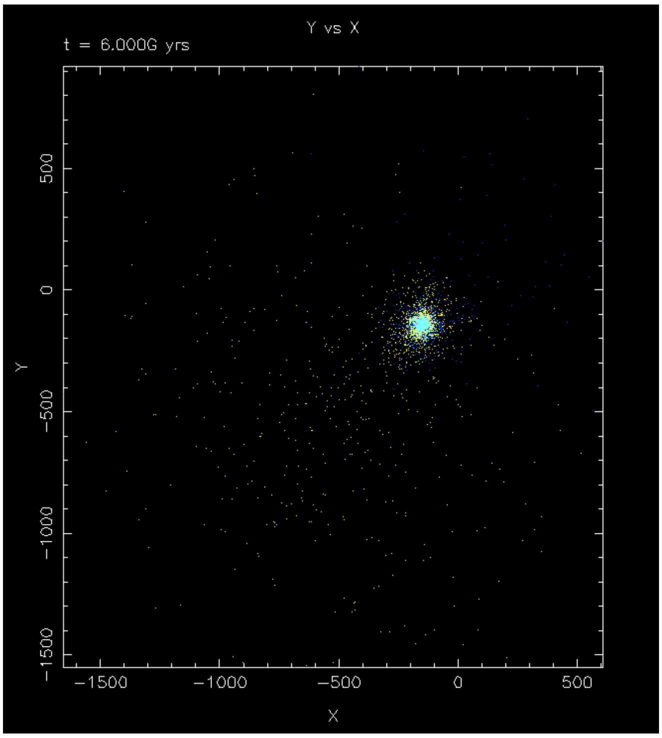


identical interaction

After 0.6 Gyr, again the morphology is very similar to the 19 degree case except that the orientation of the resultant is a little more oblique.



The final result is the same, however with a giant elliptical once again forming. The giant elliptical in the majority of the simulations looks the same (the image below is at t = 6.0 Gyr). The radius of the



most dense region is approximately 50 kpc.

Summary and Discussion

I have provided in this project the results of a series of simulations modeling the interaction between NGC 5426 and NGC 5427 otherwise known as Arp 271 in order to predict whether these galaxies will merge, or not, and when and what the resulting morphology will be. The impetus for this was two fold: firstly Arp 271 is a 'pin-up' galaxy used by popular astronomy websites such as NASA's 'Picture of the Day' and the European Southern Observatory's "Picture of the Week". In both cases, rather unusually, there was agreement about exactly what the fate of Arp 271 was to be. Fortuitously, a comprehensive observational study was completed in 2004 by Fuentes-Carrera et al ostensibly in part for the purpose of providing the data required to model the interaction. To date, there are no published simulations of this pair and it seems the community is still unsure what the fate of Arp 271 will be. This project fills this space with a number of simulations using that data.

Over the course of this project to model the interaction between NGC 5426 and NGC 5427, a broad range of the capacity of GalactICs to simulate the scenario was performed. Early attempts which had a relatively high softening factor ($2 < \varepsilon < 10$) and small number of particles (<1000 in the halo) produced an elliptical galaxy as a consequence of the merger. Many long (10 Gyr) runs were performed which confirmed that the elliptical formed was stable and lacked spiral structure or any obvious trace of the original disc and bulge. The fact we live at an epoch where Arp 271 is in the very early stages of its interaction means we witness a particularly beautiful scene. It may be less aesthetically pleasing that the second law of thermodynamics destroys the rich structure of the twin grand spirals leaving behind a rather featureless - if massive - giant elliptical.

The most robust of the simulations reported on here reduced the softening factor ε to the lowest value permitted by GalactICs producing the same result: a merging of the spirals on the order of 1 Gyr, into an elliptical. The spirals do pass through phases of barred-spiral morphology at around 0.4 - 0.6 Gyr. We must also recognize that even though ε is small, it is still non zero and this introduces a non-zero error into the simulation.

However, given theoretical considerations we can be confident that the kinetic energy of the interaction between NGC 5426 and NGC 5427 is insufficient to exceed the potential energy binding these two

Conclusions

All observational values and therefore chosen values - even at the absolute extremes for mass and velocity show that NGC 5426 and NGC 5427 will eventually merge. The sequence of events leading to an eventual elliptical "super galaxy" will likely produce the formation of tidal bridges and tails in a manner consistent with what Toomre and Toomre first found in 1972 for galaxies of similar mass undergoing direct parabolic passage. As shown, the merging is complete at 1.0 Gyr after our present epoch.

I return to the start of this project with NASA's APOD question where the caption reads, "What will become of these galaxies? Spiral galaxies NGC 5426 and NGC 5427 are passing dangerously close to each other, but each is likely to survive this collision." and can now respond that this is clearly incorrect.

The galaxies will not "survive" this collision in the sense that their spiral structure will be preserved. Simulation of this interaction demonstrates that the discs and bulges will be destroyed. What will become of them is that they will merge into a giant elliptical.

I also quote the European Southern Observatory at the beginning of this paper where they state, "It is not certain that this interaction will end in a collision and ultimately a merging of the two galaxies, although the galaxies have already been affected. Together known as Arp 271, this dance will last for tens of millions of years."

As ever in science we cannot provide certainty - but within the boundaries of what is known and constrained by our best observations, the I can be confident in my prediction that Arp 271 will 'collide' and merge because their velocities are too slow to prevent their mutual attraction from keeping them apart. I know this because of the precision measurements of the velocity fields made by Fuentes-Carrera et al (2004) and the present study which makes use of the N-body simulation package GalactICs to model the interaction with a small softening factor and a large number of particles.

Future studies may wish to increase the number of particles and provide a higher resolution analysis of the morphology of the merging process. Although other studies are

References

ArpGalaxyWeb http://arpgalaxy.com/ (accessed October 10, 2011)
Barnes, J. 1988, ApJ, 331, 699
Barnes, J., & Hernquist, L. 1992 Annu. Rev. Astron. Astrophys. 30: 705-42
Blackman, C. P. 1982, MNRAS, 200, 407
Carroll, B. & Ostlie, D. 2007, *An introduction to Modern Astrophysics* p 999 (Pearson)
ESOWeb http://apod.nasa.gov/apod/ap080721.html accessed 16/9/11
Fuentes-Carrera, I. et al. 2004, A&A 415, 451
GeminiWeb, 2008 http://www.gemini.edu/node/10979 (accessed 12/9/11)
Guo, Q., White, S., Cheng, L. & Boylan-Kolchin, M. 2009 MNRAS 404, 1111
Howard, S., Keel, W., Byrd, G., Burkey, J. 1993, ApJ 417: 502
Kuijken and Dubinski, 1995, MNRAS, 277, 1341
NASAweb, 2008 http://apod.nasa.gov/apod/ap080721.html (accessed 12/9/11)
SwinWeb, 2011 http://astronomy.swin.edu.au/supercomputing/ (accessed 6/11/11)
Toomre, A. & Toomre, J. 1972, ApJ, 178, p 6
Xue, X., et al 2008 ApJ 684, 1143
Yamagata, T., Noguchi, M., & Iye, M. 1989, ApJ, 338: 707