Properties of Interacting and Colliding Galaxies:
A study in image analysis

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INTRODUCTION

Interaction between galaxies is an important process to consider in regards to the formation and evolution of galaxies. It is the nature of large-scale structure within the universe that many of the galaxies that we observe have or will interact with other galaxies sometime within their lifetime. Our own galaxy, the Milky Way, is itself the product of past galactic interaction—having in the past cannibalized dwarf galaxies around it, being currently orbited by a number of dwarf galaxies and also currently on the trajectory to collide with the neighboring Andromeda Galaxy.

In this experiment, images were obtained of two sets of interacting galaxies using the RIGEL telescope at the Iowa Robotic Observatory. These images were used to determine the location, within the galaxies, of regions of enhanced star-formation and the size and mass of these regions.

The first two, the Antennae Galaxies (NGC 4038/NGC 4039), are two galaxies in the process of merging into what likely will become ellipitcal galaxy. The second two, The Whirlpool Galaxy and its companion drawf galaxy (respectively, NGC 5194 and NGC 5195) are galaxies whose history of interaction has strongly affected their respective histories and morphologies.

Interactions between galaxies often result in periods of highly enhanced star-formation, as the gravities of the interacting galaxies affect each other, resulting in tremendous tidal forces which greatly change their morphologies. This is especially evident in the Antennae Galaxies and the Whirlpool Galaxies, whose structures are dominated by areas of star-formation. Collision of gas clouds in the Antennae Galaxies has spurred star-formation there, while the gravitational influence of its companion has enhanced the density waves in the spiral arms of the Whirlpool Galaxy giving it a very distinctive pattern of star-formation regions.

Using images obtained using RIGEL's H-filter, the location of star-formation regions within the galaxies were determined. The distances to the galaxies were found using literature values for recessional velocity, and Hubble's Law.

$$v = H_o D$$

where v is the velocity of the object in kilometers per second, H_o is the Hubble constant kilometers per second per megaparsec and D is the distance to the object in megaparsecs. Then, using the distance and the angular size of the star-formation and the formula for small-angle approximation, the linear sizes of radii of the star-formation regions were obtained.

$$d = \frac{(D \Delta \theta)}{206{,}265}$$

where d is the linear size of the object in parsecs, D is the distance to the object in parsecs and $\Delta\theta$ is the observed angular size of the object in arcseconds.

Until about three years ago, the Antennae Galaxies were estimated to be about 65 million light-years away, a distance predicted by measuring the redshift of the galaxies. The validity of this estimate was called into question in the early part of the last decade by Saviane, Hibbard and Rich when they found a population of red giants (with ages greater than 2 Gyr). Stars in the red giant branch can only have a limited luminosity (M~-4). They are at their brightest at the tip of the giant branch when helium is ignited in their cores during the helium flash. The red giants observed by Saviane, Hibbard and Rich were too bright to be as far away as previously predicted. Using the red giants as a standard candle a newer, closer distance of ~13.3 Mpc was determined.

Using the average linear sizes of various radii of the star-formation regions, we were able to find the volume of the star-formation regions as modeled as a sphere, using the equation for the volume of a sphere

$$V = \frac{(4\pi r^3)}{3}$$

where V is the volume of the sphere in cubicparsecs, r is the radius of the sphere in parsecs, and π is as many significant digits of pi as were relevant to our previously calculated values.

With a typical value for the number density, n, of star-formation regions, the mass density, ρ, was found using the formula for mass density:

$$\rho = n * m_H$$

where ρ is the mass density in kilograms per cubic meter, n is the number density in atoms per cubic meter and m_H is the mass of a hydrogen atom in units kilograms per atoms. Using the calculated results for volume and mass density o the star-formation, the mass of the average star-formation region was calculated via the relationship

$$M = V * \rho$$

where M is the mass of the star-formation region in kilograms, V is the volume of the region in cubic meters, and ρ is the mass density in kilograms per cubic meter. The mass M was then converted into units of solar mass to determine how many stars of solar mass size could be created in the clouds identified.

PROCEDURE

Using images obtained using RIGEL's H-filter, the location of star-formation regions within the galaxies were determined. This was done the creation of a composite image of multiple images taken with the H-filter into a more correct image. Areas which appeared bright in the H-filter were modeled as spherical clouds. Annotations were made on the H-image in the form of boundary circles for the zones of enhanced luminosity, then the diameters of these circular regions was obtained, on which the calculations were performed (see Figure 1). The angular size of these diameters was determined using RIGEL's angular resolution of 1 arcsecond per pixel.

Using a literature value for the recessional velocity of the Whirlpool Galaxy of 499±39 km/s, a recent literature value for the Hubble constant of 72±8 km/s/Mpc and Hubble's Law

$$v = H_o D$$

(where v is the velocity of the object in kilometers per second, H_o is the Hubble constant kilometers per second per megaparsec and D is the distance to the object in megaparsecs) a distance of 6.93 Mpc to NGC 5194 was obtained.

For the Antennae Galaxies, a value of 13.3 Mpc (Saviane, 2008) was used as the value for distance from the Earth for reasons that will be discussed in further detail in later segments.

Using the distances to the galaxies (respectively 6.93 Mpc and 13.3 Mpc to the Whirlpool Galaxy and the Antennae Galaxies), the angular size of the star-formation regions and the formula for small-angle approximation, the linear size of the galaxies were obtained.

$$d = \frac{(D \Delta \theta)}{206{,}265}$$

where d is the linear size of the object in parsecs, D is the distance to the object in parsecs and $\Delta\theta$ is the observed angular size of the object in arcseconds. Linear size of the objects in parsecs were then translated into linear size in meters, with the knowledge that one parsec is equal to

30.857e15 meters. These values for the diameter of the star-formation regions were then halved to find the radii, which were used to find the volume of the star-formation regions via the relationship:

$$V = \frac{(4 \pi r^3)}{3}$$

where V is the volume of a sphere with radius *r*, where V is in cubic meters, r is the radius of the sphere in meters and π is 3.1416. Averages were taken for the volume of the star-formation regions (as modeled as spheres) from the respective galaxy systems, finding the average volumes of the star-formation regions as 1.47e57 and 3.90e57 kilograms for the NGC 5194/5195 and NGC 4038/4039 systems respectively. The results of these calculations are summarized in Figure 2.

NGC 5194/5195 (Whirlpool Galaxy)				**NGC 4038/4039 (Antennae Galaxies)**			
Number of regions	Radius (arcsec)	Radius (m)	Volume (m^3)	Number of regions	Radius (arcsec)	Radius (m)	Volume (m^3)
6	4	4.22E+018	3.15E+056	2	5.5	1.14E+019	6.13E+057
11	5	5.28E+018	6.15E+056	1	6.5	1.34E+019	1.01E+058
11	6	6.33E+018	1.06E+057	1	2.5	5.16E+018	5.76E+056
8	8	8.44E+018	2.52E+057	7	3.5	7.22E+018	1.58E+057
2	9	9.50E+018	3.59E+057	5	4.5	9.29E+018	3.36E+057
2	11	1.16E+019	6.55E+057	1	7.5	1.55E+019	1.55E+058
1	4	4.22E+018	3.15E+056				
1	5	5.28E+018	6.15E+056				
		Average Volume	1.47E+057			Average Volume	3.90E+057

Using spectral line data from the HII region closest and most famous to Earth, the Orion Nebula, it was assumed that the composition of the Orion Nebula cloud was similar to the extragalactic star-formation regions that have been studied here. Thus, the cloud was assumed to be composed of mostly hydrogen, at number density of n= 1e10 atoms per cubic meter. Using that and the mass of the hydrogen atom, the mass density was determined via the relationship

$$\rho = n * m_H$$

where ρ is the mass density in kilograms per cubic meter, n is the number density in atoms and m_H is the mass of a hydrogen atom in units of kilograms per atoms, as approximately 1.6 e-17 kg/m^3.

The mass of a typical star-formation region was then calculated, using the relationship

$$M = V * \rho$$

where M is the mass of the star-formation region in kilograms, V is the volume of the region in cubic meters, and ρ is the mass density of the region in kilograms per cubic meter, as 2.35e40 and 6.24e40 kilograms for the NGC 5194/5195 and NGC 4038/4039 systems respectively. Expressed in units of solar mass, with the knowledge that one solar mass is equal to 1.989e30 kg, this was again respectively 1.18e10 and 3.14e10, which implies that that many stars of solar mass could be created in that star-formation region.

Tri-color images were used to calculate how long it will for the Antennae Galaxies to fully merge into a single galaxy. The distance between the center of each galaxies nuclei were measured to be 68.31" apart which was converted into parsecs, using the Small Angle as 48.58 kpc. Assuming the Antennae Galaxies are moving toward each other at a velocity comparable the velocity at which the Milky Way and Andromeda are moving toward each other (a velocity that can be measured due to the blue shift of the Andromeda Galaxy), then a velocity of 120 km/s can be used to estimate when the nuclei of the Antennae Galaxies will merge with a result of 396 Myr. This estimation is close to the figure of 400 Myr estimated by other sources.

Summary of Results and Discussion

For the two respective galaxies, the masses of the average star-formation regions were as summarized in Figure 3. The experiemental findings for the mass of the average star-formation region was much larger than literature examples of star-formation region masses, to the point of around three orders of magnitude.

The deviation from the experiemental results from known values is most likely due to several factors, involved mainly with certain assumptions that were made in the calculations.

One of the main experimental sources of error is the assumption made wherein the regions of star-formation identified in the H-filter images were held to be spherical clouds of radii on the order of 10^3 parsecs, with a uniform density of 10^{10} atoms per m^3. From the equation for Jean's Mass,

$$M_J = 18\mathrm{M}_\Theta \sqrt{T^3} / \sqrt{n}$$

(where M is the mass in solar masses, T is the temperature in kelvins, and n is the number density in atoms per cubic meter) we know that this is impossible, since under these conditions, for the cloud to avoid collapse, it would have to have a temperature of only a couple thousanths of a Kelvin above absolute zero.

Thus, one must conclude that the regions of star-formation are not spherical, were not identified correctly within the image, do not have uniform density, and/or do not have the density and composition of the Orion Nebula. Likely, it is all three factors that contributed to the errors in the calculations. Indeed, regions of star-formation are generally irregularly shaped, although regions that collapse into unique stars are generally semi-spherical in nature. It is also likely, given the distances and the angular resolution of the images that were taken, that areas that were modeled as unique regions of star-formation were instead areas of large-scale, where many regions of star-formation were grouped together and all contributed to the enhanced H-filter luminosity visible in the images. Also, clouds of gas do not have uniform density, rather having higher density in the middle, an idea clear when one examines the hydrostatic equilibrium dynamics of such a structure. Furthermore, regions of star-formation come in a variety of sizes, densities and compositions, so while modeling these regions after the Orion Nebula, while not completely misguided, was none better than an educated guess.

In the pursuit more correct results, it would be useful to conduct spectroscopic analysis in order to determine the density and composition of the clouds. It would also be necessary to obtain images of higher resolution. In our own galaxy, the Milky Way, star-formation regions come in many varieties, and it is not reasonable to assume homogeneity across distances of 10^3 parsecs; there is no reason why this shouldn't be the same in extragalactic star-formation regions.

Cloud sizes	**NGC 5194/5195 (Whirlpool Galaxy)**	**NGC 4038/4039 (Antennae Galaxies)**
10^1-10^7	1.19e10 solar masses	3.14e10 solar masses

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