Elliptical Mergers

Executive Summary

Understanding the formation scenarios and evolution of galaxies is one of the core aspects driving the current focus of astrophysics research. One such area that is relatively unexplored is the merging of elliptical galaxies. As one of the two major classifications of galaxies, the lack of data on elliptical mergers stands as a significant missing piece of the galaxy evolution puzzle. The proposed study would serve as the first attempt to better understand the high-energy properties of early-type galaxies across the merging process.

As galaxy formation and the galaxy merging process far exceeds a human lifespan, techniques are needed to properly capture the extent of the merging process. Following methods pioneered by Toomre & Toomre (1972) in developing the eponymous spiral galaxy merging sequence, a series of different elliptical systems undergoing merging at various stages would allow for a basic timeline of events and feature development. By using "snapshots" of these merger stages, it is likely that features unique to specific merging states will be identified.

Using the superior X-ray imaging of the Chandra observatory will allow for visualization of non-optical features, such as the superheating of gas in shock-fronts, formation of hot gas halos, the growth and evolution of X-ray binaries, and the ejection of matter from a system. The high-energy data, coupled with optical imaging and properties from the NASA Extragalactic Database, will serve to establish the baseline of properties found in elliptical-elliptical mergers. The new merger sequence, which can rightly be described as the dry-merger scenario, can then be compared to the well-known wet-merger Toomre sequence.

Introduction

Within the universe, two main types of galaxies can be found; elliptical galaxies and spiral galaxies. These galaxies can be further subdivided based on shape and other features. Edwin Hubble made a further distinction splitting the spirals into two subcategories of regular and barred spirals (Hubble 1921), as shown in Fig. 1. Hubble originally hypothesized that elliptical galaxies evolved into spirals; it is now understood that elliptical galaxies are completely separate entities that exist outside of spiral evolution.

Making the distinction between elliptical galaxies and spirals is a simple classification, whereas spirals have arm structure and centralized bulges, ellipticals tend to possess older populations of stars and only spheroidal morphologies

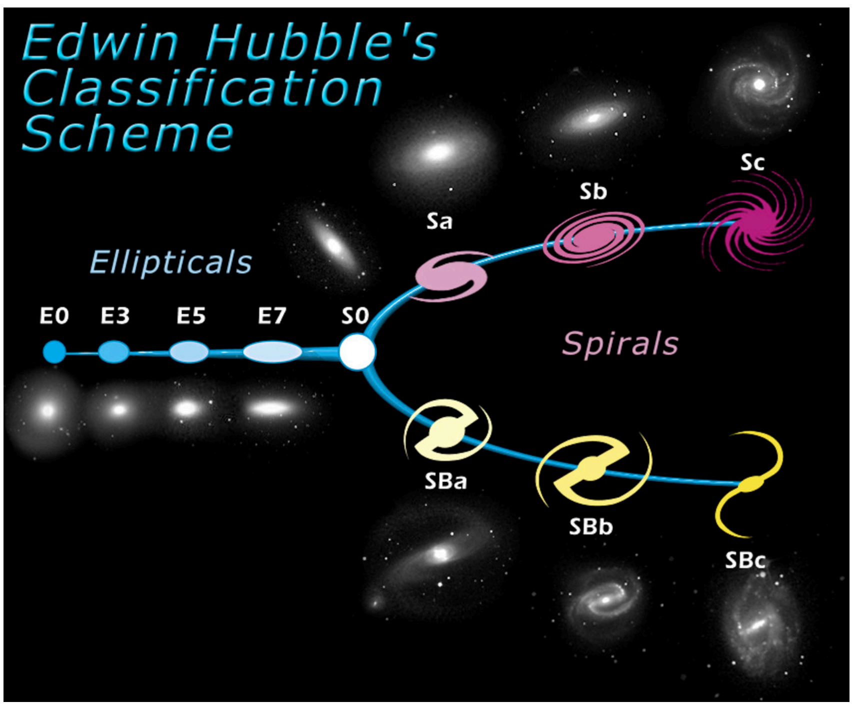

Figure 1: The Hubble Tuning fork, formerly believed to show the evolution of galaxies, created by Edward Hubble in 1936 (NASA 1999). The Tuning Fork serves as the standard means of galaxy classification.

Figure 1 depicts the Hubble Tuning Fork which is useful for the classification of galaxies, as it properly distinguishes the primary types of galaxies, elliptical and spiral. Spirals are star-forming galaxies that consist of a central bulge which is the most densely packed part of the galaxy. These galaxies are also surrounded by a disk, within which resides spiral arms. Star formation occurs primarily on the arms, whereas the center bulge houses older stars.

Elliptical galaxies consist of just a bulge populated by older, cool, red K & M stars. These galaxies do not have spiral arm structures, however, their true 3D shape can be complex and difficult to determine. Ellipticals exist in more galaxy-dense regions, such as groups and clusters. Large, bright ellipticals are more rare than spirals, as spirals tend to dominate the galaxies found in all-sky surveys.

Galaxies are also found to exist within a number of different environments, ranging from isolated, sparsely populated regions to locations with high-galaxy densities. One common high-density region is that of galaxy groups, which can vary in size from tens to hundreds of galaxies. Due to the close-packing of galaxies in groups, high-galaxy density regions are the sites of galactic merging, as galaxies exert large gravitational forces that draw other galaxies closer.

The merging of galaxies is well documented and thought to be well understood. There have been numerous studies on the merging of galaxies (Zezas et al 2002; O'Sullivan, Forbes, Ponman 2013; Tremble et al 2014). During merging, galaxies can undergo many morphological and physical changes as a result of gravitational perturbations. Merging can induce mass redistribution, altered star formation, and the additional accretion of dust and heat into a system.

The evolution of two spiral galaxies undergoing mergers has been well-established. The Toomre sequence, Toomre & Toomre (1972), of merging explores snapshots of spirals as they move closer to their cores coalescing. The Toomre sequence is core to the understanding of mergers as the merger timescale, on the order of a billion years, exceeds a single human lifetime. The Toomre sequence uses multiple sets of different galaxies at different points in their merging to fully visualize the merger process. The use of multiple "snapshots" at different periods allows for the different stages of the merger and the subsequent properties and features to be visualized.

The Toomre sequence was able to introduce the process of observing mergers happening in different stages and allowed them to be put together in a way that would allow for the entire process of a merger to be viewed. The mergers that were captured had taken place over a 4 Gyr timeframe, with each merger taking place in a different stage, and arranged as if a single set of galaxies were undergoing the complete merger process.

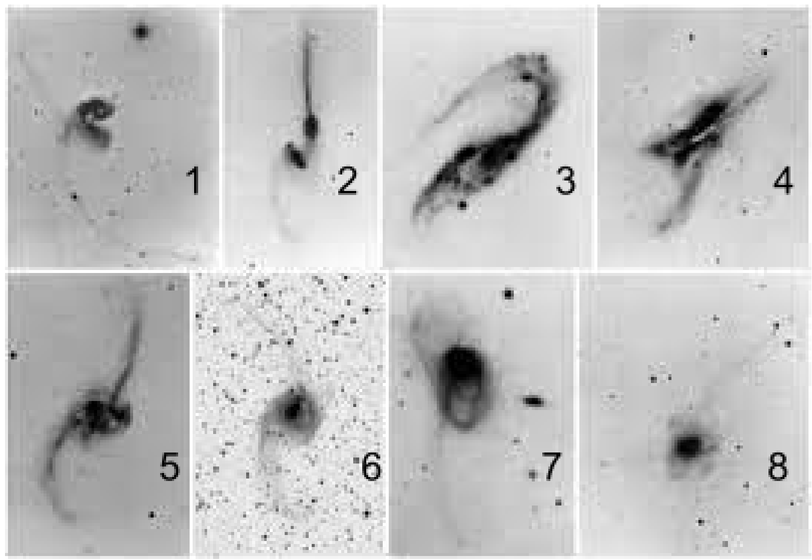

Figure 2: Merger sequence of Toomre & Toomre (1972). Individual snapshots show the various stages of merging, with each successive image moving the galaxies closer to core coalescence.

Figure 2 highlights eight images used to form the Toomre sequence. Stages one and two show two galaxies within close proximity of one another and being pulled together due to mutual gravity. Stages three through five show mergers in progress, as the cores move closer to coalescence and the spiral arms are torn off and material sinks back towards the new galactic center. Stages six through eight show one full galaxy taking form from the merging process, whereas in stage nine a merger remnant can be seen.

X-ray observations of the Toomre sequence allow for a unique perspective of the morphology and features of mergers. High-energy emission, resulting from the shocking and heating of cold gas and the enhanced star formation and the associated X-ray binaries, provides an insight into the merger process which cannot be duplicated via optical wavelength observations.

X-ray observations provide a unique means of examining the galaxy properties during the merging process. O'Sullivan et al. (2013) examined a correlation in an increased

L_X/L_B with age which also suggests an increase in the mass of the X-ray halo after star formation.

O'Sullivan et al. (2013) studied the different hot gas properties from ellipticals that formed from merging spirals. Using X-rays to look into the merger remnant NGC 7252, O'Sullivan et al. observed a typical elliptical galaxy hot gas halo albeit much smaller than expected. The study examined more than 30 galaxies to find a correlation between the X-ray luminosity - optical luminosity ratio (L_X/L_B) and the fine structure parameter (Σ), shown in Figure 3.

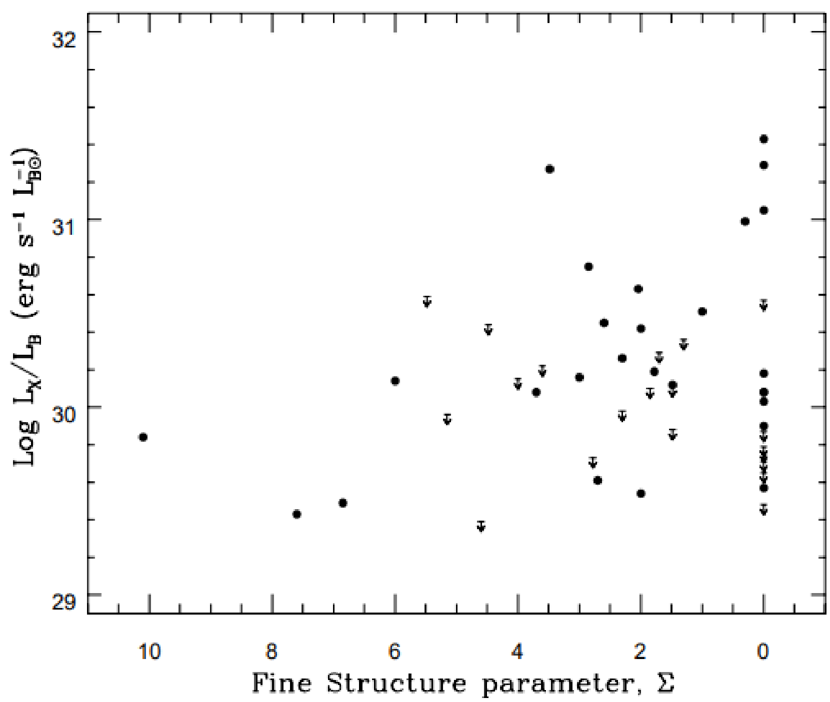

Figure 3: The figure from O'Sullivan, Forbes, and Ponman 2013 shows the results of plotting the normalized X-ray luminosities against fine structure parameters for early-type galaxies.

O'Sullivan et al. found a strong correlation between the normalized X-ray luminosities and the galactic age. X-rays provide additional insight into the luminosities of post-merger ellipticals closely resembling 'normal' ellipticals as well as show different results such as spirals having high amount of cold mass, T~k100, whereas this was absent in ellipticals as ellipticals have been shown to have many hot small hot halos.

While spiral-spiral mergers are heavily studied, little research has investigated elliptical-elliptical mergers. The proposed research will seek to view the process of the merging of elliptical galaxies in a Barber-Fuse sequence. Through such a process we will be able to distinguish the unique features arising from elliptical merging compared to the more documented process of spiral mergers. Data will be gathered through the use of the Chandra Observatory, NASA Extragalactic Database, and the X-ray data analysis software CIAO. The proposed research will seek to examine the lifetime and timing of X-ray features that develop during the merging of two elliptical galaxies.

Proposal

A plethora of research has utilized the Chandra Observatory data as Chandra is the preeminent high-energy telescope with superior wavelength coverage and less than 2-arcsecond pointing Tremblay et al (2014) exploring a major merger between two prominent ellipticals and the subsequent star formations, as well as Kim et al (2019) which uses the Chandra Observatory to identify key gas elements and the subsequent evolution. The Chandra X-ray archives host a large quantity of valuable data on elliptical galaxies and merging systems.

NASA's Chandra X-ray telescope is one of NASA's most powerful and successful telescopes. Chandra has eight times greater resolution and the ability to detect sources twenty times farther than any other previous X-ray telescope. Chandra has a resolving power of 0.5 arcseconds allowing it to spatially resolve point source emission. Chandra is an ideal tool for gathering data on the merging of ellipticals as it is hypothesized that scores of point source emission and hot gas will be created during the merging process.

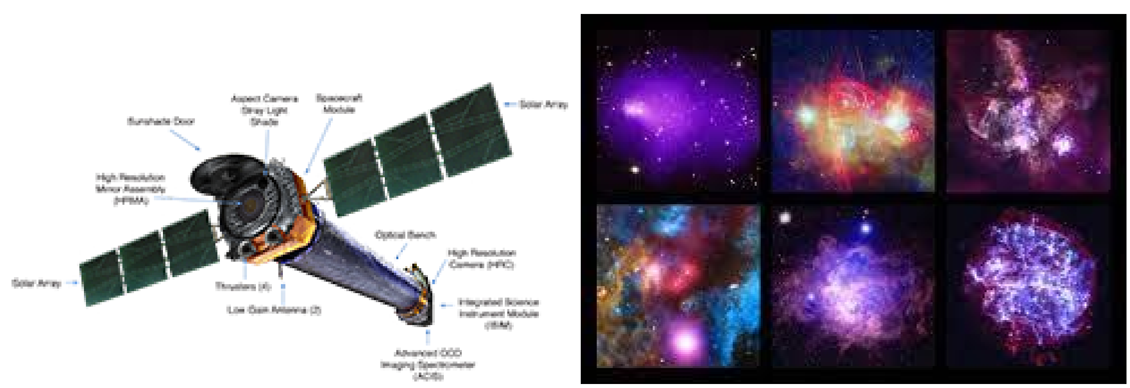

Figure 4: Diagram of the Chandra telescope (left) and images captured from the Chandra archives (right).

Figure 4 shows a diagram of the Chandra telescope, including label parts. It also shows images taken by the Chandra observatory. These images show six different X-ray images from galactic clusters to the formation of stars.

Observations at different wavelengths provide unique information, such as dust emits infrared light, hot O & B stars give off UV light, and million-degree gas produces X-ray emission. In addition to hot, low-density gas, binary systems of black holes, normal stars, or neutron stars can emit spatially narrow X-ray sources, often described as X-ray point sources. Figure 5 shows the difference in images between an optical image and an X-Ray image taken of NGC 4261.

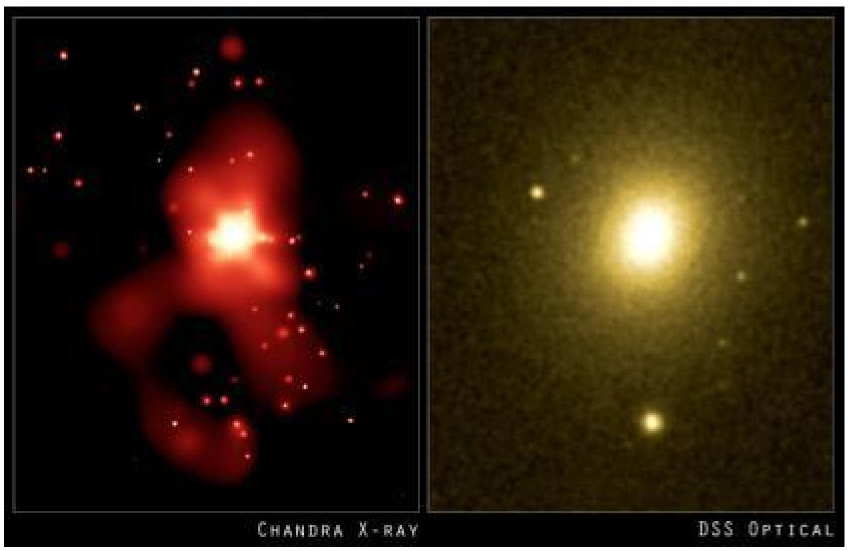

Figure 5: The image of the elliptical NGC 4261 is taken in both optical and X-Ray format. The image on the right is the optical image that shows the base galaxy. The left image displays X-rays emitting hot gas, black holes, and neutron stars.

The utility of X-rays is seen in Fig. 5, where the rightmost image is a standard optical view of NGC 4261 and the left image is the associated X-ray emission. While optically the galaxy appears as a typical round and featureless elliptical galaxy, the high-energy emission belies a more complex system. Within the X-ray image can be seen a number of small, distinct sources which are binary systems of black holes and neutron stars (Zezas et al. 2002). The more amorphous emission comes from high-temperature diffuse gas.

Data gathered from X-Ray imaging pinpoints the desired point sources and luminosities in a system. Figure 6 displays images taken of the merger and interaction of spiral galaxies NGC 4038 and NGC 4039 through the Chandra telescope. The image highlights point sources in the larger luminescence on the left. The right image in Fig. 6 presents the same galaxies with a varied intensity limit on the diffuse emission.

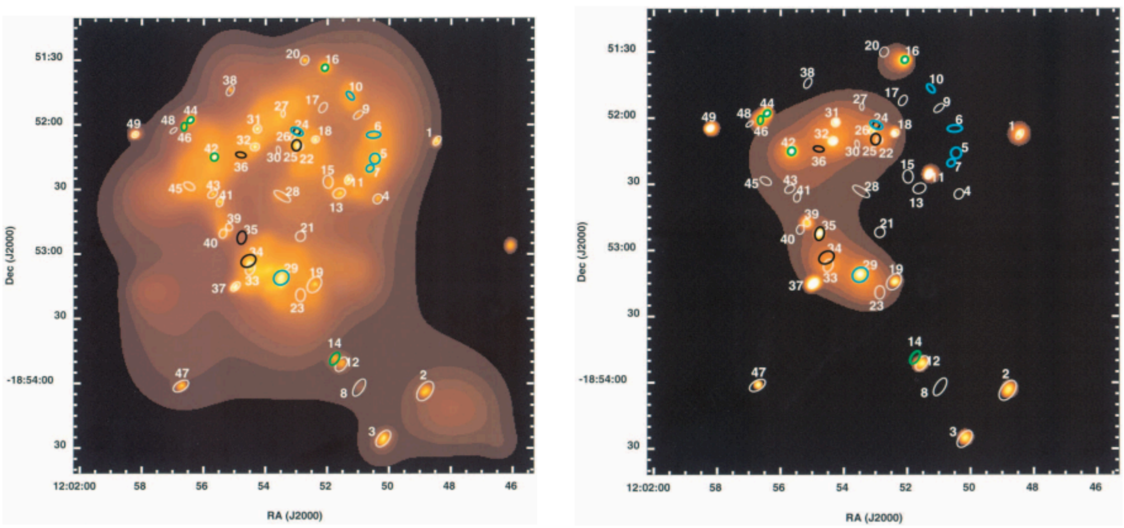

Figure 6: Images of the merging systems NGC 4038/4039 observed with the Chandra X-Ray telescope. In both images, the contours represent hot gas halos, while the point sources indicate spatially concentrated X-ray sources.

Spiral galaxy mergers have more data on them and we can look to them for possibilities on what might be seen with elliptical mergers. As previously mentioned, the Toomre sequence provides great insight into the lifecycle of mergers, and by looking into it we can have insight into the merging of ellipticals.

The Toomre sequence will prove important in our research. The Toomre sequence shows the merging process in stages, something yet to be done before. By going over the interaction of close proximity galaxies the Toomre sequence explores the interactions of such close proximity galaxies such as the fact that the tails being formed from the galaxies are due to the close interaction between them and the effect that was had and other important data found.

The Toomre Sequence explores the interactions in a relatively simple manner. By going through the encounters and simplifying the situations, turning the galaxies into point masses, and exploring the interactions in similar manners.

The proposed research on elliptical galaxy mergers is crucial to a more complete understanding of galaxy evolution. Spiral mergers are well known and thoroughly documented, while the field of elliptical mergers has been untapped. As ellipticals are one of the predominant morphologies and ellipticals tend to be the dominant type of galaxy in high-density regions, mergers between such objects are expected to be significant throughout the Universe. Providing a better understanding of the processes and features during an elliptical-elliptical merger will allow for a more complete picture of galaxy evolution.

Studies have been put forth on the development and outcomes, whether specific or broad, of spiral mergers such as the aforementioned Toomre & Toomre, O'Sullivan et al, etc. These studies fail to take into account the occurrence of the merging of multiple ellipticals. Each study has added more information into the collective and the goal of our own data processing would be no different.

I. Timeline

a. February-May 2022

i. Learn Ciao – Chandra X-ray analysis software

ii. Learn the basic astronomy analysis techniques

b. Summer 2022

i. Weeks 1-3:

1. Use Chandra database to identify intermediate isolated elliptical galaxies
2. Begin basic analyses of the intermediate isolated galaxy sample determining properties such as gas temperature and luminosity, images of hot gas and point sources

3. Establish comparison samples and download data from Chandra archive

a. Hickson compact groups (high-density region)

b. Galaxies with similar distances & brightness to the void galaxies

ii. Weeks 4 – 6: Analysis of comparison galaxies

1. Continue analysis of the isolated galaxy sample and the comparison galaxies.

iii. Weeks 7 – 8: Begin compiling results for SFCS final paper, poster, AAS poster

1. Determine what data and analyses remain

2. Begin draft of paper for SFCS and for peer-reviewed publication.

c. Fall 2022

i. Complete poster for Family Weekend poster session

ii. Submit final report for SFCS program

d. January 2023

i. Attend and present results at the 241th American Astronomical Society meeting in Seattle, WA January 8-12, 2023

e. Spring 2023

i. Submit article for publication in the Astrophysical Journal.

ii. Work on proposal for SFCS 2023

II. Budget

· Barber stipend	$3,500.00
· Fuse stipend	$3,800.00
· Miscellaneous equipment	$600.00
· Conference Travel (Seattle, WA, January 8 – 12, 2023)	$2222.00
o Barber Registration $182.00	

- Fuse Registration $520.00
- Flight (x2) $400.00
- Hotel (3 nights) $200.00/night
- Meal $40.00/day

· Total $10,122.00

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