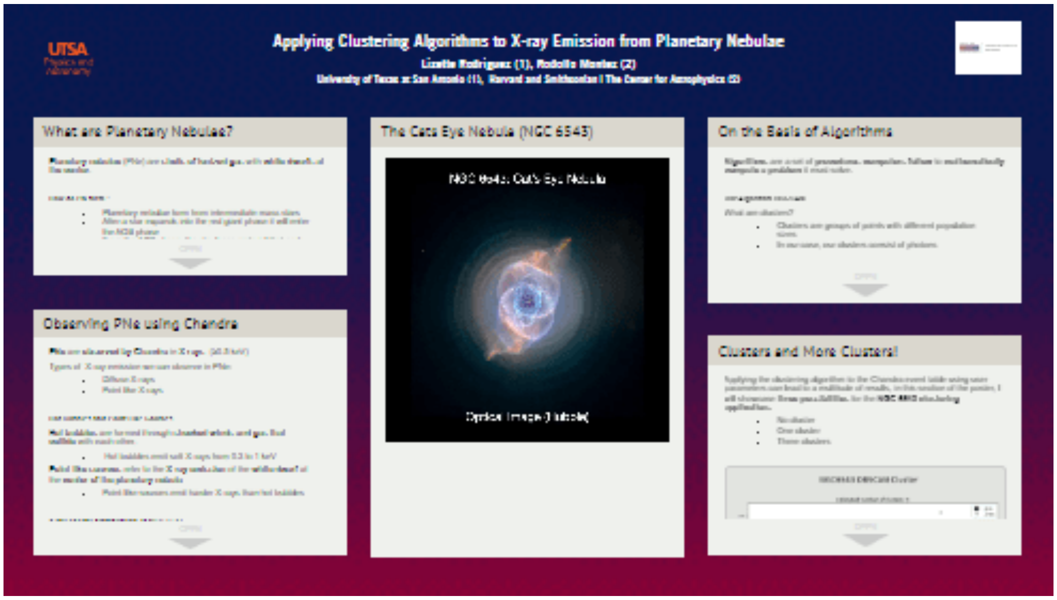
Applying Clustering Algorithms to X-ray Emission from Planetary Nebulae



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PRESENTED AT:

WHAT ARE PLANETARY NEBULAE?

Planetary nebulae (PNe) are **shells of ionized gas** with **white dwarfs at the center**.

How do PN form?

- Planetary nebulae form from intermediate-mass stars
- After a star expands into the red giant phase it will enter the AGB phase
- From the AGB phase, the star loses material that ends up in space
- After the star's core collapses the star dies and leaves ionized gas in space

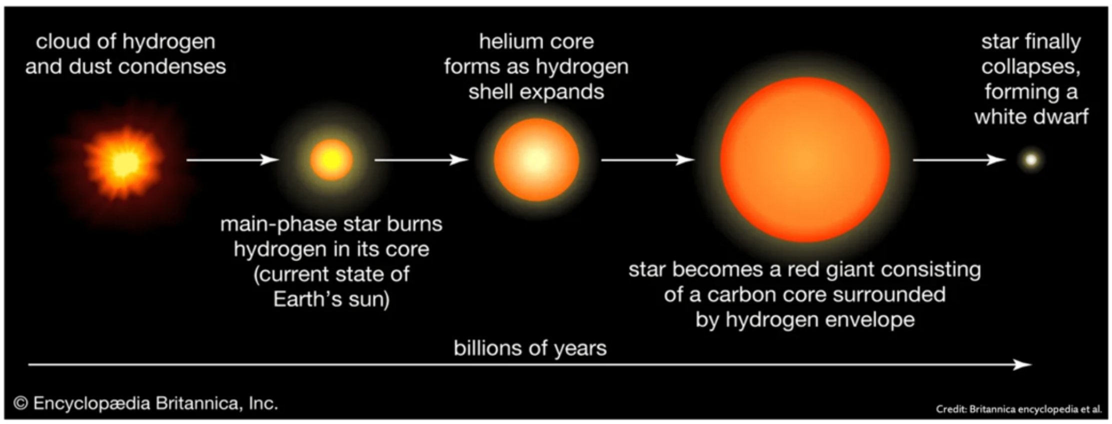


Figure 1: An image by Britannica Encyclopedia et al. showing the stellar evaluation of a main-sequence star that specifically becomes a planetary nebula with a white dwarf remnant

What are some important characteristics of PNe?

No two PNe are the same! Astronomers observe different kinds of PNe with **various shapes, sizes, and symmetry.**

The two main types of symmetry that exist within a PNe are **symmetric** and **asymmetric.**

Types of PNe shapes include but aren't limited to:

- Elliptical
- Spherical
- Bipolar
- Irregular

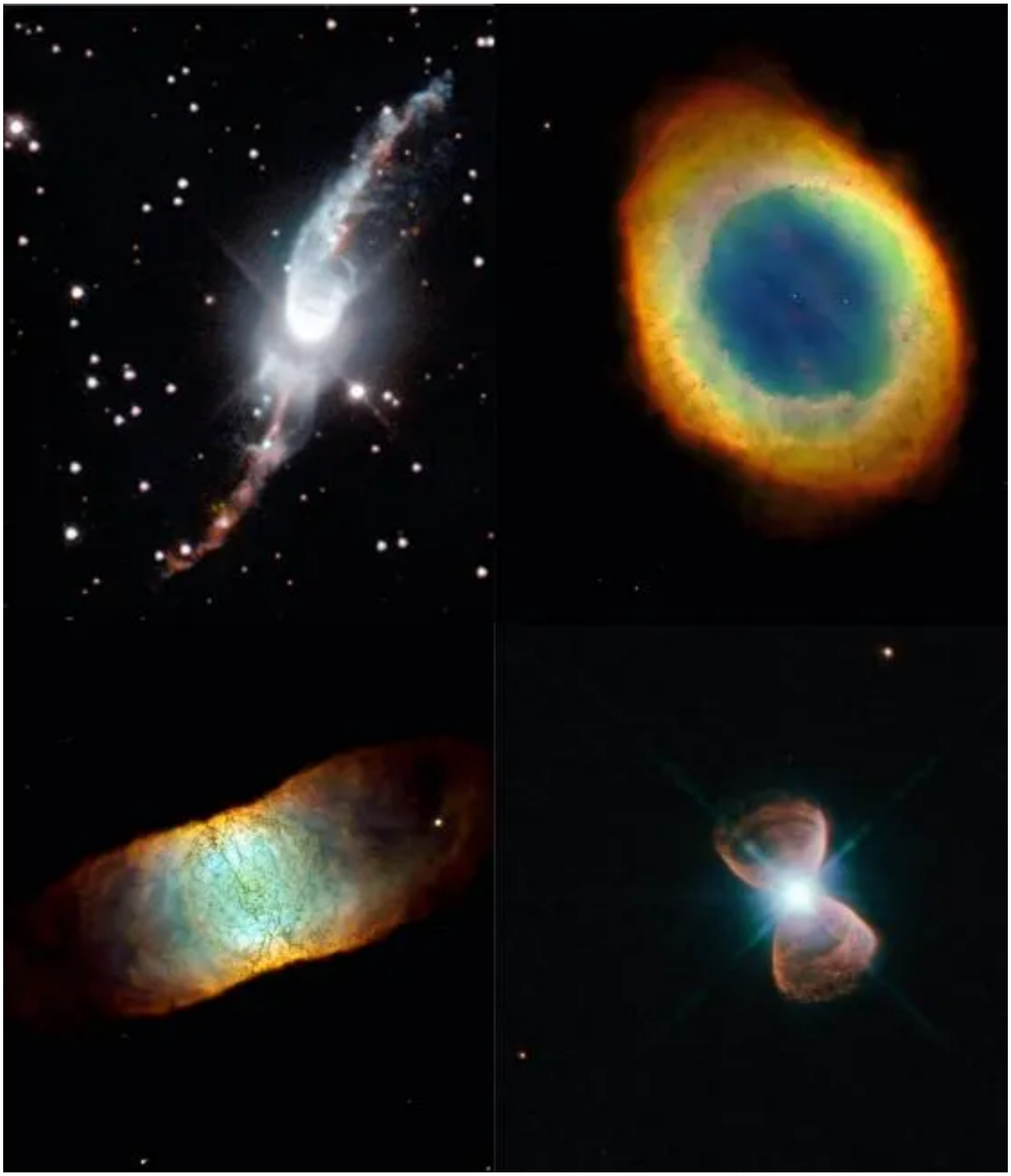


Figure 2: An image by NASA/HST showing four Planetary nebula types of morphology. Planetary Nebulae are as listed: IC 4406, IRAS 17423 -1755, NGC 6720, NGC 6302

These planetary nebulae above have the following classification types:

- IC 4406 also known as the Retina Nebulae is bipolar and symmetric
- IRAS 17423 -1755 is bipolar and symmetric
- NGC 6720, also known as the Ring Nebulae, are spherical and symmetric
- NGC 6302, also known as the Butterfly nebulae, is bipolar and not symmetric

The Cat's Eye Nebula or NGC6543

NGC 6543 was **chosen** because of its **well-sourced and extensive data sets by Chandra.** This means **evolutionary characteristics** such as **shape, size, and symmetry** were **already documented.**

- NGC 6543, also known as the Cat's Eye Nebulae, are elliptical and symmetric

This **planetary nebula** has a **White Dwarf at its center** and has **its connection to X-ray emission,** later explained thoroughly in the “X-ray observations using Chandra” section.

Figure 3: An image by Chandra/HST showing the Cat's Eye Nebulae (NGC6543) optical image background in the visible wavelength with an X-ray overlay at the center of the PNe by Chandra X-ray telescope

OBSERVING PNE USING CHANDRA

PNe are **observed by Chandra** in **X-rays** (≥0.5 keV)

Types of X-ray emission we can observe in PNe:

- Diffuse X-rays
- Point like X-rays

Hot Bubbles and Point-Like Sources

Hot bubbles are formed through **shocked winds and gas that collide** with each other.

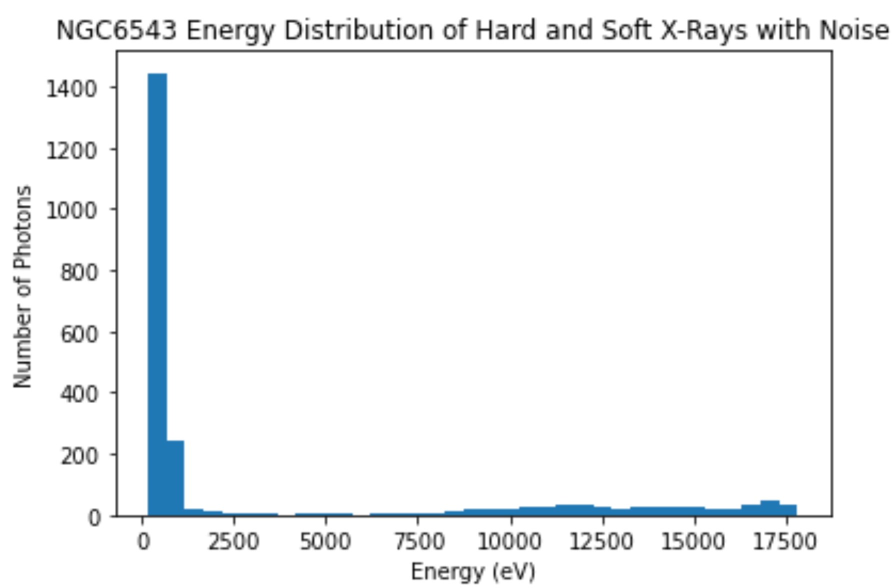
- Hot bubbles emit soft X-rays from 0.3 to 1 keV

Point-like sources refer to the **X-ray emission** of the **white dwarf** at the **center of the planetary nebula**

- Point-like sources emit harder X-rays than hot bubbles

X-ray energy distributions of NGC 6543

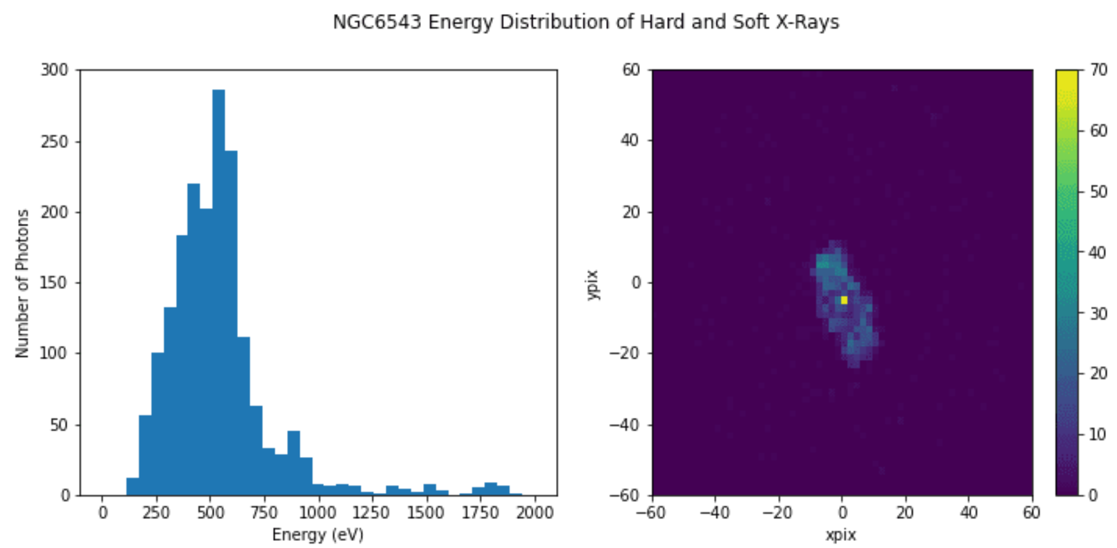
Using **Chandra's event table** for tabulated data of **distance in x and y pixels**, and **energy in eV**, we can generate **counts of X-ray photons for a specific energy value.**



Graph 1: NGC 6543 Full energy distribution of soft and hard X-rays with noise

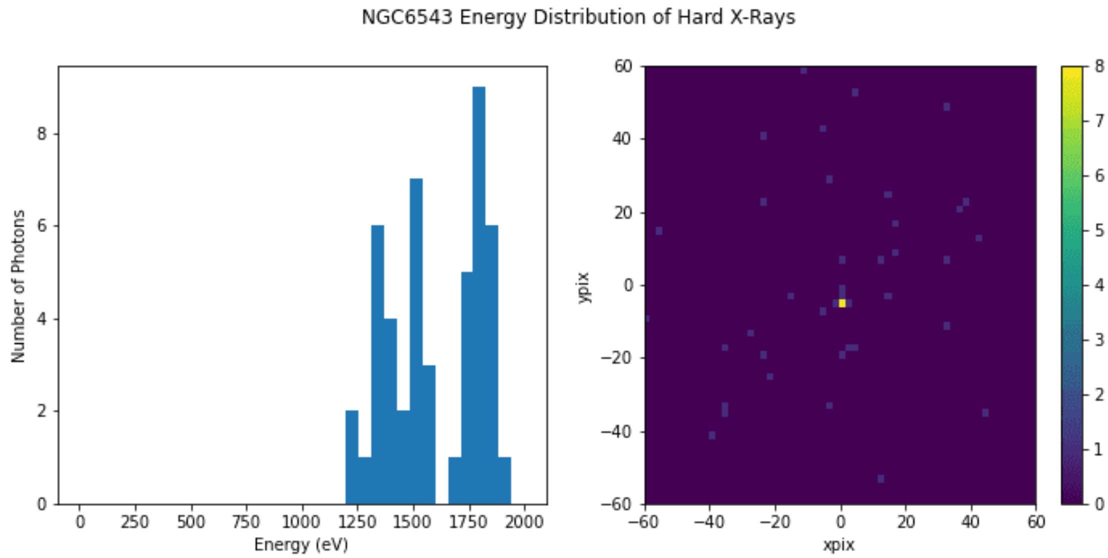
Notice how the **correlation** of the **number of photons** is with the **energy level.** The **closer** you are to the **center of the planetary nebulae**, the **lower** the **number of photons** is, **but** the **higher the energy value.**

Taking noise out of the distribution and generating separate np.where filters in phyton to categorize the difference between X-rays and noise we get:

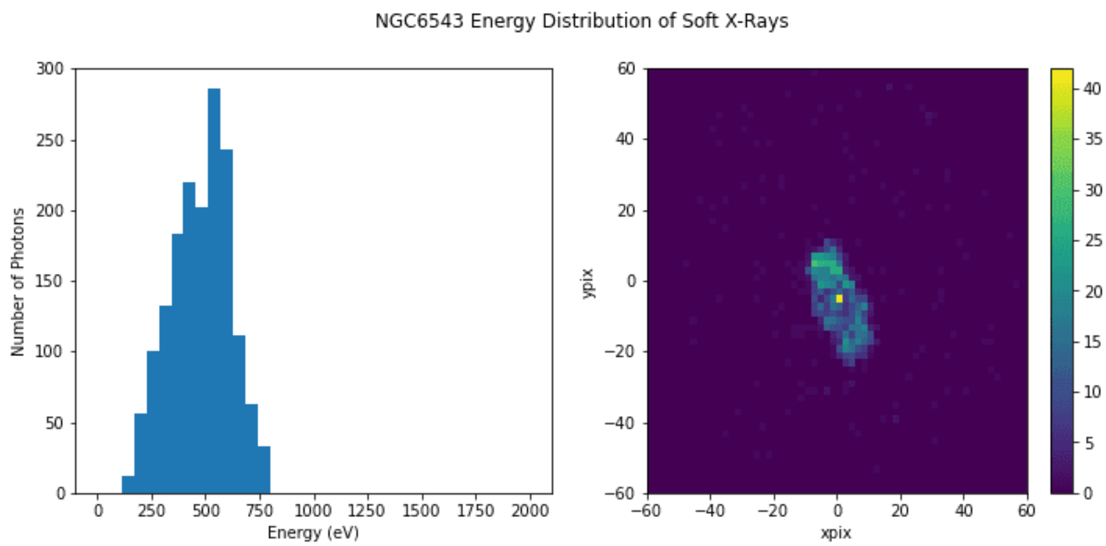


Graph 2: NGC 6543 Full energy distribution of soft and hard X-rays without noise

Let’s modify the interval value from the filter to understand not only the relationship between the number of photons and energy value but also the relationship these variables have with the physical characteristics of NGC 6543.



Graph 3: NGC 6543 energy distribution of soft X-rays



Graph 4: NGC 6543 energy distribution of hard X-rays

What Can We Learn from the Energy Photon Distributions?

Understanding the prior modifications of the separation of energy levels in the 2dhist above for graphs 3 and 4, the following becomes clear:

- **Hard X-rays** for NGC 6543 are typically **found at the center of the PNe** (white dwarf X-ray emission).
- **Softer X-rays** emit from NGC 6543 **diffuse X-rays** (elliptical hot bubbles).

THE CATS EYE NEBULA (NGC 6543)

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/q_auto/v1735848462/aas/98-BA-5E-50-15-C0-D8-FD-4E-49-0B-7D-B5-AC-BA-80/Video/clustering_slideshow_akv0wy.mp4

ON THE BASIS OF ALGORITHMS

Algorithms are a set of **procedures computers follow** to **mathematically compute a problem** it must solve.

Our Algorithm DBSCAN

What are clusters?

- Clusters are groups of points with different population sizes
- In our case, our clusters consist of photons

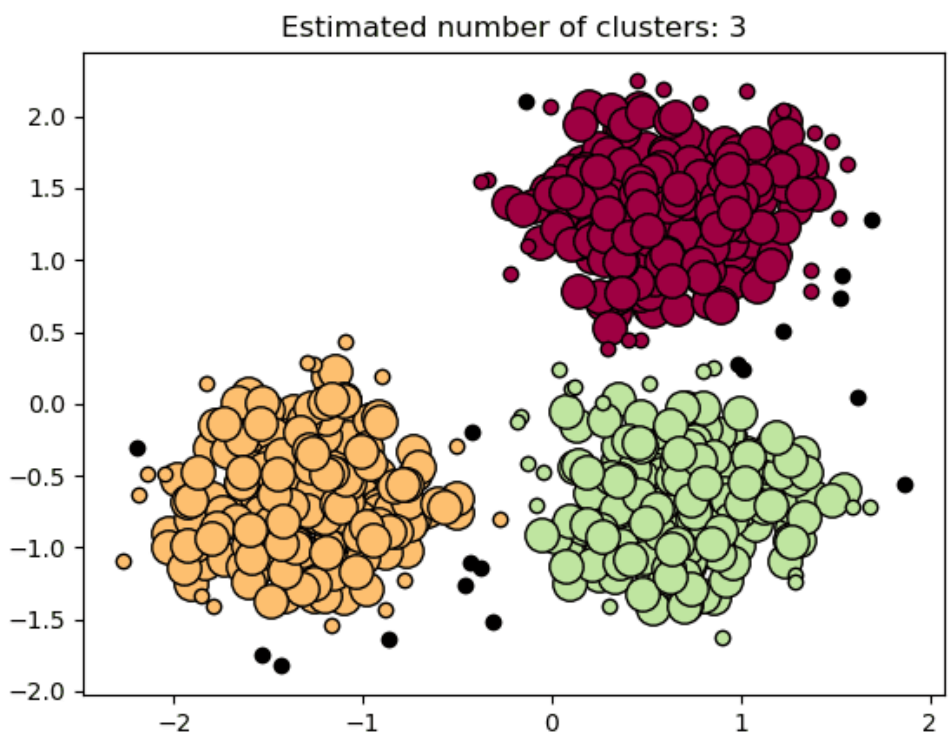


Figure 3: An image of a demo cluster graph by scikit

DBSCAN, or Density-Based Spatial Clustering of Applications with Noise, is a **clustering algorithm** that **works to cluster data** distribution sets of **high and low-density populations.**

Why DBSCAN works:

- Excellent at identifying noise (also called outliers)
- Works with irregularly shaped data distribution sets (Nested clusters in our case)
- Determines cluster count automatically

How does DBSCAN work?

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/q_auto/v1735681598/aas/98-BA-5E-50-15-C0-D8-FD-4E-49-0B-7D-B5-AC-BA-80/Video/My_Movie_11_angvio.mp4

User parameters such as epsilon (or eps) and minimum sample value (or min_samples) are user parameters that define the distance away from a chosen data point in correlation to the minimum number of points it takes to make a cluster.

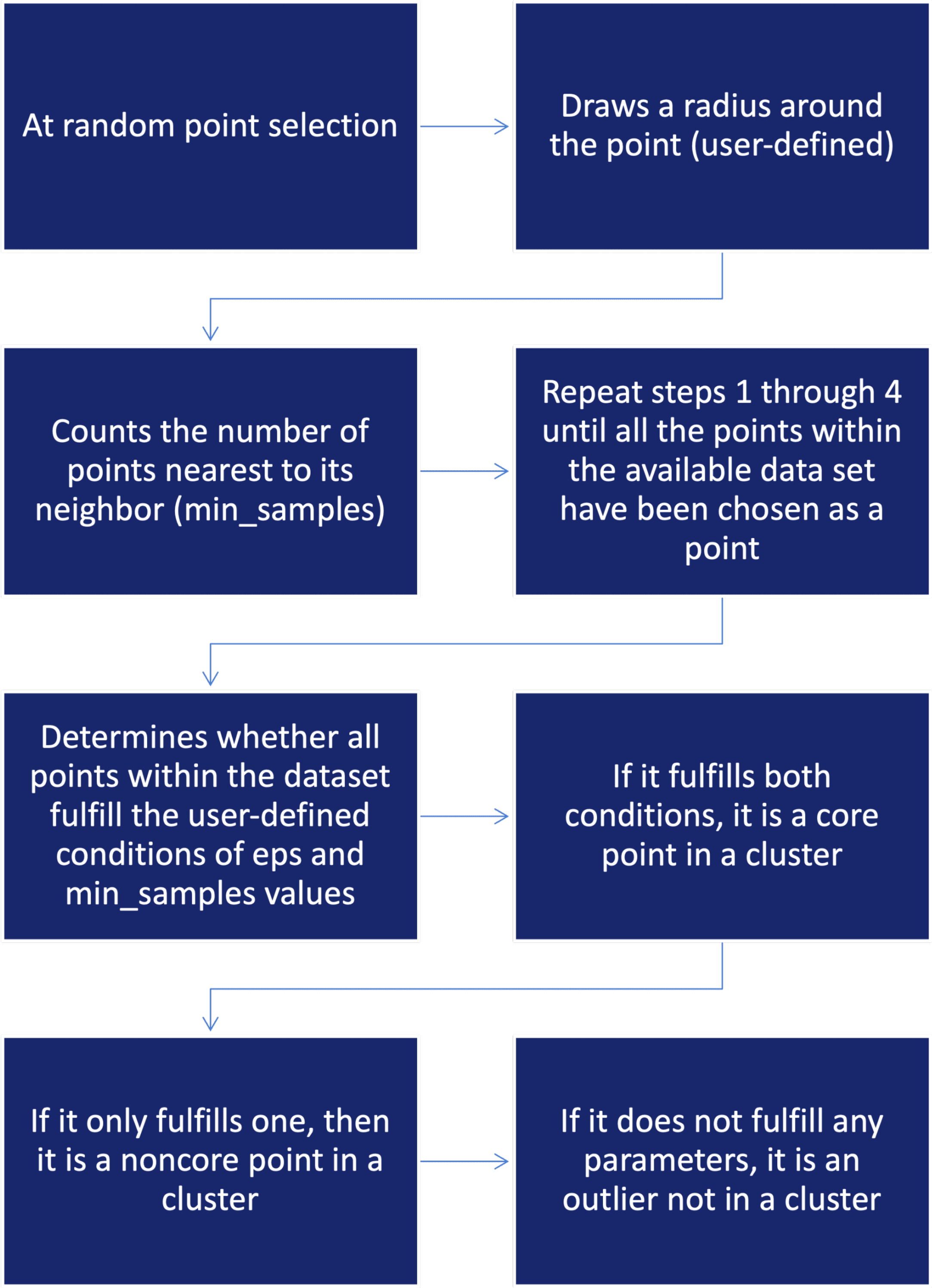
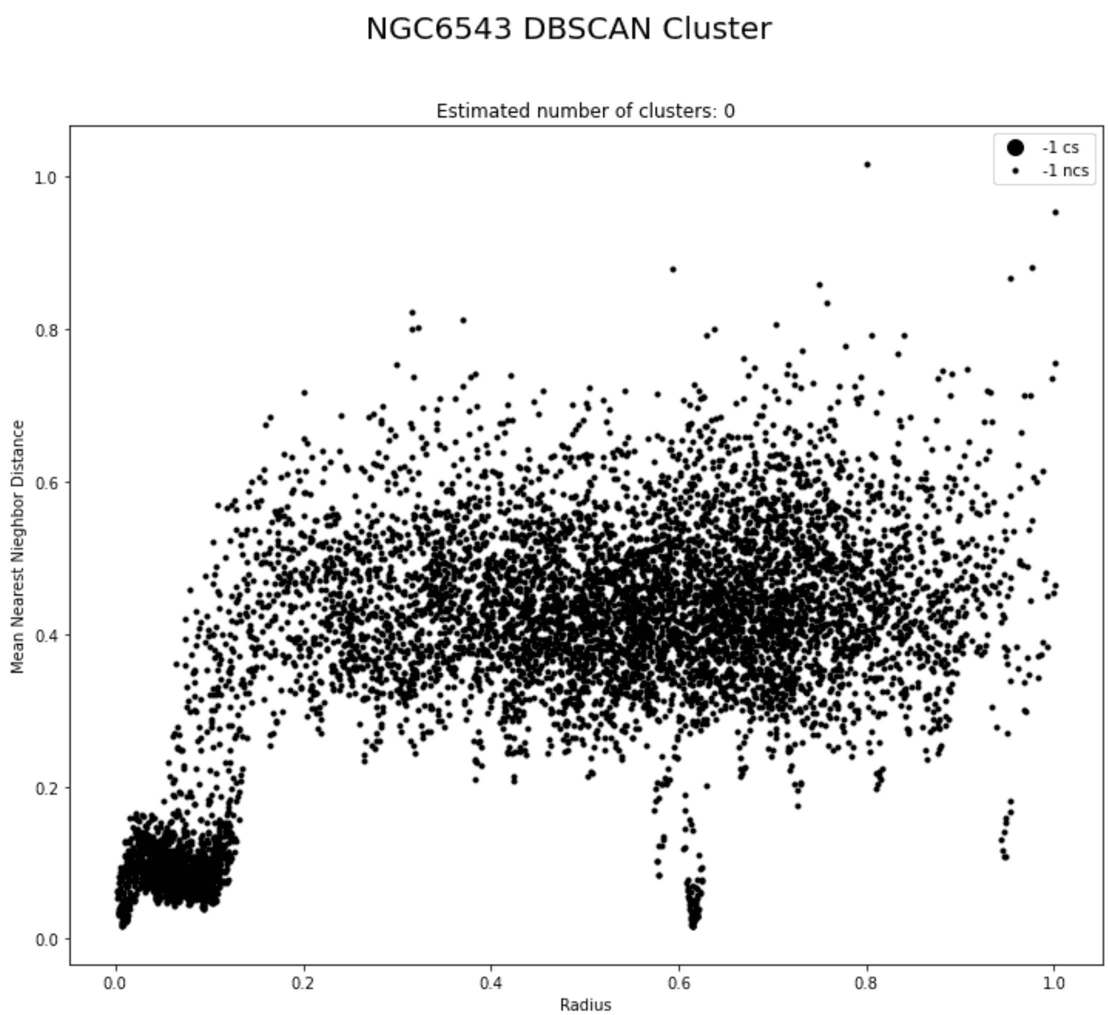


Figure 4: A flow chart of the process of how DBSCAN works

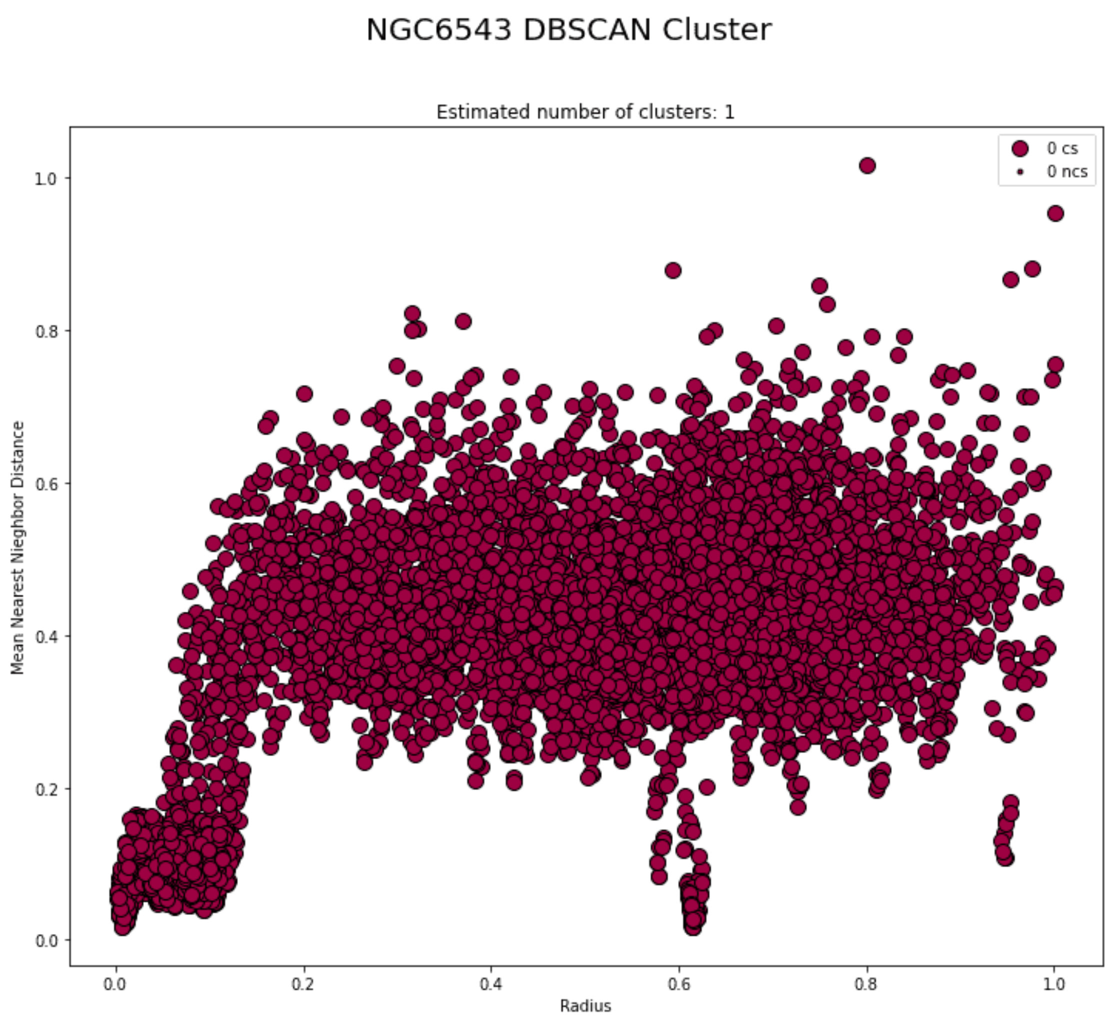
CLUSTERS AND MORE CLUSTERS!

Applying the clustering algorithm to the Chandra event table using user parameters can lead to a multitude of results, in this section of the poster, I will showcase **three possibilities** for the **NGC 6543 clustering application:**

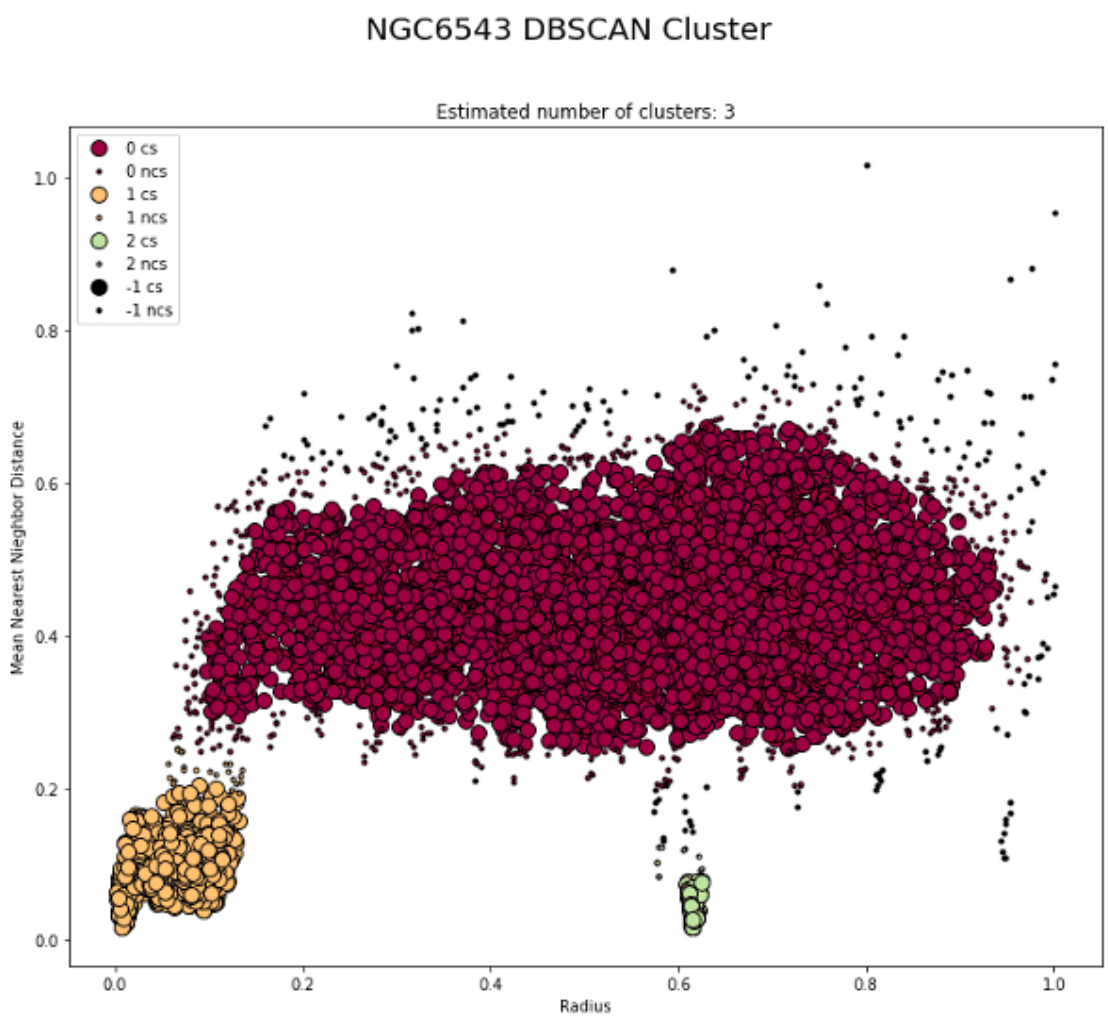
- No cluster
- One cluster
- Three clusters



Graph 5: NGC 6543’s no cluster all noise data point distribution where the user parameter values are eps = 0.0055 and min_samples = 100.

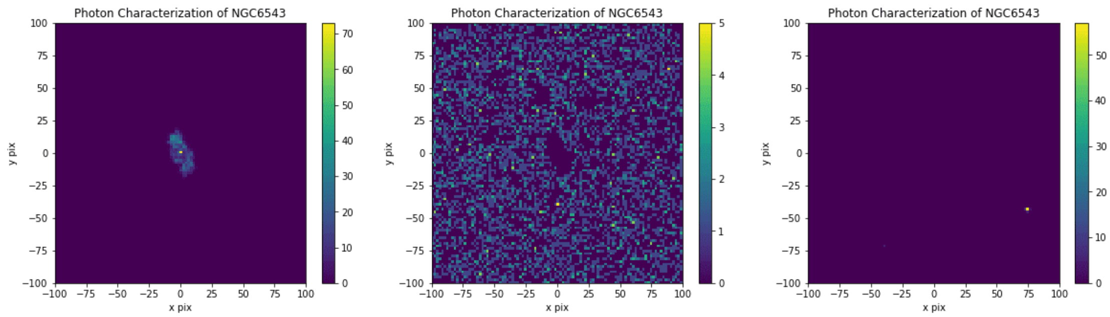


Graph 6: NGC 6543's one cluster data point distribution where the user parameter values are eps = 0.55 and min_samples = 60.



Graph 7: NGC 6543's 3 clusters data point distribution where the user parameter values are eps = 0.055 and min_sample = 60.

Notice the **relationship** between the **user parameter values** and the **number of clusters** that DBSCAN produces for the following graphs. The **higher the minimum sample parameter** and **the lower the eps value**, **the denser the data point population.** This relationship is seen throughout all the cluster possibilities.



Graph 8: NGC 6543's 3 output clusters as seen from Graph 7

What Can We Learn From the DBSCAN Clustering Algorithm?

Above are three subplots generated from the 3rd cluster DBSCAN graph. The clusters are a **physical representation** of the **different levels of spatial separation between photons**. We know that **3 clusters best represent NGC 6543** physically **because** of the **physical levels of separation** between **diffuse X-rays, center point X-rays, and noise.**

This ultimately means that **the methodology of applying a DBSCAN** clustering algorithm to a PNe can be used to **determine the unique physical characteristics of PNe.**

What have I Learned and what's next?

- I've learned how important code is!
- More time would allow for a robust algorithm for non-scaled data.
- Further research must be done into algorithms such as HDBSCAN.

DISCLOSURES

This project was supported by the CfA Research Experiences in Astronomy, Technology, & Engineering (CREATE) program. This program received federal support from the Latino Initiatives Pool, administered by the National Museum of the American Latino.

TRANSCRIPT

So, what is morphology? In this case of the planetary nebula or our nebula in NGC 6543, also known as the cat's eye nebula, morphology relates to how time changes the physical characteristics of PNe. This might not seem as a problem, but for astronomers observing PNe using Chandra, it is, and that's simply because astronomers can't look back in time to observe certain X-ray emission processes. In our case, I'm more interested in hot bubbles and point-like sources. and this leaves uncertainty because we don't exactly know when hot bubbles were formed for a planetary nebula. In this poster presentation, I attempt to tackle the question of whether we can use clustering algorithms or algorithm-based machine learning to understand how clustering relates to morphology and how we can apply that to morphology. Spoiler alert, um it works. DB scan works for the cat's eye nebula, and it not only works, it works so well that, you know, based off of the population sizes and the cluster of photons emitted from different parts of the cat eye nebula, um it recognizes the physical characteristics based off of the density populations of photons, um and it not only can do that, but it can further separate the noise from different attributes of the planetary nebula, such as the hob bubble and the white dwarf in the center. Further research suggests that more robust algorithms such as HDBSCAN can eliminate user parameters, such as eps and min_samples, which are controlled by the user.

TRANSCRIPT

ABSTRACT

At the end of a sun-like star's life, the mass lost by the star will be shaped into shells of ionized gas that are illuminated by the evolving white dwarf at the core. These planetary nebulae (PNe) are known for their dazzling morphologies primarily seen in optical emission. Less well known is the fact that PNe also emit X-rays. The formation of the nebula results in a shocked region known as a hot bubble, which emits soft X-ray photons. Occasionally, point-like sources of hard X-ray emission are also found at the core and are associated with the central star or close binary companions. Generally, hot bubble emission is detected early in the development of the PN and seems to disappear as the PN evolves, while the compact sources can persist into later stages. Identifying the presence of X-ray emission in PNe is typically performed by visual inspection. In this project, we sought a more quantitative assessment of the X-ray emission in PNe that uses machine learning algorithms. In particular, we considered multiple clustering algorithms and applied them to Chandra X-ray observations of a few PNe. PNe in our sample include some with only hot bubbles and some with compact point source emission embedded within the hot bubbles. Our analysis shows that some clustering algorithms can identify hot bubble and compact point sources. With careful tuning of the algorithm parameters, the two types of sources can be isolated into distinct clusters. As a bonus, some clustering algorithms can also spatially isolate source and background photons. However, the careful parameter tuning required to achieve isolation limits the autonomous use of the clustering algorithms. In an attempt to resolve this, we studied how the clustering algorithms perform on alternative transformations of the photon spatial distributions. We present the results of these clustering algorithm experiments and suggest future directions to apply these algorithms across similar sources with extended and compact emission. This project was supported by the CfA Research Experiences in Astronomy, Technology, & Engineering (CREATE) program. This program received federal support from the Latino Initiatives Pool, administered by the National Museum of the American Latino.

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