Decoding Nebular Oddities: Unveiling the Link between White Dwarf Positions and Irregular Planetary Nebula

Akhilesh Varanasi, Dominik Riemann[a]

[a] *University of Washington, Seattle,*

Abstract

Understanding the origins of irregularities in the shapes of planetary nebulae has been a long-standing puzzle in astrophysics. Here, we investigate the relationship between the geometric centers of planetary nebulae and the internal location of their white dwarves to find factors contributing to the irregularities of planetary nebulae. We use observations taken using ARCSAT (Astrophysical Research Consortium Small Aperture Telescope) to achieve this. We find that there is a weak causal link between the position of a planetary nebula's white dwarf and the nebula's circularity, indicating that the position of the white dwarf may be significant to the structure of a nebula. This research sets the stage for further investigations and a deeper understanding of the structure of planetary nebulae

Keywords: Planetary Nebulae, White Dwarfs

1. Introduction

A planetary nebula is comprised of the cosmic gas and dust that is ejected from the outer layers of a dying star. When stars with a mass between 0.8 and 8 solar masses die, they expand and form red giants. As the star dies it expels gas as the core contracts. The energy radiated via this contraction causes the gas to become ionized. This gives planetary nebula their distinct color and shapes. In the final stages of its life cycle, the star settles as a white dwarf with the planetary nebula surrounding it. While many planetary nebulae appear symmetric and well-defined, a significant number exhibit asymmetries that challenge our understanding of their formation and evolution.

In models of stars during the asymptotic giant branch of evolution, the stellar wind expands isotropically, leading to the formation of a spherical shell of ejected material. However, factors like magnetic fields, stellar winds, and the location of the parent white dwarf star can affect the shape (Krticka et al., 2020). In this study, we try to see how the white dwarf's position compared to the geometric center can give insight into how the structure of a nebula evolves.

Our initial hypothesis is that the further away the white dwarf is from the geometric center of a nebula, the more irregular it is. This is because hypothetically the white dwarf should have the most gravitational effect on the surrounding gases and dust, pulling the nebula clouds towards it. We begin by selecting a few nebulae to observe. Then, we discuss the data reduction process we used to transform the ARCSAT images into scientifically-usable images. We talk about what methods we used to find the position of the white dwarf and how we compared that with the nebula's circularity. Finally, we summarize our findings and discuss what steps further research would have to take.

2. Objects Observed

Nebula	RA (J2000) [h,m,s]	DEC (J2000) [o,',"]
NGC 2392	07:29:10.767	20:54:42.48
NGC 3587	11:14:47.712	55:01:08.48
NGC 6210	16:44:29.519	23:47:59.42

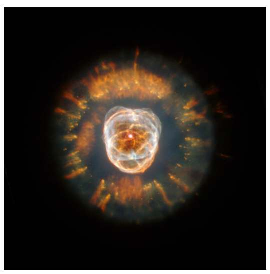
Table 1: RA and DEC for Observed Nebula

The observed objects listed in this section were selected considering a variety of factors including ellipticity, irregularity, and diffuseness. We picked nebulae relatively distinct from each other to ensure that causal links between white dwarf placement and nebulae shape could be confirmed. We also ensured that these nebulae were visible within our observing window. The limited sample size consisting of three observed nebulae represents a notable weakness of this study.

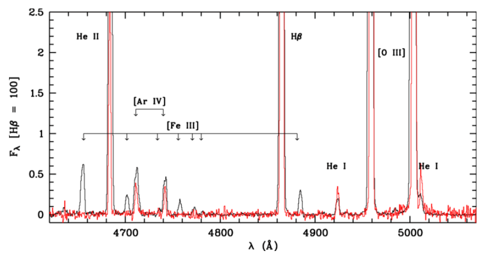
We used the ARCSAT 0.5 m Classical Cassegrain telescope to observe. It is a reflecting telescope on an equatorial mount, with a single CCD camera. The weather conditions were close to optimal for the first half of our observing period, with the airmass becoming prohibitively high for our objects around 12:30 PST.

2.1. NGC 2392

NGC 2392 is a young double-shell planetary nebula around 5000 light years away from the Earth in the constellation Gemini. It is approximately 10,000 years old. The nebula has a very unique visual shape, the center is multiple layered gaseous bubbles with filaments of dense material running through it. There is also a distinct diffuse cloud of stellar material surrounding the nebula like a shell. The spectra has FeIII, HeII, Hβ emission lines, as shown in Figure 1(b) (Zhang et al., 2012).



(a) Image captured By Hubble Space Telescope (2000)



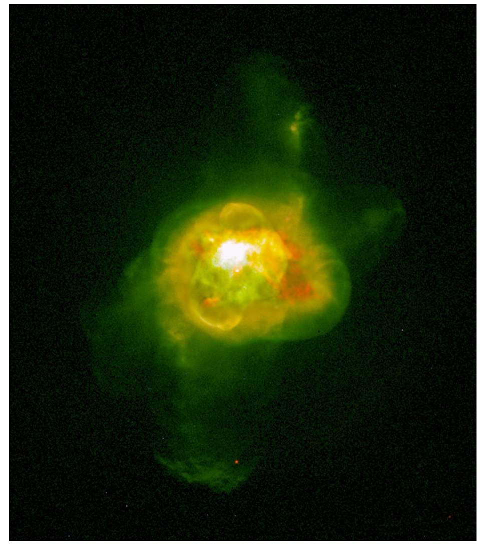
(b) YFOSC echelle spectra of the inner (black) and outer (red) regions of NGC 2392

Figure 1: Visual and Spectral Imagery of NGC 2392

2.2. NGC 3587

NGC 3578 is a planetary nebula approximately 2030 light-years away in the Ursa Major constellation. It is around 8000 years old. It has a cylindrical torus-like structure with a faint hourglass-like structure within (Sabbadin et al., 1985). The outer structure is very diffuse. The spectra has OIII, Hα, and NII emission lines.

(a) NGC 3587 captured by Kitt Peak National Observatory (2020)



(b) Image of NGC 6210 from NASA (1998)

Figure 2: NGC 3587 and NGC 6210

2.3. NGC 6210

NGC 6210 is a planetary nebula approximately 5400 light-years away in the Hercules constellation. It is relatively young, at around 2000 years old. The shape is very abnormal, roughly resembling an ellipsoid. It has a bright inner region consisting of filaments and arches and a more diffuse tubular outer region (Henney et al., 2021). The nebula has a distinctly bright central star, with emission lines at HeI, HeII, OII, and OIII wavelengths (Pottasch et al., 2009).

3. Data Collection and Reduction

3.1. Filters

We noticed that all of the nebulae shared a common peak in the spectra around 500.7 nm which corresponds to OIII and at 486.1 nm which corresponds to Hβ. We also saw that NGC 3587 had a prominent emission like at Hα. We took flats for all three of these filters and took 60s exposures with OIII and Hβ for all nebulae. We took a 60s exposure with Hα for NGC 3587. Visually, we noticed that for all nebulae the exposures with OIII had the highest level of detail so we took multiple photos and ended up using a 180s exposure for NGC 6210, 900s exposure for NGC 3587, and a 600s exposure for NGC 2392

3.2. Biases and Darks

We took 7 biases and 3 darks. The largest dark we took was 900s to match our longest exposure.

3.3. Reduction Pipeline

Using the CCD Data Reduction guide, we reduced the observation images to scientifically usable data. First, we combined the biases into a master bias and subtracted that from the darks. Then we combined and scaled the darks to fit the same exposure time as the flats. We then subtracted the darks from the flats. Finally, we normalized the flats and combined them into the master flat. The master dark, master flat, and master bias were subtracted from the images to produce science-ready data. Since we were using ARCSAT, we did not have to account for overscan. Due to planetary nebulae being diffuse and large structures, sky subtraction and PSF photometry were not possible. We used scaled circular aperture photometry to focus our image.

3.4. Causes for Error

Due to flats taking a very long time on ARCSAT, we had to use flats for OIII taken on different days. Calibration differences in the telescope on different days could have caused the master flat to be calculated incorrectly. Additionally, during the period NGC 2392 was observable in our observing window, the airmass was close to 1.5 which could have led to our images being less detailed.

4. Analysis

The initial objective was to find the geometric center of the image, the position of the white dwarf in the nebula, and the distance between these points. The data processing pipeline described above ensures that the image taken into consideration is a background-subtracted cutout image containing a single source. We define the geometric center to be the average position of elements in each dimension of the image. This calculation was performed using the ***centroid_com*** function in the python ***photoutils*** library. ***centroid_com*** considers each image axis separately, multiplies the position of each element with their value, sums these products, and normalizes the sums to find a normalized central coordinate.

The position of the white dwarf is generally considered to be the point of highest brightness, i.e. point of highest pixel density, within the nebula.

This is because the contrast in emitted wavelengths makes the white dwarf stand out in all spectrographic photos (Ahumada et al., 2019). The point of highest brightness was calculated by finding the maximum value in both the x and y axes and identifying the corresponding indices.

Distance from the geometric center to the position of the white dwarf was calculated using the formula for distance between two points on a plane

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \tag{1}$$

For NGC 2392, we can see that the calculated geometric center and the position of the white dwarf are very close. The white dwarf is at coordinate (50,50) and the center of the image is at (48.301, 49.085). Using equation (1) we see that $d = 1.929$ units.

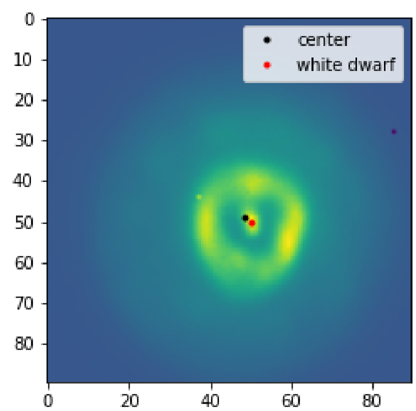


Figure 3: Position of white dwarf and center in NGC 2392

For NGC 6210, we see that the distance between the geometric center and the position of the white dwarf is more pronounced. Following a similar process as above, we see that $d = 2.55$ units

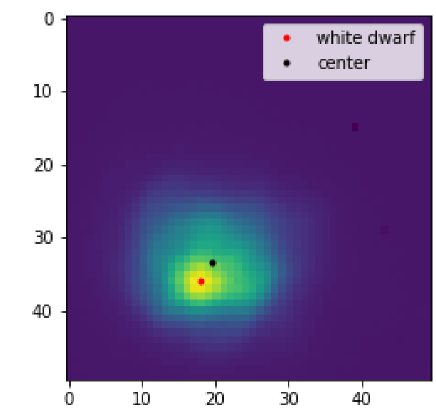


Figure 4: Position of white dwarf and center in NGC 6210

We can see that the position of the white dwarf is visibly inaccurate for NGC 3587. We speculate this is because it is by far the most diffuse nebula of the three. The geometric center is computed correctly but the position of the highest brightness is skewed by the diffuse gas/objects present in the image that cannot be accounted for in our current data reduction method. From Figure 2(a), it is clear that the white dwarf is actually present very close to the geometric center of the nebula.

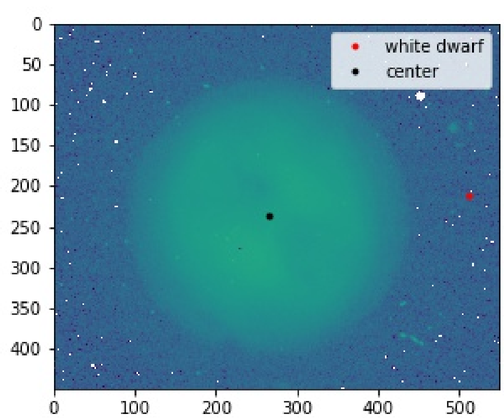


Figure 5: Position of white dwarf and center in NGC 3587

As a measure of how irregular a nebula is, we measured its circularity i.e. roundness. Circularity is defined as how closely the shape of an object mathematically approaches a circle. The definition is as follows:

$$C = \frac{4 * \pi * A}{P^2}$$

where A and P are the area and perimeter of the irregular object respectively. The closer C is to an absolute value of 1, the more circular an object is.

We used the OpenCV python library to compute circularity. First, the image was normalized and reduced to a binary format using adaptive thresholding. Adaptive thresholding considers a small set of neighboring pixels at a time, computes the threshold value for that specific local region, and then performs the segmentation between foreground and background values. This method was chosen over a simple color mask convolution due to the variation in brightness and the diffuse nature of planetary nebulae. From this segmented, binarized image contours were computed. We found the contour corresponding to the largest area and calculated its perimeter, which we used to compute the circularity.

This metric was only tested on NGC 2392 and NGC 6210 as once again, NGC 3587 was very diffuse and the FITS data did not work with the CV2 library methods.

(a) Circularity of NGC 2392 = 0.621

(b) Circularity of NGC 6210 = 0.249

Figure 6: Binarized images of NGC 2392 and NGC 6210

As we can see $C_{NGC_{2392}} = 0.621$ and $C_{NGC_{6210}} = 0.249$. This means that mathematically NGC 2392 is far more like a circle than NGC 6210. We suspect that the value for the area and perimeter in NGC 6210 is unduly affected by the gap in the contour on the edge. However, even visually it is clear that NGC 2392 has a more traditionally 'perfect' nebular structure, as the gaseous cloud has expanded more spherically away from the white dwarf at the center.

5. Discussion

Nebula	White Dwarf Offset	Circularity
NGC 2392	1.929	0.621
NGC 6210	6	0.249

Table 2: White Dwarf Offset & Circularity for Observed Nebula

The analysis of the three observed planetary nebulae, NGC 2392, NGC 3587, and NGC 6210, provided valuable insights into the relationship between the geometric center of a nebula, the position of its white dwarf, and the circularity of the nebulae. The findings indicate that there is a varying degree of alignment between the white dwarf position and the geometric center, and this alignment has implications for the circularity of the nebulae.

NGC 2392 exhibited a high degree of circularity, with a nearly symmetrical shape and a white dwarf position that closely aligned with the geometric center. This suggests that the presence of a centrally located white dwarf may play a role in shaping and maintaining the circularity of the nebula.

NGC 6210 exhibited a striking level of irregularity in its shape, with a more pronounced distance between the white dwarf and the geometric center. This offset suggests an asymmetry in the internal distribution of material, which could contribute to the observed irregular shape and lower circularity.

On the other hand, NGC 3587 was a very diffuse object, making it challenging to determine the accurate position of the white dwarf. However, based on the available data, it appears that the white dwarf is closely aligned with the geometric center.

We suspect that the gravitational influence and ejection mechanisms associated with the white dwarf contribute to the formation of symmetric and circular structures. However, the dynamics of mass ejection and the interaction between the central star and the surrounding environment can lead to the formation and evolution of asymmetrical structures in planetary nebulae.

It is important to note that in the cases of these three nebulae specifically, it is unlikely that binary star interactions at the center play a role in shaping the structure of the nebulae. This is because we did not find any evidence for multiple central stars in any of the nebulae. However, this detail should not be ruled out as a factor in shaping asymmetric nebulae.

Additionally, it should be emphasized that the low sample size of the observed nebulae is a significant limitation of this study. To establish a more robust understanding of the relationship between white dwarf positions, circularity, and irregularities in planetary nebulae, a larger sample size should be considered in future research. Additionally, incorporating multi-wavelength observations, detailed modeling, and further analysis of the physical processes driving the observed irregularities can provide a more comprehensive understanding of the interplay between white dwarf positions, circularity, and nebular morphology.

6. Summary and conclusions

These findings suggest that the position of the white dwarf plays a role in shaping and maintaining the circularity of planetary nebulae. The gravitational influence and ejection mechanisms associated with the white dwarf can contribute to the formation of symmetric and circular structures. However, the presence of asymmetries, irregular shapes, and misalignments between the white dwarf and the geometric center indicate that other factors such as stellar winds, binary interactions, magnetic fields, and the dynamics of mass ejection also influence the circularity and overall morphology of planetary nebulae.

To advance our understanding, future research should expand the sample size, employ improved data reduction techniques, and consider multi-wavelength observations. We should also consider models with more parameters, including nearby stellar objects, the age of the nebula, and stellar wind speeds and dynamics. By doing so, we can obtain more precise measurements and gain deeper insights into the physical processes involved in shaping the intricate structures, irregularities, and circularity of planetary nebulae.

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