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Isophotic Analysis of the Owl Nebula

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ABSTRACT

Isophotic contours are fitted to images of the Owl Nebula taken with the APO Arctic telescope. Four total images are analyzed with two in both the R and 5007 filter. The Nebula displays a fairly smooth brightness change with increasing radius, with the exception of two bright spots and two dim spots along the Northwest to Southeast axis and Southwest to Northeast axes, respectively. These dim spots are confirmed as the eyes of the Nebula and are regions of low density material. The outer shell, inner shell and central cavity are resolved and compared to the findings of previous analysis.

1. INTRODUCTION

1.1. *Planetary Nebula*

Planetary Nebula are formed from the ionized gas created as a low mass star moves through the late stages of the red giant branch. As the star moves along the asymptotic giant branch gas and dust are ejected out into the space surrounding the star, thus forming a complex gaseous nebula. These emission nebulae often span light years in diameter and with densities ranging from 100 to 10,0000 particles/cm^3 [2]. While they have no relation to planetary formation these nebula got their name in the 1780s when they were resolved as misty looking planets. Despite their large size planetary nebula typically only last a few tens of thousands years [2], a rather short period in the astronomical senses. However,

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during these short lives they play a crucial role in stellar evolution. This gas can be studied and by taking spectroscopic data can have its, and thus the central star's, composition determined. In addition, this ejected gas and dust often forms complex structures and by dispersing gas through the star's stellar neighborhood, spark future stellar growth. While the shape of the nebula is partially due to non-inherent factors, like the viewing angle, much of the variation in shape is not well understood.

1.2. *Owl Nebula*

The Owl Nebula (Messier 97) is located 0.62 kiloparsecs away in the constellation Ursa Major and is approximately 0.28 parsecs in diameter [6]. The nebula was first discovered by French Astronomer Pierre Mechain and was not named until William Parson observed it in 1848 and drew an image (Figure 1) vaguely resembling an owl. Through spectroscopic analysis its composition has been determined to be about 0.13 $M_{\odot}$ of gas mainly consisting of hydrogen, helium, nitrogen, oxygen, and sulfur.[1] The Owl Nebula is unique in its almost perfectly round structure, presenting an opportunity to attempt to better understand Nebula structure. As with all planetary nebula its lifetime is short in astronomical terms due to its outward velocity of 27-39 km/s [1] causing rapid dispersion.

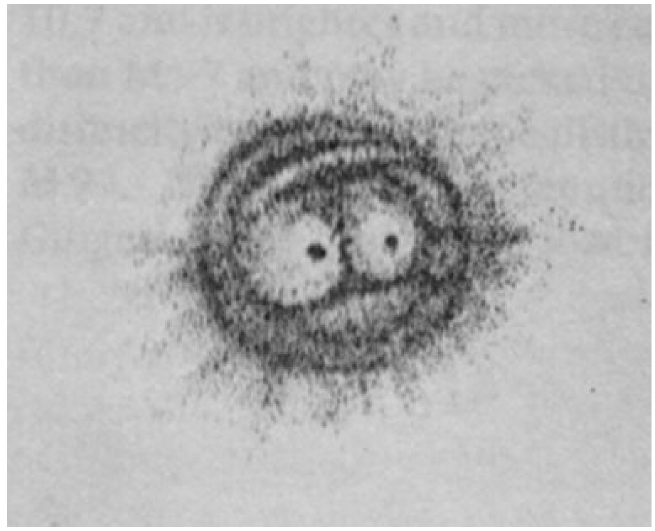

Figure 1: The first owl nebula drawing by William Parson

The nebula is broken down into three sections, the halo, outer shell, and inner shell. The central star of the nebula is a 14th magnitude white dwarf star which has stopped its ejection of gas into the nebula and will slowly radiate its heat away. The star was resolved by Spitzer and determined to have an effective temperature of about 123,000 kelvin and about 60 % the mass of the sun.[1]

1.3. *Isophotes*

Isophotes are lines of constant brightness that can be superimposed onto images of astronomical objects. These lines allow one to see and understand the structure of the object imaged. They also provide a visualization of the distribution of material within the image, allowing one to better understand the key features of the object. In the case of nebula, isophotes allow us to better understand its late stage stellar lifetime. This analysis has been crucial in understanding how gas becomes redistributed within galaxies and has been used to understand the structure of galaxies and their evolution.

1.4. *Purpose and Layout*

In this paper we analyze the structure of the Owl Nebula with isophotic contours. We use this analysis to better understand the evolution of the nebula and use this information to compare to past research and our current understanding of planetary nebula to check for any inconsistencies. We outline the observational methods, data reduction process, and finish with an analysis, comparison of the data with previous studies and conclusion.

Arctic CCD Information	
Number of rows	4096
Number of columns	4096
Pixel size	15
Gain	2.00 electrons/DN
Readout noise	3.7 electrons
Field of View	7.5 arcmin
Platescale	0.228 ”/pix, binned 2x2

Table 1: CCD Specifications from the Apache Point Observatory website [4]

2. OBSERVATION

Our data was taken with the 3.5 meter ARC telescope at the Apache Point Observatory in New Mexico on April 31st and May 1st. The telescope was operated remotely by Professor Tuttle remotely from the University of Washington. The first night only flats and biases were obtainable due to poor weather conditions, on the second night images were obtained of M97, the Owl Nebula. Six images were taken with the SDSS R,G, and 5007 filter with two in R, two in 5007, and two in G. Bias frames and flats in the R, G, I, U, Halpha, and 5007 filter were also collected prior to exposure. Data was taken in multiple filters to allow for distribution analysis and comparison of isophotes across wavelengths.

Exposure Time and Filter Information		
Image	Filter	Exposure Time
1	R	60
2	R	300
3	5007	300
4	5007	300

Table 2: Raw data observation information

3. DATA REDUCTION

Upon receiving the data all images were broken into six separate files based on the image filters. These were the R, I, U, Halpha, G, and 5007 (OIII) filters. Each folder contained all the biases taken that night, the flats that were taken in that specific filter, and all raw data taken from that filter. However, due to time constraints and weather, raw data was only obtainable in the R, G, and 5007 filters. Of these, flats were only obtained in the R and 5007 filters. This left us with four images that had flats in the same filter to analyze.

Filter	Type	Wavelength(Angstroms)
R	Broad-Band	5300-7000
OIII	Narrow band	5007

Table 3: Filters used for raw data collection and specifications.

3.1. *Bias Subtraction and Flat Normalization*

In order to account for instrumental noise, bias subtraction and flat normalization was performed. This is an important step in any astronomic data analysis because it allows one to isolate the signal from the source itself. After working through the data it was found that the flat normalization was yielding wildly inaccurate results. Working back through the subtraction and normalization it was found that the outer regions of the flat images from the CCD were reading values that were more than an order of magnitude different than the central pixels. This is likely due to an instrumental error in the CCD, but could also have been an error in the flat exposure process. In order to account for this issue each image (bias, flat, and data) were reduced down to the center 1300 by 1300 pixels, where the CCD read a more or less constant value. This number was chosen by visual inspection with the goal of keeping all the data from the Owl Nebula and removing as much of the outer region irregularities as possible. Utilizing the astropy library in python we began by subtracting our biases. Biases present the inherent noise produced by the CCD and electrons in excited state. This can be isolated in a frame by taking a zero second exposure. Five biases were taken during the observation night and these were all added together and divided by five to get an average bias image. Once this image was obtained it was subtracted from the flats and raw data images to remove instrumental noise.

With the bias removed we moved onto flat normalization. A flat image refers to an image that exposes the CCD to a uniform light source to measure any pixel to pixel variation in sensitivity to light. In theory each pixel will receive the same amount of light and the instrumental error in readout can be isolated. In our case the flats were performed by exposing the telescope to a light source projected onto the dome ceiling of the observatory. It is important to note that all flats must be performed in their respective filters since different wavelengths will have different efficiency of detection. Each set of flats in the same filter were added together and averaged out. This new image was then divided by the mean of the entire image, thus normalizing the flat. By dividing it by its own mean it gives a fractional value of that pixels read out relative to the rest of the CCD. This means that the image can now be used to correct for the pixel sensitivity seen in the data from errors in individual pixels light detection. The resulting image now has the form:

$$\frac{data - bias}{combinedflat/mean} \tag{1}$$

3.2. *Sky Subtraction*

The image has now been corrected for instrumental errors but the sky signature is still present. In order to account for this the photutils package of python was used. With this package we placed two annuli around the Owl Nebula of inner radius 485 pixels and outer radius 490 pixels. Between these annuli relatively few stars were present and this allowed us to calculated the pixel count and average pixel read of the entire annulus to obtain a fair estimate of the sky signature. Once this value was obtained it can simply be subtracted from the data and will then give a signature of just the Nebula without erroneous background noise.

This method was then compared to a method of choosing a relatively dark patch of sky, finding the mean count of the region and using that as your average sky signature. This gives the benefit of being able to completely eliminate any stellar objects within your chosen background, but the region must be much smaller which also leads to the potential error of under estimating the sky signature. While both methods have their own personal flaws and benefits, when the background noise was calculated with both methods the result were within 10 pixel counts of each other. This background can simply be subtracted from the raw data to finally isolate the Owl Nebula data.

Because of the Nebula's faint structure this type of subtraction can lead to some errors in the data. If the atmospheric correction is too high then the subtraction can lead to negative pixel counts. This is obviously impossible but was a problem that occurred in a small subset of the Nebula data.

Since a contour fits a line across constant pixel count and the sky correction subtracts a constant value across the entire nebula this subtraction had no effect on where the contours were or their shape. However, this hinges on the assumption that the sky had a perfectly constant brightness across the nebula. This is not always the case and more sophisticated sky subtraction should be performed to resolve any inconsistencies in the atmospheric correction.

3.3. *Isophotes*

With the raw data now reduced to source data, surface brightness analysis can be performed to analyze the nebulas structure. To obtain the isophotes SAOImageDS9 was used. The four images were loaded and isophote analysis was performed by using the built in contour function. This tool uses the pixel read out to map lines of constant pixel value to show where a isophotes exists. By increasing the smoothness we eliminated small isophotes that surround stars and other small constant brightness area. This isolates the larger isophotes and allows us to resolve the shape and better study the large scale structure of the nebula. This isolation was done by visual inspection of the images to attempt to isolate the lines that represent the actual nebula. A linear scale was used on all images with 17 isophotes fitted on images 1 and 2 and 20 on images 3 and 4. Fitting by visual inspection can become a large source of potential error and can cause discrepancies when comparing to other data and when analyzing our data amongst itself. This is because we are using previous assumptions of the nebula's structure to resolve its structure. While this is likely a correct assumption based on the current literature it can still be a source of error. This was partially accounted for by using the same isophotic contours on images 3 and 4 which were both in the same filter and exposure time. However, the two images taken in the R filter had varying exposure times and thus plotting the same contours would not yield the same result. To account for this the contours were selected to match the general shape of the previous images. This, however, means that the selected contours were chosen to fit the other data and could lead again to inaccurate results based on previous assumptions that the past data is correct.

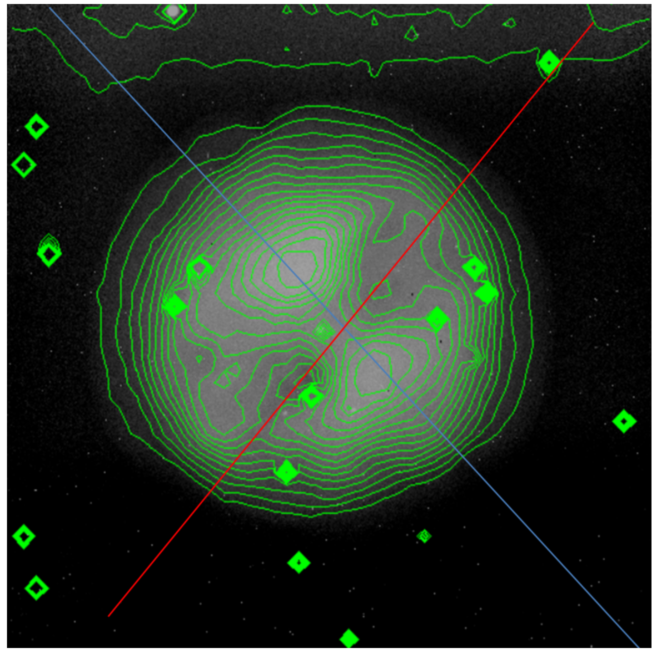

Figure 2: M97 contour map image 3 in the 5007 filter with the red (Southwest to Northeast) and blue (Northwest to Southeast) axes.

4. ANALYSIS

4.1. *5007 Filter*

Images three and four are taken in the 5007 filer and have the same value contours mapped to them. Due to these images being taken in the same filter, having the same exposure time, and being taken in the same night the two should, in theory, be near copies of each other. However, a few differences emerge on visual inspection. First, figure 3 displays erroneous lines outside the nebula. These are likely due to changing sky conditions, or other external factors. To check the data to confirm that

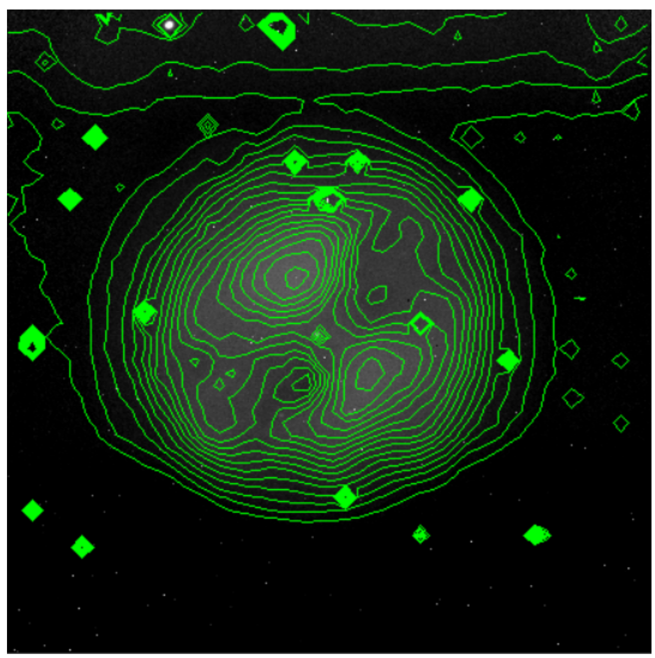

Figure 3: M97 contour map image 4 in the 5007 filter

there was not a large scale error a small sample of 7200 pixels was taken from a region in the top left of each image and their mean count, min max and standard deviations were compared. Their means were found to vary by 39 pixel counts with standard deviations varying by 7 counts. These are relatively small variations and supports the idea that these contours are likely caused by small differences in the image setup between exposures. Since contours fit lines of equal pixel count small variations can lead to completed lines that are not present in other images. While this can dramatically change the look of the image these can be discarded because of the small variations in pixel count and their placement on the image being outside of the Owl Nebula.

Moving into the nebula from the outside the halo can be resolved as the region of loosely packed contour lines. This corresponds to a low surface brightness that stays relatively constant moving inward. As one moves further towards the center the lines spacing decreases and becomes relatively constant in the outer shell. This means that the Nebula is steadily getting brighter with decreasing radius. Further inward one reaches the inner shell where the circular symmetry is lost. Contours begin to encircle two bright regions along the axis from the northwest corner to the southeast corner and two dim regions along the southwest to northeast axis (these are drawn in 2 and referred to in the rest of the paper as the blue and red axis, respectively) . These dim regions are known as the eyes of the owl. The central star can also be resolved as the central square contours.

4.2. *R Filter*

When looking at the R filter images a similar structure emerges. When comparing figures 5 and 4 their structures are largely the same. Due to these two images having varying exposure times (image 1 with a 60 second and image 2 with a 300 second) direct contour matching could not be done by simply using the same isophotes. To compensate for this the isophotic lines were chosen so the appearance of the two images resembled each other. This is a possible source of error as the data did not allow a direct comparison and we used assumptions from the data to match our other data.

The halo in each case is resolved in a similar fashion as the 5007 filter, as the region between the largest circular contour with sparsely populated lines and the region of more compactly packed contours. Moving inward a similar size outer shell is present and resolved again by an increase in contour line density while still circularly

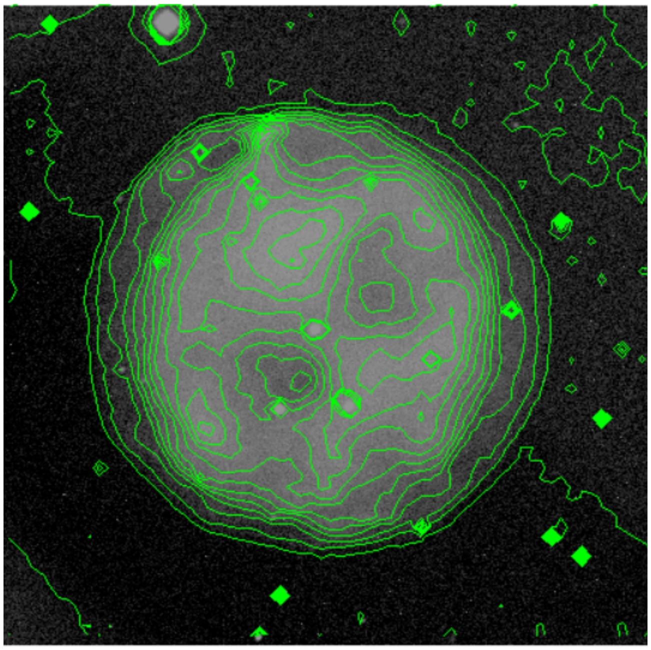

Figure 4: M97 contour map image 2 in the r filter

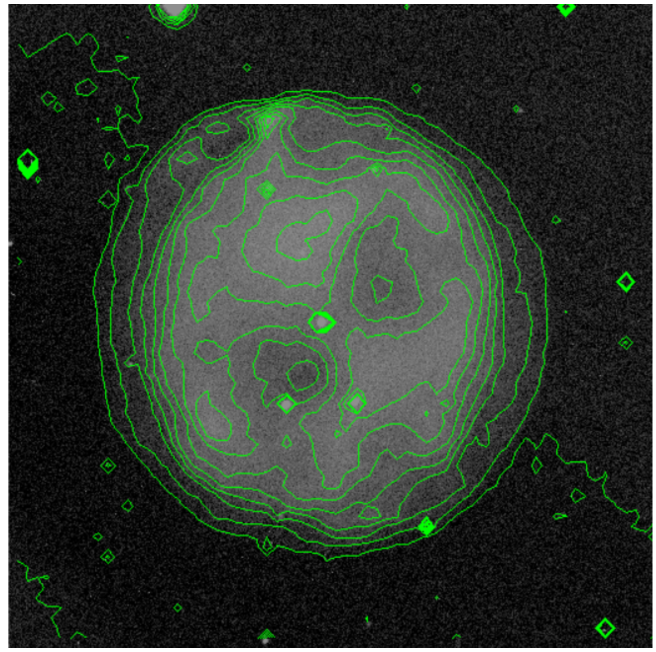

Figure 5: M97 contour map image 1 in the r filter

symmetric. The inner shell, however, takes on a distinct form from the 5007 filters. Image 1 and 2s contours lose their uniformity compared to the 5007 images. This is possibly due to the filters. Since 5007 is a single OIII line and R is a broad band filter much more background noise may exist may exist in the R filter. This background will distort some of the lines and create variations in the isophotes. Despite these visual differences closer inspection reveals that the general form of all four images is the same. Both the R and 5007 images have bright regions on the blue axis that are encircled by the isophotes and two dim regions on the red that can be resolved.

5. COMPARISON TO OTHER STUDIES

Having resolved the structure of the Owl Nebula we now seek to compare it to previous literature to compare and contrast results. Minkowski and Aller used data from a 200 inch reflector telescope to resolve the nebula [5]. They performed an analysis in the OIII filter and fit isophotic lines with a logarithmic scale to the structure. Figure 6 resolves our OIII images (3 and 4) with a logarithmic scale for comparison. When comparing the data many of the features are nearly identical. The halo and the outer shell resolve as nearly spherical while moving inward to the inner shell the symmetry breaks. The contours in Minkowski et al resolve the two bubbles along the blue axis that can be visually seen in our contours. While these regions are not resolved by complete closed isophotes they can be seen by the large inward indents in the isophotes. This suggests that these same bubbles should be resolvable in our data by changing parameters of the contours to more closely analyze the internal structure.

An additional paper written by Guerrero and Chu performed a multiband analysis of the Owl Nebula [3]. They resolve the two dimmer central cavities of the Nebula (along the red axis) as the eyes of the Nebula. Additionally, They provide an explanation of the Planetary Nebula's formation. The outer region of the nebula is believed to be caused by the early mass loss and subsequent winds from the stars asymptotic giant branch phase. After this stage the stellar winds compressed and formed the inner shell and ejected material further out, thereby creating the central cavities. These regions are now being back filled by the inner shell. This is supported in our data by their presence but a velocity dispersion must be obtained to confirm the direction of gas around the bubble and confirm these results.

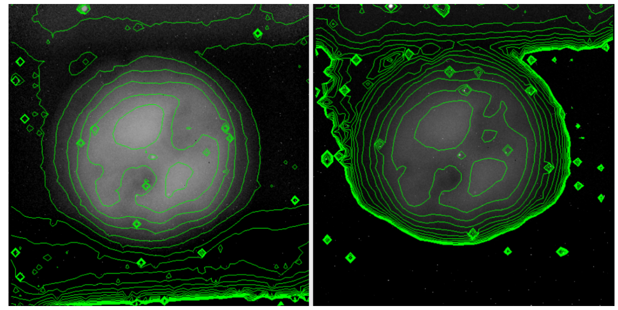

Figure 6: Images 3 and 4 in Log scale contours

6. CONCLUSION

Data was collected of the Owl Nebula from the Apache Point Arctic telescope. The images were then reduced and had sky subtraction performed, resulting in two images in both the R and 5007 filter. Isophotic contours were fitted to the nebula to resolve its structure revealing a roughly circular shape with a halo, outer shell, and inner shell. Within the inner shell two central cavities of lower surface brightness and two of increased surface brightness were resolved. The data was then compared to previous studies to compare and contrast results. Results were confirmed by visual inspection to match past results by Minkowski et al and an analysis by Guerrero and Chu showed that the resolved central cavities were formed by the stellar winds compression and ejection of material from them. These cavities are now believed to be collapsing inward and the gas around them filling the regions.

While the structure of the Owl Nebula was successfully resolved more questions about the nebula's formation and future still remain. In order to confirm the results of Guerrero and Chu a velocity map of the gas within the nebula would need to be obtained. Since the nebula is not perfectly side on, one would be able to measure the radial velocity and can analyze the data for evidence of the gaseous velocity components around the central cavities having inward velocities. Additionally, gathering more images in various narrow band filters will allow us to better understand the distribution of certain elements within the nebula. Since the nebula is mostly composed of hydrogen, helium, oxygen, and sulphur, analysis of these other three elements would be the mostly beneficial. Finally, spectroscopic data can be obtained to further analyze the composition of the nebula and, since the nebula is composed of the material from the central star, better understand the star's life and evolution.

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