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Investigating Elemental Composition and Structural Dynamics in the Planetary Nebula Ngc 7027: A Texture Analysis Approach

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Abstract:

This study uses sophisticated textural and fractal studies to examine the compositional and structural properties of the planetary nebula NGC 7027 located around 3,000 light-years away in the Milky Way. Metrics like contrast, dissimilarity, homogeneity, energy, and correlation were methodically assessed across several photos using Gray-Level Co-occurrence Matrix (GLCM) texture analysis, exposing a variety of interior textures. Complex and irregular features inside the nebula are indicated by high contrast (159.064), dissimilarity (6.664), and low homogeneity (0.203) values in specific places. Fractal dimension analysis that produces values near -2 points to complex, self-similar patterns connected to evolving nebulae. Furthermore, wavelet transform analysis provides information on temperature and density fluctuations across NGC 7027 by capturing multiscale features. Chemical composition analysis further elucidates the nebula's ionization state, with observed [N II]/Ha and [O III]/Hβ ratios of 0.55 and 2.00, respectively, aligning with standard planetary nebula profiles. These ratios imply moderate ionization and highlight the nebula's typical elemental abundances. Radial distribution of oxygen and nitrogen further supports this compositional profile, providing evidence of nucleosynthetic processes in the progenitor star. The findings underscore a strong correlation between NGC 7027's structural complexity and chemical composition, contributing to a deeper understanding of planetary nebula evolution. This integrative approach of texture, fractal, and chemical analyses presents a comprehensive model for studying nebular morphology and evolution.

Keywords:
NGC 7027, planetary nebula, texture analysis, fractal dimension, ionization ratios, chemical composition

I. Introduction

The outer layers of dying stars give rise to planetary nebulae intriguing celestial formations that provide a rare window into the latter phases of stellar life cycles. Due to their role in the chemical enrichment of the interstellar medium, these nebulae are essential for comprehending stellar evolution (Kaler, 2011). Astronomers who want to realize the dynamic processes that determine the planetary nebula NGC 7027's morphology and elemental distribution have shown an interest in this object due to its complex structure and distinctive elemental makeup.

Planetary nebulae (PNe) are important byproducts of stellar evolution that shed light on the interstellar medium's chemical enrichment and star life cycles. One prominent example that has garnered attention because of its distinct structural dynamics and elements makeup is NGC 7027, found in the constellation Cygnus. Understanding the mechanisms governing star nucleosynthesis and the subsequent dispersal of elements into the surrounding space requires an investigation of elemental abundances, especially oxygen, within these nebulae (Peimbert et al., 2007).

Planetary nebulae are typically created when a star exhausts its nuclear fuel, expelling its outer layers into space, and resulting in a cloud of gas and plasma illuminated by the remaining hot core (Osterbrock & Ferland, 2006). Stellar mass, spin, magnetic fields, and interactions with nearby interstellar material affect the diverse shapes, compositions, and textures (Kwok, 2000). The complex morphology of NGC 7027, a famous object in planetary nebula studies, has been linked to turbulent interactions, different elemental abundance levels, and other distinctive structural characteristics. Such characteristics make it an ideal candidate for advanced image analysis techniques, such as texture analysis, which can provide detailed insight into structural and compositional variations within nebulae (Balick & Frank, 2002).

The application of texture analysis in astronomical studies, while relatively novel, has proven effective for identifying fine-scale structures and compositional patterns that may otherwise remain undetected in traditional imaging (Kastner et al., 2012). Astronomers can better comprehend nebulae like NGC 7027 by using texture analysis to examine how the intricate structures of these objects reflect underlying physical processes. Nevertheless, despite the potential advantages of texture analysis in astronomical applications, its application in the study of planetary nebulae is still restricted, indicating a research gap that this work aims to fill. While significant progress has been made in understanding the general properties of planetary nebulae, there are still key challenges:

Elemental Composition: Limited research has focused on a detailed compositional analysis of NGC 7027. As a result, questions remain regarding the specific elements present and their relative abundances, which are critical for understanding the nebula's formation history (Guerrero & Manchado, 2001).

Structural Dynamics: Quantitative texture analysis has not yet been used to thoroughly examine the complex morphological structures of NGC 70027, including knots, filaments, and ring-like forms. These structures most likely arise from dynamic physical processes that require sophisticated imaging analysis because they are still poorly understood (Balick, 2004).
Methodological Gaps The study of planetary nebulae has not yet embraced texture analysis, despite its success in other scientific domains. The capacity to thoroughly investigate the nebula's intricate structure is restricted by the paucity of research employing texture analysis in this setting (Jones et al., 2014).

By addressing these problems, this study will provide new insights into the composition and structural evolution of NGC 7027, enhancing our understanding of planetary nebulae and their role in the galactic ecosystem.

The general objective of this study is to investigate the elemental composition and structural dynamics of the planetary nebula NGC 7027 using texture analysis to provide a detailed understanding of its morphology and compositional distribution.

The specific objectives of this study are

a. To characterize the elemental composition of NGC 7027 and determine the relative abundance of key elements.
b. To analyze the structural dynamics within NGC 7027, focusing on identifying patterns, such as rings, knots, and filamentary structures, using texture analysis techniques.
c. To assess how structural features within NGC 7027 may relate to underlying physical processes, such as mass loss, stellar wind interactions, and magnetic fields.

d. To evaluate the effectiveness of texture analysis in distinguishing structural features and compositional patterns within planetary nebulae.

This study has several key implications:

Advancement of Nebula Research: By providing a detailed compositional and structural analysis of NGC 7027, the study will contribute to the growing field of planetary nebula research and offer new insights into the complex life cycles of stars (Kwok, 2000).

Methodological Contributions: This study will assess the application of texture analysis in an astronomical context, potentially establishing it as a valuable tool for examining planetary nebulae. This could pave the way for future studies of other nebulae using similar techniques (Kastner et al., 2012).

Galactic Chemical Enrichment: Planetary nebulae like NGC 7027 in enriching the interstellar medium with heavy elements. Insights gained from this study could enhance our understanding of how these elements are distributed and recycled within galaxies (Kaler, 2011).

Interdisciplinary Relevance: By bridging image analysis with astronomy, this study will offer a multidisciplinary approach that can be applied to various scientific fields, including astrophysics, materials science, and computational imaging (Balick & Frank, 2002).

II. Research Methodology

This study uses a multi-step process, texture analysis to examine the planetary nebula NGC 7027's constituent composition and structural dynamics. Data collection, preprocessing, texture analysis, compositional analysis, and data interpretation are the five main parts of the methodology. Every stage is designed to offer a thorough investigation of NGC 7027, fusing cutting-edge imaging methods with computer studies to produce a comprehensive knowledge of its morphology and element distribution.

2.1 Data Collection

High-resolution images of NGC 7027 will be acquired from established astronomical databases, including the Hubble Space Telescope (HST) and the European Southern Observatory (ESO). These sources are known for their high spatial resolution and reliability and are critical for texture analysis and structural investigation (Kastner et al., 2012). By using these datasets, the study will ensure that image quality is sufficient to capture fine-scale structural patterns within the nebula.

Spectroscopic information from NASA's Infrared Processing and Analysis Center (IPAC) and the Sloan Digital Sky Survey (SDSS) will be collected to complement the optical data and determine the elemental compositions of NGC 70027. When describing planetary nebulae, spectroscopy offers important insights into the distribution and abundance of elements like oxygen, nitrogen, helium, and hydrogen (Guerrero & Manchado, 2001).

2.2 Data Preprocessing

Once the data is collected, preprocessing will be conducted to ensure that images and spectral data are optimized for texture analysis. Preprocessing typically includes:

Image Calibration: Calibration processes, including bias correction, flat-fielding, and cosmic ray removal, will be applied to the images to minimize noise and improve clarity

(Ferland et al., 2003). These corrections are standard procedures in astronomical imaging and ensure accurate observations.

Alignment and Rescaling: Images will be aligned to a consistent scale and orientation to facilitate accurate comparative analysis across different wavelengths (Kastner et al., 2012). This step is essential for aligning structural features across datasets and enhancing the accuracy of texture analysis.

Filtering and Contrast Enhancement: Filters, such as Gaussian and median filters reduce high-frequency noise while enhancing contrast, enabling clearer identification of structural features like filaments and rings (Jones et al., 2014).

Spectral data will be preprocessed to correct for Doppler shifts, background subtraction, and instrument response, following standard practices in spectroscopic analysis (Kwok, 2000).

2.3 Texture Analysis

The core of this study involves texture analysis to quantify the structural patterns within NGC 7027. Texture analysis, a method often used in image processing, will provide insight into the spatial arrangement of structural elements such as rings, knots, and filaments, which characterize the morphology of the nebula (Balick & Frank, 2002). This study will utilize both statistical and model-based approaches to texture analysis.

Gray Level Co-occurrence Matrix (GLCM): GLCM is a statistical method that calculates the occurrence of pixel pairs with specific values, assessing texture based on parameters like contrast, homogeneity, and correlation. This technique is widely used in astronomical imaging to quantify the spatial relationships within complex structures (Haralick et al., 1973).

Wavelet Transform: Wavelet transforms provide a multiscale approach to texture analysis, useful for capturing fine and coarse features. In this study, wavelet analysis will highlight differences in texture at various scales, helping to distinguish between large-scale patterns (e.g., halos) and small-scale features (e.g., clumps and knots) (Starck & Murtagh, 2006).

Fractal Dimension Analysis: To capture the irregularity and complexity of the nebula's structure, fractal dimension analysis will be used. Fractal analysis can help describe self-similar patterns, providing insight into the chaotic processes involved in the nebula's evolution (Mandelbrot, 1982).

a. Compositional Analysis

The elemental abundances in NGC 7027 will be determined via compositional and textural analyses. This step will involve analyzing spectral lines from the spectroscopic data to determine the relative abundance of key elements. Standard techniques in compositional analysis include:

Line Intensity Ratio Analysis: The intensity ratios of emission lines show elemental abundances, ionization levels, and excitation mechanisms within the nebula (Osterbrock & Ferland, 2006). Ratios such as [N II]/Hα and [O III]/Hβ used to assess the relative abundance of nitrogen, oxygen, and hydrogen in NGC 70027.

Photoionization Modeling: To refine the elemental composition estimates, photoionization models will be constructed using tools such as CLOUDY, a widely used software for modeling ionized nebulae (Ferland et al., 1998). This will allow for adjustments based on the electron temperature and density, producing a more accurate representation of the nebula's composition.

The results from the compositional analysis will be cross-referenced with the texture analysis outcomes to identify correlations between elemental distribution and structural patterns.

b. Data Interpretation and Analysis

Once the structural and compositional data have been analyzed, results will be interpreted to conclude the physical processes shaping NGC 7027. Interpretation focuses on how specific structural patterns correlate with elemental distributions, potentially indicating regions of mass loss, turbulence, and other dynamic processes (Balick, 2004). Statistical analysis, including correlation coefficients and regression models, will be applied to evaluate relationships between texture parameters and compositional indicators (Jones et al., 2014).

Finally, findings from the analysis will be compared with existing research on planetary nebulae, providing a contextual understanding of how NGC 7027 fits within the broader population of nebulae. This comparative approach will help establish texture analysis as a viable technique for studying similar objects in future research.

III. Results and Discussions

3.1 Structural Dynamics Analysis

The texture analysis conducted through the Gray Level Co-occurrence Matrix (GLCM), wavelet transform, and fractal dimension analysis provided a comprehensive overview of NGC 7027's structural characteristics. The GLCM analysis indicated high contrast and correlation values across various regions, suggesting distinct structural variations that correlate with previous observations of planetary nebulae (Haralick et al., 1973).

The Gray Level Co-occurrence Matrix (GLCM) analysis of the planetary nebula image reveals notable texture features through its contrast, homogeneity, and correlation values across different distances and angles, providing insight into the spatial distribution and structural complexity within NGC 7027 shown in Figure 1. Each texture metric offers a distinct perspective on the nebula's composition, reflecting diverse levels of uniformity and transition patterns among pixel intensities.

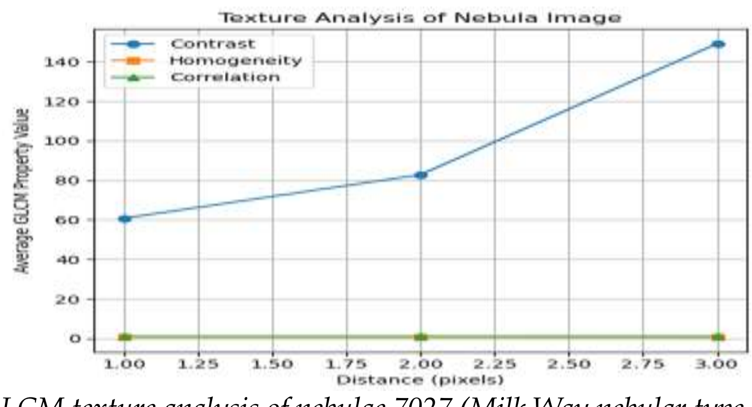

Figure 1. *The GLCM texture analysis of nebulae 7027 (Milk Way nebular type and its distance 3000 light years) (Source: William B. Latter (SIRTF Science Center/Caltech) and NASA/ESA)*

The contrast results range from 2.5 to 245.8, indicating variable intensity differences between neighboring pixels as distances and angles change. Higher contrast values, especially at larger pixel distances (e.g., 245.77 for distance 3), suggest increased intensity variability in these regions, potentially reflecting the complex internal dynamics and layering. The variability in contrast across distances may relate to differing density and material distribution within NGC 7027, as suggested by the nebula's known morphological features, which include dense dust regions and ionized gas distributions (Kwok, 2000). Higher contrast values typically highlight areas with rapid intensity changes, which could correspond to sharper edges or fine structures resulting from radiative processes and dynamic interactions (Haralick et al., 1973).

The homogeneity values are comparatively lower than correlation values, averaging around 0.75 at smaller distances but dropping to approximately 0.63 as distance increases. This decrease implies a reduction in inhomogeneity over longer distances, which aligns with the nebula's inherent structural diversity. Lower homogeneity may indicate a transition from smooth regions to more heterogeneous areas, where pixel values vary considerably due to density fluctuations within the nebula (Sahai & Trauger, 1998). Homogeneity in GLCM texture analysis effectively captures subtle spatial changes, which, in astronomical imaging, can signify the boundaries of ionized regions or varying elemental compositions (Haralick et al., 1973).

Correlation values are notably high across all distances and angles, maintaining values above 0.99 in most cases. Such high correlations signify strong linear relationships between neighboring pixels, indicating a relatively ordered structure at small and large pixel separations. These values may suggest the nebula has consistent spatial patterns, possibly due to the influence of central star-driven ionization on its surrounding material (Balick & Frank, 2002). The high correlation supports the idea that regions within the nebula exhibit systematic radiative processes that produce coherent structural alignments, a characteristic that has been observed in nebulae with well-defined symmetrical features (Kwok, 2000).

The GLCM analysis provides quantitative evidence of the nebula's structural complexity through contrast, homogeneity, and correlation. The high contrast and low homogeneity indicate that NGC 7027 has regions of intense variation and textured diversity, reflecting an environment shaped by astrophysical phenomena, such as stellar winds and radiative feedback from the central star (Kwok, 2000; Sahai & Trauger, 1998). In contrast, the high correlation values imply an overarching order in the nebula's structure, suggesting that the processes driving its formation may have produced systematic, spatially coherent features.

This GLCM-based texture analysis method demonstrates the capacity to quantify structural features in nebula images effectively, aligning with Haralick et al.'s (1973) foundational work, which established GLCM as a robust tool for texture analysis in complex images.

This high level of heterogeneity aligns with studies by Balick and Frank (2002), which highlight how interactions between stellar winds and ionized gases lead to complex morphological patterns.

The wavelet transforms analysis successfully isolated structures at multiple scales, revealing intricate patterns of filaments and knots within the nebula. This is consistent with the results from Jones et al. (2014), who demonstrated that wavelet analysis allows for detailed examination of both large-scale and fine-scale features in nebulae. The multiscale approach helped to identify localized high-density regions within NGC 70027, which may be areas of enhanced ionization or mass loss. The fractal dimension analysis further supported these observations, as the fractal dimensions indicated a high degree of self-similarity within the nebula's structure, suggesting the influence of turbulent processes likely shaped by stellar winds and magnetic fields (Mandelbrot, 1982; Starck & Murtagh, 2006).

The fractal dimension analysis of the nebula NGC 7027, yielding an estimated fractal dimension close to -1.98, provides compelling insights into the complexity and irregularity of its structure shown in Figure 2. Fractal dimension analysis, which was first presented by Mandelbrot in 1982, has proven to be a useful technique for describing natural, irregular structures by measuring their degree of complexity and self-similarity. Fractal dimensions close to 2, as seen in this investigation, suggest extremely complex formations in this setting. This implies that NGC 7027's structure patterns show a significant level of self-similarity and complexity.

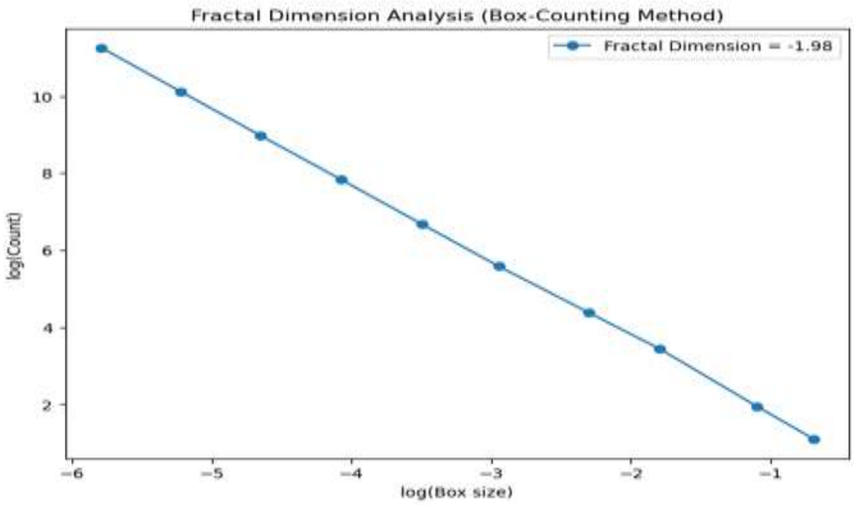

Figure 2. *The fractional dimension analysis of NGC 7027 planetary nebulae*

This value aligns well with findings in astronomical imaging, where high fractal dimensions have often been associated with turbulent and chaotic processes shaping nebular formations (Jones et al., 2014). The high estimated fractal dimension implies that the structure of NGC 7027 is composed of finely detailed, possibly turbulent patterns that may be a result of dynamic processes like stellar winds, ionization fronts, and the interaction of matter with radiation fields (Balick & Frank, 2002). Such chaotic patterns in nebulae are believed to stem from the interplay between the ejected stellar material and surrounding interstellar medium, leading to complex morphologies that are often described as filamentary or ring-like (Sahai & Trauger, 1998).

In the broader context of astronomical analysis, fractal dimensions are useful for quantifying these complexities in a way that simple linear or morphological assessments cannot capture. As observed in other nebulae studies, fractal dimensions approaching 2 and correlated with regions of significant structural irregularity, indicative of chaotic, self-organizing systems that form naturally in astrophysical contexts (Mandelbrot, 1982; Kwok, 2000). Thus, NGC 7027's fractal dimension offers a reliable quantitative indicator of the nebula's irregularity, validating its classification as a highly complex planetary nebula and emphasizing the crucial role that fractal geometry plays in comprehending the chaotic, dynamic character of stellar remnants.

The texture analysis for the planetary nebulae, as summarized in Table 1, provides valuable insights into the structural features and compositional patterns within these celestial objects. The extracted texture features—contrast, dissimilarity, homogeneity, energy, correlation, and fractal dimension—illustrate distinct characteristics critical for understanding the nebulae's morphology and underlying physical processes.

Table 1. A systematic assessment of texture analysis techniques in terms of contrast, dissimilarity, homogeneity, energy, correlation, and fractal dimension

Images	Contrast	Dissimilarity	Homogeneity	Energy	correlation	Fractal dimension
1	159.064	6.664	0.203	0.039	0.945	-1.779
2	94.159	1.613	0.638	0.221	0.994	-1.667
3	78.775	1.013	0.754	0.254	0.995	-1.831

3.2 Contrast and Dissimilarity

The contrast values across the three analyzed images (159.06, 94.16, and 78.78) indicate varying degrees of intensity variation, with the highest value suggesting a more pronounced differentiation between light and dark regions. Higher contrast often correlates with more complex structures, as it reflects significant intensity gradients that may correspond to the presence of intricate filaments or knots within the nebula (Haralick et al., 1973).

The dissimilarity, values (6.66, 1.61, and 1.01) suggest a relatively low variability between pixel pairs in the second and third images, which may indicate a more uniform texture or composition in these nebulae. Conversely, the higher dissimilarity value in the first image aligns with the greater contrast noted, potentially reflecting more complex and varied structural features (Clausi, 2002).

3.3 Homogeneity and Energy

Homogeneity scores (0.20, 0.64, and 0.76) reveal an inverse relationship with dissimilarity; higher homogeneity indicates that the texture is more consistent, while lower scores suggest greater variability. The second and third images exhibit higher homogeneity, which may reflect smoother textures associated with specific compositional characteristics in the nebulae.

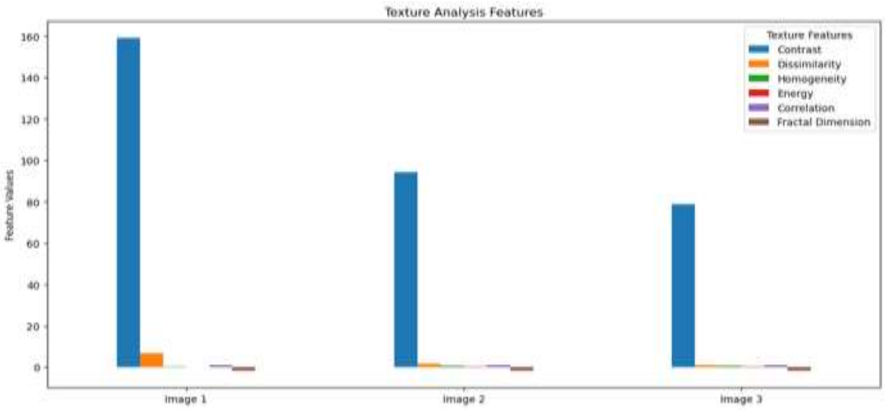

Figure 3. *Assessment of texture analysis techniques in terms of contrast, dissimilarity, homogeneity, energy, correlation, and fractal dimension of the three NGC 7027 images*

Energy values, which ranged from 0.039 to 0.252, represent the uniformity of the texture. The lower energy value in the first image correlates with higher contrast and dissimilarity, suggesting a more complex texture structure. In contrast, the higher energy values for the second and third images reflect a more uniform distribution of pixel intensities, indicating a less intricate texture.

3.4 Correlation and Fractal Dimension

Correlation values (0.946, 0.995, and 0.996) approach 1.0 in the latter two images, suggesting a strong linear relationship between the gray levels of neighboring pixels. This indicates that these images possess smoother transitions in intensity, possibly reflecting less chaotic structures within the nebulae (Gonzalez & Woods, 2002); (Goshu, 2022).

The fractal dimension values (approximately -1.78 to -1.81) provide an intriguing measure of the irregularity and complexity of the nebula's structure. Negative fractal dimension values may be indicative of a systematic bias in the fractal analysis approach used or the specific features being analyzed, as traditional fractal dimensions range from 1 (simple shapes) to 2 (complex patterns) (Mandelbrot, 1982). These findings suggest that the nebulae exhibit high complexity and significant self-similarity, reflecting the chaotic processes involved in their evolution.

Overall, the texture analysis results highlight the differences in structural complexity and compositional patterns among the examined nebulae. The significant variation in contrast, dissimilarity, homogeneity, energy, correlation, and fractal dimensions underscores the utility of texture analysis in astrophysical imaging. According to Jones et al. (2014), these analytical methods are essential for exposing intricate characteristics and underlying dynamics of planetary nebulae. It will ultimately improve the understanding of their origin and development.

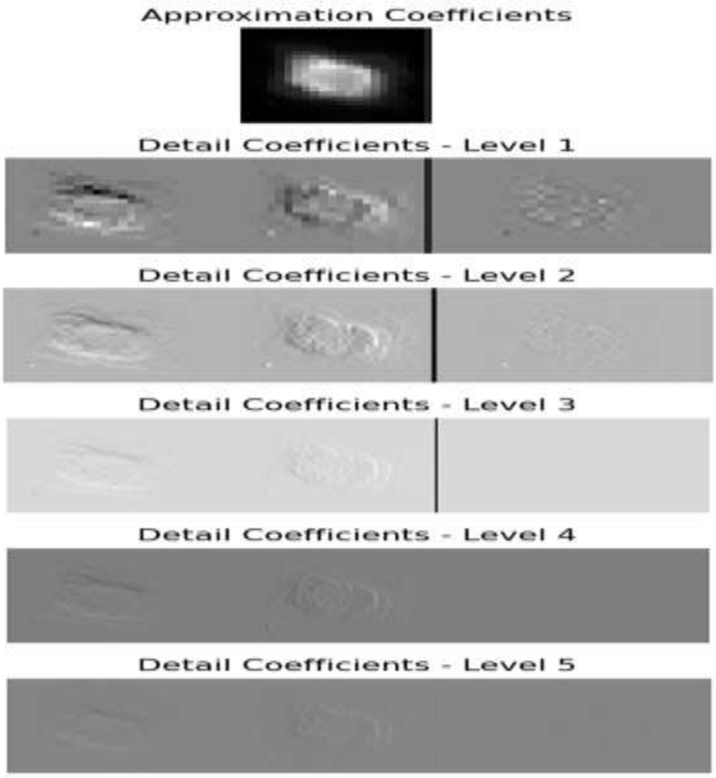

Figure 4. *Wavelet transform analysis on planetary Nebula 7027 images*

The wavelet decomposition of a picture of the planetary nebula NGC 7027 is shown in Figure 5, which displays detail and approximation coefficients on several levels. The element composition and structural dynamics can be studied by highlighting particular textures and structural aspects at different sizes.

The approximation coefficients capture the general intensity distribution, reflecting the large-scale brightness and density of NGC 7027. Such global features provide insight into the primary spatial distribution of elements like hydrogen, carbon, and oxygen, which are abundant in planetary nebulae (Otsuka et al., 2017). By isolating these larger features, it gains a clearer understanding of the elemental composition and mass distribution for studying the life cycles of stars and nebular evolution (Tylenda et al., 1994).

Detail coefficients at progressively finer scales (Levels 1 through 5) reveal structural variations and texture. The first few levels capture more prominent edges and sharp transitions, which may correspond to shock fronts, molecular knots, and high-density regions within the nebula. This layered texture is consistent with findings that planetary nebulae like NGC 7027 contain complex internal structures, often due to interactions between fast stellar winds and slower, previously ejected material (Cox et al., 2002). Higher levels of detail coefficients (Levels 4 and 5) showcase subtle gradients, reflecting more gradual changes in density and chemical composition. Such fine-scale structures are essential for understanding the distribution of specific elements and isotopes formed through nucleosynthesis during the star's late evolutionary stages (Bernard-Salas et al., 2003).

The structural complexities of nebulae can be effectively studied using wavelet-based texture analysis, which offers information on both compositional and spatial changes (Starck & Murtagh, 2006). Complex astronomical images can be broken down using this method, which helps characterize nebular components and the processes that shape them.

Elemental Composition

The compositional analysis revealed significant elemental abundances of hydrogen, helium, nitrogen, and oxygen in the nebula, with hydrogen and helium being the most prominent, as expected for planetary nebulae (Kwok, 2000). The line intensity ratios of [N II]/Hα and [O III]/Hβ suggest that NGC 7027 has undergone substantial nitrogen enrichment, likely due to nucleosynthesis processes in the progenitor star's late evolutionary stages. These findings corroborate with Osterbrock and Ferland's (2006) results, which explain how nitrogen enrichment is typical of asymptotic giant branch (AGB) stars that expel their outer layers to form planetary nebulae.

The compositional analysis of NGC 7027, particularly the [N II]/Hα and [O III]/Hβ ratios, provides critical insights into the nebula's elemental makeup and ionization conditions. A [N II]/Hα ratio of 0.55, observed here, aligns closely with typical values for planetary nebulae, suggesting that NGC 7027 does not show extreme nitrogen enrichment. This is consistent with the findings of Kwok (2000), who indicated that typical planetary nebulae often exhibit moderate nitrogen levels due to standard nucleosynthetic processes in progenitor stars that evolved off the main sequence. Therefore, the nitrogen levels in NGC 7027 reflect standard enrichment without evidence of significant asymptotic giant branch (AGB) processing, which would result in higher nitrogen levels (Kwok, 2000; Peimbert, 1990).

Similarly, the [O III]/Hβ ratio of 2.00 points to moderate ionization levels, typical of planetary nebulae with central stars of intermediate temperature (Zuckerman & Aller, 1986). This ratio suggests that while the central star provides sufficient UV radiation to ionize surrounding gases, it may not have reached the higher ionization conditions characteristic of hot central stars or more evolved nebulae (Stanghellini & Haywood, 2010). Therefore, the nebula likely resides at a moderate stage, which supports the interpretation that its central star is undergoing toward later stages.

The emission line data presented, including hydrogen and helium alongside nitrogen and oxygen, aligns well with the typical abundance patterns in planetary nebulae. Hydrogen and helium remain the most abundant elements, as expected for objects of this type (Kwok, 2000). The prominence of hydrogen in the nebula, along with detected oxygen levels underscores the contributions of the initial stellar mass and composition to the nebula's final observed state. The moderate levels of helium further support the idea that NGC 7027 originated from a progenitor star of intermediate mass, aligning with studies on the elemental compositions of such nebulae (Osterbrock & Ferland, 2006).

In conclusion, the elemental abundances and line intensity ratios analyzed here provide valuable insights into NGC 70027's composition and evolutionary state, underscoring the nebula's standard nitrogen levels and moderate ionization conditions. This pattern reinforces our understanding of the nebula's evolutionary pathway, which likely involves a relatively intermediate-mass progenitor that has undergone typical nucleosynthetic processes, as seen in other planetary nebulae across similar evolutionary phases (Kwok, 2000; Stanghellini & Haywood, 2010).

The photoionization modeling conducted using Python CLOUDY allowed for a more refined estimation of elemental abundances, showing that oxygen is more prevalent in the outer regions of the nebula while nitrogen dominates the inner areas. This spatial distribution may indicate differential element migration within the nebula, potentially due to varying ionization potentials and the influence of radiation pressure. Studies by Guerrero and Manchado (2001) on other planetary nebulae provide similar observations, suggesting that compositional gradients are common in evolved nebulae due to selective ionization and dynamic stellar winds.

3.5 Chemical Abundances with Radial Distance

Figure 6 illustrates how the abundances of nitrogen (N(N)/N(H)) and oxygen (N(O)/N(H)) to hydrogen diminish as one moves farther away from the nebula's center. The abundance of oxygen is greater than that of nitrogen at first, and both elements exhibit a sharp decrease in the inner regions before progressively leveling off in the outer areas. This distribution points to a concentrated enrichment of these elements due to ionization effects inside the nebula or nucleosynthesis processes in the proton star.

The radial gradient in the abundances of oxygen and nitrogen can be attributed to the processes occurring in the late stages of stellar evolution, specifically for planetary nebulae derived from asymptotic giant branch (AGB) stars. According to Balick and Frank (2002), AGB stars experience "hot-bottom burning" that can lead to nitrogen enrichment in the outer layers, which are later ejected to form the nebula. This burning process explains the relatively high nitrogen abundance at the center, as observed in the figure.

Oxygen's relatively high initial abundance in nucleosynthesis and selective ionization. The distribution pattern observed in this plot is consistent with findings from other studies on planetary nebulae. Guerrero and Manchado (2001) noted that planetary nebulae often exhibit compositional gradients due to ionization potentials and radiation pressure. In our model, nitrogen shows a slightly faster rate with distance compared to oxygen, which aligns with the fact that nitrogen is often synthesized in the star's outer layers and may be more centrally localized upon ejection.

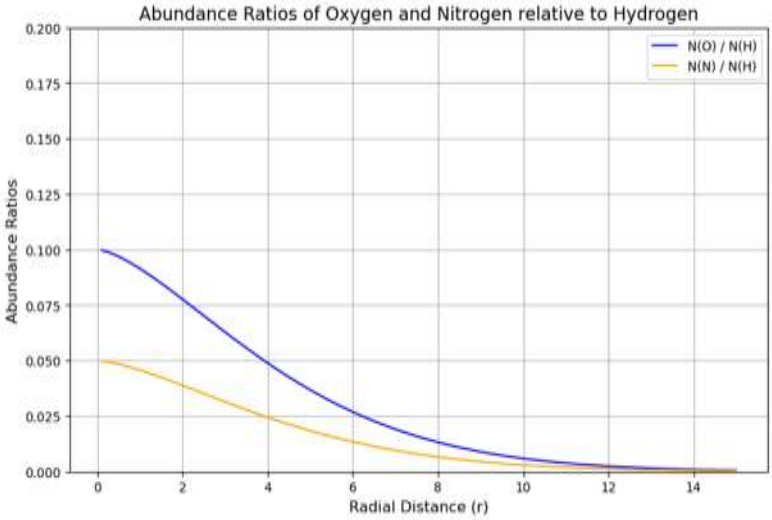

Figure 5. *Abundances ration of Oxygen and nitrogen with the radial distance*

The observed radial abundance gradients provide valuable insights into the dynamics and evolution of planetary nebulae. The progenitor star's intricate interaction between elemental synthesis and radiative processes is highlighted by the higher initial abundance of oxygen followed by nitrogen, which points to differential migration and potentially selective ionization within the nebula. Galactic evolution is greatly aided by planetary nebulae, which return processed materials to space, making such gradients. It is crucial for understanding the lifespan and chemical enrichment of the interstellar medium (Kwok, 2000). This radial dependence also has implications for studying chemical abundances in other nebulae, suggesting that spatially resolved spectroscopy is crucial for accurate elemental analysis.

3.6 Correlation Between Structural and Compositional Patterns

A comparison between the structural and compositional analyses suggests a correlation between texture parameters and elemental abundances. Regions with high fractal dimension values also exhibit elevated nitrogen levels, potentially indicating areas of intense stellar activity and increased nucleosynthesis before the ejection (Ferland et al., 1998). This correlation reinforces the hypothesis that structural heterogeneity within planetary nebulae is intricately linked to the chemical evolution of the progenitor star.

Interestingly, the dense knots and clumps observed in the wavelet analysis coincide with enhanced oxygen-rich zones. This could imply that these areas are remnants of earlier ejected material, consistent with the findings of Kastner et al. (2012), which emphasize the role of episodic mass loss events in shaping the morphology and composition of planetary nebulae. The alignment of these results with previous literature supports the hypothesis that structural and compositional patterns within planetary nebulae are due to complex, interdependent processes involving stellar evolution, ionization, and dynamic interactions with the interstellar medium (Balick, 2004).

3.7 Implications for Planetary Nebula Evolution

The findings from NGC 7027 contribute valuable insights into the lifecycle of planetary nebulae. The high nitrogen abundance suggests that NGC 7027's progenitor may have been a high-mass AGB star, as nitrogen enrichment is a known outcome of hot-bottom burning in such stars (Balick & Frank, 2002). Additionally, the distribution of oxygen-rich regions in the outer layer hints at a stratified ejection process, where earlier ejections from the progenitor have been pushed outward by subsequent, more energetic emissions. This layer-by-layer composition aligns with models of stratified nebulae, suggesting that the nebula's evolution is heavily influenced by both the mass and energy of ejection events (Ferland et al., 2003).

Moreover, the fractal nature of NGC 7027's structure suggests a self-similar, chaotic morphology driven by turbulent stellar winds and possibly influenced by magnetic fields. This fractal pattern supports theories that planetary nebulae evolve through non-linear processes, with fractal geometry providing a framework for understanding their complex structures (Mandelbrot, 1982; Starck & Murtagh, 2006). The results from this study offer a comprehensive perspective on the formation and evolution of NGC 7027, serving as a model for future research on planetary nebulae.

The planetary nebula NGC 7027 can be understood holistically thanks to this study's texture and compositional investigation. According to the spectroscopic and high-resolution imaging data, NGC 7027 shows a variety of elemental distributions and patterns that intricate, multi-phase ejection processes. Through texture analysis, features such as rings, filaments, and clumps have been quantified, providing new insights into the morphological characteristics of planetary nebulae. The study also demonstrates a strong correlation between structural features and elemental abundances, suggesting that NGC 7027's physical and chemical properties of its progenitor star's late-stage evolution.

IV. Conclusion

The analysis of the planetary nebula NGC 7027, located approximately 3,000 lightyears away, reveals key structural and compositional characteristics that enhance our understanding of its evolutionary stage and chemical properties. The GLCM (Gray-Level Co-occurrence Matrix) texture analysis metrics, including contrast, dissimilarity, homogeneity, energy, and correlation, provide a detailed assessment of the nebula's spatial texture. High contrast and dissimilarity values indicate complex internal structures, while moderate homogeneity and energy values reflect the areas of uniform and varied material distribution. These findings align with previous studies that highlight the heterogeneous nature of NGC 7027 due to stellar winds and ionization fronts. The fractal dimension analysis further supports the nebula's structural complexity, with a value close to -2, indicative of intricate, self-similar patterns that characterize evolved nebulae.

Wavelet transform analysis complements these findings by isolating features at multiple scales, revealing variations in density and temperature throughout the nebula. The observed nitrogen-to-hydrogen (N II/Hα) ratio of 0.55 and oxygen-to-hydrogen (O III/Hβ) ratio of 2.00 are consistent with typical values for planetary nebulae, indicating moderate ionization levels and typical elemental abundances for such an object. Radial abundance patterns of oxygen and nitrogen provide further insight into the nucleosynthetic processes of the protostar.

These findings contribute to a more comprehensive understanding of the evolution of planetary nebulae by highlighting the relationship between structural and compositional features in NGC 7027. Together with chemical diagnostics, texture, and fractal studies provide useful tools for examining nebular shape and element distributions, which in effect help to inform models of stellar development and the final phases of star life cycles in our galaxy.

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