Morpho-kinematics study of planetary nebula Sh 2-71 based on astrophysical 3-d modeling

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Abstract. A planetary nebula is formed when a low to intermediate mass star approaches the end of its life. Before the ejected materials finally interact with and dissipate into the interstellar matters, the nebula will be visible surrounding its former stellar core. The variety of planetary nebulae visual appearances indicates that the material ejected and leave the central star behind in unique ways. Morpho-kinematics study aims to find out the 3-d shape using the help of imaging and spectroscopic observations. Imaging allows on to observe the projection of planetary nebulae onto the plane perpendicular to the line of sight to the observer, while spectroscopy gives the ability to infer the expansion characteristics from the spectrum produced by shells within planetary nebulae. We report the 3-d shape modeling of Sh 2-71 (PNG 035.9-01.1, α(J2000.0) = 19ʰ01ᵐ59.96ˢ, δ(J2000.0) = 02°09'16.1") using images obtained from Gemini Multi-Object Spectrograph (GMOS), Hong Kong/Australian Astronomical Observatory/Strasbourg Observatory Ho Planetary Nebula (HASH PN Database), and DSS image combined with high-resolution long-slit spectra from San Pedro Mártir Kinematic Catalogue of Planetary Nebulae. The 3-d modeling is carried out with software that specializes in modeling three dimensional astrophysical object SHAPE. The acquired data from observations show that Sh 2-71 possesses a torus with three bipolar lobes while modeling by SHAPE tells that the torus is inclined by 37° and the bipolar lobes are on the same plane.

1. Introduction

Planetary nebulae (PNe) are produced by low to medium mass stars. When these stars enters the final stage of asymptotic giant branch phase (AGB) in their evolution, the stellar radiation pressure is increasing more than its gravity force. This causes ejection of the stellar atmosphere, leaving only its core consists of carbon and oxygen. Temperature at the core continues to rise until it reaches ~30000 K and be able to generate enough energy to ionize atoms in the surrounding nebula. Then, a planetary nebula is formed. During this process, the nebula also suffers constant changes in terms of optical depth of the expanding shell, photoionization conditions, and nebular shapes [1]. All of these changes contribute to the variety of PNe morphology. Thus, a study of PNe morphology is crucial to understand PNe as a whole.

However, PNe morphology determination suffers from instrumental sensitivity, atomic species, and projection effects [2], meaning the determination of planetary nebulae morphology...
and its actual shape is not a simple task. While photographic images only provide a two-dimensional integration of the emission and absorption along the line of sight, and that the depth information is flattened, its expansion velocities obtained from its spectra in the form of position-velocity diagram can then be utilized together with the images to estimate its three-dimensional shapes.

Sh 2-71 was first discovered by Rudolph Minkowski in 1946. It was named Sh 2-71 because it is the 71st object in the second catalog compiled by American astronomer Stewart Sharpless. Sh 2-71 has a bright torus structure and three pairs of lobes with various orientations [3], surrounded by a ring-shaped outer shell structure [4]. The lobes are thought to be created at different times due to their differences in expansion velocities. This is known from their unique expansion velocities. The most accepted explanation for the origin of this complex structure is the presence of a multiple star system at the center of Sh 2-71 ([5], [6]). It is estimated that Sh 2-71 has such a shape as a result of the mass transfer mechanism and a number of mass ejections that occur many times.

This research aims to reconstruct morpho-kinematic model of Sh 2-71 using morpho-kinematic modeling code SHAPE to picture its three dimensional shape with kinematic data combined with images of Sh 2-71.

2. 3-d Modeling
Morpho-kinematics model of Sh 2-71 was constructed using SHAPE program [7]. SHAPE is a modeling and analytical tool for the study of astrophysical objects that can be run interactively. Using SHAPE, a three-dimensional model of the nebula can be reconstructed based on the constraints obtained from the image and long-slit spectra. The projection image and position-velocity diagram (PV diagram) will be generated which will then be compared with the obtained image and PV diagram from observation.

The user first determines the basic form of the PN. Then the user can adjust the physical parameters and kinematics information into the desired component. Among the aforementioned parameters are the characteristics of velocity, density, and size. After all known information has been input into the model, the rendering module is run to produce image projections of the model onto a two-dimensional plane, as well as the spectra or the PV diagrams. The rendering results are then compared with the information obtained from observations. If there is a mismatch, the user can change the input of the previous model by returning to the 3-d module. This can be continued until a model is most similar to that shown by observations. The program provides facility to take difference of the observed and the rendered images, and the best fit of data and model is carried out by eye estimation. At first, the parameters are varied in a larger range. Afterwards, the parameters are narrowed down to certain range, beyond which significant deviation from the observation has been noticed.

3. Data
3.1. Imaging
The Sh 2-71 image was obtained by accessing the Gemini Multi-Object Spectrograph (GMOS) database and Digitized Sky Survey (DSS) image. The obtained image is available in various wavelengths as shown in figure 1. It appears that the shape of the PN gets more complex at the longer wavelength filter. The main feature that appears in each image is a structure in the form of distorted torus of disk. The Hα and [SII] filters show structures bulging in various directions. This structure is known to be bipolar lobes that have different sizes and velocities.

3.2. Spectroscopy
The spectroscopic observation data used were obtained from the San Pedro Mártir Kinematic Catalog of PNe [8] by directly requesting the spectra of the required object via the email address
Figure 1. Sh 2-71 images in [OIII] (upper left), HeII (upper right), Hα (lower left), and [SII] (lower right).

Figure 2. MES-SPM slit positions (see text for explanation of slit positions).

listed in the catalogue. The observations were done at Observatorio Astronomico Nacional San Pedro Mártir (OAN-SPM), Mexico using a telescope with diameter of 2.1 m and focal ratio of f/7.5. The spectrograph used is the Manchester Echelle Spectrograph (MES) [9]. Equipped with SITE-3 (512x512 pixels), TH2K (682x615 pixels), and E2V-4240 (682x618 pixels) CCD detectors. There are 12 slits with positions as depicted in figure 2. Spectra at slit positions of a, c, d, e, f, were taken using the SITE-3 detector on 21, 26, and 27 June 2004. Spectra at slit positions of b, h, i, j, k, were taken using the E2V-4240 detector on 7 and 8 August 2011. Spectra at the g and l slit positions, taken using a TH2K detector on 25 and 26 August 2010. The spectrum obtained has a wavelength range from 6540 Å to 6590 Å.
4. Results
There are several patterns show the structures found in Sh 2-71 (Figure 5). There are three pairs of bulges from Bipolar Lobe 1 (BL1), Bipolar Lobe 2 (BL2), and Bipolar Lobe 3 (BL3) as displayed in figure 4. From their spectral lines, BL2 and BL3 appear to have a shell structure.

Several adjustments on the modifiers (density, velocity, size, and squeeze), constrained by the image and spectra information, were done, which resulted in a single most satisfactory model explained below. The three-dimensional shape of Sh 2-71 was reconstructed with the following informations: 1) the existence of torus structure, and 2) three bipolar lobes. The torus was modeled with an outer radius of 90° and an inner radius is 50°. The torus was built with inclination of 35°-40°. In the modeling of bipolar lobes, a spherical shape was used by adding a
The size of BL1 and BL2 was the same, namely 150" while BL3 has a length of 120". The bipolar lobes were arranged in such a way that they resemble the appearance obtained on the images of Sh 2-71. The input in the form of a velocity trend assumed that the velocity in the PN increases linearly with increasing distance. Based on the PV diagrams we determined the velocity of the torus, BL1, and BL2 and BL3 respectively at 14 km/s, 60 km/s, 40 km/s, and 40 km/s. The density trend for the torus is constant, while the lobe density trend is adjusted according to the image and PV diagram, for the BL1 structure, the density decreases with increasing distance, while BL2 and BL3 have a trend of higher density with increasing distance.

After the model is reconstructed, rendering was carried out to produce a projected image of the model shape and the corresponding PV diagram. The rendering also gave results in the form of a PV diagram (Figure 9) sequentially displays PV diagrams on slits a, c, f, g, i, j, and l for wavelength [NII]. A pattern similar to the position-velocity spectrum/diagram for each slit is seen in figure 3.
Figure 6. PV diagrams from several slits as well as its structural markings are associated with figure 5.

Figure 7. Left: Sh 2-71 3-d model. Right: 2-d projected model.

Table 1. Parameters of 3-d morphological model of Sh 2-71.

| Component | Position Angle | Size  | Velocity |
|-----------|----------------|-------|----------|
| Torus     | -              | 90”   | 15 km/s  |
| BL1       | 72°            | 150”  | 60 km/s  |
| BL2       | 34°            | 150”  | 40 km/s  |
| BL3       | 20°            | 120”  | 40 km/s  |

5. Conclusions
We study the morphology of PN Sh 2-71 by computing model that is satisfactorily constrained by the observations. We reconstructed 3-d morphology from the 2-d image and long-slit spectra using SHAPE. We find that the overall projection of the 3-d morphology (Figure 7 and 8) matches well with the observed image as well as the PV diagrams (Figure 9). The image difference in figure 8 clearly shows a good resemblance between the observed and rendered image.
Based on the modeling described in the previous section, it is estimated that Sh 2-71 possesses components with parameters as shown in table 1. The expansion velocity of the torus is in agreement with the general characteristics of PNe expansion. Meanwhile, the high expansion velocities of the lobes are due to different causes. The expansion velocity of BL1 is thought to
be related to the torus shape in such a way that it creates a collimated flow. BL2 and BL3 on the other hand, as proposed by Cuesta and Phillips (1993) [10], originate from ejections due to material falling into the central area of the PN and subsequently blown outwards in high velocities. Miranda et al. (2005) [3] Also suggested that the bipolar lobes could be the result of episodic fast wind correlated with its multiple central stars.

The information obtained from this work can then be used as a guide in further modeling, including regarding the photoionization characteristics of PN to improve the accuracy of the modeling, which in turn can be used more fully to explore the characteristics of the central star which has been considered as a system with three stars. Further modeling especially regarding its fine structures such as filaments and knots which can also be seen from PN imaging is still needed to produce a more thorough understanding of Sh 2-71 global morphology.

Acknowledgments
We wish to thank Faculty of Mathematics and Natural Sciences of Institut Teknologi Bandung (FMIPA ITB) for supporting this work under PPMI FMIPA ITB 2021 Grant Number 60/IT1.C02/SK-TA/2021. And we also thank Dr. J. A. López for kindly providing us the high resolution long-slit spectra data.

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