Spectroscopy and Photoionization Model of Planetary Nebulae : NGC 6543 and NGC 7662

Evaria Puspitaningrum[1], **Hakim Lutfi Malasan**[1], **Hideyo Kawakita**[2]

[1]Astronomy Study Program, Institut Teknologi Bandung, Jl. Ganesha No. 10, Bandung 40116, Indonesia

[2]Koyama Astronomical Observatory, Kyoto Sangyo University, Kyoto, Japan

E-mail: evaria.p@gmail.com

Abstract. Spectroscopic observations in the wavelength range of $\lambda\lambda 4000 - 8000$ Å of the planetary nebulae (PN), NGC 6543 and NGC 7662, have been undertaken in 2014 using the compact spectrograph attached to the 28-cm Schmidt-Cassegrainian reflector at Koyama Astronomical Observatory. We derived physical parameters of NGC 6543 and NGC 7662 from the analyses of observed emission lines, i.e. electron temperature, density, and elemental abundances. To obtain more reliable physical quantities of NGC 6543 and NGC 7662, the use of photoionization model is needed. We use the computer code, CLOUDY C13.3 to build detailed photoionization models of NGC 6543 and NGC 7662. Model of NGC 6543 and 7662 can be constructed by providing sufficient information on physical parameters of the central stars and the nebula. In this work, input parameters to construct the photoionization model of NGC 6543 and NGC 7662 are distance, temperature and luminosity of central star and nebula parameters. The model results were compared with observational result taken in 2014. Observed and modeled temperatures were deduced from [O III] $\lambda\lambda(4959 + 5007)$ Å /λ4636 Å and the electron density from [S II] $\lambda\lambda$ 6716/6731 Å. There are some discrepancies between observed and modeled due to limitations inherent with the resolution and quality of spectroscopic data. Further spectroscopic observations with higher resolution of NGC 6543 and NGC 7662 is recommended.

1. Introduction

Planetary nebulae (PN) are isolated nebula, which are actually shells of gas that have been blown up in the fairly recent past by their central stars [8]. They emit strong emission-lines such as the recombination lines (hydrogen and helium) and collisionally excited lines of light elements that are observed in their optical spectra. Forbidden lines and two-photon emission were discovered from the study of PN [12],[8].

NGC 6543 is a helical nebula which lies near the north ecliptic pole. The spectral-line study of this PN is by [4]. NGC 7662 is a bright and spherical nebulae, the spectral-line study in the optical is by [3]. Harrington [2] did the photoionization modelling work on this PN.

The main target of this study is to construct a photoionization model of planetary nebulae by using information from the observation, especially low resolution spectroscopic data. This paper is organized as follows: Section 2 describe our new observational data. In Section 3, we describe an empirical analysis, our photoionization model and the derived result. Our final conclusion is in Section 4.

Table 1. Diagnostic for the electron temperature, T_e and the electron density, N_e. References: [a] – Hyung et al. (2000), [b] – Hyung & Aller (1997)

PN	Ion	Diagnostic	$T_e(K)$	Ref.	Ion	Diagnostic	$N_e(K)$	Ref.
NGC 6543	[O III]	$\frac{\lambda4959+\lambda5007}{\lambda4363}$	8500	8300[a]	[S II]	$\frac{\lambda6717}{\lambda6731}$	2800	6000[a]
NGC 7662	[O III]	$\frac{\lambda4959+\lambda5007}{\lambda4363}$	13700	13100[b]	[S II]	$\frac{\lambda6717}{\lambda6731}$	3200	8000[b]

2. Observation and data reduction

Spectra of NGC 6543 and NGC 7662 were obtained in 12 - 14 September 2014 with the 28-cm telescope in Koyama Astronomical Observatory and using a compact spectrograph (designed by Prof. Kawakita, one of our collaborator). The observations were done with a spectral resolution of $R \simeq 500$ in the 3800 - 8000 Å. The spectrograph has slit width $10''$ and slit length 7.5 mm.

The exposure time of 300 s for NGC 6543 observation yields a signal-to-noise ratio of $S/N \geq 10$ for the [O III] emission line. While the exposure time of 900 s yields a signal-to-noise ratio of $S/N \geq 10$ for the [O III] emission line in NGC 7662 observation. A spectroscopic standard star was observed for the flux calibration purpose, notably HR 7596. A series of flat-field frames and comparison lamp (F-Ne-Ar) by using HCT (Hollow Cathode Tube) were acquired for data reduction, flat-fielding and wavelength calibration.

Data reduction were carried out using `IRAF`. Data reductions involved two main processes of calibration, wavelength and flux calibration. All fluxes were corrected for reddening using $I(\lambda)_{corr} = I_{obs}(\lambda)10^{cf(\lambda)}$.The logarithmic $c(H\beta)$ value of the interstellar extinction for the case B recombination ($T_e = 10000$ K and $N_e = 1000$ cm^{-3}) has been obtained from the Hα and Hβ Balmer fluxes. We used the Galactic extinction law $f(\lambda)$ [5] for $R_V = A(V)/E(B-V) = 3.1$, and normalized such that $f(H\beta) = 0$. We obtained an extinction of $c(H\beta) = 0.1$ for the NGC 6543 and $c(H\beta) = 0.14$ for NGC 7662. Our derived nebular extinctions are in good agreement with the value derived by [14] for NGC 6543 and [7] for NGC 7662.

3. Result and analysis

3.1. Plasma diagnostic

The derived electron temperatures (T_e) and densities (N_e) are listed in Table 1. Due to low resolution spectrograph, not all emission lines appeared in the observation data. Therefore, (T_e) is only derived from the [O III] line ratio and (N_e) is derived from [S II] line ratio. We adopted the electron temperature and density from the observation for our CELs abundance analysis.

3.2. Ionic and total abundances from ORLs

Determining the ionic abundances, X^{i+}/H^+, by using the effective recombination coefficients [8] from the measured intensities of optical recombination lines (ORLs). Abundances of helium from ORLs are given in Table 2. The ionic and total helium abundances were derived from He I λ4471, λ5876 and λ6678 lines. We assumed the Case B recombination for the He I lines [11]. The total He/H abundance ratio is obtained by simply taking the sum of He$^+$/H$^+$ and He^{2+}/H$^+$.

3.3. Ionic and total abundances from CELs

We determined abundances for ionic species of N, O, Ne, S, and Ar from CELs (Collisional Excitation Lines). The ionic abundances, X^{i+}/H^+, can be derived from the line intensities of CELs. The equation given by [9] and [10] were used to derive the ionic abundances.

Table 2 shows total elemental abundances of nitrogen, oxygen, neon, sulphur and argon of CELs from the observation. Not all ionic abundances in each species can be determined due

Table 2. Input parameter for the `CLOUDY` photoionization model

PN	NGC 6543	NGC 7662		NGC 6543		NGC 7662	
Parameter				Model	Obs.	Model	Obs.
T_{eff} (kK)	63000	11300	He/H	11.04	11	10.81	10.97
$log(g_*/cms^{-2})$	7	6	C/H	8.75	-	8.9	-
$L_*(L_\odot)$	3510	2470	N/H	8.39	8.7	8.26	9.5
$N_H(\mathrm{cm}^{-3})$	2800	3200	O/H	8.98	8.78	8.77	8.75
D (kpc)	1	0.8	Ne/H	8.19	7.98	8.05	7.8
log r_{in}(cm)	16	16	S/H	7.27	-	7.49	7.57
log r_{out}(cm)	17.44	17.03	Ar/H	7.0	7.5	6.44	7.6

to low resolution. The *icf* (ionization correction factor) given by [6] was used to determine the total abundances.

3.4. Photoionization modelling

The photoionization code CLOUDY (version C13.3; [1]) was used to study the best-fitting model for NGC 6543 and NGC 7662. This code solve-consistently the radiative transfer of the stellar radiation field in a gaseous nebula with the defined total flux and spectral energy distribution of CS, density distributions and chemical abundances. We used the non-LTE model atmosphere from [13] as the ionizing source and used assumption for a spherical shell and homogeneous abundances. It generates the emission-lines spectrum, the thermal structure and the ionization structures of the nebula.

The best fitting model was obtained through CLOUDY's default optimization method of the "optimize lines" command over 100 iterations, involving the comparison flux intensities of some important lines relative to Hβ (such as He II λ4686 which highly depend on the temperature of CS, [O III] λ5007 and [N II] λ6584 describe ionization and thermal structure, He I λ5876 controls the He abundance, [Ne III] λ3869 controls Ne abundance, [S II] $\lambda\lambda(6716 + 6731)$ controls the sulfur abundances and [Ar III] λ7135 controls Ar abundance), with those measured from the observations. In NGC 6543, He II λ4686 was not detected so it is not used. χ^2 in CLOUDY is used to calculate the best fitting as follows :

$$\chi^2 = |\frac{F_i^m - F_i^o}{min(F_i^m, F_i^o)\sigma_i}| \quad (1)$$

The free parameters included distance and nebular parameters. We initially used the stellar luminosity and distance as listed in Table 2. Moreover, we adopted the nebular density and abundance derived from the empirical analysis in Section 3, but they have been gradually adjusted until the observed nebular emission-line spectrum was reproduced by the model.

3.5. Comparison of the emission fluxes

Figure 1 compares the 2-D spectra predicted by the best-fitting model and from the observations. Most emission-line fluxes presented are in reasonable agreement with the observations. χ^2 value for NGC 6543 model is 8.01, while NGC 7662 is 4.21. However, we notice there some discrepancies such as [Ar III], [Ar IV] in NGC 6543 and He II in NGC 7662. The discrepancy between our model and observed intensities of these lines can be due to the inhomogeneous condensations such as clumps and/or colder small-scale structures embedded in the global structure. It can also be due to the measurement errors of these weak and blended lines because of the low resolution instrument and blend with telluric line.

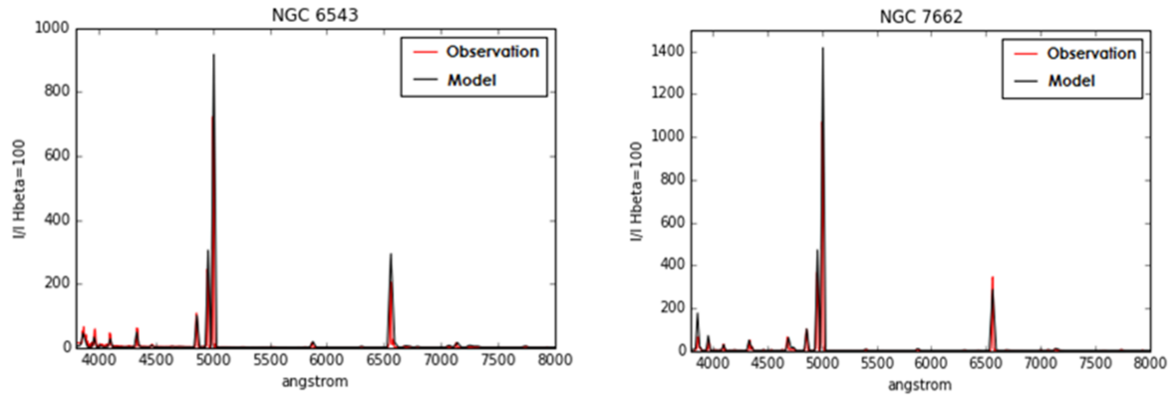

Figure 1. The 2-D spectra from the observation and model for NGC 6543 (left) and NGC 7662 (right). The red lines shows the observation result and the black lines shows the model results

4. Conclusion
Photoionization models based on CLOUDY can be build and were good applied for planetary nebula, NGC 6543 and NGC 7662. NGC 6543 has a good agreement with [4].

Photoionization model can be used to construct completed structure of PN with observational data as main constrain. A better observation data are required (i.e. higher resolution, etc) and more reliable model need to test another assumption, i.e. the nebula may not be spherically symmetric, an importance of temperature fluctuation, testing another different grain, etc.

Acknowledgments
This work would not happen without the instruments at our disposal. Therefore we thank Koyama Astronomical Observatory of Kyoto Sangyo University for providing all facilities, and the Sakura Science Program 2015 for the student exchange fund. We also thank FMIPA ITB.

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