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Photoionization Models for Planetary Nebulae: Comparison of Predictions by NEBULA and CLOUDY

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Abstract: The Galactic planetary nebulae emit many strong recombination and forbidden lines. By analyzing such lines, the physical condition of the planetary nebulae has been inferred using the strategically important diagnostic line ratios. In order to fully understand the physical condition of a planetary nebula and to derive its chemical abundances, the photoionization model codes, e.g., CLOUDY and NEBULA, were employed for an analysis of gaseous nebular spectra. For the well-studied, relatively simple planetary nebula NGC 7026, theoretical investigation was done with about the same input parameters in models. The predictions made by both codes seem to be in good accord. However, the predicted physical conditions, such as electron temperature and density, are slightly different. Especially, the electron temperatures are predicted to be higher in CLOUDY, which may cause a problem in chemical abundance determination. Our analysis shows that the main discordance may occur due to the diffuse radiation.

Keywords: Photoionization Model, Spectroscopic data, Planetary Nebula, NGC 7026

Introduction

A planetary nebula (PN) is the remnant of a dying star of $0.8M_{\odot}$-$6M_{\odot}$. The star's life at this evolutionary stage is relatively short, i.e., a couple of ten thousand years old. Nonetheless, this object provides valuable information on the chemical and physical evolution of intermediate stars, which is useful in understanding the chemical evolution of our Galaxy. The PN nucleus is a blueish white dwarf star which emits hot UV photons. The UV photons heat various atoms in the surrounding nebulous shell, and the atoms in the gaseous shell re-emit the degraded photon in the optical and the IR wavelength range. Since the PN is relatively bright, one can study it with relatively smaller telescopes, e.g. 2 m telescope, if equipped with the high dispersion spectrograph. To analyze the spectral data, one must use the photoionization code (P-I) for a chemical abundance determination or the gas dynamic code for the shaping scenario investigation.

Most contemporary P-I codes have been continuously updated with proper atomic constants, and they had been compared with one another in the workshops, e.g. Paris Mudon meeting (1984). However, this comparison had been done only for the case of radiation bounded nebula with a simplistic blackbody central star spectral energy distribution (SED). In a recent study, e.g., P-I model investigation for the symbiotic nova AG Pegasi (Kim and Hyung, 2008), the predicted electron temperatures showed the values higher than the observed. In case of the real objects, one must introduce various approximation in modeling to improve the prediction and to accommodate the real complex situation. For example, the radiative transfer problem or the stellar energy distribution (SED) for the ionizing UV photons must be taken care of in the P-I calculation. The radiative transfer of the UV lines, e.g., HeI and HeII Lyman is often ignored, and the SED is taken from a simple black body model. In P-I modeling, however, one must solve the energy balance between 'heating and cooling' and statistical equilibrium between the ionization and recombination with proper treatment of such cases.

For a relatively simple PN NGC 7026, we constructed P-I models using two P-I codes, CLOUDY (Ferland, 1997) and NEBULA (Hyung, 1994) to analyze the radiative effect and to test the predicted line

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discordance. Sec. 2 describes the photonization theory involving the nebular model. Sec. 3 compares the line predictions given by two codes. We also present the predicted physical conditions by two codes which have been compared with the observed values. We also offered a brief discussion on the modeling procedure for the diffuse radiation. Sec. 4 gives a summary.

Theoretical Background for Photoionization Model

The nebulous gas in a PN is excited by the central stellar UV radiation. The central star is very hot, $T_s \cong$ 30,000-200,000 K, which photoionizes the surrounding gas. The shell gas expands fast toward the polar axis, while it does so slowly toward the equatorial zone. The resulting non-spherical PNs are often observed. We chose a relatively simple spherical object, NGC 7026, for which we can model as a spherically symmetrical object. The gas in the nebular shell heated by the central star UV photon must cool down by emitting the strong optical region lines. We will briefly describe the line emission mechanism and equilibrium equations that should be solved in a modeling procedure.

Theoretical line flux

As discussed by Aller (1984), Pottasch (1984), Osterbrock (1989), and Sabbadin et al. (2004), the absolute flux emitted in a nebular gas in an equilibrium state will be given as,

$$F(X_m, \lambda)=N_e N(X^n) f(X^m, \lambda, N_e, T_e)$$

where T_e is electron temperature, N_e electron number density, and X^n ions involving the transition. The emissivity function, $f(X^m, \lambda, N_e, T_e)$ is for the line from an ion X^m. The emissivity is constrained by permitted radiative excitation or forbidden collisional excitation mechanisms. The former radiative excitation process involves radiative ionization by stellar UV photons. The permitted lines can be produced through recombination of electrons, cascading down to the ground level. Sometimes, resonance fluorescence seems to occur in the shell, e.g., Bowen fluorescence OIII lines. The latter purely theoretical collisional excitation process involves excitation of a low lying level of atoms due to passing by free electrons or ions. Because the majority of emissions in the nebula are expected to escape through the forbidden lines, the modeling procedure can also become a numerical experimental device for testing various atomic constant and atomic physics involving these lines. Here, the free electrons are, of course, those of the photoionized ions from the atomic gas, due to the hot central star. Usually, the free electrons are assumed to be in the Maxwell distribution which excites the bounded electron of the ions violating the selection rule.

The emissivity for the permitted lines of H, He, C, etc. is given as

$$f(X^m, \lambda_{ij}, N_e, T_e)=\frac{hc}{\lambda_{ij}}\alpha_{eff}(\lambda_{ij})$$

where $\alpha_{eff}(\lambda_{ij})=B(\lambda_{ij})\alpha_{eff}(X_i^m)$ is the recombination coefficient; $B(\lambda_{ij})$ the branching ratio,

$B(\lambda_{ij})=\frac{A_{ij}}{\Sigma_{k>i}A_{ik}}$; A_{ik} the radiative decay; $\alpha_{eff}(X_i^m)$ the recombination coefficient for ions; and c and h the light speed and the Planck constant. In general, $\alpha_{eff}(\lambda_{ij})$ is weakly inversely proportional to the electron temperature T_e.

The emissivity for the collisional lines of C, N, O, Ne, S, Cl, Ar etc. is given as

$$f(X^m, \lambda, T_e)=\frac{hc}{\lambda}q_{co}(\lambda)$$

$$\text{and } q_{co}(\lambda)=8.63\times10^{-6}\left(\frac{\Omega}{\omega_1}\right)T_e^{-0.5}e^{\frac{-\Delta E}{kT_e}},$$

where $q_{co}(\lambda)$ is the collisional excitation rate; Ω is the averaged collisional strength; ω_1 is the statistical weight of the lower level; ΔE is the upper level excitation potential. Here, $q_{co}(\lambda)$ has a strong dependence on the electron temperature, T_e. Thus, it will be important to know the correct electron temperature in deriving the chemical abundance. Usually, the model nebula is assumed to be static, so one can ignore the energy loss by the shell expansion or any shock influence by the hot stellar wind. Then, we must solve the thermal equilibrium or energy balance equation and the statistical equilibrium equation (Osterbrock, 1989) in a P-I modeling.

Photoionization Model

Nebula model geometry: One can perform a spectral line analysis for a few lines one by one. However, it would be more desirable to carry out all of them together in a idealized model environment, since this might allow us to study all the observed lines more coherently in a self-consistent way. This can be done with P-I models. In order to create such a favorable environment for the observed spectral fluxes and other observables, one must assume a nebular model geometry. Two simplified geometries are often assumed: (1) 'open' or a plane parallel geometry and (2) 'closed' or a spherically symmetric geometry. Fig. 1 shows a schematic diagram for two cases (Ferland, 1997). The diagram shows the inner and outer radii of the shell and the shell thickness Δr. The dark area represents the gaseous nebula and the UV emitting hot stars (☆) are on the left side and at the center of the nebulae, respectively. The energy balance and statistical equilibrium equations should be solved in such a nebular gas with P-I code(s).

The UV SED will be absorbed by the gaseous material in the shell of thickness Δr. In a thin shell nebula, the hardened UV photons can escape from the outer boundary layer. Here, the model can be approximated by the material bounded shell. The outer boundary of the model geometry can be either material bounded (hardened UV photons beyond the boundary) or radiation bounded (no UV radiation outside the nebula). When the outer boundary is clearly seen from a nebular image, the nebular geometry adopted by the photoionization model should be 'matter-bounded geometry'. In this matter-bounded case, the nebular region itself could be optically thin and the permitted line intensities will be determined by the occupied volume and density. The emitted nebular continuum is not perhaps directly related to the central stellar luminosity. In the case of 'radiation-bounded geometry', the nebular gas is usually optically thick since it consists of ionized hot and neutral zones. The intensities of recombination lines will be strongly dependent on the stellar UV continuum but not due to the nebular physical condition.

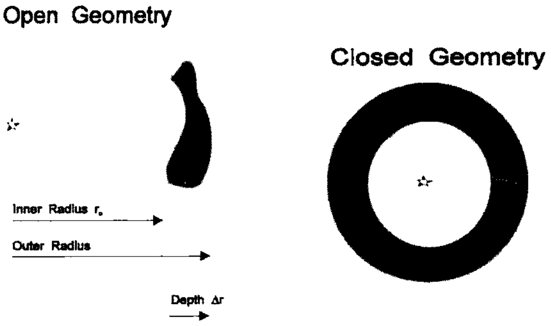

Fig. 1. Open vs. closed geometry (from Ferland, 1997).

CLOUDY and NEBULA: We assume that the PN has a relatively thin gaseous shell which has been ionized by the central star. Hence, the modeling effort is to find out the ionizing process of the gas by the central star, and we must get the nebular physical condition from a P-I model, i.e., electron temperature and number density. Whether the modeling procedure is sound or not, can be verified by the comparison of the predicted line fluxes with the observed values.

Many investigators developed their own P-I codes. It can be used not only in figuring out the geometry and physical conditions of astronomical objects but also in fitting the observed spectra of the gaseous nebulae. One of the well known P-I codes is 'CLOUDY' (Ferland, 1997). CLOUDY has been used for many investigations of the H II regions, planetary nebulae, spiral galaxies, quasar or active galactic nuclei. The other P-I code that we are using here is that of Hyung (1994). We will denote the latter code as 'NEBULA' for our convenience. NEBULA is not a user-friendly code for others and it had never been in public domain. This P-I code had been developed for the relatively low number density objects like planetary nebulae and HII regions. As described by Hyung (1994), one can model a density contrast geometry suitable for some relatively simple axi-symmetrical objects, i.e., in addition to the above mentioned simplistic open and close geometry objects.

The atomic data have been updated continuously in both codes. The input parameters in both codes for the modeling are chemical abundances, SED, nebular density variation in the shell, and the dust to gas mass ratio. Since we want to compare two results produced by the above two codes, we will use the same input parameters.

The spectral energy distribution: For the SED or the photoionizing UV continuum distribution of the central star, two different methods, a blackbody SED or a model atmosphere SED, are available. The latter would be more sound than the former, but it requires another model atmosphere code. Most contemporary P-I codes including 'Cloudy' and 'Nebula' give about the same line intensity prediction in case when they employ the same SED, i.e. the blackbody SED, as done in aforementioned Paris Mudon meeting (1984). We use 'Tlusty' by Hubeny (1988) to produce more realistic SED. The 'Tlusty' code can generate the SED, based on either local thermodynamic equilibrium (LTE) or non-LTE approximation satisfying a radiative and hydrodynamic equilibrium for a normal stellar atmosphere or a hot accretion disk source. Tlusty code is highly sophisticated, and it consists of various parts, involving atomic constants, energy levels for transition, opacities, etc. We will simply use this code to produce the model atmosphere with a similar chemical abundances in the central star as those of the nebular gas.

The input parameters for Tlusty and NEBULA are the effective stellar temperature, $T_\star$, the surface gravity, *g*, and elemental abundances. One must be careful in adopting the surface gravity, *g*, e.g., log *g* $\geq$4.0 for $T_\star$=30,000 K, log *g*$\geq$6.0 for $T_\star$=180,000 K to avoid any unrealistic situation.

Comparison of the predictions

Model predictions

To compare the predictions by two codes, we use the Optical and IUE spectra available from Hyung and Feibelman (2004, HF04 hereafter). The entrance slit size that was employed in the observation by HF04 was about 4"×2" and the observing exposures carried out at the 4" west position of the central star of the planetary nebula (CSPN) and at the CSPN position. We quoted the former 4" west offset results in this investigation. They obtained the chemical abundances of NGC 7026. We started with the same input parameters, in their Model A. Since they also used NEBULA for their studies, the prediction will be about the same. The minor difference may exist due the updated atomic constants. Although the predictions by NEBULA will be the same as those of the HF4 work, we need to recalculate to view other physical data not mentioned in the published results.

Table 1 presents the input parameters. The CSPN has $T_\star$=80,000 K and =4.95, then L_*=2400 $L_\odot$ (0.24 $R_\odot$). The central star is assumed to have He/H= 0.105 and the nebular C, N, and O abundances. The inner radius of the shell is R_{in}=0.04 pc and the outer radius is assumed to be material (matter) bounded at R_{out}(pc) =0.048 (NEBULA) or 0.0485 (CLOUDY) pc. The hydrogen number density assumed is N_H=8500 cm^{-3}. Only a small dust/gas mass ratio, 0.005, is assumed in the shell. This outer radius will give roughly the observed nebular image dimension at an assumed distance of 2000 pc.

Since two codes, CLOUDY and NEBULA, developed by different authors, the code structures in solving the energy balance and statistical equilibrium equations, are different, so we had to check the minute details of P-I program subroutines in both codes. For example, the adapting method for the SED is different in the input subroutine, therefore, we carefully chose the UV region wavelength or frequency points for the SED with Tlusty. We could

Table 1. Input parameters for NGC 7026

Parameter	Value
N_H (cm^{-3})	8500
R_{in} (pc)	0.040
R_{out} (pc)	0.048, 0.0485[b]
CSPN $T_\bigstar$ (K)[a]	80,000 (log g=4.95)
R_* ($R_\odot$)	0.24 (L_*=2400$L_\odot$)
M_{dust}/M_{gas}	0.005

[a]Hubeny model atmosphere. [b]in CLOUDY.

not check whether the same atomic constants are used in all cases in both codes. There are numerous Atomic constants newly available from the literature for the relatively weak lines, for which it is almost impossible for us to check their coincident. Although the atomic constants are the same for the well-known strong lines, the other unaddressed weak line constants can still affect the predicted physical condition, in solving the energy or statistical equilibrium equations. Nonetheless, we believe this minor difference will not change our conclusion.

Although we have started with the same input parameters as in Table 1 with CLOUDY, we need to test other input parameters to predict the observed fluxes well. It is important to know the central star temperature, correctly, since this information will tell us its age or the progenitor star mass at its main sequence evolution phase (Hyung and Aller, 1998). The approximate central star temperature can be determined by the [OII] to [OIII] and the HeI to HeII ratios, since a theoretical model atmosphere with correct effective temperature will give a correct level of nebular excitation (the energy-balance method and the Zanstra method (Zanstra, 1931). In a PN, the [O III] line intensities are generally stronger than the [O II] (cf. AGN or LINER), whose ratio serves as an indicator of the excitation in the gas. The other line ratio which should be checked is the He I and He II lines ratio. We also carried out a number of calculations with different CSPN $T_\bigstar$s, i.e., 100,000-60,000 K. From such laborious trials, we found that CLOUDY also worked well with the same CSPN $T_\bigstar$ =80,000 K and log g=4.95, as in NEBULA.

To improve the predictions, however, we further need to adjust the outer shell radius and thickness, i.e., R_{out}=0.085 pc. The other parameter that we modified is the abundances. Changing the chemical composition of one element will influence other line fluxes, though. For example, reducing the oxygen abundance will cause its intensity decrease, but this will create a chaos for other lines. This adjustment will cause an electron temperature change, too, since the gaseous materials serve as coolants in the energy balance. From such a laborious trial, we find the best model with CLOUDY.

Table 2 compares the observed line fluxes with those predicted by NEBULA and CLOUDY. All line flux intensities are given on the normalized relative to the I(H)=100.0. In NEBULA P-I modeling, two calculations can be done depending on how to solve the HeI, HeII, and HI diffuse radiation emitted by the nebular gas itself: (1) a radiative transfer (RT) solved properly by performing the whole calculation iteratively; and (2) on the spot (OTS, Osterbrock, 1989) approximation or radially outward marching approximation (ROM, hereafter; Hyung et al., 1994). NEBULA OTS result in fact can become a base for NEBULA ROM model calculation; and NEBULA ROM for NEBULA RT. Thus, HF04 presented the final NEBULA RT result only. In this investigation, however, we presented both RT and ROM results for comparison. The CLOUDY prediction would be similar to the ROM or OTS prediction of NEBULA.

Two predictions by CLOUDY are also given, but they are basically the same except for C abundance difference, C/H=2.5×10^{-4} vs. 9.3×10^{-4}. Despite minute details, e.g., atomic constants and the radiative transfer and resonance line problem treatment, the predicted fluxes between two codes agree fairly well except for C. In Fig. 2, we compare the observed and predicted fluxes based on Table 2. The line fluxes are given in the row order of Table 2. The NEBULA ROM predicted [NII] and [OII] fluxes are stronger than the observed or other predicted. This discordance, however, can be easily eliminated by adjusting the outer shell radius. This will then cause to change the

Table 2. Comparison of predicted lines

Line	I_{obs}^{a}	I_{NEBULA}		I_{CLOUDY}	
		(RT)[b]	(ROM)[c]	I[d]	II[e]
HeI λ4471 (1)	4.79	4.51	5.52	5.21	
HeI λ5876 (2)	15.18	16.38	15.67	16.21	
HeI λ6678 (3)	4.79	4.51	4.42	4.10	
HeII λ4686 (4)	9.19	8.98	7.39	9.45	
HeII λ5412	0.81	0.71	0.57	--	
HeII λ1640 (5)	40.70	59.4	47.79	64.73	
CII] λ2325 (6)	--	6.4	1.4	4.31	(10.41)
CII λ4267 (7)	0.51	0.18	0.17	0.00	(0.22)
CIII] λ1907/09 (8)	18.2	15.9	30.2	27.27	(63.87)
CIV λ1548/50 (9)	46.30	1.40	2.40	8.45	(18.46)
[NII] λ6584 (10)	216.50	194.8	387.45	213.16	
[NII] λ6548 (11)	63.31	67.23	133.74	72.23	
[NII] λ5755 (12)	2.80	2.82	6.69	4.77	
NIII] λ1747-52 (13)	6.37	3.73	7.40	0.00	
[OII] λ3726 (14)	36.18	38.21	87.42	33.37	(32.98)
[OII] λ3729 (15)	14.55	15.47	35.83	8.16	(8.06)
[OII] λ7321/2	5.09	3.23	7.99	--	--
[OII] λ7332/3 (16)	4.78	2.59	6.41	2.54	(2.48)
OIII] λ1661/66 (17)	5.58	2.04	3.90	3.64	(3.34)
[OIII] λ4363 (18)	3.53	3.00	4.90	9.66	(9.09)
[OIII] λ4959 (19)	313.70	304.6	385.3	422.5	(410.0)
[OIII] λ5007 (20)	909.40	877.4	1110.0	1219.8	(1183.8)
[NeIII] λ3868 (21)	92.55	85.65	128.32	130.70	
[NeIII] λ3969 (22)	29.57	25.56	38.29	16.73	
[NeIV] λ2422/25	1.88	0.41	0.50	--	
[SII] λ4076 (23)	1.07	0.73	2.09	0.27	
[SII] λ6717 (24)	11.52	2.29	6.42	2.96	
[SIII] λ6312 (25)	2.57	1.75	2.69	3.76	
[SIII] λ9069 (26)	68.61	54.69	69.56	59.17	
[SIII] λ9531 (27)	134.70	133.28	169.54	146.74	
[ClIII] λ5518 (28)	0.76	0.48	0.60	0.38	
[ClIII] λ5538 (29)	0.97	0.91	1.13	0.63	
[ClIV] λ8046 (30)	0.50	0.55	0.69	0.70	
[ArIII] λ5193 (31)	0.11	0.11	0.19	0.23	
[ArIII] λ7136 (32)	33.13	27.81	38.26	36.97	
[ArIII] λ7751 (33)	7.90	6.72	9.25	8.92	
[ArIV] λ4711 (34)	1.59	2.07	2.45	1.57	
[ArIV] λ4740 (35)	2.20	3.39	3.95	2.54	
[ArIV] λ7171	0.07	0.04	0.05	--	
[KIV] λ6102	0.09	0.08	0.11	--	

[a] 4" West of the CSPN. [b] (RT): radiative transfer considered; [c] (ROM): radially outward marching approximation. [d] with C/H=2.50(-4) to fit the IUE C lines. [e] with C/H=9.30(-4) to fit the CII 4267. We do not fill the last column since columns (5) and (6) are similar except for C lines.

predictions for other lines, which will force us to change other input parameter, so on. We do not try such a refinement, since we want to compare the results between RT and ROM produced by NEBULA P-I code.

For the C lines, we try to fit the strongest CIII]1907/1909 lines in the UV wavelength region: note that the NEBULA predicts the optical wavelength region CII 4267 line weakly, about 1/3! Whereas, the CLOUDY predicts it too much weakly, i.e. 0.01! If

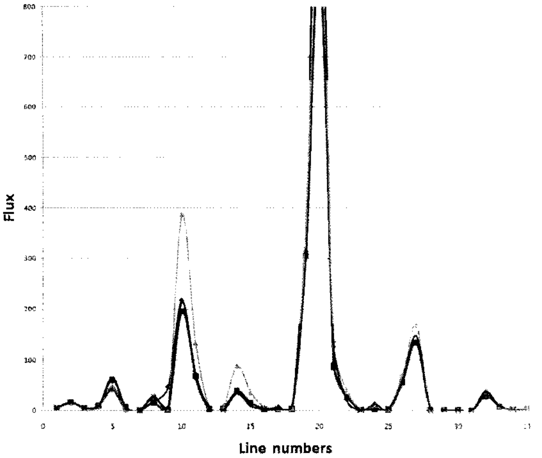

Fig. 2. Comparison of fluxes. The fluxes are given on the scale of I(Hβ)=100.0, and the line numbers in the x-axis represent the line order in Table 2.

Table 3. Abundances derived by different methods

Element	ICF[a]	N_{NEBULA}	N_{CLOUDY}	Δ
He	1.15(-1)	1.15(-1)	1.15(-1)	0.00
C	9.27(-4)	2.50(-4)	2.00(-4)[b]	0.10
N	4.97(-4)	4.50(-4)	7.90(-4)	-0.24
O	6.72(-4)	7.50(-4)	4.00(-4)	0.27
Ne	1.67(-4)	1.70(-4)	1.00(-4)	0.23
S	2.06(-5)	1.70(-5)	1.00(-5)	0.23
Ar	4.92(-6)	5.50(-6)	5.00(-6)	0.04
Cl	3.76(-7)	3.43(-7)	5.00(-7)	-0.02
K	5.00(-8)	5.00(-8)	-	-

$\Delta = N_{NEBULA} - N_{CLOUDY}$. [a]ICF result by HF04. [b]$\Delta = -0.57$ when using with C/H=9.30(−4) fits the CII 4267 (see text). $X(-Y)$ means $X \times 10^{-Y}$.

Table 4. Electron temperatures (K)

Ion	Observed[a]	NEBULA		CLOUDY
		(RT)[b]	(ROM)[c]	
[NII]	8600	9050	9530	–
[OII]	8000-12000	9100	9600	10400
[OIII]	8500	8320	8900	9600
[SIII]	8700	8650	8800	–
[ArIII]	8000	8530	9100	–
N_e	–	8300	8950	10400

[a]based on the diagnostics (HF04). [b](RT): radiative transfer considered; [c](ROM): radially outward marching approximation.

we increase the C/H abundance ratio to fit the CII 4267 in CLOUDY, we need to increase the C abundance by 4 times. This prediction is given in the last column, but only for C and O. The prediction for CIV 1548/50 differs in both case: NEBULA predicts these lines weakly since we can calculate the dust influence for the resonance lines. The C abundance is difficult to determine, since strongly predicted C lines are mostly in the UV region. If the UV data are not available, one must use the permitted C lines in the optical region. The other problem is that the UV lines are often involved with a large uncertainty of uncertain interstellar extinction correction. Moreover, sometimes it is not clear whether the permitted lines are those of recombination or some other mechanism. We were not able to get any prediction for K from CLOUDY. This must be investigated further in the future studies.

Table 3 gives the abundances: columns (2), (3), and (4) are the abundances derived by different method of HF04 Ionization Correction Factor (ICF), NEBULA, and CLOUDY, respectively. In the last column, we give the logarithmic difference between two codes, $\Delta = N_{NEBULA} - N_{CLOUDY}$. The derived abundances by NEBULA agrees with those by CLOUDY within a factor of two. However, the ICF and NEBULA results seem to agree, except for the C abundance.

Predicted physical conditions

HF04 presented the electron density and temperature diagram, based on the observed line ratios of strategically important lines. Table 4 compares electron temperatures for strongly emitted ions, i.e., T_e([NII]), T_e([OII]), T_e([OIII]), T_e([SIII]), T_e([ArIII]), and average electron temperature $T_e(N_e)$: successive columns give the observed or diagnostically determined temperatures, NEBULA's RT and ROM, and CLOUDY predictions. The electron temperatures predicted by CLOUDY are the highest, the ROM middle, and the RT lowest. Obviously, the RT solution fits the observed value well. This suggests that the radiative transfer problem of the diffuse radiation should be properly taken care of in the P-I modeling. Without proper treatment of the diffuse radiation, one cannot get the nebular physical condition correctly.

Discussion

The intermediate mass stars occupied a large portion of mass in our Galaxy. Hence, it would be important to find their chemical abundances or their modification during the stellar evolution to understand the chemical evolutionary history of the Galaxy. One way of finding this information is to derive the chemical abundances for a number of planetary nebulae, since they had been evolved from intermediate stars. The heavy elements such as Ne, Ar, S, Cl and K, are not enhanced by nucleosynthesis during the evolution of intermediate stars. These heavy elements and H, He, C, N, and O can be found from the spectroscopic investigation of planetary nebulae using P-I modeling procedure. Since one cannot observe all the gas phase in the optical or UV regions, one must employ the P-I model to guess the ionic concentrations for the unobserved ionic stages.

The P-I model predictions based on two completely different P-I codes, NEBULA and CLOUDY are compared based on the observed spectra of the relatively simple planetary nebula NGC 7026. In spite of possible difference in atomic constants in coding, the comparison seems to give a fairly agreeable result for most cases. However, there seems to be a problem with the determination of abundances, e.g., C. When the UV lines are not available, one must refer to the optical region permitted lines, e.g., CII 4267. CLOUDY cannot predict the CII 4267 unless one increases the C/H by a factor of 4. It has been a long standing problem that the observed permitted C lines cannot be predicted by the recombination theory, though, so we do not know which determination is better. The chemical abundances that we derived based on the P-I are, in fact, those in a gas phase. The chemical elements can also be locked in other phase, e.g., solid grains. Although we have not discussed this problem, this should be investigated in P-I modeling study. Predictions for some low ionization potential ions, e.g., [OI], [SII] are often disagree with the observed values. They might be produced in partially ionized or in neutral blobs. These lines are often too strongly observed, while the standard P-I model prediction gives very weak flux intensities. The 3-dimensional P-I modeling may improve the situation!

We found some scatters in some lines, e.g., [OII] and [SII]. For example, the NEBULA ROM prediction disagrees with the NEBULA RT or CLOUDY result. However, this is not a problem, since it is only matter of a slight adjustment of the shell radius: the truncation is inevitable in many material bounded PN to fit the observed spectra more precisely. The difference in electron temperature is not negligible, though, since one must employ a lower stellar temperature in CLOUDY to match the observed temperature. Hyung (1994) compared NEBULA prediction with other P-I code for planetary nebula and HII region based on the Paris Mudon workshop and found no difference. We conclude that this difference is caused by the radiative transfer solving method. As seen in ROM and RT, the predicted electron temperatures in a properly solved model can be lower than the preliminary model calculation.

Since the P-I model is indispensible in finding the chemical abundances in some gaseous objects, it would be important to know which part of modeling can cause possible error. In the P-I calculation, any one of wrongly assumed elemental abundance can cause an error for a determination of other chemical elements, since the electron equilibrium temperature can be determined from energy balance and statistical equilibrium equation for all elements. In other words, knowing the correct electron temperature is important for a determination of elemental abundances in the gas shell, since the line flux intensities are dependent on the electron temperatures, i.e. stronger in collisional lines than in permitted lines. Our study shows that CLOUDY tends to predict a high electron temperature because of diffuse radiation treatment problem. This can in fact cause an error in deriving the elemental abundance. However, the temperature fluctuation problem is far more complicated, which is beyond the scope of the current study. Since the chemical abundances are determined based on the forbidden lines, which are strongly determined on the electron temperature, a proper treatment of radiative transfer problem is necessary in P-I modeling studies.

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