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A BIPOLAR PLANETARY NEBULA NGC 6537: PHOTOIONIZATION OR SHOCK HEATING?

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ABSTRACT

NGC 6537 is an extremely high excitation bipolar planetary nebula. It exhibits a huge range of excitation from lines of [N I] to [Si VI]or [Fe VII], i.e. from neutral atoms to atoms requiring an ionization potential of ~ 167eV. Its kinematical structures are of special interest. We are here primarily concerned with its high resolution spectrum as revealed by the Hamilton Echelle Spectrograph at Lick Observatory (resolution ~0.2Å) and supplemented by UV and near-UV data. Photoionization model reproduces the observed global spectrum of NGC 6537, the absolute Hβ flux, and the observed visual or blue magnitude fairly well. The nebulosity of NGC 6537 is likely to be the result of photo-ionization by a very hot star of T_{eff} ~ 180,000 K, although the global nebular morphology and kinematics suggest an effect by strong stellar winds and resulting shock heating. NGC 6537 can be classified as a Peimbert Type I planetary nebula. It is extremely young and it may have originated from a star of about 5 $M_{\odot}$.

Key Words : ISM : chemical abundances – ISM : planetary nebulae – ISM : individual (NGC 6537)

I. INTRODUCTION

NGC 6537 is of great interest since the source of excitation is a dying star of exceedingly high temperature. One can classify this object as Peimbert Type I planetary nebula (PN), according to Peimbert (1978) definition. The Type I PNs show overabundances of helium and nitrogen when they are compared with the solar values. They are expected to be evolved from intermediate mass (5–8$M_{\odot}$) asymptotic giant branch (AGB) stars. They are also likely to have extremely hot ($T_{\star} > 1\times10^5$K) nuclei with mass ranging up to the Chandrasekhar mass limit of 1.44$M_{\odot}$. From large scale velocity maps (long slit spectroscopy), Cuesta et al. (1995) found the presence of strongly variable core outflow densities, rising to a peak value of $N_{\epsilon} \sim 1.7\times10^4$ cm^{-3} which might be related to intermediate velocity wind extending over a range $\Delta v \simeq 700$ km s^{-1}, together with a more tightly constrained component of $\Delta v \simeq 4400$ km s^{-1}. The core may be responsible for driving the outer denser shell to a typical velocity $v_{ex} \sim 18$ km s^{-1} and the overall structure can be explained by a shock outflow model, providing wind mass loss rates of order $\dot{M}_{\star} \sim 6\times10^{-8}$ — 6×10^{-7} $M_{\odot}$ yr^{-1}. Although this object is noteworthy because of its extremely hot central star, it is highly obscured by the interstellar medium; its light is attenuated by 19 decibels at a wavelength of 4861Å. Since the extinction by interstellar dust varies strongly with color, it is much more favorably observed in the red or infra-red.

Numerous nebular models for spherically symmetrical objects have been calculated by various investigators. Among those most relevant to the present study are: Aller (1984), Köppen (1983), Middlemass (1990), but even for fairly symmetrical objects, modeling has not always been successful. Non-spherically symmetric models are more promising. See e.g. Bässgen, Diesch, & Grewing (1995); and Hyung & Aller (1996, hereafter HA96). The extremely high excitation characteristic of NGC 6537 which had often been noted elsewhere, make it a challenging object for modeling study. Aller et al. (1999, AHF99 hereafter) did not pay much attention to the ionization model calculation, since they could not reproduce the observed line intensities and various other observables. Thus, they prematurely concluded that the high excitation lines or hot nebulosity is the result by shock heating due to strong winds. Their earlier model investigation was useful only to get a good ionization correction factor (ICF) with which they were able to determine the chemical abundance. This preliminary photoionization model trial by AHF99 becomes a good starting point of the current investigation. In the following, we present a new photoionization model whose result can be compared with the observables and spectra of NGC 6537.

II. THE SPECTRUM OF NGC 6537

Feibelman et al. (1985, FAKC hereafter) observed NGC 6537 with an image tube scanner (ITS) at Lick 3-m telescope, using both red- and green-sensitive tubes to cover the spectrum from 3300 Å to 8,600 Å and with the International Ultraviolet Explorer (*IUE*) to cover the UV 1000 -3100 Å. Most recently, with a much improved Hamilton Echelle spectrograph at Lick Observatory, Aller et al. revisited this and other objects. The Hamilton Echelle Spectrograph has two great advantages: a much higher spectral resolution and an extension of the spectral coverage to longer wavelengths where the interstellar attenuation is reduced, i.e., 3650

- 10286 Å. Moreover, an improved *IUE* UV data analysis method known as IUESIPS or NEWSIPS became available.

The spectroscopic data in the optical region were secured by Aller et al. (1999), i.e., with the Hamilton Echelle spectrograph (HES) on the 3 *m* telescope at Lick Observatory. The adopted slit size of the HES is 1.2″ ×4.0″ which covers only a small portion of the nebular image. Here, the slit length of 4.0″ was chosen to avoid overlapping between neighboring echelle orders. The HES spectral resolution depends on the slit width and the number of Å per pixel of the CCD. The Å/pixel ratio varies from 0.029Å at 3659Å to 0.079Å at 8500Å. A 640 μm slit width covers ~1.5 pixels of the CCD chip in the HES observations, so the effective spectral resolution may be taken as 0.2Å for 2 pixels (FWHM). The observational and reduction procedures on HES have been described by Hyung (1994). With the earlier ITS, Aller used a slightly larger slit entrance of $\simeq$ 2″ ×6″. The HES had a problem of an image rotation on the Coude focus of the 3-m Shane telescope, while the ITS did not have such a problem. The ITS spectrometer was on the prime focus. The spectral resolution of the HES is superior to that of the ITS, i.e., 0.2 vs. 2Å. The *IUE* data were secured through a much larger (10″ × 23″ oval) entrance slit aperture centered on the nucleus of the PN, which could cover the whole nebular image. The details of the *IUE* observation and reduction procedures are also given in AHF99.

The logarithmic extinction coefficient at Hβ was C = 1.80 ~ 1.95, that was determined from Hydrogen Balmer and Paschen lines, where $C \equiv \log F_c(\mathrm{H}\beta)/F(\mathrm{H}\beta)$. We have adopted $C = 1.80$ for the interstellar extinction correction of the *IUE* UV and the Hamilton optical spectra (see AHF99). Meanwhile, a slightly higher value of $C = 1.95$ was used in the ITS data analysis by FAKC. Here, we do not try to tune the observed spectrum using one common extinction value. Instead, we just quote their normalized line intensities from the above two literatures [I(Hβ) = 100]. This disparity would not cause any change of our conclusion.

Due to relatively low quantum efficiency of CCD and higher dust extinction in this object, the [O II] 3726/3728 lines were not registered in the HES observation by AHF99. However, these lines were measured in the early FAKC observation. The FAKC measurements also included the near UV [Ne V] 3341/3429 (forbidden) and other O III 3444 (permitted) lines.

The estimated nebular radial velocity relative to the sun was obtained as -14.58 km s^{-1} by AHF99 for the strong lines (I$\geq$1), while Acker et al. (1992) quote -13.0 ± 3.0 km s^{-1} for the whole PN's intrinsic velocity with respect to the local standard of rest. The formal errors in individual line intensities may be estimated by comparing measurements made with a different set of observing run which include errors arising from uncertainties in the response function, interstellar extinction, etc. These amount to about 25% for $0 < I < 0.50$, 18% for $0.5 < I < 1.0$, 11% for $1.0 < I < 10$, and 7% for I > 10. Actual errors may be even larger, especially for lines near the end of the sensitivity range, e.g. wavelengths longer than 9,000Å and shorter than 4,000Å,.

III. THEORETICAL MODEL

(a) GENERAL REMARKS

A description of the photoionization modeling procedures including references to selected atomic parameters may be found in Hyung (1994) and a later update in Hyung & Aller (1996, HA96 hereafter). As in our previous studies, we construct a shell model with a central star energy distribution from Hubeny's (1988) non-LTE model atmosphere. Although PN is a bipolar symmetric object, our model PN is regarded as a spherical object: it may be correct at least in the first approximation.

Distance estimates of NGC 6537 show a considerable spread: 0.58 to 2.95 kpc from statistical method (see Acker et al. 1992 and references quoted therein). It is more likely that kinematic estimates would give more accurate derivations, i.e., Acker (1979) found 1.5 kpc while Gathier et al. (1922) derived ~2.4 kpc (see Table 1). We assumed a distance of 2.0 kpc, close to the average value from the kinematic determination.

The Peimbert Type I PN like the young NGC 6537 is believed to have an extremely hot and very luminous central star ($L_\star > 5000L_\odot$). Ashley & Hyland (1988) derived the upper limit of a central stellar temperature as $T_\star$ <240,000 K (using [Si VI]), while the lower limits on the Zanstra temperatures given by Reay et al. (1984) are T_Z(He II) > 150,000 K and T_Z(H I) > 110,000 K.

(b) MODEL PARAMETER

The details of the model parameters are described in Table 1. The stellar energy distribution was calculated using Hubeny's (1988) non-LTE code for the following input: T_{eff} = 180,000 K and log g = 6.0 with He/H = 0.131 + nebular heavy elements in the central star. To represent the outer boundary of the optical image, we introduced a hollow shell, of which inner and outer shell radii are 0.022 and 0.041 pc, respectively. The shell is homogeneous with a hydrogen density of 16,000 cm^{-3}. There is no filling factor. The outer boundary of the nebular shell is density bounded, i.e. truncated within the Strömgren sphere radius in order to find the best fit to the observed spectra. For a distance of 2.0 kpc, the model nebular size would be comparable to the size of the PN, but not its morphology. We assume a central star radius of $R_* = 0.1R_\odot$ and, as a result, L_* = 9,600 $L_\odot$. In the radiating strata, a small amount of dust with the dust to gas mass ratio, M_{dust}/M_{gas} = 0.005, is introduced. Except for some UV lines, e.g., C IV 1549/51, the effect of such a small amount of dust is negligible in the emission line prediction.

Table 1. Assumed parameters for NGC 6537 (Radius = ~5″)

Position	$\alpha = 18^h\ 50^2\ 14^s$ (2000)
	$\delta = -19^\circ\ 50'\ 14''$
Distance =	2,000 pc
Shell inner radius	$R_{in} = 0.022$ pc
Shell outer radius	$R_{out} = 0.041$ pc (4.2″)
Number density	$N_H = 16{,}000\ \mathrm{cm}^{-3}$
Dust to gas mass ratio	$M_{dust}/M_{gas} = 0.005$
Central star	
$T(\star)^a$ =	180,000 K (log g = 6.0)
$R(\star)$ =	$0.1\ R_\odot$ ($L(\star) = 9{,}500\ L_\odot$)
Predicted Values	
Magnitude	$B_c = 14.72$, $V_c = 15.01$
T_ϵ([O III])	17,500 K
T_ϵ([Ar III])	14,100 K
F(Hβ)-pred =	2.9(−10) ergs $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
Observed Values^b	
Expansion Velocity	V(O III) = 18.0 km $^{-1}$
Magnitude	B > 19.8 (B_c >14.8), V > 18.8 (V_c > 15.0)
T_ϵ([O III])	17,200 K
T_ϵ([Ar III])	14,000 K
F(Hβ)-obs'd=	2.5(−10) ergs $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ (C = 1.80)

The outer shell radius is density bounded.
^{a}: Hubeny non-LTE model atmosphere with He/H = 0.13 + nebular heavy elements.
^{b}: from Aller et al. 1999 and Acker et al. 1992

The model reproduces the absolute Hβ flux and the observed visual and blue magnitudes within observational errors. The predicted intrinsic visual and blue magnitudes are $m_v = 15.01$ and $m_b = 14.72$, respectively, close to the observed values. The interstellar extinction corrected values can be obtained from the observed magnitudes, assuming $C = 1.80$ [$C = 1.47$ E(B–V) and 3.1 = A_v/E(B–V), here, E(B–V) is the color excess]. The average electron temperature of the gaseous nebula can be guessed from the diagnostics of the [O III] and [Ar III] lines. Thus, it is important to check whether the model can predict the electron temperature in the [O III] radiating stratum. The model predicts the electron temperatures for the [O III] and [Ar III] precisely (see Table 1).

(c) COMPARISON WITH OBSERVATION

Table 2 compares observed and predicted intensities. The first two columns list ions and wavelengths. The 3rd column gives the Hamilton spectral measurements and the low dispersion *IUE* data by AHF99, while the 4th column lists the previous measurements by Cuesta et al. (1995) and by Feibelman et al. (1985). As mentioned earlier, the slit sizes employed in the observations are 1.2 × 4″ — 2″× 6″ (on the central bright blob) which accepts a small fraction of the image, while the large *IUE* 10 ×23″ oval slit accepts most emission from the whole nebular image. The last column gives the predicted value. Large errors may exist inherently between the measurements. In our model predictions, we did not consider the actual slit entrance apertures and instead we adopt the values from the whole nebula.

The agreement between theory and observation appears to be generally good. We might have to increase the He/H ratio up to 0.13 to fit better, though. Aller et al. (1999) identified λ1640 as a P Cygni line. The observed line intensity here is taken from the emission component of its P Cygni line profile. As usual, carbon lines are observed mostly in the UV wavelength region. The prediction for C III] and C IV are satisfactory. C II] lines such as λ2325/26 were not measured, but we present the predicted value. There is a discordance for *IUE* observations of N III] and O IV]: the prediction for these lines seems abnormally strong and there are certainly a large measurement error involved. Predictions for Ne are disappointing. Especially, observed [Ne IV] and [Ne V] do not agree with model predictions - the model is not at fault here, though. It has been long well known that [Ne III] and [Ne V] cannot be fitted with conventional models (Hyung, Keyes, & Aller 1994, references therein).

The prediction for [Cl II] and [Cl III] seems fine. Sulfur seems fine. For other PNs like NGC 7009, the great strength of relatively low excitation line [S II] is observed, and partly attributed to clumpiness or shock effects. Here, we do not notice such a large discordance. [Cl IV] lines were predicted weakly, likewise some of [Ar IV] lines and all the [Ar V] lines. K, Ca, and Si

Table 2. Comparison of Observed and Predicted Intensities for NGC 6537

El–ion	λ	I(H+I)	I(CPM),I(FAKC)	Model
He I	5876	13.01	13.2F	10.04
	6678	3.18	5.2C,3.24F	2.30
	4471	4.11	1.6C,3.76F	3.60
He II	4686	112	86.7C,98.5F	64.7
	5412	8.46	7.7F	5.71
	1640	140.0		516.7
C II	2325/28	–		18.7
	4267	–		0.02
C III	1907/09	131		210
C IV	1548/51	313		316
N II	6584	350.6	330.4C,363F	488.4
	6548	111.4	117.9C,129F	168.6
	5755	21.41	18.5F	17.82
N III	1747-52	105		469
N IV	1483/86	–		665
N V	1239/42	583		699
O I	6300	0.83		1.54
	6363	0.32		0.49
O II	3726	–	14.20F	31.25
	3729	–	8.50F	11.96
	7321/2	8.21	8.4F	7.30
	7332/3	6.91	6.7F	5.87
	2470	–		7.8
O III	1660/66	105		87.6
	4363	24.51	20.1C,21.4F	26.57
	4959	306.4	369.3C,361F	329.9
	5007	974.1	1062C,1010F	950.4
O IV	1397-1407	9.0?		65.79
Ne III	3868	107.2	110F	107.0
	3969	33.97		31.91
Ne IV	2422/25	186.0		79.0
	4725/27	4.84		1.48
Ne V	3347	–	180F	27.0
	3426	–	501F	71.0
S II	4068	8.15	10.8F	6.88
	4076	2.00	2.9F	2.32
	6717	4.07	6.6C,4.5F	3.13
	6731	8.66	11.9C,9.0F	6.41
S III	6312	8.36	6.9C,6.9F	3.11
	9069	21.16		29.64
	9531	98.28		72.21
S IV	10.5μm	–		62.79
Cl II	8580	0.30	0.5F	0.41
Cl III	5518	0.38	0.54F	0.39
	5538	0.92	1.10F	0.93
Cl IV	7530	1.18	1.0F	0.45
	8046	2.56	2.3F	1.05
Ar III	5193	0.59		0.50
	7136	30.0	34.1F	34.2
	7751	8.63	8.1F	8.27
Ar IV	4711	11.67	16.0C,14.5F	9.25
	4740	21.73	21.2C,18.7F	18.87
	7238	1.41	0.93F	0.62
	7263	1.12	0.91F	0.67
	7171	1.34		0.83

Table 2. - Continued

El-ion	λ	I(H+I)	I(CPM),I(FAKC)	Model
Ar V	6435	8.66	6.5C,5.6F	4.72
	7005	18.64	13.0F	10.13
K IV	6102	0.87	0.82F	0.86
Ca V	5309	0.27		0.26
Si III	1883/92	54.9		59.0

Note. — I(H+I): Hamilton spectroscopic data in the optical region + low resolution *IUE* data. I(CPM),I(FAKC): from Cuesta, Phillips, & Mampaso (1995) and Feibelman et al. (1985). The large discordance for the IUE lines is primarily due to the lack of structural information in the tentative model, but there may be a contribution from the central star, and effects of geometrical irregularities in the nebula.

are represented by a single ionization stage only; hence agreement for these ions can be assured.

The great strength of the high excitation lines [Cl IV], [Ar IV] and [Ar V] in the observations may be attributed to clumpiness near the central star, but shock effects may also be important. Note that the present model is a hollow shell, so we do not consider the presence of clumpiness near the central star. For other similar PN NGC 6302, Lame & Ferland (1991) compared their model calculations with the spectrum of NGC 6302. They noticed unanticipated intensity excesses, especially in the very high ionization IR [Si VII] lines and suggested an appreciable portion of these lines could arise from shock ionization effect. Nonetheless, the discordance in the high excitation lines noted previously, is not so large for us to introduce the shock heating. The present model calculation predicts that a fairly large fraction of ions exist in the Si^{+4} (23%) and Si^{+5} (28%).

In summary, the geometrical irregularity in the inner part of PN could also cause a disparity between the observation and the calculation. Clearly, shock heating effect should be taken into account in an improved theoretical model.

IV. ABUNDANCE DETERMINATION

All the ionization stages are not available unless the emission lines all fell in the UV and optical wavelength range. In fact, a few other ionic stages are only observed in other regions, e.g. IR or Radio. Thus, we need to find the contribution from the unobserved ionic stages. To derive elemental abundances, we may proceed most obviously by two methods: (1) construct a theoretical model that reproduces the spectrum, and adopt the chemical abundance from the input value of the model, or (2) use a theoretical model or a conventional method, e.g. on p.258 of Aller (1984) and Barker (1986, references therein cited), to derive ionization correction factors, ICFs. We used both methods, here.

Table 3 lists the ion and line used in ionic concentration calculations, electron temperature adopted, the intensity corrected for interstellar extinction (see Tables 4 & 6 of AHF99), the values of $N(\mathrm{ion})/N(\mathrm{H}^+)$ obtained with N_ϵ = 20,000 cm^{-3} (i.e., N_H = 16,000 cm^{-3}) and with various electron temperatures. The electron temperatures in col. (3) are from the current model predictions. In deriving He^+ abundances, we corrected for collisionally excited contributions to the He I recombination lines, using the formulae of Clegg (1987). Note that we have given more significant figures than the data justify, to avoid round-off errors. The He II λ4686 line is strong in this object, but it may be affected by mesurement errors. Helium is obviously more abundant than the Sun.

Most of ionization stages were observed for some elements like N and O, while only a few ionic stages were available to us for others like C or S. Accordingly, the latter requires a large ICF. For Ne ionic concentration calculation, three Ne^{++}, Ne^{+3}, and Ne^{+4} stages are available. There is a huge uncertainty involved here. The predicted temperatures for the Ne ions are not different from those of the same stages of other elements. Can the T_ϵ adopted in the ICF method cause the large variation of abundance in Ne? Note that the diagnostic information of Ne ions indicated very high electron temperatures, i.e., 30,000 K and 41,000 K for Ne^{+3} and Ne^{+4} (see AHF99). When one recalculated the ionic concentration with the diagnostic indicated electron temperature T_ϵs, the ionic concentrations of [Ne IV] and [Ne V] would be much lower, i.e., 4.4(−6) and 1.3(−5), respectively. Such was the case of AHF99. Argon, represented by [Ar III], [Ar IV], and [Ar V] contribution, appears to be fine.

Table 4 gives the abundances in NGC 6537 derived by the following procedures: the 2nd column lists $\Sigma N(\mathrm{ion})/N(\mathrm{H}^+)$ derived from the data of Table

Table 3. Fractional Ionic Concentration for NGC 6537

Ion	Lines	T_ϵ	I_{corr}	$\frac{N(ion)}{N(H^+)}$
He I	6678	17000	3.18	7.37(-2)
	4471		4.11	8.96(-2)
	5876		13.0	6.00(-2)
He II	4686	20100	112	1.00(-1)?
	5412		8.46	5.70(-2)
C III	1907/9	19000	131	8.77(-6)
C IV	1545/51	20400	313	5.82(-6)
N I	5198,5200	10800	1.85	5.78(-6)
N II	6548/84,5755	12500	483	4.84(-5)
N III	1747-54	19300	105	2.15(-5)
N IV	1483/86	20500	163	2.08(-5)
N V	1239/43	20900	582	3.02(-5)
O I	6300/63	10800	1.15	9.93(-7)
O II	7319/30	12700	15.1	2.62(-5)
O III	4959,5007,4363	17700	1305	7.92(-5)
	1666–		105	9.94(-5)
O IV	1397-1407	20800	9.03	4.60(-6)
Ne III	3868,3967	15900	141	1.87(-5)
Ne IV	4724/6,4714	20200	6.76	2.09(-5)
Ne V	3345/3426	20800	681	4.89(-5)
	1575[1]		37.5	1.66(-4)
S II	6717/31,4068/76	12600	22.9	6.35(-7)
S III	6312/9069/9532	18300	121.8	1.60(-6)
Cl II	8580	11000	0.296	2.44(-8)
Cl III	5517/37	16000	1.30	3.73(-8)
Cl IV	7530/8045	19000	3.75	7.36(-8)
Ar III	7135,7751,5192	14200	39.02	1.25(-6)
Ar IV	4711/40,7263/40+	18600	37.27	8.12(-7)
Ar V	6435,7005	20500	27.30	7.51(-7)
K IV	6102	19000	0.875	6.08(-8)
Ca V	5309	20500	0.266	5.51(-8)
Si III	1882/92	18300	54.9	8.16(-7)

Note. — X(-Y) implies X × 10^{-Y}. $N_\epsilon = 20,000$ cm^{-3}. [1] discarded because of its uncertain intensity. [2] from Feibelman, Aller, Keyes, & Czyzak (1985).

Table 4. Elemental Abundances of NGC 6537

Elem.	$\Sigma\frac{N(ion)}{N(H^+)}$	ICF	$\frac{N(elem)}{N(H^+)}$	Model	Δ
He I, II	0.131	-	0.132	0.12	-
C III, IV	1.46(-5)	1.600	2.34(-5)	4.0(-5)	-0.23
N I, II, III, IV, V	1.27(-4)	1.081	1.37(-4)	4.0(-4)	-0.47
O I, II, III, IV	1.21(-4)	1.202	1.45(-4)	1.8(-4)	-0.09
Ne III, IV, V	8.86(-5)	1.292	1.14(-4)	4.7(-5)	0.41
S II, III	2.23(-6)	2.994	6.68(-6)	6.0(-6)	0.05
Ar III, IV, V	2.82(-6)	1.548	4.36(-6)	4.0(-6)	0.04
Cl II, III, IV	1.35(-7)	1.894	2.55(-7)	1.7(-7)	0.18
Ca V	3.51(-8)	7.143	2.51(-7)	3.0(-7)	-0.08
K IV	6.08(-8)	3.010	1.83(-7)	2.5(-7)	-0.14
Si III	8.16(-7)	10.89	0.89(-5)	1.2(-5)	-0.13

Note. — X1,X2(-Y) implies X1 × 10^{-Y}, X2 × 10^{-Y}. Δ: the logarithmic difference, i.e., $\log N(\mathrm{ICF}) - \log N(\mathrm{model})$.

3 which takes into account that although much higher electron temperatures are perhaps valid for some high excitation lines such as [Ar IV] and [Ne V], but predicted T_ϵ's may be more consistent with the actual temperature fluctuation of these ions and all the rest of others, as well. The 3rd column gives the best estimate of the ICFs from the tentative theoretical model. The 4th column gives the total elemental abundances, N(ICF)s, obtained by multiplying each entry in this 2nd column by the appropriate ICF value. The 5th column gives the tentative model predictions and the last logarithmic difference, i.e. $\Delta = \log N(\mathrm{ICF}) - \log N(\mathrm{model})$, between the ICF method and the model. The tentative model fails to predict some line intensities such as [Ne IV], [Ne V], [Ar V], and [Cl IV]. The discordance is not surprisingly large, though, compared with other typical PN modeling investigations, i.e. NGC 7662 (Hyung et al. 1997 and see also Lame & Ferland 1991). AHF99 gives $N(\mathrm{Ne})/N(\mathrm{H}) \simeq 4.7(-5)$, close to our model derivation. In general, the abundance derived by the ICF method is likely to be underestimated, while by the model indication appears to be overestimated except for He. Thus, we must adopt the abundance of NGC 6537 by averaging the above two values.

Table 5 compares the abundances with previous determination by Perinotto & Corradi (1998, PC hereafter), and also with the average value for a sample of PNs found in the extensive study by Kingsburgh & Barlow (1994, hereafter KB). The abundances of He and N exceed the averages found by KB or the solar values, while AHF99 derived a N/H ratio far smaller than ours. The chemical abundance determination by PC is likely to be in errors, since the spectrum was obtained with a low dispersion spectrometer and the abundance derivation was done based on a relatively few lines. On the other hand, AHF99 might have underestimated the abundance by strictly applying the extremely high electron temperatures, obtained from a few uncertain diagnostic lines.

C, O, S, Ca, and Si appear to have less abundant than the Sun, while Ar, Cl, and K appear to have about the solar abundance. Ca and Si are probably depleted due to grain formation, although these and K are largely uncertain due to the poor or large ICF factors. Ne is in question. If the quoted line intensity of He II 4686 is correct, $N(\mathrm{He})/N(\mathrm{H}^+)$ must be ~ 0.17, while model calculation indicates ~ 0.13 - 0.14. Although we favor the value close to ~0.13, true helium abundance could be slightly higher than this. However, the 0.17 appears to be too high.

V. CONCLUSION

We presented a new photoionization model calculation assuming a hot central star. Based on the model calculation we were able to derive chemical abundances of NGC 6537. The present model predictions globally fit the spectrum of NGC 6537. Note that no photoionization model can predict the electron temperature higher than T_ϵ = 25,000 K, no matter how hot the central stellar temperature is. This fact came out in the earlier history of nebular model investigation (see Aller & Liller 1968). Some diagnostics lines indicates high electron temperatures, e.g. ~29,000 K for [Ar IV] or much higher for [Ne IV] or [Ne V] (see AHF99) and the discordance between the observed and predicted intensities exist, which might suggest other source of excitation. Shock is likely to be the additional source, but this has not been considered, here.

It may come as no surprise that with a standard spherical photo-ionization model, one could not fit many of high excitation line intensities. Nevertheless, the overall predictions by the current model seem to verify that the excitation source of the nebular emission is the radiation coming from the hot central star. Although we do have a sophisticated modeling method for this type of morphological object, we do not try to

Table 5. Comparison of Abundances

El	NGC	6537	KB[1]	Sun[2]
	OUR	PC		
He	0.14	0.189	0.11	0.1
C	3.2(-5)	–	6.48(-4)	3.55(-4)
N	2.7(-4)	5.6(-4)	1.40(-4)	9.33(-5)
O	1.6(-4)	2.0(-4)	4.93(-4)	7.41(-4)
Ne	8.0(-5):	6.0(-5)	1.25(-4)	1.17(-4)
S	6.3(-6)	7.2(-6)	8.08(-6)	1.62(-5)
Ar	4.2(-6)	3.2(-6)	2.42(-6)	3.98(-6)
Cl	2.1(-7)		1.66(-7)[3]	3.88(-7)
Ca	2.5(-7)			2.29(-6)
K	1.8(-7)			1.35(-7)
Si	8.9(-6)			3.55(-5)

Note. — X(-Y) implies X × 10^{-Y}. OUR: the current estimates based on the model. PC: Perinotto & Corradi (1998). [1] Average nebular abundances by Kingsburgh & Barlow (1994). [2] Grevesse & Noels (1993). [3] Average abundances by Aller & Czyzak (1983). Colon = Uncertainty estimated $\geq$ 50%.

employ such axis symmetric modeling approach. We postpone such a refinement until more evidence on the shock heating is gathered. Eventually, it will become necessary to construct a more sophisticated 3 dimensional model.

The central star is rather faint due to the interstellar extinction. Agreement of the predicted magnitude with the observed is encouraging. Model prediction suggests a $L(\star)$ of about 9,800 $L(\odot)$ and $T(\star)$ of 180,000 K. Comparison with theoretical tracks by Blöcker & Schönberner (1990) suggests a mass of about $0.75 M_\odot$ and an age of about 1,500 years, while the dynamical age, deduced from the shell expansion velocity and the outer faint boundary tail along the axis ($\sim$17″), indicates $\sim$1,200 years. During 1,000 years, the central star temperature has probably increased by one order, but now at its peak point and resulted in a higher excitation status of the nebular gas. During the next century, we might be able to see the central star luminosity going down rapidly to $\sim$1,000 $L(\star)$, while the central star temperature remains pretty much the same. We must certainly monitor this object for its spectral variability. NGC 6537 is extremely young and it may have originated from a star of at least $\sim$5 $M_\odot$. NGC 6818 is a Peimbert (1978) Type I PN judging from its chemical or central star activity characteristics, or both, although N does not seem to be enhanced to an enormously large degree indicated by Perinotto & Corradi (1998).

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