RAMAN-SCATTERED He II λ6545 IN THE YOUNG AND COMPACT PLANETARY NEBULA NGC 6790

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ABSTRACT

We present the high-resolution spectra of the young and compact planetary nebula NGC 6790 obtained with the Echelle Spectrograph at Bohyunsan Optical Astronomy Observatory and report the discovery of Raman-scattered He II λ6545 in this object. This line feature is formed in a thick neutral region surrounding the hot central star, where He II λ1025 line photons are scattered inelastically by hydrogen atoms. A Monte Carlo technique is adopted to compute the line profiles with a simple geometric model, in which the neutral region is in the form of a cylindrical shell that is expanding from the central star. From our line profile analysis, the expansion velocity of the H i region lies in the range \( v_{\text{exp}} = 15-19 \text{ km s}^{-1} \). Less stringent constraints are put on the H i column density \( N_{\text{H}i} \) and covering factor \( C \), where the total flux of Raman He II λ6545 is consistent with their product \( CN_{\text{He}i} \sim 0.5 \times 10^{28} \text{ cm}^{-2} \). The Monte Carlo profiles from stationary emission models exhibit deficit in the wing parts. A much better fit is obtained when the He II emission region is assumed to take the form of a ring that slowly rotates with a rotation speed of \( \sim 18 \text{ km s}^{-1} \). Brief discussions are presented regarding the mass-loss processes and future observations.

Key words: planetary nebulae: general – planetary nebulae: individual (NGC 6790) – radiative transfer – scattering – stars: mass loss

1. INTRODUCTION

Mass loss is an important process that mainly occurs in the late stage of stellar evolution. A star with a mass less than 8 \( M_{\odot} \) loses a significant amount of mass in the giant stage before becoming a planetary nebula with a hot white dwarf at its center. Considering the Chandrasekhar limit of 1.4 \( M_{\odot} \), the mass-loss process in the giant stage with enriched heavy elements should be important in the chemical evolution of the interstellar medium. In this regard, with a recent history of mass loss, young planetary nebulae are interesting objects to study the mass-loss process.

It is expected that around a young planetary nebula there may be a significant amount of neutral material that was lost in the previous stage of stellar evolution. In this case, the neutral region is exposed to the strong UV emission line source in the vicinity of the hot central star of the planetary nebula. Therefore, important information related to the mass-loss process can be gathered from investigations of the scattering processes of the UV radiation originating from the center region.

Taylor et al. (1990) performed H i 21 cm radio observations for a number of compact planetary nebulae (see also Altschuler et al. 1986; Gussie & Taylor 1995; Schneider et al. 1987). Their target selection was made on the basis of high radio brightness temperature, which is indicative of the nebular compactness. They searched an absorption trough that may be formed at the radial velocity of a compact planetary nebula when the neutral region blocks the background H i radio emission from our Galaxy. A number of compact young planetary nebulae including IC 5117 and NGC 6790 have been detected. Adopting an excitation temperature \( T_{\text{H}i} = 100 \text{ K} \), the typical H i column density was determined to be of order \( N_{\text{H}i} \sim 10^{20} \text{ cm}^{-2} \) in these objects.

Astrophysical Raman spectroscopy involving atomic hydrogen was initiated by Schmid (1989), who identified the mysterious broad emission bands occurring at 6825 Å and 7088 Å in many symbiotic stars (see also Nussbaumer et al. 1989). He proposed that a hydrogen atom in the ground state is excited by atomic hydrogen also operates around an He II emission source.

In the spectrum of the symbiotic star RR Telescopii, Van Groningen (1993) discovered Raman scattered He II features that are formed blueward of hydrogen Balmer emission lines. He II emission lines arising from transitions between \( n = 2k \) and \( n = 2 \) levels have wavelengths that are slightly shorter than hydrogen Lyman lines owing to the fact that He II ions are single electron atoms with a slightly larger two-body reduced mass. The proximity to resonance is responsible for a large scattering cross section requiring the existence of a neutral region with \( N_{\text{He}i} \sim 10^{20} \text{ cm}^{-2} \) around an He II emission source.

Raman scattered He II features are also reported in other symbiotic stars including He 2-106, HM Sagittae, and V1016 Cygni (Lee et al. 2001; Jung & Lee 2004b; Birriel 2004).

Raman scattering of He II by atomic hydrogen also operates in young planetary nebulae. The first discovery was reported by Péquignot et al. (1997) in their spectroscopic analysis of the young planetary nebula NGC 7027. Subsequently, Groves et al. (2002) found the same Raman-scattered He II features in the planetary nebula NGC 6302. Recently, Lee et al. (2006) reported that the compact planetary nebula IC 5117 also exhibits Raman scattered He II features blueward of Hα and Hβ. In these objects, it appears that the central star is surrounded by a neutral region with a significant covering factor. In particular, Lee et al. (2006) discussed in detail the atomic physics of He II recombination and Raman scattering processes.
We present our high-resolution spectra of the young and compact planetary nebula NGC 6790 and report our finding of the Raman-scattered He II λ6545 feature in this object. Using the Hα image, Tylenda et al. (2003) measured the angular size of NGC 6790 to be 4″ × 3″. This size estimate of NGC 6790 is consistent with the Hubble Space Telescope (HST) image shown by Kwok et al. (2003), who also identified two inner shells of similar orientations in NGC 6790. The distance to NGC 6790 is poorly known. Gathier et al. (1986) proposed that NGC 6790 is further than ∼8 kpc based on their kinematic considerations. Adopting a statistical method, Zhang (1995) suggested a distance of 5.7 kpc to NGC 6790. In their high-resolution spectroscopy of NGC 6790, Aller et al. (1996) proposed a core mass of 0.6 $M_\odot$ and an age of 6000 yr with the note that these values are dependent on the uncertain distance to NGC 6790.

We perform Monte Carlo radiative transfer simulations in order to obtain the geometric and kinematic information of the neutral region. In Section 2, we describe our observation and line fitting analyses and the following section presents our results of the Monte Carlo radiative transfer. In the final section, we discuss briefly our observation and mass-loss processes of NGC 6790.

2. OBSERVATION AND ANALYSIS

2.1. Observation and Data

We observed the young planetary nebula NGC 6790 on the night of 2008 May 31 using the 1.8 m telescope at Bohyunsan Optical Astronomy Observatory (BOAO). The spectrograph that we used is the BOAO Echelle Spectrograph (BOES), which is a bench-mounted echelle system fed by optical fibers with various diameters. We used the 300 μm fiber, which yields the spectral resolution of ∼30,000 with a field of view of 3″. The spectral coverage ranges 3600 Å through 10,500 Å. We obtained two spectra with exposure times of 600 s and 7200 s, respectively. A Th–Ar lamp was used for wavelength calibrations. For more detailed information on BOES, one is referred to Kim et al. (2007). Standard procedures using the IRAF packages were followed to reduce the spectra.

In Figure 1, we show parts of our spectra around Hα and Hβ. The vertical axis represents the relative flux. We normalize the flux using [N II] λ6548, which is set to have a flux peak of unity. The top panel of Figure 1 is the spectrum around Hα with an exposure time of 600 s. We note strong forbidden emission lines of N II at 6548 Å and 6583 Å. In this short exposure spectral image, the strongest Hα is unsaturated, allowing us to fit the Hα profile. The middle panel of Figure 1 shows the Hα part of the spectrum with an exposure time of 7200 s. The strong Hα is saturated and we discern very faint emission lines including [N II] λ6548, C II λ6718, and [Fe II] λ4851, which means that the broad wing feature around [N II] λ6548 is not associated with [N II] nor is an instrumental artifact. The bottom panel shows the Hβ part of the BOES spectrum. The insufficient quality of the data hinders the clear detection of the Raman-scattered He II λ4850.

![Figure 1](image)

**Figure 1.** High-resolution spectra of NGC 6790 obtained with BOES. The top panel is a short exposure spectrum with an exposure time of 600 s, and the exposure time for the middle and bottom panels is 7200 s. The relative flux is normalized such that [N II] λ6548 has the flux peak of unity. In the top panel, the strongest emission line Hα is unsaturated. We also clearly see [N II] lines at 6548 Å and 6583 Å. In the middle panel, we note that around [N II] λ6548 there exists a broad wing feature. No similar feature is present around the three times stronger [N II] λ6583, which means that the broad wing feature around [N II] λ6548 is not associated with [N II] nor is an instrumental artifact. The bottom panel shows the Hβ part of the BOES spectrum.
NGC 7027, they detected Raman-scattered He \( \lambda 4850 \). In this object, Raman-scattered He \( \lambda 4850 \) is not blended with other strong emission lines, which is in contrast with Raman He \( \lambda 6545 \) that is severely blended with [N \( \text{II} \)] \( \lambda 6548 \). In the bottom panel of Figure 1, no broad feature around 4850 Å is detected with a level of any significance. The quite strong and sharp emission feature at 4851 Å is an emission line totally irrelevant with Raman scattering. Aller et al. (1996) identified this emission line as a forbidden line from Fe \( \text{II} \). Our spectrum is of insufficient quality to confirm the existence of Raman-scattered He \( \lambda 4850 \). However, this does not cast serious doubts on the Raman scattering nature of the 6545 feature, because Raman He \( \lambda 4850 \) is always weaker than Raman He \( \lambda 6545 \). More discussion on this point is presented in Section 3.2.

### Table 1

| Line          | \( \lambda_0 \) (Å) | \( f_0 \) | \( \Delta \lambda \) (Å) |
|---------------|----------------------|---------|-------------------------|
| H\( \alpha \) 6563 | 6563.23              | 34.8    | 0.54                    |
| He\( \alpha \) \( \lambda 6560 \) | 6560.58              | 0.072   | 0.48                    |
| He \( \alpha \) \( \lambda 6527 \) | 6527.49              | 0.00295 | 0.48                    |
| [N \( \text{II} \)] \( \lambda 6548 \) | 6548.51              | 0.897   | 0.47                    |
| [N \( \text{II} \)] \( \lambda 6583 \) | 6583.90              | 2.73    | 0.48                    |

2.2. Line Fitting Analysis

Single Gaussian functions in the form \( f(\lambda) = f_0 \exp[-(\lambda - \lambda_0)^2/2\Delta \lambda^2] \) are used to fit the permitted emission lines of H\( \alpha \), He \( \alpha \) \( \lambda 6560 \), He \( \alpha \) \( \lambda 6527 \), and the two N \( \text{II} \) forbidden lines. The least \( \chi^2 \) method is adopted to obtain the best-fitting Gaussian functions. We use the atomic spectral data from the Web site of this object, Raman-scattered He \( \alpha \) \( \lambda 4850 \). We use this emission line as a forbidden line from Fe \( \text{II} \). Our spectrum is of insufficient quality to confirm the existence of Raman-scattered He \( \lambda 4850 \). However, this does not cast serious doubts on the Raman scattering nature of the 6545 feature, because Raman He \( \lambda 4850 \) is always weaker than Raman He \( \lambda 6545 \). More discussion on this point is presented in Section 3.2.

Figure 2 illustrates our line fitting analysis of the emission lines in NGC 6790. The top panels show the result for H\( \alpha \) and He \( \alpha \) \( \lambda 6560 \). The short exposure data are used for the H\( \alpha \) emission line, which is excellently fitted by a single Gaussian function with a width \( \Delta \lambda = 0.54 \) Å. He \( \alpha \) \( \lambda 6560 \) is also well fitted by a single Gaussian function with a considerably smaller width of \( \Delta \lambda = 0.48 \) Å than that for H\( \alpha \).

The middle panels of Figure 2 show our result for He \( \alpha \) \( \lambda 6527 \), which is significantly weak compared with He \( \alpha \) \( \lambda 6560 \). He \( \alpha \) \( \lambda 6527 \) is strongly blended with another unidentified emission line. Because He \( \alpha \) \( \lambda 6527 \) is well fitted by a single Gaussian, He \( \alpha \) \( \lambda 6527 \) should be also fitted by a single Gaussian function, which is shown by the dotted line in Figure 2(c). The long dashed line in Figure 2(c) shows our Gaussian fit to the unidentified emission line. Groves et al. (2002) noted the existence of [N \( \text{II} \)] \( \lambda 6527 \) reddened of He \( \alpha \) \( \lambda 6527 \) with the wavelength difference of 0.14 Å in their spectrum of NGC 6302. However, the unidentified emission line in our spectrum of NGC 6790 cannot be [N \( \text{II} \)] \( \lambda 6527 \), because it appears redder of He \( \alpha \) \( \lambda 6527 \) by 1 Å. Furthermore, based on the NIST data, [N \( \text{II} \)] \( \lambda 6527 \) has the Einstein \( A \) coefficient \( A = 5.45 \times 10^{-7} \) s\(^{-1}\). Compared with [N \( \text{II} \)] \( \lambda 6548 \) having \( A = 9.19 \times 10^{-4} \), [N \( \text{II} \)] \( \lambda 6527 \) should be weaker than [N \( \text{II} \)] \( \lambda 6548 \) by a factor of 1700. Based on these atomic data, we plotted [N \( \text{II} \)] \( \lambda 6527 \) with a dot-dashed line in Figure 2. As is shown in the figure, [N \( \text{II} \)] \( \lambda 6527 \) is significantly weaker than He \( \alpha \) \( \lambda 6527 \), and hence cannot affect the overall line fitting result. The 6528 Å feature is much stronger than [N \( \text{II} \)] \( \lambda 6527 \) and still remains to be identified. Figure 2(d) shows the composite profiles of the two single Gaussian functions in Figure 2(c). From our profile analysis shown also in Table 1, we conclude that the flux ratio of He \( \alpha \) \( \lambda 6527 \) and He \( \alpha \) \( \lambda 6560 \) is

\[
F_{6527}/F_{6560} = 4.1 \times 10^{-2}.
\]

The bottom panels of Figure 2 show the detailed profiles of [N \( \text{II} \)] lines. It is interesting to note that [N \( \text{II} \)] \( \lambda 6548 \) exhibits a sharp absorption feature centered at 6548.60 Å. The line center of [N \( \text{II} \)] \( \lambda 6548 \) appears at 6548.51 Å, and the sharp absorption feature is excellently fitted by a single Gaussian function with a width of \( \Delta \lambda = 0.1 \) Å and center at \( \lambda_0 = 6548.60 \) Å. We find no such absorption feature in [N \( \text{II} \)] \( \lambda 6583 \), which should exhibit exactly the same profile with three times more flux (e.g., Osterbrock 1987). To our knowledge, no plausible metal transition is responsible for this sharp absorption. We also checked the telluric absorption lines without finding any strong candidate. In the spectrum of IC 5117 obtained with the 3.6 m Canada–France–Hawaii Telescope we find no similar absorption feature, for which [N \( \text{II} \)] \( \lambda 6548 \) exhibits exactly the same profile as [N \( \text{II} \)] \( \lambda 6583 \). We tentatively propose that this is attributed to H\( \alpha \) that is redshifted by an amount of \( v_{\text{abs}} \sim 800 \) km s\(^{-1}\). However, in this work, we limit our attention to the Raman-scattered He \( \alpha \) \( \lambda 6545 \) with no further discussion of this possibly interesting feature.

Lee et al. (2001) performed a line profile analysis of Raman-scattered He \( \alpha \) \( \lambda 6545 \) in a number of symbiotic stars. They subtracted one-third of the flux near [N \( \text{II} \)] \( \lambda 6583 \) from the flux near [N \( \text{II} \)] \( \lambda 6548 \) to expose a broad Raman scattering line feature successfully. However, in view of the existence of the unidentified absorption feature in [N \( \text{II} \)] \( \lambda 6548 \) and more severe blending with [N \( \text{II} \)] \( \lambda 6548 \), we took another approach, in which the Raman-scattered He \( \alpha \) \( \lambda 6545 \) feature is directly fitted from our Monte Carlo data.

3. MONTE CARLO RADIATIVE TRANSFER

3.1. Monte Carlo Procedure

In this subsection, we describe the procedure of our Monte Carlo analysis of the Raman-scattered He \( \alpha \) \( \lambda 6545 \). Many planetary nebulae exhibit nonspherical morphology, which may have its origin in the asymmetric mass-loss processes. In the case of NGC 6790, the HST image obtained by Kwok et al. (2003) shows elongated shells around the central star. As a first approximation, we adopt a cylindrical shell model for neutral material, which is schematically illustrated in Figure 3. A similar geometry was considered in the analysis of IC 5117 by Lee et al. (2006).

In this cylindrical shell geometry, the hot UV source is located at the center and H \( \text{I} \) material is uniformly distributed inside the cylindrical shell with finite height and thickness. The same geometry was adopted by Lee et al. (2006). However, the essential difference is that we now consider the scattering region is expanding with the constant expansion velocity \( v_{\text{exp}} \). The cylindrical region is characterized by a uniform H \( \text{I} \) density \( n_{\text{H}1} \), the height \( H \), and the inner and outer radii \( R_{\text{th}} \) and \( R_{\text{th}} + \Delta R \), respectively. In this case, the H \( \text{I} \) column density of the cylindrical shell is given by \( N_{\text{HI}} = n_{\text{H}1} \Delta R \).

Since the shell is of uniform density, instead of the physical length \( l \) we measure the distance inside the shell in terms of the scattering optical depth \( \tau \) defined by

\[
\tau = n_{\text{H}1} \sigma_{\text{tot}} l. \tag{2}
\]
Figure 2. Gaussian line fitting analysis. The solid lines show the observational data and the dotted lines show our Gaussian fits. The same flux normalization as in Figure 1 is used. The top panels show the results for Hα and He II λ6560. The middle panels show the line fitting result for He II λ6527 and a nearby unidentified emission line. He II λ6527 is fitted by a single Gaussian function, which is shown by the dotted line in panel (c). The long dashed line in panel (c) shows the unidentified emission line. Using the atomic data provided by NIST, we show the line contribution from [N II] λ6527 by a dot-dashed line. In panel (d), we show the composite profile from the three single Gaussians shown in panel (c). The bottom panels show the detailed views of [N II] lines. There is a sharp absorption feature in [N II] λ6548, which is also well fitted by a single Gaussian with the width $\Delta \lambda = 0.1 \AA$ and the center at $\lambda_c = 6548.60 \AA$.

Figure 3. Schematic diagram of the Raman scattering geometry adopted in this work. The hot star and He II emission region are located at the center. Surrounding the UV emission region, the H I scattering region takes the form of a cylindrical shell with the inner radius $R_H$, the outer radius $R_H + \Delta R$, and the height $H$. In this work, the cylindrical shell is assumed to expand with the speed $v_{\text{exp}}$. Hydrogen atoms are distributed uniformly with a number density $n_H$ inside the cylindrical shell.

where $\sigma_{\text{tot}}$ is the sum of the cross sections for Rayleigh and Raman scattering. Since $\sigma_{\text{tot}}$ is a sensitive function of a wavelength of the photon being considered, a given distance may correspond to different optical depths dependent on the wavelength. Therefore, once a photon is generated in the Monte Carlo simulation, we assume that the wavelength does not change as long as it is Rayleigh scattered. Considering that the scattering region is neutral, this assumption should be reasonable.

The basic atomic physics of Raman scattering adopted in our Monte Carlo code is explained in detail by Jung & Lee (2004a). Due to the proximity of He II λ1025 to H I Lyβ resonance, the scattering cross section increases steeply near Lyβ. Yoo et al. (2002) showed that the branching ratio $r_b$ into Raman scattering increases approximately linearly with wavelength, which is given by

$$r_b = \frac{\sigma_{\text{Ram}}}{\sigma_{\text{tot}}} = 0.1342 \pm 12.50(\lambda - \lambda_{\text{Ly} \beta})/\lambda_{\text{Ly} \beta},$$

(3)

where $\sigma_{\text{Ram}}$ is the cross section for Raman scattering and $\lambda_{\text{Ly} \beta}$ is the Lyβ center wavelength. Therefore, the Raman conversion into the optical region is quite sensitive to the incident wavelength, which in turn depends on the expansion velocity.
From the energy conservation, a Raman-scattered He II feature is characterized by its large width given by

$$\frac{\Delta \lambda_{\text{Ram}}}{\lambda_{\text{Ram}}} = \frac{\lambda_i}{\lambda_i} \times \frac{\Delta \lambda_i}{\Delta \lambda_i},$$  \hspace{1cm} (4)

where $\lambda_i$ and $\lambda_{\text{Ram}}$ are wavelengths of the incident and Raman scattered radiation (e.g., Schmid 1989; Nussbaumer et al. 1989).

In the case of Raman He II $\lambda 6545$, the profile width becomes about six times broader than He II $\lambda 1025$, which endows a unique property that the profile is mainly determined from the relative motion between the emitter and the scatterer.

In our Monte Carlo calculation, we also consider the re-entry of a photon emerging from the inner wall of the cylinder, for which we assume that this photon travel freely until it hits the inner wall on the opposite side. We consider a photon with a unit wavevector $\hat{k}$ supposed to travel a scattering optical depth $\tau$ from the position $r_i = (x_i, y_i, z_i)$. If this photon emerges from the inner wall of the cylinder, we find the two points of intersection with the inner wall of the cylinder. This is accomplished by solving the quadratic for $\tau_p$

$$R_{\text{H}}^2 = |(r_i + \tau_p \hat{k})|,$$  \hspace{1cm} (5)

for which we denote the solutions by $\tau_{p1}$ and $\tau_{p2}$ with $\tau_{p2} > \tau_{p1}$. Here, $\hat{\rho}$ is the unit vector pointing radially outward from the cylinder axis. The difference of the two solutions $\Delta \tau_p$ is given by

$$\Delta \tau_p = \tau_{p2} - \tau_{p1} = 2 \sqrt{R_{\text{H}}^2 (1 - k_z^2) - (k_x y_i - k_y x_i)^2},$$  \hspace{1cm} (6)

where $k_x$, $k_y$, and $k_z$ are the components of $\hat{k}$. By adding $\Delta \tau_p$ to the original photon path, we find the new scattering site in the other side of the shell.

The incident He II $\lambda 1025$ line flux and profile can be inferred from the Case B recombination theory of single electron atoms provided by Storey & Hummer (1995). In Table 2, we show the expected He II $\lambda 1025$ line flux relative to He II $\lambda 6560$ and He II $\lambda 6527$ for electron number densities $n_e = 10^4$, $10^5$, and $10^6$ cm$^{-3}$ and temperatures $T_e = 10^4$ and $2 \times 10^4$ K. We note that our observed flux ratio of He II $\lambda 6527$ and He II $\lambda 6560$ given in Equation (1) is consistent with the nebular condition of $n_e \sim 10^6$ cm$^{-3}$ and $T_e = 10^4$ K. However, this choice is not unique and the range of He II $\lambda 1025$ is already quite significant with the choice of parameters in Table 2. With this caveat in mind, we fix the electron number density $n_e = 10^6$ cm$^{-3}$ and $T_e = 10^4$ K. Adopting these values of $n_e$ and $T_e$, the recombination theory by Storey & Hummer (1995) gives $F_{1025} = 4.2 F_{6560}$, which is used for our Monte Carlo calculations.

The Monte Carlo simulation starts with a generation of He II $\lambda 1025$ line photons having the same line profile with that of observed He II $\lambda 6560$, and appropriately scaled using the recombination theory. As He II $\lambda 6560$ is fitted by a single Gaussian with a width of $\Delta \lambda = 0.48$ Å, we note that the line profile function $f_{\text{UV}}$ for He II $\lambda 1025$ is given by

$$f_{\text{UV}}(\lambda) = f_{1025} \exp \left[ - \left( \frac{\lambda - \lambda_{1025}}{\Delta \lambda_{1025}} \right)^2 \right]$$  \hspace{1cm} (7)

with $\Delta \lambda_{1025} = 0.48 \times 1025/6560$ Å = 0.075 Å. Here, the peak value $f_{1025}$ is appropriately adjusted to yield $F_{1025} = 4.2 F_{6560}$.

We trace each individual He II $\lambda 1025$ line photon until it escapes from the H I region. From Equation (4), it is noted that the profiles of the Raman-scattered features are determined from the relative kinematics between the emission source and the H I region and almost independent of the observer’s line of sight. Therefore, in this work, we collect all the photons irrespective of the final direction.

### 3.2. Simulated Raman Profiles

#### 3.2.1. Spherical Emission Region

In the work of Lee et al. (2006), the analysis of Raman-scattered He II $\lambda 6545$ was purely based on the atomic physics and focused on the exact location of line center. Their computation shows that the Raman-scattered feature should be centered significantly blueward of [N II] $\lambda 6548$. Figure 1, we note that the Raman He II $\lambda 6545$ is completely blended with [N II] $\lambda 6548$, which implies that the neutral scattering region should be receding from the central UV source.

In Figure 4, we show our Monte Carlo profiles for various expansion speeds $v_{\text{exp}}$ of the neutral scattering region with respect to the hot central star. In this figure, the height of the cylinder is taken to be infinite so that the covering factor of the scattering region is unity. The column density is fixed to $N_{\text{H}} = 1 \times 10^{20}$ cm$^{-2}$. The solid line shows our observed data and the other lines show our Monte Carlo profiles corresponding to various values of $v_{\text{exp}}$. We can clearly note the center shift of the Raman He II $\lambda 6545$, which is highly enhanced due to the line broadening given in Equation (4). The top panel shows the profiles for velocities $v_{\text{exp}} \leq 40$ km s$^{-1}$. The bottom panel shows the profiles for velocities in the smaller range $14$ km s$^{-1} \leq v_{\text{exp}} \leq 22$ km s$^{-1}$. From the figure, the plausible expansion velocity is around $20$ km s$^{-1}$, for which the peak wavelength resides inside the [N II] $\lambda 6548$ emission line.

One interesting point to note from Figure 4 is that the strength of the Raman feature increases sharply as $v_{\text{exp}}$ increases despite the fact that the covering factor and $N_{\text{H}}$ are fixed. This is explained by the fact that the Raman scattering cross section sharply increases near H$\alpha$ due to Ly$\beta$ resonance in the parent wavelength space. Therefore, a receding H I region yields more Raman-scattered He II $\lambda 6545$ photons than when the same region is stationary. This complicated dependence of the scattering cross section on wavelength also results in slightly asymmetric Raman profiles, which is barely noticeable in Figure 4. Therefore, the Raman conversion efficiency may be estimated accurately only after the kinematics of the scattering region with respect to the emission source is carefully determined.

| Line Ratio | $T_e = 10^4$ K | $T_e = 2 \times 10^4$ K |
|------------|---------------|------------------|
| $F_{1025}/F_{6560}$ | 3.600 | 4.519 |
| $F_{6527}/F_{6560}$ | 3.952 $\times 10^{-2}$ | 4.085 $\times 10^{-2}$ |
| $n_e = 10^6$ cm$^{-3}$ | $F_{1025}/F_{6560}$ | 3.804 | 4.676 |
| $F_{6527}/F_{6560}$ | 4.098 $\times 10^{-2}$ | 4.152 $\times 10^{-2}$ |
| $n_e = 10^5$ cm$^{-3}$ | $F_{1025}/F_{6560}$ | 4.439 | 5.181 |
| $F_{6527}/F_{6560}$ | 4.942 $\times 10^{-2}$ | 4.614 $\times 10^{-2}$ |

Table 2

He II Recombination Data by Storey & Hummer (1995)
unity and simulations for various expansion speeds. The covering factor is fixed to be unity and \( N_{\text{H}} = 10^{20} \text{ cm}^{-2} \). Due to the inelasticity of Raman scattering or Equation (4), the location of line center is fairly sensitive to \( v_{\text{exp}} \). The top panel shows the profiles for velocities in the range \( v_{\text{exp}} \leq 40 \text{ km s}^{-1} \) in an interval of 10 km s\(^{-1}\). The bottom panel shows the profiles for velocities in the range 14 km s\(^{-1}\) \( \leq v_{\text{exp}} \leq 22 \text{ km s}^{-1} \). It is notable that the expansion velocity \( v_{\text{exp}} \) affects both the location of line center and the total Raman flux.

In the top panel of Figure 5, we show the Raman profiles for various \( \text{H} \, \text{i} \) column densities ranging \( N_{\text{H}} = 10^{19} - 1.5 \times 10^{20} \text{ cm}^{-2} \) with the fixed values of \( H/R_{\odot} = 2 \) and \( v_{\text{exp}} = 20 \text{ km s}^{-1} \). Within this range of \( N_{\text{H}} \), the overall strength is nearly proportional to the \( \text{H} \, \text{i} \) column density, because the \( \text{H} \, \text{i} \) region is mostly optically thin with respect to the Raman scattering of \( \text{He} \, \text{ii} \). This expansion speed is very similar to the value of 16 km s\(^{-1}\) determined from Doppler-shifted Na D absorption lines by Dinerstein et al. (1995).

The bottom panel of Figure 5 shows the Monte Carlo Raman profiles for various covering factors of the cylindrical shell. As is expected, the overall strength is also proportional to the covering factor. In both the panels of Figure 5, we obtain qualitatively similar profiles. This implies that the Raman profile analysis severely suffers from the degeneracy problem involving the covering factor and \( \text{H} \, \text{i} \) column density.

With this caveat in mind related to the degeneracy in \( N_{\text{H}} \) and the covering factor, we show our best-fit profile from the Monte Carlo calculations in Figure 6. The model parameters are \( v_{\text{exp}} = 19 \text{ km s}^{-1} \), \( N_{\text{H}} = 9 \times 10^{19} \text{ cm}^{-2} \), and \( H/R_{\odot} = 1.7 \). As in IC 5117, the \( \text{H} \, \text{i} \) region significantly covers the hot central star in NGC 6790. However, in this figure, we note that the model profiles exhibit deficit both in the blue wing and red wing parts. If this deficit is real, then it implies that in the direction to the \( \text{H} \, \text{i} \) region the incident profile is broader than in the observer’s line of sight. The following subsection discusses this point.

Jung & Lee (2004b) developed a Monte Carlo code to compute the line profile of Raman-scattered \( \text{He} \, \text{ii} \) 4850 and analyzed their spectrum of the symbiotic star V1016 Cyg. Using the same code, we show in Figure 7 the Monte Carlo profile for Raman-scattered \( \text{He} \, \text{ii} \) 4850 by a long dashed line. The same column density and covering factor as in Figure 6 were used in this calculation. In the figure, the solid line shows the BOES data with an exposure time of 7200 s. Our observational data are barely consistent with our interpretation of Raman scattering nature. The poor quality of the current observational data hinders a further serious quantitative analysis. A more fruitful analysis may be made only after observational data with a better quality are secured.

3.2.2. Ringlike Emission Region

In this subsection, we perform line profile analyses in the case where the emission region takes the form of a ring that is rotating in the vicinity of the hot central star. In the previous section, it was assumed that the \( \text{He} \, \text{ii} \) emission region is spherically symmetric and stationary. However, it is highly probable that the distribution of nebular material significantly deviates from spherical symmetry considering the nonspherical shape exhibited by most planetary nebulae (e.g., Corradi & Schwarz 1995). In this case, the emission region may plausibly possess an ordered motion component, which may also be associated with the nonspherical nebular morphology. Therefore, we may expect that ionized material is concentrated on the equatorial plane having some slow rotation velocity component.

There exists little kinematic information available on the emission region very near the central star. No observational data of NGC 6790 are available in the archives of HUT and FUSE. In consideration of the absence of a unique kinematic model accounting for all the observed emission line profiles, we adopt a simple ringlike emission region, in which we investigate the line-of-sight effect on the profiles of the \( \text{He} \, \text{ii} \) emission and Raman-scattered lines. Depending on the line of sight of
Figure 6. Our best-fit Monte Carlo profile of Raman-scattered He II $\lambda$6545 from a stationary emission region surrounded by a cylindrical shell. The long-dashed line is the Monte Carlo line profile and the solid line is the observed data. The adopted parameters are $v_{\text{exp}} = 19$ km s$^{-1}$, $H/R_H = 1.7$, and $N_{\text{He}} = 9 \times 10^{19}$ cm$^{-2}$.

Figure 7. BOES data around H$\beta$ (solid line) and the Monte Carlo profile of Raman-scattered He II $\lambda$4850 (long-dashed line). The same column density and covering factor as in Figure 6 were used in the Monte Carlo calculation. The observational data are barely consistent with the Monte Carlo result.
the observer, the rotation velocity component is reduced by the factor sin i, where i is the inclination angle of the ring. However, Equation (4) dictates that the Raman profile is determined by the velocity component of the emitter with respect to the scatterer and fairly insensitive to the line of sight.

This proposition leads to an interesting interpretation of our profile fitting of Hα and He II λ6560 presented in the previous section. We may decompose the emission profiles into a bulk component and a random component. We further assume that the bulk component represents a slow rotation in the equatorial plane and that the random component is attributed to a thermal motion and a turbulent motion. For the sake of simplicity, we assume that He II λ6560 and Hα are formed in the same ringlike region that is in slow rotation in the equatorial plane with the speed \( v_{\text{bulk}} \).

An He ion being four times heavier than a hydrogen nucleus, the line width of He II due to the thermal motion is half of that for Hα if they are formed in the same region. However, if the emission region possesses some turbulent component, then overall random motion component for hydrogen is broader than that of He II by a factor less than 2. If we denote the electron temperature of NGC 6790 by \( T_e = 10^4 \ T_4 \) K, then the thermal velocity associated with Hα is given by

\[
v_{\text{th},\alpha} = \sqrt{\frac{k_B T_e}{2 m_p}} = 13 \ T_4^{1/2} \ \text{km s}^{-1},
\]

where \( m_p \) is the proton mass and \( k_B \) is the Boltzmann constant (e.g., Rybicki & Lightman 1979). Introducing \( v_{\text{turb}} \) for the turbulent velocity scale, we denote the random velocity components of Hα and He II λ6560 by \( v_{\text{ran},\alpha} \) and \( v_{\text{ran},\text{He II}} \), respectively, where

\[
\begin{align*}
  v_{\text{ran},\alpha} &= v_{\text{turb}} + v_{\text{th},\alpha}, \\
  v_{\text{ran},\text{He II}} &= v_{\text{turb}} + \left( v_{\text{th},\alpha}/2 \right).
\end{align*}
\]

Noting that there are three model parameters, namely \( i \), \( v_{\text{bulk}} \), and \( v_{\text{turb}} \) for the two line widths, we also encounter a degeneracy problem. Hoping that future observations may provide independent constraints on some of these model parameters, we just pick out a set of values that yield a reasonable fit to our observed data. In the top panels of Figure 8, we show model line profiles for He II λ6560 and Hα from one such set consisting of

\[
\begin{align*}
  \sin i &= 0.6, \\
  v_{\text{bulk}} &= 18 \ \text{km s}^{-1}, \\
  v_{\text{turb}} &= 14 \ \text{km s}^{-1}, \\
  v_{\text{th},\alpha} &= 14 \ \text{km s}^{-1}, \\
  v_{\text{th},\text{He II}} &= 0.5 v_{\text{th},\alpha}.
\end{align*}
\]

The thermal velocity \( v_{\text{th},\alpha} = 14 \ \text{km s}^{-1} \) is consistent with the electron temperature \( T_e = 10^4 \) K, which is similar to that obtained by Aller et al. (1996) from their photoionization modeling. The overall fits to both Hα and He II λ6560 appear quite good. The bulk velocity component is consistent with the size of the emission ring region of order 1 AU if we interpret the bulk motion to be Keplerian. However, the bulk motion may not be related to the Keplerian motion but may be related to the rotation component of the central star, for which case the physical size of the emission region can be at best poorly constrained.

Because the H I region is also concentrated on the equatorial plane, the full bulk velocity component should be considered.
Figure 9. Monte Carlo best-fit profile (dotted line) of Raman-scattered He \( \text{ii} \) \( \lambda 6545 \) from a ringlike emission region considered in Figure 7. The adopted model parameters are \( \sin i = 0.6 \), \( v_{\text{bulk}} = 18 \text{ km s}^{-1} \), \( v_{\text{th H}} = 14 \text{ km s}^{-1} \), and \( v_{\text{turb}} = 14 \text{ km s}^{-1} \). Refer the text for the definitions of these parameters. This profile provides a much better fit than that shown in Figure 6. It is noted that the expansion velocity of the H \( \text{i} \) shell is \( v_{\text{exp}} = 15 \text{ km s}^{-1} \), which is significantly smaller than that considered in Figure 6.

4. DISCUSSION

H \( \text{i} \) Raman spectroscopy provides an accurate determination of the expansion velocity of the H \( \text{i} \) region, for the measurement of which H \( \text{i} \) 21 cm radio observation has been the unique tool so far. Our analysis shows that the expansion velocity lies between 15 km s\(^{-1}\) and 19 km s\(^{-1}\), which is consistent with the value of 16 km s\(^{-1}\) provided by Taylor et al. (1990). As was pointed out by Lee et al. (2006) the Raman spectroscopy allows one to determine the H \( \text{i} \) column density, whereas the excitation temperature should be assumed before \( N_{\text{H}} \) is deduced from H \( \text{i} \) the 21 cm radio observation. According to Taylor et al. (1990), \( N_{\text{H}} = 2.7 \times 10^{20} \text{ cm}^{-2} \) assuming the excitation temperature \( T_{\text{H}} = 100 \text{ K} \). Our Raman profile analysis lends support to this excitation temperature.

Our current data are of insufficient quality to lift the degeneracy of the covering factor and H \( \text{i} \) column density, and the overall strength of the Raman feature is determined from the product of the two quantities. However, our Monte Carlo calculations show that Raman profiles exhibit redward asymmetry due to enhanced scattering cross section toward H\( \alpha \) resonance. With better quality spectra that may be available from bigger telescopes, it is hoped that tighter constraints are obtained from more refined profile analyses. If Raman-scattered He \( \text{ii} \) \( \lambda 4850 \) blueward of H\( \beta \) can also be used, additional constraints can be put to break the degeneracy.

Even though the distance to NGC 6790 is highly uncertain, we may assume that the distance is about 1 kpc for simple order of magnitude calculations. According to Tylenda et al. (2003),
the angular size of NGC 6790 is \( \sim 3'' \). This gives a physical size of the H\textsc{i} region \( R \sim 5 \times 10^{16} \) cm. If the H\textsc{i} region is of a thin cylindrical shell with the height similar to its radius, the total number \( N_{\text{tot}} \) of hydrogen atoms inside the shell is approximately given by \( N_{\text{tot}} = 2\pi R^2 N_{\text{H}} \sim 6 \times 10^{24} \). Here, in our order of magnitude estimate, we ignore the inclination effect, which will overestimate the total number of hydrogen atoms by the factor \( \sin i \). The H\textsc{i} mass of the neutral region is inferred to be \( M_{\text{H}} \sim 4 \times 10^{-3} M_\odot \).

Furthermore, the expansion velocity of \( v_{\text{exp}} \sim 15 \) km s\(^{-1}\) and the physical size of \( R \sim 5 \times 10^{16} \) cm together imply the age on the order of thousand years for NGC 6790. It should be pointed out that these rough calculations are highly dependent on the assumed distance to NGC 6790 and still the physical size of the H\textsc{i} region is quite uncertain.

The origin of sharp absorption feature that appeared in [N\textsc{ii}] \( \lambda 6548 \) is quite uncertain. If this absorption feature is attributed to H\textsc{ii}, then it may imply the existence of clumpy components having a small covering factor with respect to the [N\textsc{ii}] emission region and receding with a significant velocity of \( \sim 800 \) km s\(^{-1}\). In some planetary nebulae including M2-9 and NGC 6543, it is known that fast collimated outflows exist around the central star with a velocity on the order of 1000 km s\(^{-1}\) (Balick 1989; Gruendl et al. 2004; Prinja et al. 2007). Ueta et al. (2001) presented near-IR imaging observations of AFGL 618 and reported their findings of molecular bulletlike features moving faster than 200 km s\(^{-1}\). However, it still remains a mystery whether a clumpy bulletlike object can be ejected with so large a velocity from the center region.

It should be pointed out that a ringlike emission model may not be a unique choice for the observed profiles of He\textsc{ii} \( \lambda 5876 \) and H\textsc{ii}. Many kinematical models involving jetlike outflows or radial infall and/or outflows may also yield similarly well-fitting profiles. Therefore, without convincing support from other studies such as imaging observations using interferometry or hydrodynamical computations, it appears to be too early to conclude about the kinematics of the He\textsc{ii} emission region.

A ringlike emission region and H\textsc{i} region concentrated in the equatorial region may provide interesting opportunities for spectropolarimetry. In symbiotic stars, Raman-scattered O \( \lambda \lambda 6825, 7088 \) are known to exhibit strong linear polarization (e.g., Harries & Howarth 1996; Schmid 1998). The polarization structure may be closely related to the accretion and mass-loss processes that deviate from spherical symmetry (e.g., Lee & Park 1999; Lee & Kang 2007; Ikeda et al. 2004). Because Raman-scattered features consist of purely scattered photons, they make ideal targets for linear spectropolarimetry. Future spectropolarimetric studies may provide more interesting information regarding the mass-loss processes in asymptotic giant branch stars and planetary nebulae.

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