1. INTRODUCTION

It is well known that planetary nebulae (PNe) display diversified morphologies and possess complex structures involving multiple shells and collimated outflows, of which the origins still remain puzzling (e.g., Gurzadyan 1997; Corradi & Schwarz 1995). Noting that symbiotic stars, widely known to be binary systems of a cool giant and a hot white dwarf or a main-sequence star, exhibit bipolar emission nebulae, evolutionary links between symbiotic stars and bipolar PNe have been proposed by a number of researchers (e.g., Corradi 1995; Soker 1998).

Circumstantial evidence supporting this scenario was provided by Lee & Park (1999), who proposed that a disk-type emission model can naturally explain the main characteristics of the profiles and the polarized fluxes of the Raman-scattered 6830 and 7088 Å features in the symbiotic star RR Telescopii. The Raman-scattering process by atomic hydrogen was introduced by Schmid (1989), who identified the 6830 and 7088 Å bands in symbiotic stars as the Raman-scattered O I optical continuum. The conversion efficiency reaches 0.6 near the line center, where the scattering optical depth is much larger than 1, and rapidly decreases in the far wings. Assuming that close to the central star there exists an unresolved inner compact core of high density, \( n_i \approx 10^3 - 10^4 \) cm\(^{-3}\), we use the photoionization code “CLOUDY” to show that sufficient Ly\( \beta \) photons for scattering are produced. Using a top-hat incident profile for the Ly\( \beta \) flux and a scattering region with a H I column density \( N_{HI} = 2 \times 10^{20} \) cm\(^{-2}\) and a substantial covering factor, we perform a profile-fitting analysis in order to obtain a satisfactory fit to the observed flux. We briefly discuss the astrophysical implications of the Rayleigh-Raman processes in planetary nebulae and other emission objects.

Subject headings: line: profiles — planetary nebulae: general — planetary nebulae: individual (IC 4997) — radiative transfer — scattering

2. MODEL

2.1. Wing Formation from the Rayleigh-Raman Process

In this work, we adopt a simple model in order to investigate the wing formation through the Rayleigh-Raman process. We...
assume that the scattering region is in the form of a finite slab with a column density \( N_{\text{H}i} \), and a solid angle \( \Omega \), with respect to the radiation source, which coincides with the central star of the planetary nebula. We discuss the \( \text{Ly} \beta \) line radiation source in the next subsection; here we assume that the scattering region is illuminated by a far-UV radiation source with intensity \( I_{\text{f}} \).

A UV photon around \( \text{Ly} \beta \) is incident to a hydrogen atom in the ground state \( 1s \), which subsequently de-excites either to the \( 2s \) state that reemits an optical photon around \( \text{H} \alpha \) (Raman scattering) or to the \( 1s \) state that results in an outgoing UV photon with the same frequency (Rayleigh scattering). Depending on the scattering optical depth, a UV photon may suffer a number of Rayleigh scatterings, followed by Raman scattering, and escape the scattering region because the \( 2s \) state is usually negligibly populated compared with the ground state (e.g., Nussbaumer et al. 1989).

The incident wavelength \( \lambda \), and the wavelength \( \lambda_0 \), of the Raman-scattered radiation are related by the energy conservation, \( \lambda_0^{-1} = \lambda^{-1} + \lambda_{\text{RAM}}^{-1} \), which yields the conversion of the wavelength interval

\[
\Delta \lambda_0/\lambda_0 = (\lambda_0/\lambda)(\Delta \lambda/\lambda).
\]

Because of the factor \( \lambda_0/\lambda \), UV photons with a width of \( \Delta \lambda_0 \) centered at \( \text{Ly} \beta \) are spread around \( \text{H} \alpha \) with a broadened width of \( \Delta \lambda \) of 6.4 \( \Delta \lambda_0 \).

The number of UV photons incident to the scattering region per unit time per unit wavelength interval is given by \( I_{\text{f}}(T_\nu) \pi R^2 \Omega_\nu / (hc/\lambda) \). We introduce the parameter \( C_R(\lambda) \), which is the conversion factor from UV to optical through the Rayleigh-Raman scattering process. The conversion factor \( C_R(\lambda) \) depends sensitively on the wavelength and the column density as well as the detailed geometry of the scattering region, and it can be computed using a Monte Carlo technique (see Lee & Yun 1998).

The number of Raman-scattered photons coming out from the region per unit time per unit wavelength interval is given by

\[
N_{\text{H} \alpha} = [I_{\text{f}}(T_\nu) \pi R^2 \Omega_\nu / (hc/\lambda)] C_R(\lambda) \lambda^2_0/\lambda^3_0.
\]

Therefore, the Raman-scattered flux is

\[
F_{\text{Ram}}(\lambda) = N_{\text{H} \alpha} (hc/\lambda) / r^2 = F_{\text{UV}}(\lambda) C_{\text{eff}},
\]

where \( F_{\text{UV}}(\lambda) \equiv (I_{\text{f}} \pi R_\nu^2 / r^2) \) is the flux that would be observed from the radiation source with a size \( R_\nu \) located at a distance \( r \), and \( C_{\text{eff}} \equiv (\Omega C_R(\lambda) \lambda^2/\lambda^3_0) \) is the effective Raman conversion efficiency.

### 2.2. Conversion Efficiency

In Figure 1, we present the Raman conversion efficiency \( C_R(\lambda) \) for \( \text{H} \I \) column densities \( N_{\text{H}i} = 10^{19}, 10^{20}, \) and \( 10^{21} \) cm\(^{-2} \), using the Monte Carlo code developed by Lee & Yun (1998). In the optically thin regime, the single-scattering approximation holds so that

\[
C_R(\lambda) = \tau_{\text{f},\nu}(\sigma_{\text{Ram}}/\sigma_{\text{opt}}).
\]

In the optically thick limit, the conversion rate is investigated by Lee & Lee (1997), who proposed an empirical relation

\[
C_R(\lambda) = \sum_n r_n f(n) / \sum_n [(1 - r_n) \beta(n) + r_n] f(n),
\]

where \( r_n \equiv \sigma_{\text{Ram}}/\sigma_{\text{opt}} \). Here \( \beta(n) = \frac{1}{2} \exp(-n^2) \) is the escape probability from the \( n \)th scattering site, and \( f(n) \) is the photon number flux that is scattered no less than \( n \) times, which is obtained recursively by

\[
f(n + 1) = (1 - r_n) [1 - \beta(n)] f(n).
\]

A direct substitution with \( r_n = 0.11 \) near the line center yields \( C_R(\lambda) = 0.6 \), which is in excellent agreement with the result shown in Figure 1.

### 2.3. Calculation of the \( \text{Ly} \beta \) Flux

In this subsection, we discuss the \( \text{Ly} \beta \) flux that may enter the scattering region. Hyung et al. (1994) performed a photoionization computation and concluded that the observed emission lines are reproduced approximately using a model consisting of a thin shell of density \( n \sim 10^3 \) cm\(^{-3} \) surrounded by a much larger shell with a much lower density of \( \sim 10^6 \) cm\(^{-3} \). They also noted that the \( \text{N} \I \) \( \lambda 1754/\lambda 1749 \) ratio may indicate the existence of a much denser region with \( n \sim 10^6 \) cm\(^{-3} \) (e.g., see Czyzak, Keyes, & Aller 1986).

We use the photoionization code “CLOUDY 90.05” developed by Ferland (1996) to obtain the \( \text{Ly} \beta \) flux that is expected around a central star of a PN. We fix the temperature and radius of the central star to be \( T_\nu = 6 \times 10^4 \) K and \( R_\nu = R_\odot \), respectively, and compute the hydrogen emission-line fluxes for densities \( n = 10^6-10^{10} \) cm\(^{-3} \). According to Hyung et al. (1994),
the observed Hα luminosity is $4 \times 10^{35}$ ergs s$^{-1}$, assuming the distance $d = 2.4$ kpc to IC 4997 and the interstellar extinction parameter $C = \log [I(H\beta)/F(H\beta)] = 0.8$, where the observed flux $F(H\beta)$ in $H\beta = 2.95 \times 10^{-11}$ ergs s$^{-1}$ cm$^{-2}$.

In Table 1, we show that the observed Hα flux is obtained from a region of density $n \sim 10^7$ cm$^{-3}$, for which we get a much smaller Lyβ flux. However, when $n \sim 10^6-10^{10}$ cm$^{-3}$, we obtain a much larger Lyβ flux ($\geq 10^{35}$ ergs s$^{-1}$ cm$^{-2}$). Therefore, we may have a sufficient number of Lyβ photons to fill the Hα wings. The existence of this extremely dense emission region is consistent with the detection of the semiforbidden lines $N$ in $\lambda 1754, \lambda 1749$, and their strength ratio as noted above. Furthermore, this region is plausibly located much closer to the central star than other emission regions are. Hence, assuming that the distance is $\sim 0.1$ AU, we may expect that there is a high-velocity dispersion on the order of 100 km s$^{-1}$ in the region.

3. RESULT

By the dashed lines in Figure 2, we show the Hα wings that are expected from the Rayleigh-Raman processes, and these are compared with the observation by Hyung et al. (1994). For the incident Lyβ flux, we use $I_{\gamma \beta} = 6 \times 10^{15}$ ergs s$^{-1}$, which is expected to be obtained from a unresolved core of high density ($n \sim 10^6-10^{10}$ cm$^{-3}$) near the central star. We tested two types of profiles for the incident Lyβ flux, i.e., a top-hat profile with a width of 300 km s$^{-1}$ and a Gaussian with the same velocity width. We present the results for the best-fitting column density of the scattering region, which is $N_{H_\alpha} = 2 \times 10^{20}$ cm$^{-2}$ for the incident top-hat profile and $N_{H_\alpha} = 4 \times 10^{20}$ cm$^{-2}$ for the Gaussian profile. In this work, we concentrate only on the wing parts that are farther than 300 km s$^{-1}$ ($\Delta \lambda > 6.5$ Å around Hα) from the line center.

Because the top-hat profile for the incident Lyβ provides an excellent fit to the observed Hα wing profile, we expect that other types of input profiles can also produce a good fit, except for some extreme cases. This is illustrated by another good fit using the Gaussian profile shown in Figure 2b. However, we realize that the much higher column density, i.e., by a factor of 2, is required in the latter case.

In this work, the incident Lyβ flux was computed with a highly simplified assumption. An introduction of a velocity field in the emission region may alter drastically both the strength and the profile of the emergent line flux. Furthermore, the scattering region is complex and consists of a number of components differing in column density and geometrical shape. Therefore, a better fit can be assured from composite scattering region models and a more complicated radiative transfer, which are deferred to a future investigation.

### TABLE 1

| log \(n\) | \(\log F_{1a}\) | \(\log F_{1ad}\) | \(\log F_{2a}\) | \(\log F_{2ad}\) | \(\log F_{3a}\) |
| ------ | ------- | ------- | ------- | ------- | ------- |
| 10      | 36.849  | 35.687  | 35.154  | 35.382  | 34.988  |
| 9       | 36.944  | 35.233  | 34.544  | 35.874  | 35.451  |
| 8       | 36.957  | 34.025  | 33.135  | 35.957  | 34.991  |
| 7       | 36.961  | 33.268  | 33.043  | 35.890  | 35.318  |
| 6       | 36.953  | 33.146  | 33.049  | 35.875  | 35.380  |

*With \(T_e = 6 \times 10^4\) K and \(R_i = R_{\odot}\).*

The column density \(N_{H_\alpha}\) can be estimated from a H i 21 cm observation by the relation

$$N_{H_\alpha} = 1.8 \times 10^{20} \left( \frac{\int \tau dv}{1 \text{ km s}^{-1}} \right) \left( \frac{T_e}{100 \text{ K}} \right) \text{ cm}^{-2},$$

where \(T_e\) is the H i spin temperature. Altschuler et al. (1986) performed a 21 cm observation of IC 4997 so as to provide \(\int \tau dv = 2.1\) km s$^{-1}$, which yields $N_{H_\alpha} = 3.8 \times 10^{20}$ cm$^{-2}$, assuming that $T_e = 100$ K. This neutral hydrogen component was found at the velocity of the approaching edge of the nebular shell. This is consistent with the column density that we derived from the profile-fitting analysis, and we may infer that the neutral envelope detected by Altschuler et al. (1986) coincides with the Rayleigh-Raman scattering region.

More realistically, we have a scattering column density $N_{H_\alpha}$ that is larger in the equatorial region and one that is smaller in the polar directions rather than having a uniform column density. In this case, extreme wing parts are formed by scatterers in the equatorial region, and near-center parts are formed by both the equatorial scatterers and the scatterers in the polar regions. From this configuration, we expect stronger polarization in the extreme wing parts than in the near-center parts, which can be verified by spectropolarimetry.

Another object that shows broad Hα wings is the bipolar planetary nebula M2-9, for which Balick (1989) noted that the spectrum is similar to that of the symbiotic star RR Tel. Since there exists a thick circumstellar region in M2-9, the extremely wide Hα wings with a width of 11,000 km s$^{-1}$ are likely to be formed through the Raman process in a scattering region of column density $N_{H_\alpha} \sim 10^{21}$ cm$^{-2}$.

Broad Hα wings are found in a number of post–asymptotic
giant branch (AGB) stars according to a recent report by Van de Steene, Wood, & van Hoof (2000), who excluded several theoretical possibilities for the wing formation mechanism including Thomson scattering and Rayleigh scattering. Considering that in post-AGB stars, much H i can be found in the stellar wind region and/or in a dense torus surrounding the central star, it is very convincing that the broad Hα wings in these systems are also attributable to Rayleigh-Raman scattering. So far, the Raman scattering is unique to symbiotic stars, and the only exception appears to be the young planetary nebula NGC 7027, from which a Raman-scattered He ii line has been identified (Péquignot et al. 1997). From this study, broad Hα wings are expected to be found in a hot and dense H ii region surrounded by an H i region, where the conditions may be met in objects that include symbiotic stars, supernova remnants, and galactic supershells.

H.-W. L. is grateful to Bon-Chul Koo, Chul-Sung Choi, and Hwankyung Sung for helpful comments and discussions. He also thanks the hospitality of the Korea Institute for Advanced Study during his visit there. We thank an anonymous referee for useful comments, which improved the presentation of this Letter. This research was supported in part by Star Research Grant Star 99-2-500-00 sponsored by the Korea Ministry of Science and Technology and by grant 1999-1-113-001-5 by KOSEF.

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