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STRENGTH OF THE RAMAN SCATTERED HE II EMISSION LINES IN SYMBIOTIC STARS AND PLANETARY NEBULAE

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ABSTRACT

In Lee, Kang & Byun (2001) the discovery of Raman scattered 6545 Å feature was reported in symbiotic stars and the planetary nebula M2-9. The broad emission feature around 6545 Å is formed as a result of Raman scattering of He II $n = 6 \rightarrow n = 2$ photons by atomic hydrogen. In this paper, we introduce a method to compute the equivalent width of He II λ 1025 line and present an optical spectrum of the symbiotic star RR Telescopii as an example for a detailed illustration. In this spectrum, we pay attention to the broad Hα wings and the Raman scattered He II 6545 feature. The broad Hα wings are also proposed to be formed through Raman scattering of continuum around Lyβ by Lee (2000), and therefore we propose that the equivalent width of the He II λ 1025 emission line is obtained by a simple comparison of the strengths of the 6545 feature and the broad Hα wings. We prepare a template Hα wing profile from continuum radiation around Lyβ with the neutral scattering region that is supposed to be responsible for the formation of Raman scattered He II 6545 feature. Isolation of the 6545 feature that is blended with [N II] λ 6548 is made by using the fact that [N II] λ 6584 is always 3 times stronger than [N II] λ 6548. We also fit the 6545 feature by a Gaussian which has a width 6.4 times that of the He II λ 6527 line. A direct comparison of these two features for RR Tel yields the equivalent width $EW_{He1025} = 2.3$ Å of He II λ 1025 line. Even though this far UV emission line is not directly observable due to heavy interstellar extinction, nearby He II lines such as He II λ 1085 line may be observed using far UV space instruments, which will verify this calculation and hence the origins of various features occurring in spectra around Hα.

Key words : scattering — binaries:symbiotic — stars:individual (RR Tel) — radiative transfer — atomic physics

I. INTRODUCTION

A symbiotic star is believed to be a binary system consisting of a mass losing giant and a hot white dwarf (e.g. Kenyon 1986). In some symbiotic stars, the giant companion is a Mira variable with a typical mass loss rate of order 10^{-7} $M_\odot$ yr^{-1}. Spectra of symbiotic stars are characterized by TiO absorption bands indicative of the presence of a late type giant and prominent emission lines with both high and low ionization stages suggesting a dense hot plasma that surrounds a white dwarf component. Some symbiotic stars exhibited nova-like outbursts that are indicative of mass transfer processes in these binary systems. Symbiotic stars are usually long period binaries and their orbital parameters are often only poorly known.

The broad emission features around 6830 Å and 7088 Å exhibited in more than a half of symbiotic stars were identified as the Raman scattered O VI $\lambda\lambda$ 1032, 1038 by atomic hydrogen by Schmid (1989). During the Raman scattering processes, the scattering hydrogen atom initially in the $1s$ state de-excites to the $2s$ state re-emitting an optical photon redward of Hα. Simultaneous detections of the features in the far UV and optical regions support strongly the Raman scattering nature of these emission features (Birriel, Espey & Schulte-Ladbeck 1998, 2000).

Thus far, Raman scattered O VI lines have been observed only in symbiotic stars and furthermore, the existence of Raman scattered O VI lines is regarded as an important character for the definition of symbiotic stars. Van Groningen (1993) found a broad feature around 4851 Å in the spectrum of the symbiotic nova RR Telescopii, which he proposed to be formed through Raman scattering of He II emission lines by atomic hydrogen.

He II emission lines arising from the transitions between energy levels with even principal quantum numbers have very close wavelengths to those for the H I resonance transitions. Therefore, much less H I column densities are required for the operation of Raman scattering than those for O VI 1032, 1038 lines. This leads to the expectation that Raman scattered He II may be observed in broader classes of objects than symbiotic stars. In particular, in the planetary nebula NGC 7027, Péquignot et al. (1997) reported the existence of He II Raman-scattered feature around 4851 Å blueward of Hβ.

A Raman-scattered He II line is also expected to be found around 6545 Å, blueward of Hα in in young planetary nebulae and symbiotic stars, which should be stronger than those formed blueward of higher Balmer series transitions. The existence of He II Raman-scattered line implies the co-existence of a high column density component of neutral hydrogen and a highly ionized region, both of which have important astrophysical meaning relevant to the mass loss process of post AGB stars. Lee, Kang & Byun (2001) discovered 6545 features in several symbiotic stars including RR Telescopii.

Hα wings can be made through Raman scattering of Lyβ, which was advanced by Nussbaumer et al. (1989). This idea has been emphasized again in a more quantitative way by Lee (2000). Lee & Hyung(2000) showed that the Hα wings of the planetary nebula IC 4997 and many symbiotic stars are fitted very well with the template wing profiles obtained from Raman scattering of Lyβ (see also Ivison, Bode, & Meaburn 1994, and Van Winckel, Duerbeck, & Schwarz 1993).

Recently, Arrieta & Torres-Peimbert (2003) perforemd extensive spectroscopy of young planetary nebulae and post AGB stars and found that Hα lines exhibit broad wings. They showed that the wings are well fitted by a simple formula $\Delta\lambda^{-2}$, giving more support for the Raman scattering origin of Hα wings. It has been noted that similar broad wings have been also observed in many post-AGB stars (e.g. Van de Steene, Wood, & van Hoof 2000). These observations indicate that the Raman scattering process may be very useful to investigate the mass loss process occurring in the late stage of stellar evolution.

In their derivation of template wing profiles, Lee & Hyung (2000) assumed a top-hat profile in order to obtain the $\Delta\lambda^{-2}$ dependence in the spectra of IC 4997. They also considered the possibility that the incident radiation for Hα wings can be just the continuum radiation around Lyβ. In this paper, we will assume that the contiuum around Lyβ is responsible for the formation of Hα, in which case a direct comparison of the strengths of Hα wings and the 6545 feature will yield the equivalent width of He II λ 1025 that is not directly observable.

In this paper, we present an optical spectrum of RR Tel, obtained with the 1.5 m telescope at the Cerro Tololo Inter-American Observatory, in order to compute the equivalent width of He II λ 1025 line.

II. Calculation

(a) Atomic Physics

The reduced mass of a He II ion is given by

$$\mu_{HeII} = m_e/(1 + m_e/Am_p) \simeq m_e(1 - m_e/Am_p), \quad (1)$$

where $A = 4$ is the atomic weight of He II. The slight difference in the reduced mass for H I and He II is given by

$$\Delta\mu/m_e = (\mu_{HI} - \mu_{HeII})/m_e \simeq (1 - 1/A)m_e/m_p. \quad (2)$$

Due to this difference the energy associated with the $2s - 2np$ transition in He II is higher than the energy for the $1s - np$ transition in H I by an amount of

$$\Delta E_n \simeq (1 - 1/A)\frac{m_e}{m_p}E_{Ryd}(1 - n^{-2}), \quad (3)$$

where E_{Ryd} is the Rydberg energy for hydrogen.

When a far UV photon with wavelenth λ_i shorter than that of Lyα is Raman scattered by a hydrogen atom that is initially in the ground $1s$ state and subsequently de-excites to the $2s$ state, the wavelength λ_o of the outgoing photon is given by

$$\lambda_o = (\lambda_i^{-1} - \lambda_{Ly\alpha}^{-1})^{-1}, \quad (4)$$

due to the energy conservation. Therefore, for an incident line photon corresponding to the $2s - 2np (n \geq 3)$ transition in He II, the wavelength shift of the outgoing (Raman-scattered) photon from the Balmer series transition is given by

$$\begin{aligned} \Delta\lambda_o &= \Delta\lambda_i(\lambda_o/\lambda_i)^2 \\ &\simeq \left(\frac{n^2-1}{n^2-4}\right)^2 \frac{12m_e}{m_p}\lambda_i \\ &\simeq 6.5 \times 10^{-3}\left(\frac{n^2-1}{n^2-4}\right)^2 \lambda_i \\ &\simeq 5.9\left[\frac{n^2(n^2-1)}{(n^2-4)^2}\right] \text{Å}. \end{aligned} \quad (5)$$

Therefore, for $n = 3$ we get $\Delta\lambda_o \simeq 17$ Å and $\lambda_o \simeq$ 6546 Å, which is slightly redward of [N II] λ 6548. For $n = 4$, we have $\Delta\lambda_o \simeq 9.9$ Å and the expected wavelength redward of Hβ is $\lambda_o \simeq 4851$ Å, at which the He II Raman scattered line was found in the spectra of the planetary nebula NGC 7027 (Péquignot et al. 1997) and the symbiotic star RR Tel (van Groningen 1993)

We show the scattering cross sections in units of the Thomson scattering cross section $\sigma_T = 0.66 \times 10^{-24}$ cm^2. The dominant transitions are $6p_{1/2,3/2} \rightarrow 2s_{1/2}$, for which the Raman-scattering lines are expected around 6545 Å and the Rayleigh and Raman scattering cross sections are $\sim 7000\sigma_T$ and $\sim 1000\sigma_T$ respectively (e.g. Lee & Lee 1997, Nussbaumer et al. 1989). The He II line photons with the final state $2p_{3/2}$ will have the Raman scattered wavelength around 6547.4 Å, which will make a minor contribution to the formation of the Raman scattered feature but will be blended with the forbidden line [N II]λ 6548.

Dominant wavelengths for the He II transitions between levels of $n = 2$ and $n = 6$ include 1025.24593 Å from $6p_{3/2} \rightarrow 2s_{1/2}$ that will produce the Raman scattered feature at 6545.0890 Å, and 1025.24821 Å from $6p_{1/2} \rightarrow 2s_{1/2}$ giving rise to 6545.1820 Å. Less dominant transitions arise from $6s_{1/2} \rightarrow 2p_{1/2}$, for which the

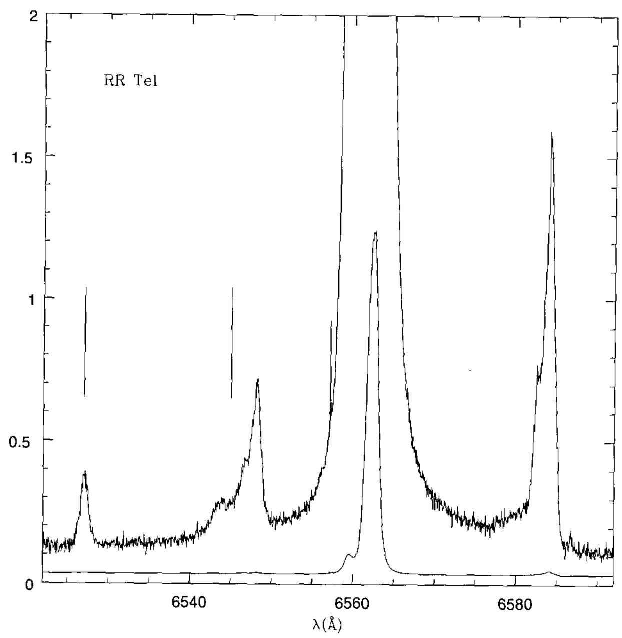

Fig. 1.— The spectrum around Hα of the symbiotic star RR Tel obtained from the Bench Mounted Echelle Spectrograph mounted on the 1.5 m telescope at the Cerro Tololo Inter-American Observatory. We illustrate the flux multiplied by 1/100 to show the whole Hα profile. The vertical bars mark the emission features at $\lambda = 6527$ Å and 6545 Å, where the former arises from the transition between $n = 14$ and $n = 5$ states of He II and the latter is proposed to be the He II Raman-scattered feature by atomic hydrogen.

Raman-scattering lines are expected at 6545.3782 Å and 6547.46 Å (e.g. Lee & Lee 1997, Nussbaumer et al. 1989). The He II line photons with the final state $2p_{3/2}$ will have the Raman scattered wavelength around 6547.4 Å, which will make a minor contribution to the formaion of the Raman scattered feature but will be blended with the forbidden line [N II]λ 6548.

III. Data and Calculation

(a) Hα Wings

In Fig. 1, we show a spectrum around Hα for the symbiotic star RR Tel obtained using the 1.5 m telescope at CTIO. The vertical bars mark the emission features at $\lambda = 6527$ Å and 6545 Å. The emission line around 6527 Å corresponds to the transition between $n = 14$ and $n = 5$ states of He II

This object shows very broad wings around Hα. Many symbiotic stars and young planetary nebulae are known to exhibit broad Hα wing profiles. Lee & Hyung (2000) proposed that these Hα broad wings are formed through Raman scattering of radiation around Lyβ. According to their argument, the shape of the wings is determined by the scattering optical depth that is proportional to the neutral hydrogen column density of the scattering region

We introduce the parameter $C_R(\lambda_i)$, which is the conversion factor from UV to optical through the Raman-scattering process. $C_R(\lambda_i)$ depends sensitively on the wavelength and the column density of the scattering region (as well as the detailed geometry of the scattering region).

In the optically thin regime, the single and the Raman scattering cross section σ_{Ram} scattering approximation holds so that

$$C_R(\lambda) = \tau_{tot}(\sigma_{Ram}/\sigma_{tot}). \quad (6)$$

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

$$C_R(\lambda) = \sum_n r_\sigma f(n) / \sum_n [(1 - r_\sigma)\beta(n) + r_\sigma] f(n), \quad (7)$$

where $r_\sigma \equiv \sigma_{Ram}/\sigma_{tot}$. Here, $\beta(n) \simeq \frac{1}{2}e^{-\sqrt{n}}$ is the escape probability from the nth scattering site, and $f(n)$ is the photon number flux scattered no less than n times which is obtained recursively by

$$f(n+1) = (1 - r_\sigma)[1 - \beta(n)]f(n). \quad (8)$$

A direct substitution with $r_\sigma = 0.11$ near the line center yields $C_R(\lambda) = 0.6$.

In Fig. 2, we show a template wing profile that is formed from a scattering region with the neutral hydrogen column density $N_{HI} = 10^{20}$ cm^{-2}. The wing profile is characterized by a flat top region around the Hα center where the scattering region is optically thick and an outside region that is proportional to $\Delta\lambda^{-2}$ indicative of the fuctional dependence of the scattering cross section.

Under the assumption that the broad Hα wings are formed through Raman scattering of continuum radiation around Lyβ, this profile can be nicely explained by assuming that the scattering region is optically thin, because the scattering cross section is proportional to $\Delta\lambda^{-2}$. Therefore, for the conversion factor we may adopt Eq. (6) for this work. Because the scattering cross section changes only little in an interval of He II emission line width, we may regard it as constant.

In Fig. 3 we show the Hα fitting result. In the lower panel, we show the residual spectrum around the 6545 feature after subtraction of the Hα wings using the template profile in Fig. 2. The Raman scattered 6545 feature is blended with the forbidden line [N II] λ 6548.

(b) Isolation of He II 6545 Feature and Fitting

[N II]$\lambda\lambda$ 6548, 6584 forbidden lines have very small Einstein A coefficient and therefore optically thin in

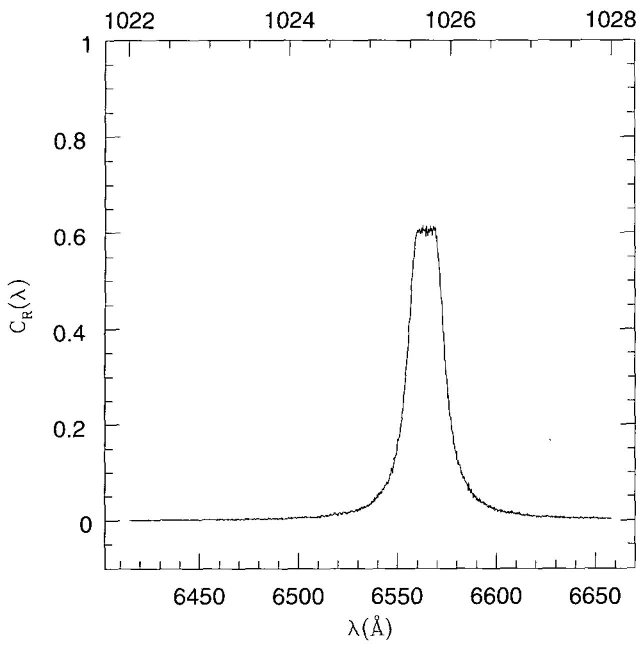

Fig. 2.— Raman conversion efficiency $C_R(\lambda)$ for H I column density, $10^{20}\mathrm{cm}^{-2}$ obtained using a Monte Carlo technique introduced in Lee & Lee (1997). The horizontal (lower) axis is the outgoing wavelength around Hα and in the upper part is shown the incident wavelength around Lyβ. Note that near the line center the conversion efficiency is almost constant ~ 0.6 and the wing part is proportional to $\Delta\lambda^{-2}$.

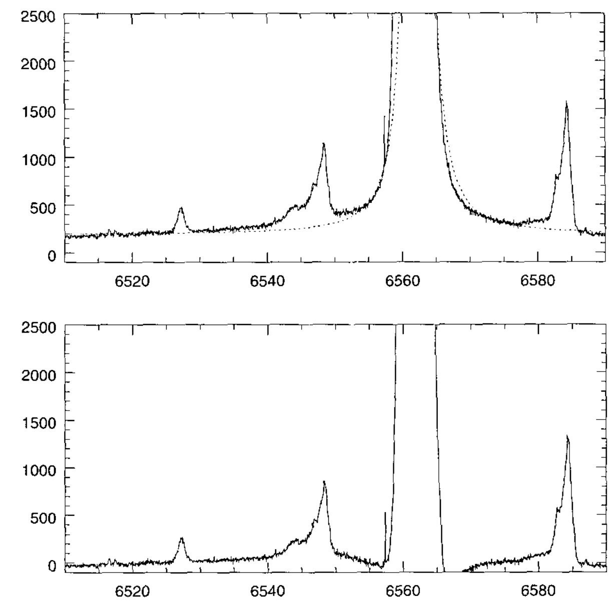

Fig. 3.— In the upper panel, we show the template wing profile prepared in Fig. 2, which is represented by a dotted line. The broad Hα wings are excellently fitted by the $\Delta\lambda^{-2} = (\lambda - \lambda_{H\alpha})^{-2}$ profile expected for the continuum around Lyβ 1025 Raman-scattered by neutral hydrogen and represented by the dashed lines. In the lower panel is shown the wing-subtracted spectrum based on our fitting of the Hα wings in Fig. 2. The wing profile is given by the relation $f(\lambda)_{wing} = 1.8 \times 10^4 (\lambda - \lambda_{H\alpha})^{-2}$.

most nebular conditions. Since both lines share the same excited state, the ratio of photon creation is fixed. Furthermore profiles should be exactly same profile except for the fact that [N II]6584 is 3 times stronger due to the atomic structure (e.g. Osterbrock 1989, Storey & Zeippen 2000).

In Fig. 4, we show the result of isolation of the He II Raman scattered feature by subtraction of the flux of the [N II]λ 6584 multiplied by 1/3 (represented by red lines) from the flux around the 6545 and [N II]λ 6548 features (represented by the black lines). The result is shown by the solid thick line, which clearly shows the 6545 features.

The relation Eq. (4) of energy conservation gives the conversion of the wavelength interval

$$\Delta\lambda_o = \Delta\lambda_i \lambda_o^2/\lambda_i^2 \quad (9)$$

This implies that the Raman scattered line feature will be broadened by a factor of λ_o/λ_i, which is 6.4 in the case of Raman scattered He II 6545.

We fit the He II λ 6527 by a Gaussian with a width σ_{He}. Then, the incident flux of He II λ 6527 is given by

$$F_{HeII}(\lambda) = F_{6527} \exp\left[-\left(\frac{\lambda - \lambda_0}{\sigma_{He}}\right)^2\right], \quad (10)$$

where $F_{6527} = 275$ is the peak flux in an arbitrary unit adopted in this paper. Note that we are only concerened with the relative fluxes so that the absolute flux calibration has been omitted. In Fig. 3, we show the Gaussian fitting to He II λ 6527, where the width $\sigma_{He\ II} = 0.65$ Å.

We may write the Raman scattered flux around 6545 Å is given by

$$\begin{aligned} F_{He}^{Ram} &= F_{1025}\Omega C(R_\lambda) \exp\left[-\left(\frac{\lambda - \lambda_0}{6.4\sigma_{He}}\right)^2\right] \\ &= F_{6545} \exp\left[-\left(\frac{\lambda - \lambda_0}{6.4\sigma_{He}}\right)^2\right], \quad (11) \end{aligned}$$

where the line broadening factor 6.4 was obtained from the ratio $\lambda_o/\lambda_i = 6545/1025$ of wavelengths of incident radiation and scattered radiation. In the lower panel of Fig. 3 we show our Gaussian fitting of He II 6545 feature by a Gaussian with a width $6.4\sigma_{He} = 4.2$ Å, and the peak value $F_{6545} = 120$

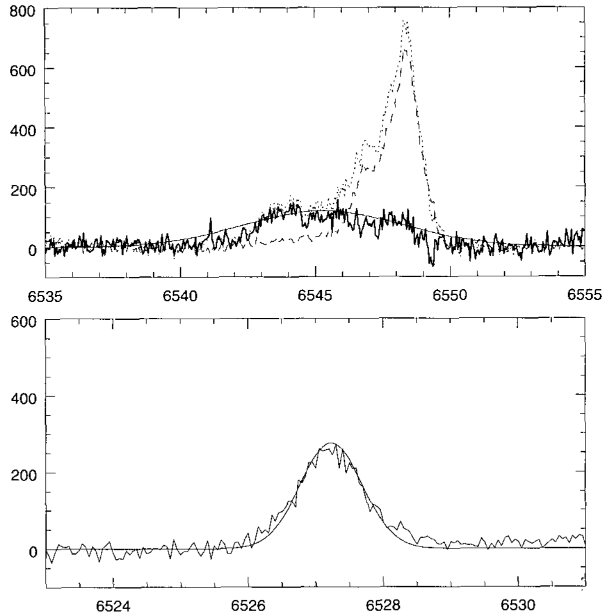

Fig. 4.— In the upper panel, we show the isolated Raman scattered He II 6545 feature by a thick solid line. The dotted line is the observed flux density around the blended feature of the 6545 Å feature [N II] 6548 line, and the dashed line represents the observed data around [N II] λ 6584 that is reduced by a factor of 1/3. The this line shows the Gaussian fitting with a width $\sigma = 4.2$ Å. In the lower panel, we show our Gaussian fitting to He II λ 6527 with a width $\sigma_{He} = 0.65$ Å.

(c) Equivalent Widths

In Fig. 2 the Hα template wing that is proportional to $\Delta\lambda^{-2}$ is explicitly given by

$$f(\lambda)_{wing} = 1.8 \times 10^4 (\lambda - \lambda_{H\alpha})^{-2}, \qquad (12)$$

where the same relative unit is used for flux density. Because this wing feature is Raman-scattered continuum radiation around He II 1025, the strength of He II 1025 relative to the continuum around He II 1025 is directly proportional to the strength of the 6545 feature with respect to the strength of the neighborhood continuum that is a small part of the Hα wings. We may call this relative strength of the 6545 feature as the equivalent width of the 6545 feature.

The equivalent width of the Raman scattered He II 6545 feature relative to this wing profile is given by

$$\begin{aligned} EW_{6545} &= \int \frac{F_{6545}}{f(6545\ \text{Å})_{wing}} \exp\left[-\left(\frac{\lambda-\lambda_0}{6.4\sigma_{He}}\right)^2\right] d\lambda \\ &= \frac{120 \cdot 17^2}{1.8\times 10^4}\sqrt{\pi}4.2\ \text{Å} = 14\ \text{Å}. \qquad (13) \end{aligned}$$

If we transform this optical spectral region into the far UV spectral region near He II λ 1025, the width decreases by a factor of $\lambda_0/\lambda_i = 6.4$, and hence we obtain the equivalent width of He II λ 1025

$$EW_{He\ II\ 1025} = 14/6.4\ \text{Å} = 2.3\ \text{Å}. \qquad (14)$$

IV. Discussion

It should be emphasized that this method of estimating the equivalent width of He IIλ 1025 line is very efficient and useful because a single exposure without knowledge of absolute calibration is sufficient. This is because the same scattering cross section applies to both the emission line He II λ 1025 and continuum nearby, where the scattering cross section is a smooth function there. However, very high signal to noise ratio data are required in order to isolate the 6545 feature from the blended feature with [N II] λ 6548, which constitutes the justification of spectroscopy with big telescopes.

The direct measurement of the far UV He II λ 1025 line is almost impossible because it is very close to the resonance transition Lyβ of H I, which is very abundant in the interstellar medium. Therefore, our calculation may be indirectly checked using other He II emission lines such as He II λ 1085 that is also in the far UV region. Using far UV spectroscopy using FUSE and other instruments, the equivalent widths of He II emission lines are hopefully obtained. These measurement will shed much light on the physical properties of the emission nebulae around white dwarf stars and the neutral scattering region around giant stars.

Recently Arrieta & Torres-Peimbert (2003) presented their study on the broad wings of Hα exhibited by many young planetary nebulae and symbiotic stars. According to them, many of these objects show dominantly bipolar nebular morphologies. It is quite uncertain whether the bipolar morphology is closely related with the binarity of the central star system even though it is a general consensus that symbiotic stars are binary systems. Some of bipolar planetary nebulae are believed to be binary systems.

In the case of symbiotic stars, it is quite plausible that the He II emission region is formed around the white dwarf component whereas the scattering site is coincident with the extended atmosphere of the giant component. This implies that the emission region is qutie separated from the scattering region. In this case, the scattering efficiency or the conversion factor will possess much information about the scattering geomtry. Therefore, simultaneous observations in far UV and optical regions will yield productive results (e.g. Birriel et al. 2000).

However, in the case of single star model, because the He II emission region should be much hotter than the neutral scattering region, the He II emission region should be surrounded by the neutral scattering region. Unless the mass loss process is highly anisotropic, it is plausible that the covering factor of the scattering region is very large and almost 1. This implies that the scattering conversion factor will be pretty much large and compared to the case of binary systems. If the mass loss process is highly anisotropic, then the Raman scattered feature will be strongly polarized as the Raman scattered O VI features in symbiotic stars. Therefore, it will be very useful to perform spectropolarimetry of broad Hα wings in young planetary nebulae.

The broad Hα wings are found in young planetary nebulae where neutral hydrogen is expected to be abundantly found from recent heavy mass loss. Therefore the existence of Raman scattered Hα wings indicates the recent mass loss and the formation of a hot white dwarf. Therefore, the Hα Raman wings may be a good indicator of a recent stellar evolution history.

Intensive studies of O VI Raman scattered lines show that much kinematic information can be obtained from high resolution spectroscopy and spectropolarimetry. In comparison to this, Hr II 6545 feature is relatively weak and therefore similar observations will require much bigger telescopes than 2 m class telescopes. Whereas O VI line photons are resonance doublets and hence escape from the emission region only after a large number of scatterings, the optical depth of He II line photons are much smaller. Therefore, intercomparison with He II line profiles and O VI profiles will provide very important clues to the mass loss process of these objects.

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REFERENCES

Arrieta, A. & Torres-Peimbert, S., 2003, Broad H α wings in Young Planetary Nebulae, ApJS in press

Birriel, J. J., Espey, B. R., & Schulte-Ladbeck, R. E., 1998, Near-simultaneous Observations of Direct and Raman-scattered Lines in the Symbiotic Star Z Andromedae, ApJ, 507, L75

Birriel, J. J., Espey, B. R., & Schulte-Ladbeck, R. E., 2000, Contemporaneous Ultraviolet and Optical Observations of Direct and Raman-scattered O VI Lines in Symbiotic Stars, ApJ, 545, 1020

Harries, T. J., & Howarth, I. D. 1996, Raman scattering in symbiotic stars. I. Spectropolarimetric observations, A&ApS, 119, 61

Harries, T. J., & Howarth, I. D. 2000, Spectropolarimetric orbits of symbiotic stars: five S-type systems, A&Ap, 361, 139

Ivison, R. J., Bode, M. F.,& Meaburn J. 1994, An atlas of high resolution line profiles of symbiotic stars. II. Echelle spectroscopy of northern sky objects A&ApS, 103, 201

Kenyon, S. J., 1986, The symbiotic stars, Cambridge University Press, Cambridge

Lee, H. -W., 2000, Raman-Scattering Wings of Hα in Symbiotic Stars ApJ, 541, L25

Lee, H. -W. & Hyung, S., 2000, Broad Hα Wing Formation in the Planetary Nebula IC 4997 ApJ, 530, L49

Lee, H. -W. & Lee, K. W, 1997, On the profiles and the polarization of Raman-scattered emission lines in symbiotic stars, MNRAS, 287, 211

Lee, H. -W. & Park, M. G, 1999, Toward the Evidence of the Accretion Disk Emission in the Symbiotic Star RR Telescopii, ApJ, 515, L89

Nussbaumer, H., Schmid, H. M., & Vogel, M., 1989, Raman scattering as a diagnostic possibility in astrophysics, A&Ap, 211, L27

Osterbrock, D. E., 1989, *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei*, University Science Books, Mill Valley

Péquignot, D., Baluteau, J.-P., Morisset, C., Boisson, C., 1997, NGC7027:discovery of a Raman line in a planetary nebula, A&Ap, 323, 217

Schmid, H. M. 1989, Identification of the emission bands at 6830, 7088 A, A&Ap, 211, L31

Schmid, H. M., & Schild, H. 1994, Raman scattered emission lines in symbiotic stars: A spectropolarimetric survey, A&Ap, 281, 145

Van de Steene, G. C., Wood, P. R., & van Hoof, P. A. M. 2000, in Asymmetrical Planetary Nebulae II: From Origins to Microstructures, ed. J. H. Kastner, N. Soker, & S. Rappaport (San Francisco: ASP Conference Series, Vol. 199), p. 191

Storey, P. J., & Zeippen, C. J., 2000, Theoretical values for the [Oiii] 5007/4959 line-intensity ratio and homologous cases MNRAS, 312, 813

Van Groningen, E., 1993, Further Evidence for Raman Scattering in Rr-Telescopii, MNRAS, 264, 975

Van Winckel, H., Duerbeck, H. W., & Schwarz,H. E. 1993, An Atlas of High Resolution Line Profiles of Symbiotic Stars - Part One - Coude Echelle Spectrometry of Southern Objects and a Classification System of H-Alpha Line Profiles A&ApS, 102, 401