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RAMAN SCATTERING WINGS OF Hα IN SYMBIOTIC STARS

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ABSTRACT

Nussbaumer et al. (1989) proposed that broad Hα wings can be formed through Raman scattering of Lyβ photons, and in this Letter we argue that the Hα wings prevalently seen in symbiotic stars may be indeed formed in this way. Assuming a flat incident UV radiation around Lyβ, we generate template wing profiles around Hα that are formed through Raman scattering in a plane-parallel H I region. We perform profile fitting analyses to show that the template wing profiles are in excellent agreement with the observed ones that are provided by van Winckel et al. (1993) and Ivison et al. (1994). The wing flux is determined by the scattering H I column density and the incident Lyβ flux strength and profile. From our profile analysis it is proposed that the Raman scattering component may be identified with the neutral envelope with a column density ranging 10^{18-20} cm^{-2} that surrounds the binary system. We briefly discuss alternative candidates for the wing formation mechanism and observational implications of Raman scattering in symbiotic stars and in other astronomical objects including planetary nebulae, post AGB stars and active galactic nuclei.

Subject headings: line: formation — line: profiles — radiative transfer — scattering — (stars) binaries : symbiotic

1. INTRODUCTION

A long standing puzzle regarding the identification of the so called symbiotic bands around 6830 Å and 7088 Å occurring in about half of symbiotic stars has been solved by Schmid (1989), who proposed that they are the O VI 1032, 1038 doublet features that are Raman scattered by atomic hydrogen. These Raman-scattered lines possess very broad profiles because of the broadening enhancement by a factor of about 6.4 due to the scattering incoherency, and they exhibit rich structures including multiple peaks and high degrees of polarization often accompanied by a position angle flip in the red wing parts (Harries & Howarth 1996, Schmid & Schild 1994, Schmid et al. 2000).

Colliding winds models are often invoked to explain the abundant structures shown in the Raman scattered lines (e.g. Girard & Willson 1987). Another point of view was presented by Lee & Park (1999), who argued that an accretion disk type emission model may be more adequate for explanations of the spectropolarimetric observational data. The Raman scattered lines should be important in that they provide unique information that can be obtained from a mirror located on the binary axis connecting the giant and the dwarf.

Nussbaumer et al. (1989) emphasized the importance of Raman scattering in astrophysics, and proposed that it may play an important role in the formation of broad Hα wings from incident Lyβ photons. Lee & Hyung (2000, hereafter LH) computed the template wing profiles that are formed through Raman scattering in a plane-parallel H I region with various H I column densities, and applied their analysis to the young and compact planetary nebula IC 4997. The excellent agreement between the template profile with the observed one supports the hypothesis that the broad Hα wings in IC 4997 are formed through Raman scattering in a neutral envelope with a H I column density $N_{HI} \sim 10^{20}$ cm^{-2}, which is also consistent with the H I 21 cm absorption observation of IC 4997 (Altschuler et al. 1986).

The neutral envelope found in IC 4997 is an important element to study the mass loss process of the central star and we turn our attention to find similar evidence in symbiotic stars. Van Winckel et al. (1993) have compiled high resolution Hα line profiles of symbiotic stars in the southern hemisphere and the northern counterparts have been done by Ivison et al. (1994). It was shown that a typical Hα profile exhibits a dip in the center part and broad wings that often cover the narrow [NII] 6548, 6584 lines. Despite many studies on the Hα profiles of symbiotic stars, it is not still clear whether they consist of multiple emission components or the center part is absorbed. A recent study by Schwank et al. (1997) shows that the central dip may represent the absorption and that the wing parts have a different origin. In this Letter, we perform profile fitting analyses to propose that Raman scattering may be responsible for the Hα broad wings observed in symbiotic stars.

2. PROFILE FITTING ANALYSIS

2.1. *Assumptions*

Most Hα wings in symbiotic stars show velocity widths ~ 1000 km s^{-1}. If they are formed through Raman scattering, then this implies that the kinematics of the emission region is characterized by a typical velocity of order 150 km s^{-1}, considering the Doppler enhancement factor $\lambda_{H\alpha}/\lambda_{Ly\beta} = 6.4$. The detailed kinematic structure of the emission region is not certain at the moment, and this velocity scale exceeds by an order of magnitude the wind velocity associated with the mass loss of the giant companion in a symbiotic system. However, the Raman scattered features at 6830 Å and 7088 Å have typical widths of ≥ 20 Å, which also requires a similar velocity scale of about 100 km s^{-1} in the O VI emission region. From the ORFEUS observations, O VI $\lambda\lambda$ 1032, 1038 lines with FWHM up to 100 km s^{-1} have been observed in several symbiotic systems (Schmid et al. 1999). One plausible suggestion is that the UV lines are formed in an accretion disk type emission region that extends a sub-AU scale around the white dwarf component (Lee & Park 1999, Morris 1987).

In the profile analysis performed on the Hα wings in IC 4997 by LH, it was assumed that there exists a dense emission region characterized by an electron density $n_e \sim 10^{9-10}$ cm^{-3} and the photoionization code 'CLOUDY' was used to show that a sufficient number of Lyβ photons are available for Raman scattering in the neutral envelope that is supposed to cover the central emission line region (Ferland 1996). Noting the similarity of the overall Hα profile of IC 4997 and those of symbiotic stars compiled by van Winckel et al. (1993) and Ivison et al. (1994), we assume that Lyβ flux is available with a smooth profile and concentrate on the wing formation through Raman scattering.

In order to generate Hα wing profiles that may extend in the range 6540 Å through 6580 Å, we assume that the incident Lyβ flux has a top-hat profile with a full width 300 km s^{-1}. This velocity scale is somewhat larger than that associated with the O VI emission lines observed in ORFEUS. It is pointed out here that if we use a narrow profile as the incident Lyβ flux such as a Gaussian with FWHM$\lesssim$ 100 km s^{-1}, then the Raman scattering will not produce the broad Hα wings observed in symbiotic stars.

The neutral envelope may possess an expansion velocity of order 10 km s^{-1} or higher, but this value is much smaller than the total wing width. The bulk velocity of the scattering region also shifts the center of the wing profiles with respect to the center of the core emission part. However, in this Letter, we neglect these small velocity shifts and concentrate on the wing formation process in a medium that is assumed to be static.

2.2. *Template Hα Wing Profiles*

In order to prepare the template profiles, LH computed the Raman conversion factor $C_R(\lambda)$ which is defined as the ratio of the number of Raman-scattered and emergent Hα photons to that of the incident Lyβ photons. In the wavelength interval 6540 Å $\leq \lambda_o \leq$ 6580 Å the branching ratio of the Raman scattering with respect to the Rayleigh scattering is approximately given by the relation

$$\sigma_{Ram}/\sigma_{Ray} \simeq 0.1342 + 11.06\ \Delta\lambda_i/\lambda_{Ly\beta}, \quad (1)$$

where $\Delta\lambda_i \equiv \lambda_i - \lambda_{Ly\beta}$ is the difference of the wavelength λ_i of the incident photon and that of the Lyβ line center (see Lee & Yun 1998).

The wing profile is obtained in the optically thin limit, where almost all the incident Lyβ photons are scattered no more than once. In this limit, from the Kramers-Heisenberg formula, the total scattering cross section that is the sum of the Rayleigh and Raman scattering cross sections is approximated by the far Lorentzian wing part, and therefore

$$\sigma_{tot} \propto \Delta\lambda_i^{-2} + O(\Delta\lambda_i^0). \quad (2)$$

Here, $O(\Delta\lambda_i^0)$ is the remainder term dominated by the zeroth order of the wavelength shift (e.g. Sakurai 1967), and we neglected the damping constant associated with the life time of the $2p$ state of hydrogen atom.

Therefore, the wing profile is given by the relation

$$f_\lambda \propto 0.1342/\Delta\lambda_i^2 + 11.06/(\Delta\lambda_i\lambda_{Ly\beta}) + \cdots. \quad (3)$$

This implies that the wing profile is approximated to the first order by the curve proportional to $f(\Delta v) = \Delta v^{-2}$ with the flat incident Lyβ profile.

In the opposite limit where the scattering optical depth is much larger than 1, C_R converges to a constant value that depends sensitively on the branching ratio $\sigma_{Ram}/\sigma_{Ray}$. Schmid (1996) showed that a Monte Carlo technique is useful to compute the efficiency of Raman scattering, and we use a Monte Carlo code to find that C_R reaches 0.6 in the optically thick limit, which is consistent with the empirical formula proposed by Lee & Lee (1997).

2.3. *Results*

In Fig. 1, we compared the template profiles with the Hα profiles of the symbiotic star SY Mus obtained by van Winckel et al. (1993). We enlarged the profiles by 5 times to show the detailed wing profiles. By the thick dashed lines we represent the profiles proportional to $f(\Delta v) = \Delta v^{-2}$, which correspond to the envelope profiles in the optically thin limit and a flat incident radiation. The dotted lines and the long dashed lines show the wing profiles that are generated using the Monte Carlo technique adopted in the work of LH. The long dashed lines represent the wing profiles obtained from the scattering region of H I column density $N_{HI} = 5\times 10^{19}$cm^{-2} and the dotted lines from $N_{HI} = 10^{19}$cm^{-2}. Notice that the wing strength is determined by the product of the Lyβ flux and the scattering column density, so that the solid blue lines are obtained from 5 times stronger incident Lyβ flux than in the case of the dotted blue lines.

In Fig. 2, we show the result of our fitting analysis to 16 symbiotic stars selected from the atlas of Hα spectra compiled by van Winckel et al. (1993) and Ivison et al. (1994). In the present work we selected objects with conspicuous wings, and no particular selection criterion was applied. We note that most Hα profiles not shown in Fig. 2 also showed similar quality of agreement with our template profiles. In Fig. 2, we used the Monte Carlo profile obtained from the scattering column of $N_{HI} = 10^{19}$cm^{-2} for simplicity of presentation. There is an excellent agreement between the observed Hα wing profiles and the template wing profiles, which implies that Raman scattering is definitely a possible mechanism for the formation of the observed Hα line wings in symbiotic stars.

3. DISCUSSION

3.1. *Alternative Candidates for the Hα Wing Formation Mechanism*

We may consider other theoretical possibilities for the Hα wing formation mechanism. These include electron scattering, fast stellar winds or outflows and Hα damping wing scattering. The electron scattering cross section is wavelength independent and therefore similar wings may be found in other emission lines including higher Balmer line series that may be formed in the same emission region as Hα. Spectroscopy with higher signal to noise ratio will be necessary to distinguish electron scattering wings from Raman wings.

If the Hα wings in symbiotic stars represent the kinematics of the ionized hydrogen, then it may imply the existence of fast stellar winds or outflows. These outflows are often found in various objects including symbiotic stars, Wolf-Rayet stars and luminous blue variables. In particular, Schild, Mürset & Schmutz (1996) fitted the line wings of RW Hydrae with synthetic wind profiles and concluded that the wings are consistent with a wind feature. Wind emission may be distinguished from the scattered features by polarimetry, which is briefly discussed later.

According to Schwank et al. (1997) the core part of Hα is formed mainly in the transition zone where ionized hydrogen recombines. They show that the Balmer lines are optically thick and therefore it is a possibility that the broad wings may be due to the Hα damping wings. Because the Hα damping wings are also characterized by the same dependence $\propto \Delta\lambda^{-2}$, this process is worth further discussion.

However, in this case the wing photons are also generated in the same region as the core photons and therefore we may expect that the wing strength should be strongly correlated with that of the core part. Schmutz et al.(1994) presented the Hα profiles at various orbital phases of the symbiotic star SY Mus. They pointed out that the Hα core part of this object shows regular variations both in the profiles and in the line intensity, whereas the wing part remains constant. This implies that the wing part may be formed in a much more extended region than in the region responsible for the core part.

It is notable that the Raman scattered Hα wings can be strongly polarized depending on the scattering geometry. Because symbiotic stars usually exhibit bipolar nebular morphology, which may represent an anisotropic matter distribution around the central stellar region, we may expect that neutral hydrogen is distributed in a similar way. In this case, the Hα wings can be strongly polarized with the polarization direction parallel or perpendicular to the polar axis. Furthermore, if the neutral envelope is expanding, then much stronger polarized flux will be obtained in the red wing part than in the blue wing part.

A hint of this behavior is shown in the spectropolarimetric observation of BI Crucis presented by Harries (1996), who proposed the accretion disk reflection as the main mechanism for polarization generation. However, the overall spectropolarimetric behavior shown in BI Cru can be also interpreted in the context of the Raman scattering in an expanding neutral envelope, of which more detailed theoretical study is under way (Bak & Lee, in preparation). Further spectropolarimetric observations of Hα in symbiotic stars are expected to provide important clues to the origin of the broad Hα wings.

At present, other mechanisms cannot be excluded as the origin of the Hα broad wings in symbiotic stars. However, in view of the current profile fitting analyses and the existence of the Raman scattered O VI lines in symbiotic stars, we propose that the Raman scattering of Lyβ by atomic hydrogen may provide the most plausible explanation for the Hα wing formation.

3.2. *Observational Ramifications*

In the present work, the essential parameters are the strength of the incident Lyβ and the scattering column density N_{HI}, of which the product determines the wing flux profile and therefore becomes the only free parameter in the profile fitting analysis. In the fitting analysis performed on the planetary nebula IC 4997 by LH, there exist H I observations to obtain an independent measurement of N_{HI} (see Altschuler et al. 1986). In the present work no such observations seem to be available at this time, and similar H I observations may provide important information about the wing formation mechanisms.

From the strength of the Raman scattered features around 6830 Å and 7088 Å, it is often proposed that they are scattered in a region with $N_{HI} \gtrsim 10^{22}\mathrm{cm}^{-2}$. It appears that these features are formed deep inside the symbiotic system where the scattering region is located near the giant component. However, since Lyβ line photons have much larger scattering cross section than O VI λλ 1032, 1034 photons do, the Hα wings may also be contributed significantly in a more extended region with a much lower N_{HI} than the O VI scattering region. Furthermore, it is not apparent that the wings are formed in a scattering region of a uniform density, because a composite profile from a number of scattering regions with different N_{HI} will produce a similar profile with the dependence of Eq. (3). More detailed information may be obtained from high resolution far UV spectroscopy around Lyβ, which may be achieved by the FUSE mission (see also Schmid et al. 1999).

The recent report by Van de Steene, Wood, & van Hoof (2000) shows that broad Hα wings are also present in a number of post AGB stars. Balick (1989) also reported the existence of very broad wings around Hα in the planetary nebula M2-9. It appears that the broad Hα wings are a common feature of post AGB stars, symbiotic stars and young compact planetary nebulae, most of which are believed to be (or have been) in the process of heavy mass loss giving rise to the formation of a neutral envelope around the hot emission region. As Nussbaumer et al. (1989) noted, the Raman scattering may also operate in active galactic nuclei (AGN) to form broad Hα wings. Romano et al. (1996) investigated the Hα wing profiles of AGN and found that they are well fitted by the relation Δv^{-2}. In AGN the Hα wing width often exceeds 10^4 km s^{-1} and we may expect to find a slight deviation from $\Delta\lambda^{-2}$ due to the contribution from the second term in Eq. (3), of which more theoretical and observational work is needed to test this hypothesis.

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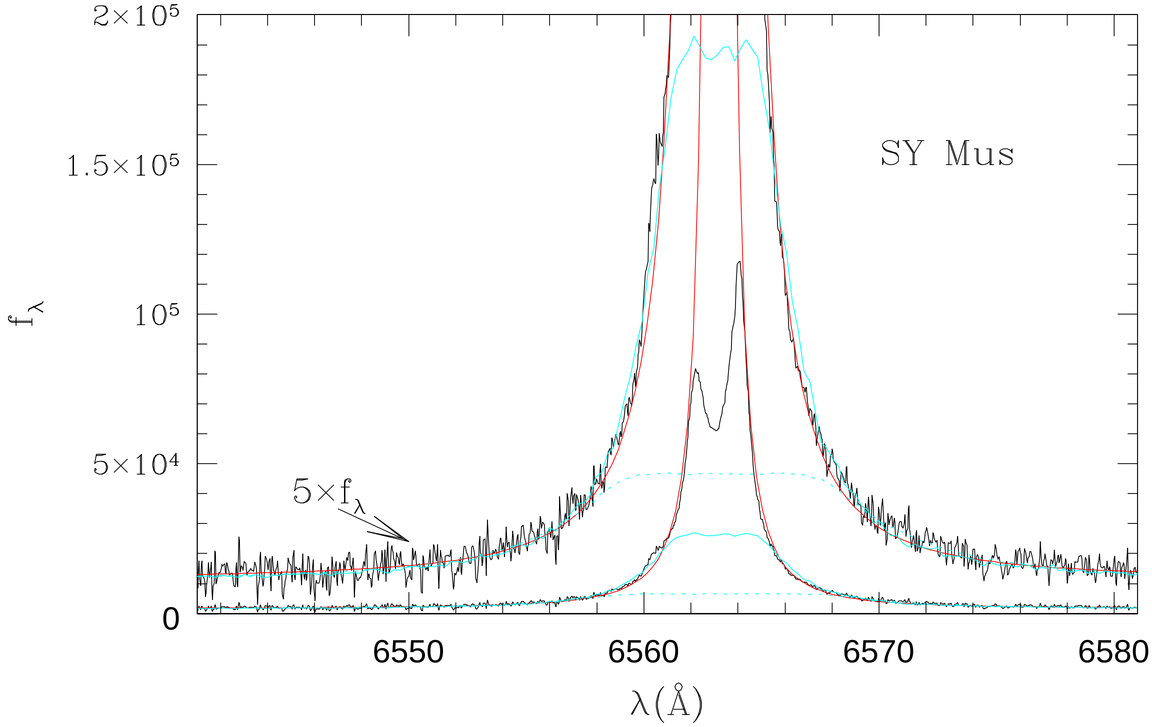

FIG. 1.— Hα profiles of the symbiotic star SY Mus obtained by van Winckel et al. (1993), and the template profiles. The profiles are enlarged by 5 times to reveal the details of the wing parts. By the thick dashed lines we represent the profiles given by the relation $f(\Delta v) \propto \Delta v^{-2}$, The dotted and long dashed lines show the wing profiles that are generated using the Monte Carlo technique adopted in the work of Lee & Hyung(2000). The long dashed lines represent the wing profiles obtained from the scattering region of H I column density $N_{HI} = 5 \times 10^{19}$ cm^{-2} and the dotted lines from $N_{HI} = 10^{19}$ cm^{-2}.

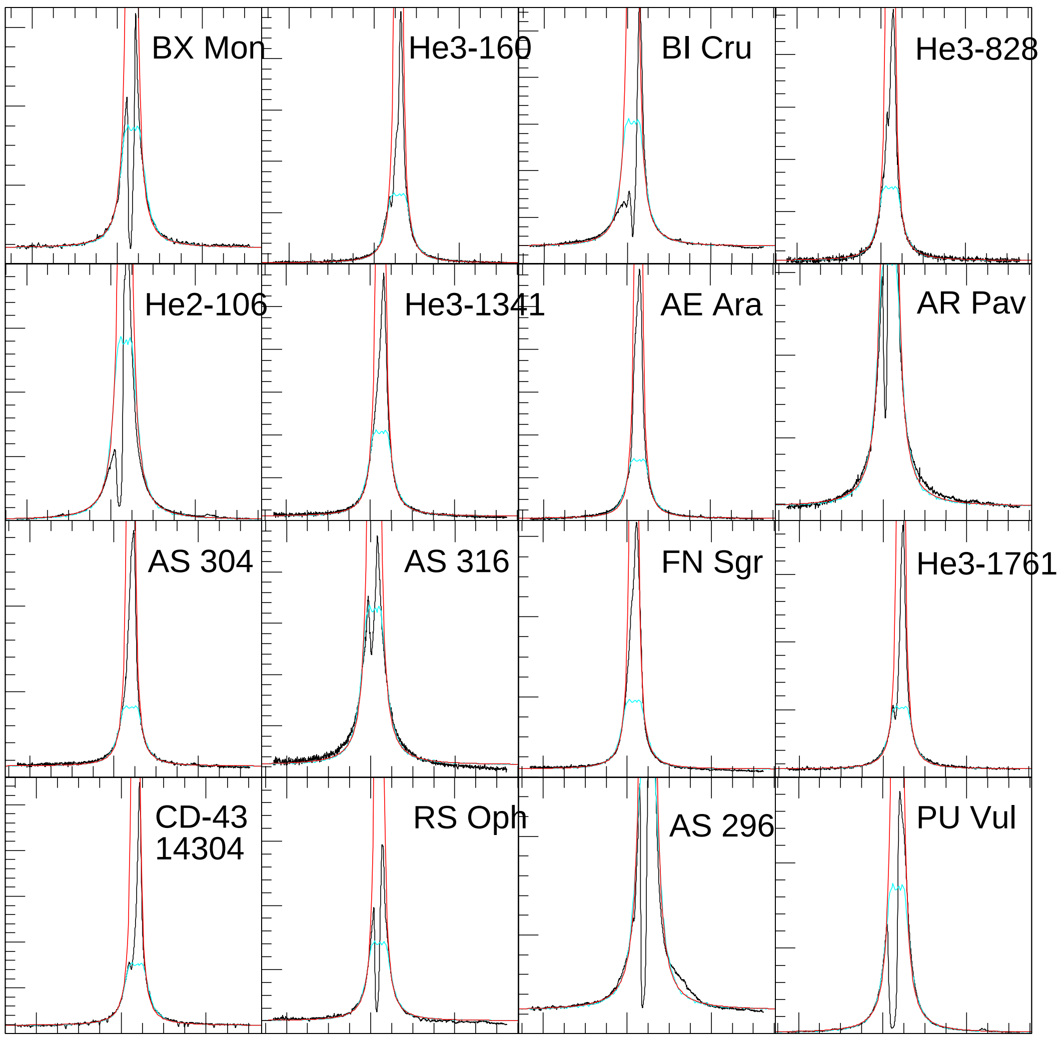

Fig. 2.— The Hα profiles of 16 symbiotic stars selected from the atlas of Hα spectra compiled by van Winckel et al. (1993) and Ivison et al. (1994). Objects with conspicuous wings were selected, and no particular selection criterion was applied. The thick dashed lines and the dotted lines represent the same quantities as in Fig. 1, and we omitted the case of $N_{HI} = 5 \times 10^{19}$ cm^{-2} for simplicity of presentation. We omit the labels of the horizontal axis and vertical axis, which are the same as in Fig. 1. The excellent agreement between the template wing profiles and the observed ones is apparent.