Raman Spectroscopy in Symbiotic Stars

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* High resolution spectroscopic observations
* Raman O VI spectroscopy in Symbiotic Stars
* Raman He II spectroscopy in young planetary nebulae
* Balmer wing formation in AGNs
- Korea-Chile collaboration project since 2015 June.

- “High Resolution Spectroscopic and Fast Photometric Study of Wind Accretion and Mass Loss in Stellar Systems Involving White Dwarfs” ([kochil.weebly.com](http://kochil.weebly.com))

- AURA/Gemini Observatory, La Serena (Adviser: Rodolfo Angeloni)
Raman Spectroscopy
in Symbiotic Stars

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• RAMAN-SCATTERING BY ATOMIC HYDROGEN
• RAMAN FEATURES IN SYMBIOTIC STARS
• OUR RESEARCH
I. Symbiotic Stars
Active White Dwarf Systems: Candidate Progenitors of Type Ia Supernovae

- **Cataclysmic Variables (CVs):**
  - Semi-detached binary systems with a late type main sequence star that fills the Roche-lobe
  - Accretion from the Roche-lobe overflow

- **Symbiotic Stars (SSs):**
  - Wide binary systems with a mass losing giant
  - Accretion of the slow stellar wind from the giant
  - Higher accretion rate is expected but less studied than CVs

S. Mohamed & Ph. Podsiadlowski, 2012
Symbiotic Stars

- Present Sample
  > 200 galactic SSs + 18 extragalactic SSs

- Long orbital period:
  S-type (w/ a normal giant) 200 ~ 1000 days
  D-type (w/ a Mira variable) 10 ~ 100 years

- High mass-loss rate:
  $10^{-4} \sim 10^{-7} \text{ M}_{\sun}/\text{yr}$ depending on the stellar evolution stage.

- Complex photometric variability
  e.g., flicker in the accretion disk, the rotation of the WD, stellar pulsations of the late-type giant, recombination in the nebula, modulations associated with the orbital period, nova-like outbursts
Symbiotic Stars

Munari & Zwitter, 2001

Magrini et al. 2005
Symbiotic Stars

- Symbiotic stars are spectroscopically characterized by strong nebular emission lines with TiO absorption bands and continuum that are typical of a giant.
Spectral Classification Criteria
- Belczyński et al., 2000

✓ Presence of strong emission lines of HI and HeI and either emission lines of ions with an ionization potential of at least 35 eV (e.g. [OIII]), or an A- or F-type continuum with additional shell absorption lines from HI, HeI, and singly-ionized metals;

✓ Presence of the absorption features of a late-type giant; in practice, these include (amongst others) TiO, H2O, CO, CN and VO bands, as well as CaI, CaII, FeI and NaI absorption lines;

✓ The presence of the $\lambda 6825$ Å emission feature, even if no features of the cool star (e.g. TiO bands) are found
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✓ The presence of the λ6825 Å emission feature, even if no features of the cool star (e.g. TiO bands) are found.
6825 and 7082 Å Bands

- Very broad emission features at 6825 and 7082 Å are observed in about a half of symbiotic stars showing high-excitation lines e.g. [Ne V] and [Fe VII].

- In 1989, Schmid identified those features are the result of Raman-scattering of O VI $\lambda\lambda$ 1032 and 1038 by atomic hydrogen.
II. Raman-Scattering
Raman-scattering by H I

- Raman-scattering is an **inelastic scattering** process.
- A far-UV photon blueward of Lyα is incident upon a hydrogen atom in the ground state. Subsequently, the hydrogen atom de-excites into the 2s state, **re-emitting an optical Raman-scattered photon**.
- Based on the principle of Energy conservation:
  \[ hν_i = hν_o + hν_α \]
- The re-emission of a photon has significantly longer wavelength than incident photon.

Schematic energy level diagram for Raman scattering by H I

Ly β 1025 (1s → 3p)  
O VI 1032  
Hα 6563 (3p → 2s)  
Raman O VI 6825
This relation implies that the Raman-scattered features will be **broadened by the factor (λ₀/λᵢ)**

In the case of Raman-scattered O VI λ1032 at 6825 Å, this factor is almost 6.6, resulting in a very broad emission features.
This relation implies that the Raman-scattered features will be broadened by the factor \( \frac{\lambda_o}{\lambda_i} \).

In the case of Raman-scattered O VI \( \lambda1032 \) at 6825 Å, this factor is almost 6.6, resulting in a very broad emission features.

Profile broadening makes the line profile analysis much easier.
6825 and 7082 Å Bands?
6825 and 7082 Å Bands? 

Raman-scattering of O VI $\lambda\lambda$ 1032, 1038 by H I!

Far-UV O VI $\lambda\lambda$ 1032, 1038 resonance doublets
Scattering Cross section

- The scattering cross section can be computed from the 2nd order perturbation theory in quantum mechanics.

\[ \sigma \sim 10^{-22} \text{ cm}^2 \text{ for O VI} \]

- It requires a thick neutral component with \( N_{\text{HI}} \sim 10^{22} \text{ cm}^{-2} \) that is illuminated by a very strong far-UV emission source.
III. Raman Features in Symbiotic Stars
What is so special? about conditions in symbiotic stars

• Symbiotic systems are binaries consisting of a hot radiation source usually white dwarf, and a cool, mass losing giant.

• The white dwarf accretes a fraction of the stellar wind from the giant, which makes it very hot ($\sim 10^5$ K) and luminous ($\sim 10^2$-$10^4$ $L_{\odot}$), and thus capable of ionizing the neutral wind from the giant.
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The environment of symbiotic stars is very suitable for observing the Raman-scattering process.
What is so special about Raman profiles?

- The Raman profiles reflect the relative kinematics between the neutral region and the far-UV emission region and are almost independent of the observer’s line of sight.
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What is so special? about Raman profiles

- The Raman profiles reflect the relative kinematics between the neutral region and the far-UV emission region and are almost independent of the observer’s line of sight.

- Nature has installed a wonderful mirror in front of the giant to provide a perfect edge-on view of the accretion flow.

An ideal tool to probe the kinematics of the emission region around WD.
What is so special? about Raman profiles

- The Raman-scattered features are usually strongly polarized. Related to this is the fact that they are composed of purely scattered photons without dilution from the direct flux.

- Since polarization is dependent on the viewing geometry, time-series measurements can be used to determine the orbital parameters.

Spectropolarimetric observations of CD−43°14304 (Harries & Howarth, 2000)
Raman-Scattering of O VI by H I

- Raman-scattered O VI $\lambda\lambda$ 1032, 1038 features at 6825 and 7082 Å are the first known Raman features in the symbiotic stars.

- About a half of symbiotic stars are known to exhibit these features.

- Recently, Raman O VI features in the peculiar emission line star LHA 115-S18 (Torres et al. 2012) and the classical nova V339 Del (Skopal et al. 2014) are reported.
Other Raman features

He II $\lambda$ 1025, 972 and 949
→ Raman He II 6545, 4850 and 4332 Å

- High resolution spectra with quite long exposure are essential.
- Raman He II features are found in 4 Young planetary nebulae. (NGC7027, NGC6302, IC 5117, NGC6790)

Lee et al., 2003
Birriel, 2004
Lee, 2012
Other Raman features

Ne VII λ 973 → Raman Ne VII 4880 Å

- Bohyun Optical Astronomical Observatory, Korea
- 1.8m optical telescope
- Bohyunsan Optical Echelle Spectrograph (BOES)
- Spectral Coverage: 3,600~10,500 Å
- Spectral Resolution: R ~ 30,000
- Exposure time: 7,200 sec
- Observing Date: 07/11/2005

Lee et al., 2014
IV. Our Research

1) Profile Analysis of Raman O VI
2) Raman Features in Sanduleak’s Star
1) Profile Analysis of Raman O VI

- Raman O VI profiles are known to exhibit complicated profiles including double-peak and triple-peak.

V1016 Cyg (CFHT, 2014)

V455 Sco (MIKE, 2015)
1) Profile Analysis of Raman O VI

- **Accretion Flow model**
  The double-peak profiles can be interpreted as a result of the kinematics of O VI 1032 and 1038 emission region associated with the accretion flow around the WD.

Lee & Kang, 2007

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1) Profile Analysis of Raman O VI

- **Bipolar outflow model** (Heo et al., in prep.)
  Adopting the accretion flow model, ① the blue peak and ② central peak are contributed from the accretion flow around the WD. ③ The remaining red peak, is formed from O VI coming from the bipolar outflowing region with a speed of ~+80km/s with respect to the giant.

V455 Sco (MIKE, 2015)
1) Profile Analysis of Raman O VI

- Depending on the optical depth of emission region, the flux ratio of O VI 1032 and 1038 differs.
- Profile disparity of Raman O VI 6825 and 7082 features comes from the local variation of O VI emissivity in the accretion flow.
- A profile comparison of two Raman O VI features could provide with the density structure in the O VI emission region.

Heo & Lee (2015)
2) Raman O VI in Sanduleak’s star

- Sanduleak’s star is a suspected symbiotic binary in the Large Magellanic Cloud.

- Despite the absence of any late-type stellar signatures, it is tentatively classified as a D-type SS on the based of the optical emission-line spectrum and the presence of the Raman-scattered O VI features.

- The discovery of a giant, highly-collimated bipolar jet extending over almost 15 pc has shed new light on the nature of this object (Angeloni et al., 2011)
2) Raman O VI in Sanduleak’s star

- The two Raman profiles are quite different: while the 6825 feature shows a single broad profile, the 7082 one exhibits a distinct triple-peak profile.

- In order to characterize the emission regions, we decomposed the far-UV OVI emission lines into five Gaussian components based on the observed Raman-scattered features.
2) Raman O VI in Sanduleak’s star

- We propose that the OVI emission region consists of five emitting components: 1. Blue emission part and 2. Red emission part of an accretion flow; 3. a bipolar outflow; 4. a localized component and 5. an extended component surrounding the white dwarf. (Heo et al., in prep.)
2) Raman O VI in Sanduleak’s star

- With the decomposition of the OVI emission region and an additional assumption that the neutral region is a single component, we performed Monte-Carlo simulations.

(Heo et al., in prep.)

Table 1: Doppler factors, corresponding wavelengths, widths and flux ratio of each gaussian components

<table>
<thead>
<tr>
<th>Emission Region</th>
<th>ΔV_{atomic} (km s^{-1})</th>
<th>ΔV_{neutral} (km s^{-1})</th>
<th>λ_{rest} (Å)</th>
<th>λ_{rest} (Å)</th>
<th>Δv (km s^{-1})</th>
<th>Flux Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accretion(BEP)</td>
<td>19</td>
<td>-34</td>
<td>1031.993</td>
<td>1037.684</td>
<td>17</td>
<td>2</td>
</tr>
<tr>
<td>Accretion(REP)</td>
<td>87</td>
<td>34</td>
<td>1032.227</td>
<td>1037.919</td>
<td>17</td>
<td>1</td>
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<tr>
<td>Outflow</td>
<td>110</td>
<td>57</td>
<td>1032.306</td>
<td>1037.998</td>
<td>40</td>
<td>2</td>
</tr>
<tr>
<td>Localized</td>
<td>58</td>
<td>5</td>
<td>1032.128</td>
<td>1037.819</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>Extended</td>
<td>50</td>
<td>6</td>
<td>1032.131</td>
<td>1037.822</td>
<td>25</td>
<td>1</td>
</tr>
<tr>
<td>Atomic center</td>
<td>0</td>
<td>-53</td>
<td>1031.928</td>
<td>1037.618</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Doppler factors ΔV_{atomic} and ΔV_{neutral} are defined by atomic center and neutral component, respectively.
Summary

Symbiotic stars, wide binary systems composed of a WD and a mass losing giant, are characterized from spectroscopy.

The environment of symbiotic stars is very suitable for observing the Raman-scattering process.

The technique by using Raman features is an ideal tool to probe the kinematics of the emission region around WD.
¡Gracias! 😊