Atomic Raman Spectroscopy of Wind Accretion in Symbiotic Stars

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CONTENTS

I. Introduction
  • Symbiotic Stars
  • 6825 Å & 7082 Å Bands?
  • Raman O VI in Symbiotic Stars

II. Raman Spectroscopy in Symbiotic Stars
  • Accretion Flow Model
  • Raman O VI Profile Analysis

III. Ongoing and Future Works
  • Photometric Search of Extragalactic Symbiotic Stars
  • Summary
INTRODUCTION

- Symbiotic Stars
- 6825 Å & 7082 Å Bands?
- Raman O VI in Symbiotic Stars
Stellar Evolution (0.8 - 8M☉)
Symbiotic Stars

- Wide binary systems of an evolved giant and a hot white dwarf

- Some fraction of the stellar wind from the giant component is gravitationally captured by the white dwarf.

(Credit: NASA/CXC/A. Hobart)
Active White Dwarf Systems

The progenitor of a Type Ia supernova

- Two normal stars are in a binary pair.
- The more massive star becomes a giant...
  ...which spills gas onto the secondary star, causing it to expand and become engulfed.
- The secondary, lighter star and the core of the giant star spiral toward within a common envelope.
- The common envelope is ejected, while the separation between the core and the secondary star decreases.
- The remaining core of the giant collapses and becomes a white dwarf.
- The aging companion star starts swelling, spilling gas onto the white dwarf.
- The white dwarf's mass increases until it reaches a critical mass and explodes...
  ...causing the companion star to be ejected away.
Symbiotic Stars

Symbiotic Star RR Tel (Munari & Zwitter 2001)

PN Sextans A (Magrini et al. 2005)

M type giants
Symbiotic Stars

Symbiotic Star RR Tel
(Munari & Zwitter 2001)

M type giants

PN Sextans A
(Magrini et al. 2005)
Symbiotic Stars - R Aquarii

HST image (2017)

SPHERE / ZIMPOL (2014)  
(Schmid et al. 2017)

High-resolution continuum map,  
ALMA (2018)  
(Bujarrabal et al. 2018)
Accretion in Symbiotic Stars

- It is highly controversial whether an accretion disk is present in a stable fashion in symbiotic stars.

- Hydrodynamic simulations show that steady accretion disk can be formed via gravitational capture of slow stellar wind.

(Mastrodemos and Morris, 1998)  
Chen et al. (2017)
6825 Å and 7082 Å Bands?

- Broad features at 6825 Å and 7082 Å are observed in about a half of symbiotic stars showing high-excitation lines e.g. [Ne V] and [Fe VII].
- Two bands have abnormally broad width of 20-30 Å.
- So far these features have been detected only in bona fide symbiotic stars, and served as one of the criteria for classifying a star as symbiotic.

(Belczyński et al. 2000)
6825 Å and 7082 Å Bands?

- 112 (in Milky Way) + 3 (in Magellan Clouds) **symbiotic stars** in Allen’s Catalogue (1979)

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<thead>
<tr>
<th>Name</th>
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Allen (1979)
6825 Å and 7082 Å Bands?

- 59/115 objects (~50%) show 6825 emission.
- 8/59 objects show 7082 band.

![List of objects with their optical spectrum and emission properties](Allen (1979))
6825 Å and 7082 Å Bands?

- A gross similarity between the profiles of the 6825 and 7082 bands.
- The intensities of the bands are correlated $I(6825)/I(7082) \sim 4$.

(Allen, 1980)
In 1989, Schmid identified those features as Raman-scattering of O VI $\lambda\lambda$ 1032 and 1038 doublet by atomic hydrogen.
Rayleigh Scattering

\[ E_f = E_i \quad \text{(Rayleigh Scattering)} \]
Raman Scattering

- **Inelastic scattering** of a photon by an atom or molecule
- Discovered in 1928 by Chandrasekhar Venkata Raman
- Commonly used in physics and chemistry to investigate molecular vibrations and crystal structures
Raman Scattering by Atomic Hydrogen

Atomic Hydrogen

1S

2S

3S

\[ e^- \]
Raman Scattering by Atomic Hydrogen

Atomic Hydrogen

\[ E_f = E_i - E_{\text{Ly}\alpha} \]
Raman O VI Bands

Atomic Hydrogen

O VI

2P
2S

P_{3/2}

P_{1/2}

O VI 1032 Å

O VI 1038 Å

3S

2S

1S

O VI 1032 Å

O VI 1038 Å
Raman O VI Bands

Atomic Hydrogen

O VI

2S ————> 1S

O VI 1032 Å

O VI 1038 Å

Raman O VI 6825 Å

Raman O VI 7082 Å
Raman-scattered O VI Features

Raman-scattering of O VI $\lambda\lambda$ 1032, 1038 by H I
Profile Broadening of Raman Scattering

$E_i = E_f + E_{Ly\alpha}$

$h\nu_i = h\nu_f + h\nu_{Ly\alpha}$

$\Delta\nu_i = \Delta\nu_f$

$\frac{\Delta\nu_i}{\nu_i} = \frac{\Delta\nu_f}{\nu_i} = \frac{\nu_f}{\nu_i} \Delta\nu_f$

- The energy conservation leads to a broadened profile exhibited in the Raman scattered features by the factor $(\lambda_f/\lambda_i)$

- In the case of Raman-scattered O VI $\lambda 1032$ 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.
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 \( N_{\text{H}I} \sim 10^{22} \text{ cm}^{-2} \) that is illuminated by a very strong far-UV emission source.

Chang et al. 2018
Raman O VI Features in Symbiotic Stars

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

$$\sigma \sim 10^{-22}\text{ cm}^2$$ 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.

The environment of symbiotic stars is ideal for the operation of Raman scattering

Chang et al. 2018
Raman O VI Detections (Akras et al. 2019)

Table 2. Number of positive and negative O VI Raman-line Detections in the Milky Way, SMC, LMC, M31, and M33

<table>
<thead>
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<th>Galaxy</th>
<th>Total number$^a$</th>
<th>Positive detections</th>
<th>Negative detections</th>
<th>O VI Raman (%)</th>
<th>[Fe/H]</th>
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$^a$Total number of optical spectra examined in this work.

RAMAN SPECTROSCOPY

- Accretion Flow Model
- Raman O VI Profile Analysis
  - V1016 Cygni
  - Sanduleak’s Star
  - RR Telescopii
Accretion Flow Model

- The double-peak profiles can be attributed to the kinematics of O VI 1032 and 1038 emission region associated with the accretion flow around the WD.

Lee & Kang, 2007

Raman O VI 6825

V1016 Cyg

HM Sge

Lee & Kang, 2007
Raman O VI Features in Symbiotic Stars

Harries & Howarth 1996
Raman O VI Features and Accretion Flow

- Divergent Flow (Optically thin)
- Convergent Flow (Optically thick)
Raman O VI Features and Accretion Flow
Resonance Doublets

- Isoelectronic configuration with Li (Valence electron in 2S)
- Fine structure of 2P level: P\(_{3/2}\), P\(_{1/2}\)
- O VI \(\lambda 1032\) Å: Transition P\(_{3/2}\) → S\(_{1/2}\)
- O VI \(\lambda 1038\) Å: Transition P\(_{1/2}\) → S\(_{1/2}\)

Flux Ratio F(1032)/F(1038)

- **Theoretical value = 2:1**
  P\(_{3/2}\) → S\(_{1/2}\) is characterized by a twice larger statistical weight than those for P\(_{1/2}\) → S\(_{1/2}\)
- In the optically thick region, complicated radiative transfer effect makes F(1032)/F(1038) ~ 1:1.
  (Kang & Lee, 2008)
Raman O VI Features and Accretion Flow

- **Divergent Flow** (Optically thin)
  - 1032
  - 1038

- **Convergent Flow** (Optically thick)
  - 1032
  - 1038
Raman O VI Features and Accretion Flow

H I Region

Far-UV O VI Doublets

1032

1038
Raman O VI Features and Accretion Flow

H I Region

RED GIANT

Raman O VI Features

6825  7082
Raman O VI Features and Accretion Flow

H I Region

RED GIANT

Raman O VI Features

6825

7082
Raman O VI Features and Accretion Flow

Nature has installed a wonderful mirror in front of the giant to provide a perfect edge-on view of the accretion flow.
Raman O VI Features and Accretion Flow
V1016 Cygni

- D (Dusty)-type symbiotic nova
- A Mira variable with $P_{\text{pul}} \sim 475$ days
  + a very hot ($\sim 150,000$K) and luminous ($\sim 30,000 \, L_\odot$) WD

- Orbital period $P_{\text{orb}} : 6 \sim 544$ years
  (Parimucha et al. 2002 and the references therein)

BOES Observation

- Bohyunsan Optical Echelle Spectrograph (BOES)
  with 1.8 m optical telescope at Mt. Bohyun observatory, Korea

- Spectral coverage: $3,600 \sim 10,500 \, \AA$
  Spectroscopic resolution $\approx 30,000$

- Observing date: 7 November, 2005
  Exposure time: 7,200 sec
Raman O VI Profile Analysis - V1016 Cygni

Heo & Lee (2015)

- BOES spectrum of V1016 Cyg

- Emissivity maps for the Raman 6825, 7082

- The red emission region is more extended than the blue counterpart.

- The blue emission region for the 6825 feature is relatively more extended than that of the 7088.
Raman O VI Profile Analysis - V1016 Cygni

- The flux ratio varies from 1 to 2, which is the maximum range allowed theoretically.
- The inner red emission region is of the highest density, followed by the inner blue emission region and the outer region is of the lowest density.

Flux ratio map of the O VI 1032 and 1038

Flux ratio as a function of the Doppler factor with the normalization of equal red peak strengths

Heo & Lee (2015)
The flux ratio varies from 1 to 2, which is the maximum range allowed theoretically.
The inner red emission region is of the highest density, followed by the inner blue emission region and the outer region is of the lowest density.

The quantitative comparison of two Raman bands can provide detailed information including the kinematics and the density distribution of the O VI emission region.

Heo & Lee (2015)
Raman O VI Profile Analysis - Sanduleak’s Star

Sanduleak’s star

- A suspected symbiotic binary in LMC
- The discovery of a giant, highly-collimated bipolar jet extending over almost 15 pc (Angeloni et al. 2011)
- Despite the absence of any late-type stellar signatures, it is tentatively classified as a D-type symbiotic star on the basis of the optical emission-line spectrum and the presence of the Raman-scattered OVI features (Allen 1980)

MIKE Observation

- The Magellan Inamori Kyocera Echelle (MIKE)
  6.5m Clay Telescope, Las Campanas Observatory, Chile
- Spectral coverage: (Red) 4,900~9,500 Å
  Resolving power: ~32,000
- Observing date: Nov. 21, 2010
  Exposure time: 3×900 sec
Raman O VI Profile Analysis - Sanduleak’s Star

Heo et al. (2016)

Raman O VI 6825  Raman O VI 7082

O VI 1032  O VI 1038

a) Blue Emission Part and Red Emission Part of Accretion Disk
b) Central Emission Part of Accretion disk
d) Optically Thick Compact Component
c) Bipolar Outflow

Heo et al. (2016)
• We performed Monte Carlo simulations in order to estimate the representative value of $N_{\text{HI}}$ by reproducing the observed $F(6825)/F(7082)$.

• A neutral scattering region is a cylindrical slab characterized by a single column density $N_{\text{HI}}$ and static with respect to the emission region.

• $N_{\text{HI}} \sim 1 \times 10^{23}\text{cm}^{-2}$

Monte Carlo results depending on the column density $N_{\text{HI}}$
We performed Monte Carlo simulations in order to estimate the representative value of $N_{\text{HI}}$ by reproducing the observed $F(6825)/F(7082)$.

A neutral scattering region is a cylindrical slab characterized by a single column density $N_{\text{HI}}$ and static with respect to the emission region.

$N_{\text{HI}} \sim 1 \times 10^{23}\text{cm}^{-2}$

Raman O VI features can be used to constrain the physical parameters of the H I scattering region.

Monte Carlo results depending on the column density $N_{\text{HI}}$
Raman O VI Profile Analysis - RR Tel

RR Telescopii

- D (Dusty)-type symbiotic nova
  M6-type Mira variable with $P_{\text{pul}} \sim 387$ days
  + a very hot (~140,000K) and luminous (~5,000 $L_\odot$) WD
  (Feast et al. 1983; Mürset & Schmid 1999; Gromadzki et al. 2009)

- $D \sim 2.7$ kpc (Jurkic & kotnik- Karuza, 2012)

MIKE Observation

- The Magellan Inamori Kyocera Echelle (MIKE)
  6.5m Clay Telescope, Las Campanas Observatory, Chile

- Spectral Coverage: (Blue) 3,350~5,000 Å
  (Red) 4,900~9,500 Å

- Resolving Power: (Blue) $R \sim 27,000$
  (Red) $R \sim 35,500$

- Observing Date: 26, July, 2017
  Exposure Time: 4 x 600 sec

Basic parameters proposed for RR Tel
• **Spherical stellar wind** from the giant follows a beta law,

\[ v_r(r) = v_\infty \left(1 - R_*/r\right)^\beta \]

• **The ionization front in the stellar wind region** around the giant is determined by the balance of photoionization by the H-ionizing flux from the hot component and recombination represented by the mass loss rate of the giant.

• **STB geometry** (Seaquist, Taylor & Button, 1984)

\[ X = 4\pi a \frac{L_H}{\alpha_B} \left( \frac{m_H v_\infty}{\dot{M}} \right)^2 \]
• Keplerian accretion disk model with \textit{azimuthally asymmetric matter distribution}

• $v_{\text{min}} \approx 30 \text{ km/s}$, which corresponds to a physical size of the disk $\approx 1 \text{ au}$

• Giant wind terminal velocity $v_{\infty} \approx 10 \text{ km/s}$

• Mass loss rate $\dot{M} \approx 2 \times 10^{-6} \text{M}_\odot$/yr

\begin{itemize}
  \item MIKE spectrum of RR Tel
\end{itemize}
Keplerian accretion disk model with azimuthally asymmetric matter distribution.

$v_{\text{min}} \approx 30 \text{ km/s}$, which corresponds to a physical size of the disk $\approx 1 \text{ au}$.

Giant wind terminal velocity $v_{\infty} \approx 10 \text{ km/s}$.

Mass loss rate $\dot{M} \approx 2 \times 10^{-6} \text{M}_\odot/\text{yr}$.

Raman O VI profile analysis enable us to investigate the scattering geometry and further infer the mass-loss rates of the cool components in symbiotic systems.
ONGOING AND FUTURE WORKS

- Photometric Search of Extragalactic Symbiotic Stars
- Summary
RAMSES II Project

• Galactic Symbiotic Stars
  - Predicted population: $10^3$-$10^5$ (Allen 1984; Lu et al., 2012)

• Population of Symbiotic Stars in Local Group Galaxies

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Distance (kpc)</th>
<th>M (M$_\odot$)</th>
<th>Size (arcmin$^2$)</th>
<th>Expected # of SySt</th>
<th>Observed # of SySt</th>
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</thead>
<tbody>
<tr>
<td>IC10</td>
<td>862±30</td>
<td>6.0 x $10^8$</td>
<td>6.8X5.9</td>
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<td>NGC 147</td>
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<td>13.2x7.8</td>
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<td>11.7x10.0</td>
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<tr>
<td>NGC 205</td>
<td>824±27</td>
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<td>21.9x11.0</td>
<td>17 000</td>
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<td>M 32</td>
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<td>8.7x6.5</td>
<td>19 000</td>
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<tr>
<td>M 31</td>
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<td>190x60</td>
<td>660 000</td>
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<tr>
<td>M 33</td>
<td>883±246</td>
<td>0.8-1.4 x $10^{10}$</td>
<td>70.8x41.7</td>
<td>45 000</td>
<td>12</td>
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<tr>
<td>Fornax</td>
<td>138±5</td>
<td>6.8 x $10^7$</td>
<td>17.0x12.0</td>
<td>500</td>
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<tr>
<td>Leo I</td>
<td>254±17</td>
<td>&gt; 2.0 x $10^7$</td>
<td>9.8x7.4</td>
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<td>Leo II</td>
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<td>12.0x11.0</td>
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<tr>
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<td>1.7 x $10^7$</td>
<td>35.5x24.5</td>
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</tr>
</tbody>
</table>
RAMSES II Project

**RAMMan Search for Extragalactic Symbiotic Stars**

Using Raman O VI emission as a new photometric diagnostic tool to systematically discover new symbiotic stars

- **D.R. Gonçalves** (PI, Observatório do Valongo, UFRJ, Brazil)
- **H.-W. Lee, J.-E. Heo** (Sejong University, Korea)
- **R. Angeloni** (Universidad de La Serena, Chile)
- **R. Diaz, G. Gimeno** (Gemini Observatory, Chile)
- **S. Akras, M.D. Ribeiro** (Observatório do Valongo, UFRJ, Brazil)
- **G.J. Luna** (IAFE-CONICET, Argentina)
- **N.E. Nuñez** (ICATE-CONICET, Argentina)
- **J.L. Sokoloski. L. Adrian** (Columbia University, USA)

+ several present (and future) students...
Gemini Instrument Upgrade Project

Instrument Upgrade Projects: Awarded Proposals
Gemini Observatory > Scipps > Future Instrumentation & Current Development > Instrument Upgrade Projects

2015-2017 IUP Project
During the 2015 program cycle, Gemini awarded Professor Casey Popovich from Texas A&M University (USA) for the proposal “Two K-filters for F-2 (K2F).” Professor Popovich and his team proposed a small upgrade to F-2 by providing two medium band filters, which split the spectral range 1.9-2.5 microns. The team also includes astronomers from the University of Toronto (Canada), Swinburne University of Technology and Macquarie University (Australia), and Leiden University (Netherlands). The main science case supporting the upgrade uses imaging K-band color deep surveys to perform redshift demography and exploit synergies with current and forthcoming synoptic surveys. The project envisions other applications as censuses of low mass stars in high extinction environments. In addition to funding the design, procurement, and testing of the filters, Gemini has awarded the team with 10 hours of telescope time to demonstrate the scientific benefits of the new capability. The filters have been commissioned, the team is preparing their first publication and the new capability of Flamingos-2 is already offered to users. It is worth to note that several queue and fast turn around proposals have requested to use the filters.

2016-2018 IUP Projects
During the 2016 program cycle, Gemini awarded three proposals.

Professor Denise Gonçalves from the Federal University of Rio de Janeiro (Brazil) for the proposal “Raman OVI narrowband imaging with Gemini/GMOS.” The team also includes Professor Rodolfo Angeloni from the University of La Serena (Chile) as co-PI, and researchers from Sejong University (Korea), National Observatory of Brazil, Institute of Earth and Space Sciences (Argentina), and Columbia University USA. The project envisions a promising new technique to discover symbiotic stars in the Local Group of Galaxies by providing a special set of narrow band filters for both GMOS-S and GMCS-N instruments. The symbiotic stars are binary systems in which a dwarf star accretes mass from a red giant companion, possibly the progenitors of one type of supernovae. In addition to funding the procurement and testing of the filters, Gemini has awarded the team with 10 hours of telescope time to demonstrate the scientific benefits of the new capability. The filters acceptance tests have been completed, commissioning is underway, and the new capability will be offered to users after November 2018.

GMOS Raman OVI Filters Upgrade
Acceptance Test Plan

Denise K. Gonçalves, Rodolfo Angeloni, Seunghee Ahn, Hans Bok
on behalf of the Raman Search for Extragalactic Symbiotic Stars (RAmESS) Team

Robert D. Osterbrock, Jorge Schmutzler
on behalf of the Gemini Instrumentation Program
RAMSES II Project

Gemini-North (Mauna Kea, Hawaii)

Gemini-South (La Serena, Chile)
RAMSES II Project - Angeloni et al. (2019)

**V1016 Cyg**

**OVI (6835 Å)**

**OVI - OVIC**

**Sanduleak’s Star**
<table>
<thead>
<tr>
<th>NGC 55</th>
<th>F1</th>
<th>GS-2012B-Q-10</th>
<th>GS-2018B-Q-219 (Korean Time)</th>
<th>2019B submitted</th>
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<td>GN-2018B-Q-211</td>
<td>GN-2018B-Q-211</td>
<td>GN-2018B-DD-103</td>
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</table>

**2018B regular CfP**  **2019A 10hr DDT**
The quantitative comparison of two Raman bands can provide detailed information including the kinematics and the density distribution of the O VI emission region.

Raman O VI features can be used to constrain the physical parameters of the H I scattering region.

Raman O VI profile analysis enable us to investigate the scattering geometry and further infer the mass-loss rates of the cool components in symbiotic systems.

By combining high-resolution spectroscopy and narrow-band imaging, it will greatly contribute to advancement of our understanding of symbiotic stars and their evolution.
THANK YOU