Accretion Flow and Raman Scattered O VI and C II Features in the Symbiotic Nova RR Telescopii

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I. Introduction
   - Symbiotic Stars
   - Raman Scattering
   - Raman Scattering in Symbiotic Stars

II. Observation
   - RR Tel
   - MIKE Spectroscopy
   - Raman Lines in RR Tel

III. Results
   - Raman O VI and Accretion Flow
   - Raman C II and Interstellar Extinction

IV. Summary
✓ **Symbiotic Stars**

- Wide binary systems consisting of a hot radiation source, usually a white dwarf, and a cool mass losing giant
- A fraction of the slow stellar wind from the giant is gravitationally captured by the white dwarf to presumably form an accretion disk.

SPH Simulation (Mastrodemos and Morris, 1998)
✓ **Symbiotic Stars**

- Wide binary systems consisting of a hot radiation source, usually a white dwarf, and a cool mass losing giant

- A fraction of the slow stellar wind from the giant is gravitationally captured by the white dwarf to presumably form an accretion disk. *(A progenitor of Type Ia SN)*
✓ **Symbiotic Stars**

- Present Sample: 257 (galactic) + 66 (extragalactic) 
  (Stavros et al. 2018, ApJS)

- 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:
  $10^{-4} ~ 10^{-7}$ $M_{\text{Sun/yr}}$ depending on the stellar evolution stage.
✓ **Symbiotic Stars**

- Strong nebular emission lines of H I, He II and forbidden lines of [O III], [Ne III], [Ne V] and [Fe VII]

- Absorption features and continuum of a late type giant

- Broad features at 6825 Å and 7082 Å
✓ **6825 & 7082 Å Bands**

- Strong nebular emission lines of H I, He II and forbidden lines of [O III], [Ne III], [Ne V] and [Fe VII]

- Absorption features and continuum of a late type giant

- **Broad features at 6825 Å and 7082 Å**
✓ Raman Scattering

- Raman-scattering by H I
  O VI λ1032 Å → **Raman O VI at 6825 Å**
  O VI λ1038 Å → **Raman O VI at 7082 Å**

- Based on the principle of energy conservation
  \[ h\nu_i = h\nu_o + h\nu_\alpha \]

- The re-emitted photon has a significantly longer wavelength than the incident one.
  \[ \lambda_o = \frac{\lambda_{Ly\alpha}\lambda_i}{\lambda_{Ly\alpha} - \lambda_i} \quad (\lambda_{Ly\alpha} = 1215.67\text{Å}) \]

![Diagram showing Raman scattering and energy transitions for O VI and H I](image-url)
✓ **Raman Scattering**

- The Raman-scattering cross section for O VI:
  \[ \sigma \approx 10^{-22} \text{ cm}^2 \text{ for O VI} \]

- It requires a thick neutral component with \( N_{\text{HI}} \approx 10^{22} \text{ cm}^{-2} \) that is illuminated by a very strong far-UV emission source.
✓ Raman Scattering in Symbiotic Stars

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The environment of symbiotic stars is ideal for the operation of Raman scattering.
✓ Raman Scattering in Symbiotic Stars

Harries & Howarth 1996
RR Telescopii

- D(Dusty)-type symbiotic nova: a Mira variable + a WD (Whitelock 2003)

- After a nova-like outburst in 1944, its brightness is slowly fading from its peak $V \sim 7$ mag in 1946 to $V \sim 11.5$ mag in 2017.

- Raman O VI features with double-peaked profiles (Schild & Schmid 1992)

  Raman He II features at 4850 and 4332 Å (van Groningen 1993)
MIKE High Resolution Spectroscopy

- 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 ~ 27,000 (Red) R~ 35,500
- Observing Date: 26, July, 2017
- Exposure Time: 2,400 sec
✓ Raman Lines in RR Tel

- We find broad features at 6825, 7025, 7052 and 7082 Å, which are formed through Raman-scattering of O VI and C II by H I.

MIKE spectrum of RR Tel exhibiting Raman O VI and C II features
✓ Raman O VI Features in RR Tel

![Graphs showing Raman O VI features in RR Tel](image)

**O VI**

- $2S \rightarrow 2P$
- $P_{1/2}, P_{3/2}$

**H I**

- $3S \rightarrow 2S$
- $1S \rightarrow 2S$
- Raman 7082
- O VI 1032, 1038
- O VI 6825

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Cheongsong, Korea
Oct. 10, 2018
Raman O VI Features and Accretion Flow

The inelasticity of Raman-scattering requires that the Raman profiles reflect only the relative kinematics between the emission region and the scattering region, irrespective of the observer’s sightline.

Schematic model of RR Tel. The O VI emission region is assumed to constitute a part of the accretion disk with asymmetric density distribution.
- Keplerian accretion disk model with $v_{\text{min}} \sim 30$ km/s, which corresponds to a physical size of the disk $\sim 1$AU

- Giant wind terminal velocity $v \sim 10$ km/s

- Mass loss rate $\dot{M} \sim 2 \times 10^{-6} M_\odot/\text{yr}$
Raman C II Features in RR Tel

\[ \text{Flux} \times 10^{-14} \text{ erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1} \]

\[ \lambda \ [\text{Å}] \]

Raman C II 7025
Raman C II 7052

C II

\( 2S \)

\( 2P \)

\( P_{3/2} \)

\( P_{1/2} \)

\( 2S^2 \ 2P^1 \)

\( 2S \ 2P^2 \)

H I

\( 3S \)

\( 2S \)

\( 1S \)

C II 1036
C II 1037
C II 1037
C II 1036

Raman 7025
Raman 7052

Oct. 10, 2018
✓ **Raman C II Features in RR Tel**

![Graph showing Raman C II features]

**Raman Conversion Efficiency for C II ~ 5%**

\[
F_{\text{exp}}(1036) = 5.78 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1} \\
F_{\text{exp}}(1037) = 5.78 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}
\]
Comparison with FUSE data

- Significant fluxes of C II $\lambda\lambda$ 1036 and 1037 are expected, from our Monte Carlo analysis of the observed Raman-scattered C II features.

$$F_{\text{exp}}(1036) = 5.78 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$$

$$F_{\text{exp}}(1037) = 5.78 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$$

- These far UV lines are absent in the FUSE data.

- Because the C II emissions originate from the ground states consisting two fine structures, they are subject to heavy interstellar extinction.
C II 1335 Multiplet in IUE Spectrum

- \(2s2p^2 \ 2D \rightarrow 2s2p \ 2P^0: 1334.53, 1335.66 \) and 1335.71Å

\[ F_{\text{obs}}(1335) = 6.58 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1} \]

\[ F_{\text{obs}}(1336) = 2.20 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1} \]
✓ C II 1335 Multiplet

- $2s2p^2 \, ^2D - 2s^22p \, ^2P^0$: 1334.53 Å, 1335.66 and 1335.71 Å

CLOUDY Calculation

$F(1335)/F(1036) \approx 1.2$

$F_{exp}(1335) = 6.58 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$
- $2s^2 2p^2 2D \rightarrow 2s^2 2p^2 2P^0$: 1334.53, 1335.66 and 1335.71 Å

CLOUDY Calculation
$F(1336)/F(1037) \approx 3.8$

$F_{exp}(1336) = 2.20 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$
C II 1335 Multiplet

\[ C II \]

\[ 2S_{1/2} \]

\[ 2D_{5/2} \]

\[ 2D_{3/2} \]

\[ 1036.34 \text{ Å} \]

\[ 1037.02 \text{ Å} \]

\[ 1335 \text{ triplet} \]

\[ F_{\text{obs}}(1335) \sim F_{\text{exp}}(1335)/150 \]

\[ F_{\text{obs}}(1336) \sim F_{\text{exp}}(1336)/307 \]
Optical Depth of C II Emissions

\[ \tau = \ln \left( \frac{F_{\text{int}}}{F_{\text{obs}}} \right) \]

- \( F_{\text{obs}}(1335) \sim \frac{F_{\text{exp}}(1335)}{150} \)
  - \( \tau(1335) \sim 5.01 \)
- \( F_{\text{obs}}(1336) \sim \frac{F_{\text{exp}}(1336)}{307} \)
  - \( \tau(1336) \sim 5.73 \)
Optical Depth of C II Emissions

Optically thick ISM for C II 1036 and 1037

$\tau(1335) \sim 5.01$

$\tau(1336) \sim 5.73$

$\tau(1036) = \frac{A(1036)}{A(1335)} \times \tau(1335)$

$\tau(1036) \sim 15.5$

$\tau(1037) = \frac{A(1037)}{A(1336)} \times \tau(1336)$

$\tau(1037) \sim 25.2$
✓ **C II and Interstellar Extinction**

- With the adopted optical depths of C II lines, we estimate the C II column density $N(\text{C II})$ of ISM.
  
- $N(\text{CII}) > 7.0 \times 10^{13} \text{cm}^{-2}$
  
- $N(\text{CII}) = 2.45 \times 10^{14} \text{cm}^{-2}$ (Roy et al. 2017)
✓ We find Raman-scattered features of O VI and C II in the high-resolution spectrum of the symbiotic nova RR Tel.

✓ The Raman O VI profiles are well fit by assuming an O VI emission region that traces the accretion flow around the white dwarf with a representative scale of 1 AU. Considering the STB ionization front, we propose the mass loss rate, $\dot{M} \sim 2 \times 10^{-6} \ M_\odot/yr$.

✓ By combining the data from FUSE, IUE and optical Raman C II data, we deduce the optical depths of far UV C II $\lambda\lambda1036/1037$ doublet and C II 1335 triplet to set a lower bound of the C II column density $N(CII) > 7.0 \times 10^{13} \text{cm}^{-2}$ toward RR Tel.
THANKS