MIKE High Resolution Observation and Raman-scattering by Atomic Hydrogen in the Symbiotic Nova RR Telescopii

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I. Introduction
   - [C II] 158 μm
   - C II 1036, 1037 Doublet
   - Raman-Scattered C II Lines

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

III. Raman C II and ISM
   - Incident C II 1036, 1037 Emissions
   - C II 1335 Triplet
   - Optical Depth of C II Emissions
   - Extinction of ISM

IV. Summary and Discussion
I. Introduction

✓ [C II] 158 μm and ISM

- $2P_{3/2} - 2P_{1/2} : 157.74 \, \mu m$
- In cold regions, cooling is dominated by collisional excitation of C+ by collisions with other particles (e.g., H or free electrons and protons).
- An efficient and dominating coolant for neutral gas
- Powerful spectral diagnostics of ISM

$T^* \Delta E/k = 91.25\, K$

[C II] 157.74 μm
I. Introduction

✓ C II 1036, 1037 Doublet

- $2S\ 2P^2\ ^2S_{1/2} \rightarrow 2S^2\ 2P^1\ ^2P_{1/2} : 1036.337\ \text{Å}$
- $2S\ 2P^2\ ^2S_{1/2} \rightarrow 2S^2\ 2P^1\ ^2P_{3/2} : 1037.018\ \text{Å}$
✓ C II 1036, 1037 Doublet

- The CII 1036, 1037 photons are incident on H I in the ground state to excite them in an intermediate level.
I. Introduction

✓ Raman-scattered C II Lines

- The H I de-excite to 2S level with re-emission of an optical photon with center wavelength at 7025 and 7052, respectively.
- \( \text{C II 1036} \rightarrow \text{Raman scattering by H I} \rightarrow \text{Raman C II at 7023.24 Å} \)
- \( \text{C II 1037} \rightarrow \text{Raman scattering by H I} \rightarrow \text{Raman C II at 7053.30 Å} \)
I. Introduction

✓ Raman-scattered C II Lines
  - Only detected in the symbiotic nova V1016 Cyg (Schild & Schmid, 1996)

Fig. 6. C II Raman features in the spectrum of V 1016 Cyg obtained in September 1994.
II. Observation

✓ RR Telescopii

- D(Dusty)-type symbiotic nova consisting of a Mira variable and a white dwarf (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.
- Distance $\sim 2.6$ kpc (Schmid & Schild 2002)

Basic Parameters for RR Tel
(Feast et al. 1983; Mürset & Schmid 1999; Gromadzki et al. 2009)

Gromadzki et al. (2009)
II. Observation

✓ **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: 30, July, 2016
  - Exposure Time: 2000 sec
II. Observation

✓ Raman-scattered C II Lines in RR Tel

Raman C II

\[ F(\text{Raman 7023}) \]
\[ 6.01 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1} \]

\[ F(\text{Raman 7053}) \]
\[ 6.74 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1} \]
III. Raman C II and ISM

✓ Incident Far-UV C II 1036,1037 Emissions

Incident C II

Raman C II
- $F(\text{Raman 7023}) = 6.01 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$
- $F(\text{Raman 7053}) = 6.74 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$

Raman Conversion Efficiencies
III. Raman C II and ISM

✓ Incident Far-UV C II 1036,1037 Emissions

**Incident C II**

- $F_{\text{int}}(1036) = 3.15 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$
- $F_{\text{int}}(1037) = 4.19 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$

**Raman C II**

- $F(\text{Raman 7023}) = 6.01 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$
- $F(\text{Raman 7053}) = 6.74 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$

**Raman Conversion Efficiencies**

- $\eta(1036\rightarrow7023) = 0.12$
- $\eta(1037\rightarrow7053) = 0.10$
III. Raman C II and ISM

✓ Comparison with FUSE data

Incident C II

\[ F_{\text{int}}(1036) = 3.15 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1} \]

\[ F_{\text{int}}(1037) = 4.19 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1} \]

✓ A significant amount of C II 1036 and 1037 Å emissions are expected, however they are clearly absent in FUSE data.
III. Raman C II and ISM

✓ C II 1335 Multiplet in IUE Spectrum
- \( 2s2p^2 \ 2D \rightarrow 2s2p^2 \ 2P^0 \): 1334.53, 1335.66 and 1335.71 Å

\[ F_{\text{obs}}(1335) = 4.43 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1} \]

\[ F_{\text{obs}}(1336) = 7.15 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1} \]
III. Raman C II and ISM

✓ C II 1335 Multiplet
- $2s2p^2 \, ^2D \rightarrow 2s^22p \, ^2P^0$: 1334.53, 1335.66 and 1335.71 Å

$$F_{ij} = F_{ik} \times \frac{\gamma_{ij}}{\gamma_{ik}}$$

$$F_{\text{int}}(1335) = F_{\text{int}}(1036) \times \frac{\gamma_{1335}}{\gamma_{1036}}$$

$$F_{\text{int}}(1336) = F_{\text{int}}(1037) \times \frac{\gamma_{1336}}{\gamma_{1037}}$$

EAYAM 2017
@ Ishigaki Island, Japan
Nov. 14, 2017
III. Raman C II and ISM

✓ C II 1335 Multiplet in IUE Spectrum

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

\[ F_{ij} = F_{ik} \times \frac{\gamma_{ij}}{\gamma_{ik}} \]

\[ F_{\text{int}(1335)} = F_{\text{int}(1036)} \times \frac{\gamma_{1335}}{\gamma_{1036}} \]
\[ 7.41 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1} \sim 167 \, F_{\text{obs}(1335)} \]

\[ F_{\text{int}(1336)} = F_{\text{int}(1037)} \times \frac{\gamma_{1336}}{\gamma_{1037}} \]
\[ 1.425 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1-11} \sim 200 \, F_{\text{obs}(1336)} \]
III. Raman C II and ISM

✓ Optical depth of C II emissions

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

\( \tau(1335) \sim 5.1 \)

\( \tau(1336) \sim 5.3 \)
III. Raman C II and ISM

✓ Optical depth of C II emissions

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

\[ \tau(1335) \approx 5.1 \]
\[ \tau(1336) \approx 5.3 \]
\[ \tau(1036) \approx 15.81 \]
\[ \tau(1037) \approx 27.24 \]
III. Raman C II and ISM

✓ Optical depth of C II emissions

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

\( \tau(1335) \sim 5.1 \)
\( \tau(1336) \sim 5.3 \)
\( \tau(1036) \sim 15.81 \)
\( \tau(1037) \sim 27.24 \)

Extremely Optically thick ISM for C II emissions

Expected Spectrum

FUSE (2002–06–14)
III. Raman C II and ISM

✓ Extinction of ISM

- Considering a long distance $d \sim 2.5\text{kpc}$ of RR Tel, it can be originated from the heavy extinction along ISM.

- The column density is expressed by the optical depth and the cross section: $N(\text{C II}) = \frac{\tau}{\sigma}$

- $N(\text{CII}) \sim 9.87 \times 10^{13}\text{cm}^{-2}$
IV. Summary and Discussion

✓ We find two Raman-scattered features of C II at 7023 and 7053 Å in the high-resolution spectrum of the symbiotic nova RR Tel.

✓ A significant amount of C II 1036 and 1037 Å emissions are expected, however they are clearly absent in FUSE data.

✓ By comparing with other observed C II emissions in IUE data, we conclude that the discrepancy between the observed data and the theoretical expectation is originated from the heavy extinction along ISM.

✓ We determine the lower limit of the column density of C II in ISM $N(C\text{II}) \sim 9.87 \times 10^{13} \text{cm}^{-2}$.
THANKS