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

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EAYAM 2017

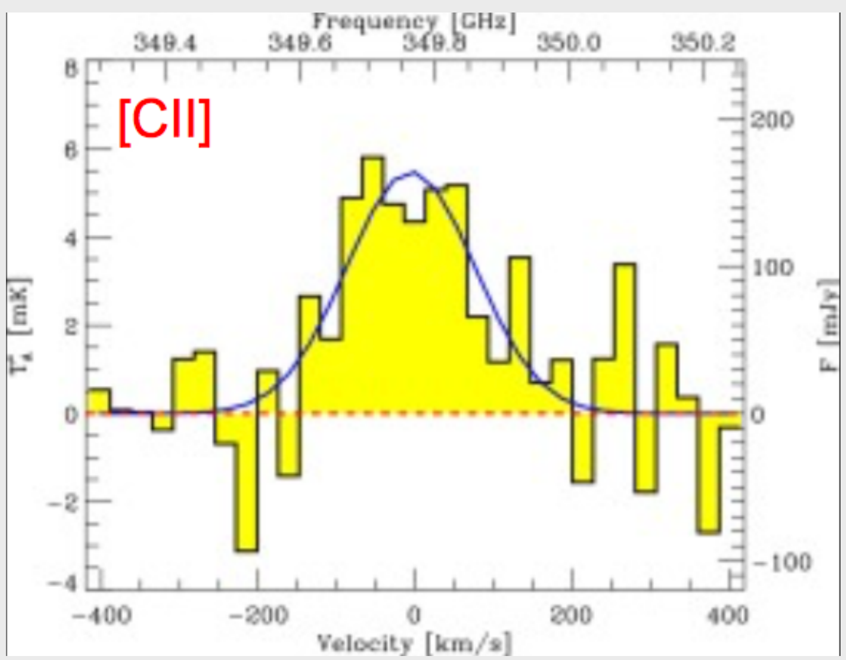
@ Ishigaki Island, Japan

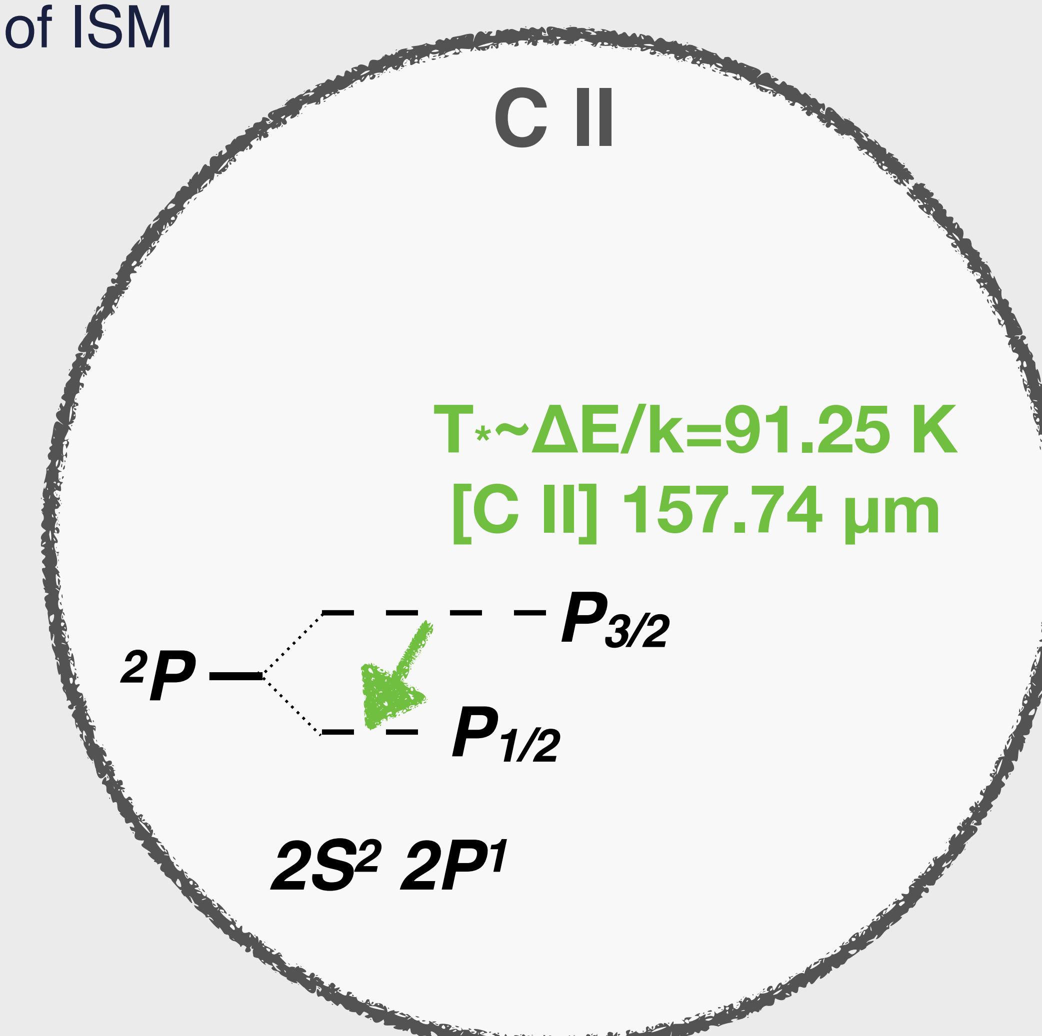
Nov. 14, 2017

I. Introduction

✓ [C II] 158 µm and ISM

- $2P_{3/2}$ — $2P_{1/2}$: **157.74 µm**
- 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

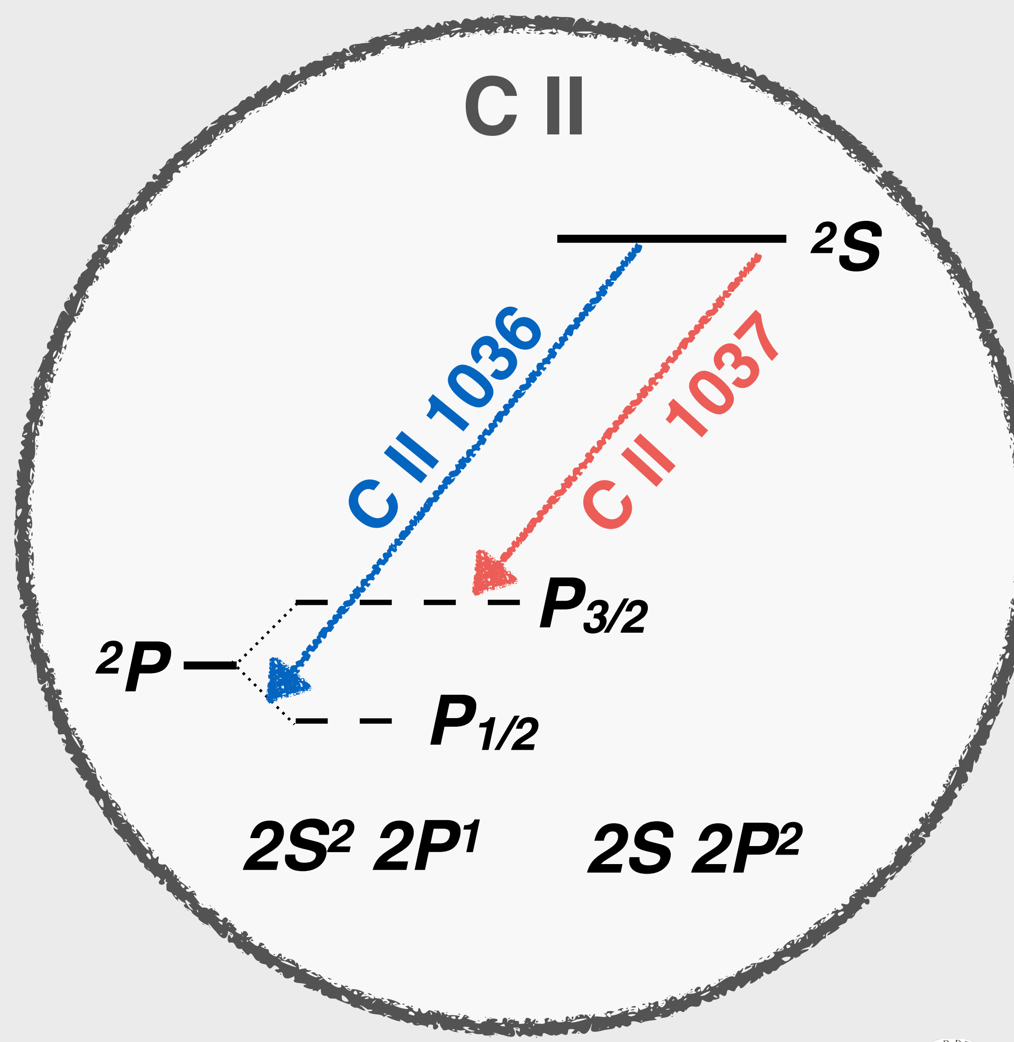




I. Introduction

✓ C II 1036, 1037 Doublet

- 2S 2P^2 $^2S_{1/2}$ — 2S^2 2P^1 $^2P^0_{1/2}$: **1036.337 Å**
- 2S 2P^2 $^2S_{1/2}$ — 2S^2 2P^1 $^2P^0_{3/2}$: **1037.018 Å**



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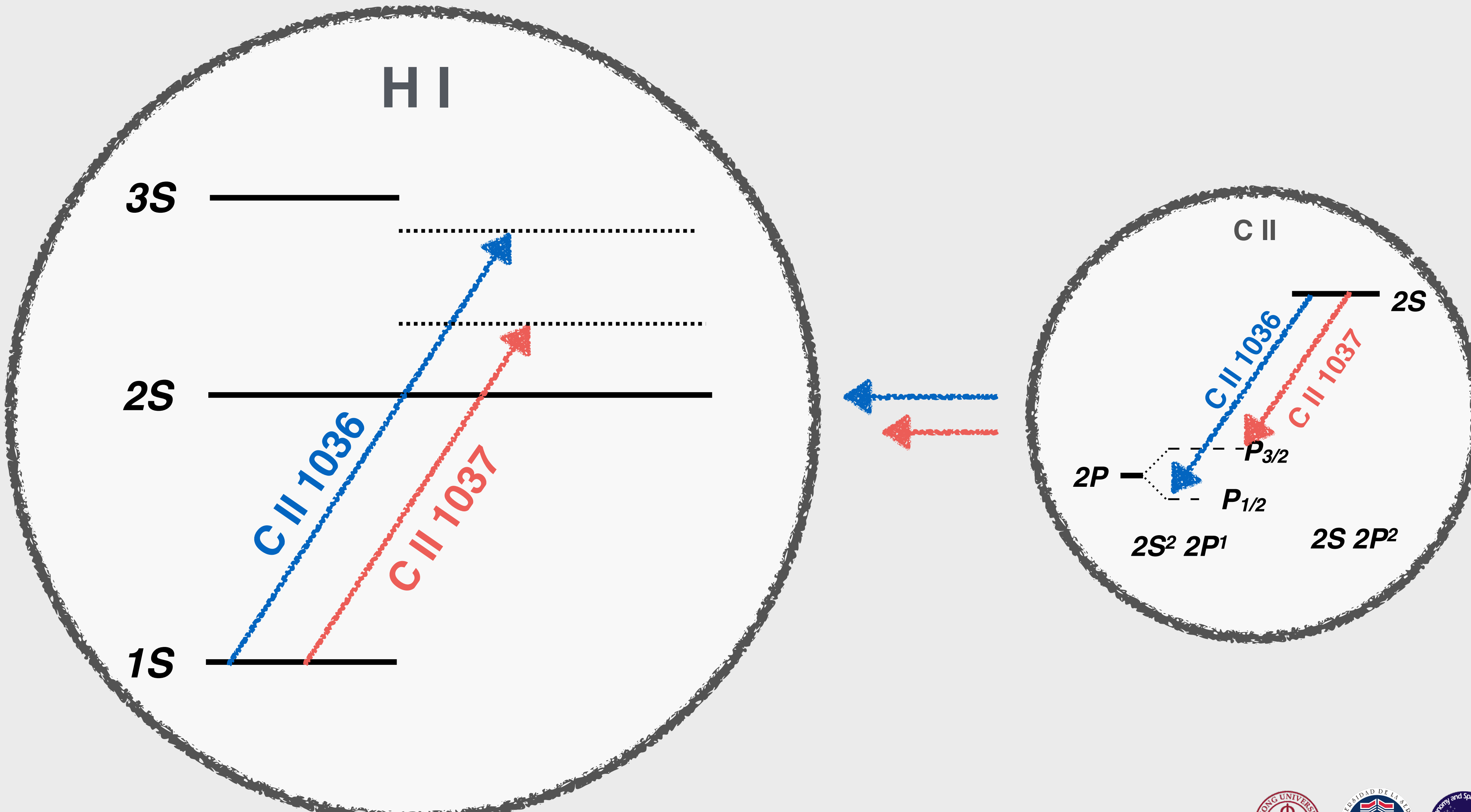
I. Introduction

✓ C II 1036, 1037 Doublet

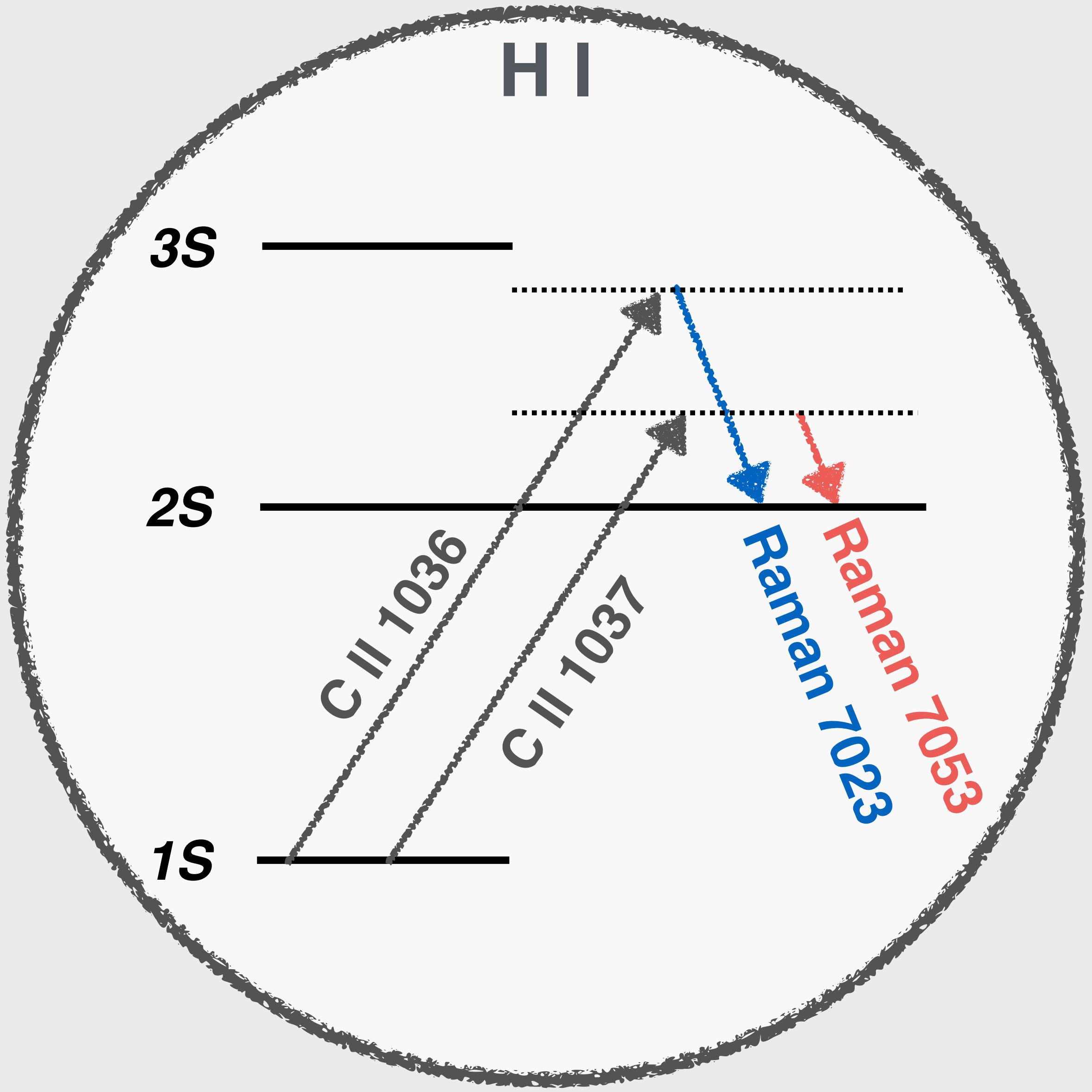
- The CII 1036, 1037 photons are incident on H I in the ground state to excite them in an intermediate level.



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.
- **C II 1036** → Raman scattering by H I → **Raman C II at 7023.24 Å**
- **C II 1037** → Raman scattering by H I → **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)

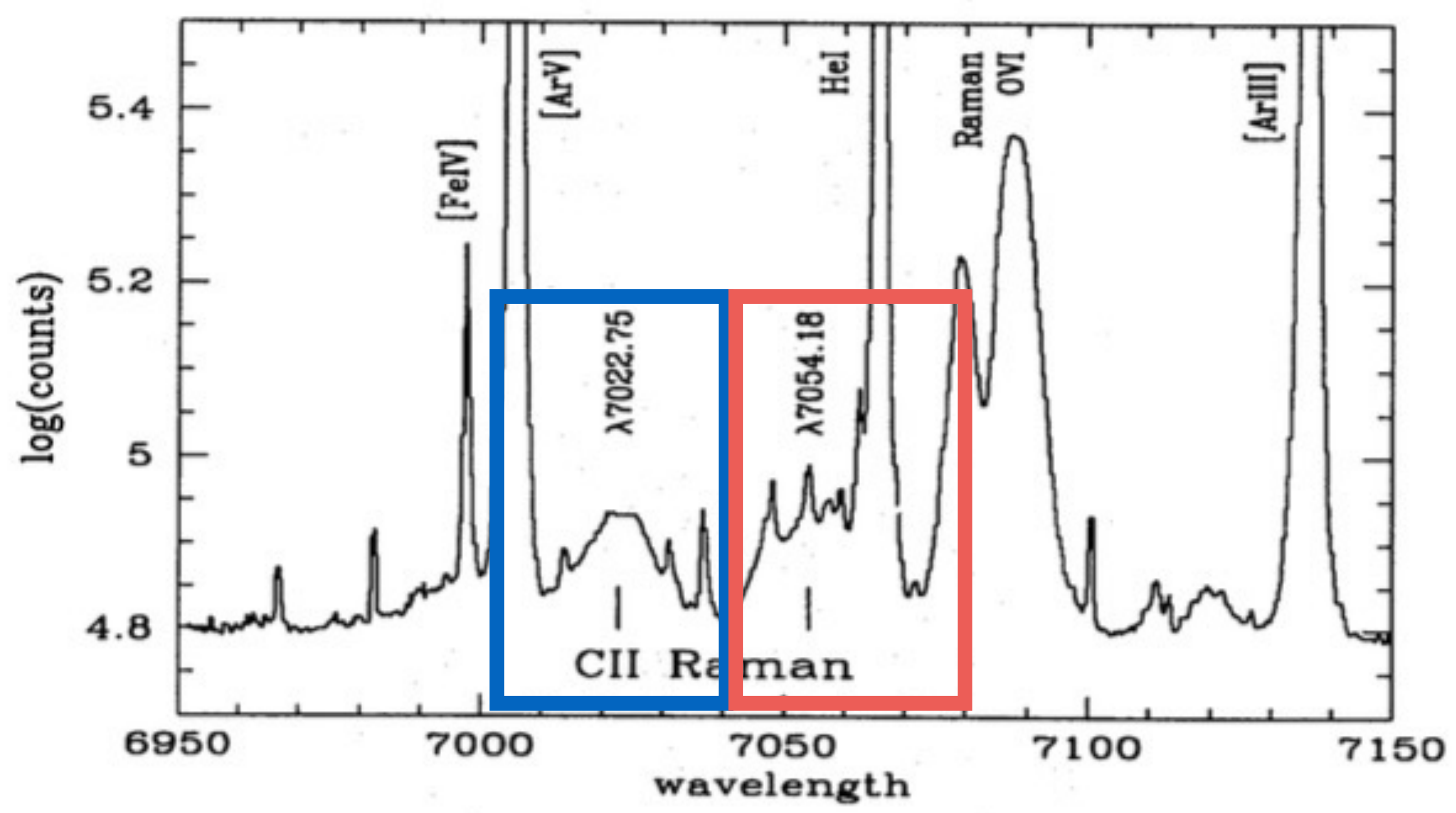


Fig. 6. C II Raman features in the spectrum of V 1016 Cyg obtained in September 1994.

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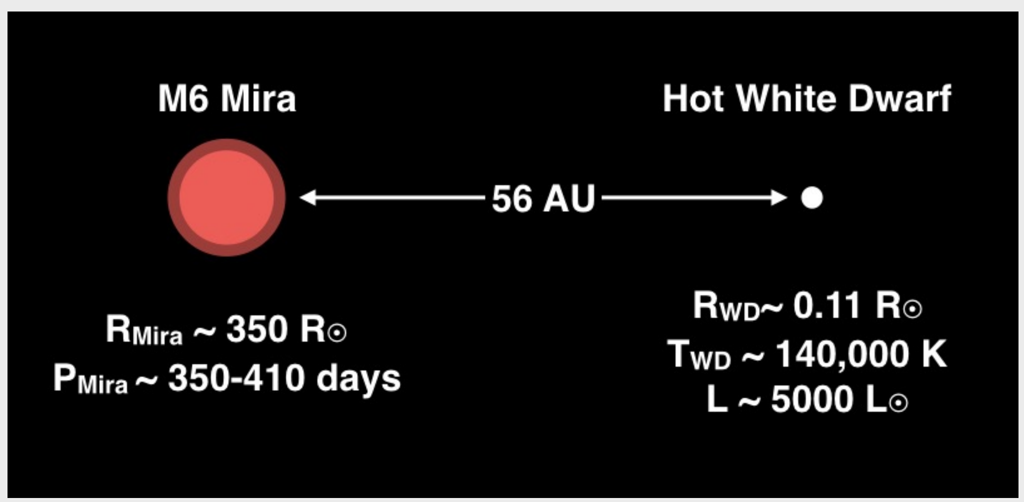
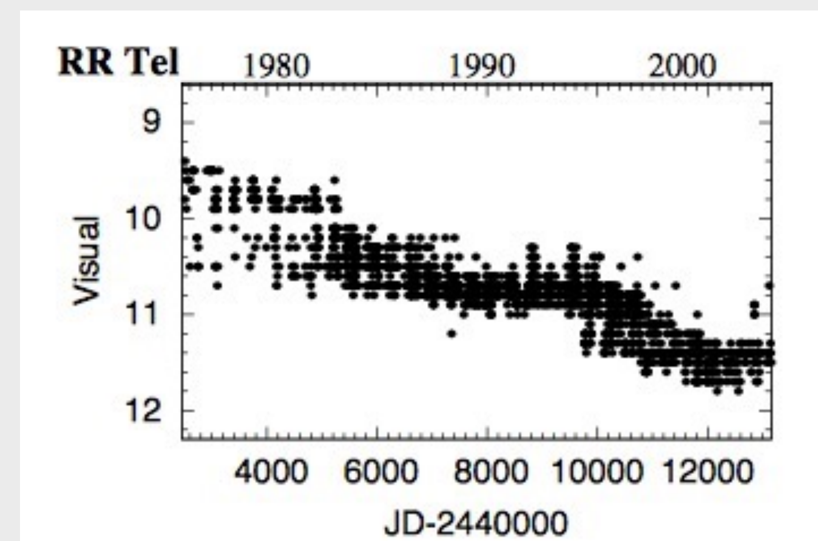
✓ RR Telescopii

- 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~7mag in 1946 to V~11.5 mag in 2017.
- Distance ~ 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)

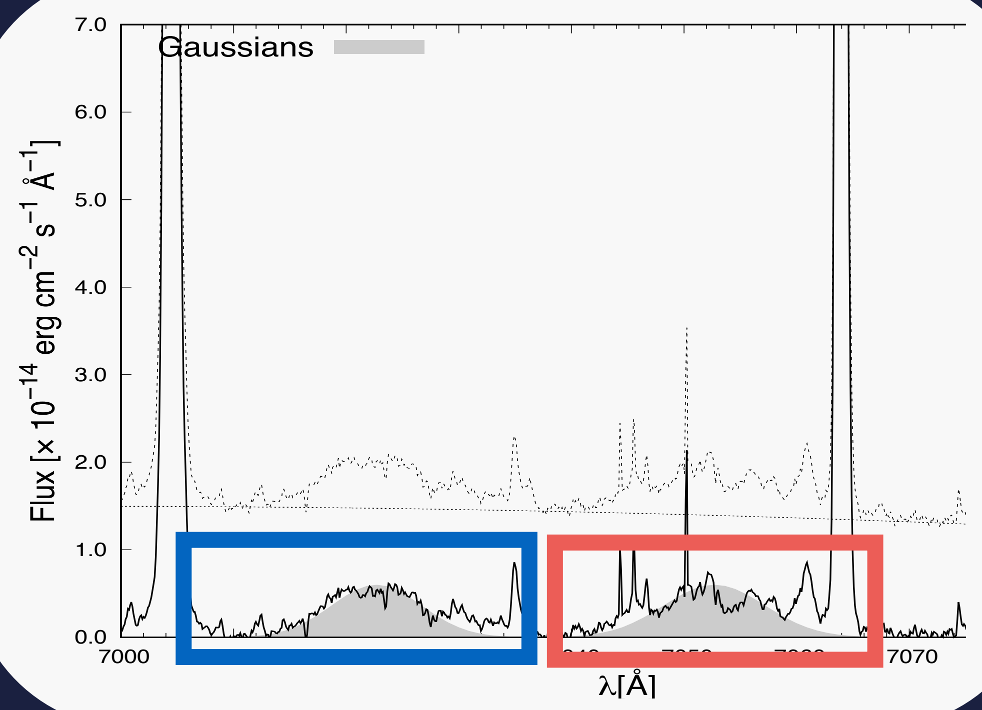
II. Observation

✓ *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(Raman 7023)
6.01×10^{-14} erg cm^{-2} s^{-1} Å^{-1}

F(Raman 7053)
6.74×10^{-14} erg cm^{-2} s^{-1} Å^{-1}

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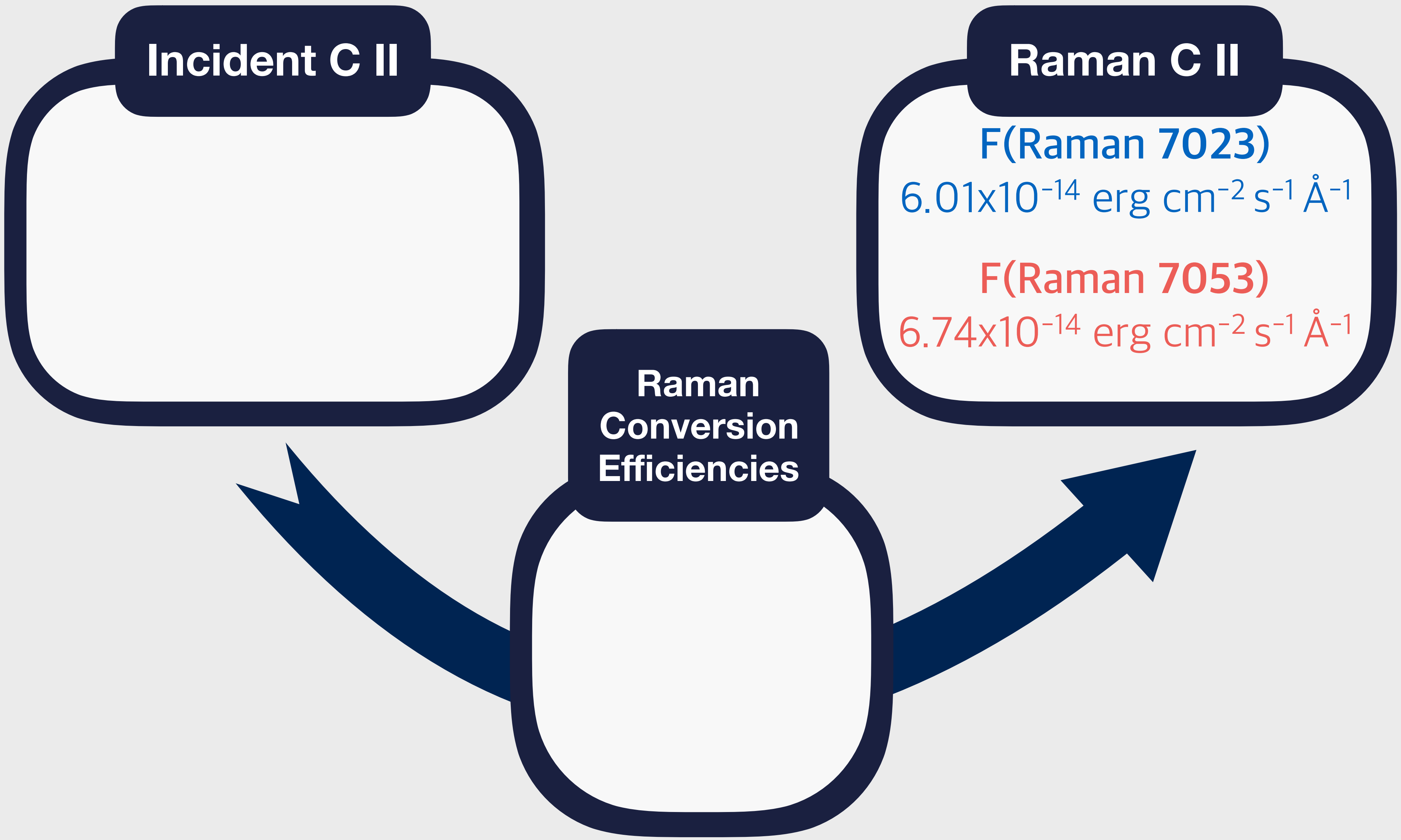
III. Raman C II and ISM

✓ Incident Far-UV C II 1036,1037 Emissions



III. Raman C II and ISM

✓ Incident Far-UV C II 1036,1037 Emissions

Incident C II

$F_{int}(1036)$

3.15×10^{-11} erg cm^{-2} s^{-1} Å^{-1}

$F_{int}(1037)$

4.19×10^{-11} erg cm^{-2} s^{-1} Å^{-1}

Raman Conversion Efficiencies

η(1036->7023)

0.12

η(1037->7053)

0.10

Raman C II

F(Raman 7023)

6.01×10^{-14} erg cm^{-2} s^{-1} Å^{-1}

F(Raman 7053)

6.74×10^{-14} erg cm^{-2} s^{-1} Å^{-1}

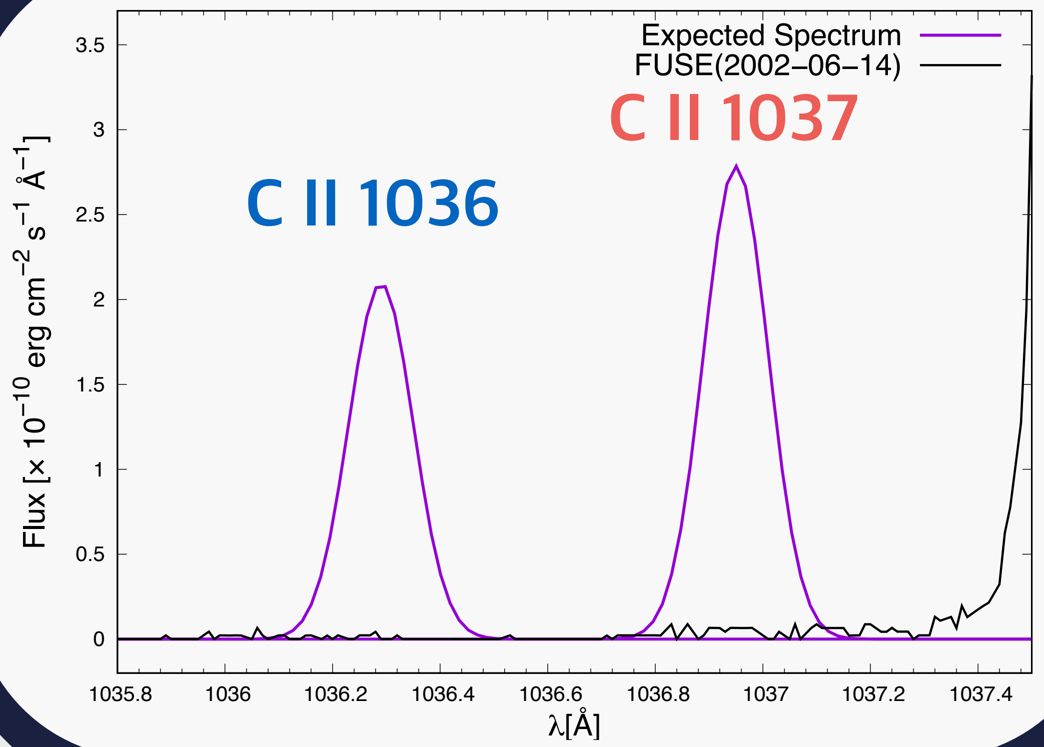
III. Raman C II and ISM

✓ Comparison with FUSE data

Incident C II

$F_{int}(1036)$
3.15×10^{-11} erg cm^{-2} s^{-1} Å^{-1}

$F_{int}(1037)$
4.19×10^{-11} erg cm^{-2} s^{-1} Å^{-1}

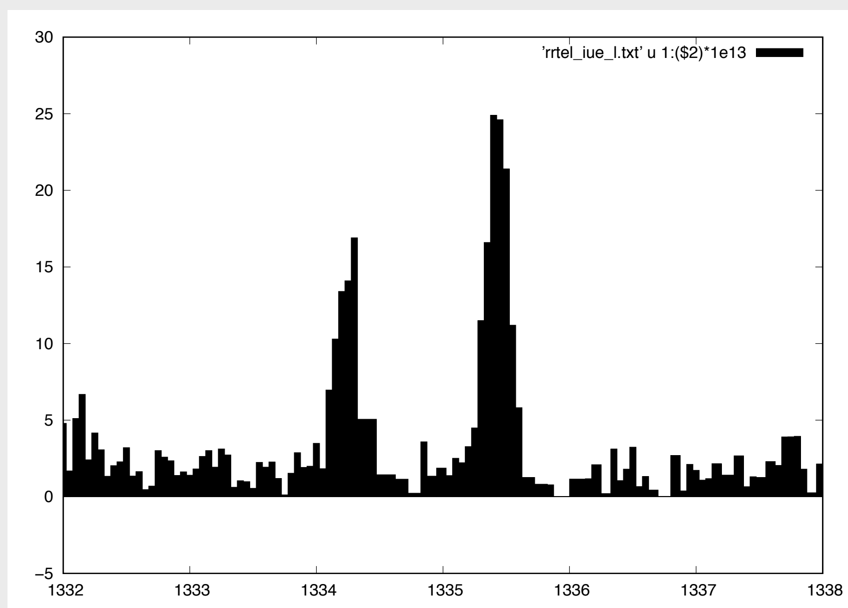


✓ A significant amount of C II 1036 and 1037 Å emissions are expected, however they are clearly absent in FUSE data.

III. Raman C II and ISM

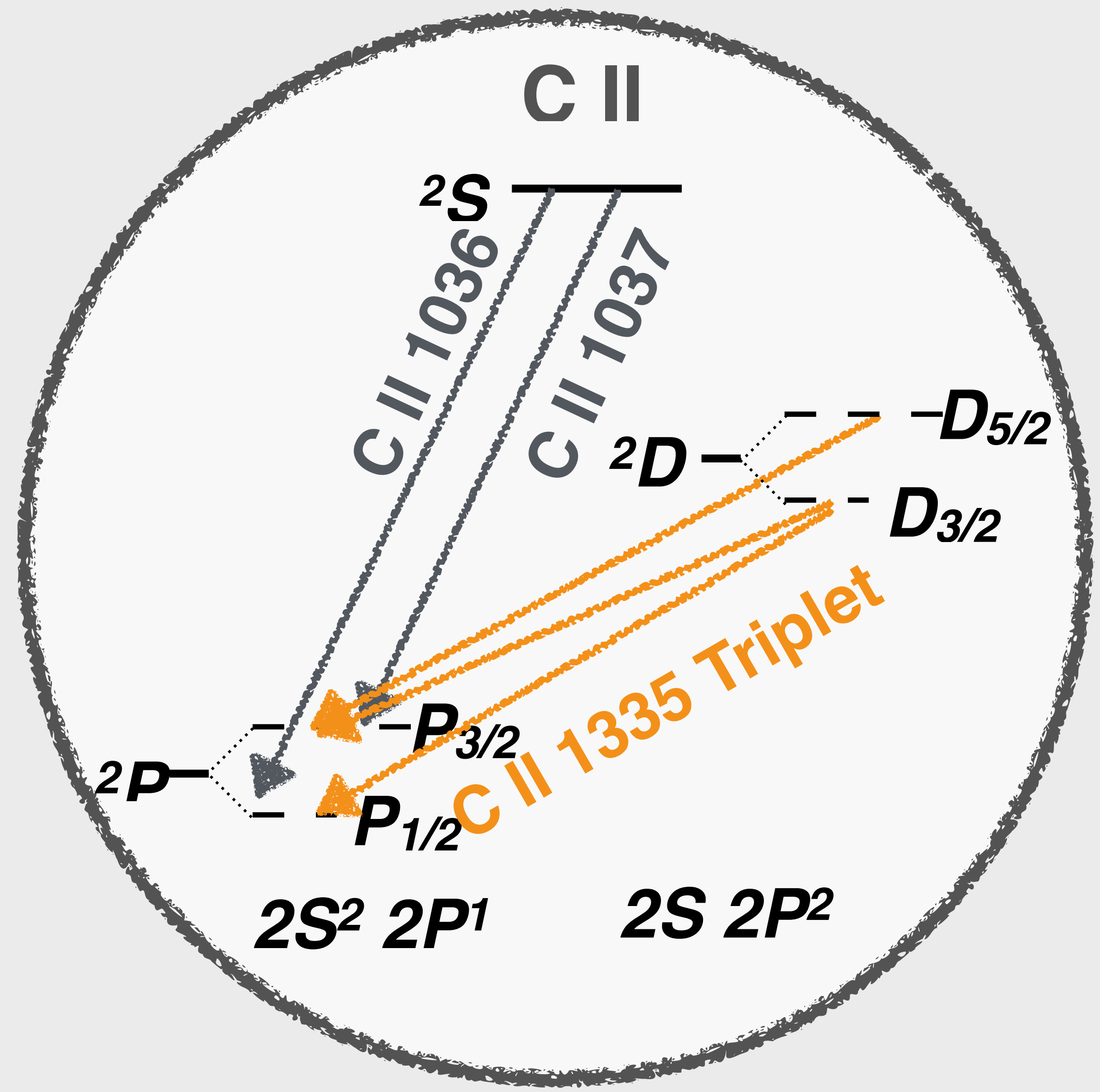
✓ C II 1335 Multiplet in IUE Spectrum

- 2s2p^2 ^{2}D — 2s^{2}2p ^{2}P^0: **1334.53, 1335.66 and 1335.71Å**



$F_{obs}(1335)$
4.43×10^{-13} erg cm^{-2} s^{-1} Å^{-1}

$F_{obs}(1336)$
7.15×10^{-13} erg cm^{-2} s^{-1} Å^{-1}



III. Raman C II and ISM

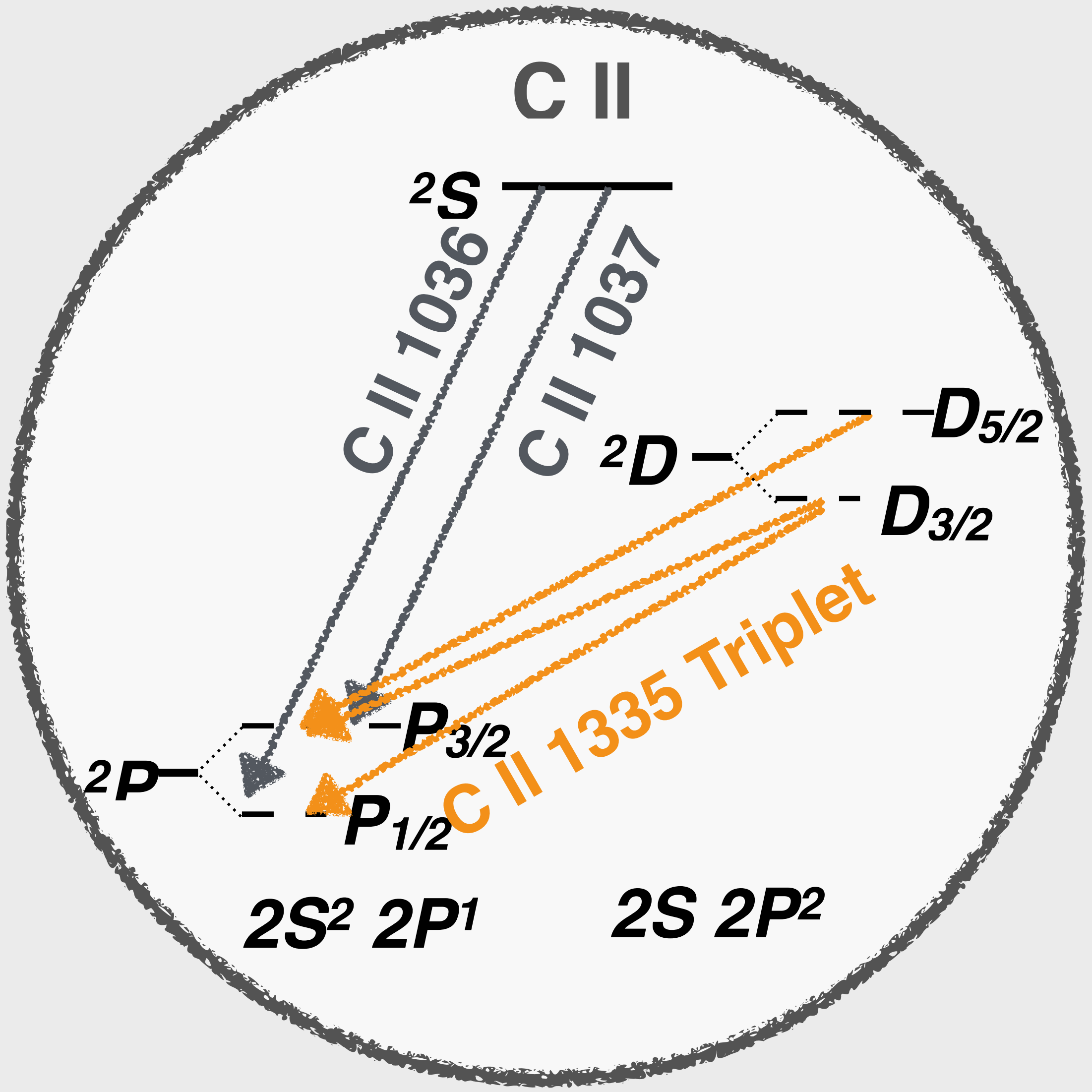
✓ C II 1335 Multiplet

- 2s2p^2 ^{2}D — 2s^{2}2p ^{2}P^0: **1334.53, 1335.66 and 1335.71Å**

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

$F_{int}(1335) = F_{int}(1036) \times \Upsilon_{1335}/\Upsilon_{1036}$

$F_{int}(1336) = F_{int}(1037) \times \Upsilon_{1336}/\Upsilon_{1037}$

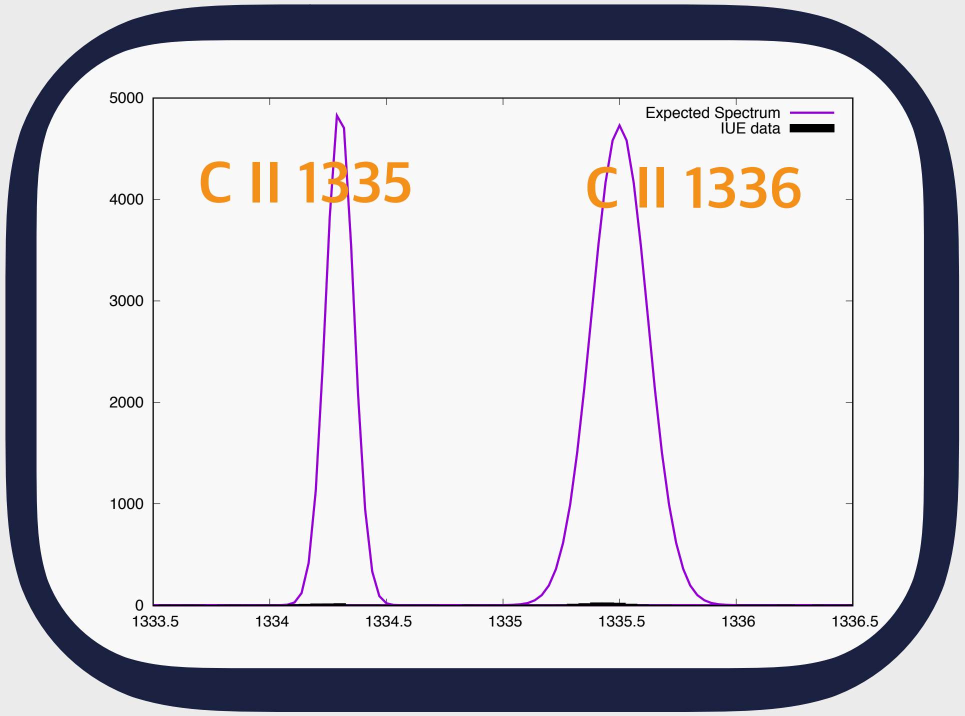


III. Raman C II and ISM

✓ C II 1335 Multiplet in IUE Spectrum

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

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



$F_{int}(1335) = F_{int}(1036) \times \Upsilon_{1335}/\Upsilon_{1036}$

7.41×10^{-11} erg cm^{-2} s^{-1} Å^{-1} **~167 $F_{obs}(1335)$**

$F_{int}(1336) = F_{int}(1037) \times \Upsilon_{1336}/\Upsilon_{1037}$

1.425×10^{-10} erg cm^{-2} s^{-1} Å^{-1-11}**~200 $F_{obs}(1336)$**

III. Raman C II and ISM

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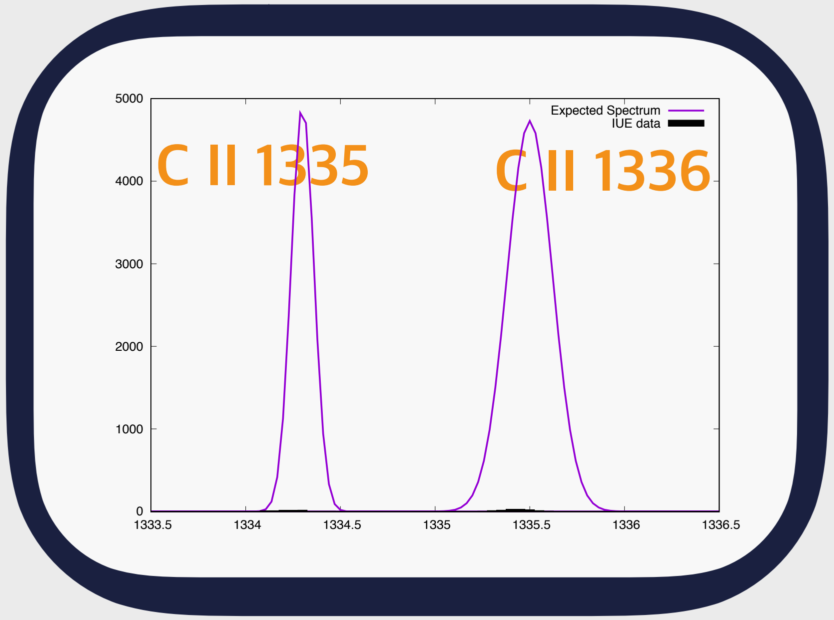
✓ Optical depth of C II emissions

$\tau = \ln(F_{int}/F_{obs})$

$\tau(1335) \sim 5.1$

$\tau(1336) \sim 5.3$



III. Raman C II and ISM

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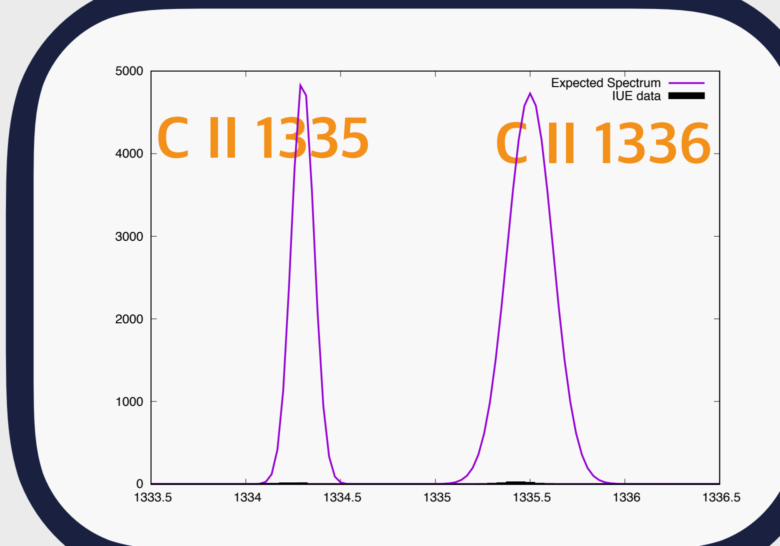
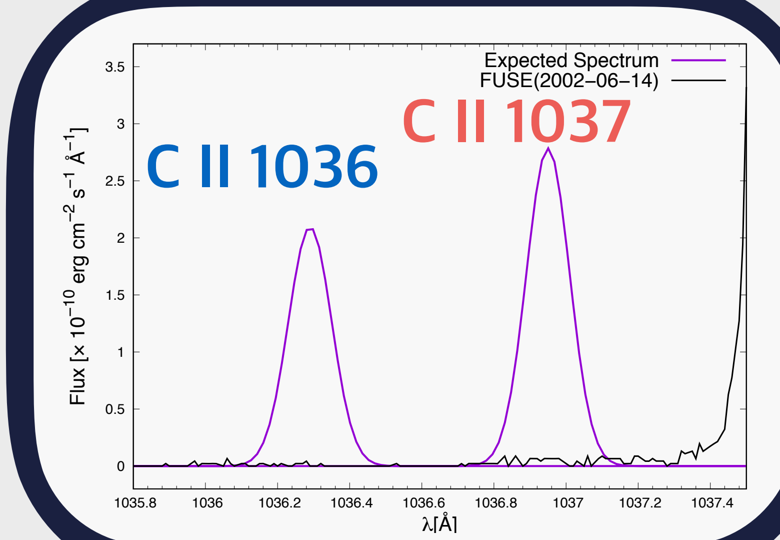


$\tau(1036) \sim 15.81$

$\tau(1037) \sim 27.24$



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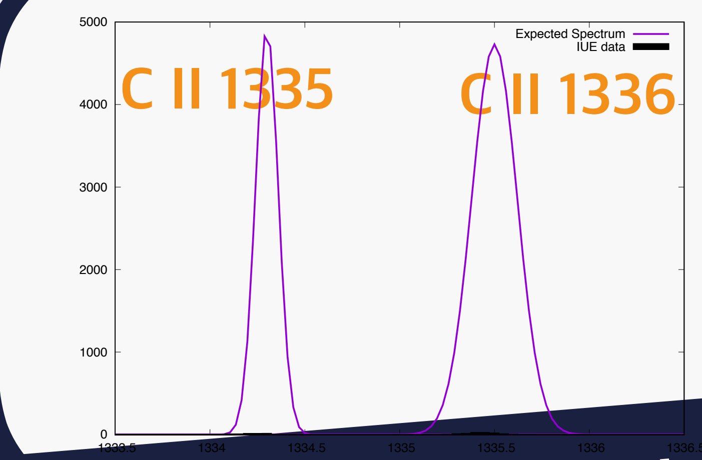
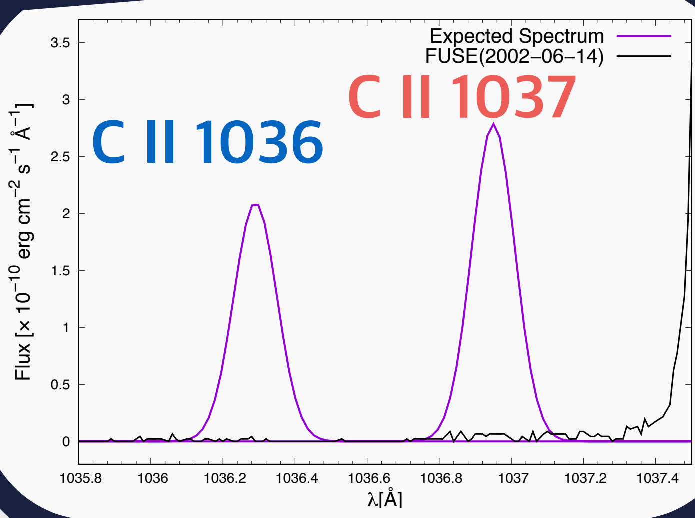


Optically thick ISM for C II emissions

$\tau(1036) \sim 15.81$

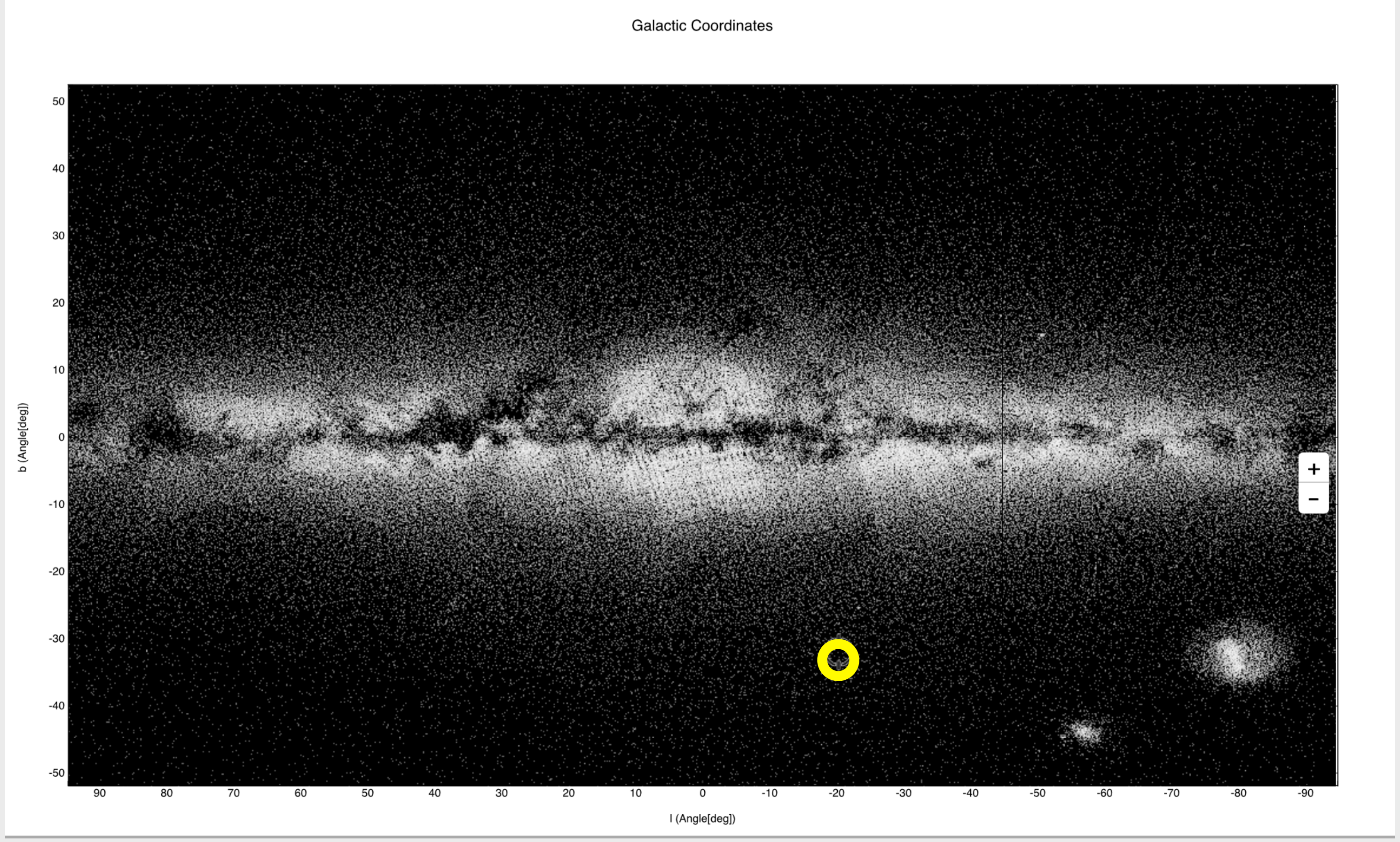
$\tau(1037) \sim 27.24$



III. Raman C II and ISM

✓ Extinction of ISM

- Considering a long distance d ~ 2.5kpc 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(C II) = τ / σ
- **N(CII) ~ 9.87×10^{13}cm^{-2}**

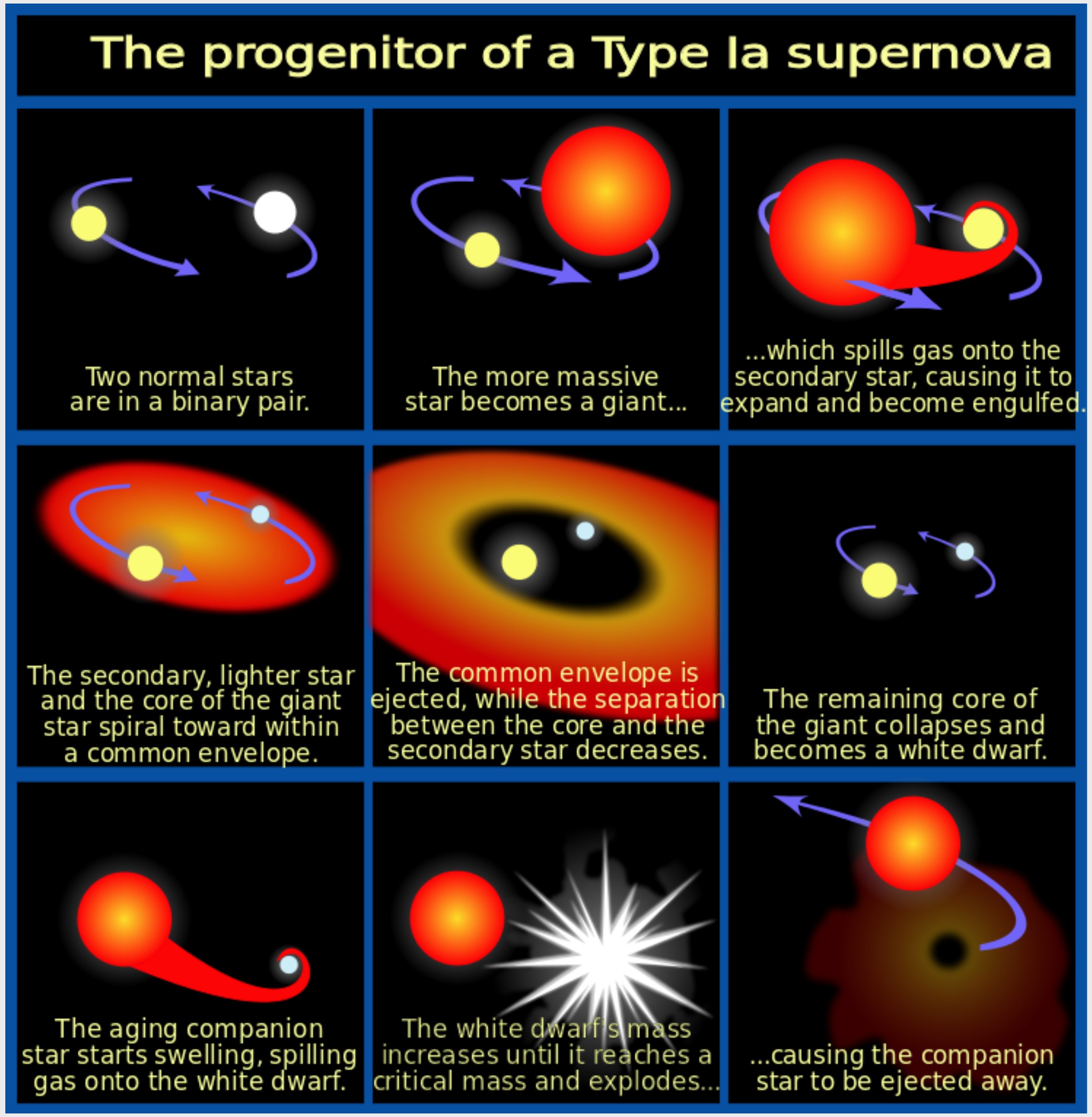


IV. Summary and Discussion

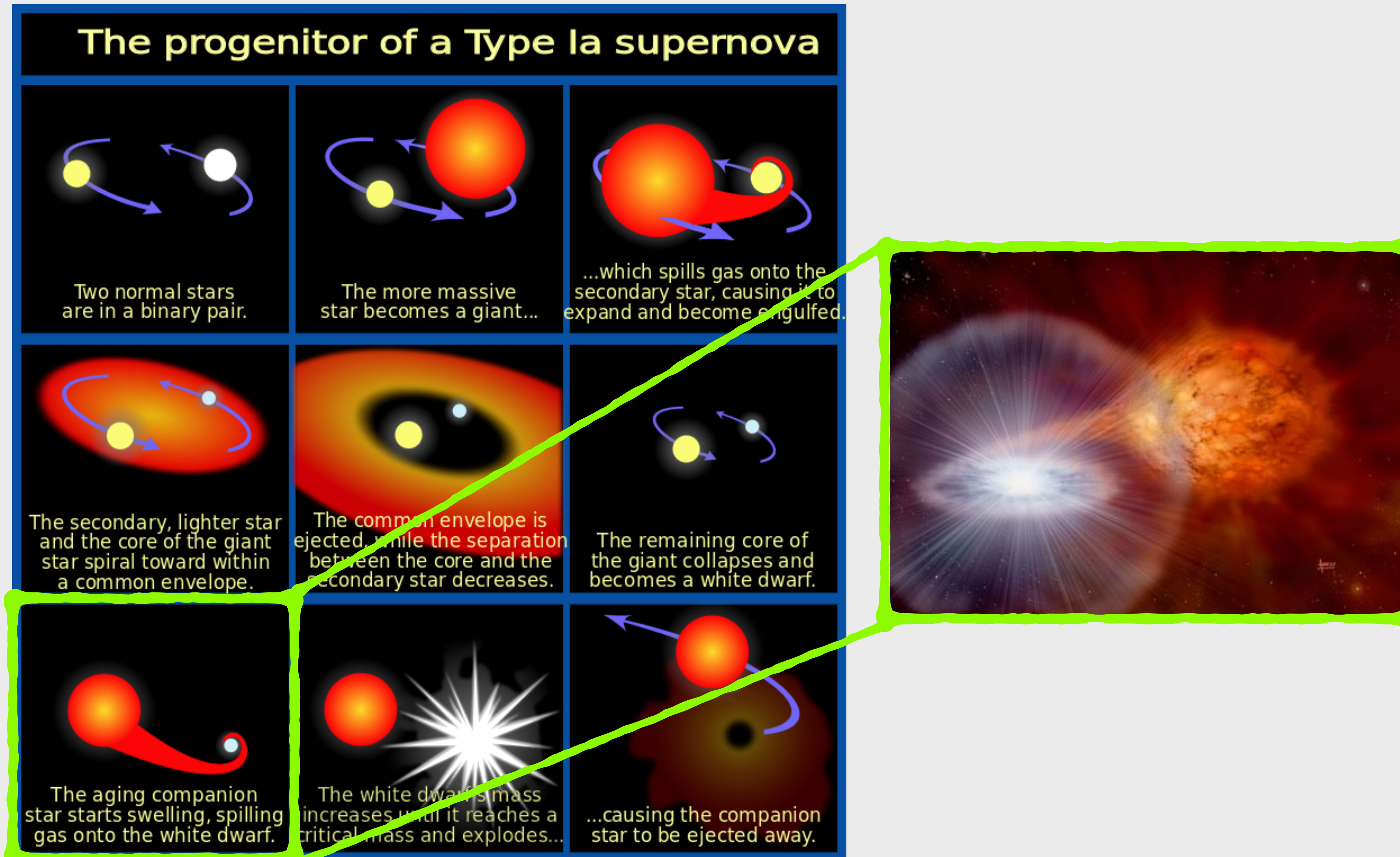
- ✓ We find two Raman-scattered features of C II at 7023 and 7053 Å in the high-resolution spectrum of the symbiotic nova RR Tel.
- ✓ A significant amount of C II 1036 and 1037 Å emissions are expected, however they are clearly absent in FUSE data.
- ✓ By comparing with other observed C II emissions 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(CII) ~ 9.87x10^{13}cm^{-2}**.

THANKS

I. Introduction



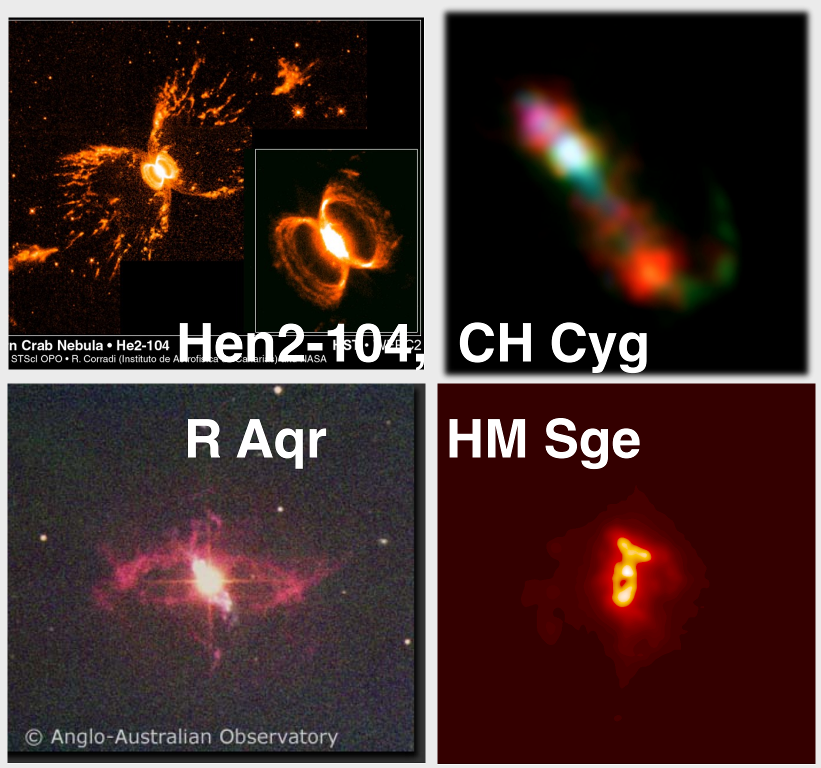
I. Introduction

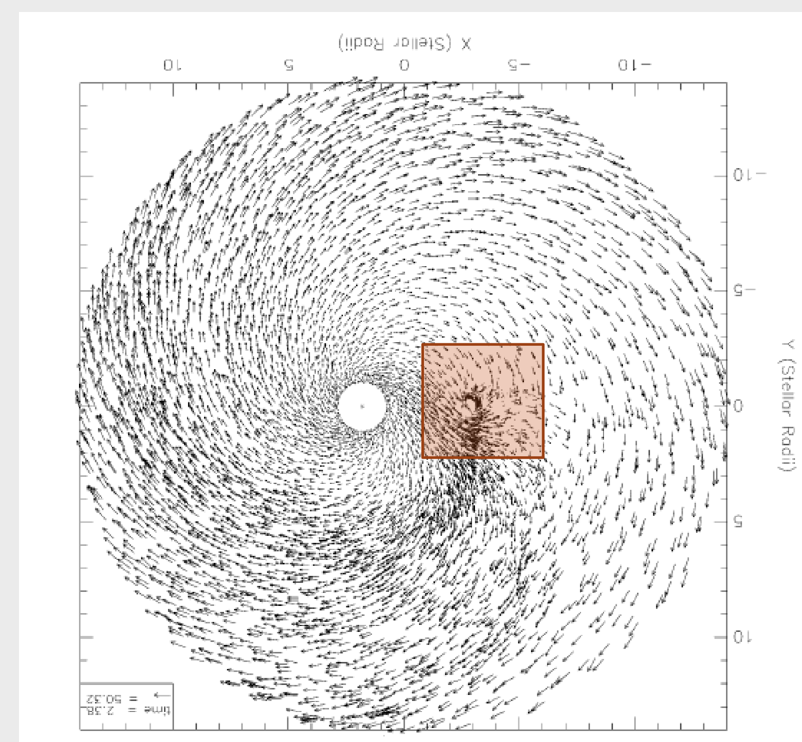


I. Introduction

✓ Symbiotic Stars

- Binary systems consisting of a hot radiation source, usually 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 presumable form an accretion disk.





SPH Simulation (Mastrodemos and Morris, 1998)

I. Introduction

✓ Raman Scattering

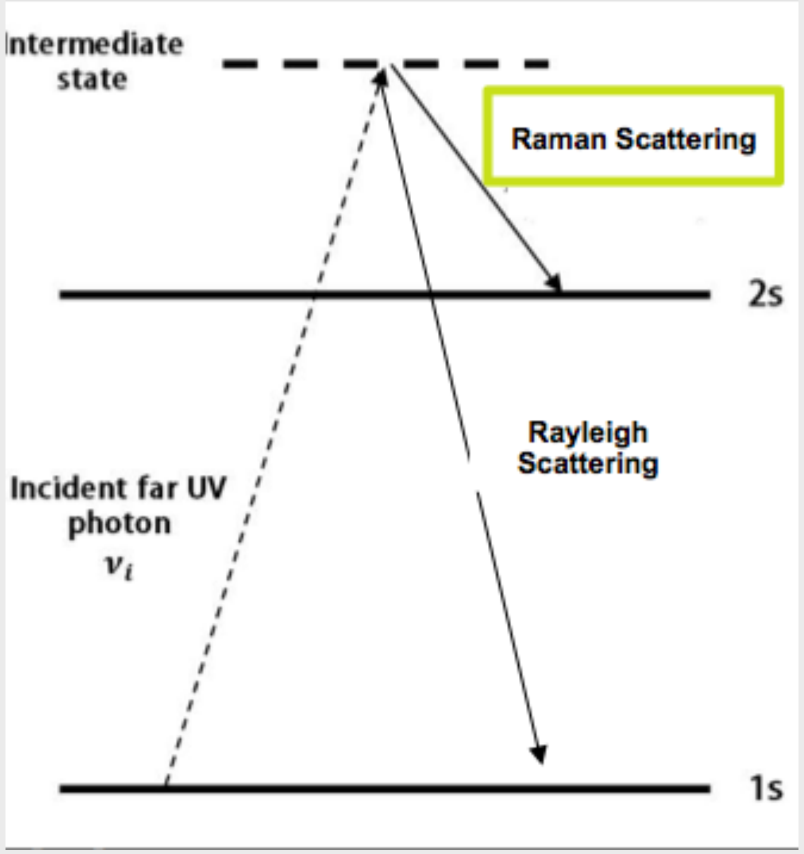
- **A far-UV photon** blueward of Lyα is incident upon a hydrogen atom in the ground state. Subsequently, the hydrogen atom de-excites into the 2s state, **re-emitting an optical Raman-scattered photon**.

- Based on the principle of Energy conservations

$$h\nu_i = h\nu_o + h\nu_\alpha$$

- **The re-emission of a photon has significantly longer wavelength than incident photon.**

$$\lambda_{RV} = \frac{\lambda_{Ly\alpha}\lambda_i}{\lambda_{Ly\alpha}-\lambda_i} \quad (\lambda_{Ly\alpha} = 1215.67Å\ )$$



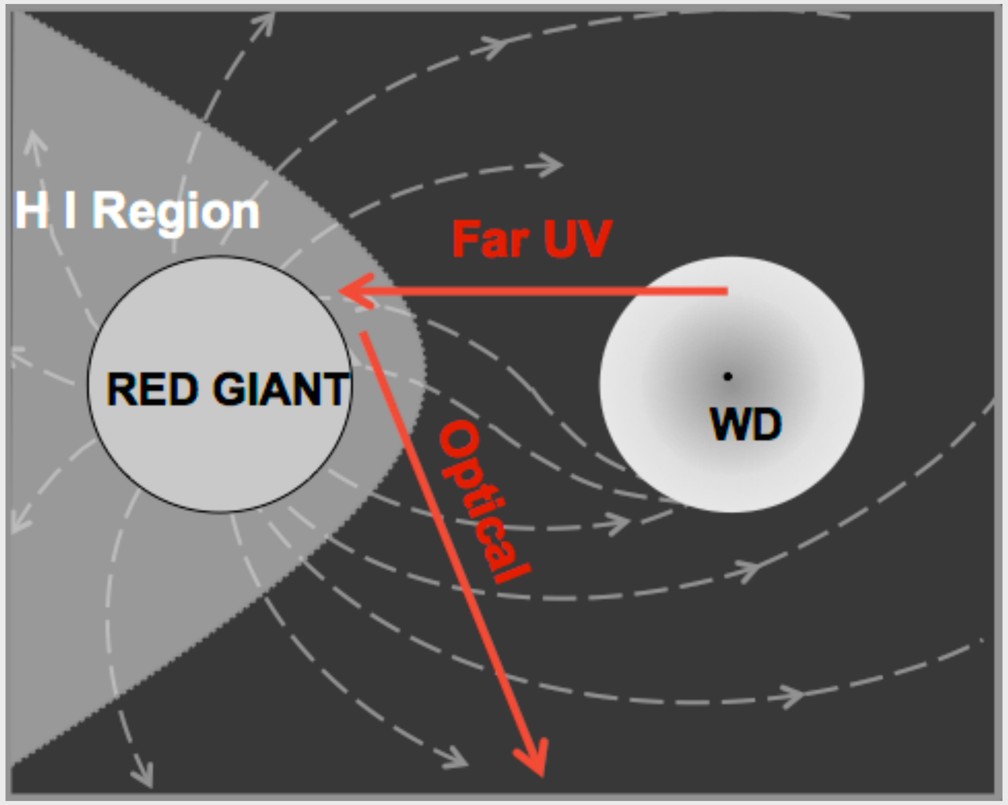
Schematic energy level diagram for Raman-Scattering by H I

Ly β 1025 (1s → 3p) → Hα 6563 (3p → 2s)

I. Introduction

✓ Raman Scattering in Symbiotic Stars

- The white dwarf accretes a fraction of the stellar wind from the giant, which makes it very hot (~10^5 K) and luminous(~10^2-10^4 L_{sun}), and thus capable of ionizing the neutral wind from the giant.



I. Introduction

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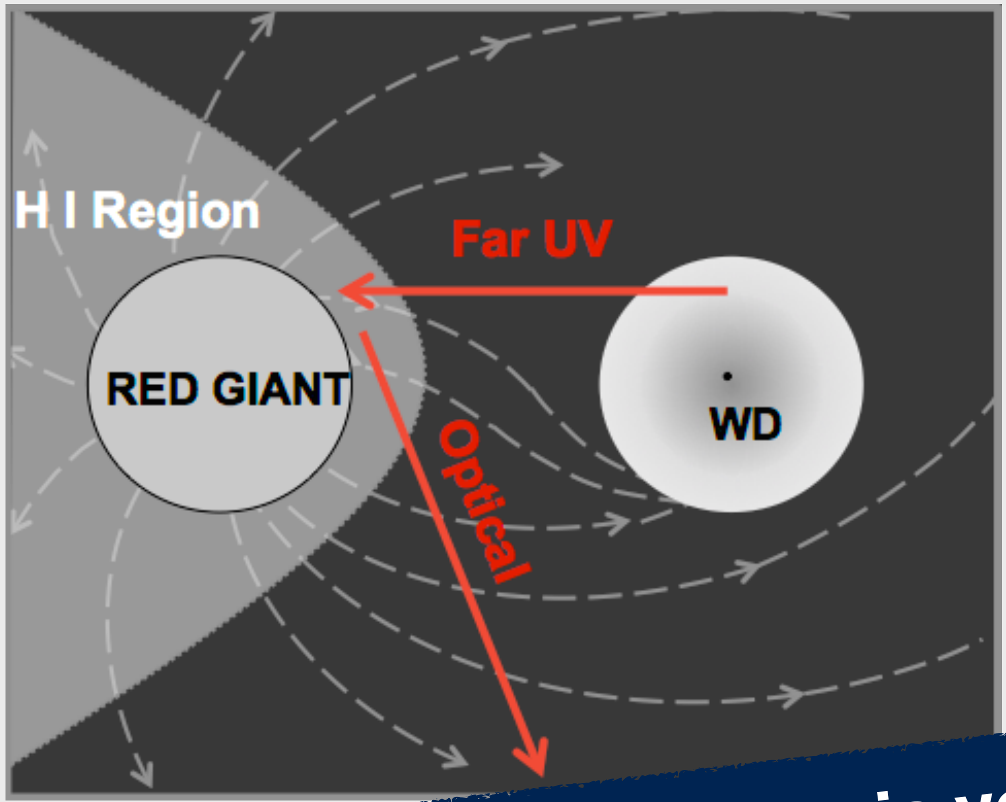

The environment of symbiotic stars is very suitable for observing the Raman-scattering process.

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II. Observation

✓ Raman Lines in RR Tel

- We find seven broad features at 4332, 4850, 6545, 6825, 7025, 7052 and 7082 Å, which are formed through Raman-scattering of He II, C II and O VI by H I.

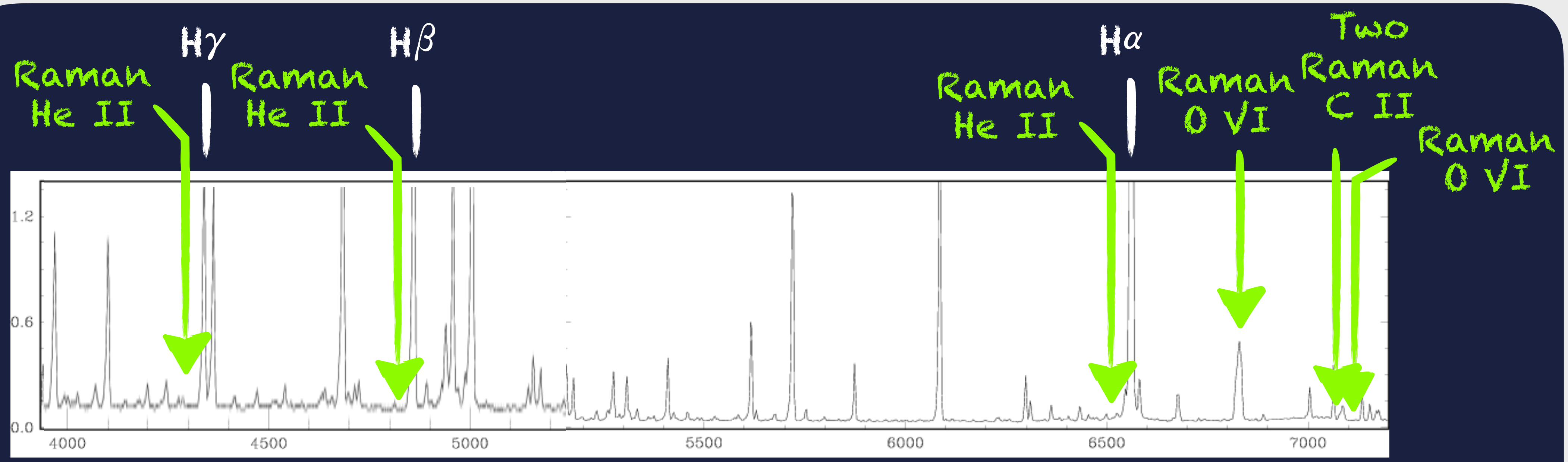
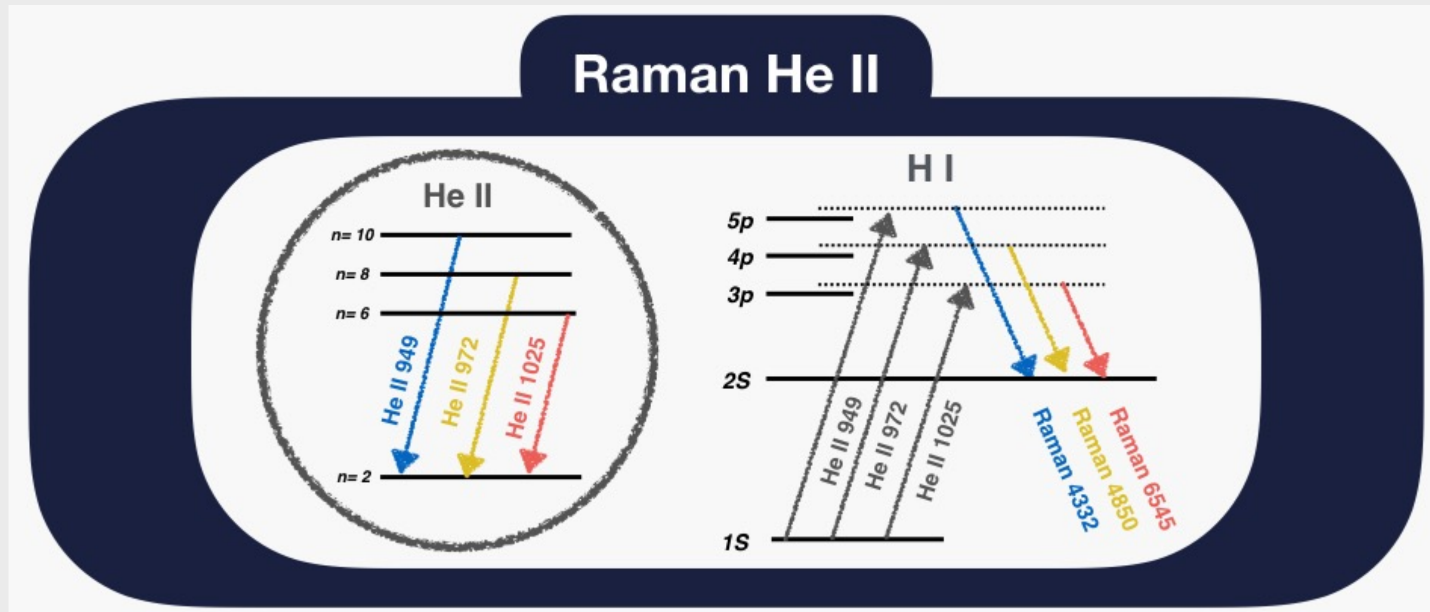
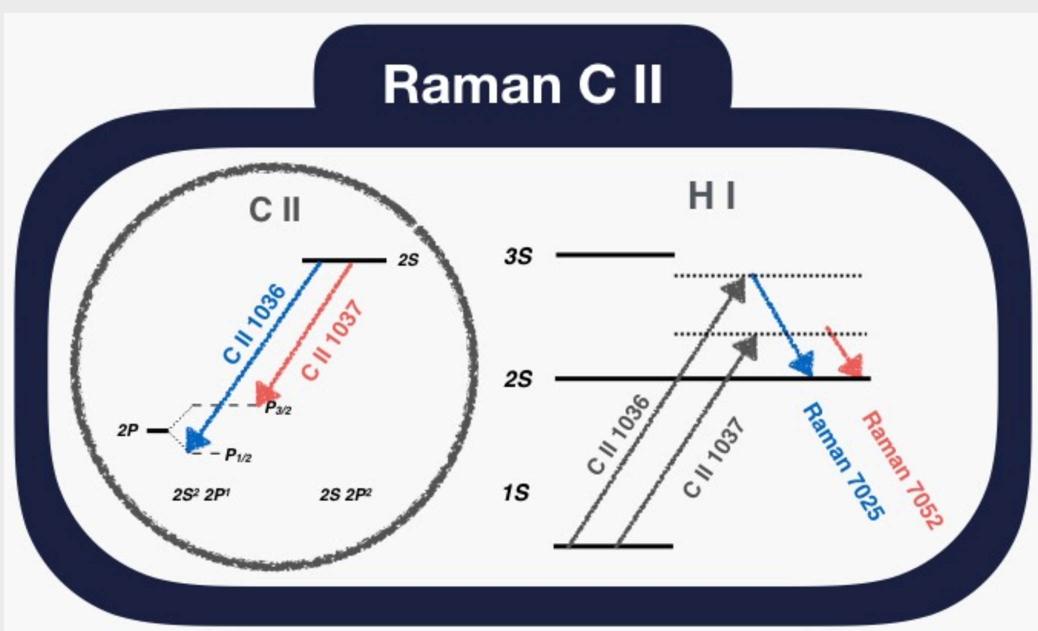


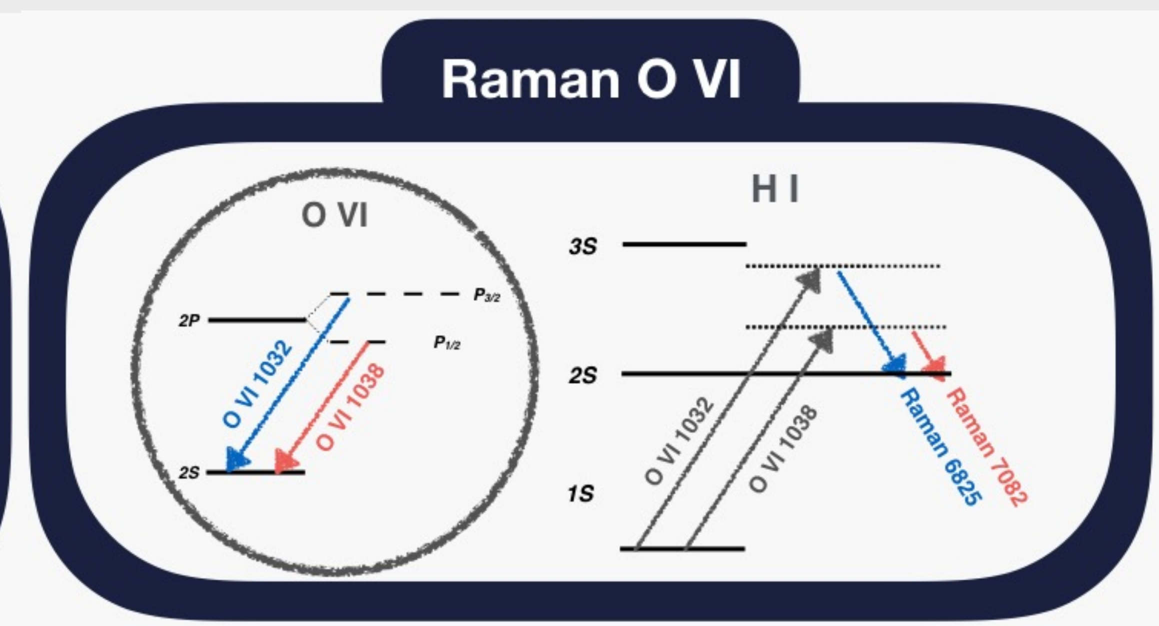
Figure 2. Low-resolution optical spectrum of RR Tel (ESO 1.5m + B&C, Munari & Zwitter, 2002).
Green lines indicate the positions of the observed Raman-scattered lines.

II. Observation

✓ Raman Lines in RR Tel







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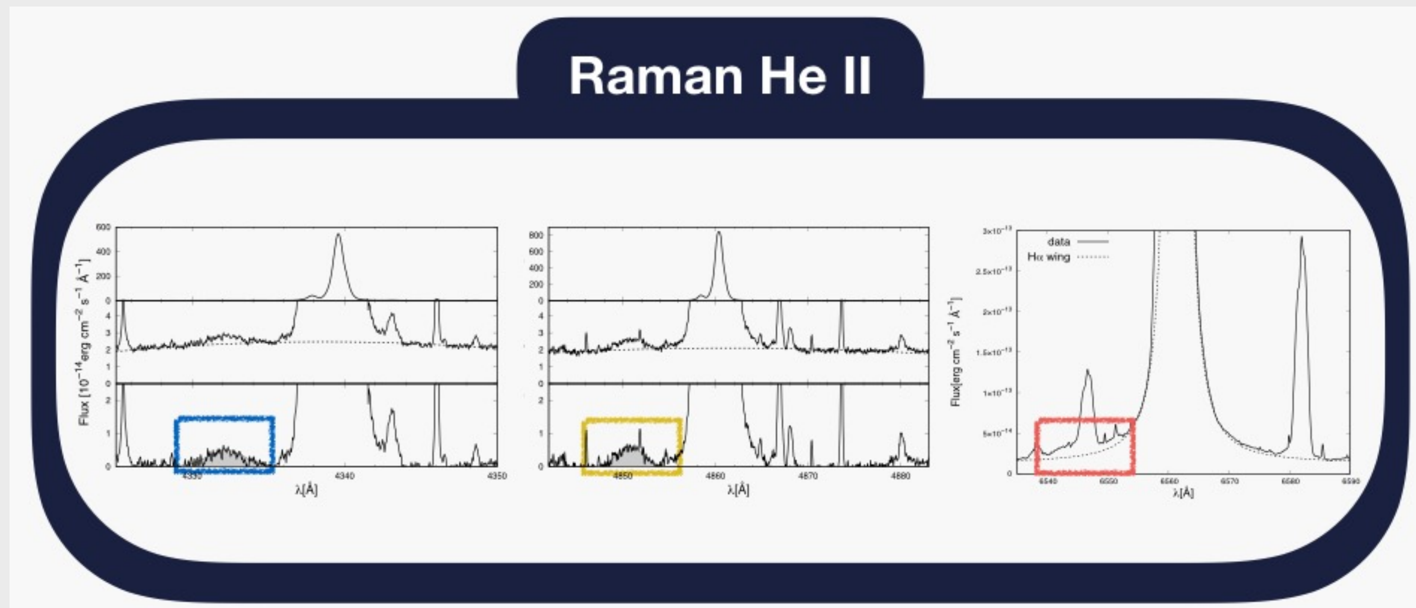
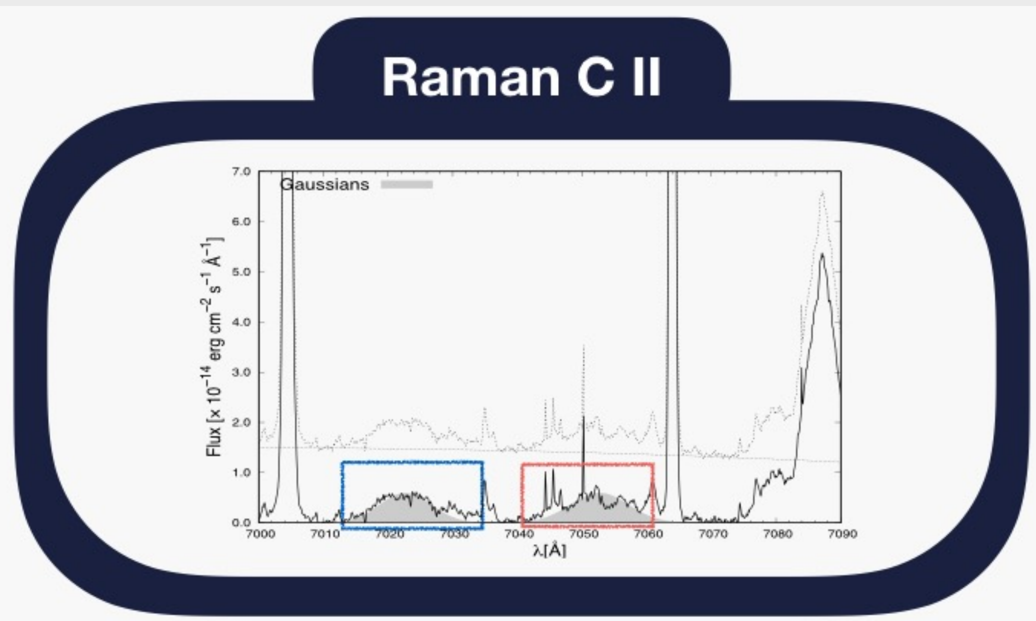
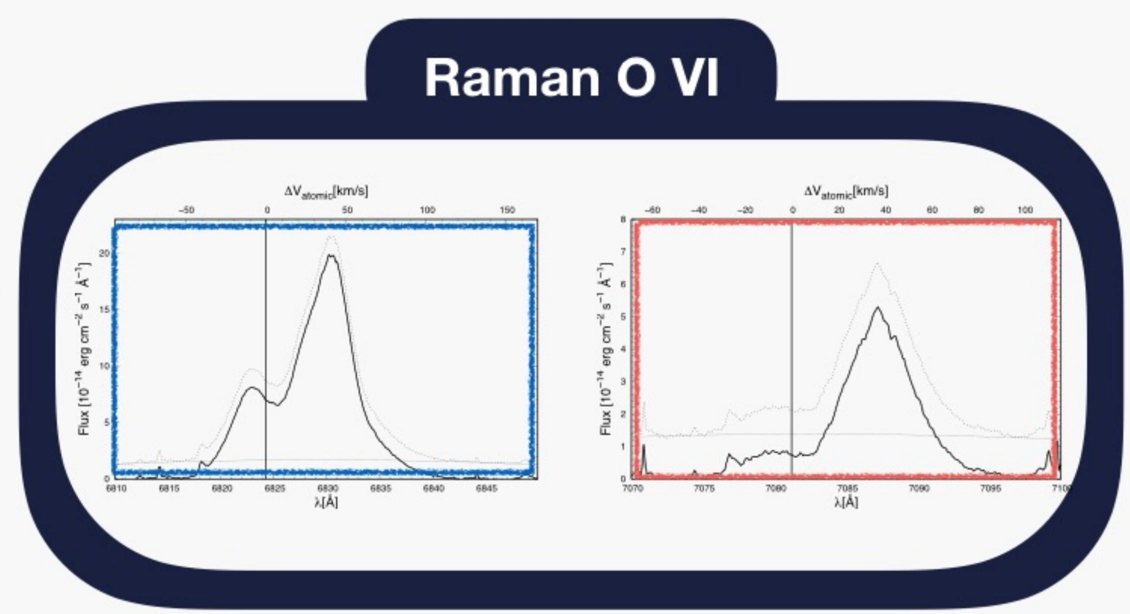
✓ Raman Lines in RR Tel







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III. Monte Carlo Simulations

✓ STB ionization front

- In STB (Seaquist, Taylor & Button, 1984) model, 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.
- A parameter X in STB geometry is given by $X = 4\pi a L_H / \alpha_B (m_H v_\infty / \dot{M})^2$.

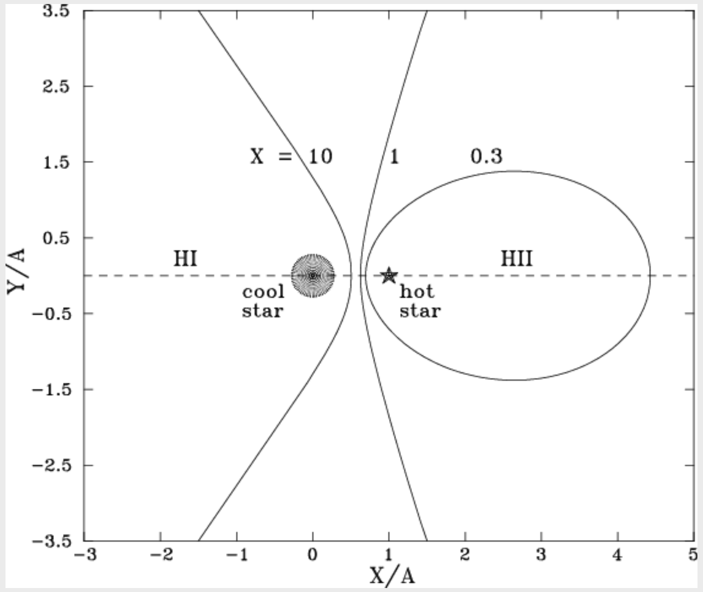

Figure 4. An ionization structure with STB Geometry (left)

III. Raman C II and ISM

✓ C II 1335 Triplet

Table 4. C II emissions

Transition $2s^22p$	$2s2p^2$	λ (Å)	Υ^{a} $T=10^4$K	$A_L{}^{b}$ (s^{-1})	F_{obs} (erg cm^{-2} s^{-1})	F_{int} (erg cm^{-2} s^{-1})
$^2P^0_{1/2}$	$^2S_{1/2}$	1036.34	0.608	7.971×10^8	...	3.15×10^{-11}
$^2P^0_{2/3}$	$^2S_{1/2}$	1037.02	1.222	1.575×10^9	...	4.19×10^{-11}
$^2P^0_{1/2}$	$^2D_{3/2}$	1334.53	1.431	2.567×10^8	4.43×10^{-13}	7.41×10^{-11}
$^2P^0_{2/3}$	$^2D_{3/2}$	1335.66	1.058	5.08×10^7	7.15×10^{-13}	1.425×10^{-10}
$^2P^0_{2/3}$	$^2D_{5/2}$	1335.71	3.098	3.067×10^8		

[a] Tayal 2008
[b] NIST database

III. Monte Carlo Simulations

✓ Hierarchical Emission Region Model

- In order to reproduce the Raman-scattered line profiles, we suggest that the emission nebulae around the white dwarf has **a hierarchical structure including inner most part with O VI disk and the outer part with C II and He II sphere,** which is consistent with the higher ionization potential of O VI than those of He II and C II.

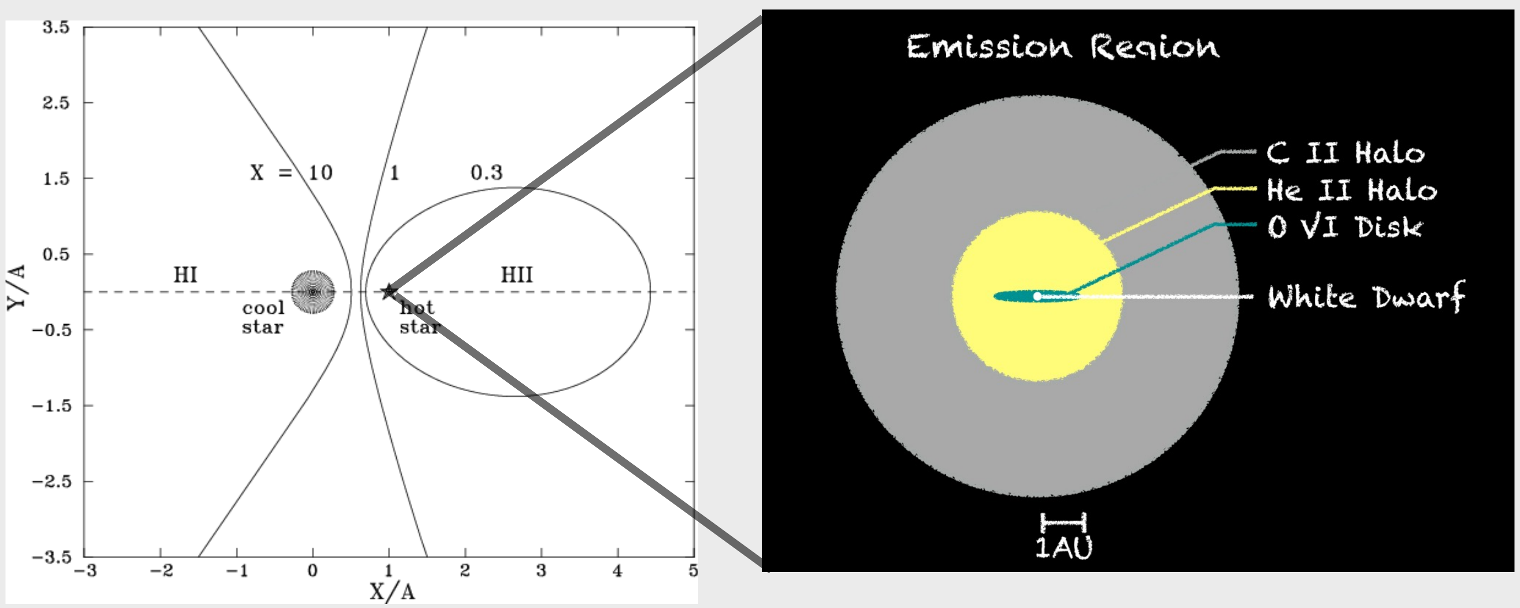

Figure 4. An ionization structure with STB Geometry (left) and schematic model for the emission nebula around the WD (right)

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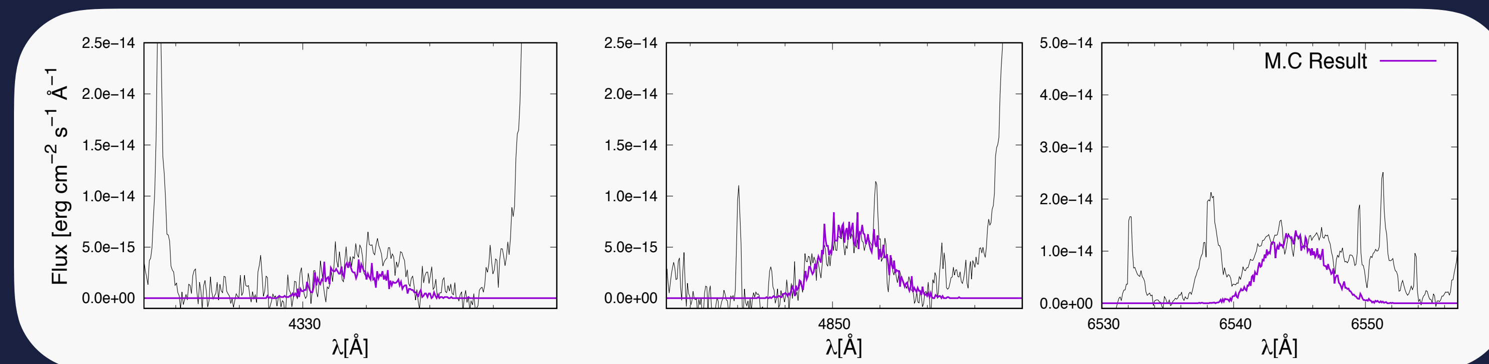
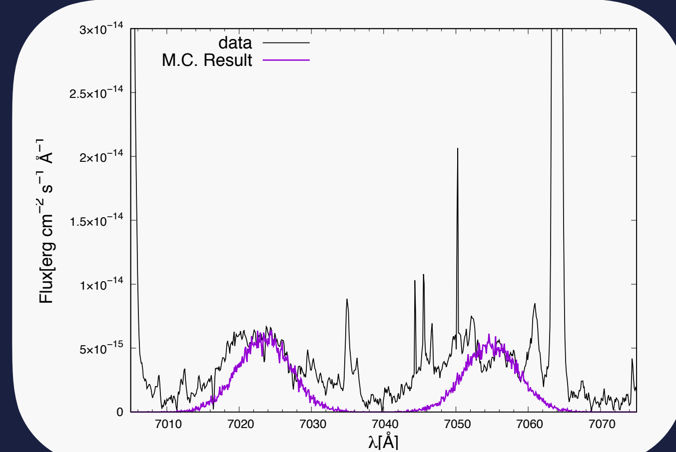
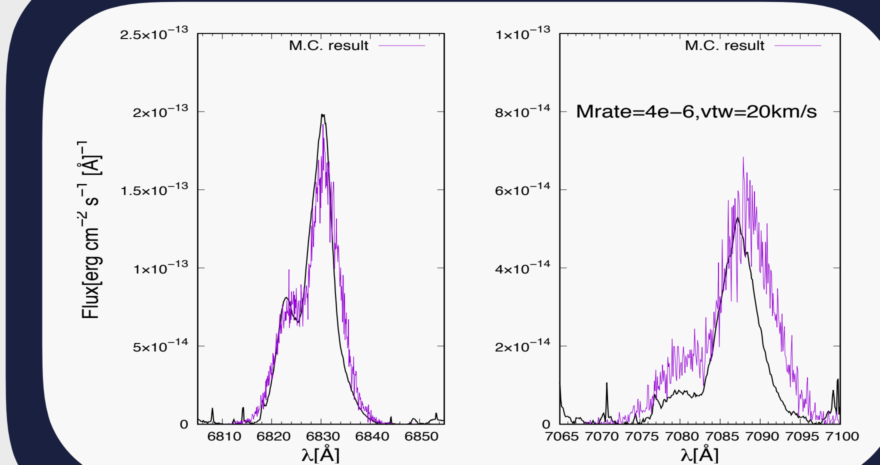
Raman He II



Raman C II



Raman O VI



- A good fit is obtained for the mass loss rate $\dot{M} \sim 3 \times 10^{-6}$ M⊙/yr and v_∞ =10 km/s, which corresponds to X ~ 7.5.
- Raman lines are well fitted with hierarchical emission region composed of the O VI disk extending 1AU and the He II and C II spheres with a size of sub AU.

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III. Monte Carlo Simulations

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DISCUSSION

✓ STB ionization front

- In STB (Seaquist, Taylor & Button, 1984) model, 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.
- A parameter X in STB geometry is given by $X = 4\pi a L_H / \alpha_B (m_H v_\infty / \dot{M})^2$.

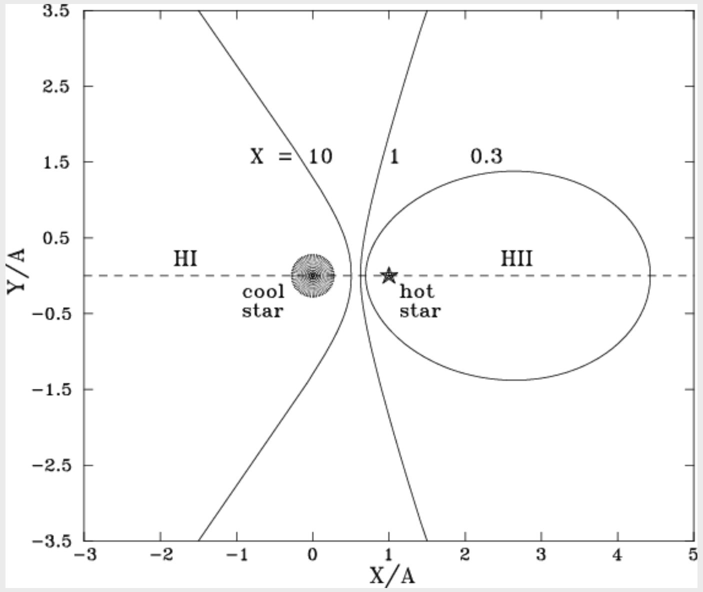

Figure 4. An ionization structure with STB Geometry (left)