2020 102nd KAS Fall Meeting

Discovery of Raman-scattered He II λ6545 in Planetary Nebulae NGC 6886 and NGC 6881 from BOES Spectroscopy

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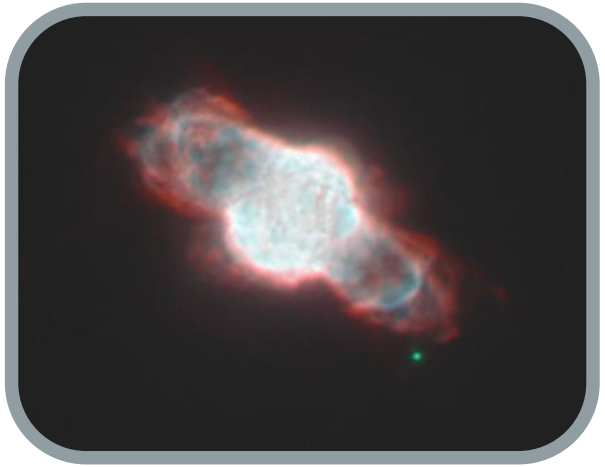
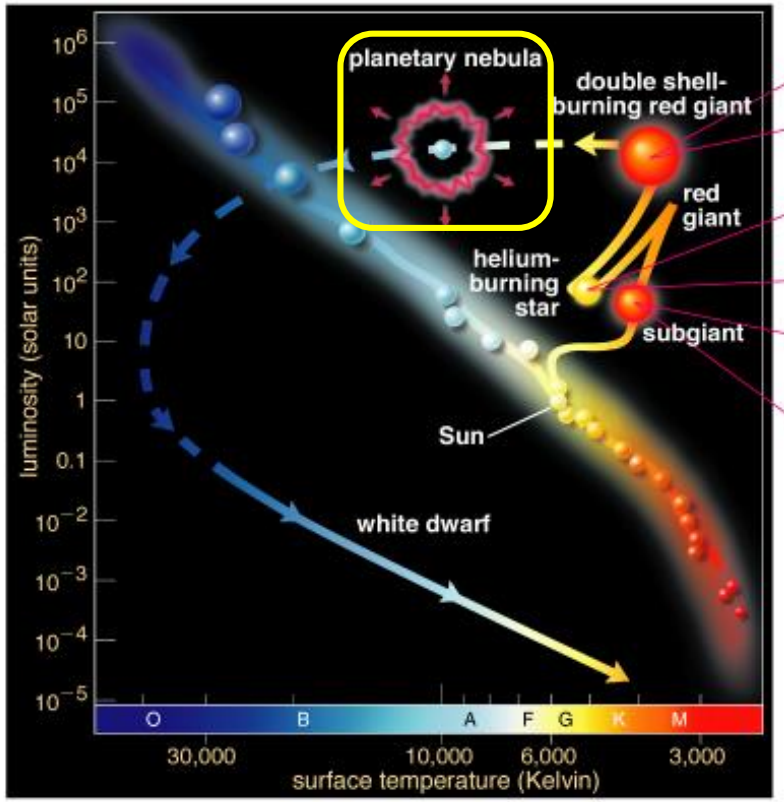
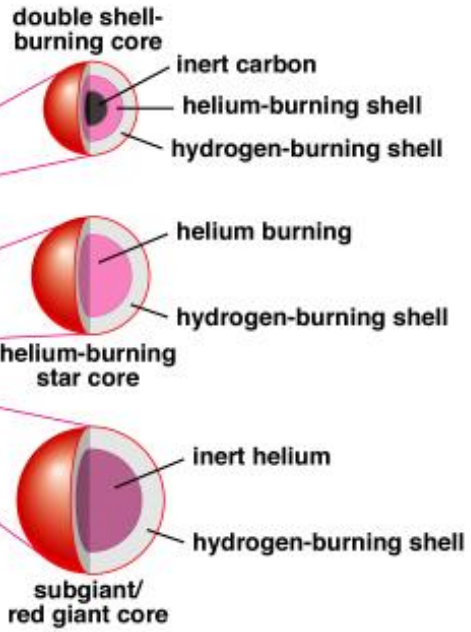
Contents



Young Planetary Nebulae

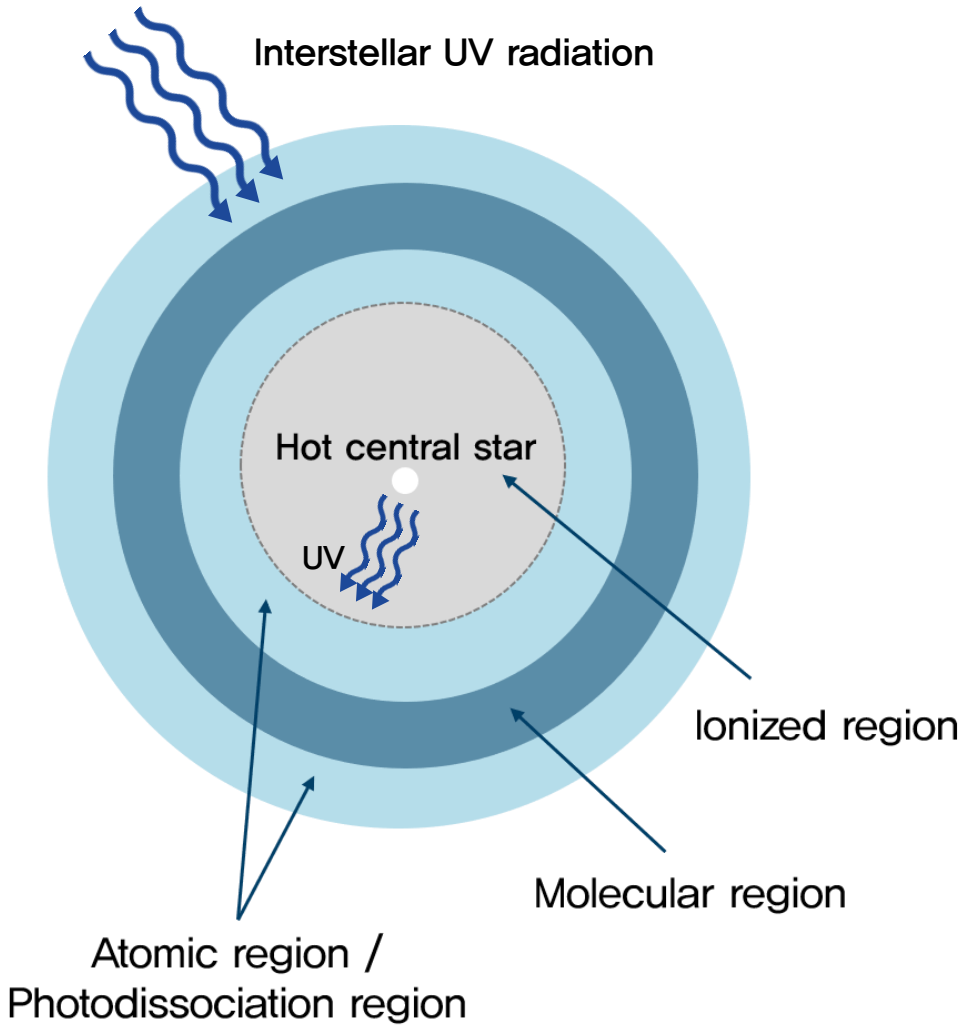




Credit: NASA/ESA

- **Planetary nebula (PN)**
  - The late evolutionary stage of stars with 0.8 – 8 $M_{\odot}$
  - Hot central star + ejected matter
- **The study of young PNe**
  - Nucleosynthesis at asymptotic giant branch (AGB)
  - Chemical enrichment of interstellar medium
  - Mass-loss process in previous stage

Neutral Matter in PNe



▶ Various gas phase

- Highly ionized region (X-ray, UV)
- Lowly ionized region
- H_2, CO, HCN molecular lines

(Kastner et al. 1997; Schmidt & Ziurys 2017; Guzman-Ramirez et al. 2018)

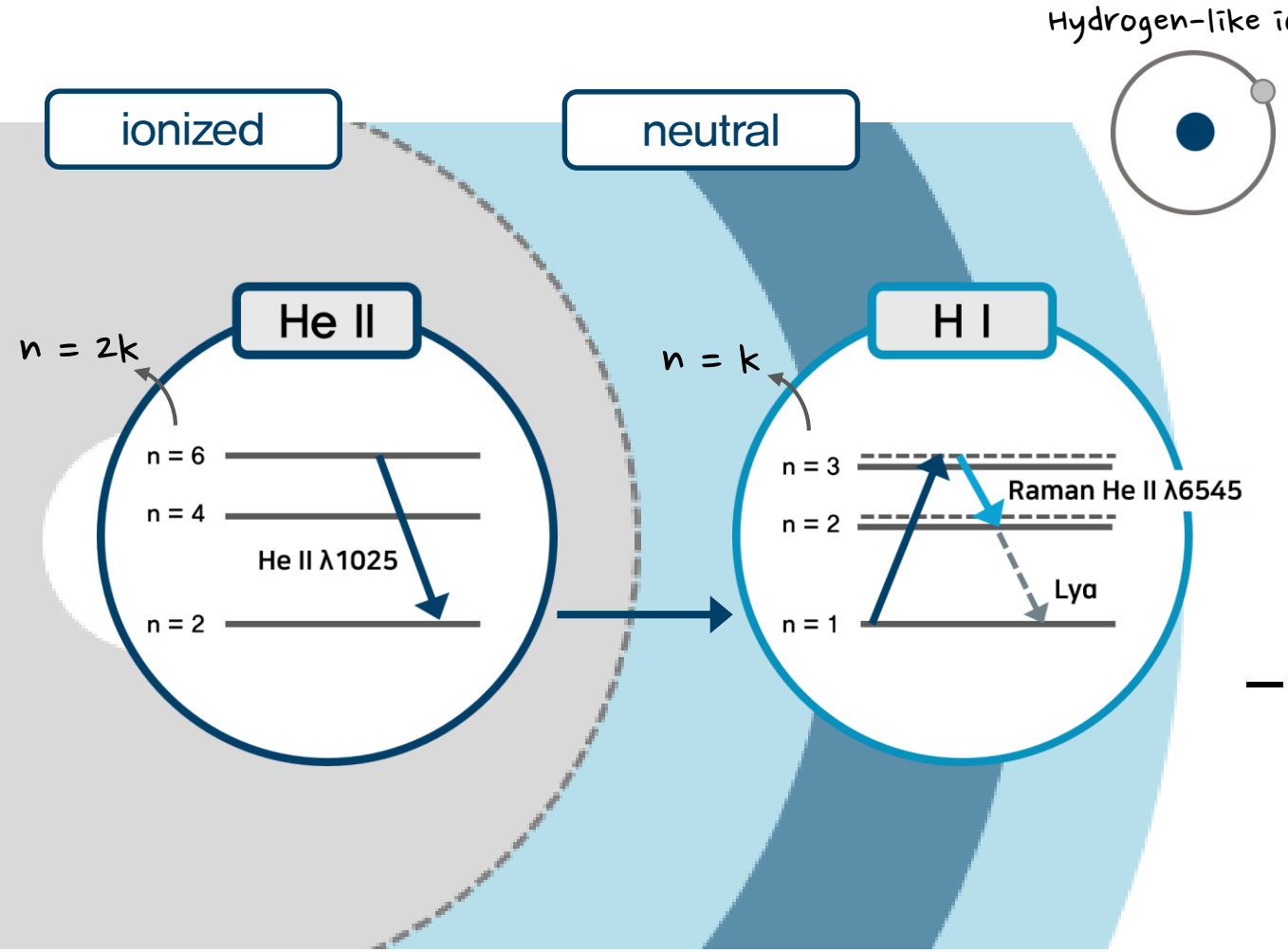
- H I 21 cm observation for ~ 15 PNe

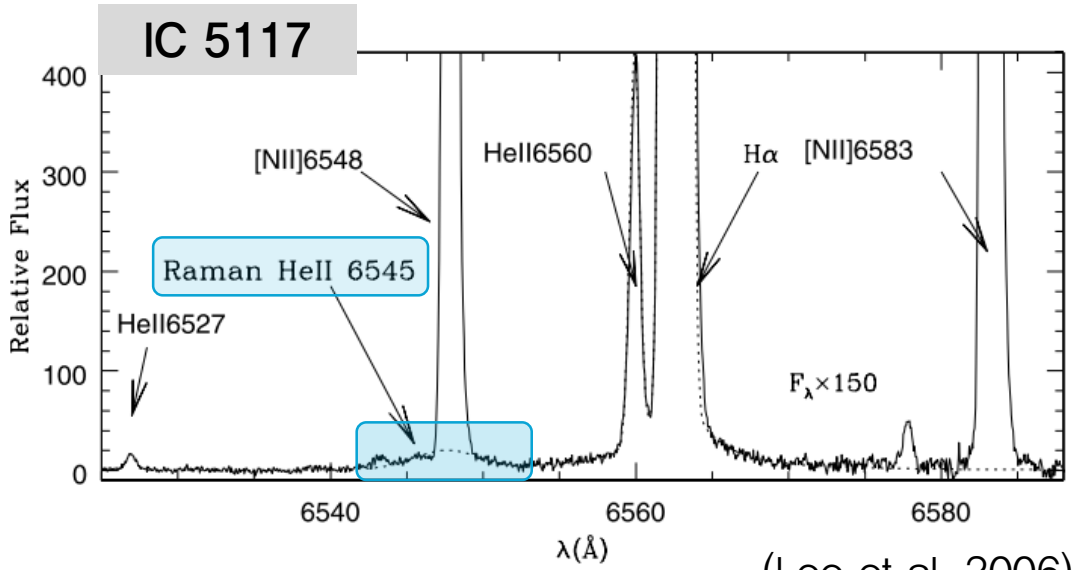
(Taylor et al. 1990; Gussie & Taylor 1995)

▶ H I component in PNe

- Photodissociation region
- Atomic stellar wind

Raman Scattering of He II



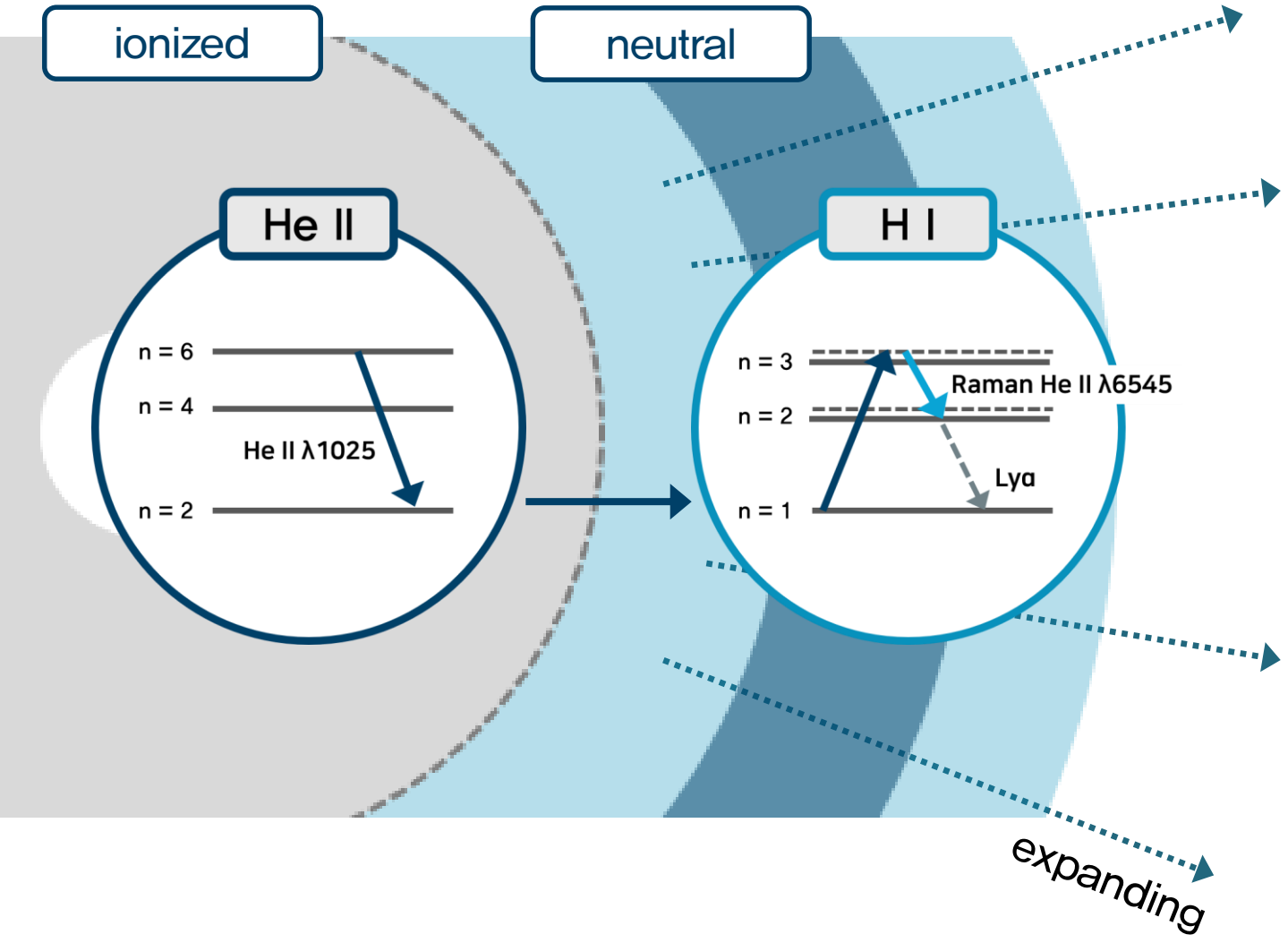


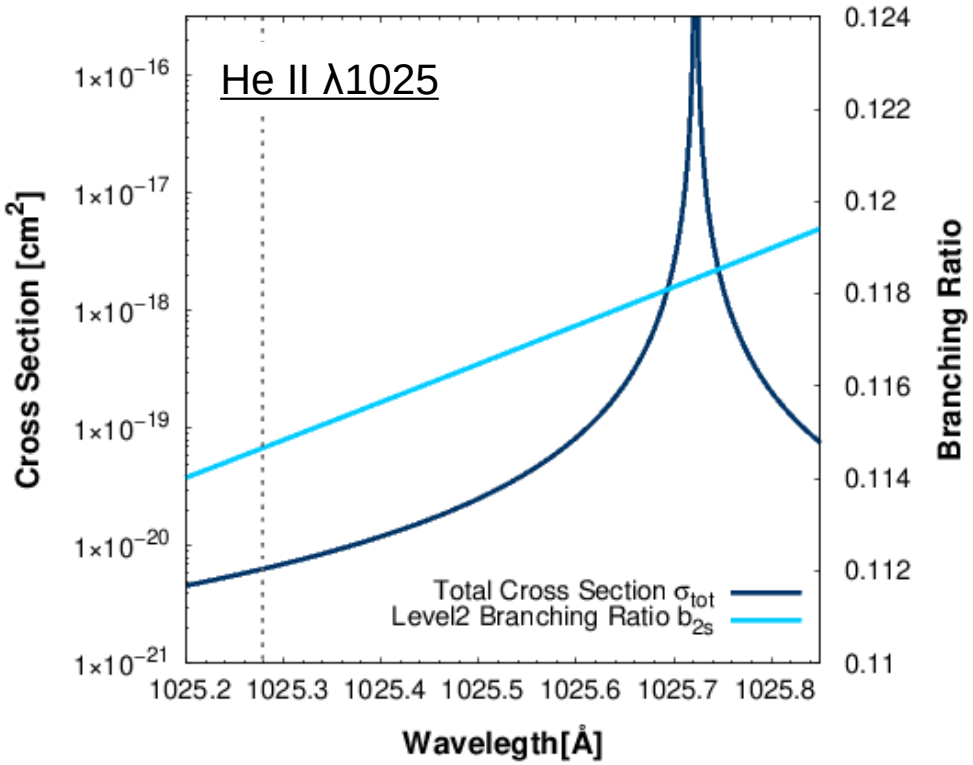
(Lee et al. 2006)

– Line broadening

$$\frac{\Delta\lambda_o}{\lambda_o} = \left(\frac{\lambda_o}{\lambda_i}\right)\frac{\Delta\lambda_i}{\lambda_i}$$ ex) He II λ1025 → λ6545 : $\frac{\lambda_o}{\lambda_i} \sim 6.4$

Raman Scattering of He II





$$\sigma_{1025,\mathrm{Ram}} = 7.4 \times 10^{-22}\ \mathrm{cm}^{-2}$$

An excellent probe of H I regions with H I column density $N_{HI} \geq 10^{20}\ \mathrm{cm}^{-2}$

Raman He II Survey

▶ Young PNe exhibiting Raman He II features

– Raman He II features have been found in 5 PNe thus far

: NGC 7027, NGC 6302, NGC 6886, IC 5117, NGC 6790

– Young and non–spherical PNe

– The small number of PNe → Worth further search in a systematic way !

▶ Candidate selection criteria

– Copious He II emission → High values for He II λ4686 / Hα ($\geq$ 0.05)

(Tylenda et al. 1994)

– Abundant neutral matter → Smaller size, Young PNe, Molecular components

(Kastners et al. 1997; Sahai et al. 2011)

Raman He II Survey

▶ BOES Spectroscopy

- Bohyunsan Optical Echelle Spectrograph
- Installed on the 1.8m telescope of BOAO
- The fiber having spectral resolution R ~ 30,000 / field of view = 4.2″
- Obtained spectra of 12 PNe during April 2019 – March 2020
- 2×2 binning to improve signal to noise

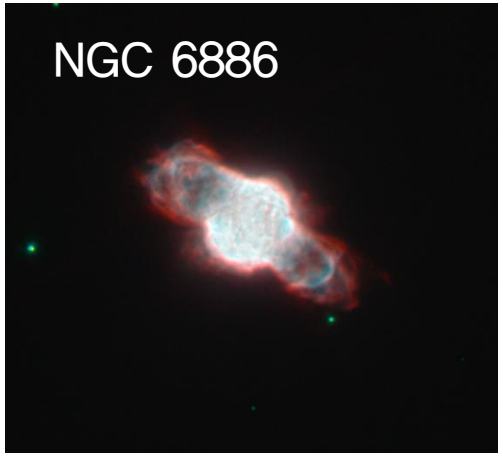
Raman He II Survey

Spectroscopy

Name	PN G	Date	Exp. Time (sec)	I(HeII4686)/I(Hα) (%)
NGC 6741	033.8-02.6	2020-03-28	1200	6.67
H 4-1	049.3+88.1	2019-04-06	1800	3.10
Hu 2-1	051.4+09.6	2020-03-30	2400	0.24
Hen 2-447	057.9-01.5	2019-06-05	1500	-
NGC 6886	060.1-07.7	2020-10-30	2400	6.13
NGC 6881	074.5+02.1	2020-03-30	3300	2.58
NGC 6884	082.1+07.0	2020-03-28	3600	2.50
J 900	194.2+02.5	2019-04-06	1800	7.74
NGC 2392	197.8+17.3	2020-03-30	1200	13.93
M 1-8	210.3+01.9	2020-03-30	3600	6.46
NGC 2346	215.6+03.6	2019-04-05	1800	6.00
NGC 3242	261.0+32.0	2020-03-30	3600	8.52

Raman He II Survey

Spectroscopy



Credit: NASA/ESA

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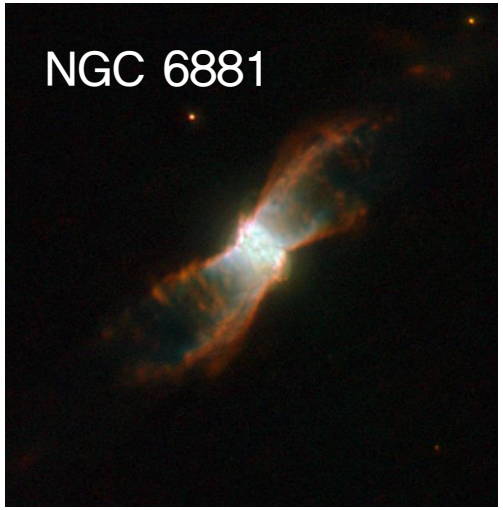
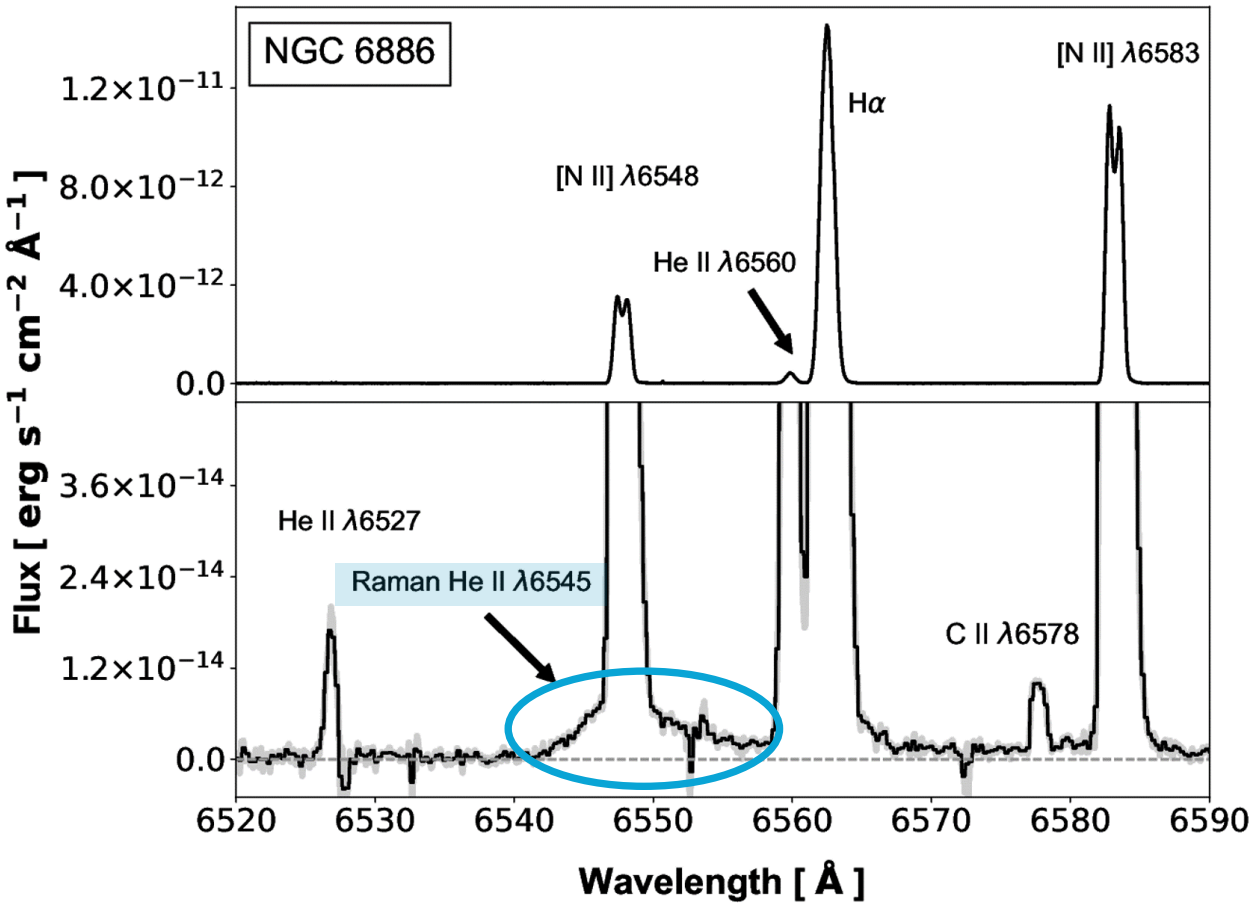
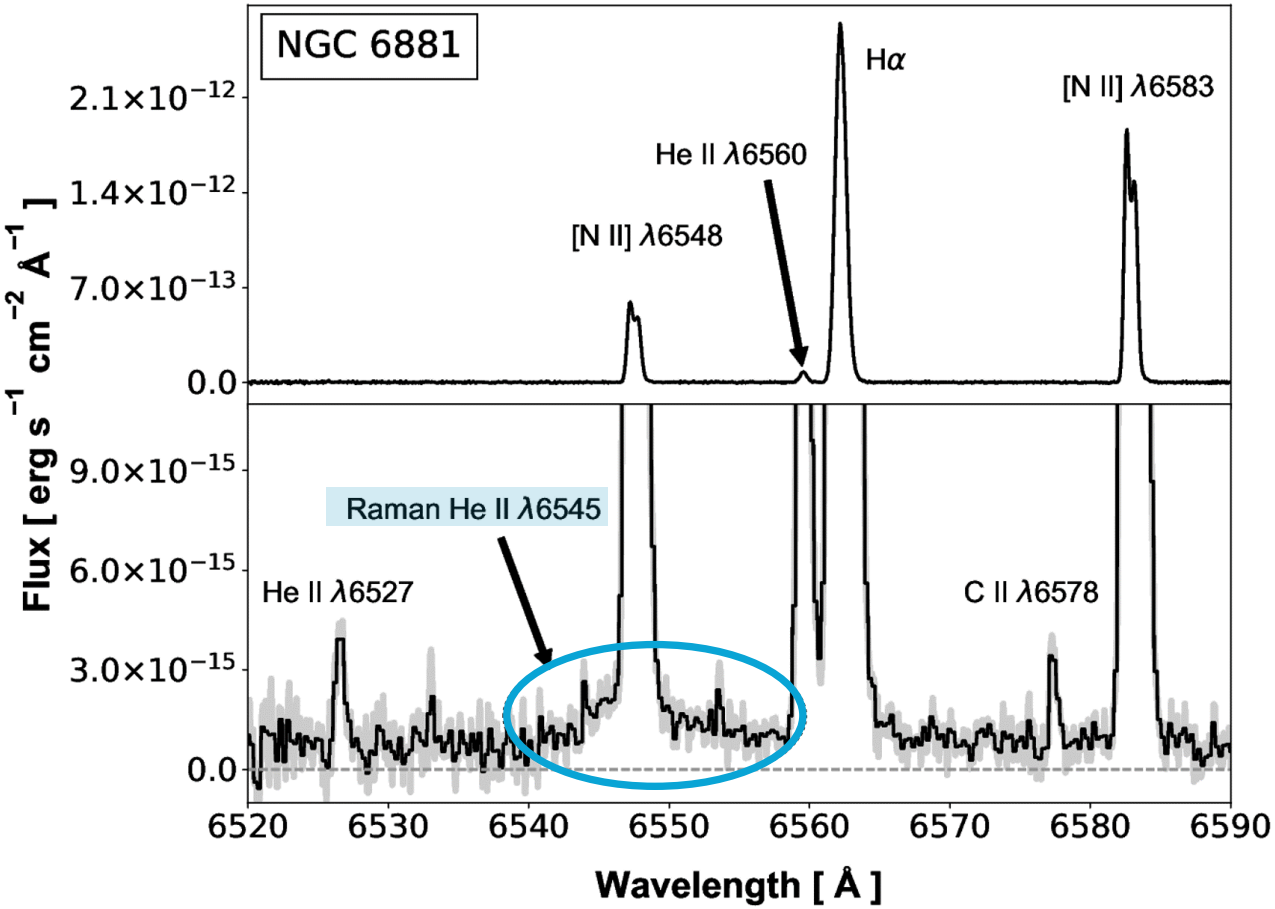


Credit: NASA/ESA

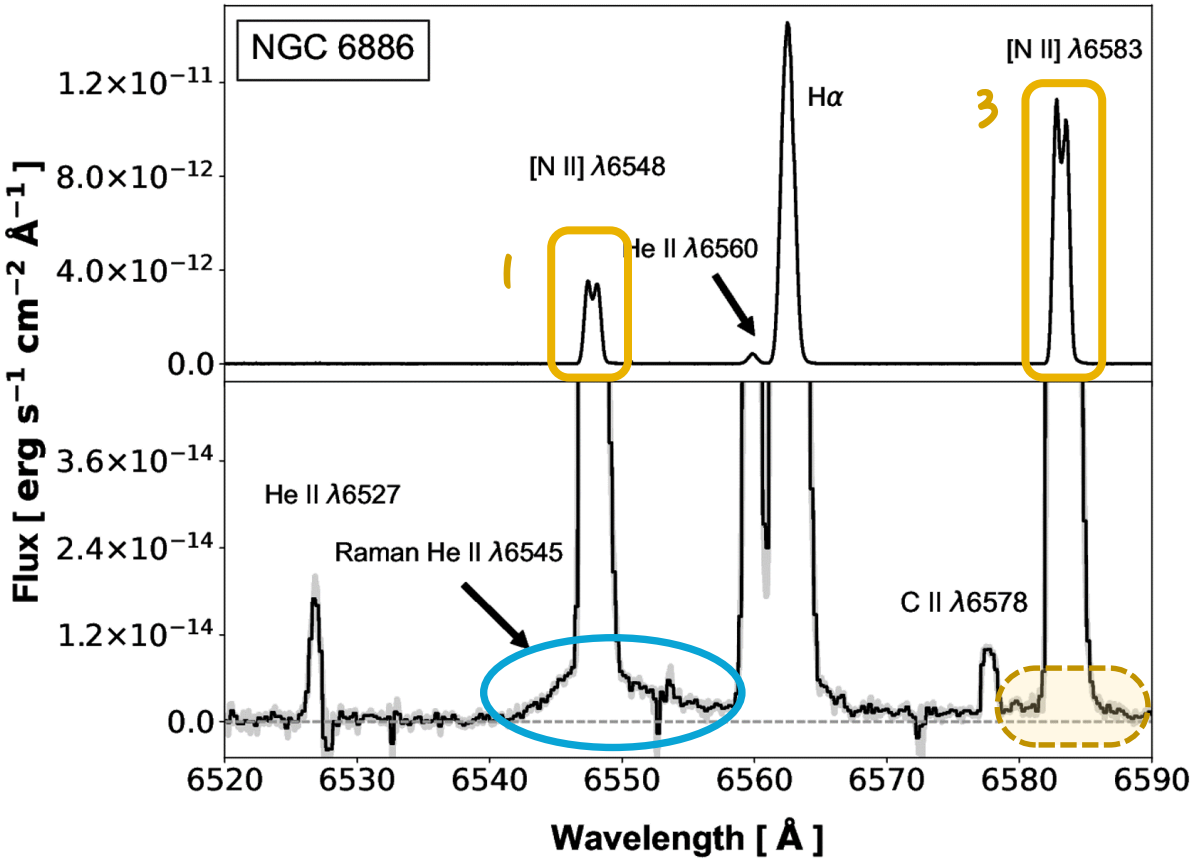
Raman He II in NGC 6886 & NGC 6881

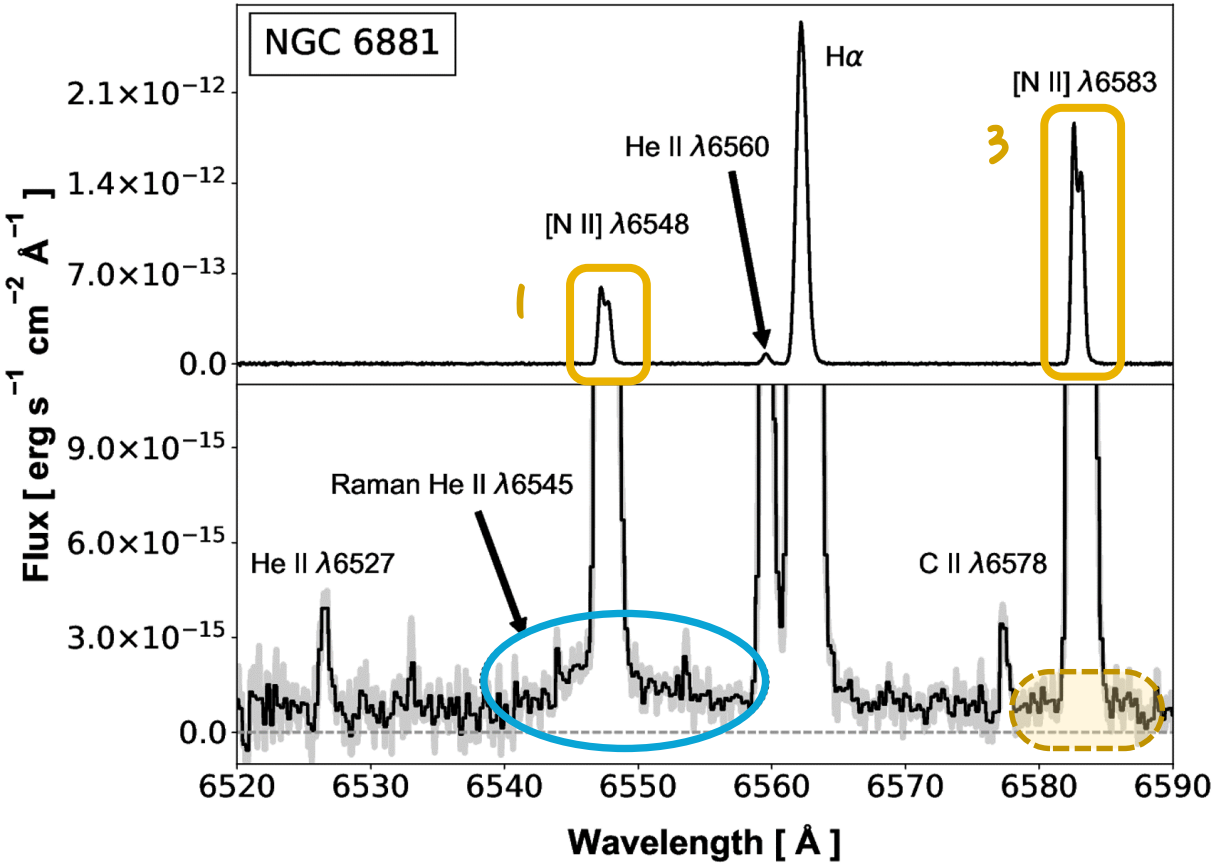




Raman He II in NGC 6886 & NGC 6881

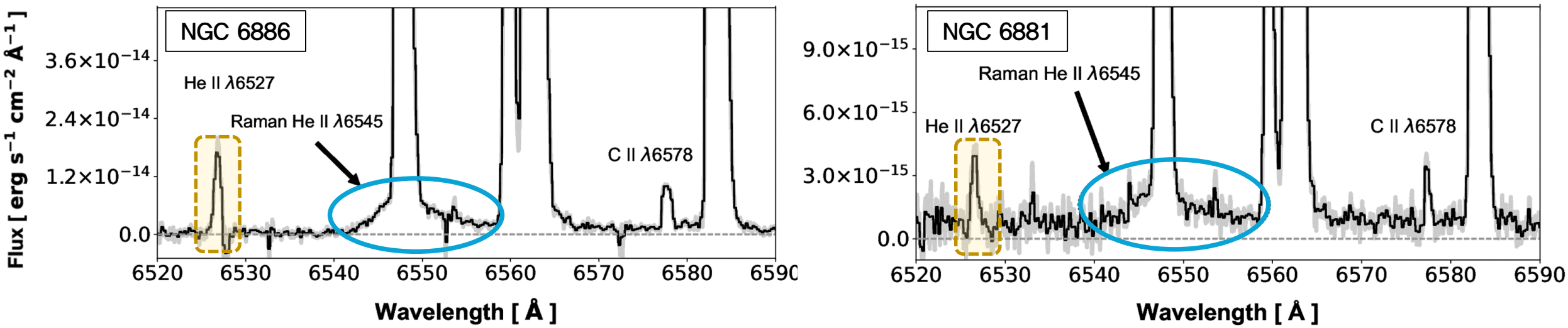
Spectroscopy





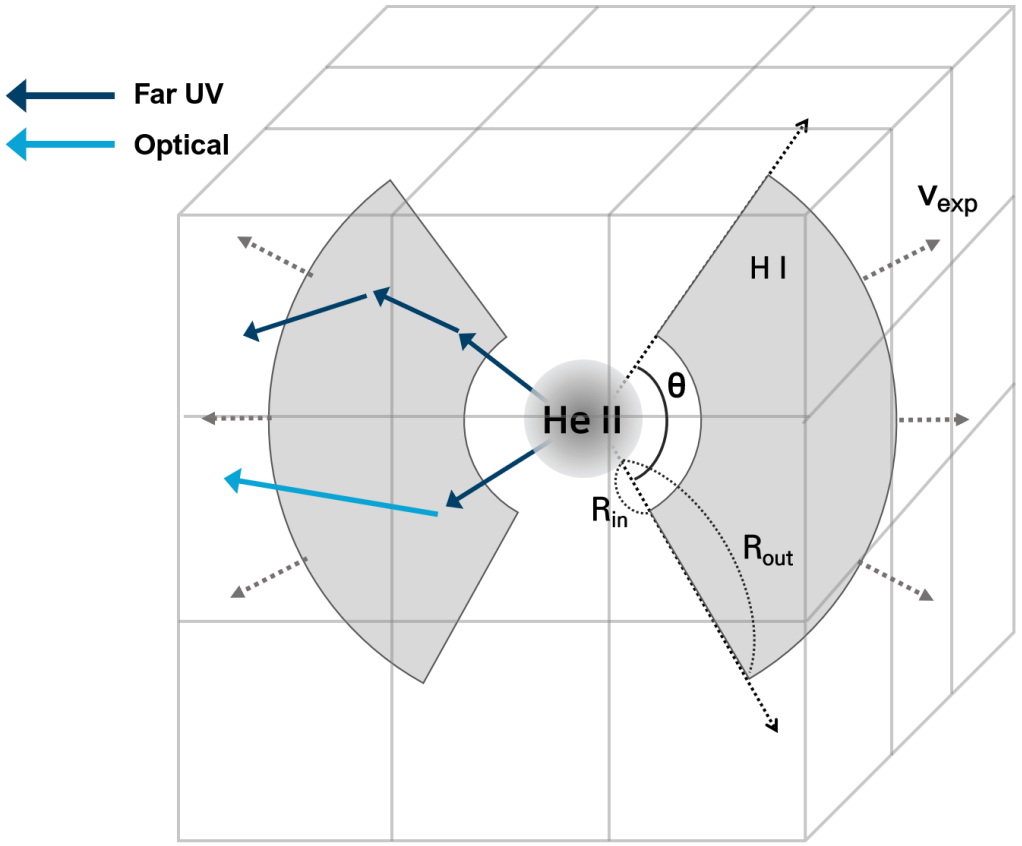
1. The absence of broad feature around the [N II] λ6583 line
   - [N II] λλ6548, 6583 doublet
   - [N II] λ6583 line is theoretically 3 times stronger than [N II] λ6548

Raman He II in NGC 6886 & NGC 6881



2. The comparable peak value with the He II λ6527 line
   - When He II λ1025 photons are completely Raman-scattered,
     the peak value of Raman He II λ6545 is expected to be 2 times higher than that of He II λ6527 based on case B recombination theory with moderate condition

Line Formation of Raman He II



* STaRS : http://github.com/csj607/STaRS

▶ STaRS

– A grid–based Monte–Carlo radiative transfer code
(Chang & Lee submitted to JKAS)

– Input He II emission
- ✓ Gaussian profile
- ✓ Flux is estimated from He II λ6560 flux based on case B theory

(Kaler et al. 1987; Hyung et al. 1995; Pottash & Surendiranath 2005)

– Parameter
- ✓ CF : θ / π, covering factor of scattering region
- ✓ N_{HI} : H I column density
- ✓ v_{exp} : expanding speed

Best Fit Results

Severely blended with [N II] λ6548

▶NGC 6886

– Best–fit (CF = 0.3)

$N_{HI} = 5 \times 10^{20}$ cm^{-2}

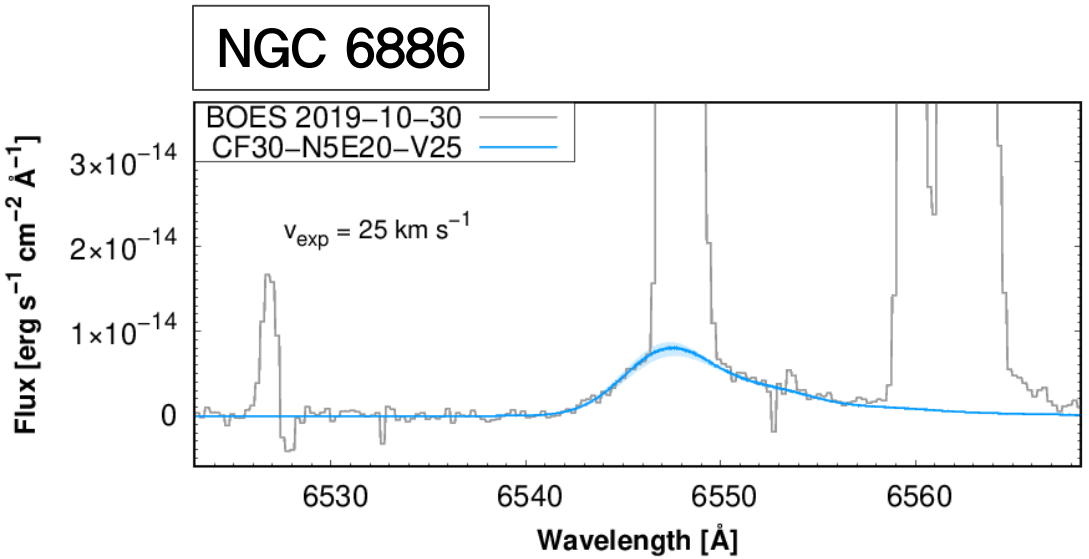
$v_{exp} = 25$ km s^{-1} (± 5 km s^{-1})

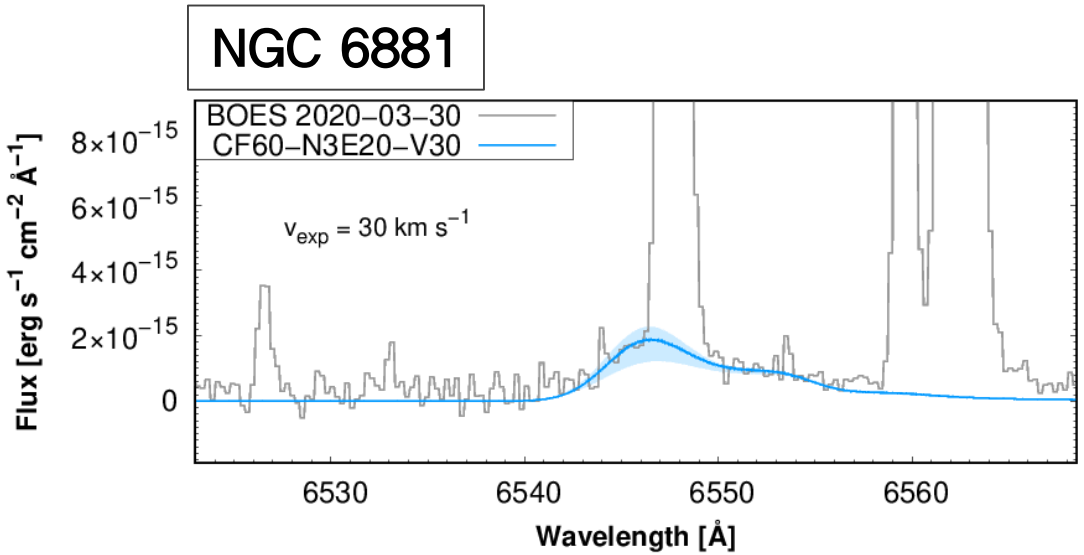
▶NGC 6881

– Best–fit (CF = 0.6)

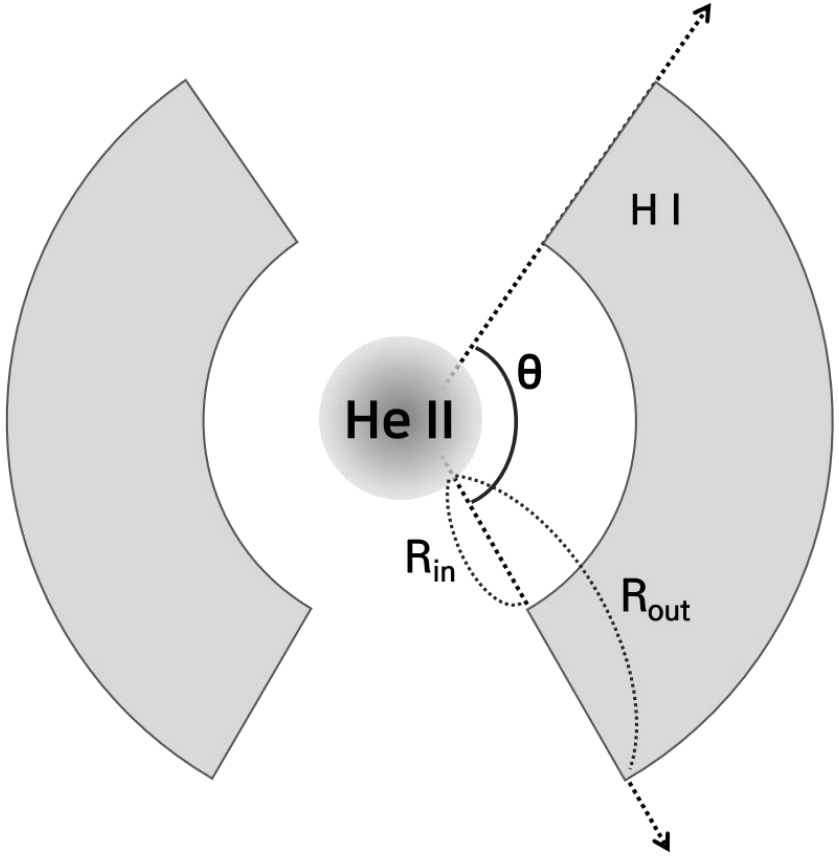
$N_{HI} = 3 \times 10^{20}$ cm^{-2}

$v_{exp} = 30$ km s^{-1} (± 10 km s^{-1})





H I Mass Estimation



(Assume that $R_{out} = 2\ R_{in}$)

$$M_{HI} \simeq 1.4 \times 10^{-4} \left(\frac{N_{HI}}{10^{20}\ cm^{-2}}\right)\left(\frac{R_{out}}{10^{3}\ au}\right)^{2} CF\ M_{\odot}$$

▶ **NGC 6886**

– Distance ~2.6 kpc / angular size ~ 5″
(Pottasch & Surendiranath 2005)

– $M_{HI} \sim 0.03\ M_{\odot}$

▶ **NGC 6881**

– Distance ~2.5 kpc / angular size ~ 5″
(Cahn et al. 1992; Kwok & Su 2005)

– $M_{HI} \sim 0.04\ M_{\odot}$

: Comparable with the study of Taylor et al. 1990

Summary

- We report our successful detection of Raman He II λ6545 in NGC 6886 and NGC 6881 using BOES

- The first direct detection of H I component in NGC 6881

- Best fits are found in the model with

  CF = 0.3, $N_{HI} = 5\times10^{20}$ cm^{-2}, v_{exp} = 25 km s^{-1} for NGC 6886

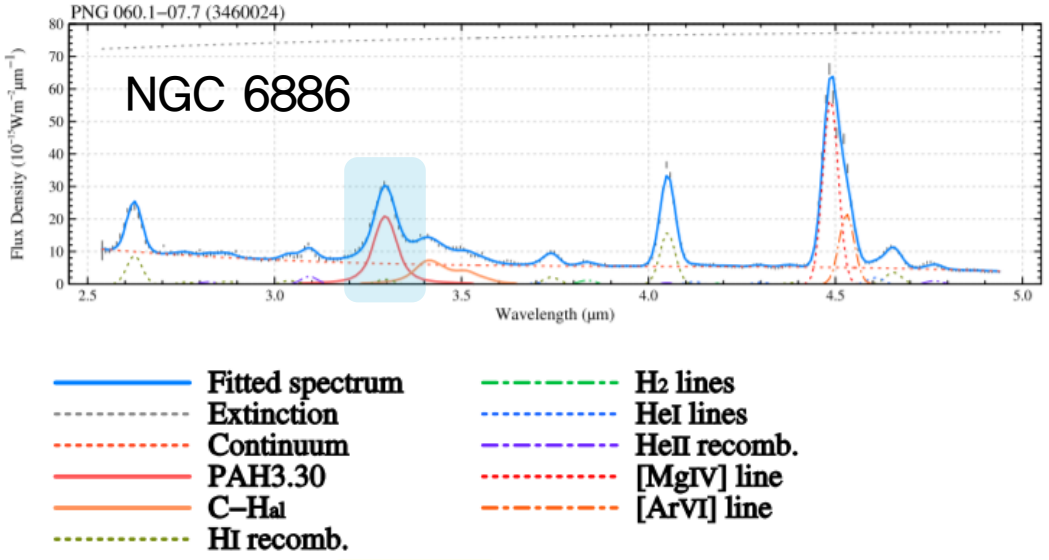
  CF = 0.6, $N_{HI} = 2\times10^{20}$ cm^{-2}, v_{exp} = 30 km s^{-1} for NGC 6881

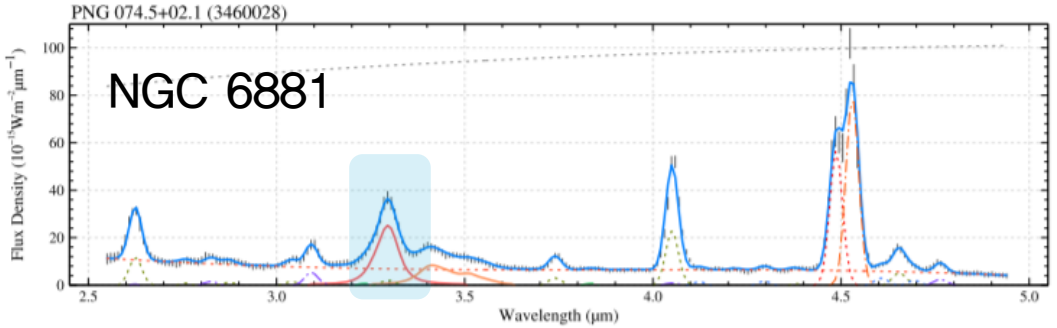
- Corresponding H I mass is about $M_{HI} \sim 0.03\ M_{\odot}$ for NGC 6886 and $\sim$0.04 $M_{\odot}$ for NGC 6881

Future Work

- Relation with chemical abundance
  - ✓ Polycyclic aromatic hydrocarbon (PAH) emitters

    (Smith & McLean 2008; Ohsawa et al. 2016)
  - ✓ C/O, He/H, N/H abundance
  - ✓ Progenitor properties : Dredge-up process, Nucleosynthesis, Mass-loss





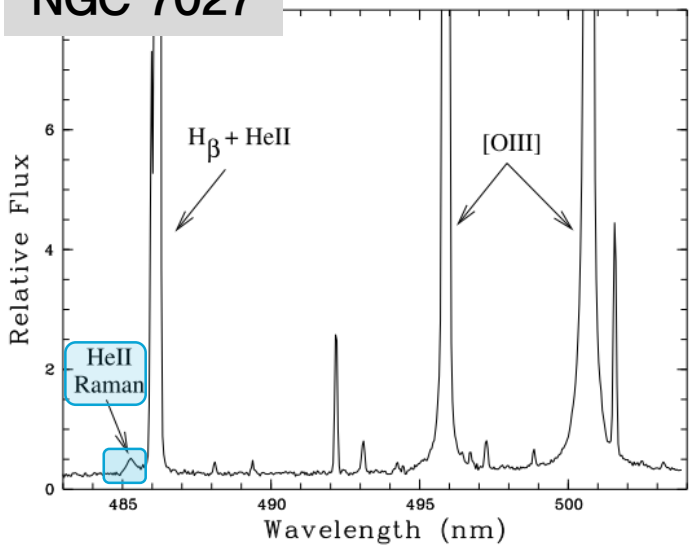
(Ohsawa et al. 2016)

Future Work

- Raman He II λ4851, λ4332 : $N_{HI} = 10^{21\sim23}$ cm^{-2}

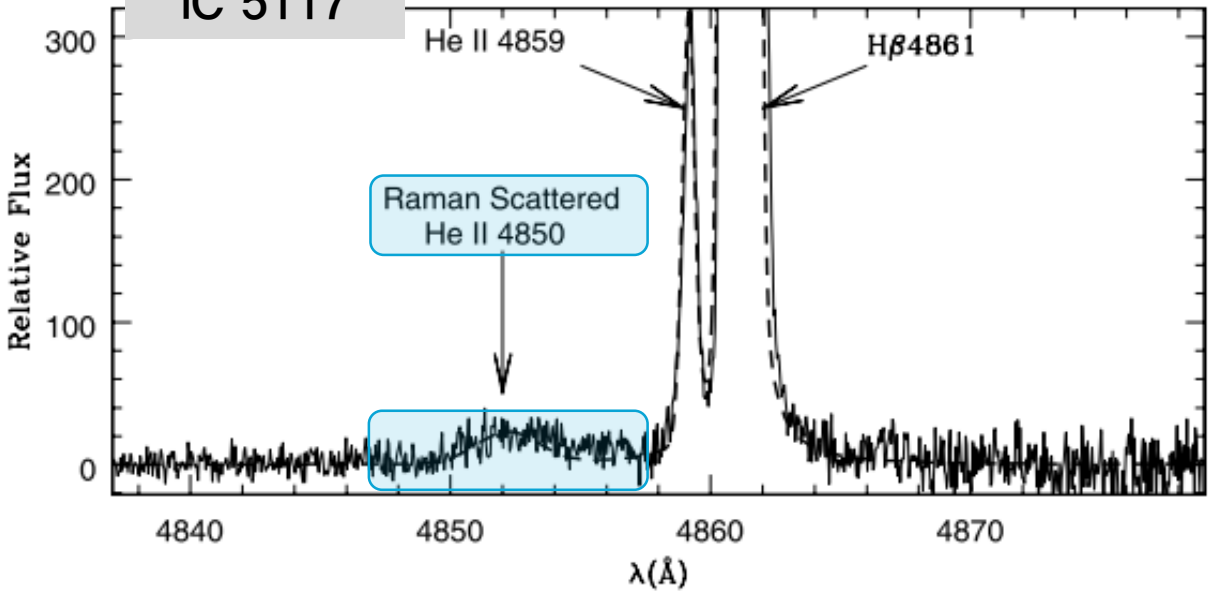
- Excellent spectroscopic probe of H I distribution and kinematics

NGC 7027



Péquignot et al. 1997

IC 5117



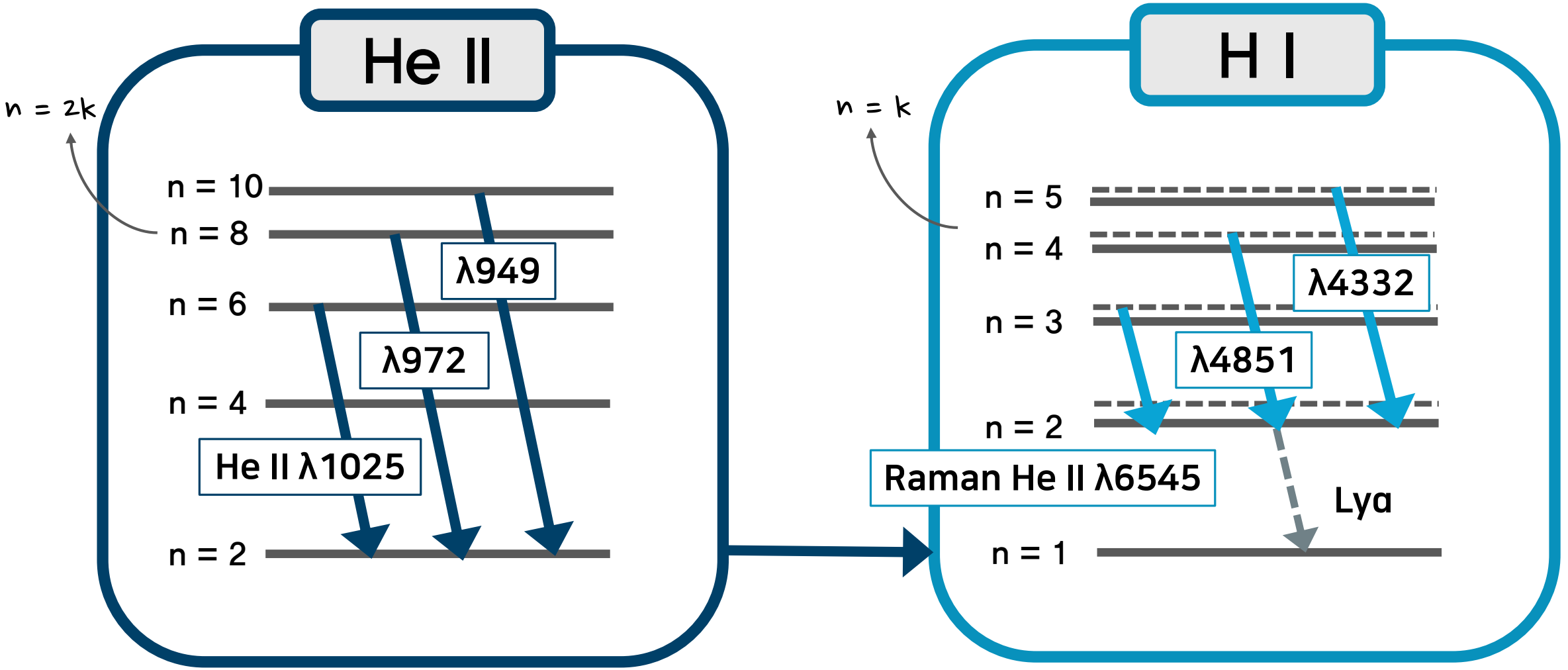
Lee et al. 2006

THANK YOU

Q & A

SUPPLEMENT

Raman Scattering of He II



Raman He II Line Profile

- Raman He II λ4851
  (Choi et al. 2020)