Helium Absorption Lines in Kilonova Spectra

Koya Chiba, Masaomi Tanaka (Tohoku University),
Kenta Hotokezaka (The University of Tokyo)

Email: chiba.koya@astr.tohoku.ac.jp

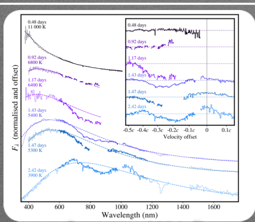
Introduction

1 μm P-Cygni feature in the early spectra of kilonova

Binary neutron star (BNS) merger

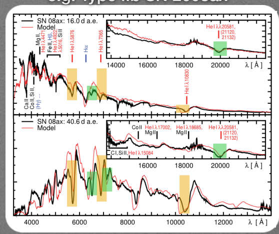
- One of the origins of heavy elements synthesized by r-process nucleosynthesis.
- The thermal emission from BNS merger ejecta is called "Kilonova".
- Kilonova spectra bring information on r-process nucleosynthesis in BNS merger ejecta.

- In the spectra of the kilonova AT2017gfo, a P-Cygni feature at around 1 μm is important due to its strength.
- Candidate elements contributing this feature:
  - Sr II → well investigated in LTE radiative transfer simulations
  - He I → not yet due to the need for taking into account the "Non-LTE" effect

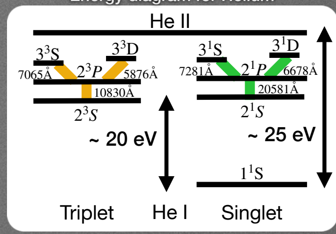

Sneppen+ 2024, Figure 4

Helium absorption lines in KNe/SNe spectra

e.g. Type IIb SN 2008ax


Hachinger+ 2012, Figure 2 modified

Energy diagram for Helium

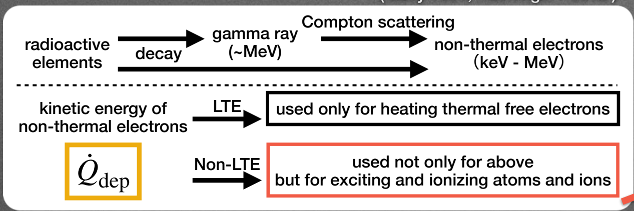


radiation temperature $T_R \sim 5000\,\mathrm{K} \approx 0.4\,\mathrm{eV}$ ⟷ **large gap !** ⟷ first excitation energy $\sim 20\,\mathrm{eV}$

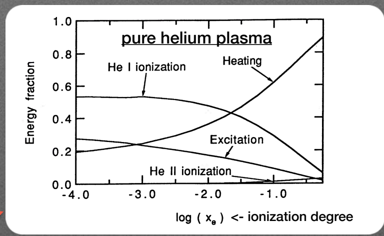
→ Impossible to reproduce He I lines by the LTE assumption

"Non-LTE" effect

(Lucy 1991; Hachinger+ 2012)



described by Spencer-Fano Equation



Kozma & Fransson 1992, Figure 3 modified

This study

- We search for the condition, in the $X_{\rm He} - \dot{Q}_{\rm dep}$ plane, under which helium absorption lines appear in kilonova spectra.
- We compare the result for kilonova (KN) with those for Core-Collapse Supernova (CCSN) and Type Ia Supernova (Type Ia SN).

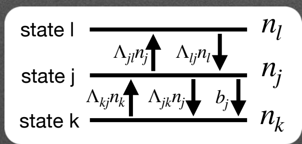
Method

Rate Equation

Balance of transition flows between each state in the steady state

$$\sum_{i=1}^{N} (\Lambda_{ij} n_i - \Lambda_{ji} n_j) = b_j \quad (j = 1,2,\ldots,N)$$

(Lucy 1991; Hachinger+ 2012)



* Λ_{ij} and b_j depend on atomic data

helium atomic data reference: Nahar 2010; Ralchenko+ 2008; NIST ASD (Kramida+ 2023)

Ionization by non-thermal electrons

ionization rate [$\mathrm{cm^{-3}\,s^{-1}}$]

$$\Gamma = \frac{D^{\rm pure}_{\rm ion} Y_{\rm He} \dot{Q}_{\rm dep}}{I_{\rm ion}}$$

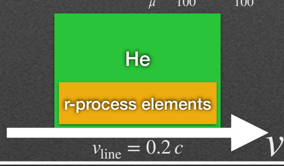
- $D^{\rm pure}_{\rm ion}$: deposition fraction for ionization in the pure helium plasma
- $Y_{\rm He}$: number fraction of helium
- $\dot{Q}_{\rm dep}$: heating rate by non-thermal electrons
- $I_{\rm ion}$: ionization potential

Ejecta model

- We assume $\rho_{\rm line} = 10^{-14}\,\mathrm{g\,cm^{-3}}$, $T = 5{,}000\,\mathrm{K}$ in the line forming region for all models.
- We define $\rho_{\rm core}$ for SN model in order to consider gamma ray transfer effect from the core region.
- $n_{e,\rm free} = n^{\rm He}_{e,\rm free} + (1 - X_{\rm He}) \dfrac{\rho_{\rm line}}{\mu m_u} Z_{\rm ion}$

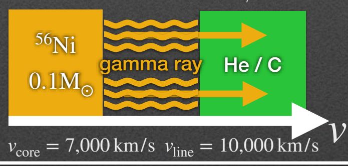
KN model

$t_{\rm expl} = 1.5$ days
$Z_{\rm ion} = 2.5$
$\frac{1}{\mu} = \frac{24}{100} X_{\rm He} + \frac{1}{100}$



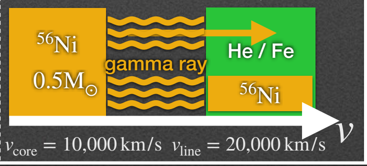
(stripped envelope) CCSN model

$t_{\rm expl} = 40$ days
$Z_{\rm ion} = 0.5$
$\frac{1}{\mu} = \frac{1}{6} X_{\rm He} + \frac{1}{12}$



Type Ia SN model

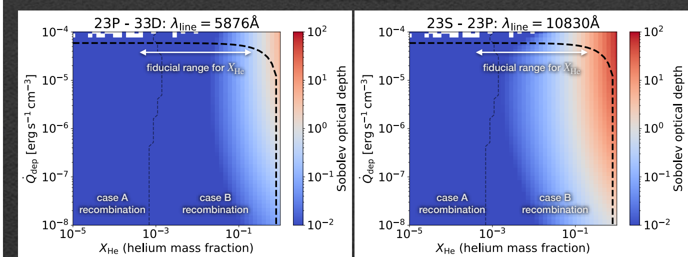
$t_{\rm expl} = 10$ days
$Z_{\rm ion} = 2$
$\frac{1}{\mu} = \frac{13}{56} X_{\rm He} + \frac{1}{56}$



Result & Discussion

* thick black dashed line: fiducial $\dot{Q}_{\rm dep}$ for each model

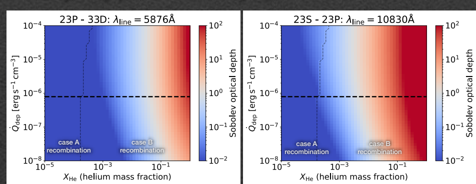
KN model



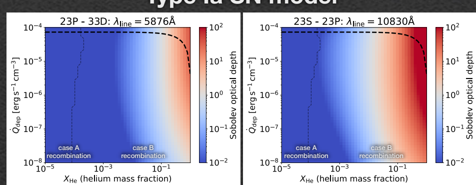
$$\tau_{\rm sob} = \frac{\pi e^2}{m_e c} \lambda_{\rm line} f_{lu} n_l t_{\rm expl}$$

difference timescale of $t_{\rm expl}$

(stripped envelope) CCSN model



Type Ia SN model



- Helium absorption line strength is less dependent on $\dot{Q}_{\rm dep}$, but strongly dependent on $X_{\rm He}$.
- fiducial condition: $X_{\rm He} \gtrsim 0.1$ (Note that there is a large uncertainty about $X_{\rm He}$ in BNS merger ejecta.)