Helium Absorption Lines in Kilonova Spectra

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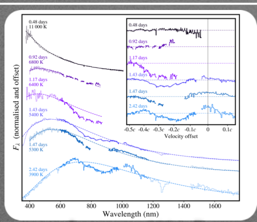
Introduction

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.

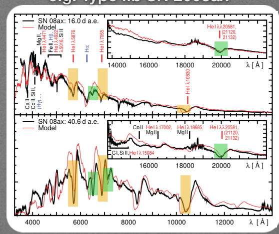
- In the spectra of the kilonova AT2017gfo, a P-Cygni feature at around 1 μm is important due to its strength.
- Candidate elements contributing this feature:
  - Sr II → well investigated in LTE radiative transfer simulations
  - He I → not yet due to the need for taking into account the "Non-LTE" effect



Sneppen+ 2024, Figure 4

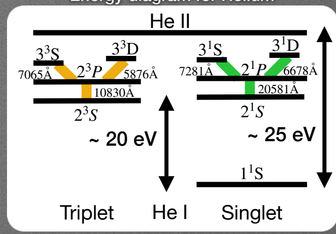
Helium absorption lines in KNe/SNe spectra

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

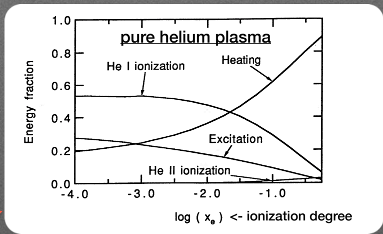
"Non-LTE" effect

(Lucy 1991; Hachinger+ 2012)

radioactive elements → decay → gamma ray (~MeV) → Compton scattering → non-thermal electrons (keV - MeV)

kinetic energy of non-thermal electrons $\dot{Q}_{\mathrm{dep}}$
- LTE → used only for heating thermal free electrons
- Non-LTE → used not only for above but for exciting and ionizing atoms and ions

described by Spencer-Fano Equation



Kozma & Fransson 1992, Figure 3 modified

This study

- We search for the condition, in the $X_{\mathrm{He}} - \dot{Q}_{\mathrm{dep}}$ 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).

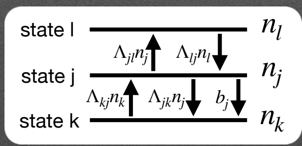
Method

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

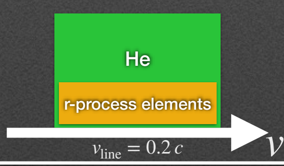
$$\Gamma = \frac{D_{\mathrm{ion}}^{\mathrm{pure}} Y_{\mathrm{He}} \dot{Q}_{\mathrm{dep}}}{I_{\mathrm{ion}}}$$

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

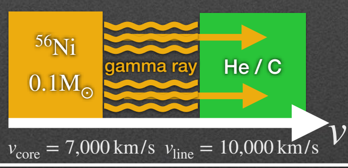
Ejecta model

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

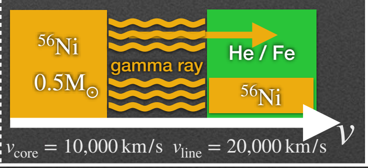
KN model ($t_{\mathrm{expl}} = 1.5\,\mathrm{days}$, $Z_{\mathrm{ion}} = 2.5$, $A_{\mathrm{mix}} = 100$)



(stripped envelope) CCSN model ($t_{\mathrm{expl}} = 40\,\mathrm{days}$, $Z_{\mathrm{ion}} = 0.5$, $A_{\mathrm{mix}} = 12$)



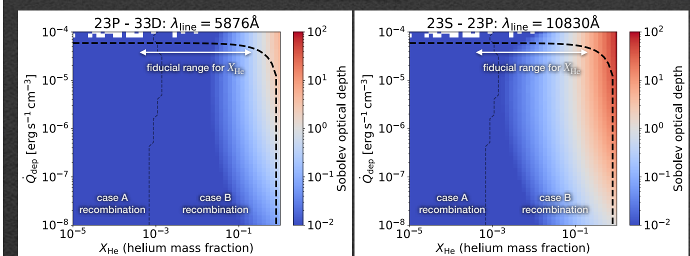
Type Ia SN model ($t_{\mathrm{expl}} = 10\,\mathrm{days}$, $Z_{\mathrm{ion}} = 2$, $A_{\mathrm{mix}} = 56$)



Result & Discussion

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

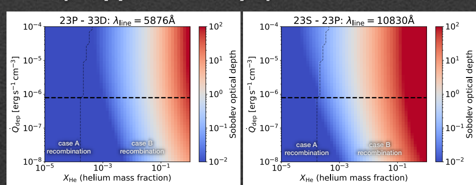
KN model



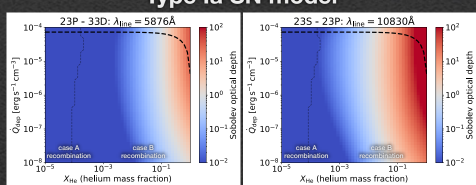
$$\tau_{\mathrm{sob}} = \frac{\pi e^2}{m_e c} \lambda_{\mathrm{line}} f_{lu} n_l t_{\mathrm{expl}}$$

difference: timescale of t_{expl} ←→

(stripped envelope) CCSN model



Type Ia SN model



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