Kilonova and r-process in neutron star mergers

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Introduction: Kilonova

• "*Kilonova*" is an electromagnetic counterpart of *neutron star mergers (Li & Paczynski 98)*.

• *Radioactivity* of r-process nuclei powers kilonvoae. (e.g. Metzger+10).

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- A kilonova after the 1st *gravitational-wave merger* **GW170817**.
- This is only the kilonova associated with GWs.
- © Tohoku University • A kilonova candidate was discovered after the second brightest long GRB 230307A.
- JWST took the spectra of this event.

We wish to learn the elements' origin from kilonova observations

Merging Neutron Stars Dying Low Mass Stars

Exploding Massive Stars Exploding White Dwarfs Cosmic Ray Fission

Big Bang

coreated by Jennifer Johnson

Li & Paczynski 98, Kulkarni 05, Metzger + 10, Barnes & Kasen 13, Tanaka & KH 13

Time

10km 10-100km

The energy budget of the Kilonova in GW170817

Kilonova: Mass, Velocity, Opacity, Radioactivity mass system around the location of AT2017gfo.²³¹ Therefore, GW170817 is likely nifoliova. Mass, velocity, opacity, nauloactivit Merger of 2 kpc and 2 kpc award the center of the the center of the center of the system of the Sanda China Ch did not receive a strong national kick of α to have a merger time of \mathbf{r}_i , the projected distance of th llonova: Mass, Velocity, Opacity, Radioactivity did not receive a strong natal kick of & 200 km/s.230–233

imately satisfy the following relations for a given ejecta mass, velocity, and opacity.

◆¹*/*² ✓ *M*ej

✓

The light curve rises on a division time: ابان.
 s Peak time:

s

4⇡*v*²

ej*t*² p

Boltzmann constant. Here, we use *^Q*˙(*t*) ⇡ ¹⁰¹⁰*^t*

$$
t_{\rm p} \approx \sqrt{\frac{\xi \kappa M_{\rm ej}}{4\pi c v_{\rm ej}}} \approx 5 \,\mathrm{days} \,\xi^{1/2} \left(\frac{\kappa}{10 \,\mathrm{cm}^2/\mathrm{g}}\right)^{1/2} \left(\frac{M_{\rm ej}}{0.01 M_{\odot}}\right)^{1/2} \left(\frac{v_{\rm ej}}{0.1 c}\right)^{-1/2},
$$
\n
$$
\text{Peak Luminosity:} \qquad \text{Radioactivity} \qquad L_{\rm bol}(t > t_{\rm p}) \approx M_{\rm ej} \cdot \dot{Q}(t) \approx \frac{2.5 \cdot 10^{40} \,\mathrm{erg/s}}{2.5 \cdot 10^{40} \,\mathrm{erg/s}} \left(\frac{t_{p}}{5 \,\mathrm{day}}\right)^{-1.3} \left(\frac{M_{\rm ej}}{0.01 M_{\odot}}\right),
$$
\n
$$
\text{Temperature:} \qquad T_{\rm eff}(t_{\rm p}) \approx \left(\frac{L_{\rm bol}(t_{\rm p})}{4\pi \sigma v_{\rm ej}^{2} t_{\rm p}^{2}}\right)^{1/4} \approx 2200 \,\mathrm{K} \left(\frac{L_{\rm bol, p}}{2.5 \cdot 10^{40} \,\mathrm{erg/s}}\right)^{1/4} \left(\frac{v_{\rm ej}}{0.1 c}\right)^{-1/2} \left(\frac{t_{\rm p}}{5 \,\mathrm{day}}\right)^{-1/2} (5).
$$

2*.*5 *·* 10⁴⁰ erg*/*s

0*.*1*c*

day erg/s/g, which is a general

◆¹*/*²

The energy budget of the Kilonova in GW170817

- Ejecta mass is~ 0.05Msun.
- The photospheric velocity ~0.1-0.3c. ejecta mass of 0*.*05*M*, the beta-decay heating rate with the solar r-process abundance (85 *A* 209), and the ejecta profile with *n* = 4*.*5,

Observed Spectrum of kilonova GW170817

Observed Spectrum of a kilonova GW170817

The temperature is low ~ 5000 K even at 1.5 day.

Observed Spectrum of a kilonova GW170817

Two clear absorption line features at 8000A & 15000A.

Observed Spectrum of a kilonova GW170817

Later, >7.5d, an emission line feature appears at 2.1 μ m.

Kilonova vs R-rich star

Strong absorption lines in kilonova should exist in r-rich stars' spectra.

Absorption line identification in GW70817

P-Cygni lines (absorption-emission line)

- Sr II: 0.8μm feature (Watson+19, Gillanders+21, but see Tarumi, KH, + 23 for He I)
- Y II: Sneppen & Watson 23
- La III: 1.3μm feature (Domoto…KH, 22)
- Ce III: 1.6μm feature (Domoto…KH, 22, Tanaka… KH, 23)

H 1 He 2 K 19 Ca 20 Sc 21 Ti 22 V 23 Cr 24 Mn 25 Fe 26 Co 27 Ni 28 Cu 29 Zn 30 Ga 31 Ge 32 As 33 Se 34 Br 35 Kr 36 Na 11 Mg 12 Al 13 Si 14 P 15 S 16 Cl 17 Ar 18 Ne 10 F 9 O 8 N 7 C 6 B 5 Be 4 Rb 37 Sr 38 Y 39 Zr 40 Nb 41 Mo 42 Tc 43 Ru 44 Rh 45 Pd 46 Ag 47 Cd 48 In 49 Sn 50 Sb 51 Te 52 I 53 Xe 54 Cs 55 Ba 56 Ln Hf 72 Ta 73 W 74 Re 75 Os 76 Ir 77 Pt 78 Au 79 Hg 80 Tl 81 Pb 82 Bi 83 Po 84 At 85 Rn 86 Fr Ra An 87 88 3 Li

Fine structure lines

• For example, [O III] 51.81 μm, 88.36 μm in the ISM, [Co III] 11.89 μm in SNe Ia.

Example: Supernova Ia Nebula

- SN Ia is clearly an iron explosion photometry and the MIRI flux is scaled to the MIRI F1000W photometry. The NIRSpec flux is unscaled from the *JWST* pipeline and matches up well to the spectrum has been dereddent and mirror the spectrum has been dered and corrected for presentatio optical spectrum and the MIR spectrum past 12.5 *µ*m have been rebinned to lower resolution. The flux axis uses a non-linear (arcsinh) scale to
- **Example 5 and Seen.** The structure lines are seen. \sim and dark subtraction, background subtraction, flat field subtraction, flat field \sim

Emission line list: Fine-structure of heavy elements Emission line list: Fine-structure of heavy elements

which the energy levels are available in the energy level in the first fine structure level. Singly ionized, the first fine structure level

- Heavy elements have fine-structure lines at \sim 1 30 µm.
- **Figure 1. Energy dierence index** into structure into at \cdot in the print. of the energy scale of 18
The Ground term line • The energy scale of 1st, 2nd, and 3rd peak elements ~ 1 μm ~ temperature.
	- The fine structure lines can dominate the kilonova cooling.

A list up to Z=99 (Einsteinium) 4 (\sim 0 (\sim 0 \sim **5 . The disc of the CEA of the Disc of the USIC**

KH+in prep.

Ions included in our line list

• 10⁵ lines are included.

splitting of lower ionized ions for a give atomic number. Heavy

is typically determined by the competition between radiative de-

cay rates and collisional deexcitaion rates of the upper level. The

where $\frac{1}{2}$

 \mathbf{H}

The strength of each emission line in the optically thin regime

, (6)

Ionization

Ionization

Figure 2. ions. • Wavelengths and transition rates are reasonably accurate (<1%)

Kilonova Nebular Spectrum

Preliminary result (KH+ in prep), collision strengths are computed with HULLAC.

- The solar abundance (2nd 3rd r-process peaks) is assumed. $X^{+1} = X^{+2} = 0.5$
- [Te III] 2.1μm is the strongest M1 line.

Te III line in the kilonova GW170817

KH+23

• The Te III line is expected to be the strongest M1 line because it is a second r-process peak element.

Te III line in the kilonova GW170817

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Out line

- Introduction Kilonova and nebular emission
- Kilonova in a long GRB 230307A
- Discussion

Extremely bright GRB 230307A

Levan,..,KH+23

shows an expected slope of 3*/*2 for a uniform distribution. The faint end deviates from this line

 $F_{\rm A}$ The fight contract CDD • The 2nd brightest GRB. plot lines representing the expected frequency of events under the assumption of a 3*/*2 slope. We would expect to observe bursts akin to GRB 230307A only once per several decades. \bullet T₉₀ ~ 35 s : Typical long GRB.

GRB 230307A: JWST NIRCam Image

• 30 days post burst. The upper panel shows the wide field of the upper panel shows the wide field of the wide fie image combining the F115W individual and F444W in the putative host is the putative host is the putation of pu \bullet Large off-set \sim 40kpc. extremely red. \bullet panel shows cut-outs of the NIRCAM data around the GRB afterglow location. The source is faint • Large off-set ~ 40kpc, extremely red.

GRB 230307A light curve and JWST photometry Levan,..KH+23

JWST Spectrum

Levan,..,KH+23

- A line feature at 2.1 μ m exists in both 30 & 60 days after the burst.
- from the nearby galaxy at *z* = 3*.*87 can also be seen o↵set from the afterglow trace. The lower panel • M(Te III)=10-3M $_{\sf sun}$ in the line forming region, v $_{\sf ej}$ =0.08c.
- α The total moses α OEM β . If the select persons abundance • The total mass $\sim 0.05 M_{sun}$ if the solar r-process abundance.

R-process mass budget from GWTC-2

Ref: Goriely 1999, Lodders et al 2009, Wanderman & Piran 2015, Fong+2015, KH, Piran, Paul 2015, Beniamini, KH, Piran 2016, Pol, McLaughlin, Lorimer 2019, KH & Nakar 2020, LVC 2020

Summary

- Sr, Y, Ce, La, He may be identified as absorption lines in the kilonova in GW70817.
- Te emission line 2.1 µm seems to produce the late time spectral peak.
- GRB 230307A was associated with a kilonova-like counterpart.
- 2.1μm line exists in the JWST spectrum, which may be Te.
- We will test the line identifications with future kilonovae.