Radioactively Powered Emission from Neutron Star Mergers

(kilonova, macronova, r-process nova, goldnova, ...)

Masaomi Tanaka (NAOJ)

- MT & Hotokezaka 2013, ApJ, 775, 113

- MT, Hotokezaka, Kyutoku, Wanajo, Kiuchi, Sekiguchi, Shibata 2013, ApJ, in press (arXiv:1310.2774)

- Hotokezaka, Kyutoku, MT, Kiuchi, Sekiguchi, Shibata, Wanajo 2013, ApJ, 778, L16

EM emission from = EM counterparts of NS-NS merger GW sources

On-axis short GRB
Off-axis radio/optical afterglow
Radioactive emission (r-process nuclei)



N. Gehrels's, A. Fruchter's, S. Wanajo's, S. Rosswog's, and B. Metzger's talks

2 deg Kiso Supernova Survey (KISS) Kiso Im Schmidt telescope









GW alert error box e.g. 10 deg x 10 deg ~ 5000 galaxies (< 200 Mpc)



Expected emission

Li & Paczynski 98 Kulkarni 05 Metzger+10 A. Bauswein's and B. Metzger's talks

Timescale

$$t_p \sim 1 \, \text{day} \left(\frac{M}{0.01 M_{\odot}}\right)^{1/2} \left(\frac{v}{0.2c}\right)^{-1/2} \left(\frac{\kappa}{0.1 \, \text{cm}^2 \, \text{g}^{-1}}\right)^{1/2}$$

Luminosity

$$L \sim 10^{42} \text{ erg s}^{-1} \left(\frac{M}{0.01M_{\odot}}\right)^{1/2} \left(\frac{v}{0.2c}\right)^{1/2} \left(\frac{\kappa}{0.1 \text{ cm}^2 \text{ g}^{-1}}\right)^{1/2}$$

energy

deposition

Opacity of Fe

energy

deposition

-1/2

~ 20 mag at 200 Mpc (Im-class telescopes)

Opacity of Lanthanoid Ce



High opacity (x 100) => Lower luminosity (x 1/10)

Kasen et al. 2013 Barnes & Kasen 2013

hydrogen 1 H 1.0079																		2 He 4.0026
Ithium 3	beryllium 4												boron 5	carbon 6	nitrogen 7	oxygen 8	fluorine	neon 10
ľ	Ro												Ř	ċ	Ń	Ô	Ĕ	No
6.041	De												D	-	14.007	15.000	10.000	INC.
sodium	magnesium												aluminium	silicon	phosphorus	sulfur	chlorine	argon
11	12												13	14	15	16	17	18
Na	Ma												A	Si	P	S	CI	Ar
22.990	24.305												26.982	28.096	30.974	32.065	35,453	39,948
potassium 10	calcium 20		scandium 21	titanium 22	vanadium 22	chromium 24	manganese 25	iron 26	cobalt 27	nickel 29	copper 20	zinc 20	gallium 21	germanium 22	arsenic 22	selenium 24	bromine 25	krypton 26
	20		ć		23	24	25	20	<i></i>	20	25	7	0	32	33	<u> </u>	- 35 - D	30
1 14					v	(r	win	FO	0.0			/n	(₁ a)		ΔC	50	Br	Kr
n	Ud I		30		v		TALL	10	00		U u		<u>u</u>		73	96		
39.098	40.078		44.956	47.867	50.942	51.996	54.938	55.845	58,933	58.693	63.546	65.39	69.723	72.61	74.922	78.96	79.904 Jodine	83.7
39.098 rubidium 37	40.078 strontium 38		44.956 yttrium 39	47.867 zirconium 40	50.942 niobium 41	51.996 molybdenum 42	54.938 technetium 43	55.845 ruthenium 44	58.933 rhodium 45	58.693 palladium 46	63.546 silver 47	65.39 cadmium 48	69.723 Indium 49	72.61 tin 50	74.922 antimony 51	78.96 tellurium 52	79.904 lodine 53	83.7 xenon 54
39.098 rubidium 37	40.078 strontum 38		44.956 yttrium 39	47.867 zirconium 40 7 r	50.942 niobium 41	51.996 motybdenum 42	54.938 technetium 43	55.845 ruthenium 44	58.933 rhodium 45	58.693 palladium 46	63.546 silver 47	65.39 cadmium 48	69.723 indium 49	72.61 tin 50	74.922 antimony 51	78.96 teturium 52	19,904 lodine 53	xenon 54
39.098 rubidium 37 Rb	40.078 strontium 38 Sr		44.966 yttrium 39 Y	47.867 zirconium 40 Zr	50.942 niobium 41 Nb	51.996 molybdenum 42 Mo	54.938 technetium 43 Tc	55.845 ruthenium 44 Ru	45 Rh	58.693 palladium 46 Pd	63.546 silver 47 Ad	65.39 cadmium 48 Cd	indium 49	12.61 10 50 Sn	antimony 51 Sb	18.96 telurium 52 Te	iodine 53	xenon 54 X 2
39.098 rubidium 37 Rb 85.468 caesium	40.078 strontlum 38 Sr 87.62 barlum		44.966 yttrium 39 Y 88.906 lutetium	47.867 zirconium 40 Zr 91.224 hafnium	50.942 niobium 41 Nb 92.906 tantalum	51,996 motybdenum 42 Mo 95,94 tungsten	54.938 technetium 43 Tc	55.845 ruthenium 44 Ru 101.07 osmium	58,933 rhodium 45 Rh 102,91 iridium	58.693 palladium 46 Pd 106.42 platinum	63.546 silver 47 AC 107.87 gold	65.39 cadmium 48 Cd 112.41 mercury	69.723 indium 49 In 114.82 thallium	72.61 tin 50 Sn 118,71 lead	74.922 antimony 51 Sb 121.76 bismuth	78.96 teturium 52 Te 127.60 potonium	79.904 iodine 53 126.90 astatine	8.3.7 xenon 54 X 2 137 29 radon
39.098 rubidium 37 Rb 85.468 caesium 55	40.078 strontum 38 Sr 87.62 barium 56	57-70	44.966 yttrium 39 Y 88.906 lutetium 71	47.867 zirconium 40 Zr 91.224 hafnium 72	50.942 nioblum 41 Nb 92.906 tantalum 73	51,996 motybdenum 42 Mo 95,94 tungsten 74	54,938 technetium 43 Tc [98] rhenium 75	55.845 ruthenium 44 Ru 101.07 osmium 76	58.933 rhodium 45 Rh 102.91 iidium 77	58.693 palladium 46 Pd 106.42 platinum 78	63.546 silver 47 AC 107.87 gold 79	65.39 cadmium 48 Cd 112.41 mercury 80	69.723 Indium 49 In 114.82 thallium 81	72.61 tin 50 Sn 118.71 lead 82	74.922 antimony 51 Sb 121.76 bismuth 83	78.96 teturium 52 Te 127.60 polonium 84	126.90 126.90 astatine 85	83.7 xenon 54 X 137.29 radon 86
Rb 39.098 rubidium 37 Rb 85.468 caesium 55 Cs	40.078 strontium 38 Sr 87.62 barium 56	57-70 ★	44.966 yttrium 39 Y 88.906 lutetium 71	47.867 zirconium 40 Zr 91.224 hafnium 72	50.942 niobium 41 Nb 92.906 tantalum 73 Ta	51,996 molybdenum 42 Mo 95,94 tungsten 74	54.938 technetium 43 TC [98] rhenium 75 RA	55.845 ruthenium 44 Ru 101.07 osmium 76	58,933 rhodium 45 Rh 102,91 iridium 77	58,693 pallactium 46 Pd 106,42 platinum 78 Pt	63.546 silver 47 AC 107.87 gold 79 A	65.39 cadmium 48 Cd 112.41 mercury 80	69.723 indium 49 In 114.82 thallium 81	72.61 tin 50 Sn 118.71 lead 82 Ph	74.922 antimony 51 Sb 121.76 bismuth 83 Bi	78.96 teturium 52 Te 127.60 polonium 84	126.90 astatine 85	83.9 xenon 54 X 2 131.29 radon 86 R
122.04	40.078 strontum 38 Sr 87.62 barium 56 B	57-70 ×	44.966 yttrium 39 Y 88.906 lutetium 71	47.867 zirconium 40 Zr 91.224 hafnium 72 Hf	50.942 nioblum 41 Nb 92.906 tantalum 73 Ta	51,996 molybdenum 42 Mo 95,94 tungsten 74 W	54,938 technetium 43 Tc [98] menium 75 Ro	55.845 ruthenium 44 Ru 101.07 osmium 76 OS	58,933 rhodium 45 Rh 102,91 iridium 77 Ir	58.693 palladium 46 Pd 106.42 platinum 78 Pf	63.546 silver 47 AC 107.87 gold 79 ALL	65.39 cadmium 48 Cd 112.41 mercury 80	69.723 Indium 49 In 114.82 thailium 81 TI	72.61 tin 50 Sn 118.71 lead 82 Ph	74.922 antimony 51 Sb 121.76 bismuth 83 Bi	78.96 teturium 52 Te 127.60 potonium 84 Pool	75,904 iodine 53 126.90 astatine 85 A +	xenon 54 Xee 137.29 radon 86 R
132.91 francium	40.078 strontium 38 Sr 87.62 barium 56 B 137.33 radium	57-70 X	44.966 yttrium 39 Y 88.906 lutetium 71 174.97 lawrencium	47.867 zirconium 40 Zr 91.224 hafnium 72 Hf 178.49 rutherfordium	50.942 niobium 41 Nb 92.906 tantalum 73 Ta 180.95 dubnium	51,996 molybdenum 42 MO 95,94 tungsten 74 W 183.84 seaborgium	54.938 technetium 43 TC [98] rhenium 75 RC 186.21 bohrium	55.845 ruthenium 44 Ru 101.07 osmium 76 06 190.23 hassium	58.933 rhodium 45 Rh 102.91 iridium 77 Ir 192.22 meitnerium	58.693 pailactium 46 Pd 106.42 platinum 78 Pt 195.08 ununnitium	63.546 silver 47 AC 107.87 gold 79 ALL 196.97 unununium	65.39 cadmium 48 Cd 112.41 mercury 80 Hg 200.59 unurbium	69.723 Indium 49 114.82 thallium 81 TI 204.38	72.61 tin 50 Sn 118.71 lead 82 Dh 207.2 unsequadium	74.922 antimony 51 Sb 121.76 bismuth 83 Bi 208.98	78.96 telurium 52 Te 127.60 polonium 84 PO	126.90 astatine 85 A + [210]	83.9 xenon 54 X 2 131 25 radon 86 R
132.91 francium 37 Rb 85.468 caesium 55 Cc 132.91 francium 87	40.078 strontlum 38 Sr 87.62 barium 56 R 137.33 radium 88	57-70 ★ 89-102	44.966 yttrium 39 Y 88.906 lutetium 71 174.97 lawrencium 103	47.867 zirconium 40 Zr 91.224 hafnium 72 Lif 178.49 rutherfordium 104	50.942 niobium 41 Nb 92.906 tantalum 73 Ta 180.95 dubnium 105	51.996 molybdenum 42 Mo 95.94 tungsten 74 W 183.84 seaborgium 106	54,938 technetium 43 Tc [98] rhenium 75 Ro 186.21 bohrium 107	55,845 ruthenium 44 Ruu 101.07 osmium 76 OS 190.23 hassium 108	58,933 rhodium 45 Rh 102.91 iridium 77 Ir 192.22 meitnerium 109	58.693 palladium 46 Pd 106.42 platinum 78 Df 196.08 ununnilium 110	63.546 silver 47 AC 107.87 gold 79 ALL 196.97 unununium 111	65.39 cadmium 48 Cd 112.41 mercury 80 HC 200.59 unurbium 112	69.723 Indium 49 In 114.82 thallium 81 TI 204.38	72.61 tin 50 Sn 118.71 lead 82 Ph 207.2 unenquadium 114	74.922 antimony 51 Sb 121.76 bismuth 83 Ri 208.98	78.96 teturium 52 Te 127.60 potonium 84 Po	126.90 astatine 85 A + [210]	83.7 xenon 54 X 29 radon 86 R [222]
132.91 francium 37 Rb 85.468 caesium 55 Cs 132.91 francium 87 Fr	40.078 strontium 38 Sr 87.62 barium 56 B 137.33 radium 88 R2	57-70 ★ 89-102 ★ ★	44.966 yttrium 39 Y 88.906 Iutetium 71 174.97 Iawrencium 103	47.867 zirconium 40 Zr 91.224 hafnium 72 Hf 178.49 rutherfordium 104 Rf	50.942 niobium 41 Nb 92.906 tantalum 73 Ta 180.95 dubnium 105 Db	51,996 molybdenum 42 MO 95,94 tungsten 74 W 183.84 seaborgium 106 SCI	54.938 technetium 43 TC [98] rhenium 75 RC 186.21 bohrium 107 Bh	55.845 ruthenium 44 Ru 101.07 osmium 76 06 190.23 hassium 108 HS	58,933 rhodium 45 Rh 102,91 iridium 77 Ir 192,22 meitnerium 109 Mt	58.693 pailacium 46 Pd 106.42 platinum 78 Pt 196.08 ununnilium 110 Uun	63.546 silver 47 Ad 107.87 gold 79 Au 196.97 unununium 111	65.39 cadmium 48 Cd 112.41 mercury 80 HG 200.59 ununbium 112 Uub	69.723 Indium 49 114.82 thailium 81 TI 204.38	72.61 tin 50 Sn 118.71 lead 82 Ph 207.2 unenquadium 114	74.922 antimony 51 Sb 121.76 bismuth 83 Ri 208.98	78.96 teturium 52 Te 127.60 polonium 84 Po	79.904 iodine 53 126.90 astatine 85 A +	83.9 xenon 54 X 20 131/29 radon 86 R [222]



Radiative transfer in NS merger ejecta with all the r-process elements

Numerical relativity

3D, time-dependent, multi-frequency radiative transfer





Hotokezaka et al. 2013

MT & Hotokezaka 2013

Opacity of r-process-dominated ejecta?
 Characteristic feature of NS merger?
 Dependence on EOSs and progenitors?



~500,000 transitions (up to Fe) +100,000 transitions (r-process)

Evaluate bound-bound opacity (in each time step)



Higher opacity by factor of 100 Fainter than previously expected by a factor of 10 (consistent with Kasen+13, Barnes & Kasen 13)



Very red SED (peak at NIR)
 Extremely broad-line (feature-less) spectra
 (Identification of r-process elements seems difficult)



Very red SED (peak at NIR)
 Extremely broad-line (feature-less) spectra
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Radius of 1.35 Msun NS

R = 11.1 km R = 13.6 km

Softer EOS/Higher NS mass ratio

Brighter emission

(Hotokezaka+13; Bauswein+13, M. Shibata's, A. Bauswein's talks)

Observing strategy after GW detection





HR diagram



MT, Hotokezaka, Kyutoku, Wanajo, Kiuchi, Sekiguchi, Shibata 2013, ApJ, in press (arXiv:1310.2774)

Application to GRB 130603B

Berger+13 Tanvir+13 A. Fruchter's talk WFC3/F160W





Constraints on Progenitors/EOSs Efficient mass ejection Mej ~ 0.02 Msun NS-NS BH-NS => soft EOS => stiff EOS



Hotokezaka, Kyutoku, MT, Kiuchi, Sekiguchi, Shibata, Wanajo 2013, ApJ, 778, L16

Summary

- EM emission from NS-NS/BH-NS mergers
 - Accurate localization of GW sources
- "Full" radiative transfer simulations
 - Higher opacity than Fe by a factor of 100
 - SED peak at near-IR
 - Bluer emission from BH-NS mergers
- Observing strategy
 - 22-25 mag (i band) => 4-8m class telescopes
 - Extremely broad-line spectra
- GRB 130603B
 - Constraints on progenitors and EOSs