Electromagnetic Counterparts of Gravitational Waves

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University of Nevada, Las Vegas

Nov. 3, 2016

Compact Stars and Gravitational Waves, YITP, Kyoto, Nov. 2016

Gravitational waves detected!



GW 150914, GW 151226, LVT 151012

BH-BH mergers (Abbott et al. 2016a,b)



NS-NS, NS-BH mergers?

Nuttall's talk

Gravitational waves

• Quadrupole rather than dipole

$$-\dot{E} = \frac{G}{5c^3} \left\langle \ddot{I}_{ij}\ddot{I}^{ij} \right\rangle$$

Quadrupole moment tensor:

$$I_{ij} = \int \rho(x_i x_j - r^2 \delta_{ij}/3) d^3 x$$

- Speed of light
- Luminosity $L_{\text{GW}} \sim \frac{c^5}{G} \left(\frac{GM}{c^2L}\right)^5 \sim \frac{c^5}{G} \left(\frac{r_g}{L}\right)^5 \qquad \frac{c^5}{G} \simeq 3.6 \times 10^{59} \text{ erg s}^{-1}$
- Top candidates: NS-NS, BH-NS, BH-BH mergers
- Amplitude proportional to r⁻¹
- Final frequency

$$\Omega \sim \frac{c^3}{GM} \simeq 2.0 \times 10^5 \text{ Hz } \left(\frac{M}{M_{\odot}}\right)^{-1}$$



EM signals associated with GWs: Not firmly detected yet





- Confirm the astrophysical origin of the GW signals
- Study the astrophysical physical origin of the GW sources (e.g. host galaxy, environment, etc)
- Study the detailed physics involved in GW events (e.g. equation of state of nuclear matter, black hole electrodynamics)
- Need matter or EM field

Plan of the Talk

Discuss 3 types of merger systems:

- BH NS mergers
- NS NS mergers
 - BH remnant
 - millisecond magnetar remnant
- BH BH mergers

Discuss 5 types of EM counterparts:

- short GRBs and afterglows
- kilonova / macronova / mergernova
- kilonova afterglow
- X-ray emission from magnetar
- fast radio bursts

BH-NS mergers



Bartos, I., Brady, P., Marka, S. 2013, CQGrav., 30, 123001

BH-NS mergers (small mass ratio)



- Jetted component (likely, but low probability):
 - Short GRB (sGRB)
 - sGRB afterglow (X-ray, UV/ optical/IR, radio)
- Quasi-Isotropic component (likely, but faint):
 - Macronova/kilonova/ mergernova (optical/IR) detected with sGRBs
 - kilonova afterglow (radio flare)

Talks by Nissanke, Tanaka, Janka, Piran

Halloween Pumpkin





Halloween Pumpkin





EM counterpart 1 (likely): Short GRBs/afterglows





- In different types of host galaxies, including a few in elliptical/early-type galaxies, but most in star-forming galaxies
- Large offsets, in regions of low star formation rate in the host galaxy. Some are outside the galaxy.
- Relatively faint afterglows
- Leading model: NS-NS or NS-BH mergers



Rezzolla et al. 2011

Short GRBs as GW EM counterpart: Caveats



- Not all SGRBs are related to mergers – some may be related to massive stars (similar to LGRBs) (Zhang et al. 2009; Virgili et al. 2012; Bromberg et al. 2013)
- SGRBs are collimated only a small fraction of GW events will be associated with SGRBs.

EM counterpart 2 (likely): Kilonova, macronova, mergernova



- Kilonova (macronova, Li-Paczynski nova, r-process nova, mergernova): SN-like transients powered by nuclear radioactivity (and possible a magnetar) in the ejecta of compact star mergers
 - 1-day V-band luminosity: 3×10⁴¹ erg/s (Metzger et al. 2010): 3-5 orders of magnitude fainter than GRB afterglow
- High opacity from heavier
 elements (e.g. lanthanides) –
 peak in IR (Barnes & Kasen 2013)
- Detections in GRB 130603B and several others

Kilonova, macronova, mergernova



GRB 060614 Yang et al. (2015)



GRB 050709 Jin et al. (2016)

The Kilonova Handbook

Brian D. Metzger*

November 1, 2016

- 1974 Lattimer & Schramm: *r*-process from BH-NS mergers
- 1975 Hulse & Taylor: discovery of binary pulsar system PSR 1913+16
- 1989 Eichler et al.: GRBs, *r*-process from NS-NS mergers
- 1998 Li & Paczynski: first kilonova model, with parametrized heating
- 1999 Freiburghaus et al.: NS-NS dynamical ejecta \Rightarrow r-process abundances
- 2005 Kulkarni: kilonova powered by free neutron-decay ("macronova")
- 2009 Perley et al.: optical kilonova candidate following GRB 080503 (Fig. 10)
- $2010 \bullet$ Metzger et al., Roberts et al.: kilonova powered by r-process heating
- 2013 Barnes & Kasen, Tanaka & Hotokezaka: La/Ac opacities \Rightarrow NIR spectral peak
- 2013 Tanvir et al., Berger et al.: NIR kilonova candidate following GRB 130603B
- 2013 Yu, Zhang, Gao: magnetar-boosted kilonova ("merger-nova")
- 2014 Metzger & Fernandez, Kasen et al.: blue kilonova from the disk winds

Figure 1: Timeline of major developments in kilonova research

EM counterpart 3 (likely): Radio afterglow of kilonova (radio flare)



- Radio afterglow: synchrotron emission from shock when the kilonova ejecta is decelerated (Nakar & Piran, 2011; Piran et al. 2013; Hotokezaka & Piran 2015)
- No candidate yet
- Issue:
 - Long delay
 - Density n is likely small (kick)

NS-NS mergers: Three types of merger products



EM counterparts of NS-NS mergers the case of a BH engine: similar to BH-NS mergers



- Jetted component (likely, but low probability):
 - Short GRB (sGRB)
 - sGRB afterglow (X-ray, UV/ optical/IR, radio)
- Quasi-Isotropic component (likely, but faint):
 - Macronova/kilonova/ mergernova (optical/IR) detected with sGRBs
 - kilonova afterglow (radio flare)

Metzger & Berger (2012)

Supra-massive and stable NSs



Observational hints of a possible supra-massive / stable NS as the merger product (I)

MARTINEZ ET AL.

THE ASTROPHYSICAL JOURNAL, 812:143 (8pp), 2015 October 20

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J1804-2718 (e) J2019+2425 (h)	•	
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0.0 0.5	1.0 1.5 2.	0 2.5 3.
	Neutron star mass (M	o/

Lattimer & Prakash (2010)

Table 1 Double Neutron Star Systems Known in the Galaxy								
Pulsar	Period (ms)	P _b (days)	x (lt-s)	е	$M \ (M_{\odot})$	$M_{ m p}$ (M_{\odot})	$M_{ m c}$ (M_{\odot})	References
J0737-3039A	22.699	0.102	1.415	0.0877775(9)	2.58708(16)	1.3381(7)	1.2489(7)	(1)
J0737-3039B	2773.461		1.516					
J1518+4904	40.935	8.634	20.044	0.24948451(3)	2.7183(7)			(2)
B1534+12	37.904	0.421	3.729	0.27367740(4)	2.678463(4)	1.3330(2)	1.3454(2)	(3)
J1753-2240	95.138	13.638	18.115	0.303582(10)				(4)
J1756-2251	28.462	0.320	2.756	0.1805694(2)	2.56999(6)	1.341(7)	1.230(7)	(5)
J1811-1736	104.1	18.779	34.783	0.82802(2)	2.57(10)			(6)
J1829+2456	41.009	1.760	7.236	0.13914(4)	2.59(2)			(7)
J1906+0746 ^a	144.073	0.166	1.420	0.0852996(6)	2.6134(3)	1.291(11)	1.322(11)	(8)
B1913+16	59.031	0.323	2.342	0.6171334(5)	2.8284(1)	1.4398(2)	1.3886(2)	(9)
J1930-1852	185.520	45.060	86.890	0.39886340(17)	2.59(4)			(10)
J0453+1559	45.782	4.072	14.467	0.11251832(4)	2.734(3)	1.559(5)	1.174(4)	This letter
Globular Cluster Systems								
J1807-2500B ^a	4.186	9.957	28.920	0.747033198(40)	2.57190(73)	1.3655(21)	1.2064(20)	(12)
B2127+11C	30.529	0.335	2.518	0.681395(2)	2.71279(13)	1.358(10)	1.354(10)	(13)

- NS with mass > 2 M_{\odot} has been discovered
- NS-NS systems: total mass ~ 2.5-2.6 M<sub>
 [®]</sub>

Talks by Lattimer, Baldo, Freire ...

Observational hints of a possible supra-massive / stable NS as the merger product (I)



Figure by Norbert Wex. See http://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html

Freire's talk

Supra-massive and stable NSs/QSs



A. Li et al. (2016, PRD, 94, 083010, arXiv:1606.02934)

Forming a supra-massive / stable neutron star via a NS-NS merger



For small enough NS masses and a reasonable NS equation of state, a stable magnetar can survive a NS-NS merger.

Giacomazzo & Perna (2013)

Observational hints of a possible supra-massive / stable NS as the merger product (II)

Internal X-ray plateaus in some short GRB afterglows



Rowlinson et al. (2010)

Rowlinson et al. (2013)





GRB model: internal vs. external

Afterglow



External vs. internal plateaus

- Plateaus in GRB X-ray afterglows
- Internal: steep decay, chromatic, "internal" origin



Internal Plateau in short GRBs

- Require engine lasts for 100's of seconds, then disappears
- A supra-massive magnetar collapses into a BH at the end of plateau

(alternative view: Rezzolla & Kumar 2015; Ciolfi & Siegel 2015)



A multi-messenger approach to constrain NS/QS equation-of-state

- GW signal: NS-NS system parameters (mass of the merger product)
- EM signal: brightness of the X-ray emission, collapse time – infer initial period, magnetic field, ellipticity, etc.
- Putting everything together: constrain NS/QS EoS!



Rowlinson et al. (2010)

Without GW signal, one can already make some constraints

 $M_{\rm max} = M_{\rm TOV}(1 + \alpha P^{\beta}),$

PHYSICAL REVIEW D 93, 044065 (2016)

Constraints on binary neutron star merger product from short GRB observations

He Gao,^{1,*} Bing Zhang,^{2,3,4} and Hou-Jun Lü^{5,6}



 $P_{c} = \left(\frac{M_{s} - M_{\text{TOV}}}{\alpha M_{\text{TOV}}}\right)^{1/\beta}.$ $\therefore \qquad 32GI^{2}e^{2}\Omega^{6} \quad B_{z}^{2}R^{6}\Omega^{4}$

$$\dot{E} = I\Omega\dot{\Omega} = -\frac{32GI^2\epsilon^2\Omega^6}{5c^5} - \frac{B_p^2R^6}{6c^3}$$
$$L_b = \frac{\eta B_p^2R^6\Omega_{\rm col}^4}{6c^3},$$

Use a sample of sGRBs

Look at the collapse fraction, collapse time distribution, plateau luminosity distribution

Constraints on NS-NS merger products from known short GRBs

- For one EoS (GM1)
- Maximum mass: ~ 2.37 M_☉
- Initial spin: ~ 1 ms
- BH:SMNS:SNS ~ 4:3:3
- Surface B field: ~10¹⁵ G
- ellipticity: 0.004-0.007
- Energy output in the EM channel: 10⁴⁹ – 10⁵² erg
- Other energy channels:
 - GW emission
 - Fall into BH



Gao, Zhang & Lu, 2016, PRD, 93, 044065

More Equations of State

Internal X-ray plateau in short GRBs: Signature of supramassive fast-rotating quark stars?

Ang Li^{1,2*}, Bing Zhang^{2,3,4†}, Nai-Bo Zhang⁵, He Gao⁶, Bin Qi⁵, Tong Liu^{1,2}

2016, PRD, 94, 083010, arXiv:1606.02934)

		$P_{\rm K}$	$I_{\rm K,max}$	M _{TOV}	R _{eq}	α	β	Α	В	С	а	q	k
	EoS	(ms)	$(10^{45} \mathrm{g} \mathrm{cm}^2)$	(M_{\odot})	(km)	$(P^{-\beta})$		(P^{-B})		(km)		(ms)	(P^{-1})
	BCPM	0.5584	2.857	1.98	9.941	0.03859	-2.651	0.7172	-2.674	9.910	0.4509	0.3877	7.334
NS	BSk20	0.5391	3.503	2.17	10.17	0.03587	-2.675	0.6347	-2.638	10.18	0.4714	0.4062	6.929
	BSk21	0.6021	4.368	2.28	11.08	0.04868	-2.746	0.9429	-2.696	11.03	0.4838	0.3500	7.085
	Shen	0.7143	4.675	2.18	12.40	0.07657	-2.738	1.393	-3.431	12.47	0.4102	0.5725	8.644
	CIDDM	0.8326	8.645	2.09	12.43	0.16146	-4.932	2.583	-5.223	12.75	0.4433	0.8079	80.76
QS	CDDM1	0.9960	11.67	2.21	13.99	0.39154	-4.999	7.920	-5.322	14.32	0.4253	0.9608	57.94
	CDDM2	1.1249	16.34	2.45	15.76	0.74477	-5.175	17.27	-5.479	16.13	0.4205	1.087	55.14
]								
Ec	oS	ε	P_i (r	ns)			1	$B_p(G)$				η	$P_{\text{best}}(t_b)$
BS	k20	0.002	0.70 - 0.7	75 (0.75)	$N(\mu_{\rm Bp} =$	$= 10^{14.8 - 15.}$	$^4, \sigma_{Bp} \leq$	0.2) $[N(\mu)]$	$_{Bp} = 10^{14}$	$^{9}, \sigma_{Bp} =$	= 0.2)]0.5	-1(0.9)	0.20
BS	k21	0.002	0.60 - 0.8	30 (0.70)	$N(\mu_{Bp} =$	$= 10^{14.7 - 15.}$	$1, \sigma_{Bp} \leq$	0.2) $[N(\mu)]$	$_{\rm Bp}^{\rm I} = 10^{15.}$	$^{0}, \sigma_{Bp}$ =	= 0.2)]0.7	-1(0.9)	0.29
C1-	0.000	0.002 (0		$\dot{0}$	M	10146-15	0	\mathbf{n}	1014	6 _	0 2010 5		0.41

Shen	0.002 - 0.003 (0.002)	0.70 - 0.90(0.70)	$N(\mu_{\rm Bp} = 10^{14.0-15.0}, \sigma_{\rm Bp} \le 0.2) [N(\mu_{\rm Bp} = 10^{14.0}, \sigma_{\rm Bp} = 0.2)][0.5 - 1 \ (0.9)]$	0.41
CIDDM	/ 0.001	0.95 - 1.05 (0.95)	$N(\mu_{\rm Bp} = 10^{14.8-15.4}, \sigma_{\rm Bp} \le 0.2) [N(\mu_{\rm Bp} = 10^{15.0}, \sigma_{\rm Bp} = 0.2)] [0.5 - 1(0.5)]$	0.44
CDDM1	$0.002 - 0.003 \ (0.003)$	1.00 - 1.40(1.0)	$N(\mu_{\rm Bp} = 10^{14.7-15.1}, \sigma_{\rm Bp} \le 0.3) [N(\mu_{\rm Bp} = 10^{14.7}, \sigma_{\rm Bp} = 0.2)] 0.5 - 1(1)$	0.65
CDDM2	0.004 - 0.007 (0.005)	1.10 - 1.70(1.3)	$N(\mu_{Bp} = 10^{14.8-15.3}, \sigma_{Bp} \le 0.4) [N(\mu_{Bp} = 10^{14.9}, \sigma_{Bp} = 0.4)] 0.5 - 1(1)$	0.84

Degeneracy with EM data only, with GW, can greatly narrow down



Collapse time: QSs favored Quark de-confinement during the merger?





Li et al. (2016)

Rowlinson et al. (2013)

EM counterparts of NS-NS mergers (forming a stable or supra-massive NS)





Gao et al. (2013)

- Jetted component (likely, still low probability):
 - Short GRB (sGRB)
 - sGRB afterglow (X-ray, UV/optical/IR, radio)
- Quasi-Isotropic component:
 - Macronova/kilonova/mergernova (optical/IR): enhanced
 - mergernova afterglow: enhanced
 - sGRB-less X-ray transients (plausible)
 - Fast radio bursts (speculative)

EM counterpart 4 (plausible): sGRB-less X-ray counterpart (orphan internal plateau)



EM counterpart 4 (plausible): sGRB-less X-ray counterpart (orphan internal plateau)



sGRB-less X-ray counterpart: light curve gallery





Sun, Zhang & Gao, arXiv:1610.03860

Alternative idea: X-ray scattering (Kisaka, Ioka & Nakamura 2015)

sGRB-less X-ray counterpart: Iuminosity function & event rate density



Sun, Zhang & Gao, arXiv:1610.03860

Candidate(s) found - stay tuned

Enhanced (Magnetar powered) Merger Novae

Yu, Zhang & Gao, 2013, ApJ, 763, L22



Enhanced (Magnetar powered) Merger Novae

Yu, Zhang & Gao, 2013, ApJ, 763, L22





Figure 2. Light curves of the merger-nova (thick) and afterglow (thin) emissions at different observational frequencies as labeled. The dashed and dotted lines are obtained for an optionally taken magnetar collapsing time as $t_{col} = 2t_{rad}$ and $t_{col} = 10^4$ s, respectively. The ambient density is taken as 0.1 cm^{-3} , and other model parameters are the same as Figure 1.

Figure 3. Optical (~1 eV) light curves of the millisecond-magnetar-powered merger-nova, in comparison with the light curves of two supernovae (bolometric) and one radioactive-powered merger-nova (as labeled). The dash-dotted (blue) and solid (orange) lines represent $M_{\rm ej} = 10^{-2} M_{\odot}$ and $10^{-4} M_{\odot}$, respectively. The thick and thin lines correspond to a magnetar collapsing time as $t_{\rm col} = 10^4 \, {\rm s} \ll t_{\rm md}$ and $t_{\rm col} = 2t_{\rm md}$, respectively. The zero-times of the supernovae are set at the first available data.

Kilonova, macronova, mergernova



Gao et al. (2016, arXiv:1608.03375)

10⁴

Time (s)

10⁵

10³

10

10-6

10¹

10²

10

10⁴

Time (s)

10⁵

10⁶

10⁷

10⁶

10⁷

10-8

10¹

10

10¹

10

10

10⁴

Time (s)

10⁵

10⁶

10

Kilonova, macronova, mergernova



Some could be super-kilo Some could be hecto

Gao et al. (2016, arXiv:1608.03375)

Enhanced magnetar-powered afterglow



Gao et al, 2013, ApJ, 771, 86

Ejecta-ISM shock with Energy Injection

Gao et al. 2013, ApJ, 771, 86

 $B_{\perp} \sim 10^{15} G, \quad M_{ej} \sim 10^{-3} M_{\odot}$





Constraints on magnetar parameters



Horesh, Hotokezaka, Piran et al. (2016)

However, $E_k = 3 \times 10^{52}$ erg. $\epsilon_e = 0.1$ $\epsilon_B = 0.1$

has been assumed

Piran's talk

The magnetar energy in sGRB remnants is much smaller, due to GW emission and falling into the BH Gao et al. (2016)



0.5

EM Counterpart 5: Speculative A possible connection with FRBs



1.1 FRB 110220 1.0 0.5 www.www. 0.0 1. FRB 110627 1.0 0.5 Density (ly) Flux, FRB 110703 1.0 0.5 FRB 120127 1.0 0.5 140 80 Time (ms)

Fig. 1. The frequency-integrated flux densities for the four FRBs. The time resolutions match the level of dispersive smearing in the central frequency channel (0.8, 0.6, 0.9, and 0.5 milliseconds, respectively).

Lorimer's talk

FRBs vs. GRBs

- Physically related???
- Culturally/socially related!







Fig. 1. The frequency-integrated flux densities for the four FRBs. The time resolutions match the level of dispersive smearing in the central frequency channel (0.8, 0.6, 0.9, and 0.5 milliseconds, respectively).





FRBs vs. GRBs

	GRBs	FRBs
Step one: Are they astrophysical?	1967 – 1973	2007 – 2015
Step two: Where are they (distance)?	1973 – 1997 – 2004	2016??
Step three: What make them?	1998 – ???	???

Observationally driven Healthy dialog between observers and theorists

FRBs: Where are they?

- Cosmological
- Extragalactic but not cosmological
- Galactic

What may make them?

(An incomplete list)

- Collapses of supra-massive neutron stars to black holes (thousands to million years later after birth, or in a small fraction hundreds/thousands of seconds after birth), ejecting "magnetic hair" (Falcke & Rezzolla 2013; Zhang 2014)
- BH-BH mergers (charged) (Zhang 2016; Liu et al. 2016)
- Magnetospheric activity after NS-NS mergers (Totani 2013)
- Unipolar inductor in NS-NS mergers (Piro 2012; Wang et al. 2016)
- Mergers of binary white dwarfs (Kashiyama et al. 2013)
- Supergiant radio pulses (Cordes & Wasserman 2015; Connor et al. 2015; Pen & Connor 2015) good for the repeating FRB
- Magnetar giant flare radio bursts (Popov et al. 2007, 2013; Kulkarni et al. 2014; Katz 2015)
- Cosmic sparks from superconducting strings (Vachaspati 2008; Yu et al. 2014)
- Evaporation of primordial black holes (Rees 1977; Keane et al. 2012)
- White holes (Barrau et al. 2014; Haggard)
- Flaring stars (Loeb et al. 2013; Maoz et al. 2015)
- Axion miniclusters, axion stars (Tkachev 2015; Iwazaki 2015)
- NS-Asteroid collisions (Geng & Huang 2015; Dai et al. (repeaters))
- Quark Nova (Shand et al. 2015)

.

- Dark matter-induced collapse of NSs (Fuller & Ott 2015)
- Higgs portals to pulsar collapse (Bramante & Elahi 2015)

Lessons from GRBs

- Discovered in late 1960s
- Didn't know where they come from
- More than 100 models
- "The only feature that all but one (and perhaps all) of the very many proposed models have in common is that they will not be the explanation of gamma-ray bursts"
 - Malvin Ruderman (1975)
- The same may be stated for FRB models

*	Author	Year Pub	Reference	Main Body	2nd Body	Place	Description
_	Colores	1000	CORPORA AN AND		-	005	9N abodie station earliers in distant advers
	Colgare	100.4	Aul. 187, 355			005	Type II 8N shock been, by Compared at stallar system
	Enclose at al.	1073	Nature, 241, 24201			DISK	Dellar moreflare from nearby star
	Sheeker et al.	1075	Nature 145, Phila	March 1		DOWN	Enterthere from enterthe WD
	Barnin en al.	1975	Aul. 186, L97	10.0	0004	DUSK	Balic comet perturbed to collide with old subsctic NS
	Looph et al.	1975	Nature 946 PERS	WTD.	-	DUSK	Acception onto WB from flam in companion
	Looph et al.	1973	Nature, 244, P552	NIL	87	DOIN	Acception unto NE from flute in companion
	Looph et al.	1973	Nature, 246, P552	10.14	ST.	DOW	Accession onto BH from flare in companion
	Zwicky	1974	Apr & 25, 28, 111	201		HALO	NS churk contained by external pressure escapes, explodes
	Grindlay et al.	1974	ApJ, 147, L93	DO.		506	Belativistic ison dust grain un eratters solar radiation
	Brocher et al.	1974	ApJ, 187, 1.97	ST.		DORK	Directed shellor flare on nearby star
	Behlevakii	1074	Sec. Astron. 18, 200	WD	COM	DOW	Comet from system's cloud stellars WD
	Schlowskii	1974	Southsteen, 18, 200	NS.	COM	DON	Comet from system's cloud strikes NS
	Bianovatri, et al.	1975	Ap & 85, 35, 23	ST.		008	Absorption of neutrino emission from SN in stellar envelope
	Bianowatric et al.	1975	An & 88, 31, 23	8T	830	008	Thermal emission when small star heated by SN shock wave
	Bisnovatyl- et al.	1975	Ap & 55, 35, 23	305		005	Ejected matter from NS explodes
	Pacini et al.	1974	Nature, 951, 899	NE		DOM	NS crustal starquake glitch; should time coincide with GRB
	Narlikar et al.	1974	Nature, 251, 590	WH		008	White hole emits spectrum that softens with time
	Trougan	1975	A&A, 44, 21	703		HALO	NS corresponder excitors vibrations, changing E & B fields
	Chanmagam	1974	ApJ, 193, L75	WD		DISK	Convection inside WD with high B field produces flare
	Prilutaki et al.	1978	Ap & 88, 34, 305	AGN	ST	008	Collapse of supermassive body in sucleus of active galaxy
	Narlikar et al.	1975	Ap & 88, 31, 321	WOL		008	Will eacites synchrotron emission, inverse Compton scattering
	Pinan et al.	1975	Nature, 256, 112	10.04		DON	Inv Comp stat deep in ergosphere of fast rotating, accreting BH
	Fabian et al.	1976	Ap & 55, 42, 77	N.5.		DISK	NS crustquake shocks NS surface
	Chanmagam	1976	Ap & 55, 42, 83	WD		DISK	Magnetic WD suffers MHD instabilities, fares
	Mullan	1976	ApJ, 208, 199	WD		DON	Thermal radiation from flare near magnetic WD
	Woosley et al.	1976	Nature, 263, 101	5.5		DISK	Carbon detonation from accreted matter onto NS
	Louth et al.	1977	ApJ, 217, 197	5.5		DOM:	Mag grating of accret disk around NS causes sudden accretion
	Piran et al.	1977	ApJ, 214, 268	1804		DOSK.	Instability in accretion onto rapidly rotating BB
	Dasgupta	1979	Ap & 88, 63, 517	DG		806	Charged intergal rel dust grain enters sol sys, breaks up
	Taygan	1980	A&A, 87, 224	W D		DOM:	WD surface nuclear burst causes thromospheric flares
	Trougan	1980	A&A, 87, 224	N.S.		DISK	NS surface nuclear burst causes chromospheric flares
	Ramaty et al.	1991	Ap & 85, 75, 193	348		DOK	NS vibrations heat atm to pair produce, analhilate, synch cool
	Newman et al.	1980	ApJ, 242, 319	218	AST	DISK	Astoroid from interstellar medium hits N8
	Romaty et al.	1980	Nature, 287, 122	315		HALO	NS core quake caused by phase transition, vibrations
	Roward et al.	1981	ApJ, 249, 302	N8	AST	DISK	Astoroid hits NS, B-field confines mass, creates high temp
	Mitrofanov et al.	1981	Ap & 88, 77, 469	2.8		DORK	Helium flash cooled by MHD waves in NS outer layers
	Colgate et al.	1991	ApJ, 248, 771	5.5	ATT	D15N	Asteroid hits NS, tidally disrupts, heated, expelled along B lines
	wan Bluren	110401	ApJ, 249, 297	N.S.	AST	DOM	Asturoid eaters NS II field, dragged to earlace collision
	Kusselsow	1982	CosRes, 20, 72	MG		806	Magnetic reconnection at heliopause
	Kata	1982	ApJ, 260, 371	26.8		DOBK.	NS flares from pule plasma confined in NS magnetoephere
	Woosley et al.	1982	ApJ, 258, 716	5.5		DOM:	Magnetic reconnection after NS surface He flash
	Figurell et al.	1982	ApJ, 258, 793	N.B.		DOM	He fusion runaway on NS II-pole helium lake
	Ramoury et al.	1982	A&A, 111, 242	2.8		DOSK	e- capture triggers H flash triggers He flash on NS surface
	Mitpofanov et al	1982	MNRA5, 200, 1008	53		DOM:	D induced cyclo res in rad absorp giving rel e-s, inv C scat
	Fealmore et al.	1982	Nature, 297, 665	19.15		DISK	BB X-rays inv Comp scat by hotter overlying plasma
	Lipunov et al.	1987	Ap & 55, 85, 459	5.5	15 M	DON	ISM matter accum at NS magnetopause then suddenly accretes
	Fiant	1.04(2	ApJ, 261, L71	WD.		HALO	Nonexplosive collapse of WD into solating, cooling NS
	Ventura et al.	1983	Nuture, 301, 491	1919	81	DOWN	NS accretion from low mass binary companion
	Disnovatyi- et al.	1985	Ap & 55, 89, 447	50		DOM:	Neutron sich ensisents to NS surface with quake, undergo fission
	Bianovatyi- et al.	1984	Sov.A.Aron, 28, 62	1.5		DOSK	Thermonuclear explosion beneath NS surface
	Ellison et al.	1983	A&A, 128, 102	2.3		HALO	NS correquise + uneven heating yield SGR publishes
	Rameury et al.	198.5	A&A, 128, 169	5.5		DOM:	3 Beld contains matter on NS cap allowing fusion
	The second second second second	a reason of	A 8 4 5 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	100.00		and the second second	WE supplied high supplications choose annual scale is supplied with

Table 1

Nemiroff, 1994, Comments on Astrophysics, 17, 189

128 models

Multiple progenitor systems?



High event rate: Easy to make! More than one way to make!

Blitzar: Magnetic hair ejection of neutron star implosion



Falcke & Rezzolla (2014): happen thousands to millions of years after the birth of SMNSs Zhang (2014): a small fraction can happen minutes to days after the birth of SMNSs

Rezzolla's talk

FRBs in GRBs

- Internal plateaus cannot be interpreted within the framework of the external shock models
- The rapid drop at the end of plateau may mark collapse of a millisecond magnetar to a black hole
- So the end of plateau may be the epoch when an FRB is emitted
- Rapid radio follow-up (within 100 s) of GRBs may lead to discovery of an associated FRB, may be brighter than normal FRBs.



BH-BH mergers



- Two naked BHs: No EM counterpart expected!
- EM counterparts can be generated if at least one BH can retain matter or EM fields

GRB following GW 150914? (GW150914-GBM)



Abbott et al. 2016)





- Weak burst above 50 keV
- Onset time: 0.4 s after GW 150914
- Duration 1s
- Direction broadly consistent
- False alarm probability 0.0022 (2.9 σ)
- L~ $1.8^{+1.5}_{-1.0} \times 10^{49} \text{ erg s}^{-1}$

but see Greiner et al. (2016); Xiong (2016)

Unconventional Ideas for EM counterparts of BH-BH mergers

- Models with matter
 - Twin BHs inside one star (Loeb 2016, but see Woosley 2016)
 - Reactivated accretion disk (Perna et al. 2016, but see Kimura et al. 2016)
 - Multi-body interactions ...
- Models with EM fields
 - Charged BH-BH mergers (Zhang 2016, Liu et al. 2016; Fraschetti 2016; Liebling & Palenzuela 2016)



Charged









(Zhang, ApJ, 827, L31)

Part 1: Consequence of charges



High school E&M



Charged BH merger model (Zhang, ApJ, 827, L31)

Part 2: How to make and maintain charged BHs?



Mosta, Nathanail & Rezzolla (2016)

Rezzolla's talk



Collapse to what?



collapse to Schwarzschild BH collapse to Kerr-Newman BH

Rezzolla's talk

Bottom line

A rotating magnet is charged and remain charged - a pulsar is charged

Theory of pulsar magnetospheres

F. Curtis Michel

Space Physics and Astronomy Department, Rice University, Houston, Texas

There is a wide range of fundamental physical problems directly related to how pulsars function. Some of these are independent of the specific pulsar mechanism. Others relate directly to the physics of the pulsar and already shed some light on the properties of matter at high density $(-10^{15} g/cc)$ and in strong magnetic fields $(-10^{12} G)$. Pulsars are assumed to be rotating neutron stars surrounded by strong magnetic fields and energetic particles. It is somewhere within this "magnetosphere" that the pulsar action is expected to take place. Currently there has been considerable difficulty in formulating an entirely self-consistent theory of the magnetospheric behavior and there may be rapid revisions in the near future, which is all the more surprising since many of the issues involve "elementary" problems in electromagnetism. One interesting discovery is that charge-separated plasmas apparently can support stable static discontinuities.

b. The central charge

Let us now ask why there should be a huge charge associated with a point dipole. See, for example, Cohen *et al.* (1975). From E_r (outside) and Gauss's law we have a positive central charge

$$Q = 8\pi\varepsilon_0 a \Phi_0/3$$
,

which is of the order of 10^{12} C (or about 10^{7} moles of electrons!) for the Crab pulsar. This charge is actually

TABLE VIa. The vacuum solution (point dipole field).

		Surface values	
QuantityExpressionQuantityInside star Φ $\sin^2\theta/r$ E_r $\sin^2\theta/r^2$ E_{θ} $-2\sin\theta\cos\theta/r^2$ q/ϵ_0 $2(1-3\cos^2\theta)/r^3$ $\underline{E} \cdot \underline{B}$ 0Outside star Φ $\frac{2}{3r} + \frac{1}{3r^3}(1-3\cos^2\theta)$ E_r $\frac{2}{3r^2} + \frac{1}{r^4}(1-3\cos^2\theta)$ E_{θ} $-2\sin\theta\cos\theta/r^4$ q/ϵ_0 0	Equator ^a	Pole ^b	
	Inside star		
Φ	$\sin^2\theta/r$	+ 1	0
E,	$\sin^2\theta/r^2$	+ 1	0
E_{θ}	$-2\sin\theta\cos\theta/r^2$	0	0
q/ϵ_0	$2(1-3\cos^2\theta)/r^3$	+2	-4
<u>E · B</u>	0	0	0
	Outside star		
Φ	$\frac{2}{3r} + \frac{1}{3r^3}(1-3\cos^2\theta)$	+ 1	0
E _r	$\frac{2}{3r^2} + \frac{1}{r^4}(1-3\cos^2\theta)$	$+\frac{5}{3}$	$-\frac{4}{3}$
E_{θ}	$-2\sin\theta\cos\theta/r^4$	0	0
q/ϵ_0	0	0	0
$\underline{E} \cdot \underline{B}$	$4\cos\theta(1-3\cos^2\theta/r^2)/3r^5$	0	$-\frac{8}{3}$
	Surface		
σ/ϵ_0^c	$2(1-3\cos^2\theta)/3$	$+\frac{2}{3}$	$-\frac{4}{2}$
$\underline{E} \cdot \underline{B}$ (average)	$2\cos\theta(1-3\cos^2\theta)/3$	0	$-\frac{3}{4}{3}$
	Everywhere		
В,	$2\cos\theta/r^3$	0	+ 2
$\dot{B_{\theta}}$	$\sin\theta/r^3$	+ 1	0
÷			

^aHere f = 1, $\theta = \pi/2$.

^bHere $f = 0, \theta = 0$.

^cThe surface charge density σ is given from $E_r(\text{out}) - E_r(\text{in})$.

Charged pulsars

THE ASTROPHYSICAL JOURNAL, **196**: 51-72, 1975 February 15 © 1975. The American Astronomical Society. All rights reserved. Printed in U.S.A.

THEORY OF PULSARS: POLAR GAPS, SPARKS, AND COHERENT MICROWAVE RADIATION M. A. Ruderman*

AND



Goldreich and Julian (1969) elucidated the characteristics of the corotating magnetosphere surrounding an axisymmetric neutron star with aligned magnetic moment and rotation axes. They assumed that (a) the neutron star can supply the necessary negative charges (electrons) and positive charges (ions and positrons) required to fill and maintain the magnetosphere with $E \cdot B \sim 0$, and (b) the currents in the magnetosphere are negligible. They showed that the magnetosphere would then corotate with a local charge density

$$\rho_e = -\frac{\mathbf{\Omega} \cdot \mathbf{B}}{2\pi c} \frac{1}{1 - \Omega^2 r_\perp^2/c^2} \tag{1}$$

The magnetic fields inside/outside a NS is co-rotating with the NS, so charged

When a NS collapses to a BH, the BH is a spinning, charged BH - Kerr Newman

How long does a Kerr-Newman BH sustain?

I don't know. More work is needed.

But not easy to neutralize because of the pulsar-like magnetosphere activities.

If the BHs merge before discharged, then an FRB or even a GRB will be produced

$$Q\sim rac{\Omega_*\mu_*}{3c},$$

$$\mu_* \Omega_* \sim (9 \times 10^{36} \,\mathrm{G \, cm^3 \, s^{-1}}) \left(\frac{M}{10 \, M_\odot}\right) \hat{q}_{-5}.$$



Rezzolla's talk

FRB (Zhang, ApJL, 827, L31)

Frequency:

$$\nu = \frac{3}{4\pi} \frac{c}{\rho} \gamma_e^3 \simeq (0.9 \times 10^9 \text{ Hz}) \hat{a}^{-1} \left(\frac{M}{10M_{\odot}}\right)^{-1} \gamma_{e,2}^3,$$

Duration:

$$\tau_{1.5} \lesssim \frac{P}{|\dot{P}|} = \frac{20}{3} \frac{GM}{c^3} \hat{a}^4 \simeq (1.7 \text{ ms}) \left(\frac{M}{10M_{\odot}}\right) \left(\frac{\hat{a}}{1.5}\right)^4,$$

$$L_w \simeq \frac{2\ddot{\mu}^2}{3c^3} \simeq \frac{49}{120000} \frac{c^5}{G} \hat{q}^2 \hat{a}^{-15}$$
$$\simeq (1.5 \times 10^{48} \text{ erg s}^{-1}) \hat{q}_{-4}^2 \hat{a}^{-15},$$

To produce an FRB with L $\sim 10^{41}$ erg/s, one needs:

$$\hat{q} > 3 \times 10^{-8}$$
 for $\hat{a} = 1$
 $\hat{q} > 2 \times 10^{-10}$ for $\hat{a} = 0.5$



GRB

GRB (Zhang, ApJL, 827, L31)

$$t_1 = \frac{R_1}{2\Gamma_1^2 c}, \quad t_2 = \frac{R_2}{2\Gamma_2^2 c}.$$

• The delay time between the onset of the GRB and the final GW chirp signal is

$$\Delta t_{\rm GRB} \sim (t_1 - \tau_{1.5})(1+z). \tag{19}$$

• The rising time scale of the GRB is defined by

$$t_r \sim \max(\tau_{1.5}, t_2 - t_1)(1+z).$$
 (20)

• The decay time scale of the GRB is defined by

$$t_d \sim t_2(1+z).$$
 (21)

• The total duration of the GRB is

$$\tau = t_r + t_d. \tag{22}$$

Model parameters:

$$\hat{q}_{-4} \simeq 3.5 \hat{a}^{15/2} \eta_{\gamma}^{-1/2} \simeq 0.02 \left(\frac{\hat{a}}{0.5}\right)^{15/2} \eta_{\gamma}^{-1/2},$$

$$R_1 \sim 2\Gamma_1^2 c t_{\rm GRB} = (2.4 \times 10^{14} \text{ cm}) \left(\frac{\Gamma_1}{100}\right)^2 \left(\frac{\Delta t_{\rm GRB}}{0.4 \text{ s}}\right)$$

$$R_2 \sim 2\Gamma_2^2 c t_2 \sim 2\Gamma_2^2 c \tau = (6.0 \times 10^{14} \text{ cm}) \left(\frac{\Gamma_2}{100}\right)^2 \left(\frac{\tau}{1 \text{ s}}\right)$$



BH-BH merger & FRB rate

- BH-BH merger event rate density (Abbott et al. 2016) $(9-240) \text{ Gpc}^{-3} \text{ yr}^{-1}$
- FRB event rate density

$$\dot{\rho}_{\text{FRB}} = \frac{365 \dot{N}_{\text{FRB}}}{(4\pi/3) D_z^3} \simeq (5.7 \times 10^3 \text{ Gpc}^{-3} \text{ yr}^{-1}) \\ \times \left(\frac{D_z}{3.4 \text{ Gpc}}\right)^{-3} \left(\frac{\dot{N}_{\text{FRB}}}{2500}\right),$$

Charged compact star mergers

- Since NSs do carry a magnetosphere, they should be "charged" also
- The theory applies to NS-NS and NS-BH mergers as well – a precursor of NS-NS and NS-BH mergers; FRBs could be associated with all compact star mergers!

Summary:

Possible EM counterparts of GW events

- Short GRBs (gamma-rays) and afterglows (multiwavelength)
 - NS-NS mergers, BH-NS mergers
 - BH-BH mergers?
- Kilonova/Macronova/Mergernova (optical/IR) and afterglows (multi-wavelength, strongest in radio)
 - BH-NS mergers, NS-NS mergers
 - Enhanced in some NS-NS mergers with a supra-massive/ stable NS
- Early X-ray emission (X-rays)
 - NS-NS mergers with a supra-massive/stable NS
- Fast radio bursts (radio)
 - NS-NS mergers with a supra-massive NS
 - Mergers of charged BH-BH systems (also NS-NS, BH-NS?)