Judging Category: Science

# Modeling Late-Time Radio Emissions from Neutron Star Mergers


*Josh Portnoy*

*Mentors: Eleonora Troja, Amy Lien Astrophysics 661*

*Physics-University of Colorado at Boulder, NASA Goddard Space Flight Center*


## Abstract


Neutron star mergers (NSM) are one of the primary sources of gravitational waves (GW) detected by the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO). To explore possible electromagnetic (EM) signatures associated with these gravitational wave events, I construct a theoretical model of the NSM, specifically focusing on the dynamics of the ejecta and the radio afterglow it may produce. This model assumes an isotropic distribution of ejecta on the timescales of interest and, as such, supports an observable EM signature regardless of the orientation of the NSM's rotational axis. Upon subsequent external shocks with the circumburst medium (CBM), relativistic shells of decelerating particles will produce a broadband spectrum afterglow via synchrotron radiation. The dynamic evolution of the ejecta and calculated time of observation $t_{obs}$ gives a relative timeframe on which radio observations should be made, following up on the model of Nakar & Piran (2011). Finally, I discuss the case of a stable magnetar remnant with energy injections orders of magnitude greater than the standard case, and compare this model to the most recent radio observations of short gamma-ray bursts (sGRB's). I offer a new possible lower limit of ~2.4 years for the observation time of late radio emissions, suggesting future observational follow-ups of sGRB radio afterglows to be made years after the original burst detection.

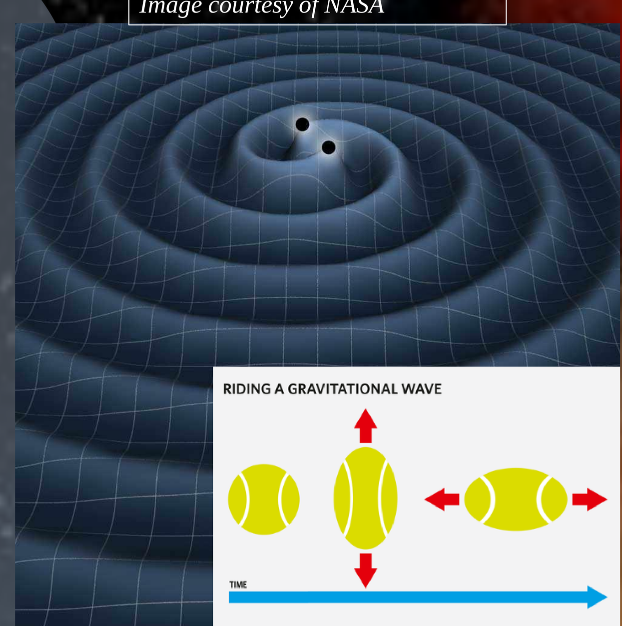

## Method

- Given the theoretical nature of this project, the first step was to research the current, well acknowledged models and theories
  - strongly speculate that the process by which the ejecta will produce a late-time afterglow is the same process by which the GRB is observed to produce an afterglow upon external collisions, as well as the similar afterglow seen in some macronovae
- To setup basic constraints, input parameters of my model are chosen to be:
  - Energy $E$
  - density $n$
  - coefficients of electromagnetic energy $\epsilon_B$ & $\epsilon_e$
  - relativistic speed $\beta_0$
  - time $t$
- Using these parameters and the equations for synchrotron radiation found in *Radiative Processes in Astrophysics*, I calculate the defining frequencies:
  - Minimum frequency of the distribution $\nu_m$
  - Critical frequency $\nu_c$
  - Self-absorption frequency $\nu_a$
- The peak flux $F_{\nu,max}$, and frequency luminosity $\nu L_\nu$ is also derived as a function of time in order to construct a light curve for the radio frequency $\nu = 2.1\ GHz$
- I model the hydrodynamic evolution of the ejecta through conservation of energy and momentum, solving for the radial evolution as a function of time
- The time of the expected afterglow $t_{obs}$, is calculated based on this hydrodynamic evolution
- Observation times are then compared in the model for various logarithmic powers of energy injections $(10^{49} - 10^{52}\ erg)$ to set a lower limit in the possible case of a stable magnetar remnant

## Background

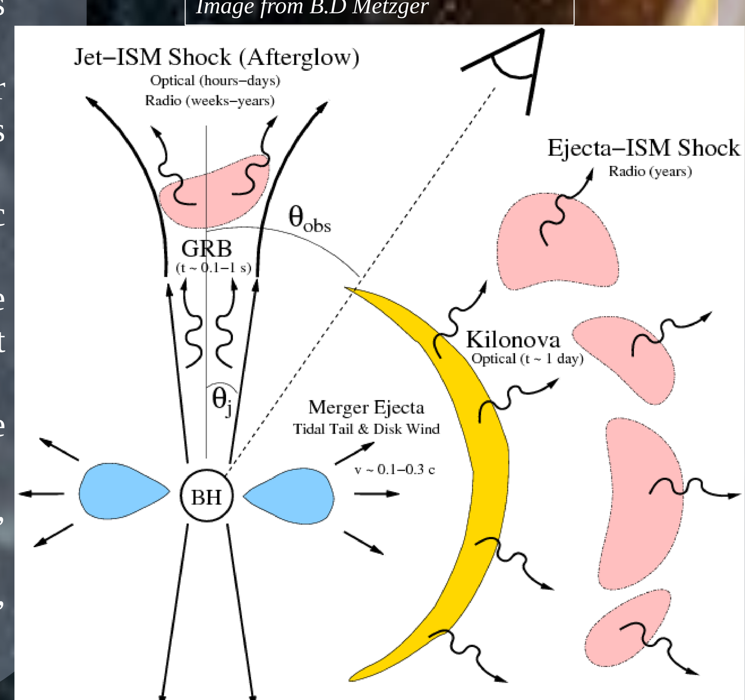
- Gravitational waves where originally predicted by Einstein and his theory of general relativity in 1916
- 100 years later (2016), LIGO detection finally confirms their existence!
- Thought to be caused by the collapse of extremely massive binary systems:
  - Neutron Star + Neutron Star
  - Black Hole + Black Hole
  - Black Hole + Neutron Star
- As the orbit of the binary system spirals inward and the frequency of oscillation increases, the incredible gravitational energy from the two objects begins to emit radiation in the form of these gravitational waves which distort space-time
- Gravitational Waves are still very difficult to directly detect and localize (travel at speed of light)
- A worldwide initiative has been launched to search for electromagnetic signatures that are directly associated with GW events
- Such an EM counterpart would be a huge breakthrough in Gravitational-Wave Astronomy
- Gamma-ray bursts, as the most luminescent EM flash in the known Universe, are a prime and well observed candidate
  - Unfortunately, collimation of GRB's only allows on axis detection
- Alternatively, an EM counterpart associated with the ejected matter provides an opportunity to detect it from any angle (ejecta is isotropic)
- Particles that experience acceleration (or deceleration) in a magnetic field, emit radiation known as synchrotron radiation
- As the ejected particles collide with other particles, such as the surrounding medium, they will decelerate and theoretically emit radiation
  - Each additional collision will lower the energy of the particle and thus lower the frequency of radiation emitted
  - This will produce a broadband afterglow observable in X-ray, optical, and radio frequencies at varying times
  - Gamma-Ray burst are produced under very similar principles, only with internal shocks between particle shells.

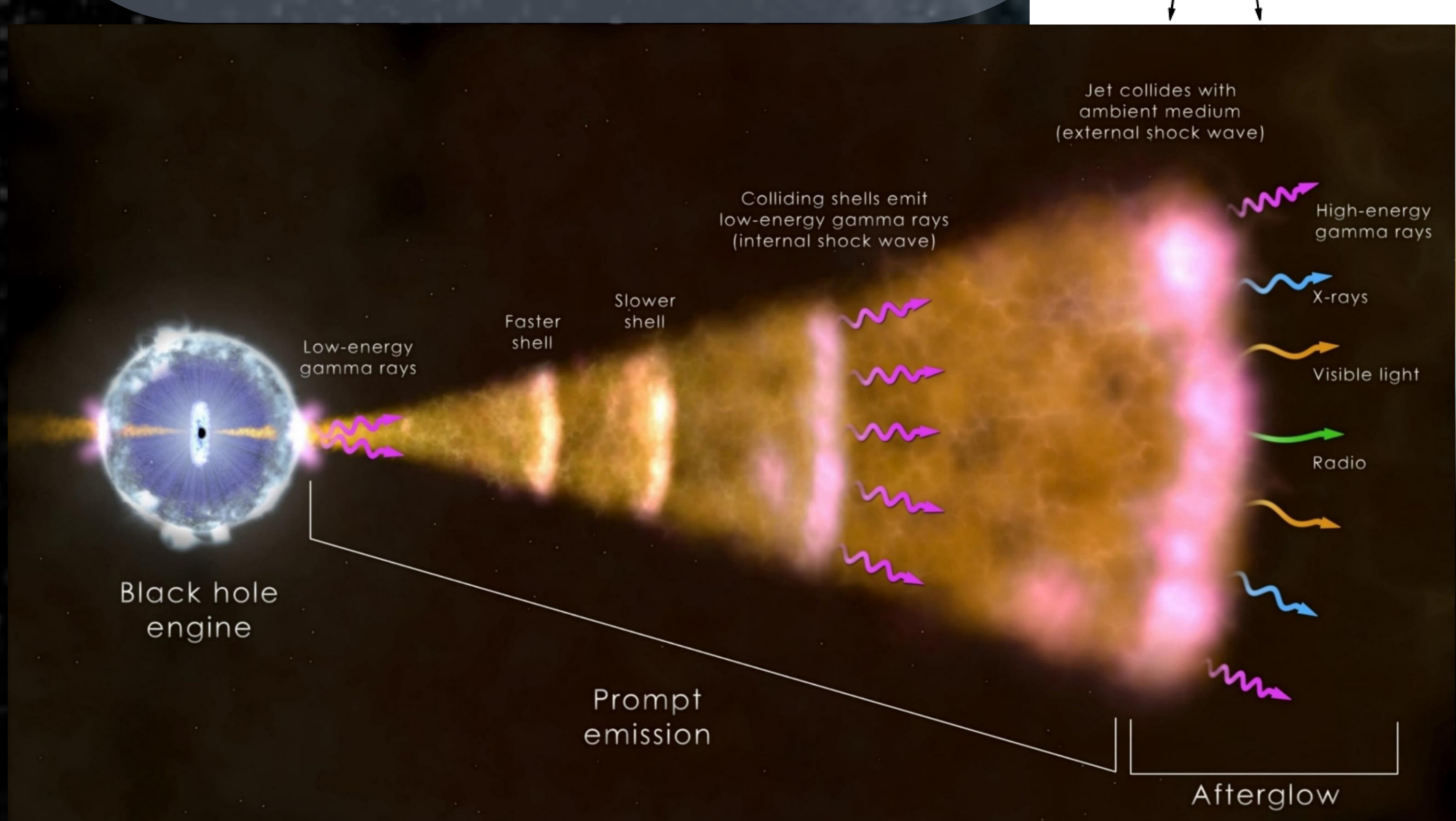
The collapse of two black holes produces gravitational waves as they orbit about the central axis.
*Image courtesy of NASA*




Space-time distortion caused by passing gravitational wave

GRB model showing the process by which the radio afterglow would be produced.
*Image from B.D Metzger*




Schematic of the Fireball model, illustrating the production of the 'prompt' and 'afterglow' emission.
*Image courtesy of NASA*

## Hydrodynamic Evolution

Assuming a relatively isotropic distribution of ejecta, I start with the simple model of a single shell of ejecta propagating radially from the blast. This homogeneous spherical shell of ejecta with rest mass energy M, collides with the CBM and sweeps up a mass $m(R)$. The initial energy of the shell is given by $E_0 = M_0 c^2 \Gamma_0$ where $\Gamma_0$ is the initial lorentz factor of the shell. As additional resting mass elements of the ISM, $dm$, collide inelastically with the shell, conservation of energy and momentum yield the following results:

$$\frac{d\Gamma}{\Gamma^2} - 1 = \frac{-dm}{M}$$

$$dE = (\Gamma - 1)dm$$

where $dE$ is the thermal energy produced from each collision. Setting ε as the fraction of $dE$ that is radiated away,

$$dM = (1-\epsilon)dE + dm = [(1-\epsilon)\Gamma + \epsilon]dm$$

yielding analytic relations between the Lorentz factor and the total shell mass, which give a complete description of the hydrodynamic evolution:

$$\left(\frac{M}{M_0}\right)^{-2} = \frac{(\Gamma-1)(\Gamma+1)^{1-2\epsilon}}{(\Gamma_0-1)(\Gamma_0+1)^{1-2\epsilon}}$$

$$\frac{m(R)}{M_0} = -(\Gamma+1)^{\frac{1}{2}}(\Gamma_0+1)^{\frac{1}{2}-\epsilon}\int_{\Gamma_0}^{\Gamma}(\Gamma'-1)^{\frac{-3}{2}}(\Gamma'+1)^{\frac{-3}{2}+\epsilon}d\Gamma'$$

In the limiting case of $\Gamma_0 \gg \Gamma \gg 1$, which we can safely assume especially for the late-emission afterglows we are modeling,

$$m(R) = \left(\frac{M_0}{(2-\epsilon)\Gamma_0}\right)\left(\frac{\Gamma}{\Gamma_0}\right)^{-2+\epsilon}$$

For fully adiabatic hydrodynamics $\epsilon = 0$ while the energy of the system remains constant, thus we are left with the result

$$E = E_0 = \frac{4}{3}\pi R^3 m_p n c^2 \Gamma^2$$

Following the relation $t_{dec} = \frac{R}{c_T \Gamma^2 c} \cong \frac{R}{c\beta_0}$ where $c_T$ is a constant dependent on the hydrodynamic evolution ($c_T$= 16 for fully adiabatic), I derive from the energy equation above the ejecta radius and Lorentz factor Γ as a function of time.

$$R(t) = \left(\frac{3Et}{\pi m_p n c}\right)^{\frac{1}{4}}$$

$$\Gamma(t) = \left(\frac{3E}{256\pi m_p n c^5 t^3}\right)^{\frac{1}{8}}$$

Assuming the ejecta decelerates after sweeping up a mass of ISM equal to its own, I denote the radius at which this mass equality occurs by:

$$R(t_{dec}) = R_{dec} = \left(\frac{3E}{4\pi m_p n c^2 \beta_0}\right)^{\frac{1}{3}}$$

This is the minimum time at which we can expect a strong afterglow from external collisions between the shells of ejecta and the CBM, that is $t_{obs} \geq t_{dec}$. For the standard case of energy injections of $10^{49} - 10^{51}\ erg$:

$$average\ t_{obs} \approx 8.66\ months \left(\frac{E}{10^{49}}\right)^{\frac{1}{3}}\left(\frac{n}{cm^{-3}}\right)^{\frac{1}{3}}\beta_0^{\frac{-5}{3}}$$

Investigating the case of a magnetar remnant, Metzger and Bower (2014) point out that the formation of a stable magnetar could inject increasing energy through the NS rotational energy. This proposed case could have a modest energy injection of $10^{52}\ erg$, orders of magnitude higher than the range discussed above.

$$t_{obs} \approx 2.56\ years \left(\frac{E}{10^{52}}\right)^{\frac{1}{3}}\left(\frac{n}{cm^{-3}}\right)^{\frac{1}{3}}\beta_0^{\frac{-5}{3}}$$

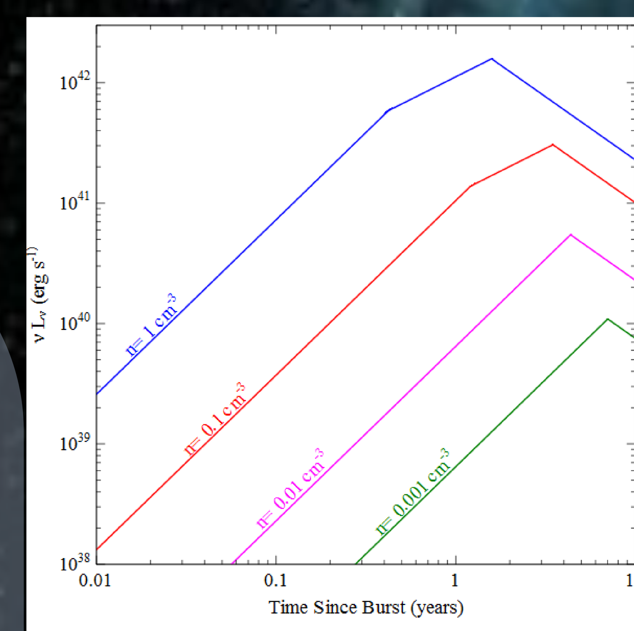
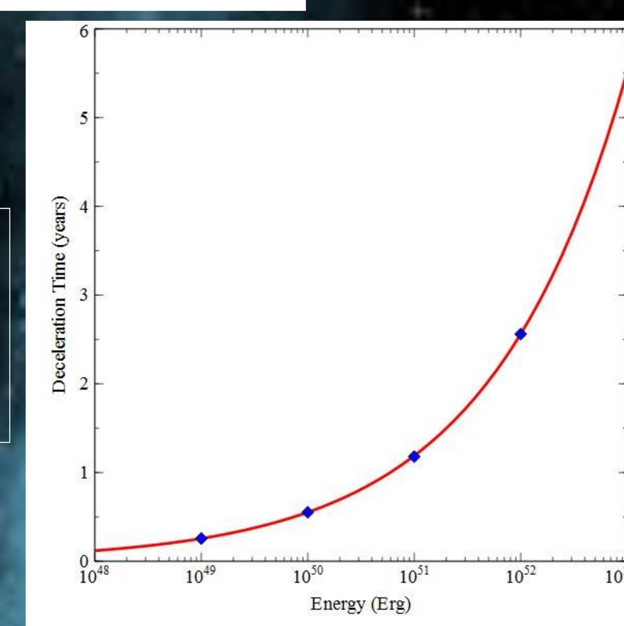



Figure 1
Theoretical light curve for radio frequency of 2.1 GHz, considering evolution for different densities of the surrounding medium.
*(Shown left)*

*Figure 2*
Time dependence on initial energy injection, comparing the standard case to that of a magnetar remnant.
*(Shown Right)*




## Discussion

Neutron star mergers are theorized to be a prime cause of gravitational waves and thus their understanding is an integral step to the burgeoning field of gravitational-wave astronomy. As such, I create an analytical model to investigate the possibility of a late-time radio emission in the ejecta afterglow and set a lower limit for the time of observation. Assuming an average ISM density $n = 1\ cm^{-3}$, a minimum energy of $E = 10^{49}\ erg$, and ultra-relativistic particles with $\beta_0 \approx 1$, the lower limit for the time observed is 3 months. Because $t_{obs} \propto \beta_0^{\frac{-5}{3}}$ and the particles will realistically be travelling in the ranges of $0.2 \leq \beta_0 \leq 0.8$, this is a hard lower limit on my model. As shown in *Figure 1*, the lower densities of the surrounding environment will also result in a longer time until the radio afterglow is observable. However, when I consider the possibility of a neutron star merger collapsing into a magnetar with energy injection of $E = 10^{52}\ erg$, *Figure 2* shows the lower limit for the observation time increasing exponentially to 2.56 years. Although this is roughly twice the value cited by Metzger and Bower, their investigations of GRB's on those timescales showed no evidence of radio afterglows. This warrants an extensive follow-up of isotropic afterglow emissions around the cite of GRB's years after the burst; specifically, at a radio frequency of 2.1 GHz.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