Astrophysical Sources of Gravitational Radiation

Agnieszka Janiuk

(1) Center for Theoretical Physics
Polish Academy of Sciences
Warsaw

Workshop on Singularities, Warsaw, 25.05.2018
Origin and fate of GW sources from astrophysicist perspective. Outline.

- LIGO discovered black holes. Stellar collapse.
- Gamma ray bursts. Counterparts to Neutron Star Merger.
- Binary Black Hole merger and electromagnetic signal. Possible scenarios.
How to produce such BHs?

- LIGO BHs are probably produced by direct collapse, when the entire star at the end of its life collapses to form the BH.
- This is appealing because you can form large BHs without invoking very rare, significantly more massive stars.
- This collapse should lead to a quasi-spherical accretion in order for feedback to not be too damaging.

Spera et al. 2015
LIGO spin constraints
Spherical accretion

- Bernoulli equation

\[(\frac{\rho + P}{n})^2(1 - \frac{2}{r} + u^2_r) = \varepsilon\]

- mass-energy density \(\rho = \rho_0 + u\)
- internal energy \(u = P/(\gamma - 1)\)
- rest mass density \(n = \rho_0\)
- parameters: sonic radius, \(r_s\), polytropic index \(\gamma\)
- equation converged up and down from \(r_s\)
**HARM code:** High Accuracy Relativistic Magnetohydrodynamics (Gammie et al. 2003). The code provides solver for continuity and energy-momentum conservation equations in GR:

\[
\nabla_\mu (\rho u^\mu) = 0 \quad \nabla_\mu T^{\mu\nu} = 0
\]

Energy tensor contains in general electromagnetic and gas parts:

\[
T^{\mu\nu} = T_{\text{gas}}^{\mu\nu} + T_{\text{EM}}^{\mu\nu}
\]

\[
T_{\text{gas}}^{\mu\nu} = \rho h u^\mu u^\nu + pg^{\mu\nu} = (\rho + u + p)u^\mu u^\nu + pg^{\mu\nu}
\]

\[
T_{\text{EM}}^{\mu\nu} = b^2 u^\mu u^\nu + \frac{1}{2}b^2 g^{\mu\nu} - b^\mu b^\nu; \quad b^\mu = u_\nu F^{\mu\nu}
\]

The magnetic field is here at first neglected. EOS in simplest case is that of ideal gas

\[
p = K \rho^\gamma = (\gamma - 1)u
\]
Black hole accretes both mass and angular momentum. Adopting Kerr-Schild coordinates $t, r, \theta, \phi$, this accretion rate is given by the stress-energy tensor integrated on the horizon

$$j \equiv \int d\theta d\phi \sqrt{-g} T^r_\phi$$

$$\dot{M} = \dot{E} \equiv \int d\theta d\phi \sqrt{-g} T^r_t$$


Initial condition for HARM-2D. Bondi cloud plus small rotation. (AJ, P. Sukova, I. Palit, 2018, in prep)
The changing black hole spin and mass are subsequently affecting the spacetime metric, which is updated in every time step according to the growing mass:

\[ \Delta M = \frac{M_{BH}^{curr}}{M_{BH}^0} - 1 \]

where \( M_{BH}^0 \) is the initial mass of the black hole, and the current mass is given by integration of the mass flux over the horizon at every time-step:

\[ M_{BH}^{curr} = M_{BH}^{i} = M_{BH}^{i-1} + \int_{r=r_{in}} dM_{in} 2\pi d\theta \sqrt{-g} \]
We subsequently update the six relevant coefficients of the $g_{\mu\nu}$ metric in the Kerr-Schild form, which are dependent on the central mass, and are also sensitive to the spin change, namely:

\[ g_{tt} = -1 + 2(1 + \Delta M) \frac{r}{r^2 + a^2 \cos^2 \theta} \]
\[ g_{tr} = 2(1 + \Delta M) \frac{r}{r^2 + a^2 \cos^2 \theta} \]
\[ g_{t\phi} = -2(1 + \Delta M)ar \frac{\sin^2 \theta}{r^2 + a^2 \cos^2 \theta} \]
\[ g_{rr} = 1 + 2(1 + \Delta M) \frac{r}{r^2 + a^2 \cos^2 \theta} \]
\[ g_{r\phi} = -a \sin^2 \theta (1 + 2(1 + \Delta M) \frac{r}{r^2 + a^2 \cos^2 \theta} ) \]
\[ g_{\phi\phi} = \sin^2 \theta (r^2 + a^2 \cos^2 \theta + a^2 \sin^2 \theta (1 + 2(1 + \Delta M) \frac{r}{r^2 + a^2 \cos^2 \theta} )). \]
Sonic surface evolution in rotating star

- Spherical accretion, small angular momentum normalized to that of a circular orbit at $6 \, r_g$.
- Initial black hole mass $M = 3M_\odot$, initial spin $a = 0$, initial cloud mass $M_c = 25M_\odot$, non-magnetized, adiabatic $\gamma = 4/3$.
- Sonic point initially at $r_s = 80r_g$
- Run to $t=200,000 \, M$ (0.5 day computation, resolution of 256x256, Okeanos supercomputer at Warsaw ICM)

Sonic surfaces at time 20,000 M, for $l=1.4$ and $l=1.0$
- Black hole accretes both mass and angular momentum.
- Dimensionless spin computed as $s = \frac{a}{1 + dM}$, may reach maximum Kerr value.

Lines correspond to 3 values of star’s angular momentum magnitude.
- Stellar core empties due to supersonic accretion.
- The rest mass is accreted through the horizon.
- Variability due to (i) shock oscillation (ii) mini-disk turbulence?

Lines correspond to families with 3 values of angular momentum
• Our models out severe constraints on the angular momentum content of the progenitor star, and on the resultant mass and spin of the BH.

• The binding energy of the star is much lower than that of the resulting BH by a factor of \((v_{\text{esc}}/c)^2 \sim 1/10^6\), which implies that a small amount of feedback from mini-disk could help unbind the star and prevent the formation of a massive BH (A. Murguia-Berthier et al. in prep)

• Further work: supply the initial conditions with a more realistic density profile, as results from the stellar evolutionary model
Neutron Star mergers Search for Gold and gravitational waves
Gravitational waves were discovered with the detection of binary black hole mergers and they should also be detectable from neutron star mergers.

NS-NS are predicted to eject material rich in heavy radioactive isotopes that can power an electromagnetic signal called a kilonova (e.g. Li & Paczynski 1998; see Tanvir, 2013, Nature).

The source GW170817 arose from a binary neutron star merger in the nearby Universe with a relatively well confined sky position and distance estimate.

A rapidly fading electromagnetic transient in the galaxy NGC4993, is spatially coincident with GW170817 and a weak short gamma-ray burst (e.g., Smartt et al. 2017; Zhang et al. 2017...).
UV, optical, and NIR Light curves of the counterpart of GW170817. The two-component model for r-process heating and opacities is shown as solid lines. The right panels focus on the g (top), i (middle), and H-band photometry (bottom), over the first 10 nights (from Cowperthwaite et al., 2017)

- Dynamical ejecta from compact binary mergers, $M_{\text{ej}} \sim 0.01 M_\odot$, can emit about $10^{40} - 10^{41}$ erg/s in a timescale of 1 week

- Subsequent accretion can provide bluer emission, if it is not absorbed by precedent ejecta (Tanaka M., 2016)
Hyperaccretion and jet ejection

- If the black hole starts fastly rotate, jet ejection is inevitable
- The presence of magnetic fields and/or neutrino-antineutrino pairs power the jet acceleration
- Blandford-Znajek process quantified with
  \[ \dot{E} \equiv \int d\theta d\phi \sqrt{-g} T^r_t \]
- Luminosities due to BZ and neutrinos: comparably large, depend on BH spin

- Hyperaccretion requires detailed description of microphysics (degenerate Fermi gas EOS, with $P(\rho, T)$ non-linear dependence
- Matter is neutronized, $Y_e = n_p/(n_p + n_n) < 0.5$
- Non-trivial transformation between conserved variables and 'primitives' in HARM due to GR MHD scheme

Elements synthesized in GRB engines modeled under NSE

Nucleosynthesis within the torus accreting onto BH, under nuclear statistical equilibrium (Janiuk 2017; Wojczuk & Janiuk, 2018)
Heavy elements: r-process nucleosynthesis

Nucleosynthesis of r-process elements on the outflow trajectories from the accretion torus around BH (Wu et al. 2017; see also Siegel & Metzger 2017)
Elements synthesized in the outflows from GRB engines modeled dynamically, with HARM
Are binary Black Holes mergers expected to have electromagnetic counterpart?

High Mass X-ray binary Cygnus X-3
In general, no!
We envisaged (Janiuk, Charzynski & Bejger, 2013, A&A, 560, 25) a model for a gamma ray burst, with possible double jets and/or jets redirected, and leaving an orphan afterglow, while accompanied by a gravitational wave signal from the collapse of a massive rotating star in a binary system with a companion BH.
First gravitational wave detection

- The source GW150914 was interpreted to be a merger of two BHs of the masses of $36^{+5}_{-4} \ M_\odot$ and $29^{+4}_{-4}$ (Abbott et al. 2016).
- Final BH parameters are estimated to be of $62^{+4}_{-4} \ M_\odot$ and $0.67^{+0.05}_{-0.07}$ for its mass and spin.
- Probabilities that the angles between spins and the normal to the orbital plane are between $45^\circ$ and $135^\circ$ are about 0.8 for each component BH.
- Spin magnitudes are constrained to be smaller than 0.7 and 0.8 at 90% probability.
- Assumption of a strict co-alignment of spins with the orbital angular momentum results in an upper limit of 0.2 and 0.3 for the merging BHs spins.
- Distance of $410^{+160}_{-180} \ \text{Mpc}$, corresponding to a redshift of about $z = 0.09$. 
• Duration of about 1 sec and appeared about 0.4 seconds after the GW signal
• within the limit of uncertainty of LIGO and Fermi detector capabilities could also be associated spatially
• GRB fluence in the range 1 keV-10 MeV, is of $2.8 \times 10^{-7}$ erg cm$^{-2}$
• Implied source luminosity in gamma rays equals to $1.8^{+1.5}_{-1.0} \times 10^{49}$ erg/s
  (Connaughton et al. 2016; reanalysis confirmed this GRB in Connaughton et al. 2018)
Some recent scenarios for GW-GRB origin

- A. Loeb (2016, ApJL) The two BHs merge within a common envelope of a very massive star. These two BHs must have formed simultaneously from the two clumps that were created via the bar instability during the core collapse.

- S. Woosley (2016, ApJL): core-collapse of a single, chemically homogeneous, rapidly rotating single star of a mass about $150 M_\odot$. GW signal should result from the Kerr parameter of the collapsing core being significantly larger than unity, so the angular momentum of the newly born BH is lost via gravitational wave emission. Or, the two massive stars of the initial separation on the order of 1 AU would undergo core collapses one after another and experience twice the common envelope phase.

- B. Zhang (2016, ApJL): magnetospheric activities during the merging phase would make a fireball if the BH charge is large

- ... and our (fine-tuned) model with redirected, off-axis jet following the 'wet merger' (Janiuk et al. 2017, NewA., 57, 1)