Theory of Gamma Ray Bursts

Agnieszka Janiuk

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

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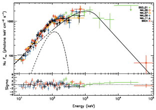
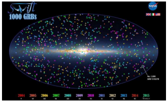
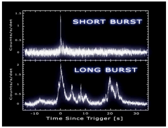
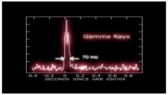
Gamma ray bursts

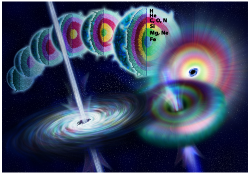


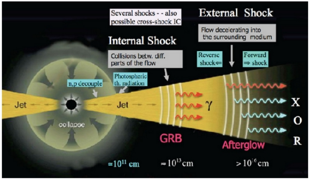






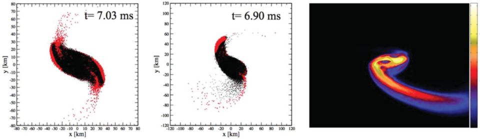
- Rapid, bright flashes of radiation peaking in the gamma-ray band
- Occur at an average rate of one event per day at cosmological distances.
- Characterized by a collimated relativistic outflow pushing through the interstellar medium.
- Powered by a central engine.

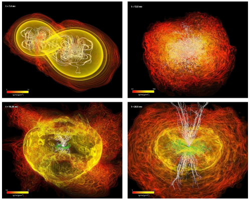




- Collapse of a rotating massive star into black hole. Predicted is beamed explosion, accompanied by a supernova-like ejection
- Their lightcurves show power law decay: support for relativistic blast wave explosion models
- Hosts of long GRBs are in star forming regions, because of higher gas densities and metalicities (Holland 2001; Chevalier 2003)
- Emission lines characteristic for SN found (Stanek et al. 2003)

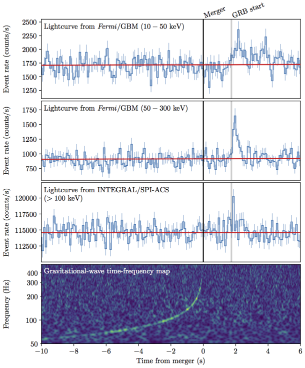
Short GRBs



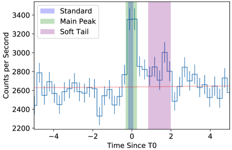


Korobkin et al. 2012; Rezzolla et al. 2014

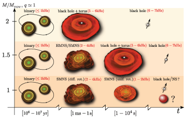
- Leading candidates include mergers (or for a small fraction, collisions) of NSNS and NSBH systems.
- An alternative candidate is accretion induced collapse of a NS to BH. A small fraction of short GRBs can be the giant flares of soft gamma-ray repeaters in nearby galaxies.



LIGO observation GW 170818A



FERMI-GBM (Goldstein et al., 2017, ApJ)



Theoretical predictions (review by Baiotti & Rezzolla, 2017)

GRB central engine: black hole accretion

- Models must satisfy the basic equations of hydrodynamics
  - Continuity equation
  - Energy equation
  - Conservation of momentum (radial transport, rotation)
- Supplement with equation of state. Simplest case: ideal gas
- Describe dissipation of energy, simplest case: α-disk, stress scales with pressure (Shakura & Sunyaev 1973). Mimics the angular momentum transport by (MHD) turbulences

Popham et al. 1999; Janiuk et al. 2004; Reynoso et al. 2006; Lei et al. 2009

Properties of jets in GRBs

- Observed non-thermal γ-ray spectra gave rise to the 'compactness problem'
- Huge optical depth due to the electron-positron pair production would produce a thermal emission
- Relativistic expansion with a rather large bulk Lorentz factor, $\Gamma > 10^2$ (Paczynski 1986; Baring 1997)
- High Lorentz factor requires exceedingly clean explosions with ejecta masses of $< 10^{-5} M_{\odot}$; leading to the 'baryon loading' problem (Shemi & Piran 1990)

HARM code: High Accuracy Relativistic Magnetohydrodynamics (Gammie et al. 2003). The code provides solver for continuity and energy-momentum conservation equations in GR:

$$\nabla_\mu(\rho u^\mu) = 0 \qquad \nabla_\mu T^{\mu\nu} = 0$$

Energy tensor contains in general electromagnetic and gas parts:

$$T^{\mu\nu} = T^{\mu\nu}_{\rm gas} + T^{\mu\nu}_{EM}$$

$$T^{\mu\nu}_{gas} = \rho h u^\mu u^\nu + p g^{\mu\nu} = (\rho + u + p) u^\mu u^\nu + p g^{\mu\nu}$$

$$T^{\mu\nu}_{EM} = b^2 u^\mu u^\nu + \frac{1}{2} b^2 g^{\mu\nu} - b^\mu b^\nu; \quad b^\mu = u_\nu {}^{*}\!F^{\mu\nu}$$

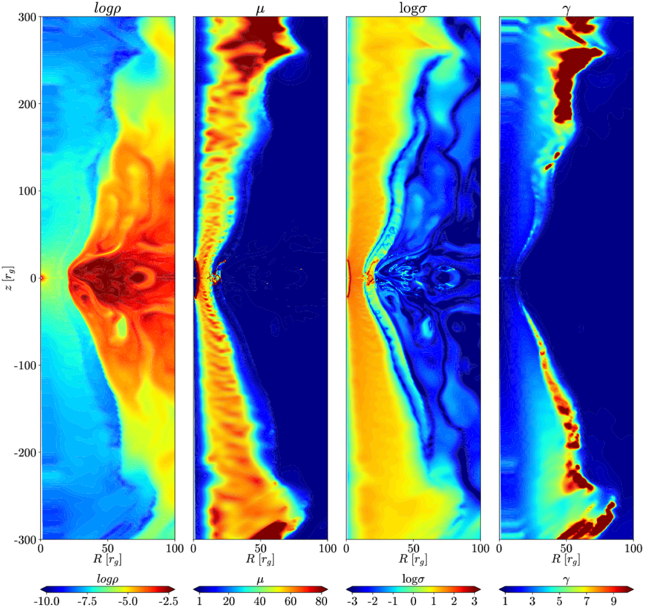
where u^μ is four-velocity of gas, u is internal energy density, and $b^\mu = \frac{1}{2}\varepsilon^{\mu\nu\rho\sigma} u_\nu F_{\rho\sigma}$ and F is the electromagnetic tensor. In force-free approximation, $E_\nu = u_\mu F^{\mu\nu} = 0$. EOS in simplest case is that of ideal gas

$$p = K\rho^\gamma = (\gamma - 1)u$$

- Magnetization σ and normalized energy, μ:

$$\sigma = \frac{(T_{em})^r_t}{(T_m)^r_t} \qquad \mu = -\frac{T^r_t}{\rho u^r}$$

- Energy conservation along a field line gives $\mu = \gamma h(1+\sigma)$ as the sum of the inertial-thermal energy of the plasma, γh, and its Poynting flux, $\gamma h \sigma$
- Maximum achievable Lorentz factor $\Gamma_\infty = \mu$, when all the Poynting and the thermal energy is transformed to baryon bulk kinetic ($\sigma \to 0, \xi \to 1$) (Vlahakis & Koenigl 2003)


logρ
μ
logσ
γ
300
200
100
0
-100
-200
-300
z [r_g]
0 50 100
R [r_g]
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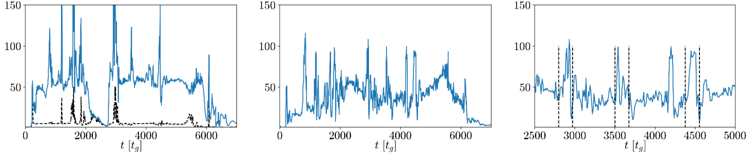
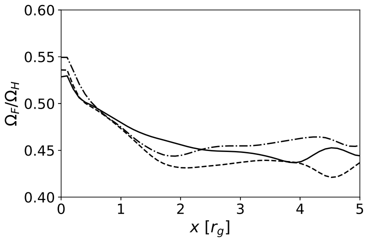


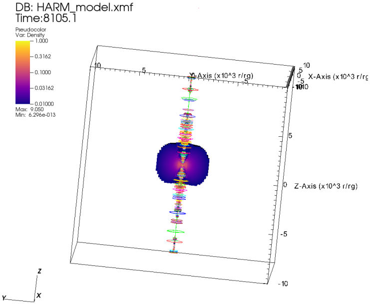
Time variability of μ as measured at outer and inner regions of jet . Right: variability as correlated with T^{MRI}, timescale of the fastest growing mode (Sapountzis & Janiuk, 2019, ApJ, 873, 12)

Power source for GRB

Rotational velocity of the magnetic field $\Omega_F = F_{t\theta}/F_{\theta\phi}$

Angular frequency of the black hole $\Omega_{BH} = (a/2)\left(1 + \sqrt{1 - a^2}\right)$





Sapountzis & Janiuk (2019, ApJ)

II. Hyperaccretion and microphysics

- Hyperaccretion: rates of 0.01-10 $M_\odot/s$
- Steady state and time-dependent models were proposed
- EOS is not ideal, plasma composed of n, p, e^+, e^-
- Chemical and pressure balance required by nuclear reactions: electron-positron capture on nucleons, and neutron decay (Reddy, Prakash & Lattimer 1998)
- Neutrino absorption & scattering

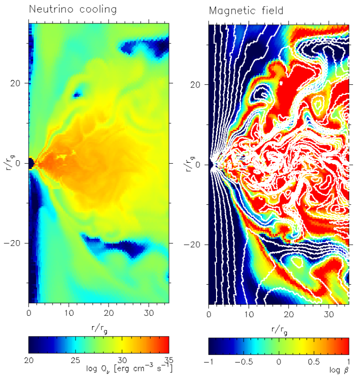
Di Matteo et al. 2002; Kohri et al. 2002, 2005; Chen & Beloborodov 2007; Janiuk et al. 2007; Janiuk & Yuan 2010; Lei et al. 2009; Janiuk et al. 2013; Liang et al. 2015; Janiuk 2017, 2019

Hyperaccretion in GR MHD

- Magnetic fields and/or neutrino-antintineutrino pairs power the jet
- Neutrino energies peak in MeV range (Wei et al. 2019)
- Blandford-Znajek process quantified with

$$\dot{E} \equiv \int d\theta d\phi \sqrt{-g}\, T^r{}_t$$

- Luminosities due to BZ and neutrinos comparable, depend on BH spin



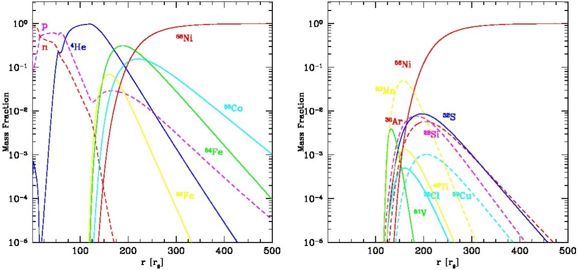
Janiuk (2017, ApJ, 837, 39)

Equation of state and nucleosynthesis

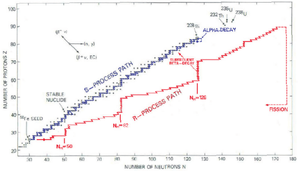
In the EOS, contribution to the pressure is by the free nuclei and $e^+ - e^-$ pairs, helium, radiation and the trapped neutrinos:

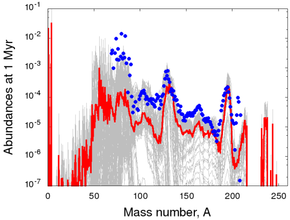
$$P = P_{\rm nucl} + P_{\rm He} + P_{\rm rad} + P_{\nu}$$

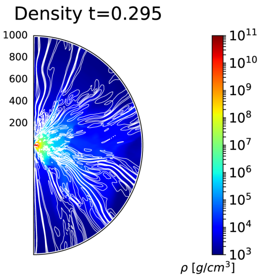
$P_{\rm nucl}$ includes free neutrons, protons, electrons, and positrons (relativistic and partially degenerate, Fermi gas EOS).



Nucleosynthesis under NSE conditions (Janiuk A., 2014, A&A, 568, 105)

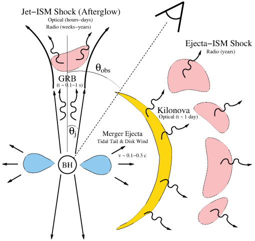






Nucleosynthesis in dynamical outflows, driven by magnetic fields (Janiuk A., 2019, ApJ, submitted)

- NS-NS eject material rich in heavy radioactive isotopes. Can power an electromagnetic signal called a kilonova (e.g. Li & Paczynski 1998; Tanvir et al. 2013)
- Dynamical ejecta from compact binary mergers, $M_{\rm ej} \sim 0.01 M_{\odot}$, 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)

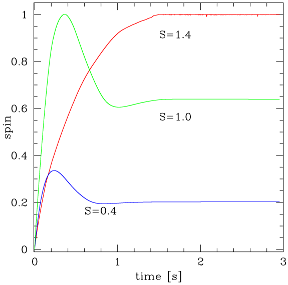


Supercomputing

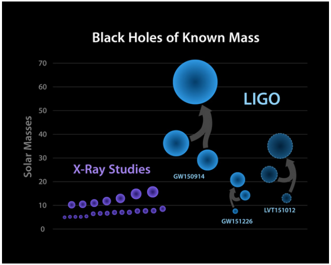
Warsaw University, ICM: cluster Okeanos 1084 computing nodes with 24 Intel Xeon CPU cores with a 2-way Hyper Threading.
PL-Grid infrastructure: Cyfronet AGH in Krakow; cluster Prometheus
Postprocessing & visualisations: Local CTP-PAS cluster, 1 node, 32 CPU. Parallel-Python computations

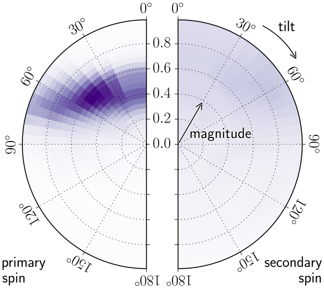
III. General Relativity. Spinning up the black hole in collapsar

- Collapsar model with slowly-rotating quasi spherical collapse with changing black hole spin and mass, and Kerr-Schild metric
- Our method to follow collapse is GR Hydro, not by exactly solving the Einsteins equations (see Semerak & Sukova 2010; Hamersky & Karas 2013). Some attempts with EToolkit made recently (Kuroda et al. 2018) but with Schwarzschild metric.



Janiuk, Sukova & Palit, 2018, ApJ, 868, 68





Our models may out some constraints on the angular momentum content of the collapsing progenitor star, who leaves a massive BH as observed by LIGO

Summary

- GRB theory has to cover Central Engine and jets physics.
- In Central Engine, both accretion and wind ejection are playing role (MRI turbulence, magneticlally/neutrino driven winds)
- Observables are: emission from jets (energetics, minimum time variability scales), and emission from afterglows, including now the Kilonovae. The latter may bring information on accretion physics.
- Gravitational waves give new window and relate progenitor properties with the GRBs prompt phase

- Current PhD student, Ishika Palit
- Former postdocs: Szymon Charzynski (2015-2017, now lecturer at Warsaw University); Petra Sukova (2013-2016, now research associate at Astronomical Institute in Prague); Kostas Sapountzis (2016-2018)
- Former PhD student: Mikolaj Grzedzielski (2013-2018; now post-doc in Turino)

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