Relativistic hydrodynamic simulations of the Induced Gravitational Collapse GRB paradigm

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July 3rd, 2014
In introduction, hypercritical accretion onto neutron stars is mentioned. Observations of Gamma-ray Bursts and induced gravitational collapse are also discussed. The University of Notre Dame/Lawrence Livermore Supernova Model is introduced. Initial conditions are outlined, followed by the results section which includes inducing gravitational collapse and X-Ray emission. Future work and conclusions are also included.
Super-Eddington accretion: neutrino vs photon cooling

- Thorne-Zytkow Objects
- Supernova fallback
- Induced Gravitational Collapse paradigm of long GRBs
Observations of Gamma-ray Bursts

Flux \( \left( \frac{\text{ergs}}{\text{cm}^2 \text{s}} \right) \)

Episode 1

Episode 2

GRB 090618, I. Izzo et al. (2012)
Observed X-ray Photosphere

$\text{r}_{SN}$ (km)

$\text{t (s)}$

GRB 090618, Izzo et al (2012)
Observed X-ray Photosphere

$\frac{k T(\text{keV})}{50}$

$\frac{\text{time(s)}}{50}$

GRB 090618, Izzo et al (2012)
**Induced Gravitational Collapse**

- **Episode 1:** Type Ib/c supernova explosion triggers accretion onto companion NS
- **Episode 2:** Companion NS reaches critical mass and collapses to BH

Ruffini et al. (2014)
Bondi-Hoyle Accretion
Accretion Shock Structure

- **X-ray photosphere**: $r \sim 10^9$ cm
- **Shock radius**
- **Neutrinosphere**: $r \sim 10^6$ cm
- **Bondi-Hoyle Accretion radius**: $r \sim 10^8$ cm

- Neutrinos: $\nu_e$, $\bar{\nu}_e$
Goal: Find contribution to observations from $\nu$ processes

- Collapse timescale $\sim 50$ s
- Behaviour of x-ray photosphere

Simulations will also tell us:

- Sensitivity to accretion rates, progenitor masses, EoS, etc
- Detailed structure of accretion region
- Neutrino luminosities and spectra
University of Notre Dame/Lawrence Livermore Supernova Model

- Self-consistent core-collapse supernova model
  - Relativistic hydrodynamics
  - Neutrino transport: MGFLD
  - “Realistic” equation of state
- Spherically symmetric
Model: General Relativistic Hydrodynamics

**Strong gravitational field:** GR effects vital

\[
ds^2 = -a^2 \left[ 1 - \left( \frac{U}{\Gamma} \right)^2 \right] dt^2 - \frac{2aU}{\Gamma^2} dR dt + \frac{dR^2}{\Gamma^2} + R^2 (d\theta^2 + \sin^2 \theta d\phi^2)
\]

where \( a = 1/U^t \) and \( \Gamma = (1 + U^2 - \frac{2M}{R})^{1/2} \).

- R & metric coefficients functions of mass & time
- Hydrodynamics solved using operator splitting and artificial viscosity
- Convection: Quasi-Ledoux mixing length theory
Flux-limited diffusion:
Boltzmann equation $\implies$ diffusion equation

$$\frac{1}{a} \frac{\partial G_i}{\partial t} = \nabla \cdot (D_i \nabla G_i)$$

where $G_i$ is angle-integrated energy distribution, $D_i$ is diffusion coefficient.

- 101 logarithmic neutrino energy groups
- $\nu_e, \bar{\nu}_e$: charged- and neutral-current interactions
- $\nu_{\mu,\tau}$: neutral-current interactions
Initial EoS: Wilson & Bowers Equation of State

- Nuclear statistical equilibrium/nuclear burning
- Photon, electron, and pion contributions
- Baryonic EoS:
  - Below $\rho_{nuc}$, not in NSE
  - Below $\rho_{nuc}$, in NSE
  - Supranuclear EoS

Later work: use more realistic EoSs
Initial Conditions: Neutron star

Cooled neutron star: result of UND/LLNL supernova model

- $M_{NS} = 1.38M_{\odot}$
- $R_{NS} = 10.6$ km
- Still cooling, $t \sim 40s$
Bondi-Hoyle accretion rate given by:

\[ \dot{M} = 4\pi r_B^2 \rho_{SN} \left( v_{SN}^2 + v_{orb}^2 + c_s^2 \right)^{1/2} \]

where \( v_{SN} \sim 10^9 \text{cm/s} \) (\( \gg v_{orb}, c_s \))

\[ r_B = \frac{GM_{NS}}{v_{SN}^2 + v_{orb}^2 + c_s^2} \approx 2 \times 10^8 \text{cm} \]

\( \rho_{SN} \) given by model of SN expansion

- Constant accretion rate
Density profile initially homogeneous:

\[ \rho_0 = \frac{M_{ej}}{\frac{4}{3} \pi r_{SN}^3} \]

and evolves in times as

\[ \rho_{SN} = \frac{\rho_0}{(1 + t/\tau)^3} \]

where \( \tau = r_{SN}/v_{SN} \sim 9\,s \)

Gives accretion rate

\[ \dot{M} = \frac{0.014}{(1 + t/9)^3} M_\odot/s \]

Ruffini et al (2014) 

\[ \begin{array}{c}
0.01 \\
0.008 \\
0.006 \\
0.004 \\
0.002 \\
0.01 \\
0.008 \\
0.006 \\
0.004 \\
0.002 \\
0.01 \\
0.008 \\
0.006 \\
0.004 \\
0.002 \\
\end{array} \]

\[ \begin{array}{c}
0 \\
5 \\
10 \\
15 \\
20 \\
25 \\
30 \\
\end{array} \]
Insert matter at NS surface:

- Mass given by accretion rate
- Velocity below shock
  \( \sim 0.1v_{SN} \)
- NSE: Composition matches local matter

Observe effects at photosphere

\( ^{a} \) Fryer et al (1996)
Results: Constant accretion rate

Enhanced accretion rate:

\[ \dot{M} = 3M_\odot/s \]
Results: Uniform expanding sphere

Accretion rate:

\[ \dot{M} = \frac{0.2 M_{\odot}}{(1 + t/9)^3} \]
Results: Neutrino luminosities

Initially: $L_\nu \sim 10^{49}$ ergs/s
Results: X-Ray Emission

Temperature $\sim 15$ keV
Future work

1. Simulate through BH collapse on longer timescale
   - Utilize realistic accretion rates over $\sim50$ s timescale
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   - Utilize realistic accretion rates over $\sim 50\text{s}$ timescale

2. Model details of accretion structure
   - Add material at Bondi radius
   - Explore structure of neutrino heated region
Future work

1. Simulate through BH collapse on longer timescale
   - Utilize realistic accretion rates over $\sim 50$ s timescale

2. Model details of accretion structure
   - Add material at Bondi radius
   - Explore structure of neutrino heated region

3. More realistic EoS
   - Obtain higher NS mass
Conclusions

- **Observations**: indicate distinct emission sources
  - Episode 1: non relativistic expansion of emission photosphere
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- **Proposed model:** binary system of massive star and NS
  - Episode 1: Type Ib/c supernova triggers accretion onto companion NS

More to come...
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Thank you!

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