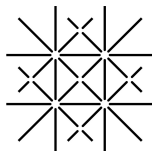


Gravitational waves from core collapse supernovae

Simon Scheidegger

Department of Physics (Group Liebendörfer/Thielemann)

Eurograd
Todtmoos 2007



UNI
BASEL

Outline

- 1 Gravitational waves in general
 - Introduction
 - Physical properties of Gravitational radiation
 - Why are we interested in detecting GW in general?
- 2 Gravitational radiation from core collapse supernovae
 - Information carried by GW from core collapse supernovae
 - Signal types
- 3 My current work

What is a gravitational wave?

According to General relativity:

- Compact mass concentrations (e.g. neutron stars; black holes) should warp space time strongly.
- Whenever such an energy distribution changes shape, it creates a dynamically changing space-time warpage that propagates throughout the universe with the speed of light c
- \Rightarrow This propagating warpage is called **GRAVITATIONAL WAVE (GW)**

What is a gravitational wave?

⇒ Accelerated mass-distributions radiate GW, just as radio waves are generated when electric charge is accelerated.



Figure: Qualitative Sketch: GW from two coalescing super massive black holes (Thorne '94)

Physical properties of Gravitational radiation

- Two linear polarisations: h_+ , h_\times
- Have their mathematical origin in the linearized Einstein field equations.
Ansatz: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$; $|h_{\mu\nu}| \ll 1$
- We can interpret GW as an excited mode of the empty/flat space time.
- Helicity=2
- Each wave field produces tidal forces (squeezing and stretching forces) on any object or detector which it passes.

Tidal forces

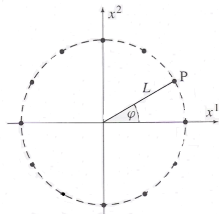


Figure: Test particles.

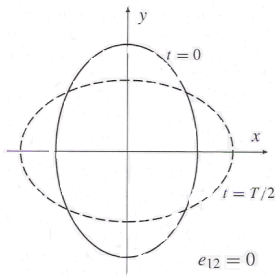


Figure: Infalling + polarised GW along z-axis: GW causes displacement of test particles.

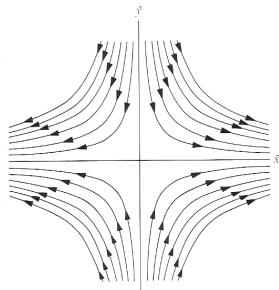


Figure: The corresponding force field.

A way of detecting GW: Laser Interferometer



Figure: View on 'Virgo', a 3km Interferometer (near Pisa/Italy)

Other collaborations hunting for GW:

LIGO (USA), TAMA (J), GEO600 (GER), AIGO (AUS)

Quadrupole approximation

- Field strength can in first order be estimated by using the Newtonian quadrupole

$$\Rightarrow h \approx \frac{G}{c^4} \frac{\ddot{Q}}{r}$$

Q:=source's transverse traceless quadrupole moment

r:=distance to observer

- Trouble: very weak!
- Strongest astrophysical catastrophes cause on earth typical relative changes of space in the order of $h \approx \frac{\Delta L}{L} \approx (10^{-21} - 10^{-22})$.

\Rightarrow equivalent to change the distance between the Earth and the Moon by about the diameter of an atomic nucleus.

\Rightarrow Huge challenge to detect.

Quadrupole approximation

- Field strength can in first order be estimated by using the Newtonian quadrupole

$$\Rightarrow h \approx \frac{G}{c^4} \frac{\ddot{Q}}{r}$$

Q:=source's transverse traceless quadrupole moment

r:=distance to observer

- Trouble: very weak!
- Strongest astrophysical catastrophes cause on earth typical relative changes of space in the order of $h \approx \frac{\Delta L}{L} \approx (10^{-21} - 10^{-22})$.

\Rightarrow equivalent to change the distance between the Earth and the Moon by about the diameter of an atomic nucleus.

\Rightarrow Huge challenge to detect.

Today's understanding of the cosmos

Today's understanding of Cosmos depends entirely on:

- Observations of electromagnetic radiation:

⇒ Have their origin in the acceleration of individual electric charges.

⇒ They show thermodynamic state of optically thin concentrations of matter i.e. the surface of its astronomical source

- Observations of neutrinos:

⇒ extremely sensitive to details in the micro-physics

What could GW observation provide us?

- Gravitational radiation arises from bulk motion of dense mass/energy concentrations
- GW could provide access to high density regimes (e.g. supernova cores; usually optically hidden behind dense layers of stellar gas.
- GW interact only weakly with matter \Rightarrow they can pass through regions of space that scatter or even absorb strongly photons.
- \Rightarrow GW could open a completely new window on the universe.

What could GW observation provide us?

- Gravitational radiation arises from bulk motion of dense mass/energy concentrations
- GW could provide access to high density regimes (e.g. supernova cores; usually optically hidden behind dense layers of stellar gas.
- GW interact only weakly with matter \Rightarrow they can pass through regions of space that scatter or even absorb strongly photons.
- \Rightarrow GW could open a completely new window on the universe.

Core collapse supernova: a possible GW-source

GW from core collapse supernovae deliver information about:

- the rotational state and angular momentum distribution of the progenitor/ protoneutron star (PNS)
- Convective motions inside PNS and 'hot bubble'
- Asymmetries in the ν -emission
- Equation of state (EoS)

Core bounce and the subsequent ringdown

- Induced by large scale asymmetries
- Strongly depending on initial rotation

Core bounce and the subsequent ringdown

- Induced by large scale asymmetries
- Strongly depending on initial rotation
- Three clear defined signal subclasses
 - Type I: Large amplitude at core bounce & damped ring-down oscillations. Core bounce due to the stiffening of the EoS.
 - Type II: Has several distinct peaks, caused by strong centrifugal forces. The core bounces with following coherent re-expansion phases of the inner core.
 - Type III: 'Large' positive peak at bounce, followed by some smaller oscillations with very short periods. Appears in case of a fast, pressure-dominated core collapse due to very efficient electron capture.
 - ⇒ 'Realistic' input physics: Only type I (Dimmelmeier et al. 2007/Ott et al.2007)

Core bounce and the subsequent ringdown

- Induced by large scale asymmetries
- Strongly depending on initial rotation
- Three clear defined signal subclasses
 - Type I: Large amplitude at core bounce & damped ring-down oscillations. Core bounce due to the stiffening of the EoS.
 - Type II: Has several distinct peaks, caused by strong centrifugal forces. The core bounces with following coherent re-expansion phases of the inner core.
 - Type III: 'Large' positive peak at bounce, followed by some smaller oscillations with very short periods. Appears in case of a fast, pressure-dominated core collapse due to very efficient electron capture.
 - ⇒ 'Realistic' input physics: Only type I (Dimmelmeier et al. 2007/Ott et al.2007)

Signal shapes from core bounce & ring-down

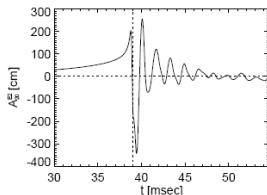


Figure: Type I; Zwerger & Müller (1997)

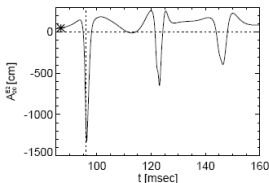


Figure: Type II; Zwerger & Müller (1997)

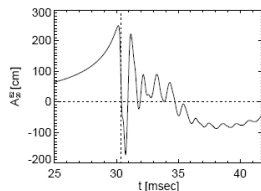


Figure: Type III; Zwerger & Müller (1997)

Convective motions in the PNS, hot bubble & Anisotropic ν -emission

- Amplitudes caused by small-scale statistical mass-energy fluctuations.
- Characterized by an amplitude that rises from zero to a non-zero value. \Rightarrow 'Burst with memory'.
- No strict signal classes yet \Rightarrow Simulations still hampered by the computationally expensive complete inclusion of micro-physics.

All signal features at once

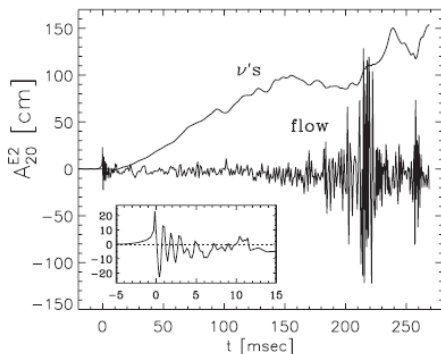


Figure: GW Signals from core bounce, Convection & asymmetric ν -emission; Müller et al. (2004)

Movie: xy-plane of a rotating core collapse simulation (run s15g)

run s15g

The corresponding GW signal in polar and equatorial direction (run s15g)

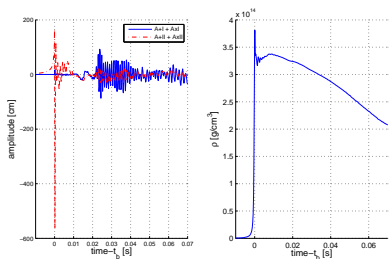


Figure: Typical type I signal.

Central density at bounce:

$$3.8 \times 10^{14} \left[\frac{\text{g}}{\text{cm}^3} \right].$$

GW from Convection ($t > 20\text{ms}$): polar signal dominant.

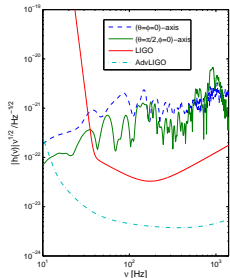


Figure: Spectral energy distribution of s15g (movie), evaluated at 10kpc, in comparison with LIGO/AdvLIGO sensitivity.

Outline of my current work.

- Extracting gravitational radiation of 3D MHD core collapse supernovae simulations with very accurate input physics.
- vary parameters systematically and study their influence on the wave forms.
- Interpret results/ link them to physical phenomena
⇒ More details in [arXiv:0709.0168v1](https://arxiv.org/abs/0709.0168v1) [astro-ph]