Gravitational waves and core-collapse supernovae

G.S.Bisnovatyi-Kogan(1,2)

(1)Space Research Institute of RAS, Moscow, Russia,
(2)National Research Nuclear University “MEPhI”, Moscow, Russia

In collaboration with
S.G.Moiseenko, N.V. Argelyan

GRBs and other transient sources:
25 Years of Konus-Wind Experiment (KW25)
9-13 September 2019
MERGING of COMPACT STARS in CLOSE BINARIES (LIGO-VIRGO)
Probability density function that represents our expectation that the actual DNS binary merger rate in the Galaxy (bottom axis) and the predicted initial LIGO rate (top axis) take on particular values, given the observations. The solid line shows the total probability density along with those obtained for each of the three binary systems (dashed lines). **Inset:** Total probability density, and corresponding 68%, 95%, and 99% confidence limits, shown in a linear scale.

For the model of pulsar evolution, the mean galactic merging rate of BNS systems is $R \sim 83 / \text{Myr}$. The 68%- and 95%-confidence level intervals are $40 \pm 140$ and $20 \pm 290 / \text{Myr}$, respectively. The expected detection rate of a gravitational-wave pulse from neighboring galaxies is 0.035 and 190 events per year for the initial (the detection limit 20 Mpc) and advanced (the detection limit 350 Mpc) LIGO interferometers, respectively. The corresponding 95%-confidence intervals are $0.007 \pm 0.12$ and $40 \pm 660$ events per year, respectively. The discovery of the double pulsar J0737-3039 increased R by 6.4 times compared to earlier calculations, because it dominates in computing the total probability, as seen in Fig.

Examination of a broader class of evolutionary models of pulsars showed that in all cases, accounting for the double pulsar J0737 ± 3039 increases the BNS merging rate by 6 - 7 times, although the rates can differ by more than 50 times in individual cases.

Observed 2017-08-17, 12:41:04
First announced discovery: 2 massive BH merging 2015-09-14, 5:1sigma.
Nonspherical Gravitational Collapse
Core-collapsed supernovae
Supernovae type Ib, Ic, II
Supernova explosion – star’s death.
Supernova remnant – neutron star, black hole.
Iron core collapse. Neutronization.
Neutrino radiation.

Supernova observed (kinetic + radiation)
explosion energy \(\sim 10^{51}\) erg(!)
Uniform collapse without rotation

\[ E(\text{RAD}) = \frac{2}{375} \frac{GM^2}{c^2} (\ddot{A}^2 - \ddot{C}^2)^2 \]

\[ \Delta E(\text{RAD}) = 0.0370 (\frac{r_{\text{Sch}}}{r_{\text{min}}} \frac{7}{2}) MC^2 \lessapprox 10^{51} \text{ erg} \]

\[ 0.109 \gtrapprox 2 \times 10^{45} \text{ erg for rapid rotation} \]

Radiated during the collapse to maximal compression

Schwarzschild radius, minimal value of large semi-axis
Gravitational radiation from a star collapsing into a disk
I. D. Novikov

GW radiation during the bounce at finite entropy

$$\Delta e \approx KMC^2 \left( \frac{rS}{A} \right)^{\nu/2} \frac{A}{C_f}$$

A - the large axis, $C_f$ - minimal value of C, $A/C_f < \sim 10$, $K \sim 0.01$

The formal upper limit:

$$\Delta e_{\text{max}} \approx M(dC/dt)^2 \approx MC^2rS/A,$$

Never reached
Magnetorotational mechanism for the supernova explosion Bisnovatyi-Kogan (1970)

Amplification of magnetic fields due to differential rotation, angular momentum transfer by magnetic field. Part of the rotational energy is transformed to the energy of explosion.

**NUMERICAL SIMULATIONS**


Magnetorotational mechanism for core-collapsed supernova is one of the most reliable for energy production.
Maximal compression state

Max. density = $2.5 \cdot 10^{14} \text{g/cm}^3$
The period of rotation of the young neutron star is about 0.001-0.003 sec.

Rapidly rotating pre-SN
Crab pulsar $P=33$ms – rapid rotation at birth
Core collapse in binaries
Initial magnetic field – quadrupole-like symmetry

S.G.Moiseenko, G.S.Bisnovatyi-Kogan, Astronomy Reports, 2015, 59, 7, 573-580
Magnetorotational supernova explosion quadruple field

Temperature and velocity field

Specific angular momentum $rV_\phi$
Ejected energy and mass

Ejected energy \(0.6 \cdot 10^{51} \text{ erg}\) \[\text{Ejected mass } 0.14 \text{M}_\odot\]

Particle is considered “ejected” – if its kinetic energy is greater than its potential energy

```markdown
<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Ejected Mass/Mass_{sun}</th>
<th>Ejected Energy (ergs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.1</td>
<td>0.1</td>
<td>1.0 \times 10^{50}</td>
</tr>
<tr>
<td>0.2</td>
<td>0.2</td>
<td>2.0 \times 10^{50}</td>
</tr>
<tr>
<td>0.3</td>
<td>0.3</td>
<td>3.0 \times 10^{50}</td>
</tr>
<tr>
<td>0.4</td>
<td>0.4</td>
<td>4.0 \times 10^{50}</td>
</tr>
</tbody>
</table>
```

Ejected mass and energy graphs are shown with time on the x-axis and mass and energy on the y-axis.
Magnetorotational instability

Central part of the computational domain. Formation of the MRI.
Initial magnetic field – dipole-like symmetry
S.G.Moiseenko, G.S.Bisnovatyi-Kogan, Astronomy Reports, 2015, 59, 7, 573-580
Magnetorotational supernova explosion

dipole-like field

jet formation

Entropy

Velocity field

Specific angular momentum
Ejected energy and mass (dipole)

Ejected energy \( \approx 0.5 \cdot 10^{51} \text{erg} \)  
Ejected mass \( \approx 0.14M_\odot \)

Particle is considered “ejected” – if its kinetic energy is greater than its potential energy.
INFERRING THE CORE-COLLAPSE SUPERNova EXPLOSION MECHANISM WITH GRAVITATIONAL WAVES

Jade Powell, Sarah E. Gossan, Joshua Logue, Ik Siong Heng

PHYSICAL REVIEW D 94, 123012 (2016)

GW signal from magneto-rotational and neutrino modeling of CCSE
Time evolution of the GW amplitude $h$ and maximum density for three representative models with different rotation profiles and initial rotation rate $\beta_i = T_i/|W_i|$, at a distance $d = 10$ kpc.
Characteristic GW strain spectra $h_{c,sp}$ at a distance $d = 10$ kpc to the source for three representative models in GR with microphysical EoS and deleptonization that do not undergo centrifugal bounce. As for most other models the individual maxima $f_{\text{max}}$ of their frequency spectrum is very close to $f_{\text{max}} \simeq 718$ Hz.
Estimations of GW signal from non-spherical collapse

G.S. Bisnovatyi-Kogan, S.G. Moiseenko “Gravitational waves and core-collapse supernovae”

*Phys. Usp. 60* (8) (2017)
Collapse of rotating WD with $1.2 \, M_\odot$

Collapse is bounced at formation of a hot neutron star

$M$ is a mass inside a given iso-density

\[
A_{\text{min}} = 5.5 \times 10^5 \text{ см} , \quad \frac{C_{\text{min}}}{A_{\text{min}}} = 0.50 \quad \text{при} \quad M = 0.24 M_\odot ,
\]

\[
E_{\text{GW}} = 1.3 \times 10^{49} \text{ эрг} ,
\]

\[
A_{\text{min}} = 5.3 \times 10^6 \text{ см} , \quad \frac{C_{\text{min}}}{A_{\text{min}}} = 0.79 \quad \text{при} \quad M = 0.3 M_\odot ,
\]

\[
E_{\text{GW}} = 1.2 \times 10^{46} \text{ эрг} ,
\]

\[
A_{\text{min}} = 9.5 \times 10^6 \text{ см} , \quad \frac{C_{\text{min}}}{A_{\text{min}}} = 0.83 \quad \text{при} \quad M = 0.5 M_\odot ,
\]

\[
E_{\text{GW}} = 5.4 \times 10^{45} \text{ эрг} , \quad (9)
\]

\[
A_{\text{min}} = 3 \times 10^7 \text{ см} , \quad \frac{C_{\text{min}}}{A_{\text{min}}} = 0.89 \quad \text{при} \quad M = 0.8 M_\odot ,
\]

\[
E_{\text{GW}} = 7.4 \times 10^{44} \text{ эрг} ,
\]

\[
A_{\text{min}} = 4.2 \times 10^7 \text{ см} , \quad \frac{C_{\text{min}}}{A_{\text{min}}} = 0.94 \quad \text{при} \quad M = M_\odot ,
\]

\[
E_{\text{GW}} = 5.9 \times 10^{44} \text{ эрг} .
\]
$$h_{\phi\phi} = -h_{\theta\theta} = \frac{GM}{5rc^4} \sin^2 \theta_0 (\ddot{A}^2 - \ddot{C}^2), \quad h_{\theta\phi} = 0.$$  

Approximately:

$$h_{\phi\phi} = -h_{\theta\theta} = \frac{GM}{5rc^4} \frac{A_{\text{min}}^2}{(\Delta t)^2}.$$  

The GW amplitude:  \( \beta_b \approx 0.028. \)  \( f_{\text{max}} \sim 1200 \)  

$$h = h_{\phi\phi} = -h_{\theta\theta} = \frac{6.7 \times 10^{-8}(0.48 \times 10^{33})}{5rc^4} \times$$

$$\times \frac{(5.5 \times 10^5)^2}{(0.75 \times 10^{-3})^2} \approx 1.4 \times 10^{-22} \frac{10 \text{ кПк}}{r}.$$
Joke about GW registration
(information for consideration)

100 Hz corresponds to 3000 rot/min
Rotation rate of a powerful auto

4 bursts during 3 years are inside 40 minutes of the day
Modern **automobile engines** are typically operated around 2,000–3,000 rpm (33–50 Hz) when cruising, with a minimum (idle) speed around 750–900 rpm (12.5–15 Hz), and an upper limit anywhere from 4500 to 10,000 rpm (75–166 Hz) for a road car.

GW frequency is doubled!
Conclusions

1. GW have been discovered indirectly 25 years ago in observations of binary pulsar.

2. In addition to merging, GW are radiated during the first bounce in non-spherical core collapse (e.g. supernovae), frequency \( \sim 1000 \text{ Hz} \). This GW signal may be registered from core-collapse SN in our Galaxy.