Magnetorotational Supernovae and Jet Formation

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8^{th} October 2015
HEPRO-5, La Plata, Argentina

Supernova is one of the most powerful explosion in the Universe, energy (radiation and kinetic) about 10^51 egr

End of the evolution of massive stars, with initial mass more than about 8 Solar mass.

Tracks in HR diagram of a representative selection of stars from the main sequence till the end of the evolution Iben (1985)

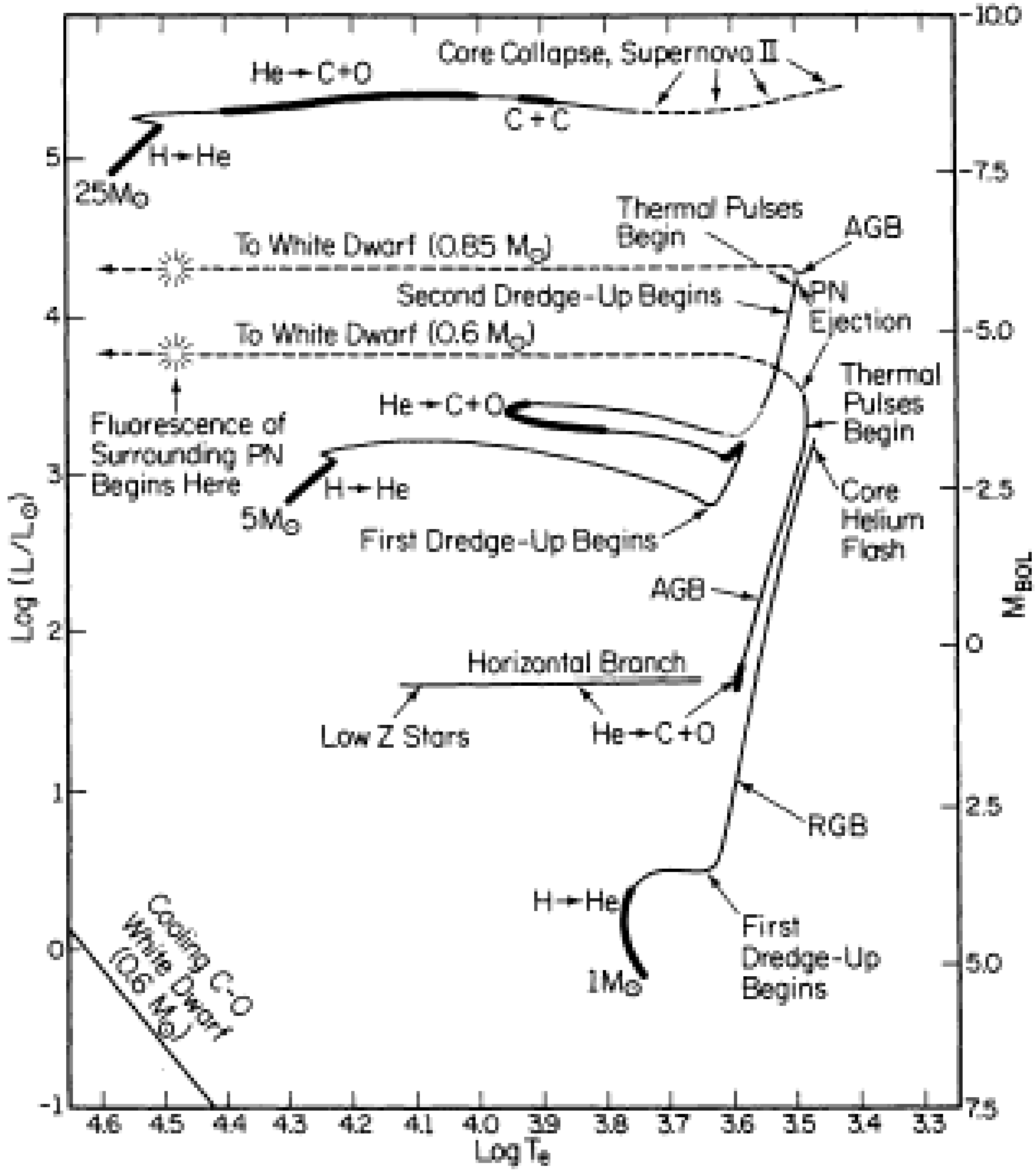


Fig. 15. Tracks in the HR diagram of a representative selection of stars. The heavy portions of each curve define locations where the major core nuclear burning phases occur. Details of tracks during transitory phases between major nuclear burning phases are suppressed. For stars of initial mass less than about 2·3 $M_\odot$,

Explosion mechanisms of spherically symmetric star

1. **Thermonuclear explosion** of C-O degenerate core **(SN Ia)**

1. **Core collapse and formation of a neutron star, neutrino deposition**

gravitational energy release up to 5 10^{53} erg, carried away by neutrino **(SN II, SN Ib,c)**

Equal to binding energy of the neutron star

NUCLEOSYNTHESIS IN SUPERNOVAE

F. Hoyle
St. John's College, Cambridge, and California Institute of Technology

AND

William A. Fowler
California Institute of Technology
Received May 21, 1960

ABSTRACT

The role of Type I and Type II supernovae in nucleosynthesis is treated in some detail. It is concluded that *e*-process formation of the iron-group elements takes place in Type II supernovae, while *r*-process formation of the neutron-rich isotopes of the heavy elements takes place in Type I supernovae. The explosion of Type II supernovae is shown to follow implosion of the non-degenerate core material. The explosion of Type I supernovae results from the ignition of degenerate nuclear fuel in stellar material.

Astrophysical Journal, vol. 143, p.626 (1966)

The Hydrodynamic Behavior of Supernovae Explosions

S.Colgate, R.White

Received June 29, 1965

We regard the release of gravitational energy attending a dynamic change in configuration to be the primary energy source in supernovae explosions. Although we were initially inspired by and agree in detail with the mechanism for initiating gravitational instability proposed by Burbidge, Burbidge, Fowler, and Hoyle, we find that the dynamical implosion is so violent that an energy many times greater than the available thermonuclear energy is released from the star's core and transferred to the star's mantle in a supernova explosion. The energy released corresponds to the change in gravitational potential of the unstable imploding core; the transfer of energy takes place by the emission and deposition of neutrinos.

D. Arnett (1966, 1967)

L.Ivanova, V. Imshennik, D. Nadyozhin (1969)

In a simple 1-D model neurino deposition cannot give enough energy to matter (heating) for SN explosion

Neutrino convection – Epstein (1979)

leads to emission of higher energy neutrino, may transfer more energy into heating

Results are still controversial

2D and 3D calculations

3D calculations give less effective explosion because of opposite energy fluxes in 2 and 3 D

formation of larger eddies in 2D (artificial)

formation of smaller eddies in 3D (real),

1968: PULSARS – rapidly rotating, strongly magnetized neutron stars

Magnetorotational explosion (MRE): transformation of the rotational energy of the neutron star into explosion energy by means of the magnetic field in core collapse SN

Soviet Astronomy, Vol. 14, p.652 (1971)

The Explosion of a Rotating Star As a Supernova Mechanism.

G.S.Bisnovatyi-Kogan

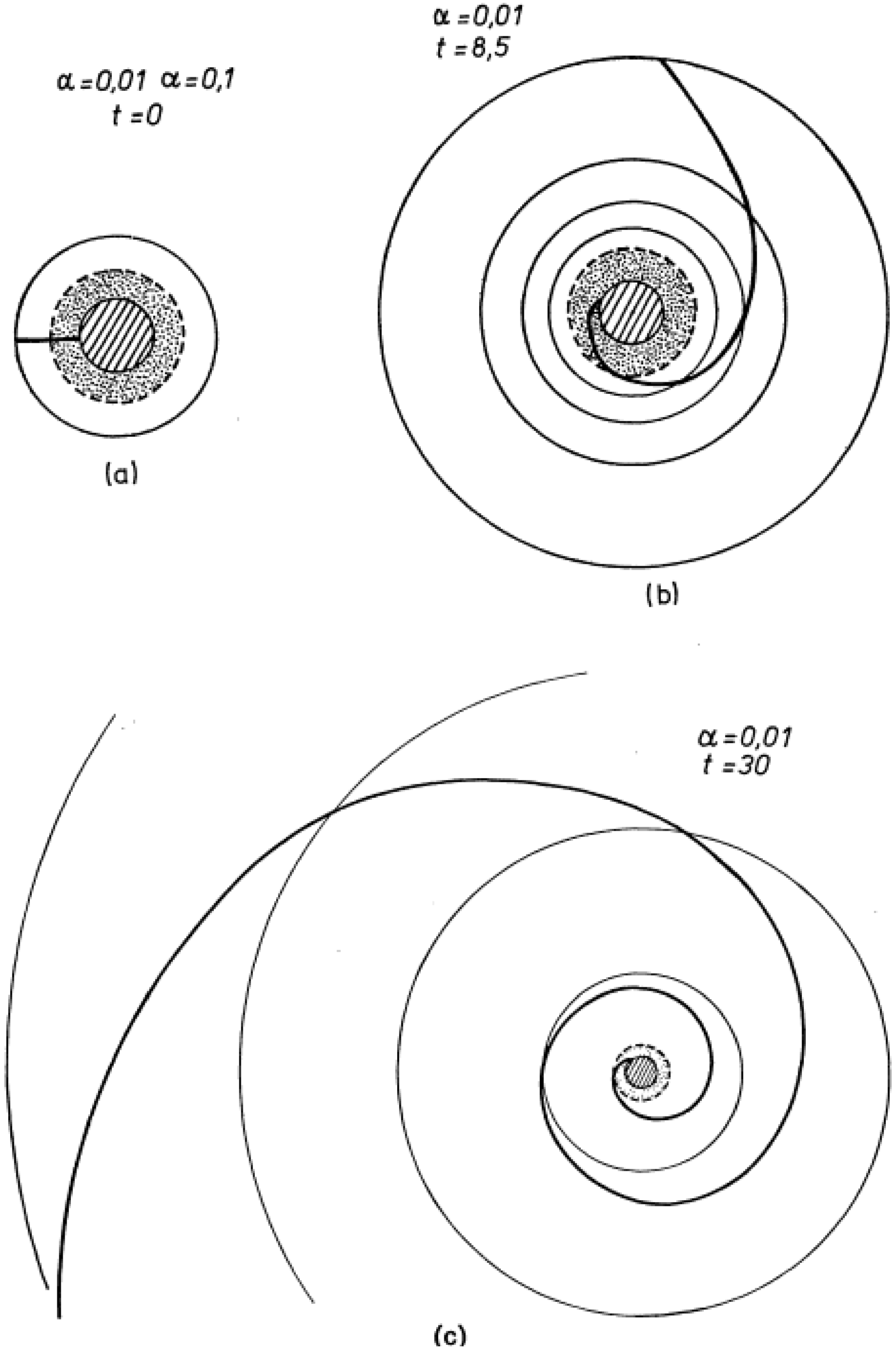
Translated from Astronomicheskii Zhurnal, Vol. 47, No. 4,
pp. 813-816, July-August, 1970
Original article submitted September 3, 1969

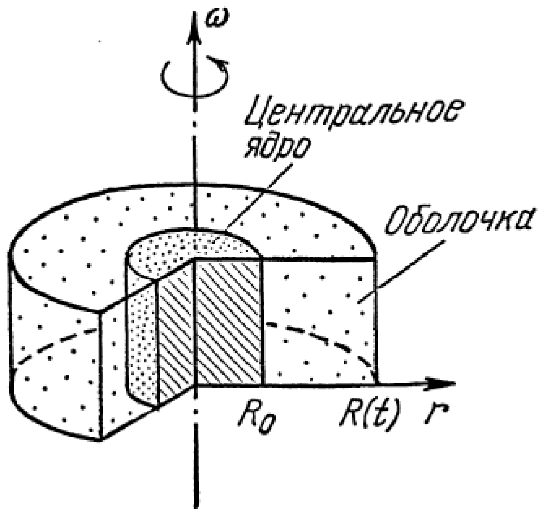
A supernova-explosion mechanism not associated with nuclear detonation is proposed for a rotating star. It involves the transfer of angular momentum from a rapidly rotating neutron star, formed through collapse, to the envelope, where the centrifugal force is nearly equal to the gravitational force. An explosion will result when the centrifugal force inside the envelope exceeds the gravitational force, with a shock wave being generated. Angular momentum will be transferred efficiently if a sufficiently strong magnetic field, $H \approx 3 \cdot 10^9$ gauss, is present.

G. S. BISNOVATYI-KOGAN*, YU. P. POPOV**, and A. A. SAMOCHIN**

(1976)

alpha=0.01,
t=8.5





1-D calculations of magnetorotational explosion

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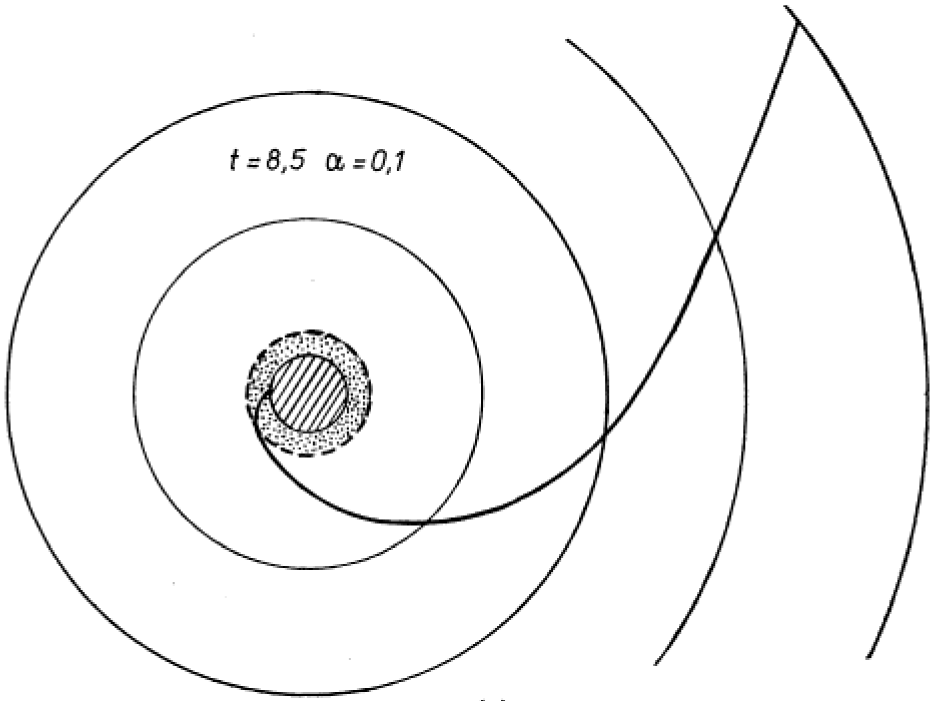
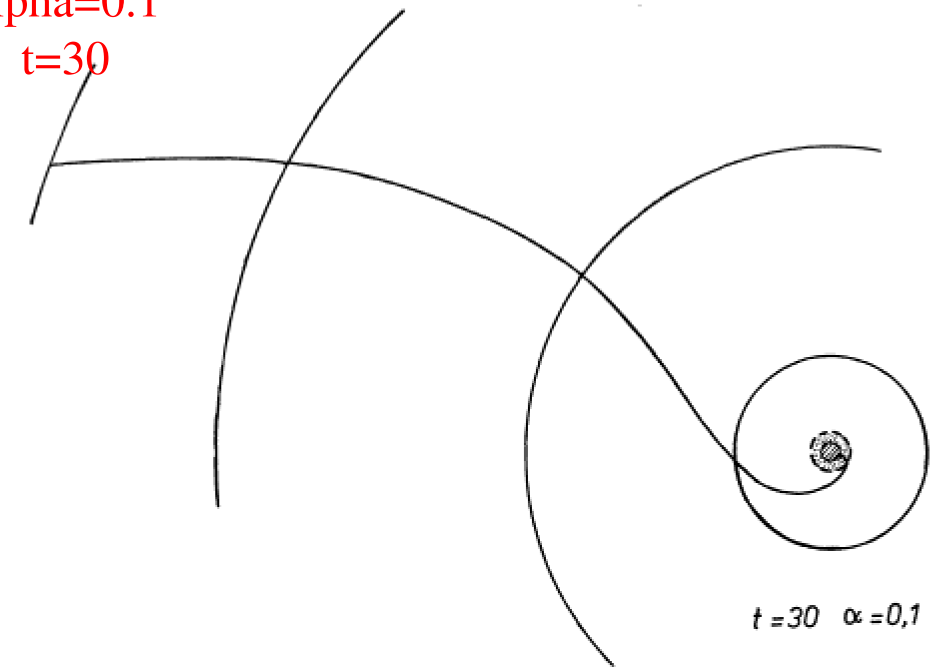
$$\alpha = \frac{E_{mag0}}{E_{grav}}.$$

1-D calculations of
magnetorotational explosion
B.-K., Popov, Samokhin (1976).



(a)

alpha=0.1
t=30

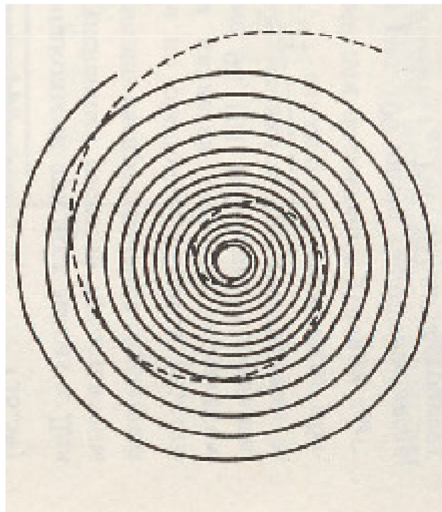


(b)

Ardeljan, Bisnovatyi-Kogan, Popov (1979),
Astron. Zh., **56**, 1244

$\alpha=10^{-2}, 10^{-4}, 10^{-8}$

$\alpha=10^{-2}$- dashed line, $\alpha=10^{-4}$- full line



The main results of 1-D calculations:

Magneto-rotational explosion (MRE) has an efficiency about 10% of rotational energy.

For the neutron star mass the ejected mass $\approx 0.1 M_{\odot}$,
Explosion energy $\approx 10^{51}$ erg
Ejected mass and explosion energy depend very weekly on the parameter α
Explosion time strongly depends on α .

$$\text{Explosion time} = \boxed{t_{\text{взрыва}} \sim \frac{1}{\sqrt{\alpha}}}$$

Small α is difficult for numerical calculations with EXPLICIT numerical schemes because of the Courant restriction on the time step, "stiff" system of equations: α determines a "stiffness".

In 2-D numerical IMPLICIT schemes have been used.

Difference scheme (Ardeljan, Chernigovskii, Kosmachevskii, Moiseenko)

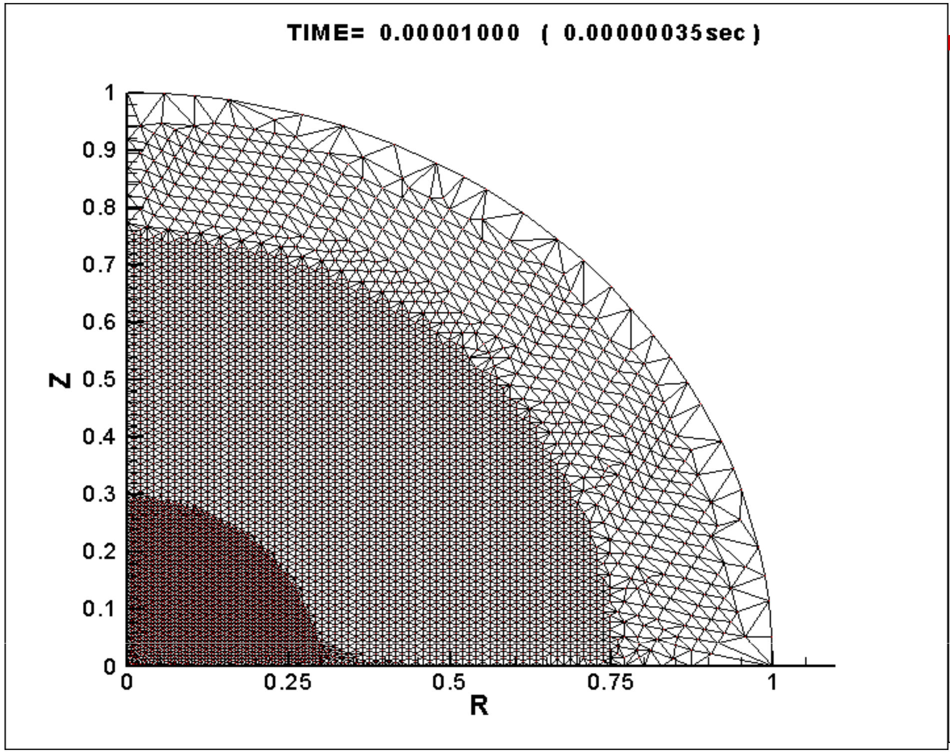
Lagrangian, on triangular reconstructing grid, implicite, fully conservative

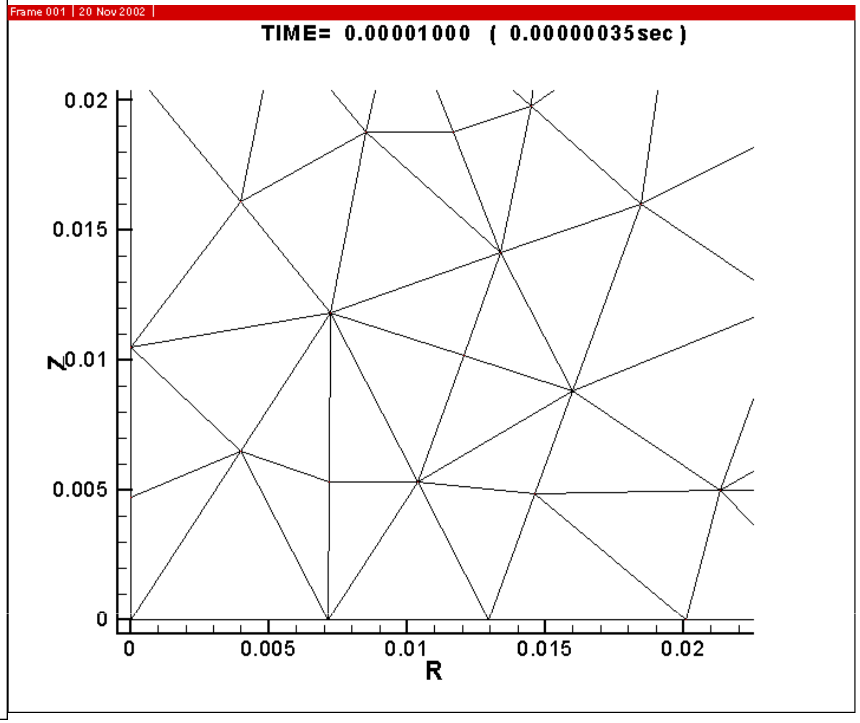
Ardeljan N.V, Kosmachevskii K.V., Chernigovskii S.V., 1987, Problems of construction and research of conservative difference schemes for magneto-gas-dynamics, MSU, Moscow (in Russian)

Ardeljan N.V, Kosmachevskii K.V. 1995, Computational mathematics and modeling, **6**, 209

Ardeljan N.V., Bisnovatyi-Kogan G.S., Kosmachevskii K.V., Moiseenko S.G., 1996, Astron. Astrophys. Supl.Ser., **115**, 573

Grid reconstruction (example)





Presupernova Core Collapse

Ardeljan et. al., 2004, Astrophysics, **47,** 47

Equations of state takes into account degeneracy of electrons and neutrons, relativity for the electrons, nuclear transitions and nuclear interactions. Temperature effects were taken into account approximately by the addition of the pressure of radiation and of an ideal gas.

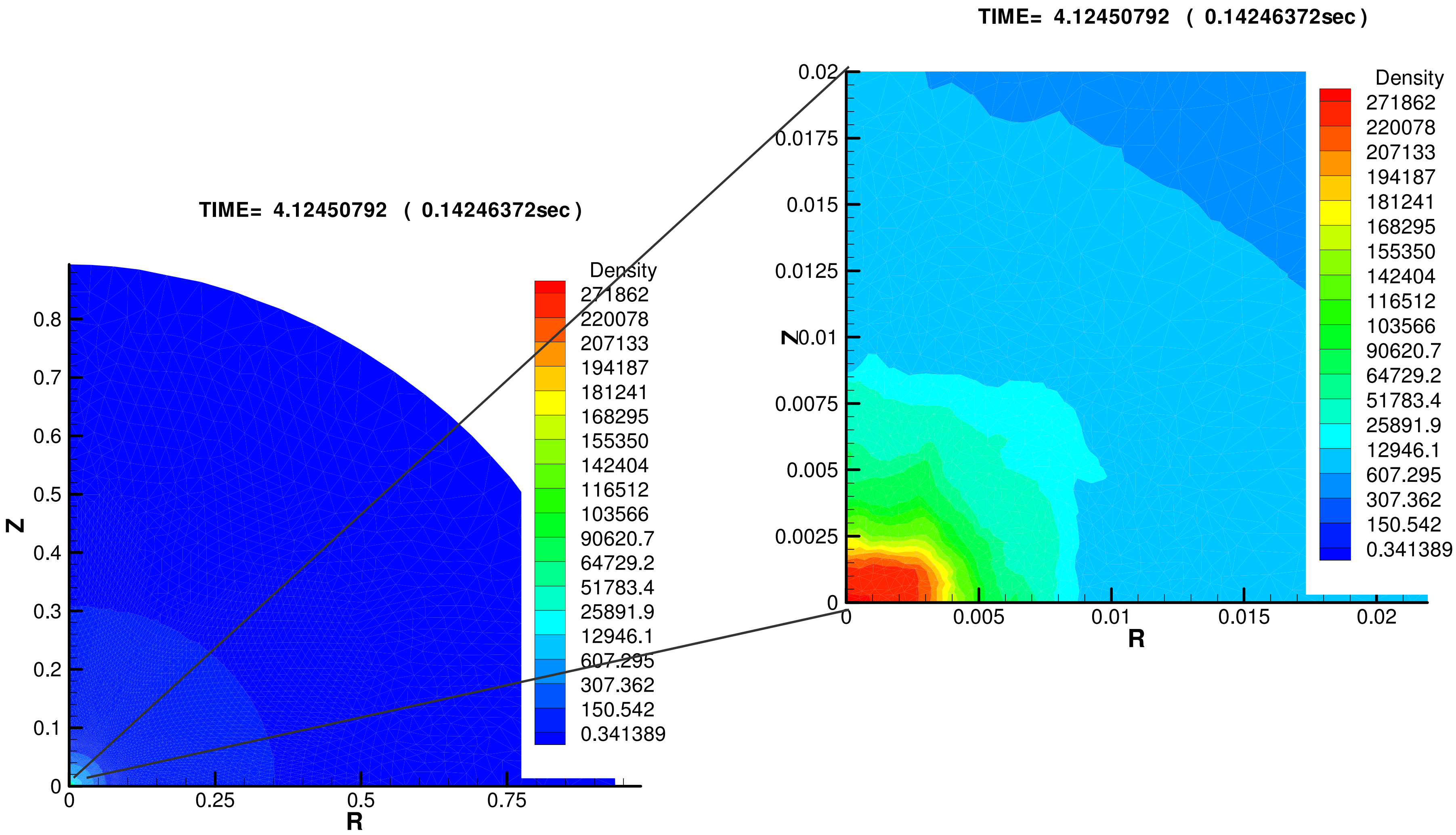
Neutrino losses and iron dissociation were taken into account in the energy equations.

A cool iron white dwarf was considered at the stability border with a mass equal to the Chandrasekhar limit.

$$M = 1.0042 \cdot M_{sun}$$

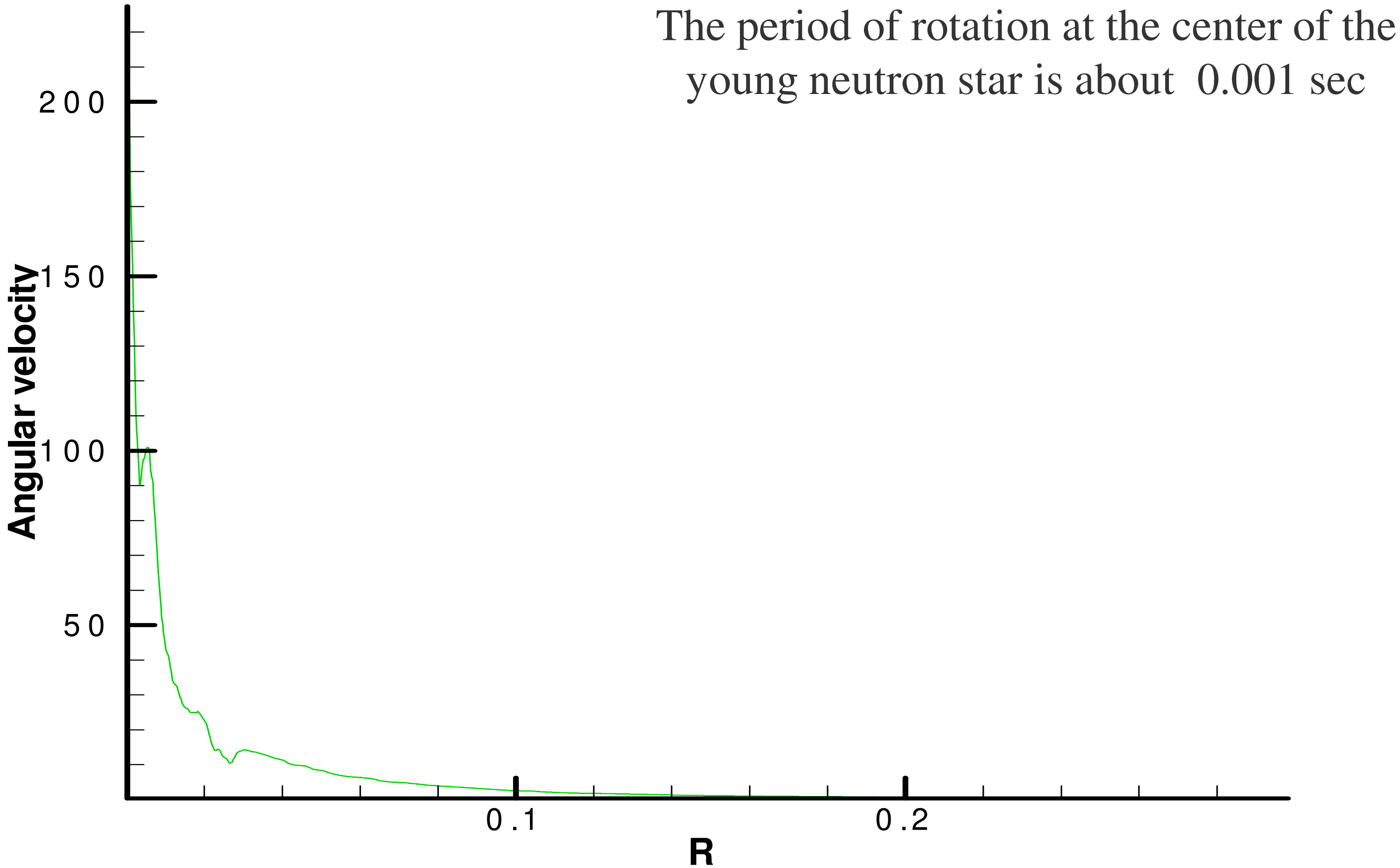
To obtain the collapse we increase the density at each point by 20% and switch on a uniform rotation.

Maximal compression state



Shock wave does not produce SN explosion :

Distribution of the angular velocity



2-D magnetorotational supernova

N.V.Ardeljan, G.S.BK, S.G.Moiseenko MNRAS, **359**, 333 (2005)

A magnetorotational core-collapse model with jets

S. G. Moiseenko, G. S. BK and N. V. Ardeljan MNRAS **370,** 501 (2006)

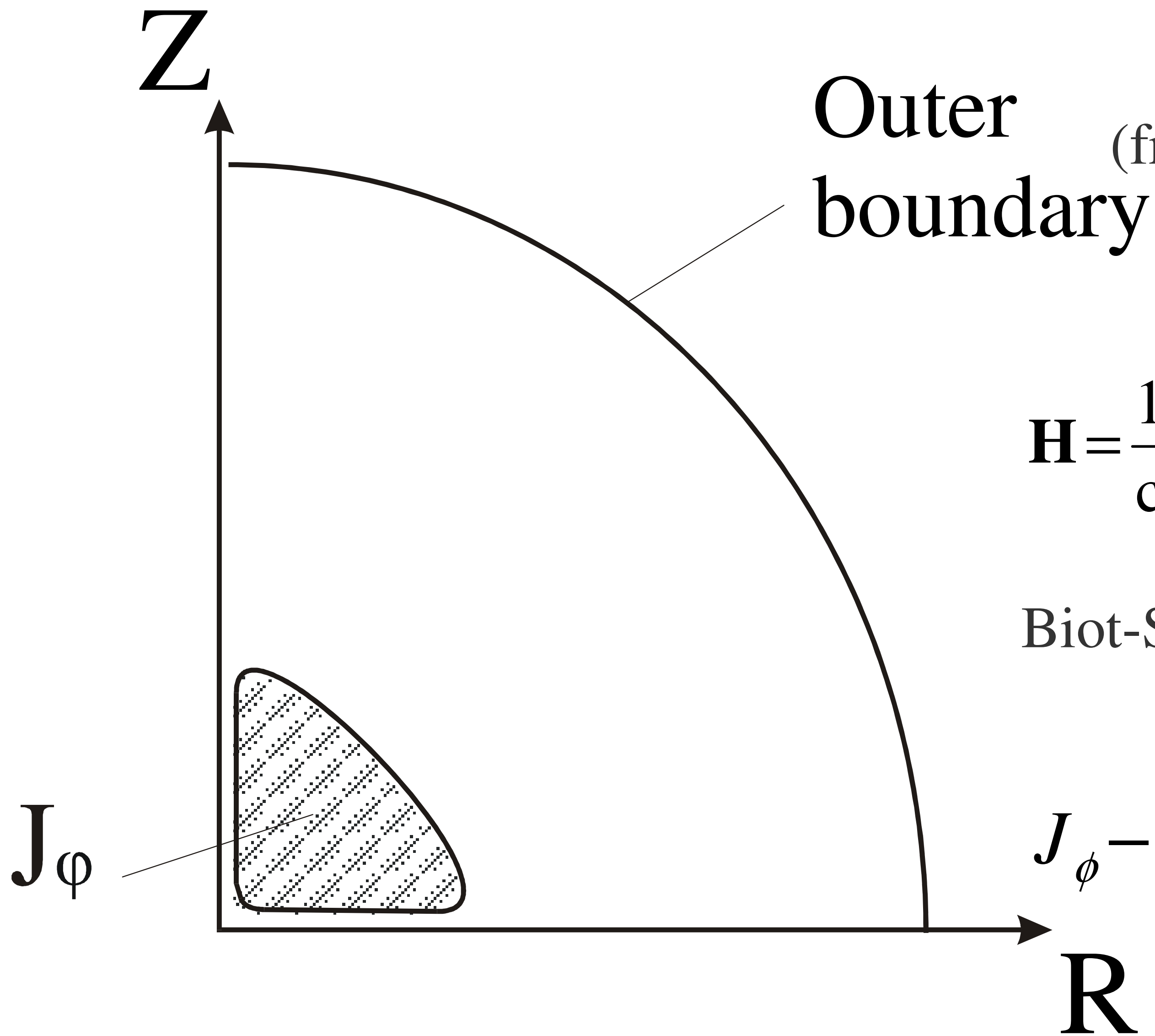
Different magneto-rotational supernovae

BK, G. S.; Moiseenko, S. G.; Ardelyan, N. V., Astr. Rep.**52**, 997 (2008)

Equations: MHD + self-gravitation, infinite conductivity.

Axial symmetry ($\frac{\partial}{\partial \phi} = 0$) , equatorial symmetry (z=0).

Initial toroidal current J_φ



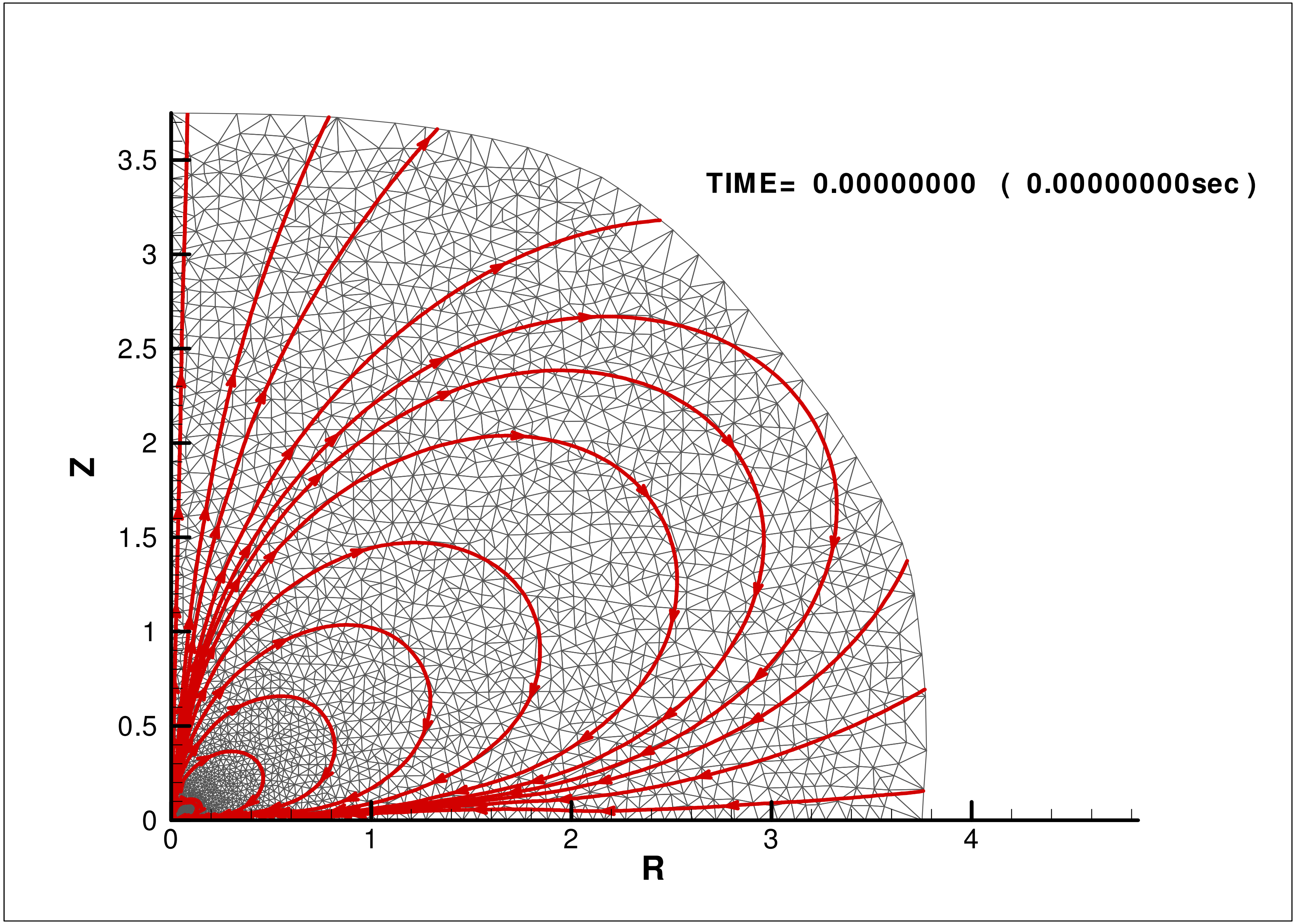
(free boundary)

$$\mathbf{H} = \frac{1}{c}\int \frac{\mathbf{J}\times\mathbf{R}}{R^3}\,dv,$$

Biot-Savarat law

$$J_\phi -> (H_r, H_z)$$

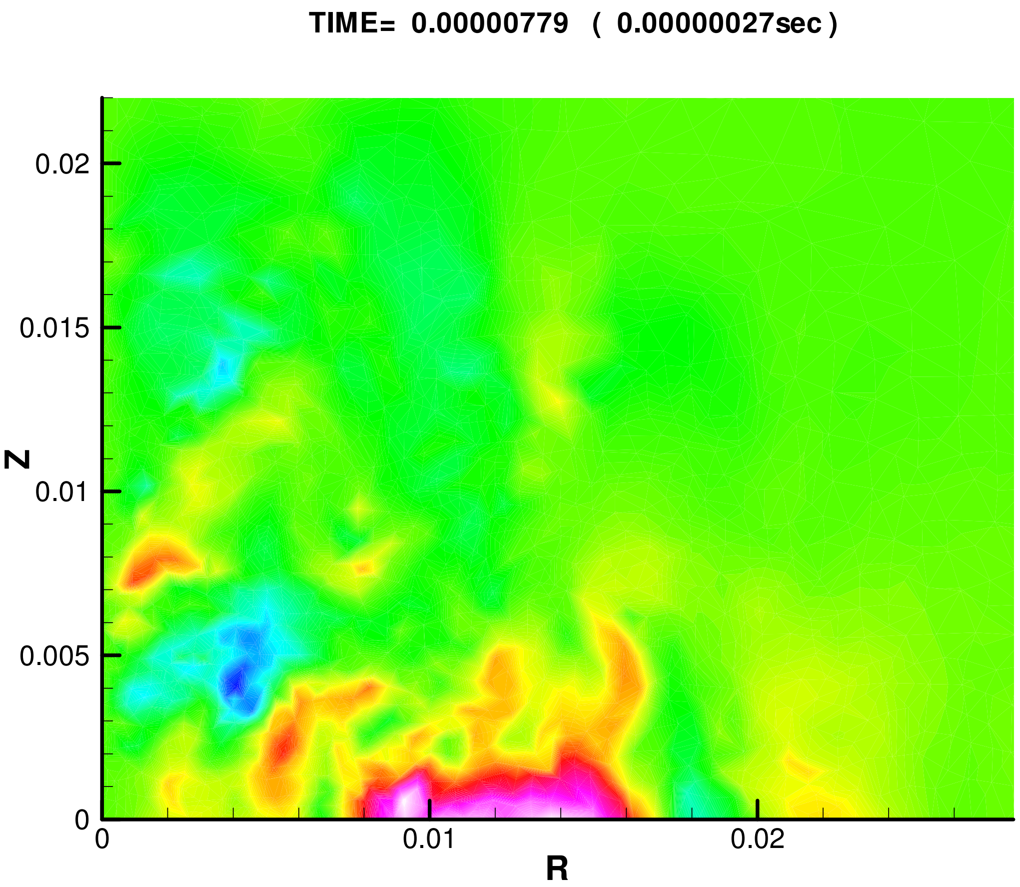
Initial magnetic field –quadrupole-like symmetry



Toroidal magnetic field amplification.

pink – maximum_1 of Hf^2   blue – maximum_2 of Hf^2

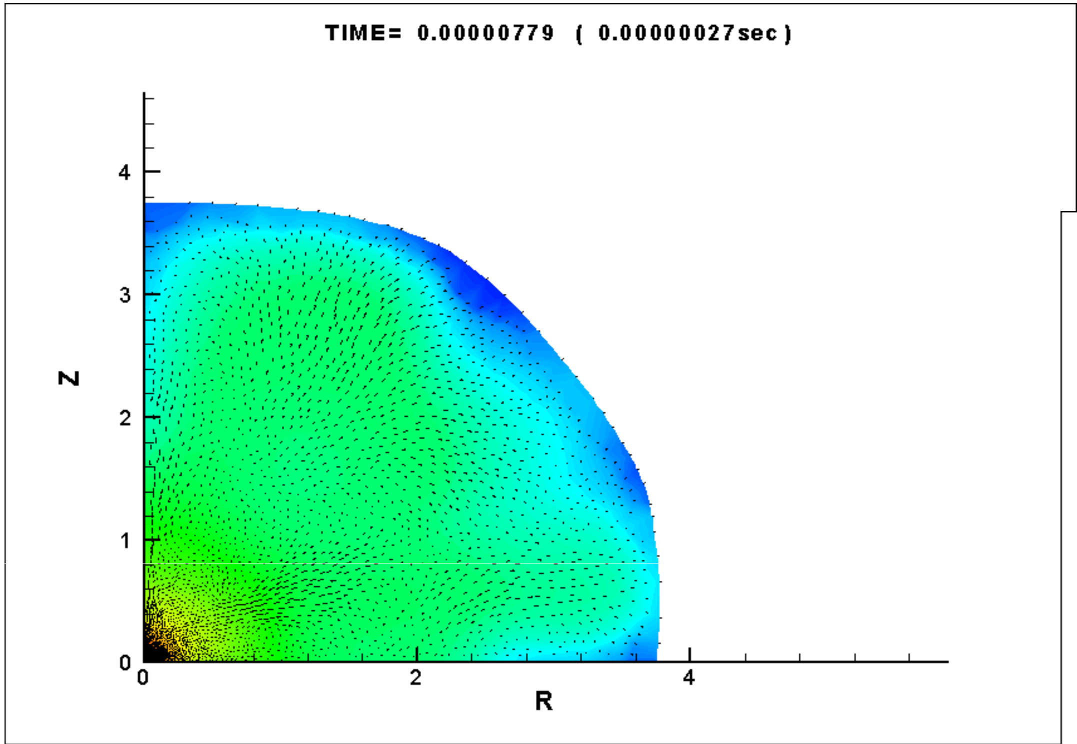
Maximal values of Hf=2.5 10(16)G



The magnetic field at the surface of the neutron star after the explosion is

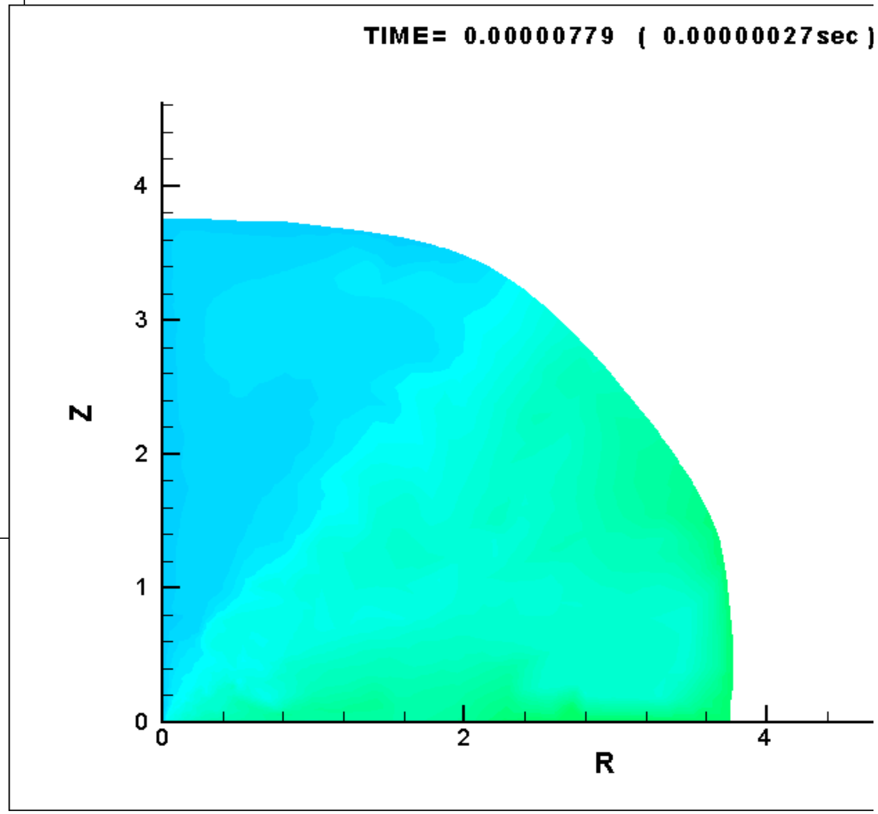
$H = 4 \cdot 10^{12}$ Gs

Temperature and velocity field



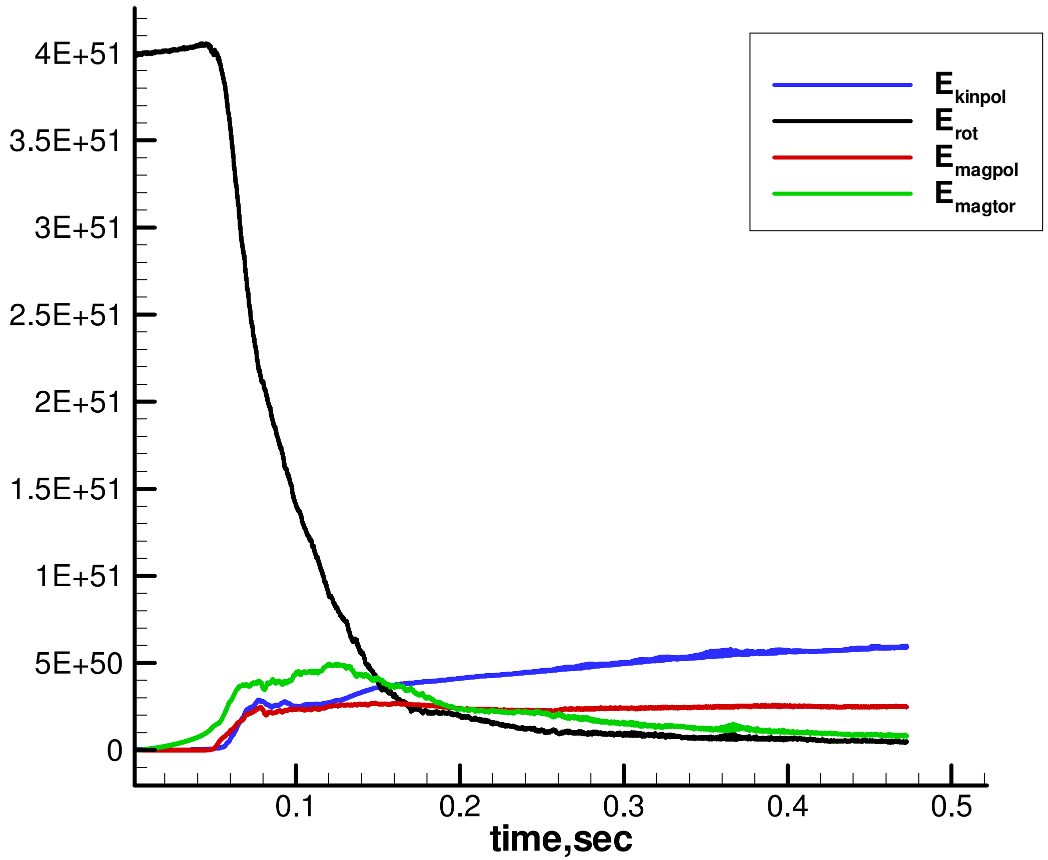
Specific angular momentum

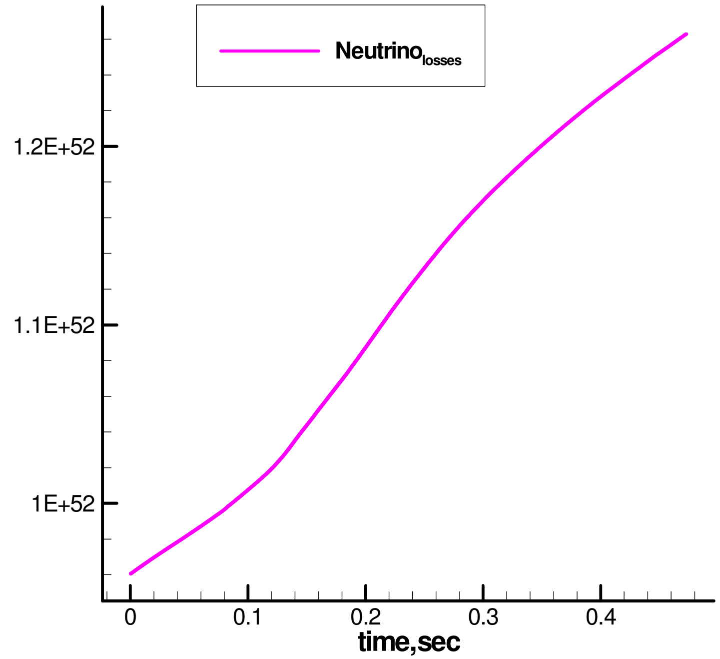
rV_{φ}



Rotational energy
Magnetic poloidal energy
Magnetic toroidal energy
Kinetic poloidal energy

Neutrino losses



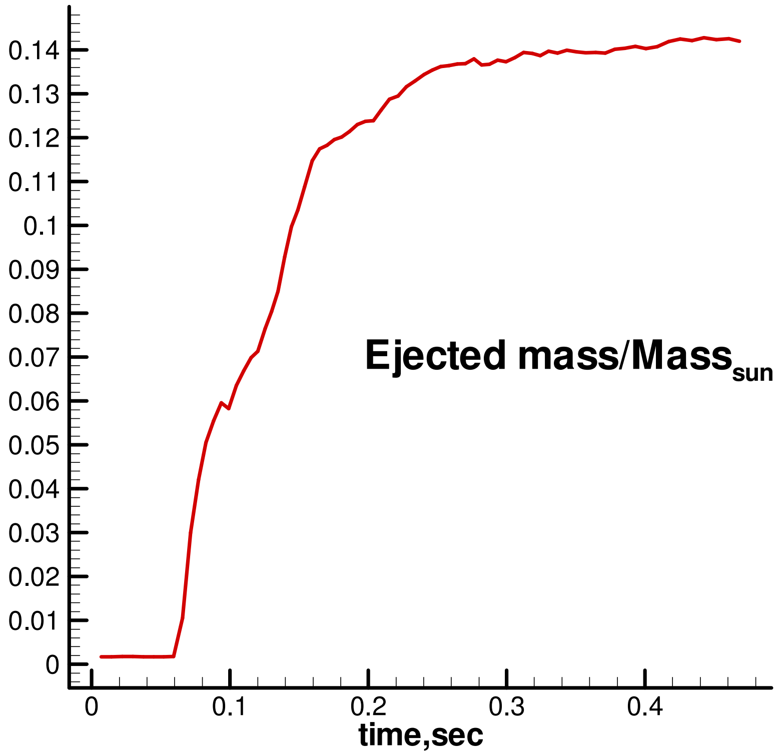


Particle is considered "ejected" if its kinetic energy is greater than its potential energy (alpha=10^{-6})

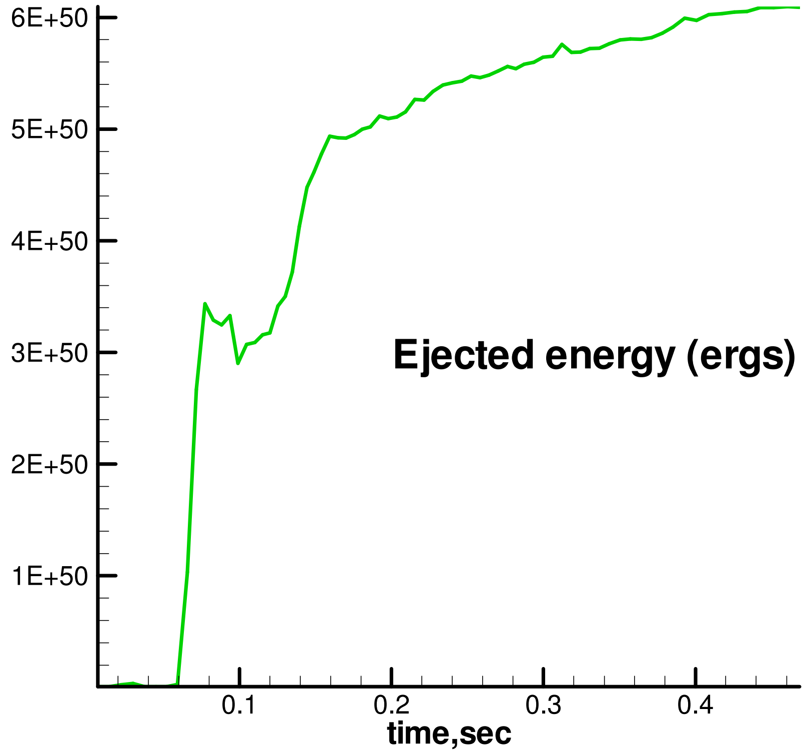
Ejected energy

0.6 10 ^{51} эрг

Ejected mass **$0.14M_\odot$**



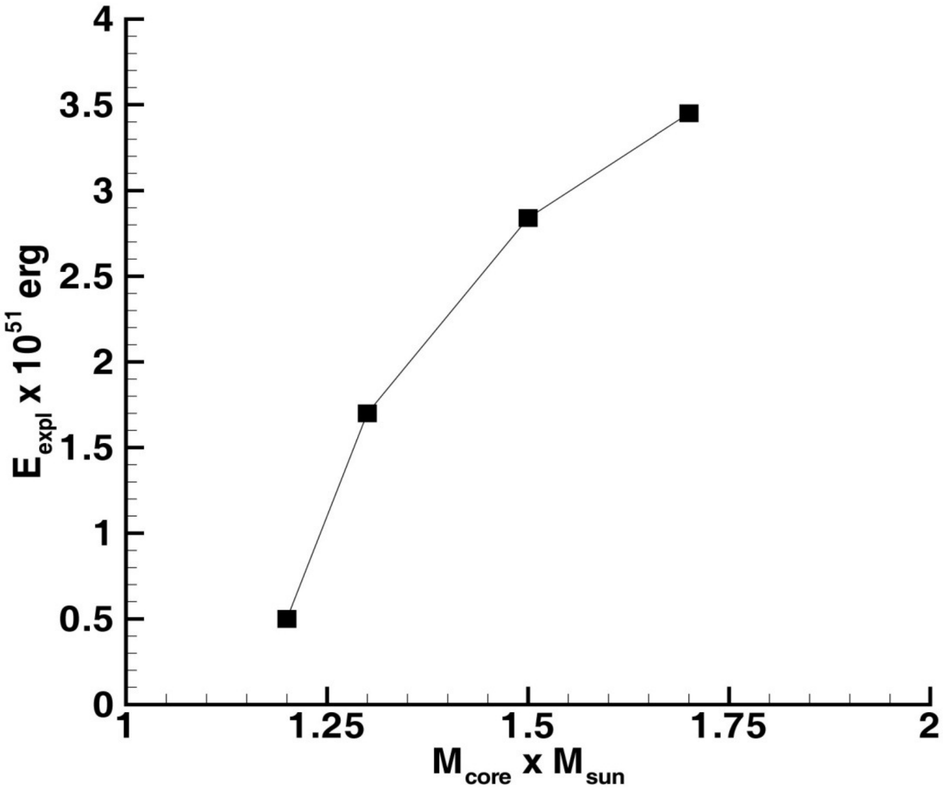
51



MR supernova – different core masses

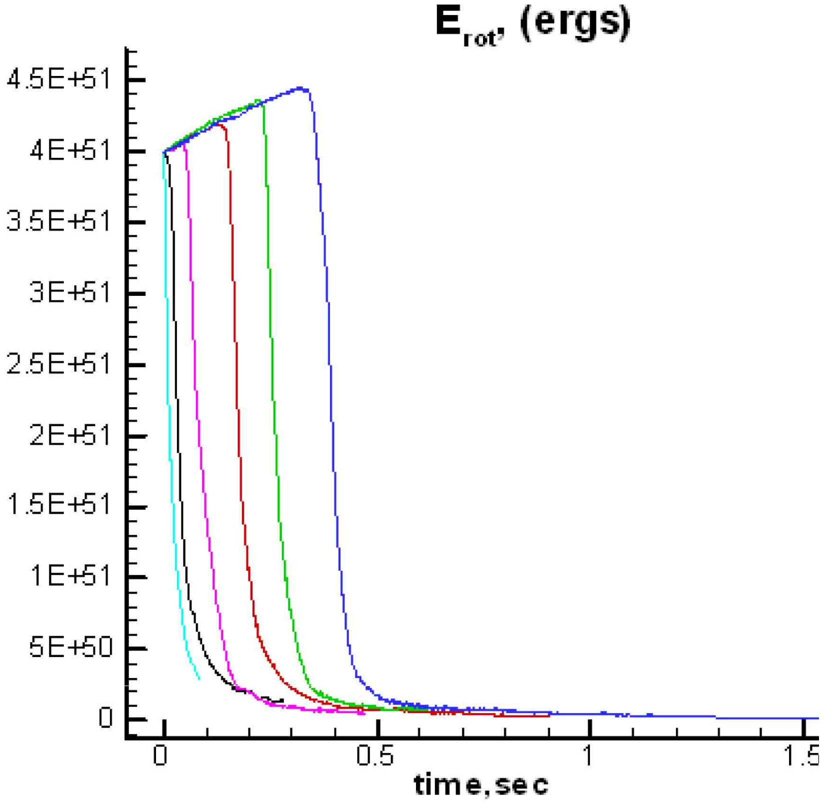
BK, SM, NA, Astron. Zh. (2008), 85, 1109

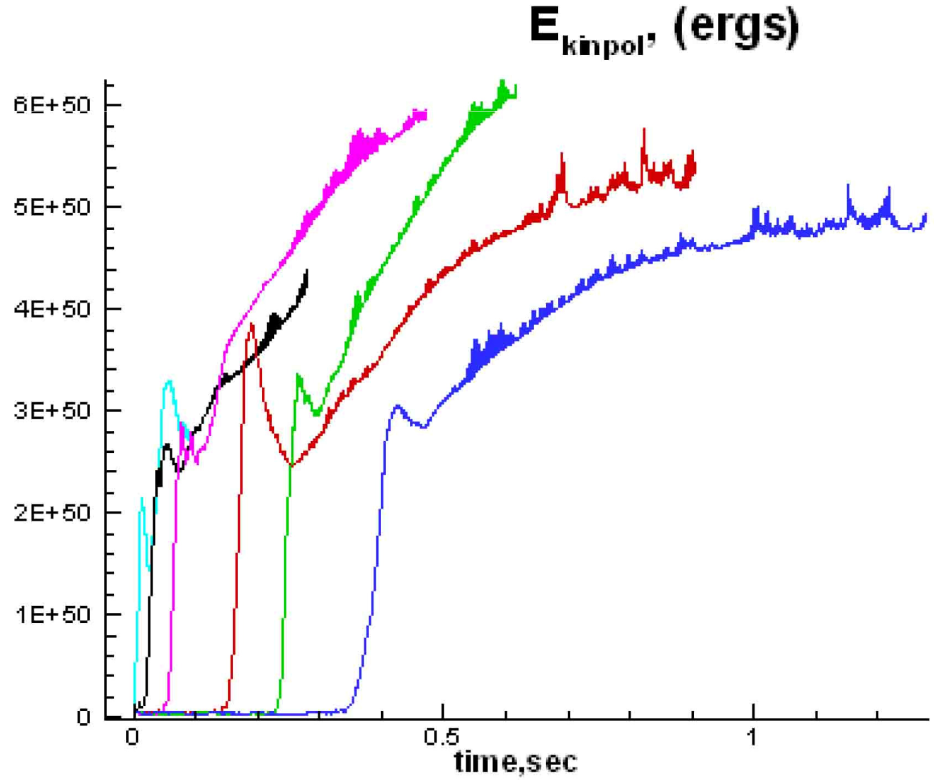
Dependence of the MR supernova explosion energy on the core mass



Magnetorotational explosion at different

$$\alpha = 10^{-2} - 10^{-12}$$





Dependence of the explosion time on $\alpha = \frac{E_{mag0}}{E_{grav0}}$

1-D calculattions: Explosion time

$$t_{\text{взрыва}} \sim \frac{1}{\sqrt{\alpha}}$$

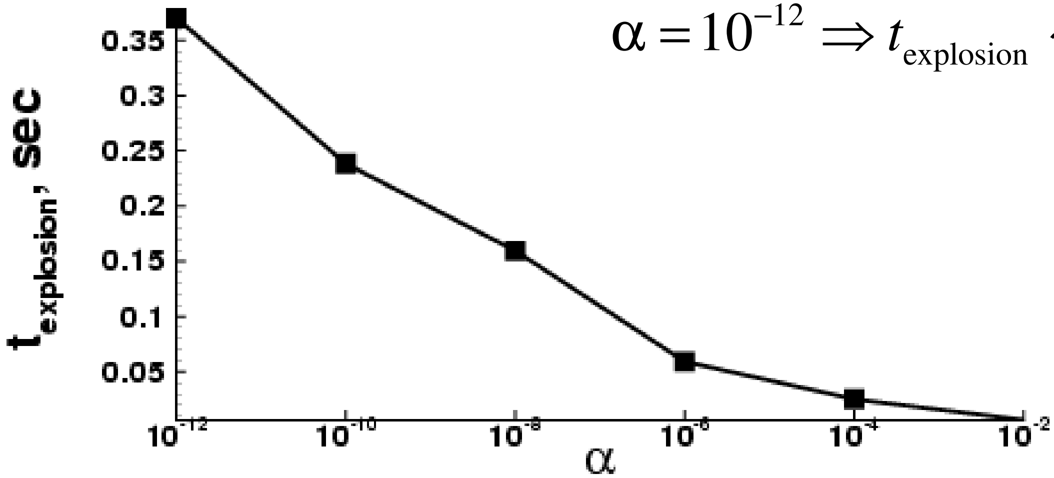
$$\alpha = 10^{-2} \Rightarrow t_{\text{explosion}} = 10,$$
$$\alpha = 10^{-12} \Rightarrow t_{\text{explosion}} = 10^{6}(!)$$

2-D calculattions: Explosion time

$$t_{\text{взрыва}} \sim -\log(\alpha)$$

(for small α)

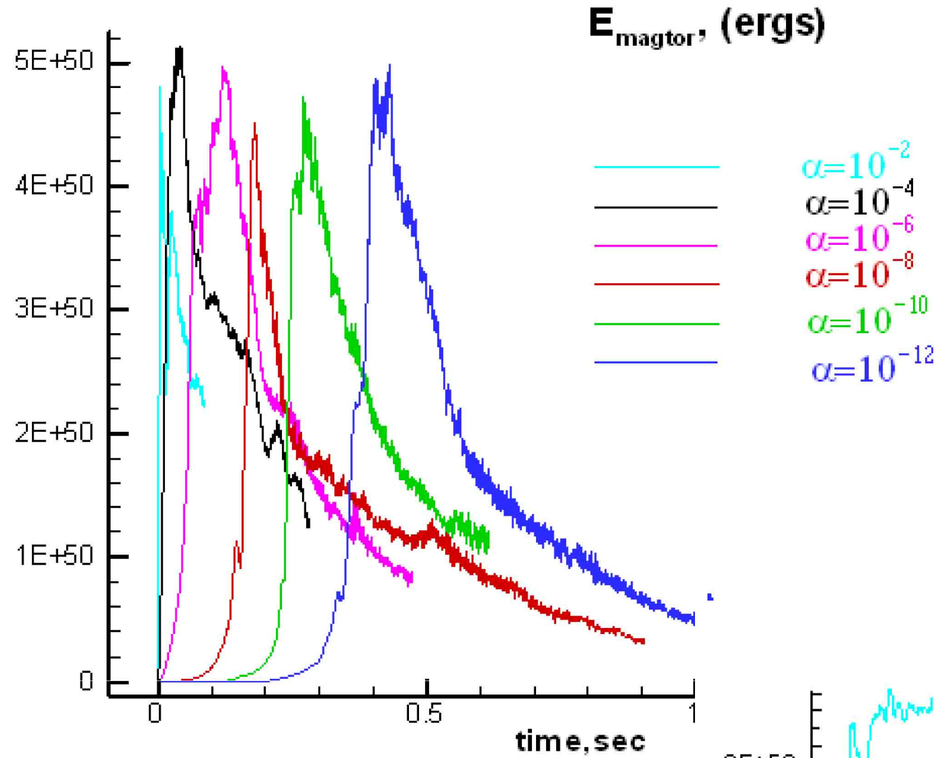
$$\alpha = 10^{-6} \Rightarrow t_{\text{explosion}} \sim 6,$$
$$\alpha = 10^{-12} \Rightarrow t_{\text{explosion}} \sim 12.$$

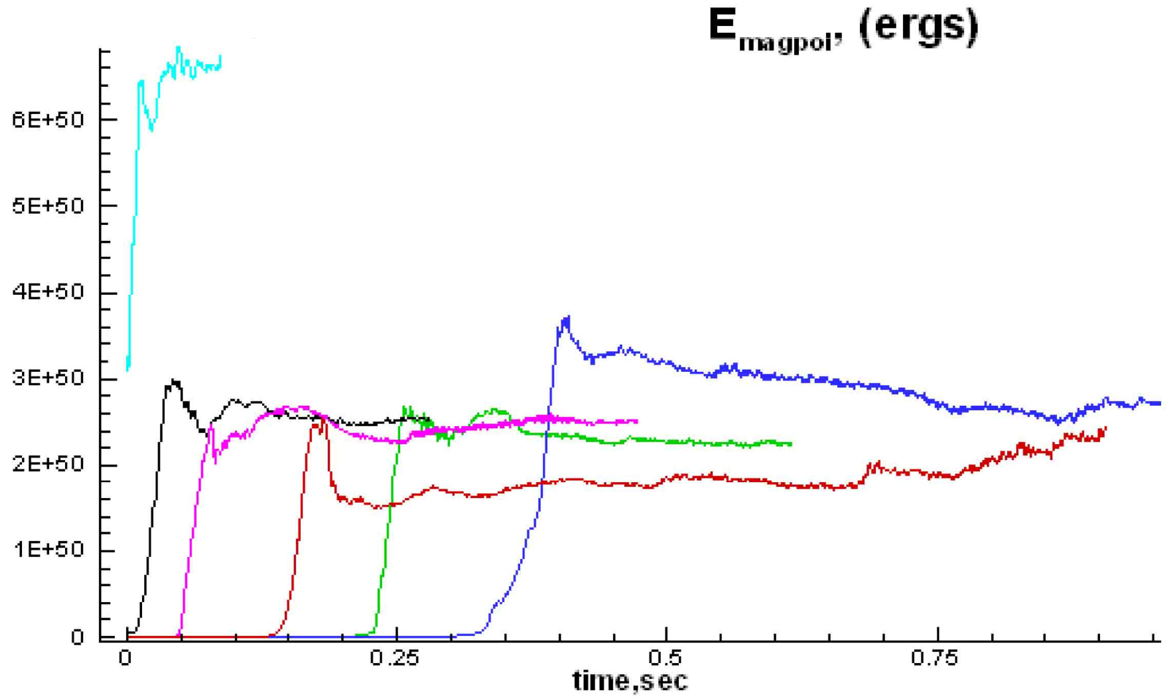


Magnetorotational instability

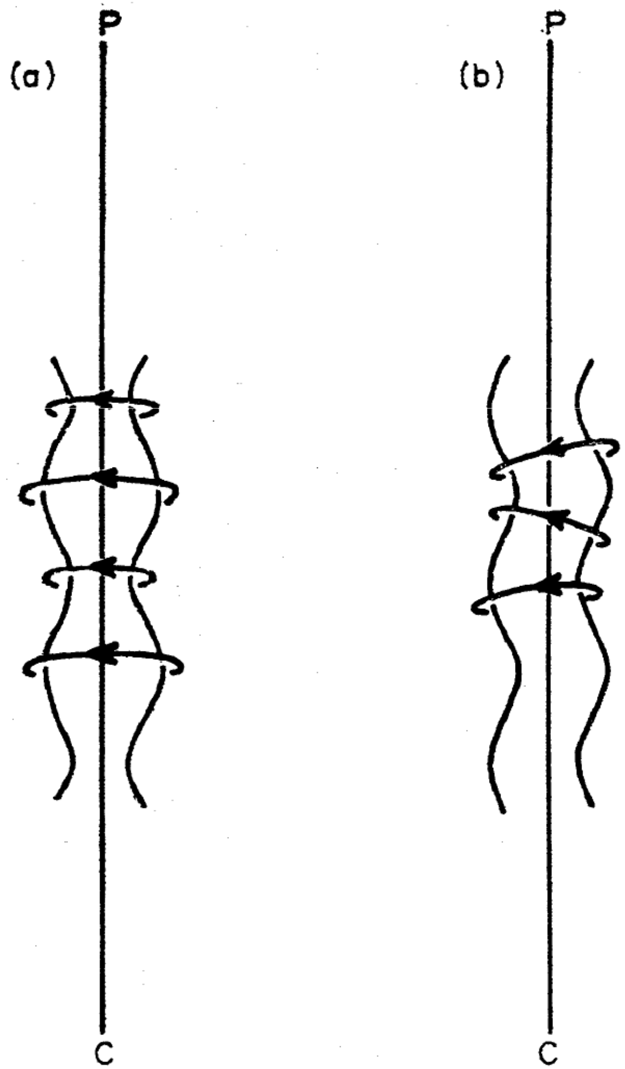
$\Rightarrow$ exponential growth of magnetic fields.

Dungey 1958, Velikhov 1959, Spruit 2002, Akiyama et al. 2003



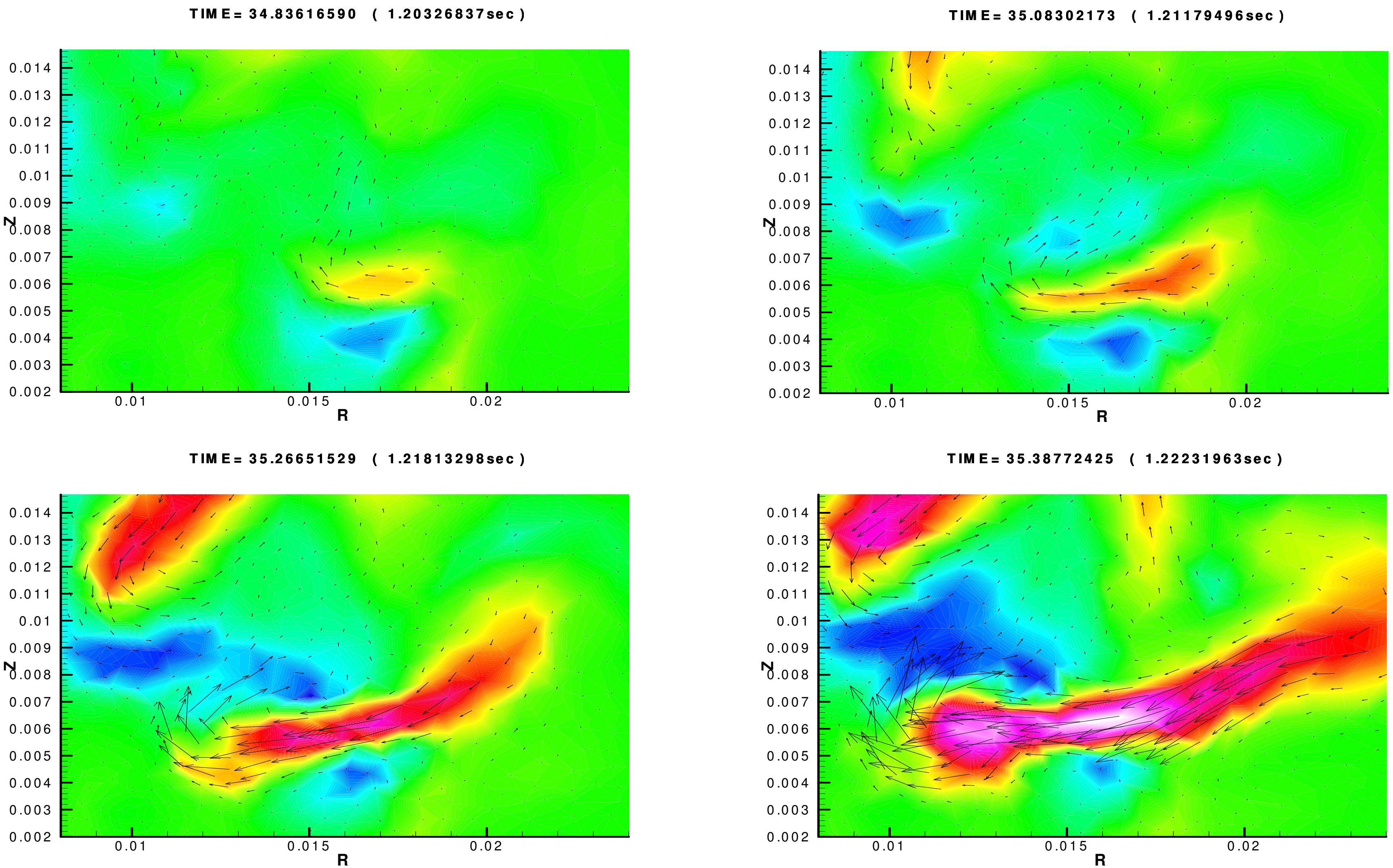


MHD instability: in 2D and 3D – Tayler instability (no rotation)
Magnetic Differential Rotation Instability (MDRI)



Tayler, R. MNRAS 1973

Inner region: development of MDRI



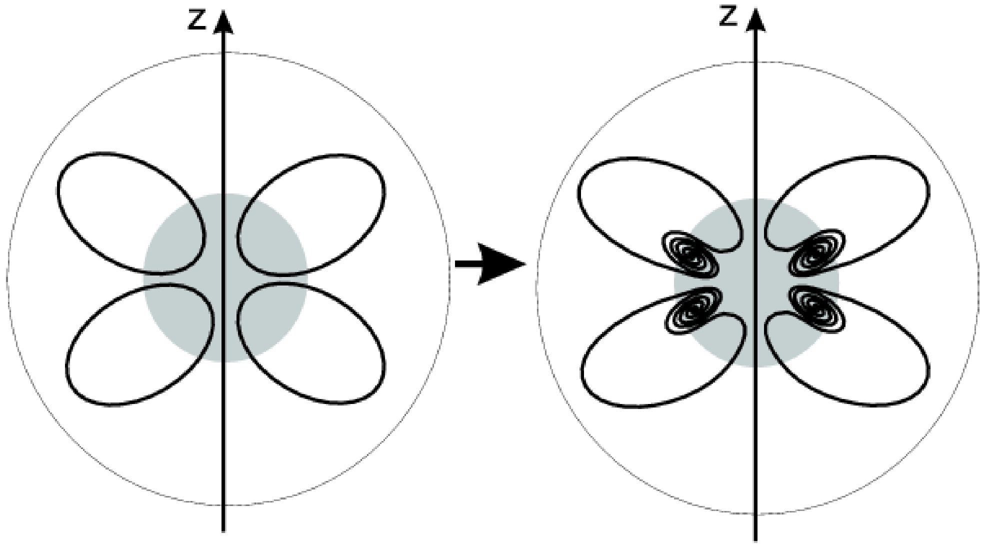
Toroidal (color) and poloidal (arrows) magnetic fields (quadrupole)

Toy model of the MDRI development: exponential growth of the magnetic fields

$$\frac{dH_\varphi}{dt} = H_r\left(r\frac{d\Omega}{dr}\right);$$ at initial stages $$H_\varphi < H_\varphi^* : \quad \left(r\frac{d\Omega}{dr}\right) = A \approx \text{const},$$

MRI leads to formation of multiple *poloidal* differentially rotating vortexes. Angular velocity of vortexes is growing (linearly) with a growth of H_φ.

$$\frac{dH_r}{dt} = H_{r0}\left(\frac{d\omega_v}{dl}l\right), \qquad \left(\frac{d\omega_v}{dl}l\right) \approx \alpha(H_\varphi - H_\varphi^*).$$



$$\frac{d^2}{dt^2}\left(H_\varphi - H_\varphi^*\right) = AH_{r0}\alpha(H_\varphi - H_\varphi^*)$$

$$\Downarrow$$

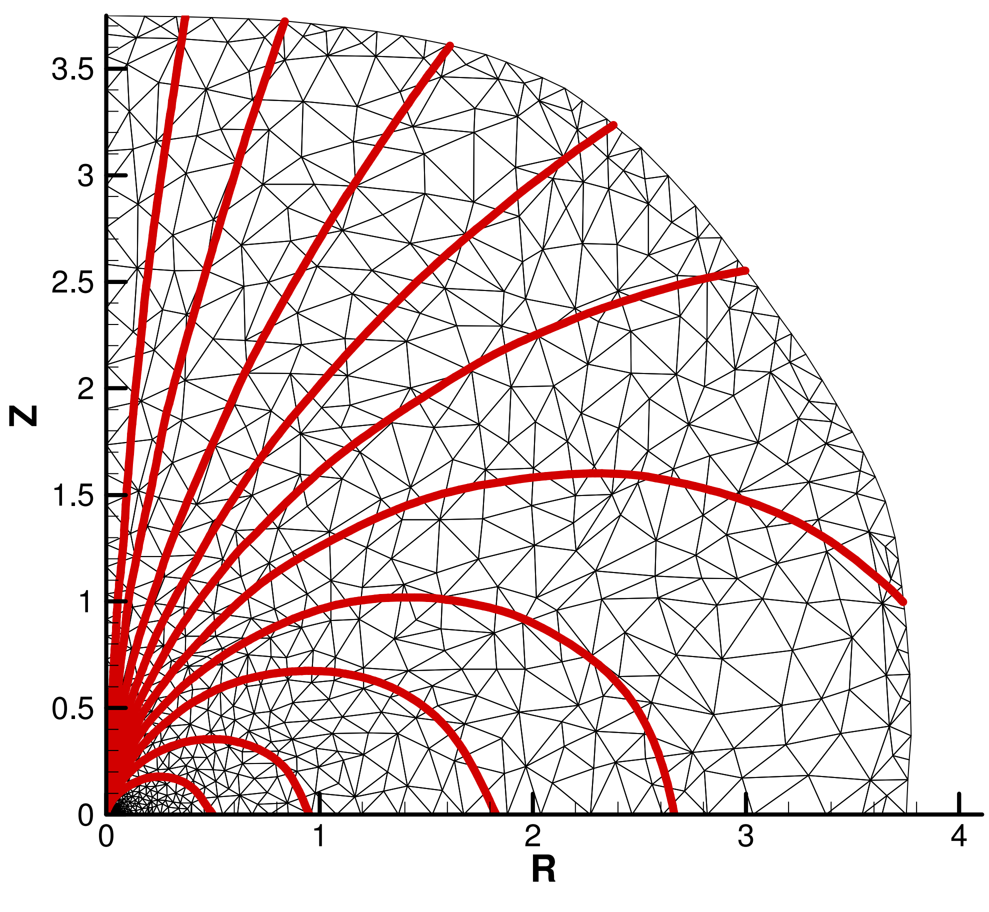
$$\begin{cases} H_\varphi = H_\varphi^* + H_{r0}e^{\sqrt{A\alpha H_{r0}}\,(t-t^*)}, \\ H_r = H_{r0} + \dfrac{H_{r0}^{3/2}\alpha^{1/2}}{\sqrt{A}}\left(e^{\sqrt{A\alpha H_{r0}}\,(t-t^*)} - 1\right). \end{cases}$$

Jet formation in MDRE

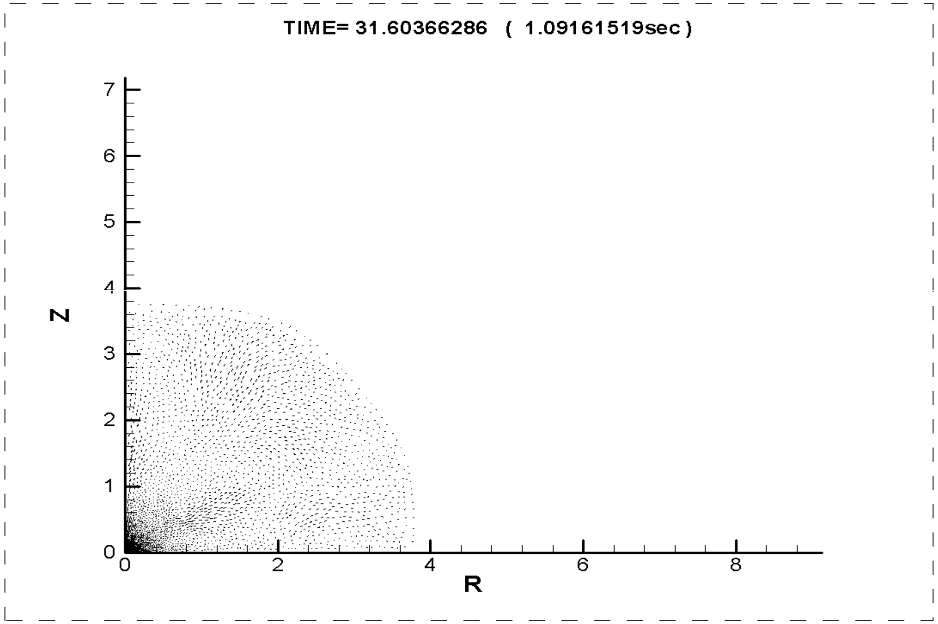
Moiseenko et al. Astro-ph/0603789

Magnetorotational supernovae with jets

Dipole-like initial magnetic field

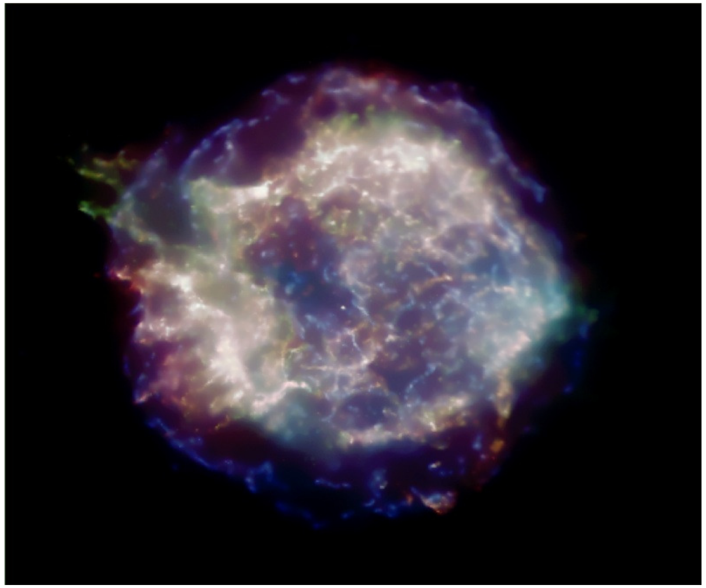


Jet formation in MDRE:
velocity field evolution

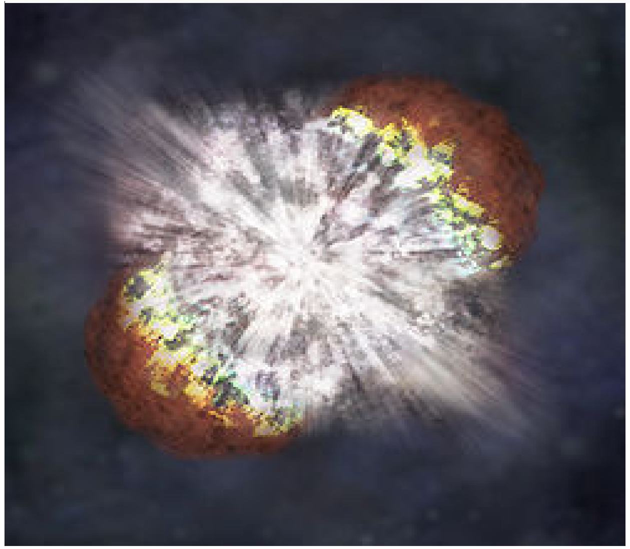


Composite Optical/X-ray image of the Crab Nebula, showings ynchrotron emission in the surrounding pulsar wind nebula, powered by injection of magnetic fields and particles from the central pulsar.

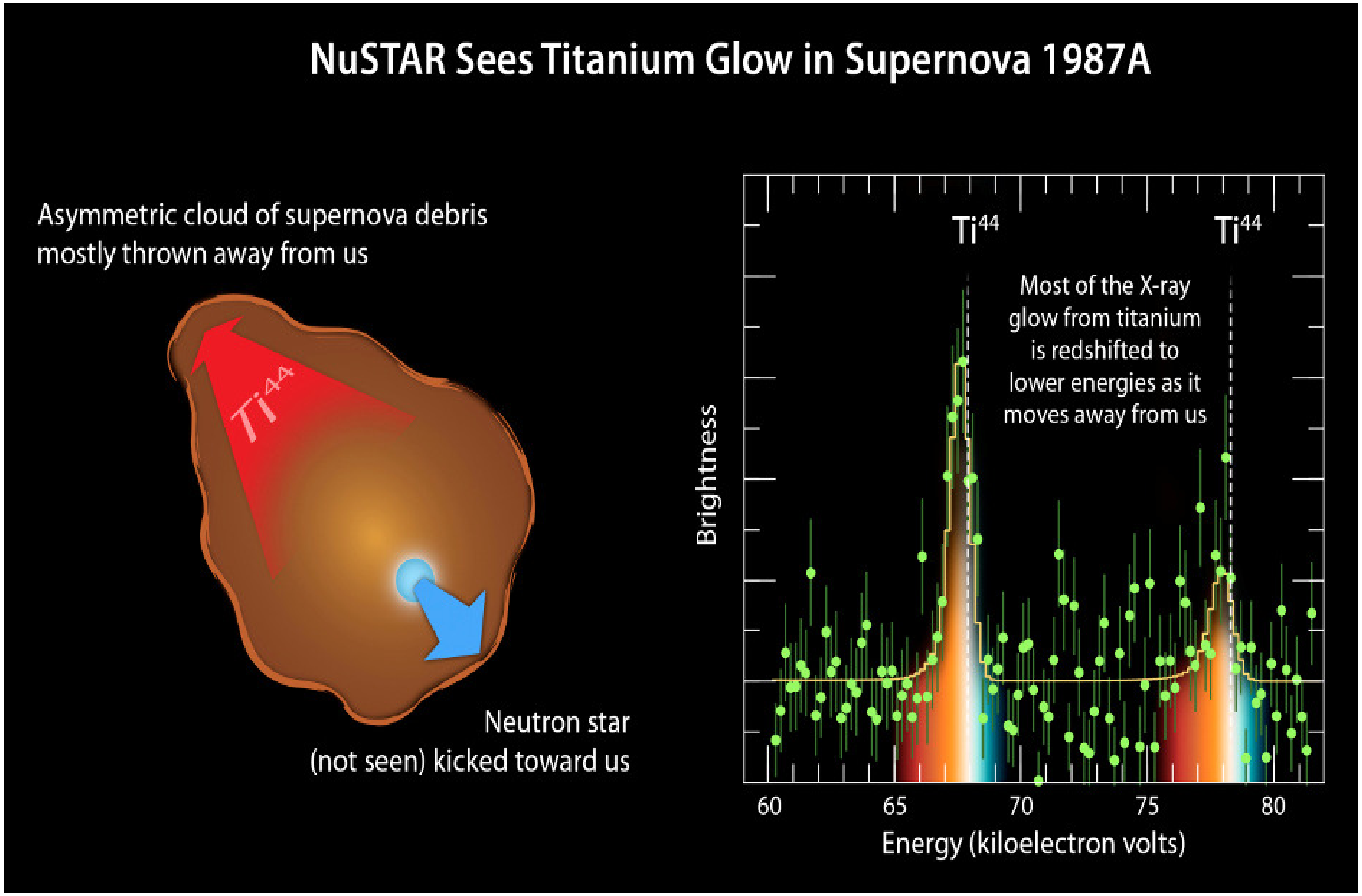
The Vela Pulsar and its surrounding pulsar wind nebula.



X-ray images of Cassiopeia A, taken by the Chandra satellite



NASA's artist impression of SN 2006gy, one of the most luminous hypernovae seen

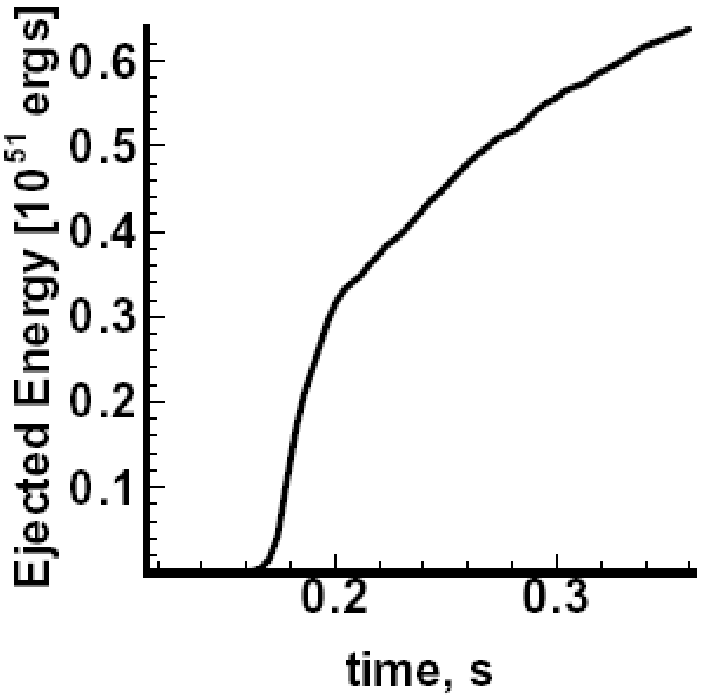


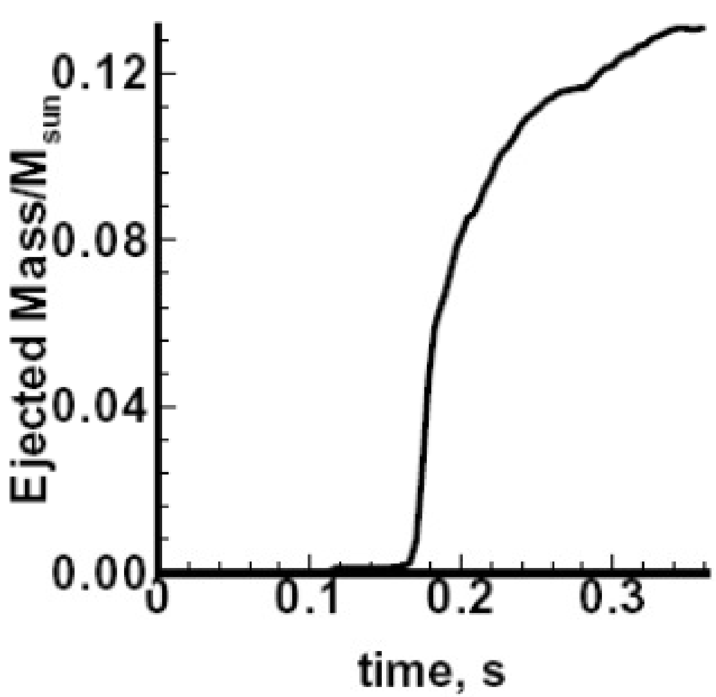
The plot of data from NASA's Nuclear Spectroscopic Telescope Array, or NuSTAR (right), amounts to a"smoking gun" of evidence in the mystery of how massive stars explode. The observations indicate that supernovae belonging to a class called Type II or core-collapse blast apart in a lopsided fashion, with the core of the star hurtling in one direction, and the ejected material mostly expanding the other way

Jet formation in MDRE: (dipole magnetic field)

Energy of explosion≈$0.6\cdot 10^{51}$эрг

Ejected mass ≈ $0.14M_{\odot}$





RECENT RESULTS

Improvement of EoS, neutrino emission rate, neutrino transfer description (**Shen et al., 1998; K. Sato et al. 2005-2010**)

Calculations show results similar to what was obtained using a simplified description of physical processes.

Bisnovatyi-Kogan, G. S.; Moiseenko, S. G.; Ardeljan, N. V.
Numerical Modeling of Space Plasma Flows (ASTRONUM2012).
Proceedings of a 7th International Conference. ASPC, 474, 47 (2013)

S.G.Moiseenko, G.S.Bisnovatyi-Kogan, K.Kotake, T.Takiwaki, K.Sato (in preparation)

S.G.Moiseenko, G.S.Bisnovatyi-Kogan
Development of the Magneto-Differential-Rotational Instability in Magnetorotional Supernova
Astronomy Reports, 2015, Vol. 59, No. 7, pp. 573–580.

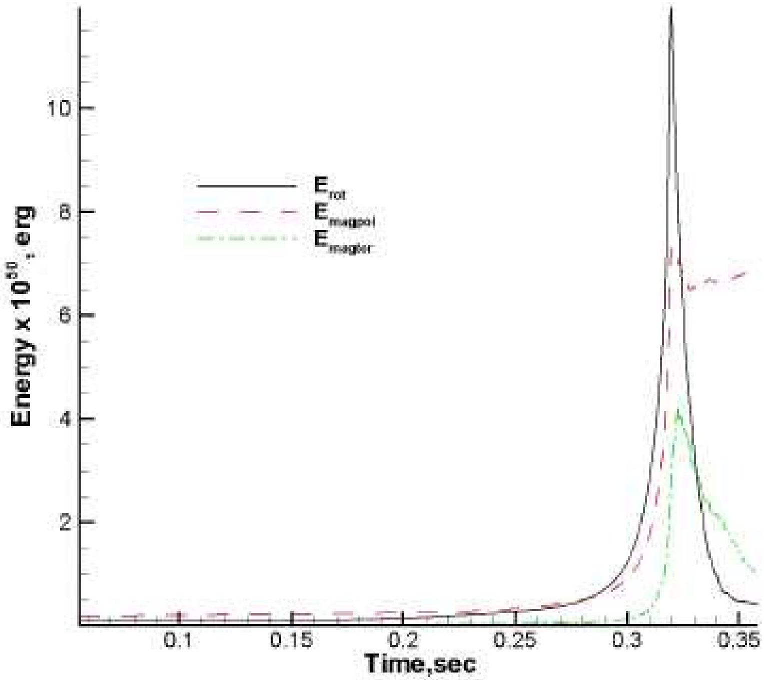
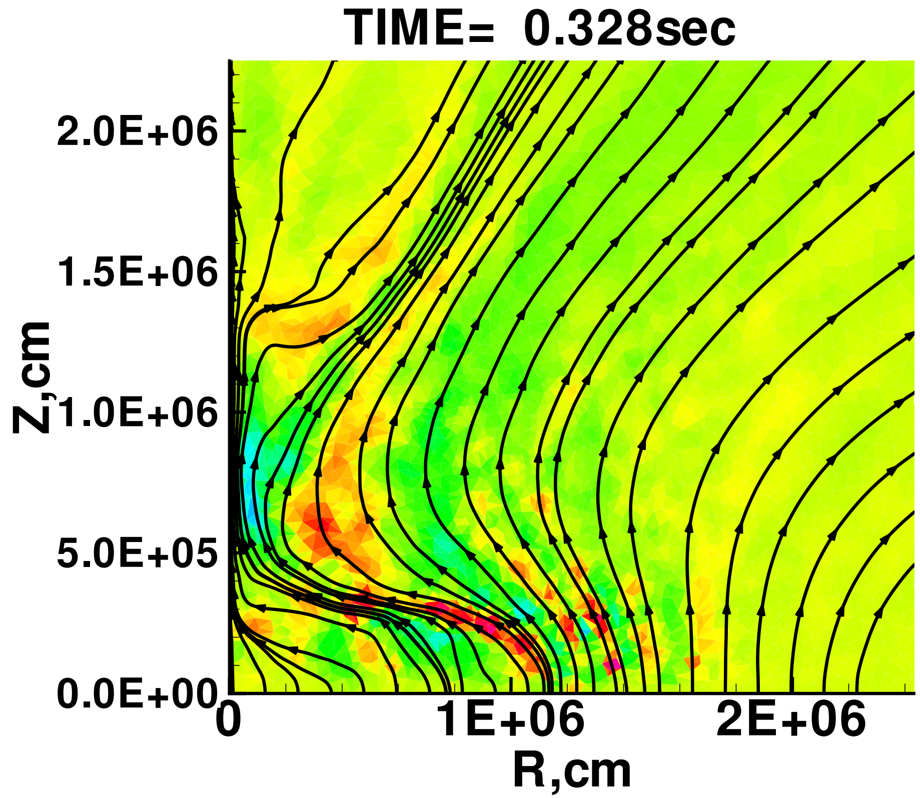


Figure 7. Time evolution of rotational energy E_{rot} (solid line), magnetic poloidal energy E_{magpol} (dashed line) and magnetic toroidal energy E_{magtor} (dash-dotted line) for the case $H_0 = 10^{12}$, G., $E_{rot0}/E_{grav0} = 1\%$.



Absence of MDRI at t = 328 ms for the case H0 = 10^12 G, Erot0/Egrav0 = 1% (contour plot - the toroidal magnetic field, black lines indicate the poloidal magnetic field).

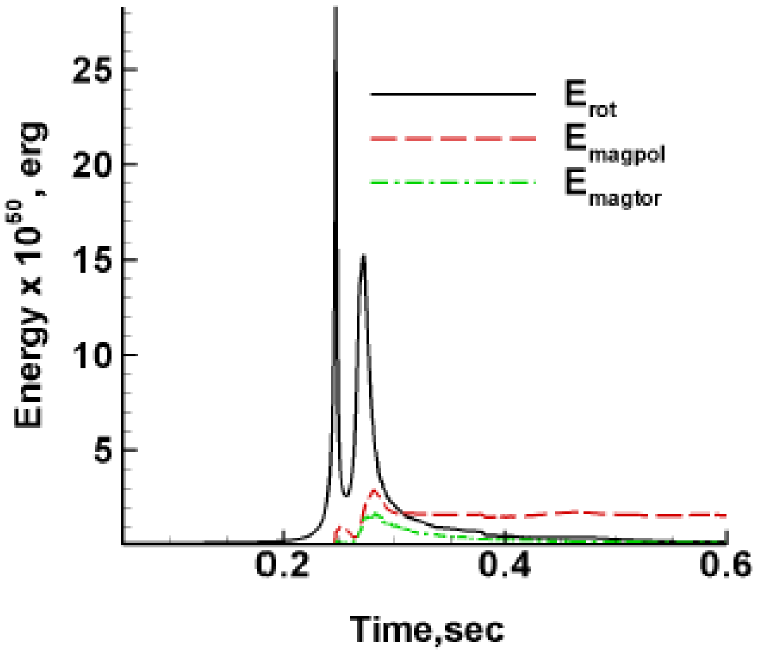


Figure 4. Time evolution of rotational energy E_{rot} (solid line), magnetic poloidal energy E_{magpol} (dashed line) and magnetic toroidal energy E_{magtor} (dash-dotted line) for the case $H_0 = 10^9$G, $E_{rot0}/E_{grav0} = 1\%$.

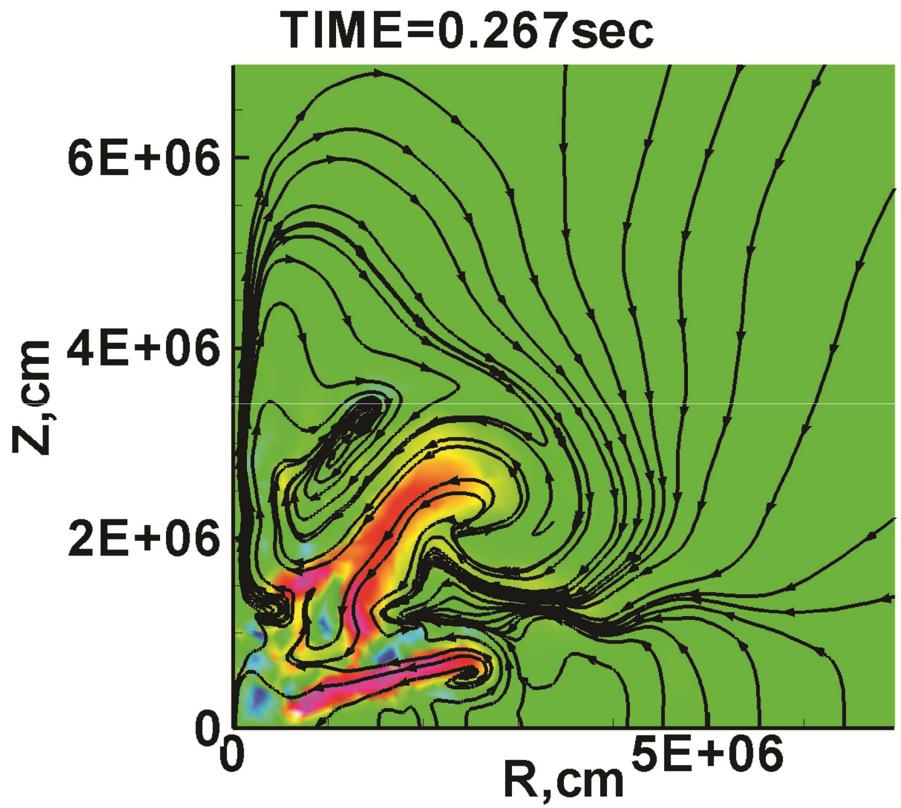
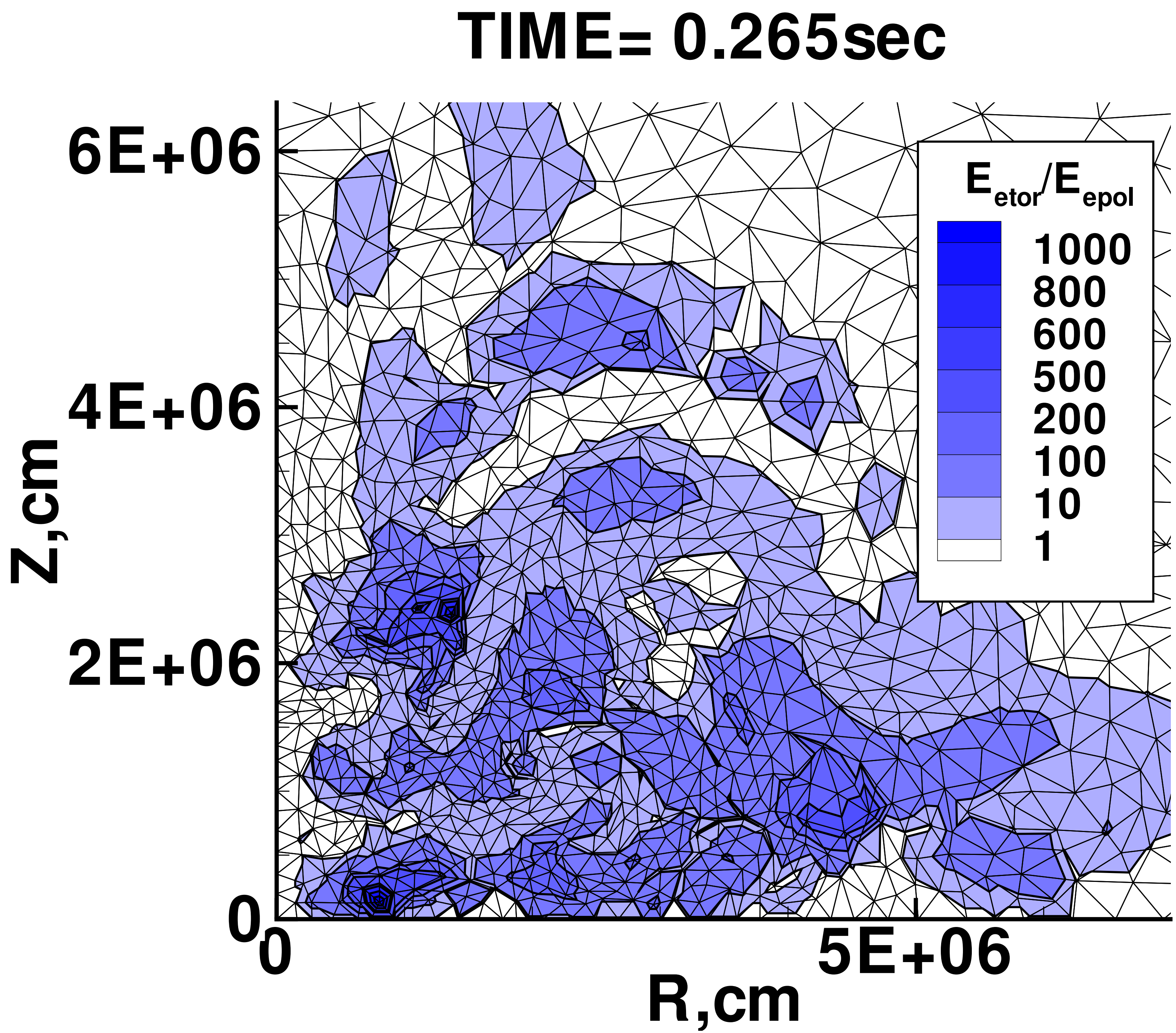


Figure 2. Developed MDRI due to convection and MRI/Tayler instability at $t = 267$ms for the case $H_0 = 10^9$G, $E_{rot0}/E_{grav0} = 1\%$ (contour plot - the toroidal magnetic field, arrow lines - force lines of the poloidal magnetic field).



TIME= 0.265sec
E_{etor}/E_{epol}
1000
800
600
500
200
100
10
1
6E+06
4E+06
2E+06
0
0
5E+06
Z,cm
R,cm

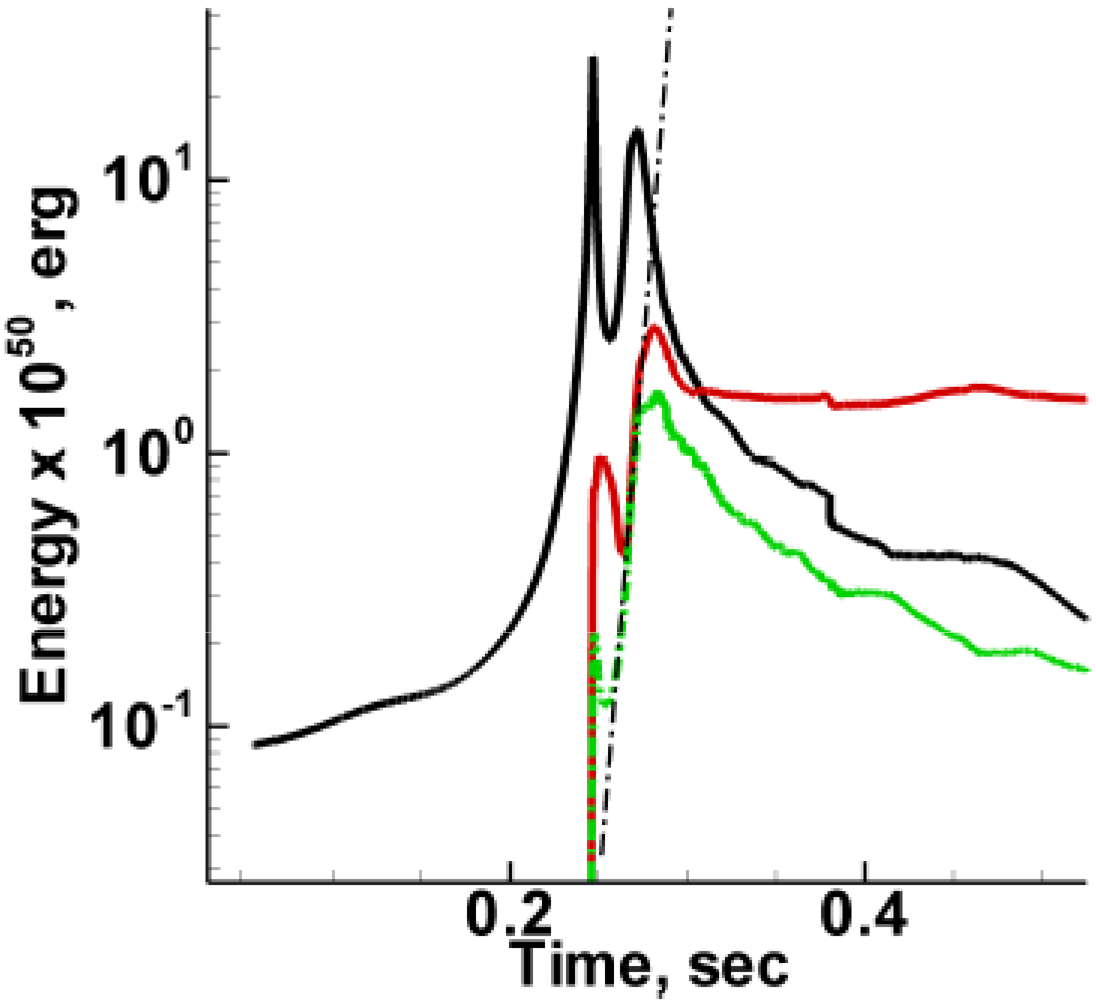
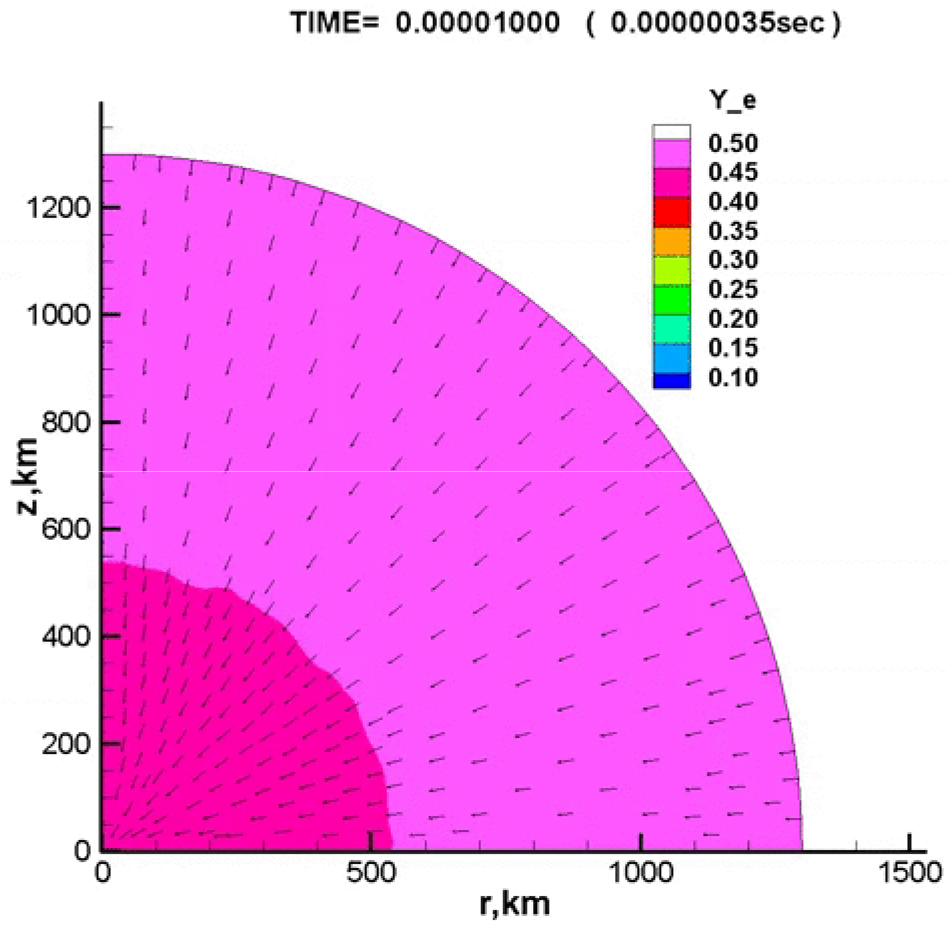


Figure 5. Zoomed time evolution of rotational energy E_{rot} (solid line), magnetic poloidal energy E_{magpol} (dashed line) and magnetic toroidal energy E_{magtor} (dash-dotted line) for the case $H_0 = 10^9$G$, E_{rot0}/E_{grav0} = 1\%$. Straight dash-dotted line shows exponential growth of the toroidal and poloidal magnetic energies.


TIME= 0.00001000 (0.00000035sec)
Y_e
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
z,km
1200
1000
800
600
400
200
0
r,km
0
500
1000
1500

Asymmetry of the explosion

CP violation in week processes in regular magnetic field: does not work, because MRI leads to formation of highly chaotic field.

Astro-ph/0510229

MULTI-DIMENSIONAL RADIATION HYDRODYNAMIC SIMULATIONS OF PROTONEUTRON STAR CONVECTION

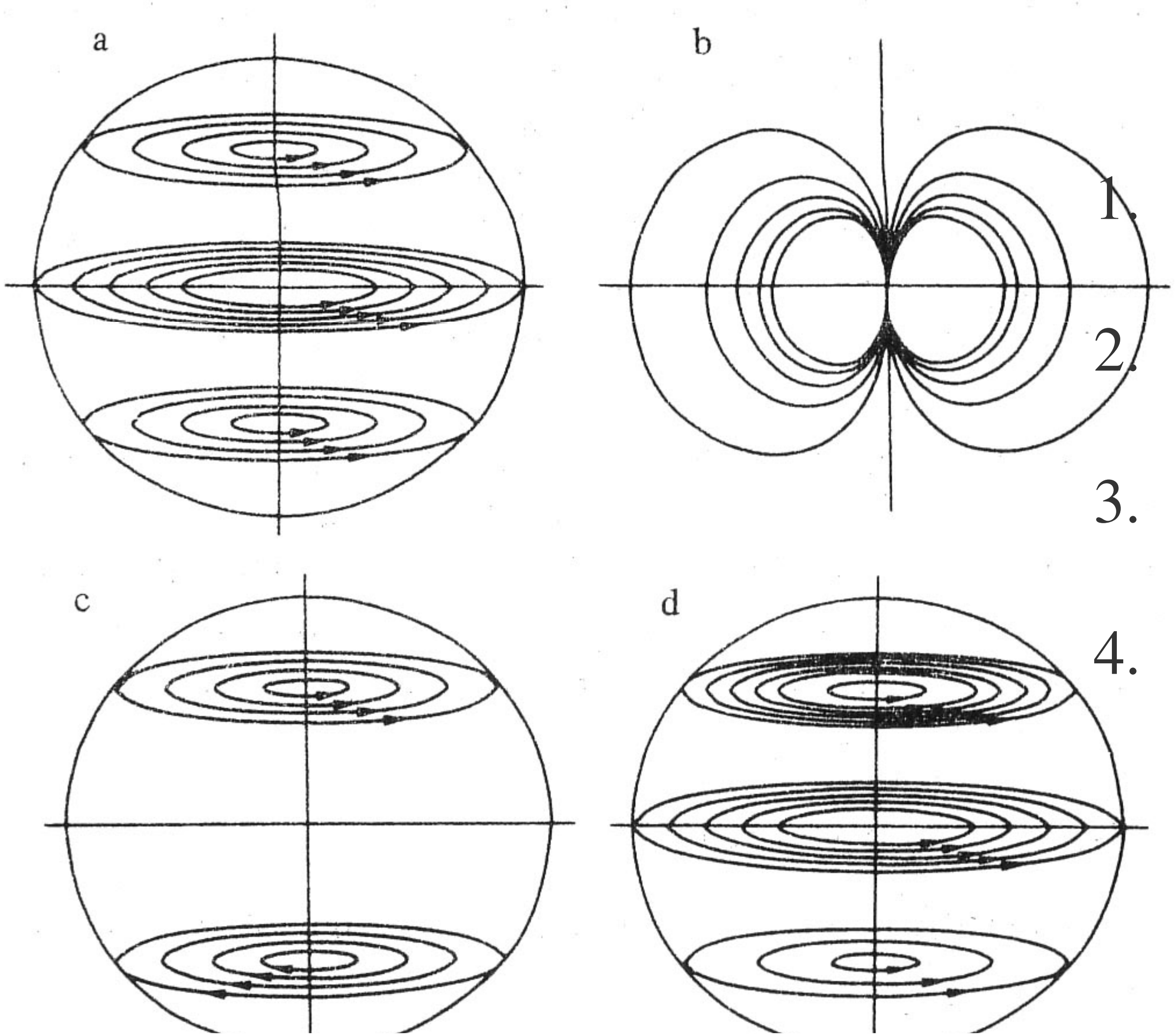
L. Dessart, A. Burrows, E. Livne, C.D. Ott

PNS convection is thus found to be a secondary feature of the core-collapse phenomenon, rather than a decisive ingredient for a successful explosion.

Asymmetry of the explosion

Violation of mirror symmetry of magnetic field

(BK, Moiseenko, 1992 Astron. Zh., 69, 563 (SvA, 1992, 36, 285)



1. Initial toroidal field
2. Initial dipole field
3. Generated toroidal field
4. Resulted toroidal field

BK, 1993, Astron. Ap. Transactions **3,** 287

Interaction of the neutrino with asymmetric magnetic field

$$B_c = \frac{m_e^2 c^3}{e\hbar} = 4.4 \times 10^{13}\mathrm{Gs}$$

The probability of the neutron decay W_n in vacuum is

$$W_n = W_0[1 + 0.17(B/B_c)^2 + ...] \quad \text{at} \quad B \ll B_c$$

$$W_n = 0.77 W_0 (B/B_c) \quad \text{at} \quad B \gg B_c$$

Dependence of the week interaction cross-section on the magnetic field strength lead to the asymmetric neutrino flux and formation of rapidly mooving pulsars due to the recoil action as well as rapidly moving black holes.

Neutrino heat conductivity

$$H_\nu = -\frac{7}{8}\frac{4acT^3}{3} l_T \frac{\partial T}{\partial r}$$

energy flux

$$\kappa_\nu = 1/(l_T \rho)$$

neutrino opacity

The anisotropy of the flux

$$\delta_L = \frac{L_+ - L_-}{L_+ + L_-}$$

Kick velocity **along the rotational axis**

Approximate estimation

$$v_{nf} = \frac{2}{\pi}\frac{L_\nu}{M_n c}\frac{P B_{\phi 0}}{|B_p|}(0.5 + \ln\left(\frac{20\,s}{P}\frac{|B_p|}{B_{\phi 0}}\right))$$

$x = \frac{B_{\phi 0}}{|B_p|}$ between 20 and 10^3, we have v_{nf} between 140 and 3000 km/s

Important to do:

Numerical simulations without mirror symmetry

Accurate formulae for neutrino processes at high magnetic field

T. V. SMIRNOVA, V. I. SHISHOV, AND V. M. MALOFEEV

THE SPATIAL STRUCTURE OF PULSAR EMISSION SOURCES DETERMINED USING INTERSTELLAR SCINTILLATION

THE ASTROPHYSICAL JOURNAL, 462:289–295, 1996 May 1

we can conclude that the velocity vector of the movement of the pulsar in space is close to the orientation of the rotation axis of the pulsar. Of course, this interpretation assumes

S. Johnston et al. astro/ph 0510260 (MNRAS, 2005, **364**, 1397)

Evidence for alignment of the rotation and velocity vectors in pulsars

We present strong observational evidence for a relationship between the direction of a pulsar's motion and its rotation axis. We show carefully calibrated polarization data for 25pulsars, 20 of which display linearly polarized emission from the pulse longitude at closest approach to the magnetic pole… **we conclude that the velocity vector and the rotation axis are aligned at birth.**

S. Johnston, M. Kramer, A. Karastergiou, G. Hobbs, S. Ord , J. Wallman
MNRAS, 381, Issue 4, pp. 1625 (2007)

Evidence for alignment of the rotation and velocity vectors in pulsars. II. Further data and emission heights

Pulsar Spin–Velocity Alignment: Further Results and Discussion

A. Noutsos, M. Kramer, P. Carr and S. Johnston

arXiv:1205.2305v1 [astro-ph.GA] 10 May 2012

We estimate that the observed alignment is robust to within 10% systematic uncertainties on the determination of the spin-axis direction from polarisation data.

W.H.T. Vlemmings et al. astro-ph/0509025 (Mm. SAI, 2005, **76**, 531)

Pulsar Astrometry at the Microarcsecond Level

Determination of pulsar parallaxes and proper motions addresses fundamental astrophysical questions. We have recently finished a VLBI astrometry project to determine the proper motions and parallaxes of 27 pulsars, thereby doubling the total number of pulsar parallaxes. Here we summarize our astrometric technique and present the discovery of a pulsar moving in excess of 1000 kms, **PSR B1508+55**.

Conclusions

1. In the magnetorotational explosion (MRE) the efficiency of transformation of rotational energy into the energy of explosion is 10%. This is enough for producing core – collapse SN from rapidly rotating magnetized neutron star.

2. Development of magneto-differential-rotational instability strongly accelerate MRE, at lower values of the initial magnetic fields.

3. The new born neutron star has inside a large (about 10^14 Gauss) chaotic magnetic field.

4. Jet formation is possible for dipole-like initial topology of the field: possible relation to cosmic gamma-ray bursts; equatorial ejection happens at prevailing of the quadrupole-like component.

5. Development of magneto-differential-rotational instability (MDRI) starts in regions, where the toroidal component significantly prevails the poloidal one.

6. MRE explosion energy is not sensitive to the precision of the input microphysics, and to the numerical scheme.