Magnetorotational Core-Collapse SN: Explosions and Jet Formation

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Vulcano, 25 May 2006

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 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)

hydrogen-rich matter is lost from the star in the superwind. Hydrogen continues to burn at the base of the remnant envelope and, as the star contracts and evolves towards higher surface temperatures on a nuclear burning time-scale, photons emitted from the surface become energetic enough to cause the previously ejected nebular matter to fluoresce. The result is known as a planetary nebula.

A summary of the evolutionary history of intermediate mass stars up to the point of planetary nebula excitation is given in Fig. 15 and in the caption for this figure.

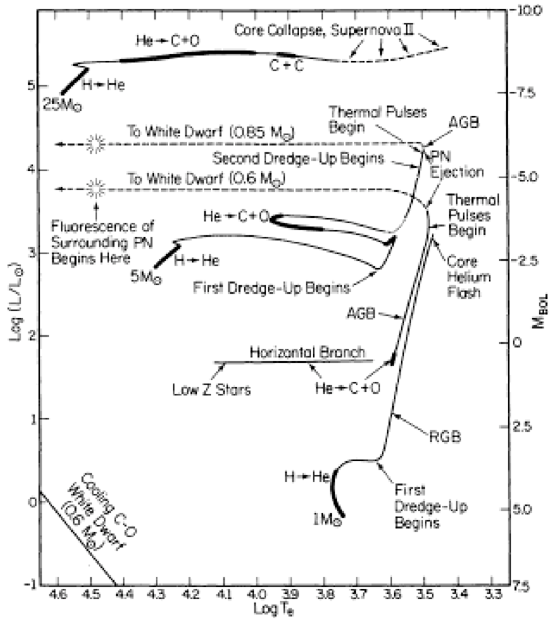


FIG. 15. Tracks in the HR diagram of a representative selection of stars. The heavy portions of each curve define locations where the major core nuclear burning phases occur. Details of tracks during transitory phases between major nuclear burning phases are suppressed. For stars of initial mass less than about 2·3 $M_\odot$, where in the HR diagram quiescent core helium burning (He → C+O) takes place after the core helium flash depends on the metallicity and on the extent of mass loss during the first red giant branch (RGB) phase. All stars which experience a core helium flash spend roughly 10^7 yr evolving upward along the 'early' asymptotic giant branch (E-AGB) burning helium in a shell. When helium is exhausted over about 0·53 $M_\odot$, hydrogen burning is rekindled and thermal pulses begin. How far a star evolves upward during the thermally pulsing AGB phase depends on the total mass of the star at the beginning of this phase, on the rate of mass loss by an ordinary stellar wind, and on the core-mass dependent critical mass in the hydrogen-rich envelope when planetary nebula (PN) ejection occurs. This latter phenomenon produces an expanding shell of matter and a remnant which evolves rapidly to the blue in the HR diagram, burning hydrogen at the base of a surface layer of very small mass. For a star of initial mass less than about 2 $M_\odot$, the lifetime in the TP-AGB phase is roughly 2×10^6 yr, the mass of a typical remnant is 0·6 $M_\odot$, and the time-scale for evolving to the blue far enough that photons from the surface

Explosion mechanism.

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

2. **Core collapse and formation of a neutron star**, gravitational energy release 6 10 erg, carried away by neutrino **(SN II, SN Ib,c)**

W.Baade and F.Zwicky, Phys.Rev., 1934, **45**, 138 (Jan. 15)

38. Supernovae and Cosmic Rays. W. BAADE, *Mt. Wilson Observatory*, AND F. ZWICKY, *California Institute of Technology*.—Supernovae flare up in every stellar system (nebula) once in several centuries. The lifetime of a supernova is about twenty days and its absolute brightness at maximum may be as high as $M_{\text{vis}} = -14^M$. The visible radiation L_ν of a supernova is about 10^8 times the radiation of our sun, that is, $L_\nu = 3.78 \times 10^{41}$ ergs/sec. Calculations indicate that the total radiation, visible and invisible, is of the order $L_\tau = 10^7 L_\nu = 3.78 \times 10^{48}$ ergs/sec. The supernova therefore emits during its life a total energy $E_\tau \geq 10^5 L_\tau = 3.78 \times 10^{53}$ ergs. If supernovae initially are quite ordinary stars of mass $M < 10^{34}$ g, E_τ/c^2 is of the same order as M itself. In the *supernova* process *mass in bulk is annihilated*. In addition the hypothesis suggests itself that *cosmic rays are produced by supernovae*. Assuming that in every nebula one supernova occurs every thousand years, the intensity of the cosmic rays to be observed on the earth should be of the order $\sigma = 2 \times 10^{-3}$ erg/cm^2 sec. The observational values are about $\sigma = 3 \times 10^{-3}$ erg/cm^2 sec. (Millikan, Regener). With all reserve we advance the view that supernovae represent the transitions from ordinary stars into *neutron stars*, which in their final stages consist of extremely closely packed neutrons.

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.

Transformation of the neutrino energy into kinetic one - ???

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

Most of supernova explosions and ejections are not spherically symmetrical. A lot of stars are rotating and have magnetic fields. Often we can see one-side ejections.

Magnetorotational mechanism: transforms rotational energy of the star to the explosion energy.

In the case of the differential rotation the rotational energy can be transformed to the explosion energy by magnetic fields.

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.

The magnetohydrodynamic rotational model of supernova explosion

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

Astrophysics and Space Science, vol. 41, June 1976, p. 287-320

(Received 16 July, 1975)

Calculations of supernova explosion are made using the one-dimensional nonstationary equations of magnetic hydrodynamics for the case of cylindrical symmetry. The energy source is supposed to be the rotational energy of the system (the neutron star in the center and the surrounding envelope). The magnetic field plays the role of a mechanism of the transfer of rotational momentum. The calculations show that the envelope splits up during the dynamical evolution of the system, the main part of the envelope joins the neutron star and becomes uniformly rotating with it, and the outer part of the envelope expands with large velocity, carrying out a considerable part of rotational energy and rotational momentum. These results correspond qualitatively with the observational picture of supernova explosions.

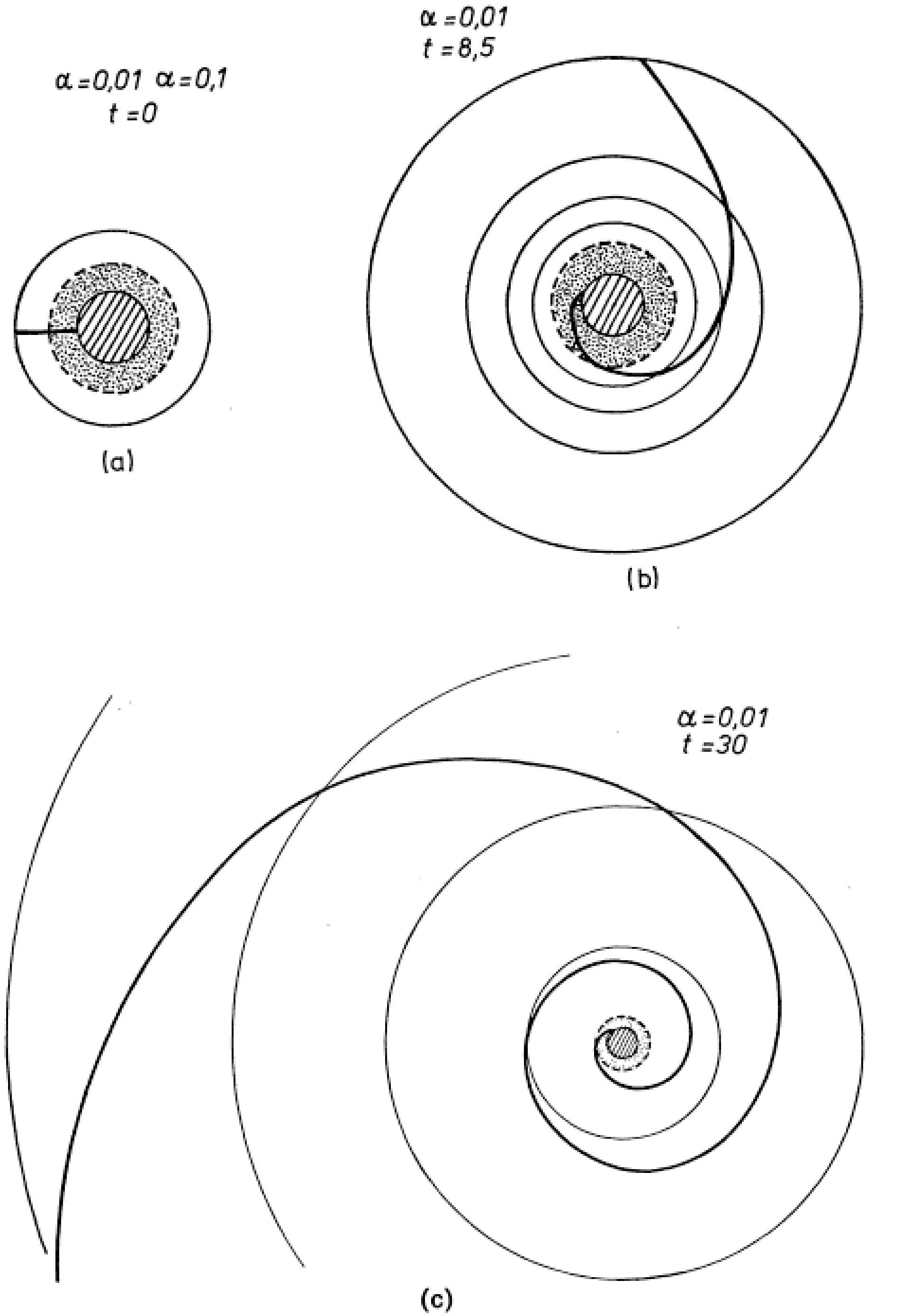
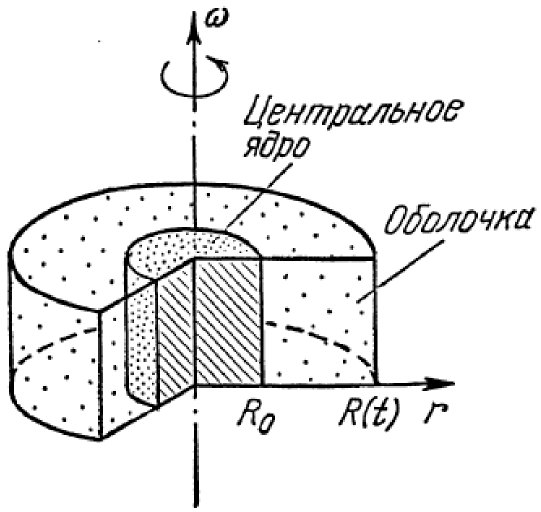


Fig. 5(a), (b), and (c). The configuration of the magnetic field line in the subsequent moments of

alpha=0.01,
t=8.5



1-D calculations of magnetorotational explosion

.

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

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 □0.1_⊙,
Explosion energy □ 10^{51} erg
Ejected mass and explosion energy depend very weekly on the parameter □
Explosion time strongly depends on □ .

$$\text{Explosion time} = \boxed{t\_\_\_\_ \sim \frac{\square}{\sqrt{\ }}}$$

Small □ is difficult for numerical calculations with EXPLICIT numerical schemes because of the Courant restriction on the time step, “hard” system of equations: □ determines a “hardness”.

In 2-D numerical IMPLICIT schemes have been used.

Astrophysical Journal, vol. 161, p.541 (1970)

A Numerical Example of the Collapse of a Rotating Magnetized Star

J.LeBlanc, J.Wilson

Received 1969 September 25, revised 1970 January 5

The time history of a star of 7 $M_{\odot}$ undergoing gravitational collapse due to iron decomposition is calculated numerically. The angular velocity assumes a vortexlike distribution which halts the collapse at a relatively low density, 10^{11} g cm^{-3}. The large shear in the velocity field gives an enhancement of about 100 in the multiplication of magnetic-field energy over the energy multiplication from simple compression. The combined effect of rotation and magnetic field is to produce an axial jet. At a radius of 4×10^{8} cm where the jet material leaves the calculational grid, the jet carries a mass of 2.1×10^{31} g and a total energy of 1.6×10^{50} ergs. The energy is principally kinetic, 1.6×10^{50} ergs, but it also has a large magnetic energy equal to 3.5×10^{49} ergs, and only 1.1×10^{49} ergs of internal energy.

Difference scheme (Ardeljan, Chernigovskii, Kosmachevskii, Moiseenko)

Lagrangian, on triangular grid

The scheme is based on the method of basic operators - grid analogs of the main differential operators:

GRAD(scalar) (differential) ~ GRAD(scalar) (grid analog)

DIV(vector) (differential) ~ DIV(vector) (grid analog)

CURL(vector) (differential) ~ CURL(vector) (grid analog)

GRAD(vector) (differential) ~ GRAD(vector) (grid analog)

DIV(tensor) (differential) ~ DIV(tensor) (grid analog)

The scheme is implicit.

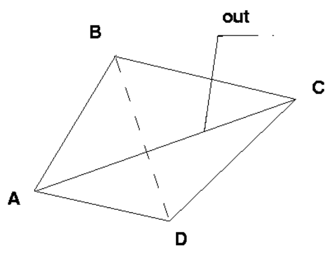
It is developed and its stability and convergence are investigated
by the group of N.V.Ardeljan (Moscow State University)

The scheme is fully conservative:

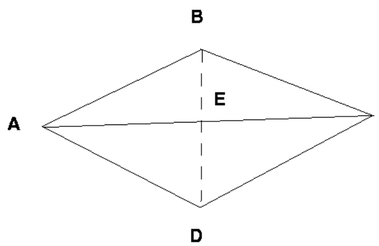
conservation of the mass, momentum and total energy,
correct calculation of the transitions between different types of energies.

Difference scheme: Lagrangian, triangular grid with grid reconstruction (completely conservative=>angular momentum conserves automatically)

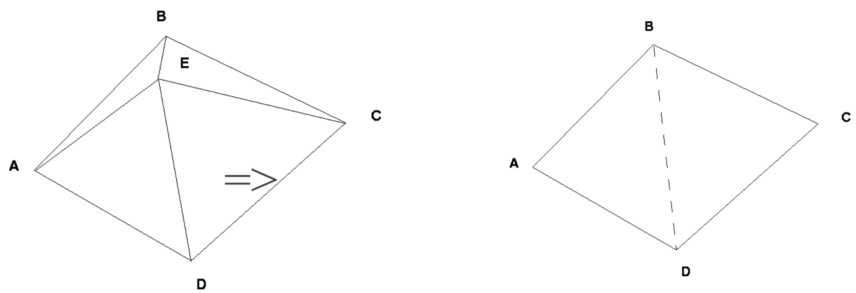
Grid reconstruction



Elementary reconstruction: BD connection is introduced instead of AC connection. The total number of the knots and the cells in the grid is not changed.

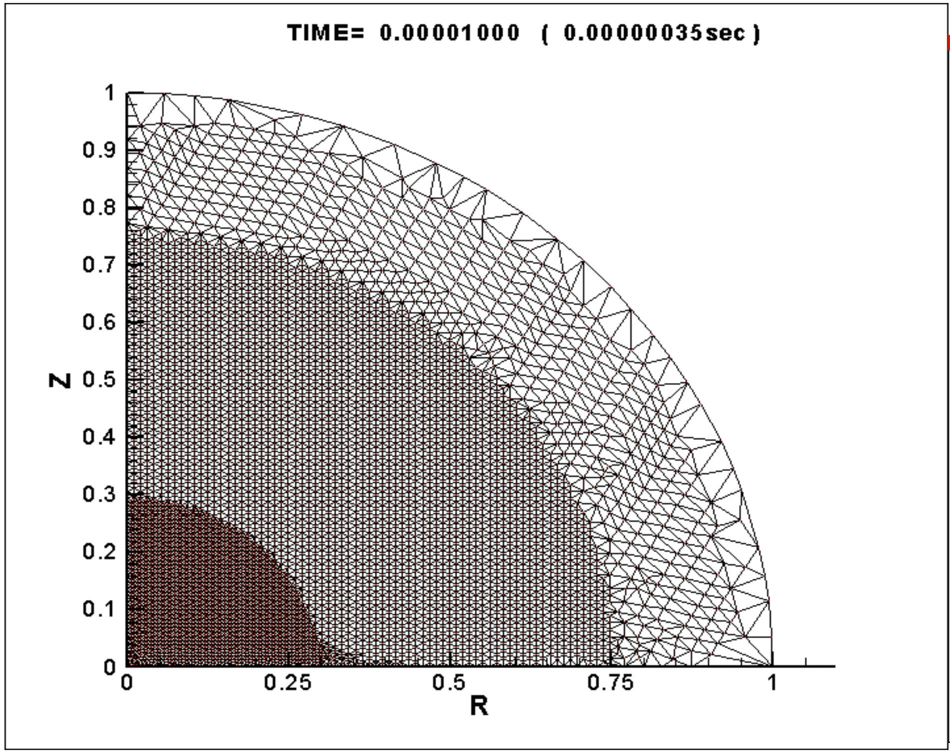


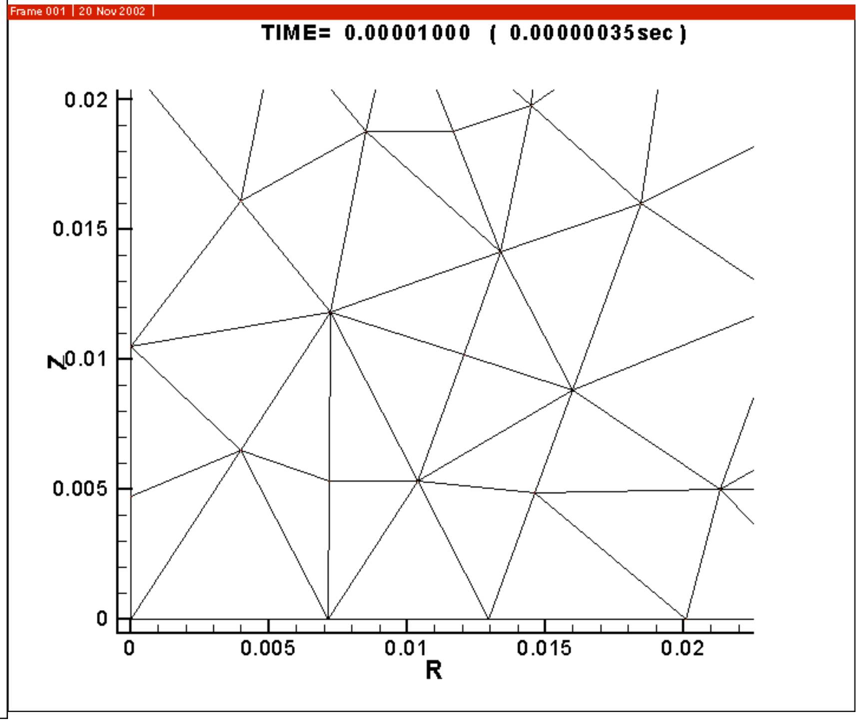
Addition a knot at the middle of the connection:
the knot E is added to the existing knots ABCD on the middle of the BD connection, 2 connections AE and EC appear and the total number of cells is increased by 2 cells.



Removal a knot: the knot E is removed from the grid and the total number of the cells is decreased by 2 cells

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.

Gas dynamic equations with a self-gravitation, realistic equation of state, account of neutrino losses and iron dissociation

$$\frac{\mathrm{d}\mathbf{x}}{\mathrm{d}t} = \mathbf{v}, \quad \frac{\mathrm{d}\rho}{\mathrm{d}t} + \rho\nabla\cdot\mathbf{v} = 0,$$

$$\rho\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = -\nabla\left(P\right) - \rho\nabla\Phi,$$

$$\rho\frac{\mathrm{d}\varepsilon}{\mathrm{d}t} + P\nabla\cdot\mathbf{v} + \rho F(\rho, T) = 0,$$

$$\Delta\Phi = 4\pi G\rho.$$

$$P \equiv P(\rho, T) = P_0(\rho) + \rho\Re T + \frac{\sigma T^4}{3},$$

$$\varepsilon = \varepsilon_0(\rho) + \frac{3}{2}\Re T + \frac{\sigma T^4}{\rho} + \varepsilon_{Fe}(\rho, T).$$

-iron dissociation energy

F(□,T) - neutrino losses

Equations of state (approximation of tables)

$$P \equiv P(\rho,T) = P_0(\rho) + \quad T\square + \frac{T^4\square}{3}$$

$$P_0(\rho) = \begin{cases} P_0^{(1)} = b_1\rho^{5/3}(1+c_1\rho^{1/3}), \; for\; \rho \le \rho_1 \\ P_0^{(k)} = a\cdot 10^{b_k(\lg\rho - 8.419)^{c_k}} \; for\; \rho_{(k-1)} \le \rho \le \rho_k,\; k=\overline{2,6}. \end{cases} \qquad \varepsilon_0(\rho) = \int_0^{\rho} \frac{P_0(x)}{x^2}dx.$$

Fe –dis-sociation

Neutrino losses: **URCA processes, pair annihilation, photo production of neutrino, plasma neutrino**

URCA:

$$f(\rho,\bar T) = 1.3\cdot 10^9\,\varphi(\bar T)/[1+(7.1\cdot 10^{-5}\rho/\bar T^3)^{2/5}]\,erg\cdot g^{-1}\cdot c^{-1}$$

$$\varphi(T) = \begin{cases} 1, & \bar T < 7, \\ 664.31 + 51.024(\bar T - 20), & 7 \le \bar T \le 20, \\ 664.31, & \bar T > 20, \end{cases} \qquad \bar T = T\cdot 10^{-9}.$$

Approximation of tables from Ivanova, Imshennik, Nadyozhin, 1969

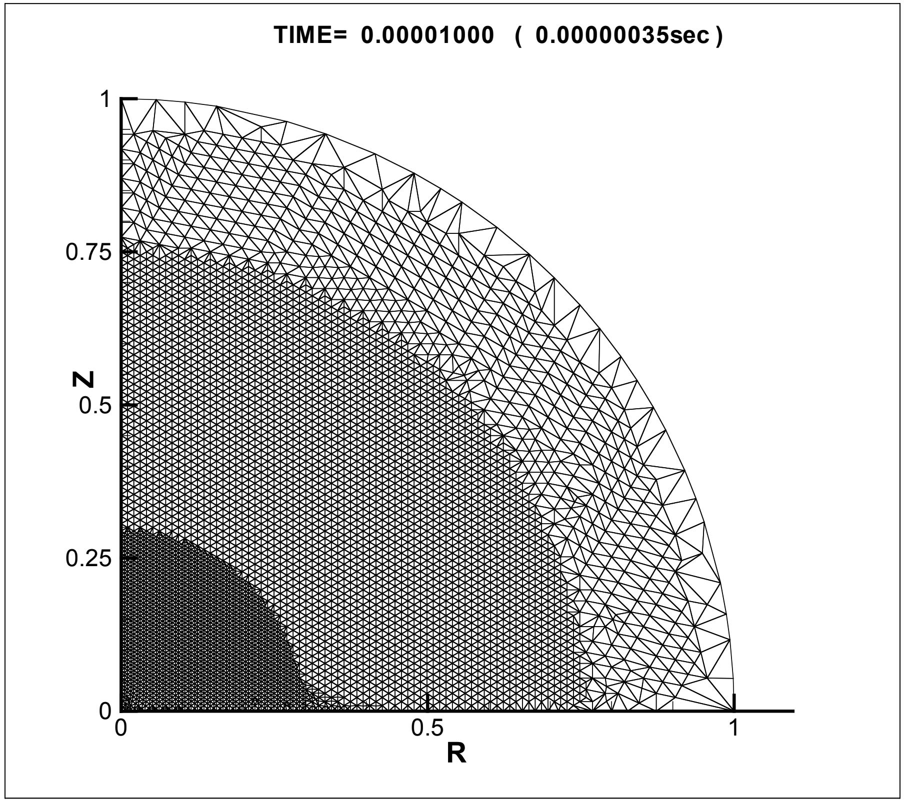
Initial State

Spherically Symmetric configuration, Uniform rotation with angular velocity 2.519 (1/___). Temperature distribution: $T = \square\square^{2/3}$

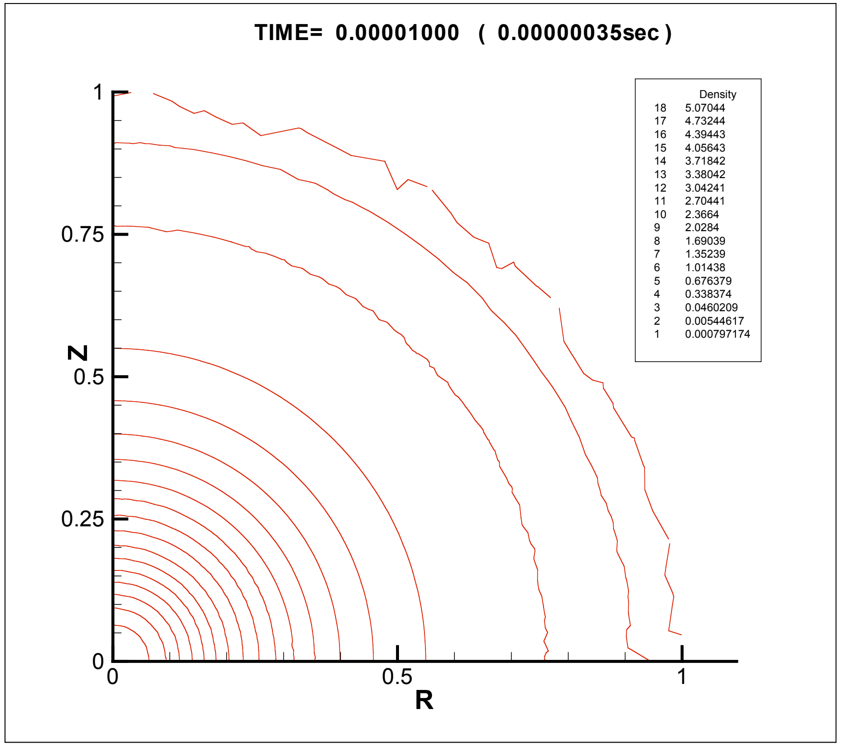
$M = 1.0042 \cdot M_{sun} + 20\%$

Grid

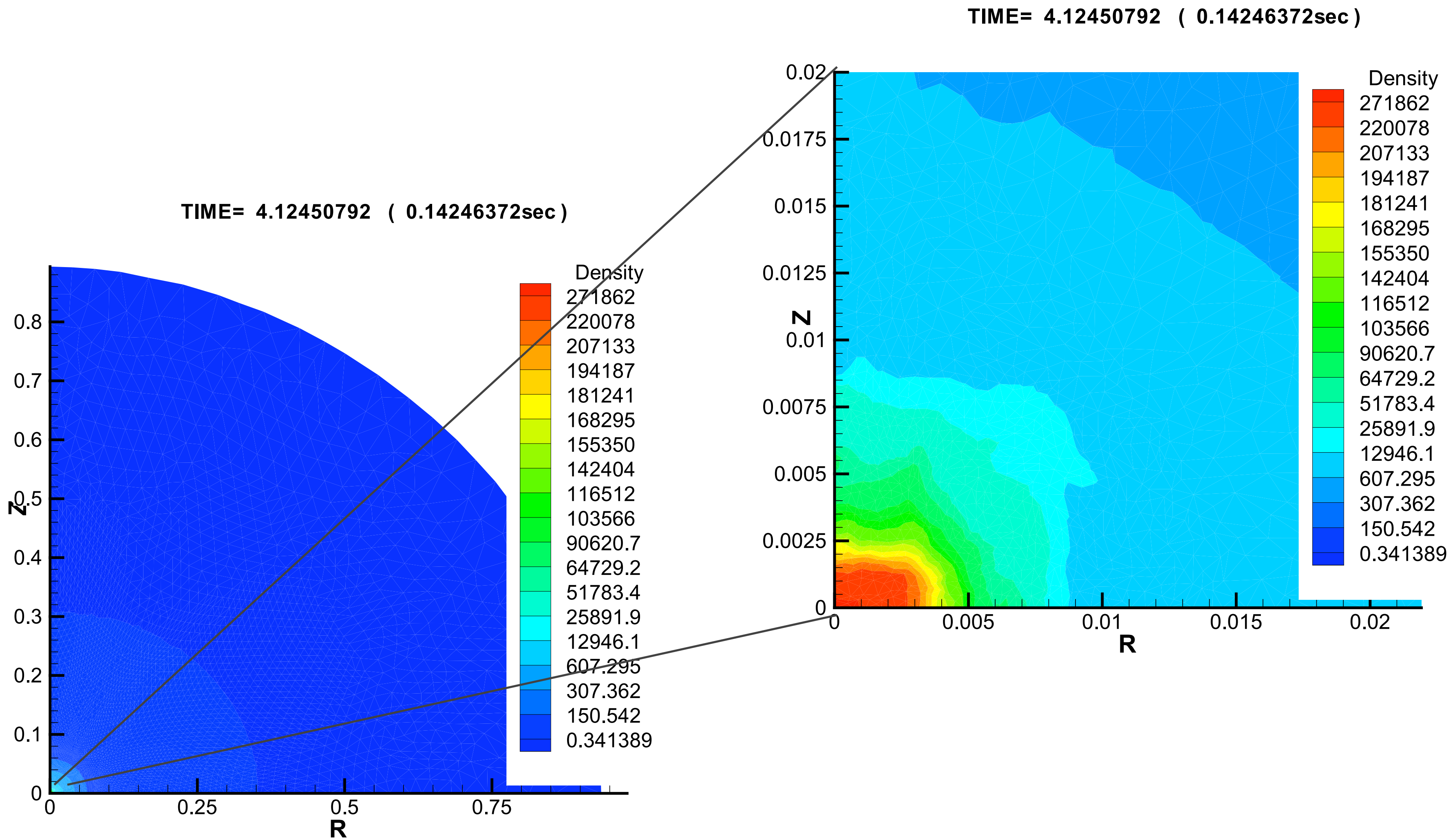
Density contours



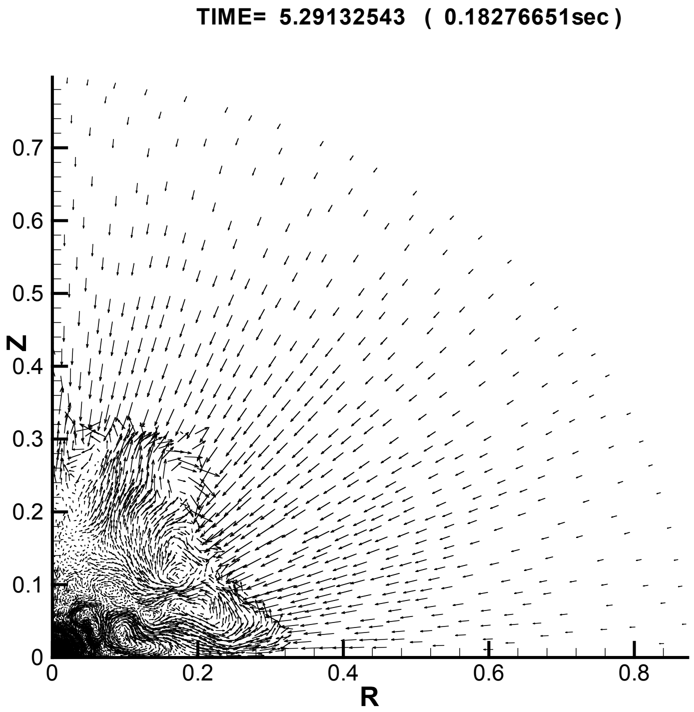
T



Maximal compression state



Mixing


TIME= 5.29132543 (0.18276651sec)
Z
0.7
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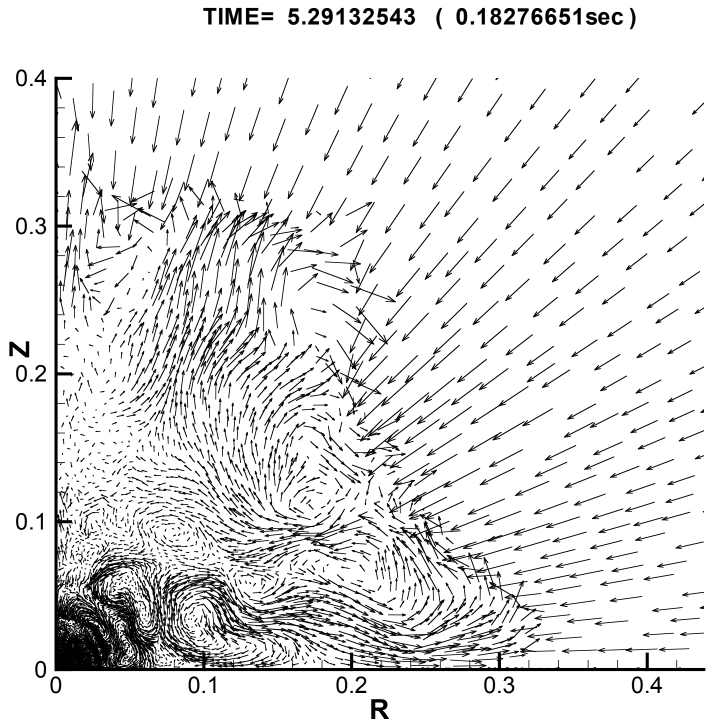
0.6
0.8
R


TIME= 5.29132543 (0.18276651sec)
Z
0.4
0.3
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0
0
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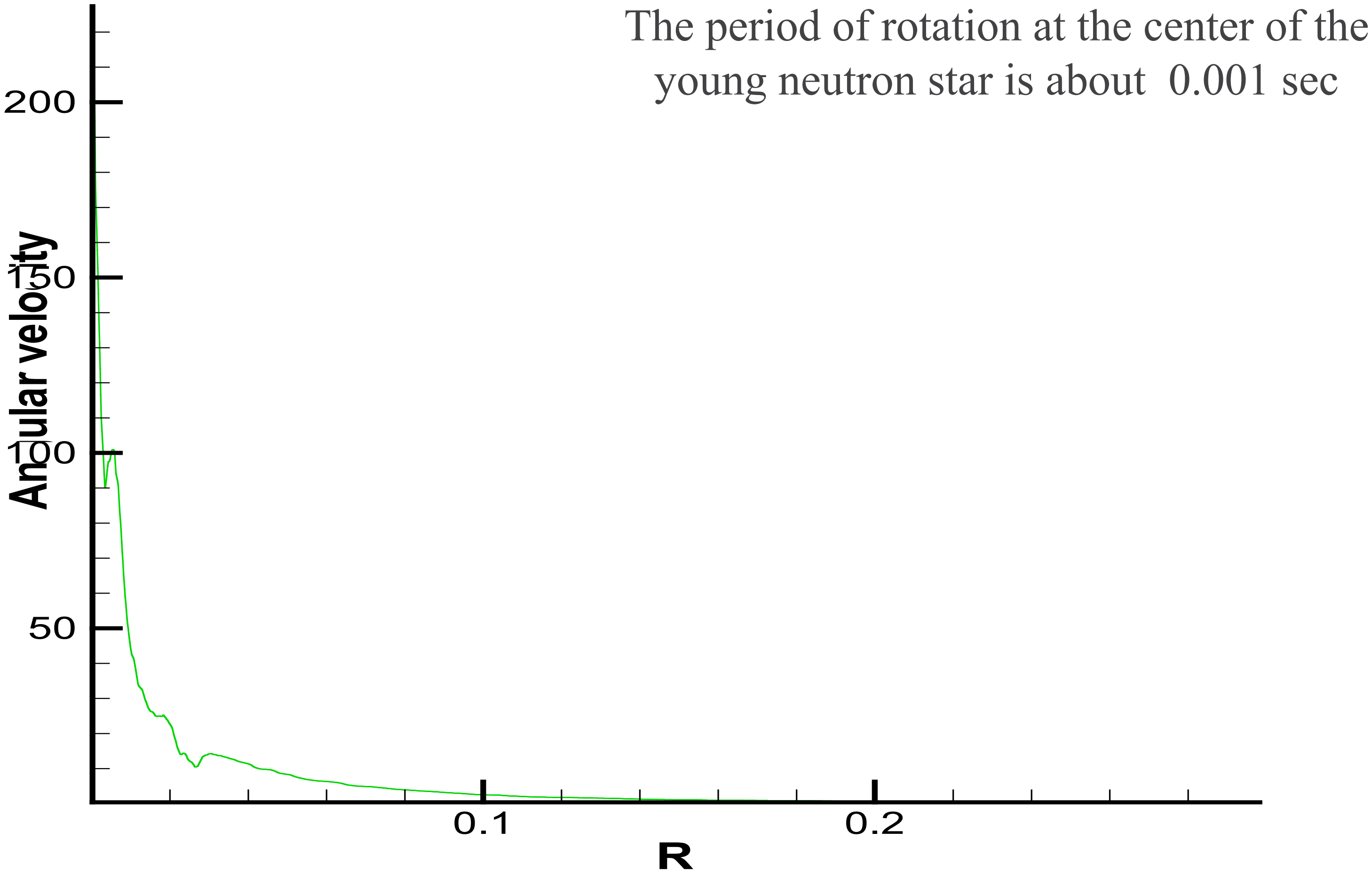
0.2
0.3
0.4
R

Shock wave does not produce SN explosion :

Distribution of the angular velocity



2-D magnetorotational supernova

N.V.Ardeljan, G.S.Bisnovatyi-Kogan, S.G.Moiseenko MNRAS, 2005, **359**, 333.

Equations: MHD + self-gravitation, infinite conductivity:

Additional condition: div**H**=0

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

Boundary conditions

Rotational axis:

$$r = 0 : u_r = u_{\varphi} = H_r = H_{\varphi} = \mathrm{rot}_r \mathbf{H} = \mathrm{rot}_{\varphi} \mathbf{H} = 0,$$

Equatorial plane

$$u_z = H_z = 0,$$

Quadrupole-like field

$$z = 0 :$$

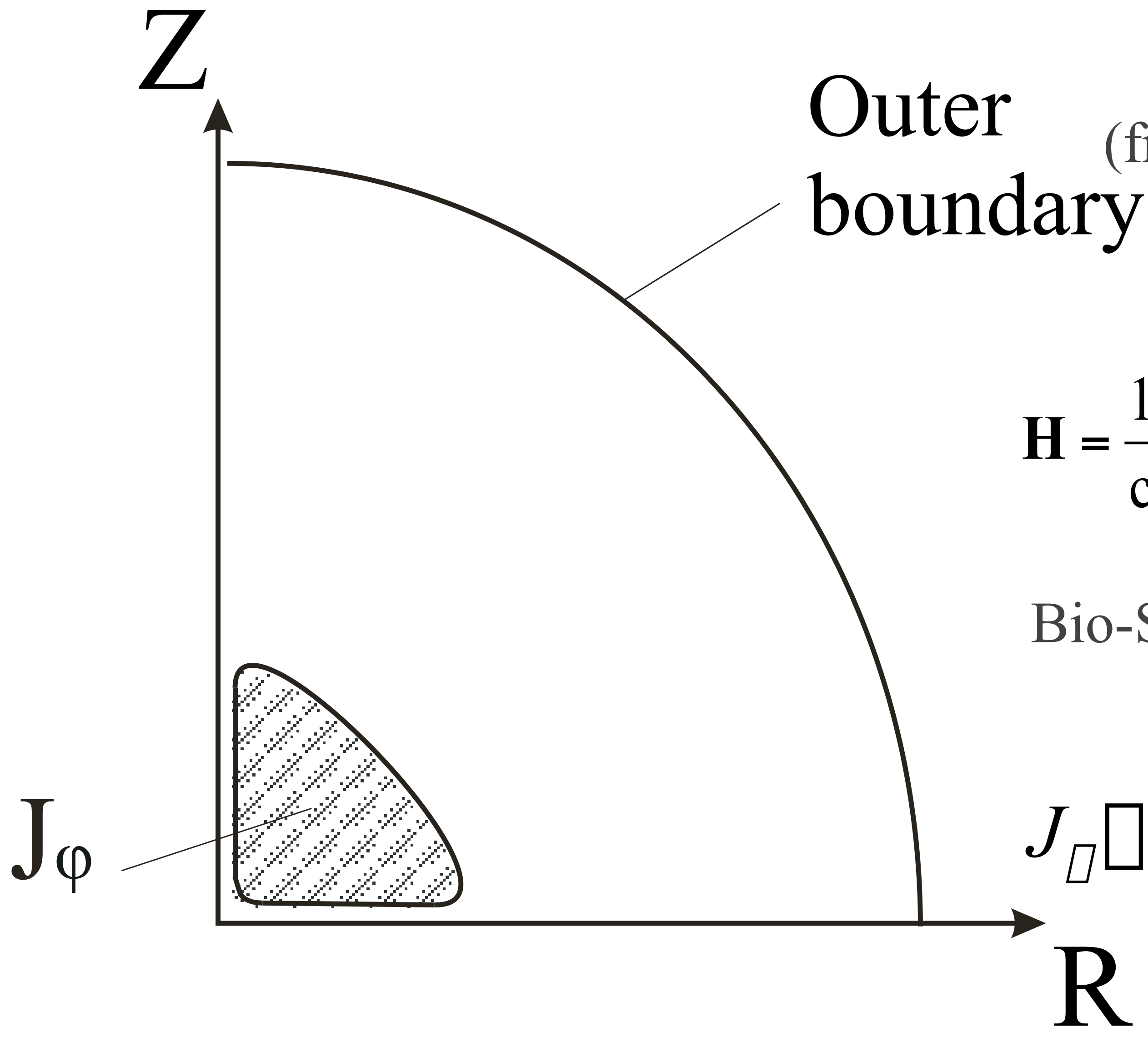
or

$$u_z = \frac{\partial B_z}{\partial z} = 0,$$

Dipole-like field

$$\text{outer boundary} : P = \square = T = H_{\varphi} = 0, \mathbf{H}_{\text{poloidal}} = \mathbf{H}_{\text{q}}$$

Initial toroidal current J_{φ}



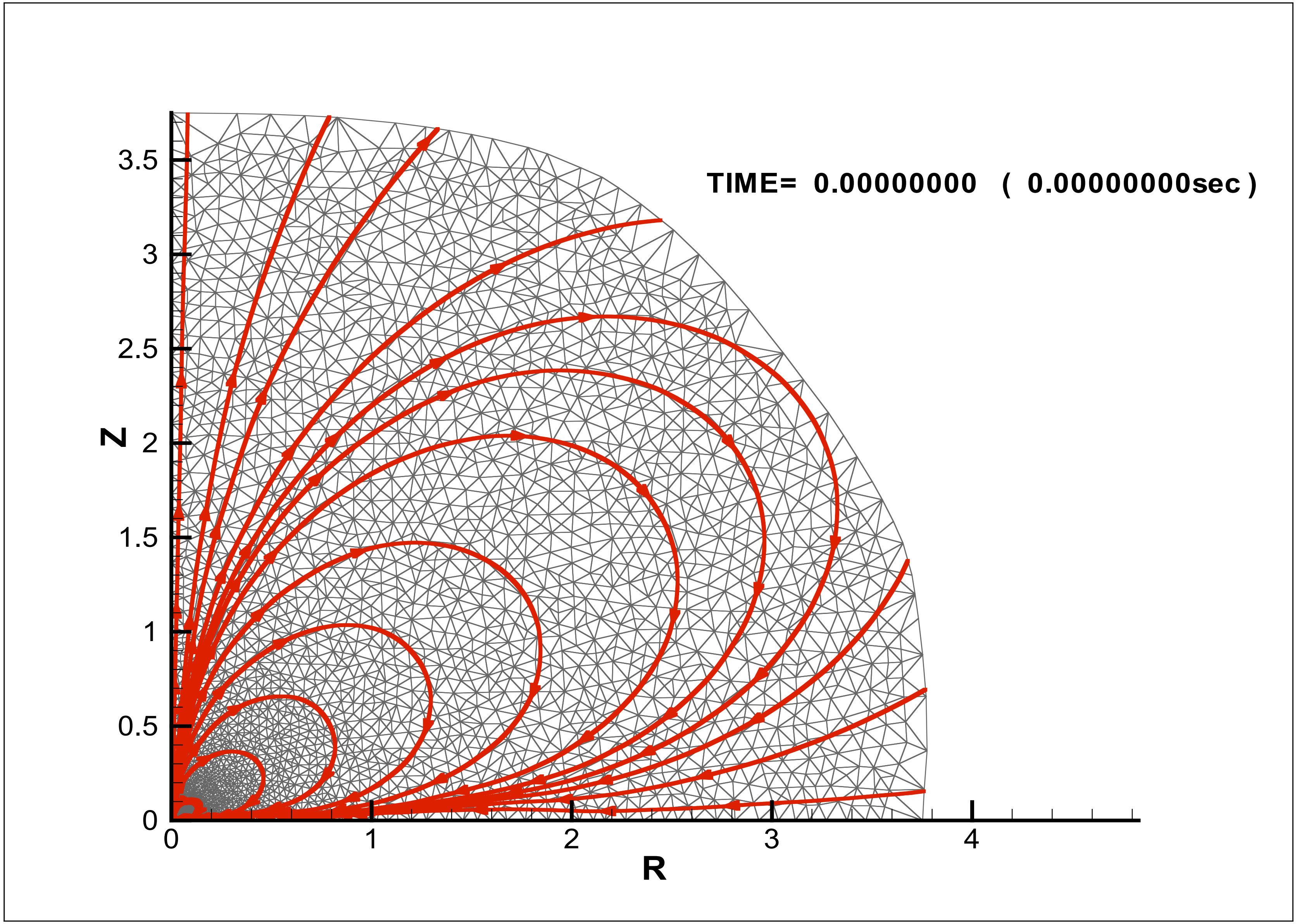
(free boundary)

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

Bio-Savara law

$$J_{\varphi} \Rightarrow (H_r, H_z)$$

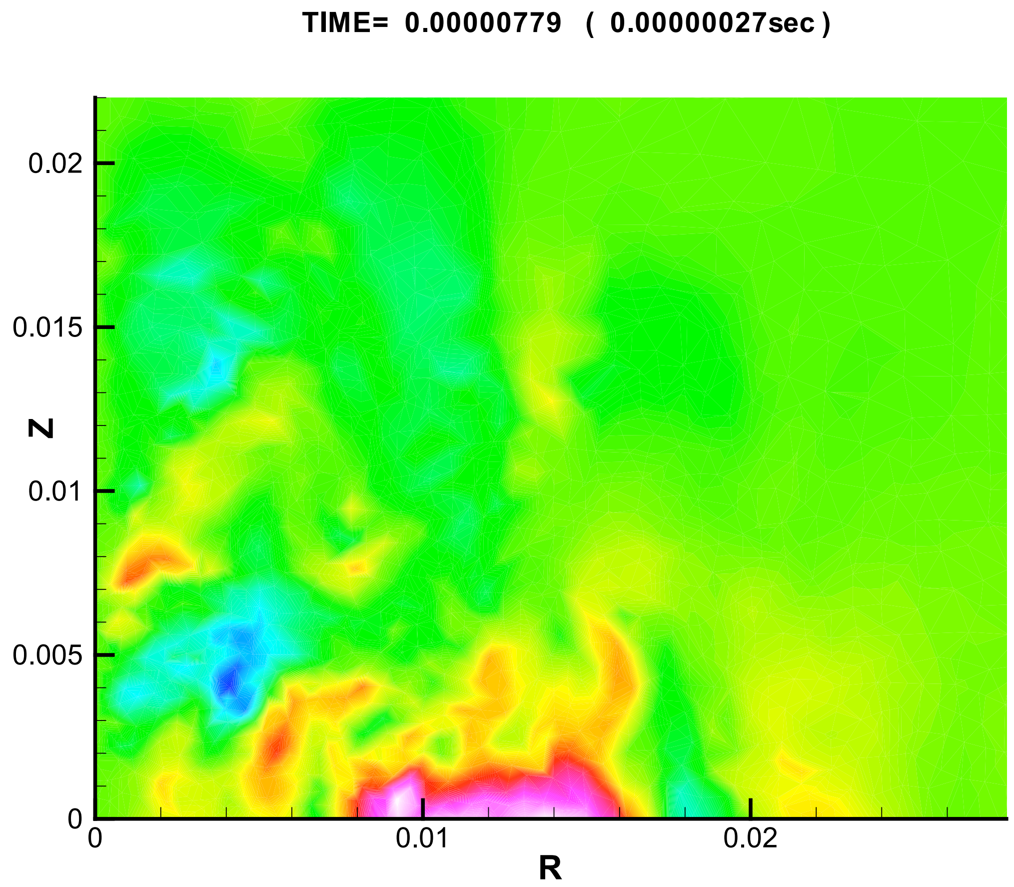
Initial magnetic field –quadrupole-like symmetry



Toroidal magnetic field amplification.

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

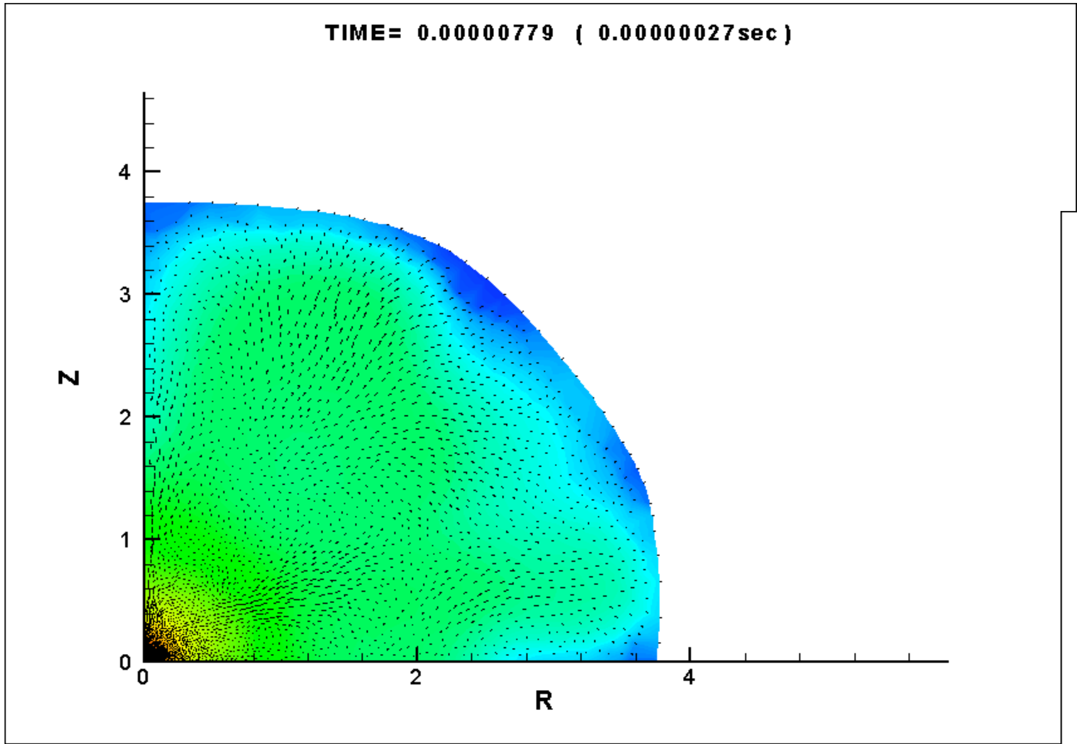
Maximal values of Hf=2.5 10(16)G



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

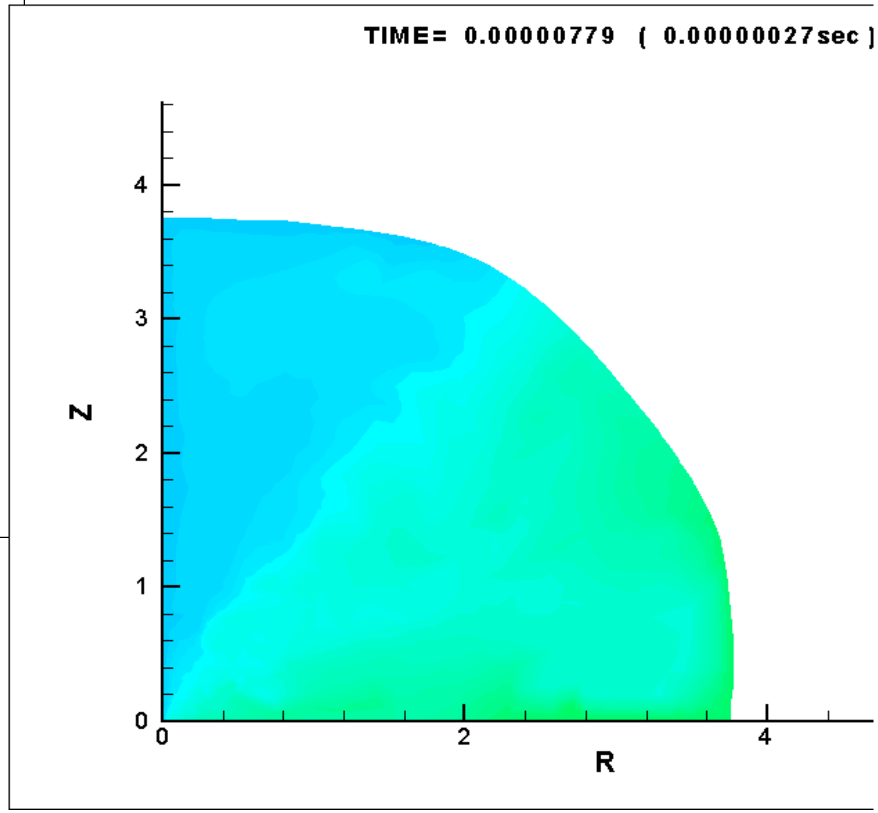
$H=4 \cdot 10^{12}$ Gs

Temperature and velocity field



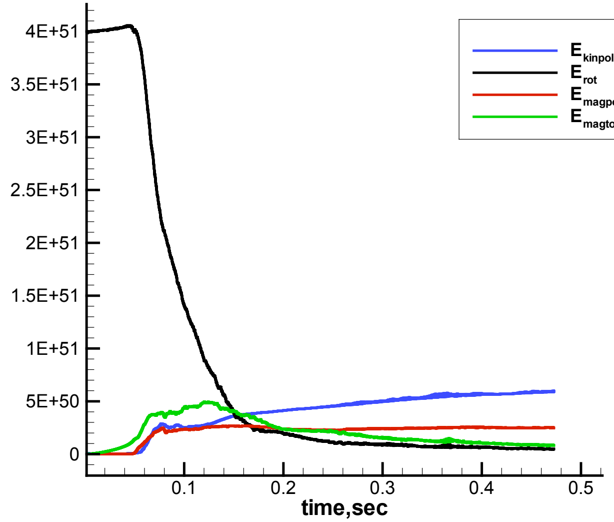
Specific angular momentum

rV_{ϕ}

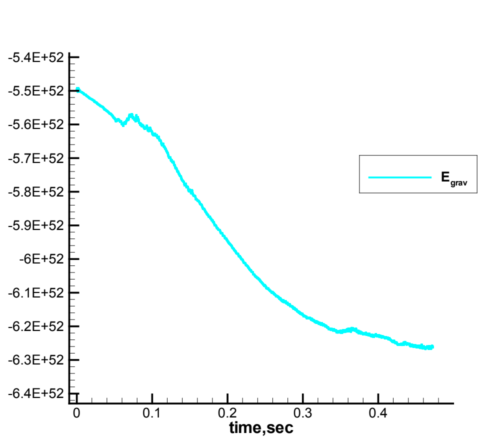


Time dependences

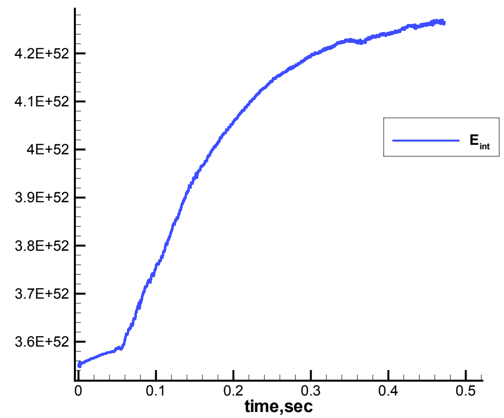
Rotational energy
Magnetic poloidal energy
Magnetic toroidal energy
Kinetic poloidal energy



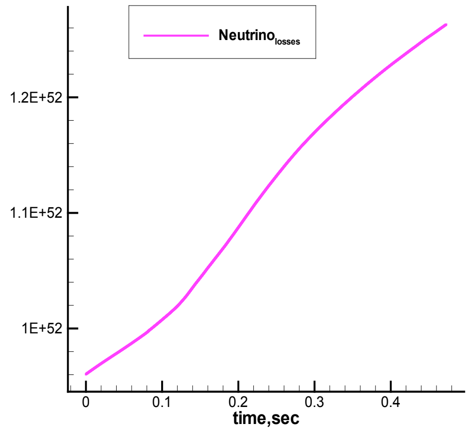
Gravitational energy



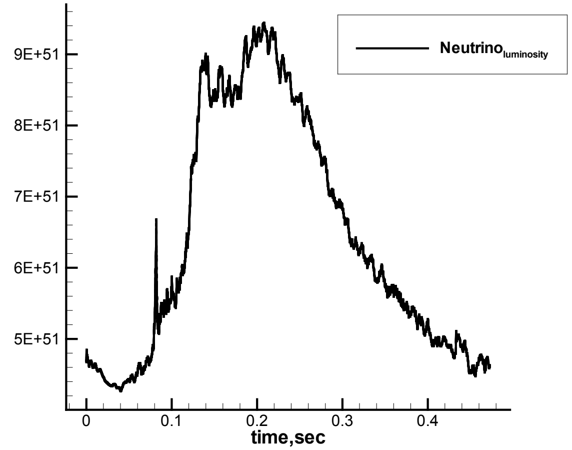
Internal energy



Neutrino losses



Neutrino luminosity

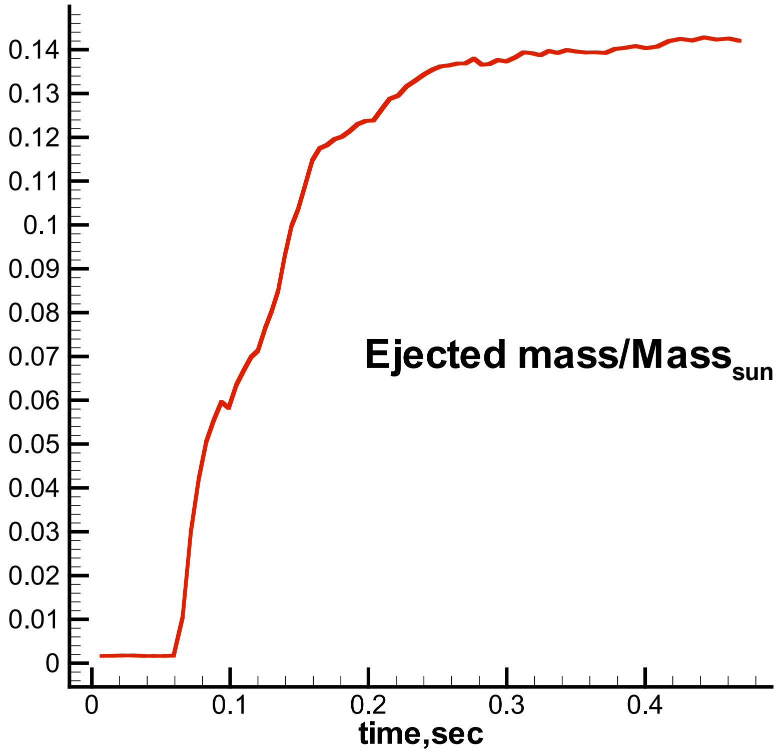


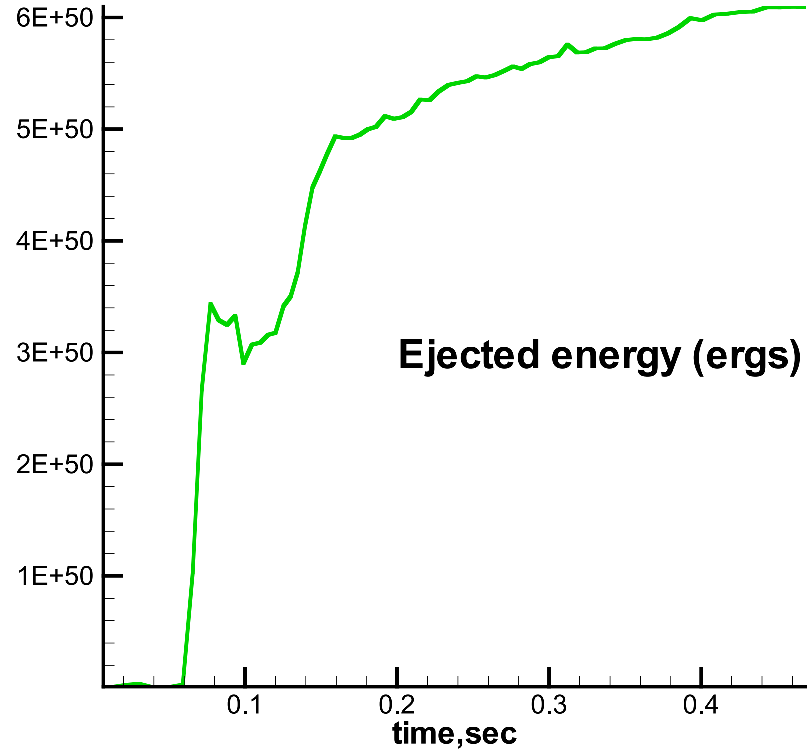
Particle is considered "ejected" if its kinetic energy is greater than its potential energy

Ejected energy

0.6 10

Ejected mass **0.14M**$_\odot$



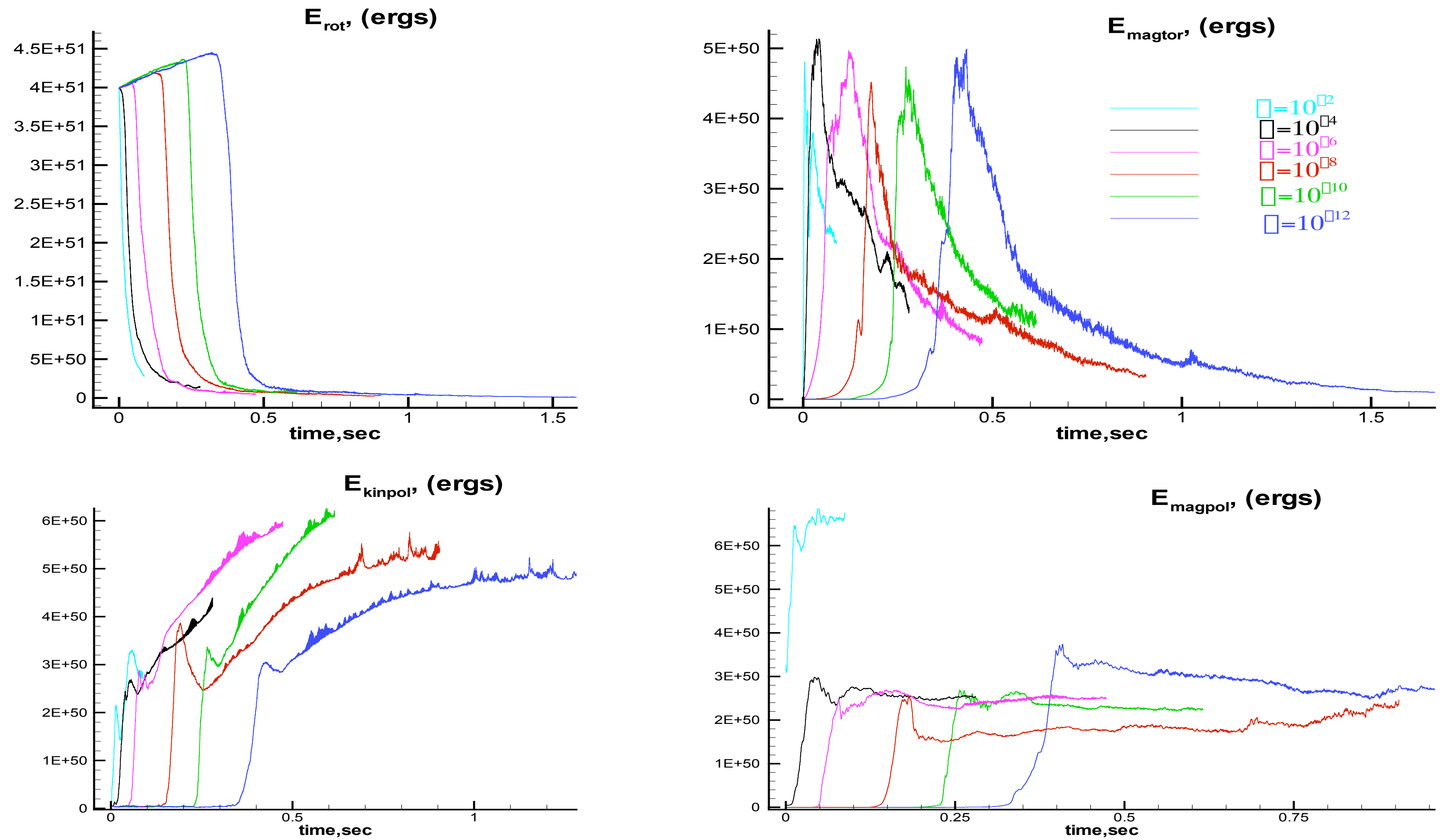


Magnetorotational explosion at different

Magnetorotational instability exponential growth of magnetic fields.

Different types of MRI:

Dungey 1958,Velikhov 1959, Balbus & Hawley 1991, Spruit 2002, Akiyama et al. 2003



Dependence of the explosion time on

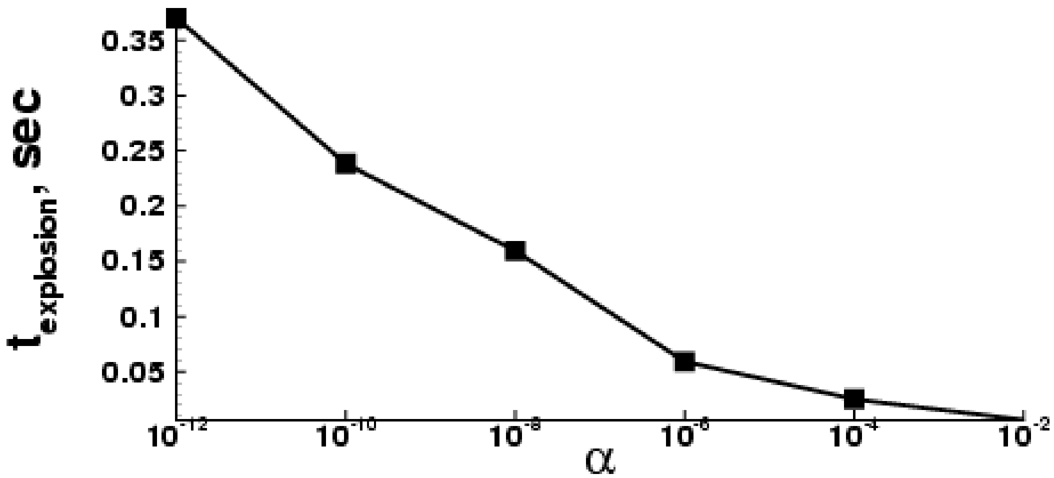
1-D calculattions:
Explosion time

2-D calculattions:
Explosion time

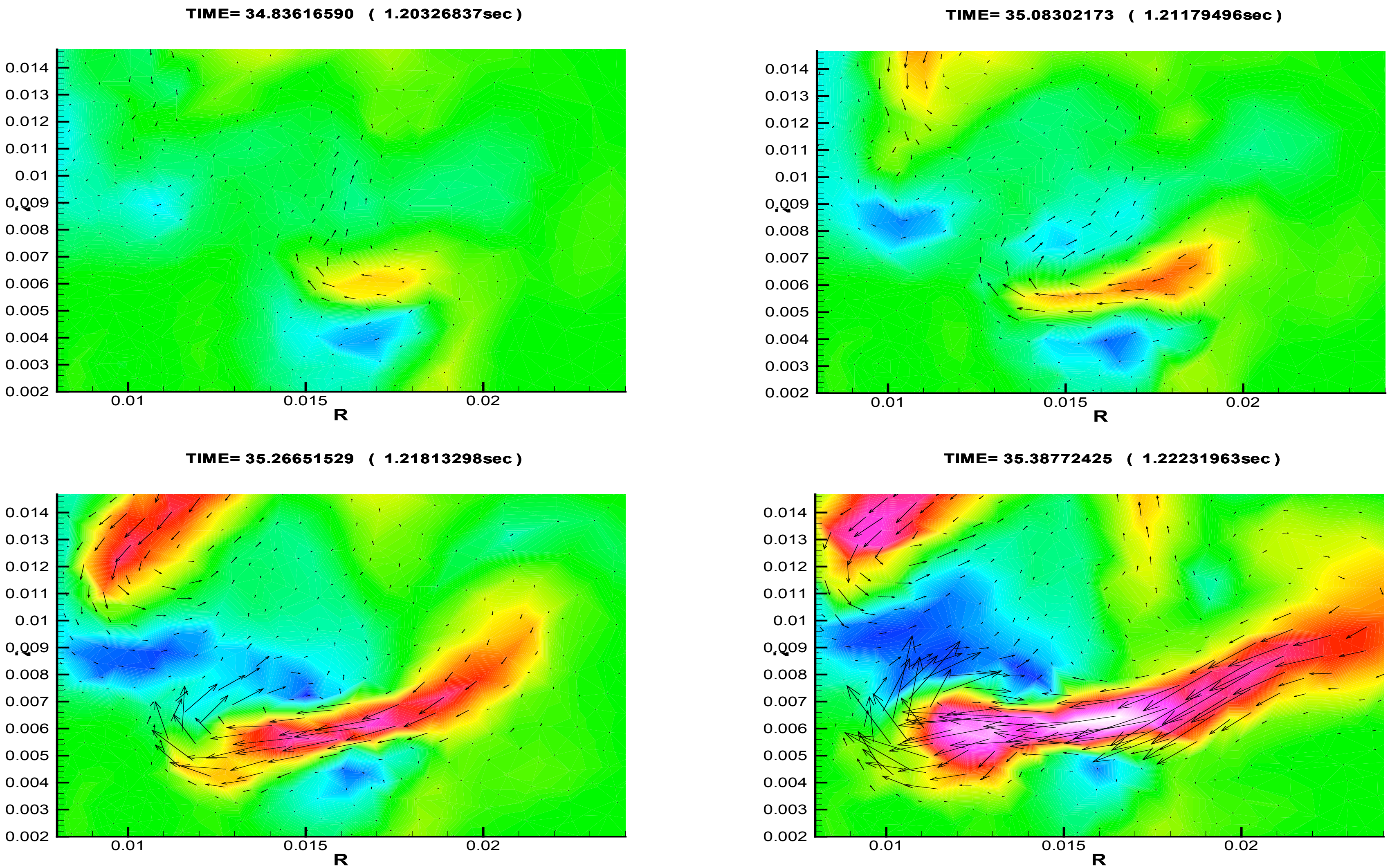
(for small)

astro-ph/0410234

astro-ph/0410330



Inner region: development of magnetorotational instability (MRI)

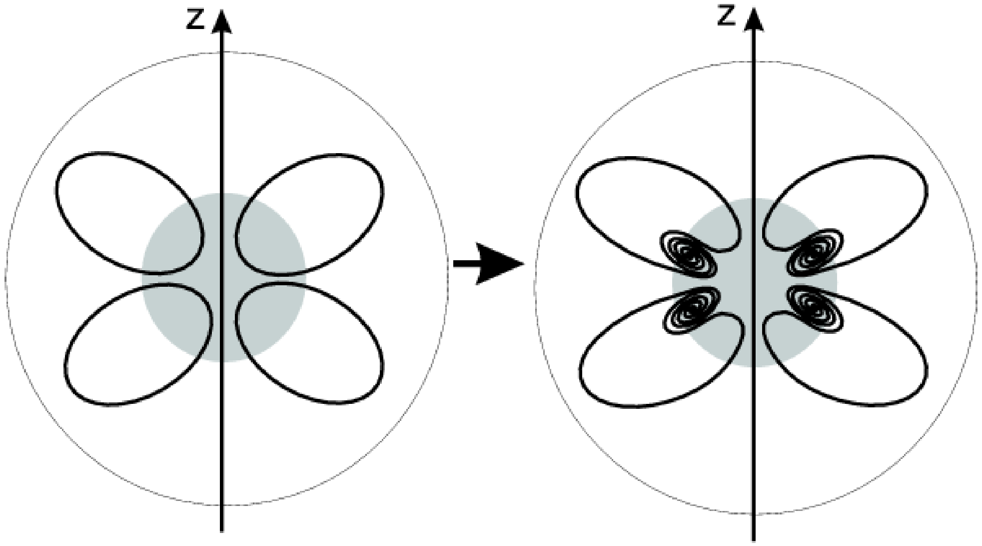


Toroidal (color) and poloidal (arrows) magnetic fields (quadrupole)

Toy model of the MRI development: expomemtial growth of the magnetic fields

at initial stages

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

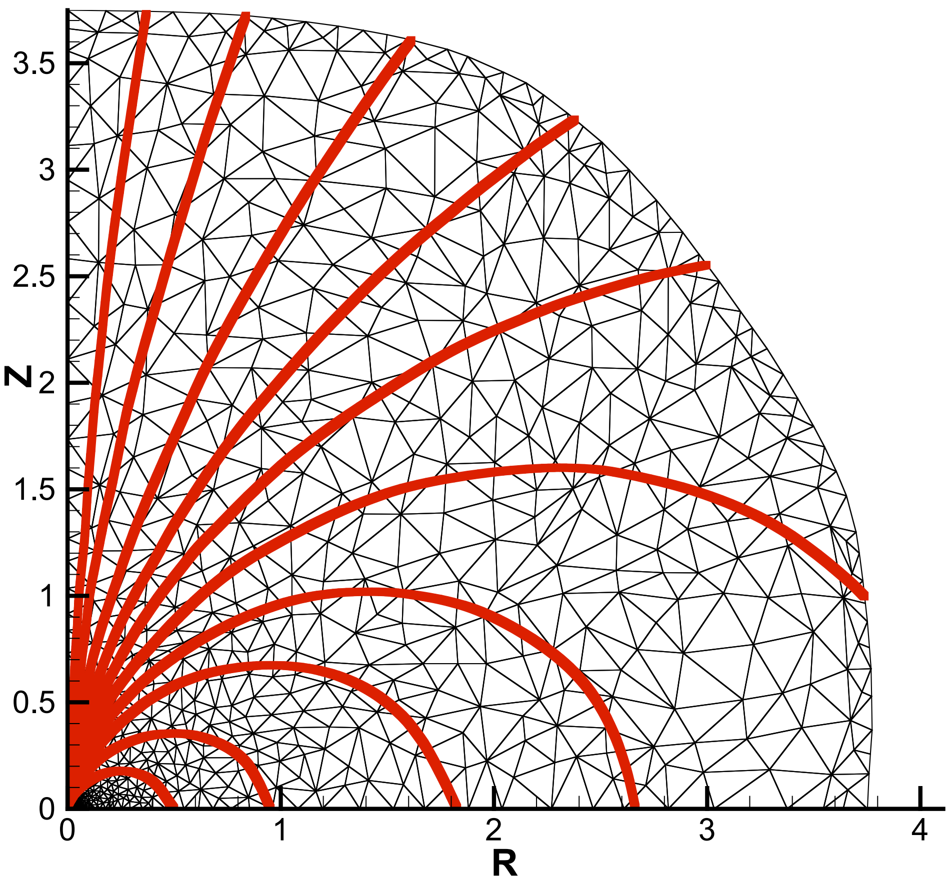


Jet formation in MRE

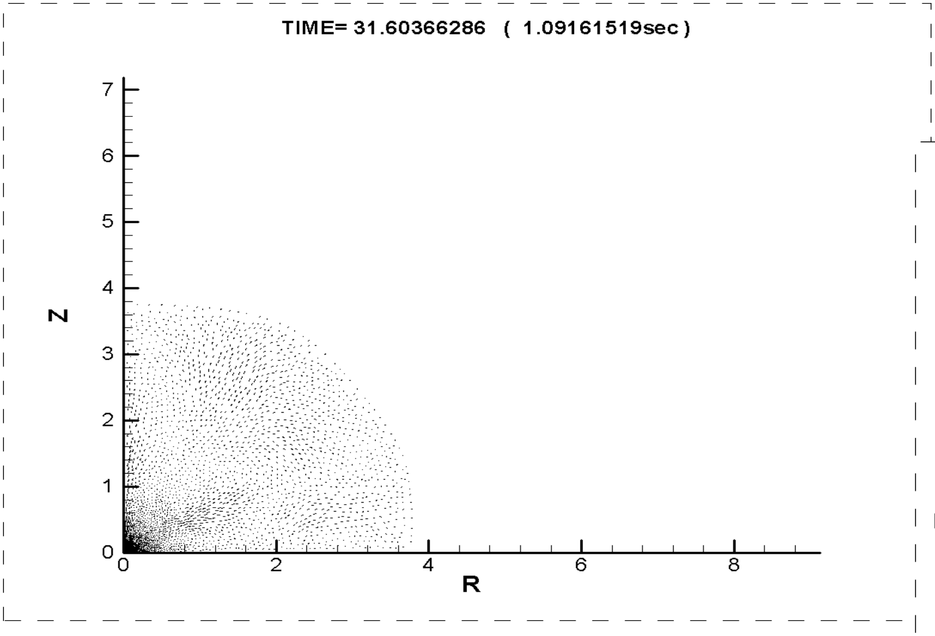
Moiseenko et al. Astro-ph/0603789

Magnetorotational supernovae with jets

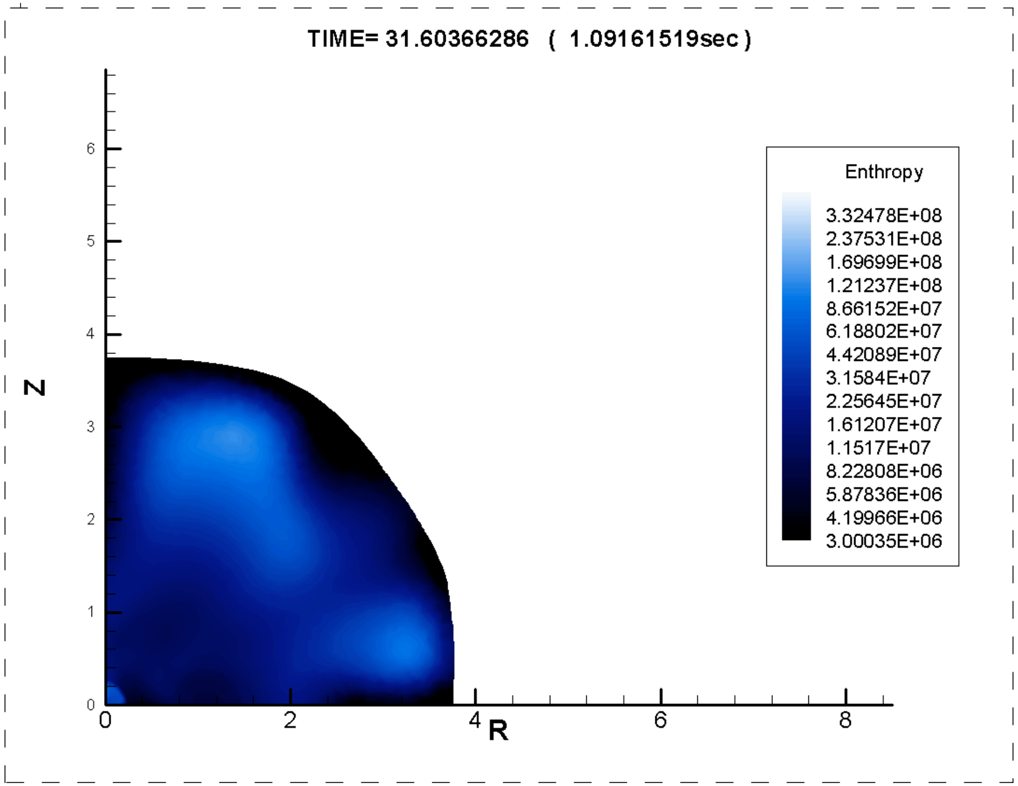
Dipole-like initial magnetic field



Jet formation in MRE:
velocity field evolution

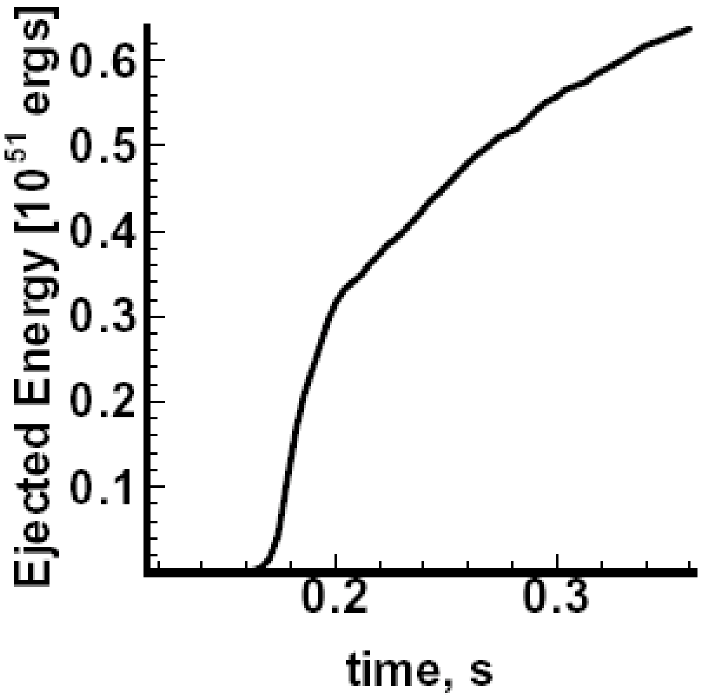


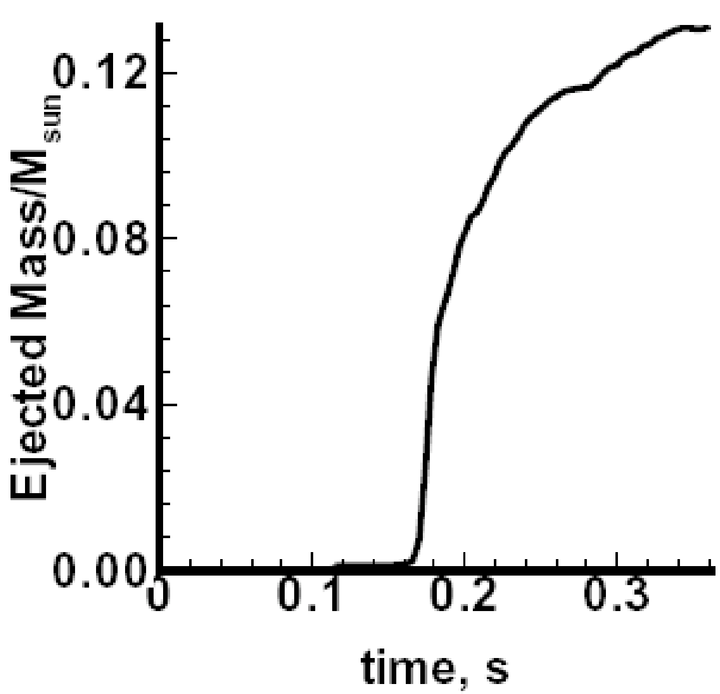
Jet formation in MRE:
entropy evolution



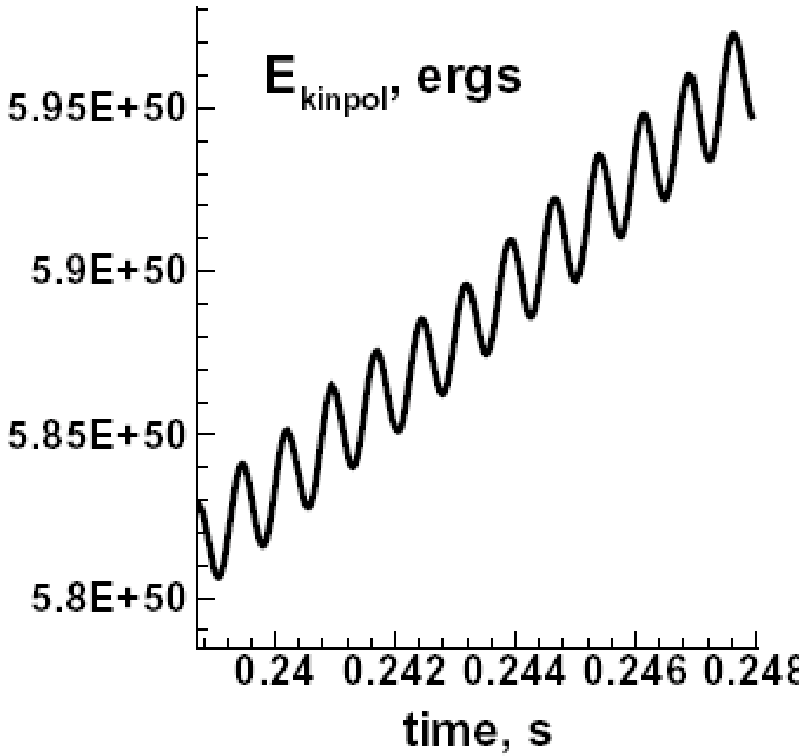
Jet formation in MRE: (dipole magnetic field)

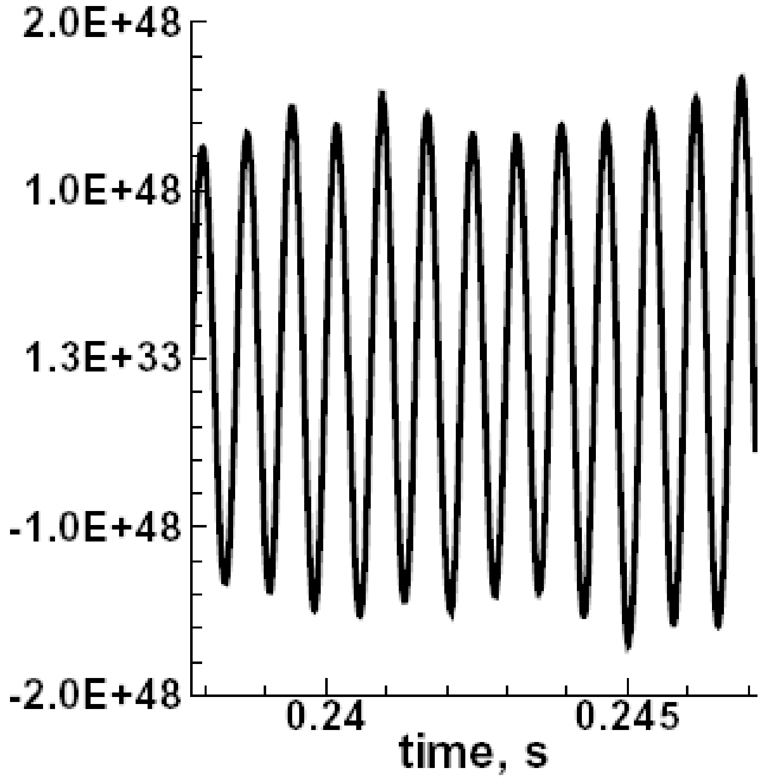
Energy of explosion□0.6·10^{51}___ **Ejected mass □ 0.14$M_\odot$**

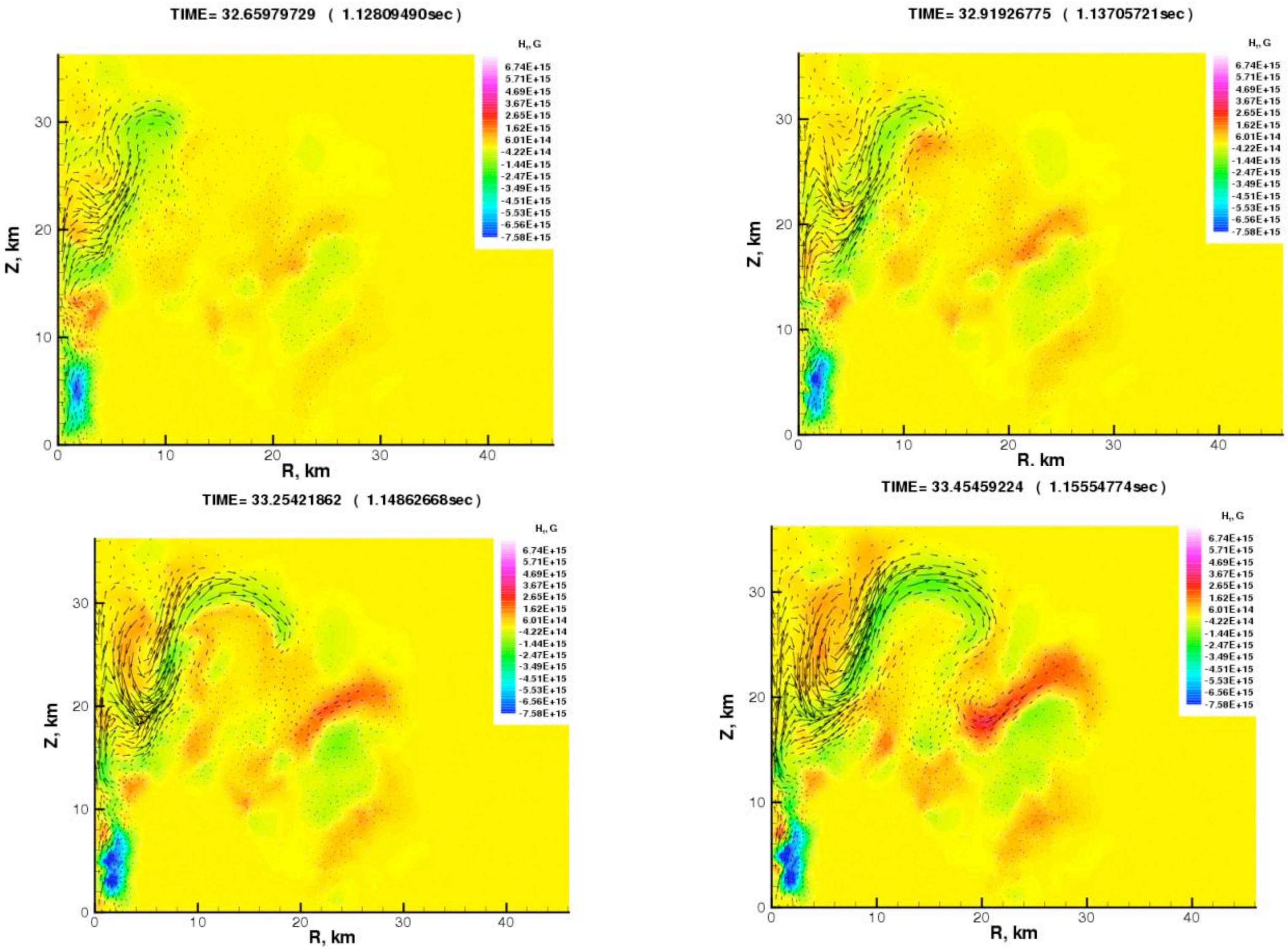




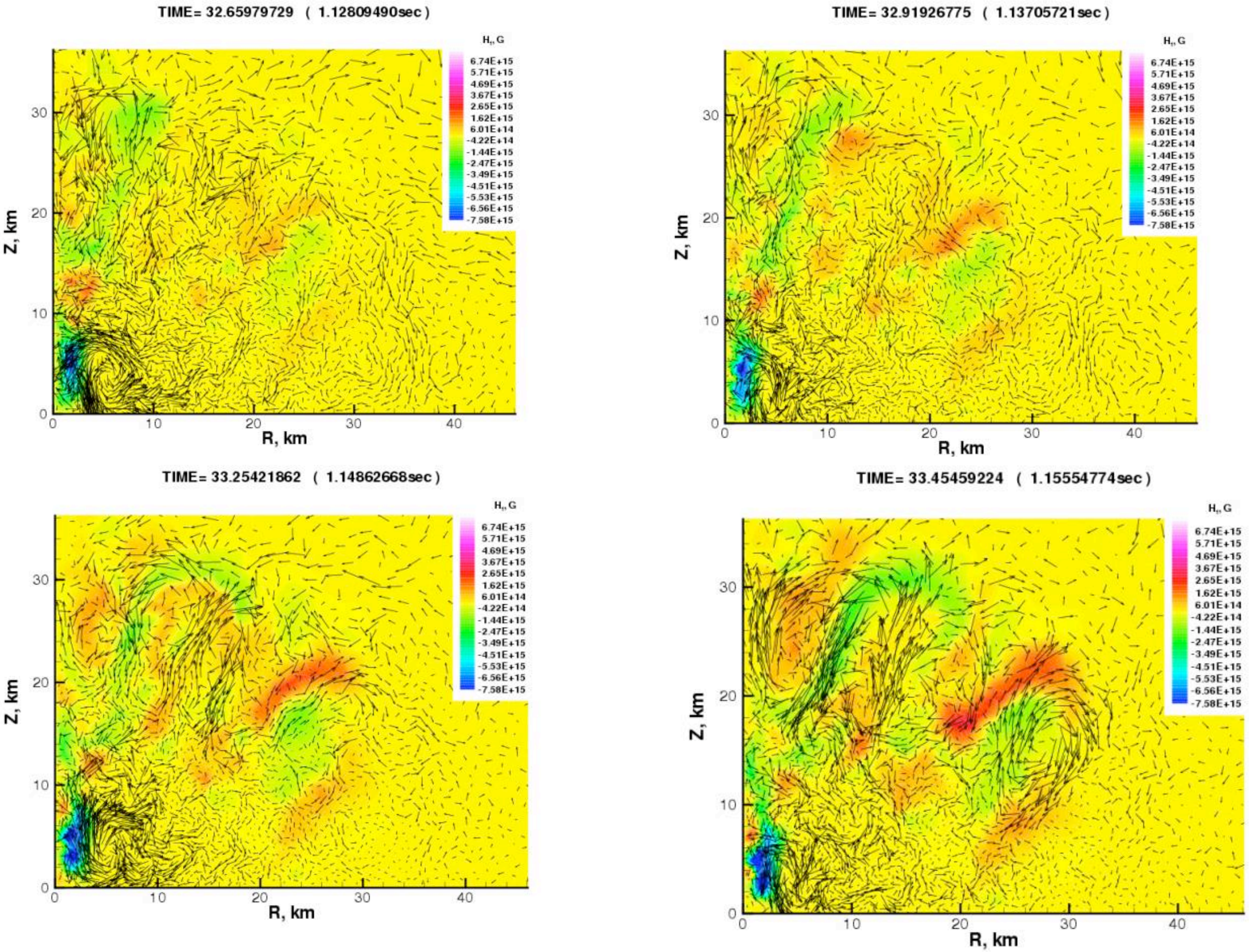
Exitation of NS oscillations during MRE with magnetic dipole





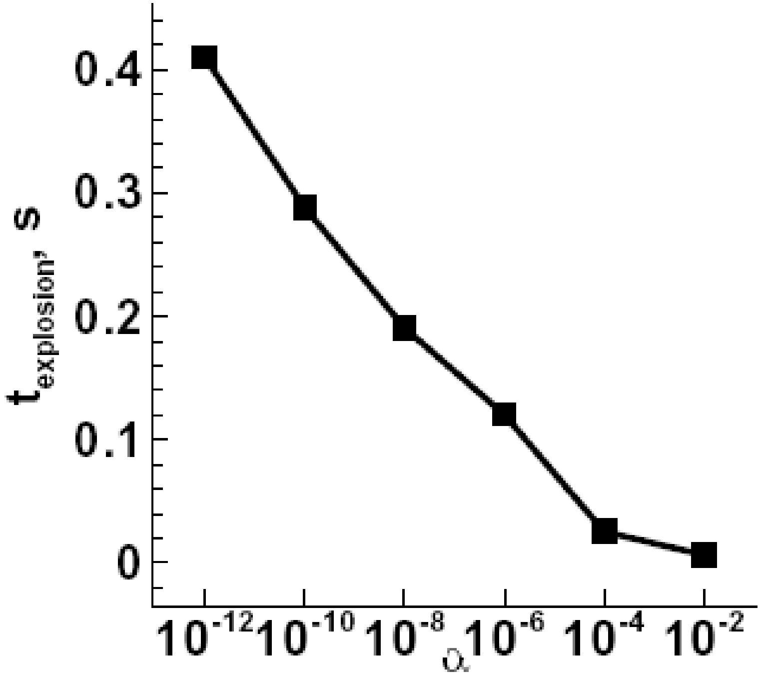


Toroidal (color) and poloidal (arrows) magnetic fields (dipole)



Toroidal magnetic field (color) and poloidal velocity field (dipole)

Why time of MRE depends logarithmically on alpha in presence of MRI



The logarithmic functional dependence at very small α has a simple qualitative explanation. First, we should have in mind, that the development of MRI starts at $t = t_{mri}$, approximately at the same moment for *all* initial values of the magnetic field. The MRI development begins in the part of the star, where the ratio of the toroidal and poloidal magnetic fields reaches a definite value $f \sim$ few tens, what happens after about 100 rotational periods of the inner core. In another words, the time of the field growth until the beginning of MRI t_{mri} does not depend on α, if α is small enough. At larger α the explosion starts before the beginning of MRI.

Second, we should take into account that MR explosion happens approximately at the same ratio $F < 1$ of the magnetic E_{mag} and internal E_{int} (gravitational E_{grav}) energies of the star, also for all α, $E_{magE} = F E_{grav}$. The magnetic energy E_{mag} is growing exponentially with time during MRI development at $t > t_{mri}$,

$$\frac{E_{mag}}{f E_{mag0}} = \exp[\gamma_m (t - t_{mri})],$$

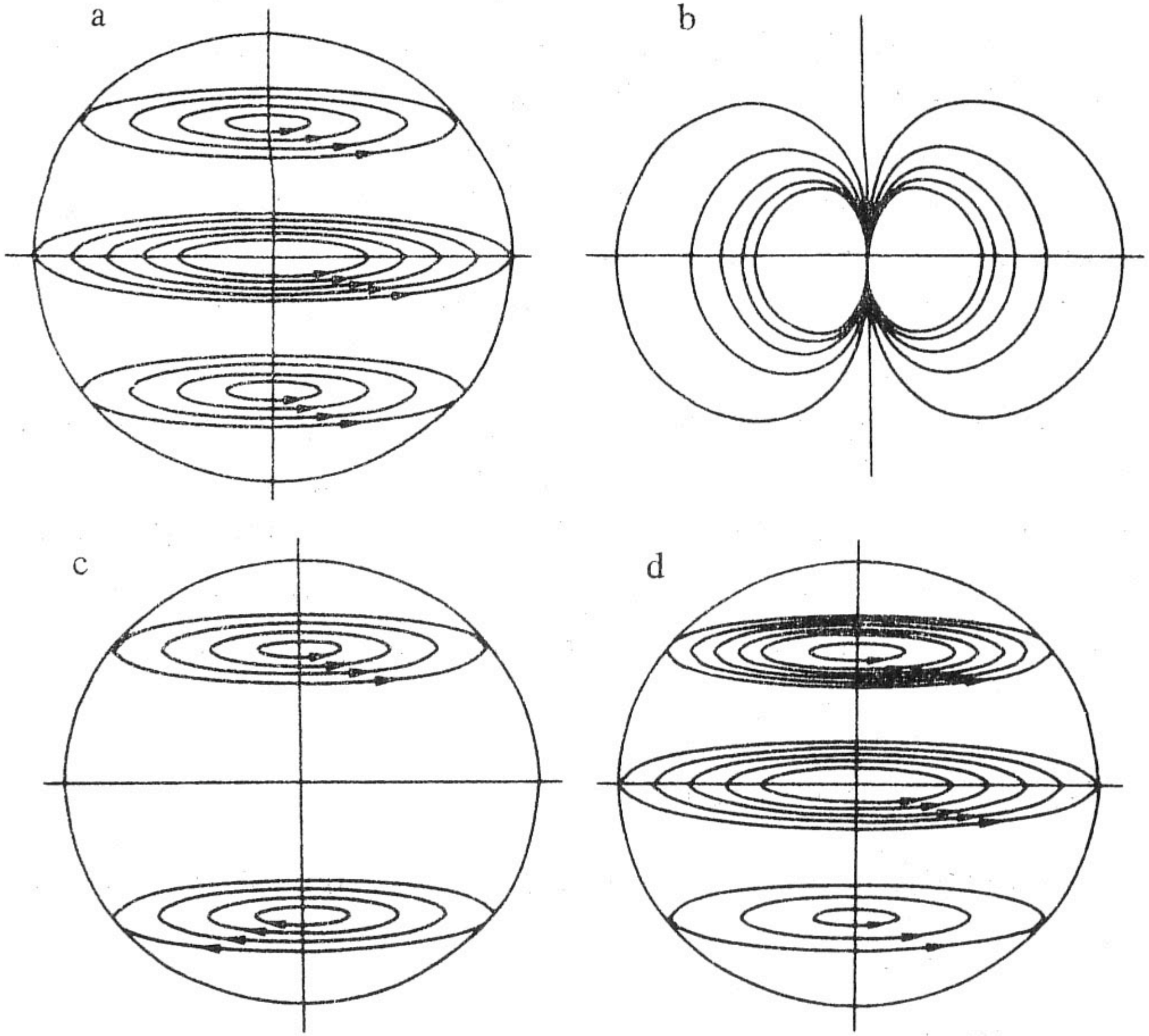
where γ_m is an increment of the MRI instability. Therefore, the time between the the start of MRI, until the moment of the explosion t_{expl}, is growing logarithmically with decreasing α

$$t_{expl} - t_{mri} = \frac{1}{\gamma_m} \log \frac{E_{magE}}{f E_{mag0}} = \frac{1}{\gamma_m} \log \frac{F E_{grav}}{f E_{mag0}}$$

$$\approx \frac{1}{\gamma_m} \log \frac{F E_{grav0}}{f E_{mag0}} = \frac{1}{\gamma_m} (\log \frac{F}{f} - \log \alpha).$$

Violation of mirror symmetry of magnetic field

(Bisnovatyi-Kogan, Moiseenko, 1992)



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

In reality we have dipole + quadrupole + other multipoles… Lovelace et al. 1992

The magnetorotational explosion will be always asymmetrical due to development of MRI.

Kick velocity, **along the rotational axis**, due to the asymmetry of the magnetic field ~ up to 300km/sec

Bisnovatyi-Kogan, Moiseenko (1992) Astron. Zh., **69**, 563

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

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

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

Kick velocity, **along the rotational axis,** ~ up to 1000km/sec

Bisnovatyi-Kogan, 1993, Astron. Ap. Transactions **3,** 287

S. Johnston et al. astro/ph 0510260

Evidence for alignment of the rotation and velocity vectorsin pulsars

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

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

W.H.T. Vlemmings et al. astro-ph/0509025

Pulsar Astrometry at the Microarcsecond Level

Determination of pulsar parallaxes and proper motionsaddresses fundamental astrophysical questions. We have recentlyfinished a VLBI astrometry project to determine the proper motions andparallaxes of 27 pulsars, thereby doubling the total number of pulsarparallaxes. Here we summarise our astrometric technique and presentthe discovery of a pulsar moving in excess of 1000 kms, **PSR B1508+55**.

Conclusions

1. In the magnetorotational explosion (MTE) 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-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. MRI leads to violation of mirror symmetry, asymmetry in MRE explosion, and in the neutrino flux, producing kick.