Instabilty of magnetohydro-jet in supernova

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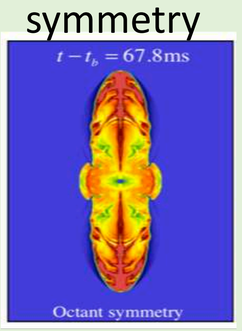
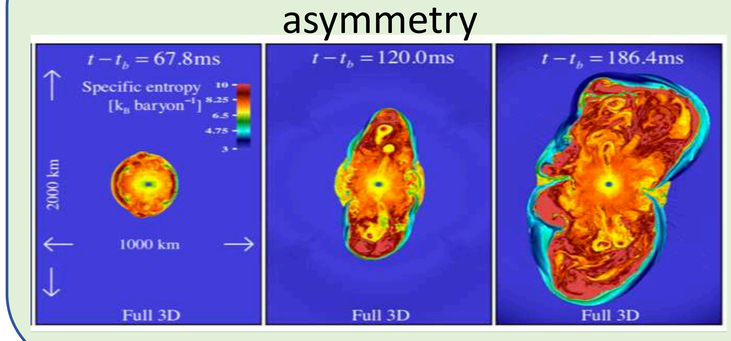
Background

- Magnetohydrodynamic (MHD) mechanism is one of the candidates of Explosion mechanism of core-collapse supernova (CCSN)
- In its canonical form, rapid rotation of the core and magnetic field with a dominant toroidal component make a bipolar jet-like explosion that could result in a hypernova.
- Dynamics of magneto rotational CCSN in 3D simulations are fundamentally different from what was anticipated on the basis of the 2D(octant 3D) because of MHD instability.

Axial symmetry



Axial asymmetry



Purpose

To evaluate linear growth rate and time scale of non-linear saturation of the kink instability by simulation with non-axisymmetric perturbation. The goal is to clarify dynamics of MHD instability in CCSN explosion.

Method

MHD simulation code : cans+

- HLLD approximate Riemann solver
- MP5 scheme
- Hyperbolic divergence cleaning method
- Cylindrical coordinate

Ideal non-relativistic MHD equation

$$\frac{\partial \mathbf{U}}{\partial t}+\nabla\cdot\mathbf{F}=\mathbf{0}$$

$$\mathbf{U}=\begin{pmatrix}\rho\\ \rho\mathbf{v}\\ \mathbf{B}\\ e\end{pmatrix}\quad \mathbf{F}=\begin{pmatrix}\rho\mathbf{v}\\ \rho\mathbf{v}\mathbf{v}+P_t\mathbf{I}-\mathbf{B}\mathbf{B}\\ \mathbf{v}\mathbf{B}-\mathbf{B}\mathbf{v}\\ (e+P_t)\mathbf{v}-\mathbf{B}(\mathbf{v}\cdot\mathbf{B})\end{pmatrix}$$

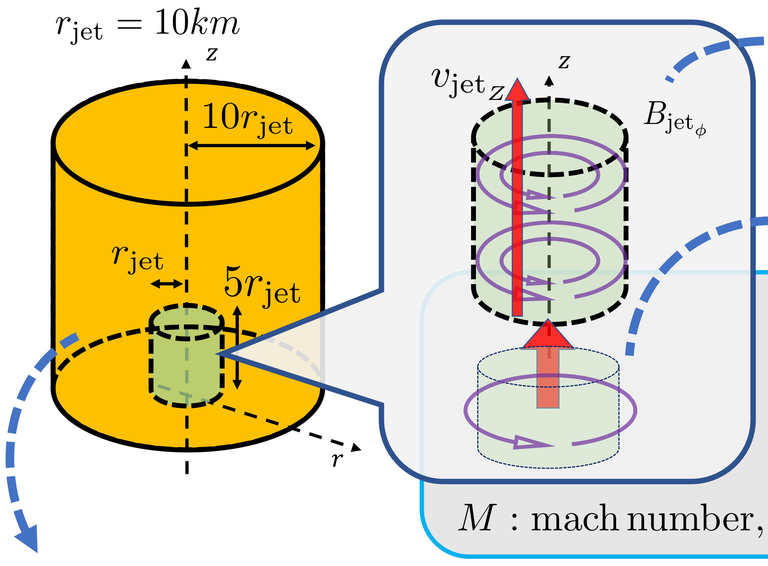
$$e=\frac{1}{2}\rho v^2+\rho\epsilon+\frac{1}{2}B^2,\ P_t=p+\frac{1}{2}B^2$$

- Viscosity and gravity are neglected
- Abiabatic process

Settings

Initial settings

A cylindrical plasma was placed as a jet at the bottom of the calculation area.



The jet has toroidal magnetic field and a vertically upward velocity.

A jet blows out from within the r_{jet} at the bottom of the calculation area.

$$\rho_{\rm jet}=0.1\times10^{10}[g/cm^3]$$
$$B_{{\rm jet}_\phi}=\sqrt{2p_{\rm jet}/\beta},\ v_{{\rm jet}_z}=Mc_s$$
$$p_{\rm jet}=0.6\times10^{28}[g\cdot cm^{-1}s^{-2}]$$

M : mach number, β : plasma beta c_s : speed of sound

Ambient plasma : state of rest and no magnetic field

$$\rho_{\rm am}=1\times10^{10}[g/cm^3]$$
$$\boldsymbol{B}_{\rm am}=\mathbf{0},\quad \boldsymbol{v}_{\rm am}=\mathbf{0}$$
$$P_{am}=P_{jet}+B^2/2$$

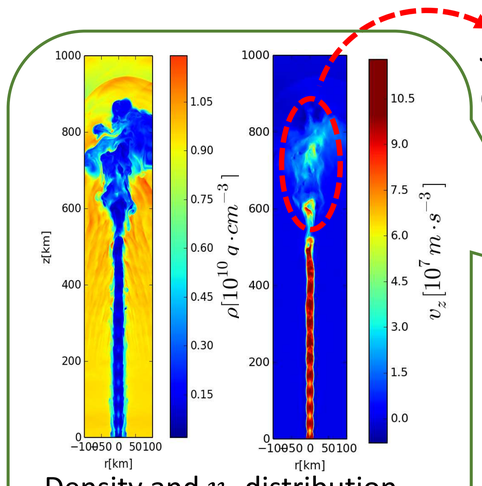
Perturbation

1% m=1 perturbation.

$$\delta B_{{\rm jet}_r}=B_{\rm ptb}\sin(z\pi/5r_{jet})\cos\phi$$
$$\delta B_{{\rm jet}_r}=B_{\rm ptb}\sin(z\pi/5r_{jet})\sin\phi$$
$$B_{ptb}=0.01\times B_{{\rm jet}_\phi}$$

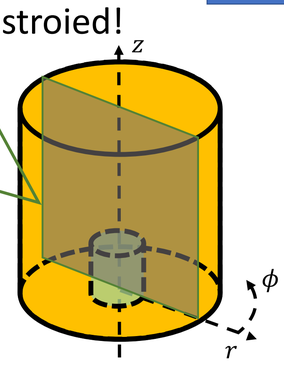
Result & Discussion

When $\beta=1, M=3$



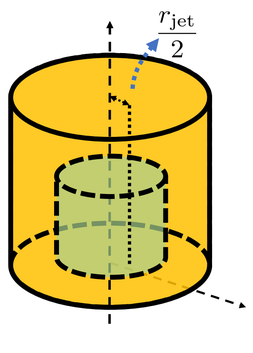
Density and v_z distribution (t=70ms)

Jet was destroied!



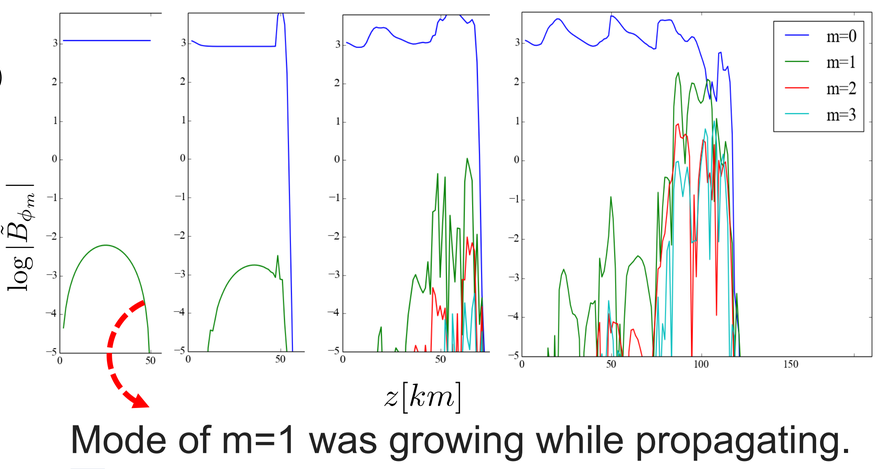
Fourier transform

$$B_\phi(r_{\rm jet}/2,\phi,z)=\sum_{\rm m=0}^{15}\tilde{B}_{\phi_{\rm m}}(z,t)\exp(im\phi)$$



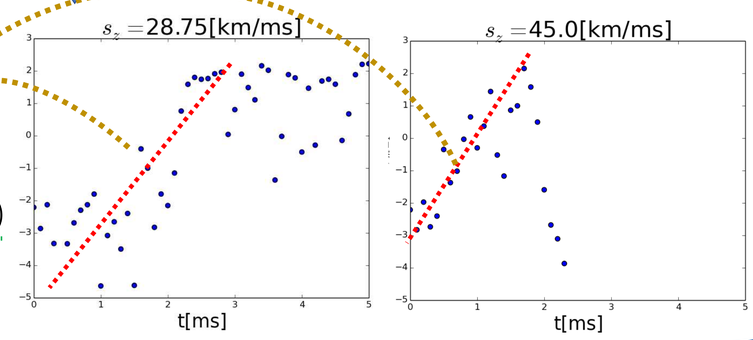
How was the absolute value of the Fourier coefficient in each mode?

$t=0[ms]$ $t=0.1[ms]$ $t=0.5[ms]$ $t=2[ms]$



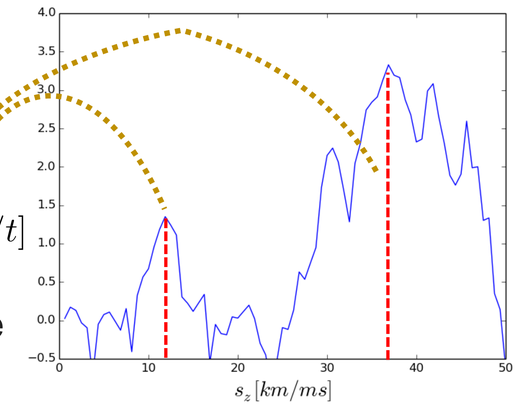
Mode of m=1 was growing while propagating.

Watch the time variation of $\tilde{B}_{\phi_{m=1}}$ with moving.



Incline = growth rate ≡ σ

$$\log\tilde{B}_{\phi_{m=1}}(t,s_zt)$$



Two peaks

County speed with the highest growth rate

Conclusion

- The growth of kink instability could be confirmed.
- There were two peaks where the growth rate increased, and the county speed at that time could be determined.

Future work

- Comparison the solution of linear analysis and this result
- Simulation with a rotating or vertical magnetic field

References [1]P. Mo¨sta et al., 2014, ApJ, 785, L29
[2]Matsumoto et al., ”Magnetohydrodynamic Simulation Code CANS+: Assessments and Applications”, arXiv:1611.01775