セッション４：磁気流体力学（MHD）
ー天体MHDシミュレーションの現状と今後ー

柴田一成
京大理花山天文台

天体MHD simulation 論文数の変遷

- Astrophysical Journal のみ対象
  Simulation および MHD Simulation
  という用語を Abstract/Keywords に含む論文の数

	simulation	MHD simulation	all papers
1982-86	273	23	6416
1987-91	438	57	7444
1992-96	1056	127	9939
1997-01	1451	232	11737

ちなみに K.Shibata の論文数は？

- １９８２－２００１　共著論文数

MHD simulation in ApJ 39

MHD simulation in other Journal 32

(世界の天体MHDシミュレーション論文の１割くらいを、私の周辺で生産)

観測の論文 31

理論・流体simulation・ほか 18

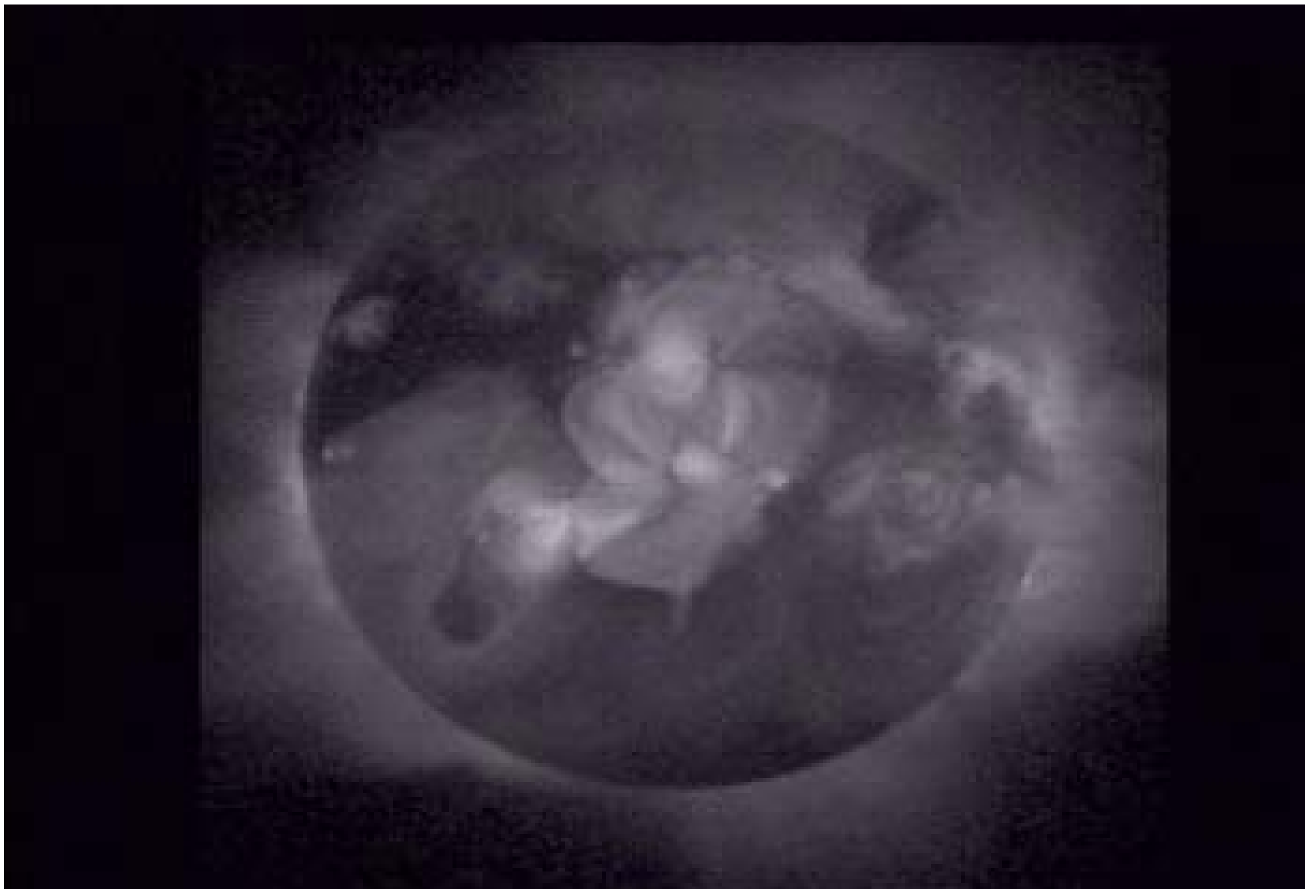
Contents　(Korea meeting 2001 + **α**)

- はじめに (基本問題、問題の位置づけ)
  - 対象となる天体・天体現象
  - 基本問題の例
- 基礎方程式系
  - 定式化
  - 近似
- 数値計算法
  - 基本アルゴリズム
  - 他手法との比較
  - 計算の難しさと工夫
- 最前線の天体シミュレーション
- 今後の課題

1. はじめに
(基本問題、問題の位置づけ)

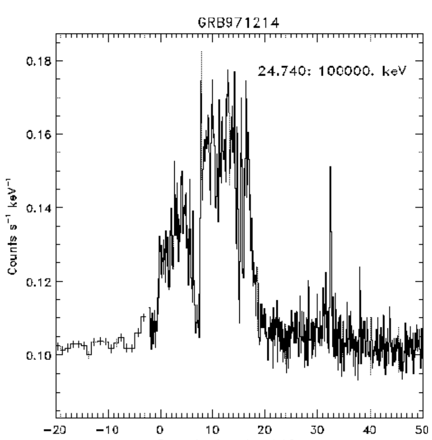
- 天体ＭＨＤ現象
  - 惑星磁気圏現象 (サブストームなど)
  - 太陽活動現象 (フレア、コロナ、太陽風、コロナ質量放出など)
  - 恒星活動現象 (フレア、コロナ、恒星風、、、)
  - 降着円盤、宇宙ジェット
    (ＡＧＮ、連星系、原始星)
  - 星形成
  - 星間物質
  - 銀河団プラズマ

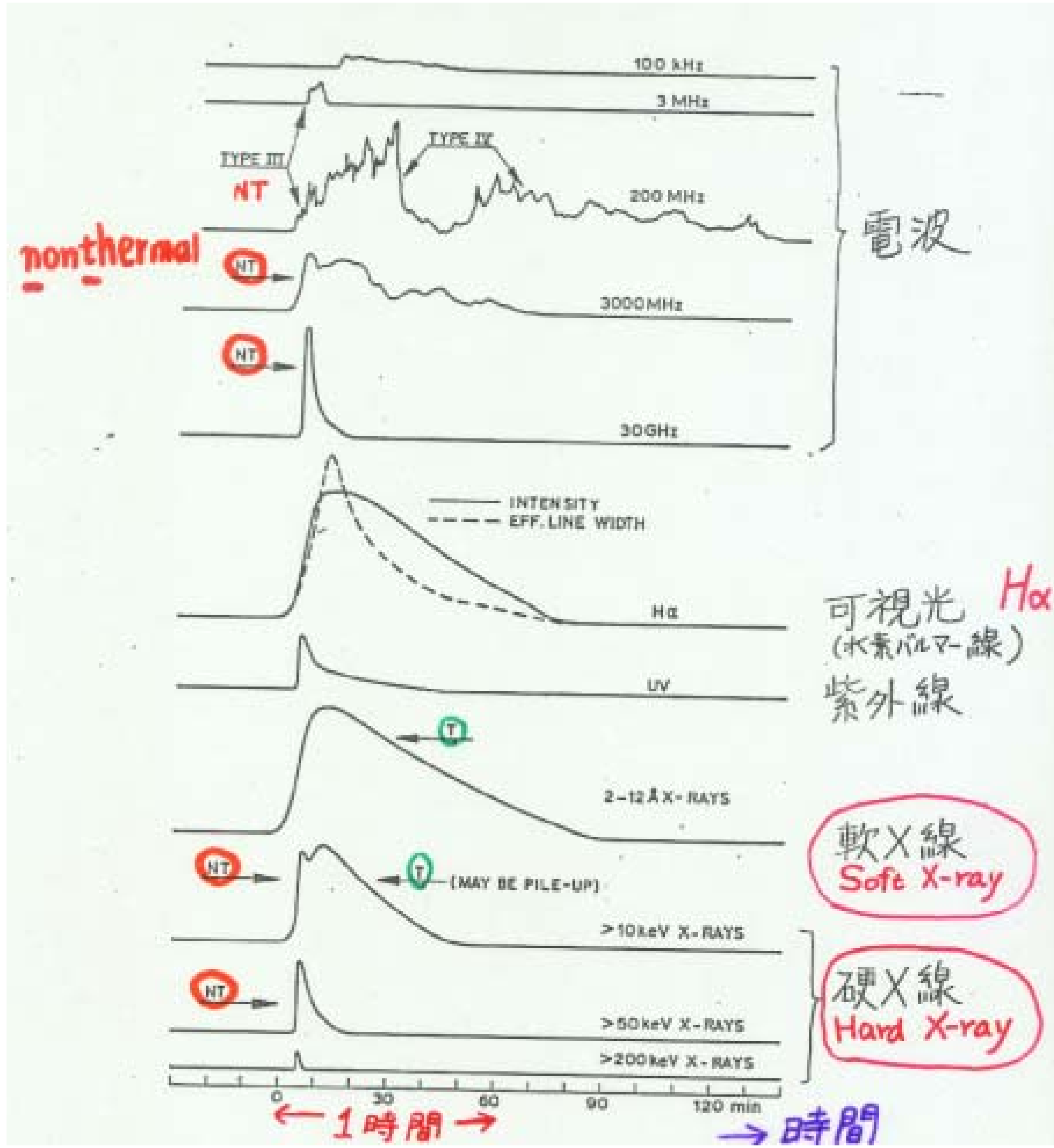
太陽コロナ・フレア・ジェット
(ようこう軟X線)



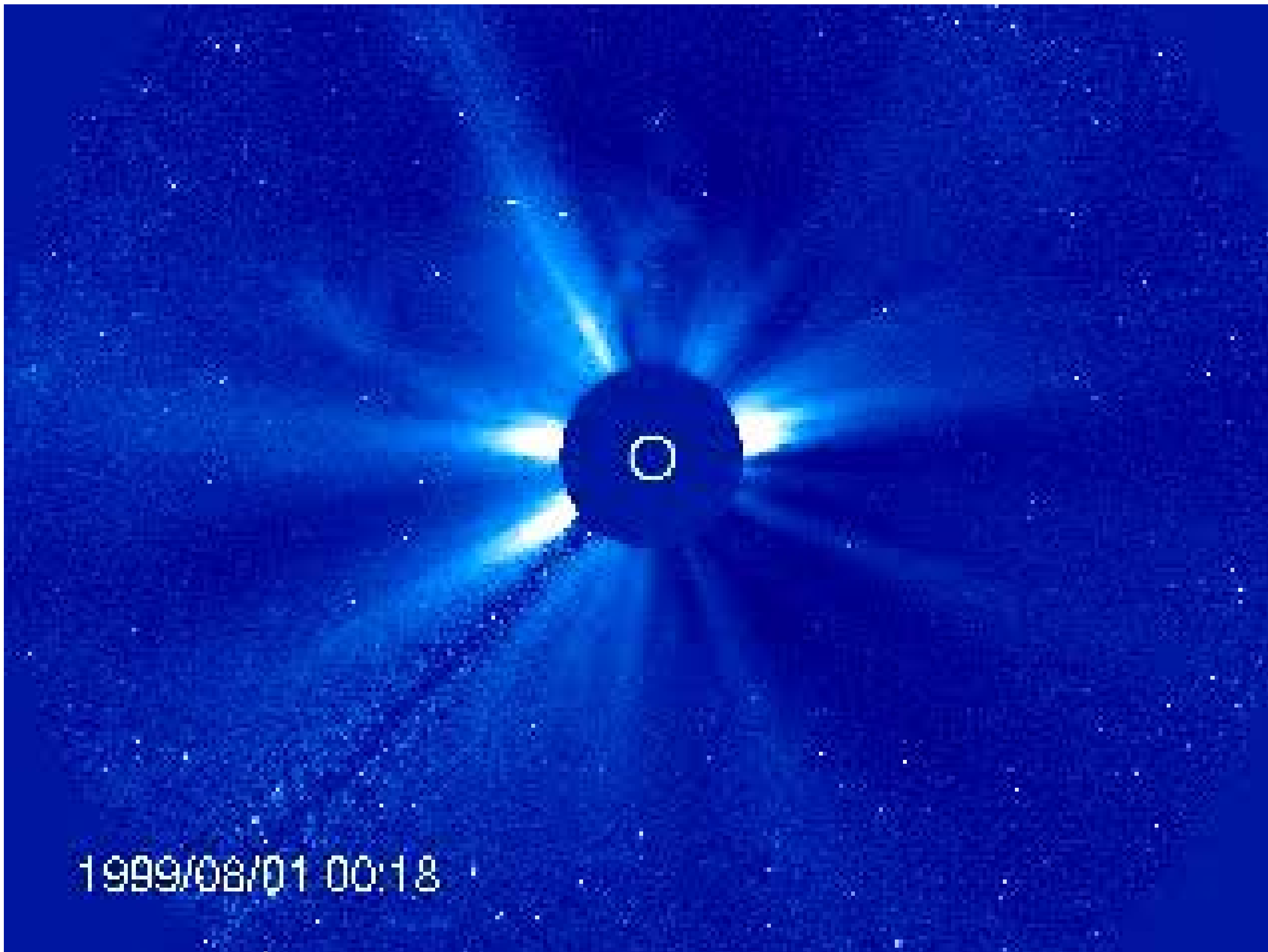
太陽フレアから放出される電磁波

Gamma ray burst

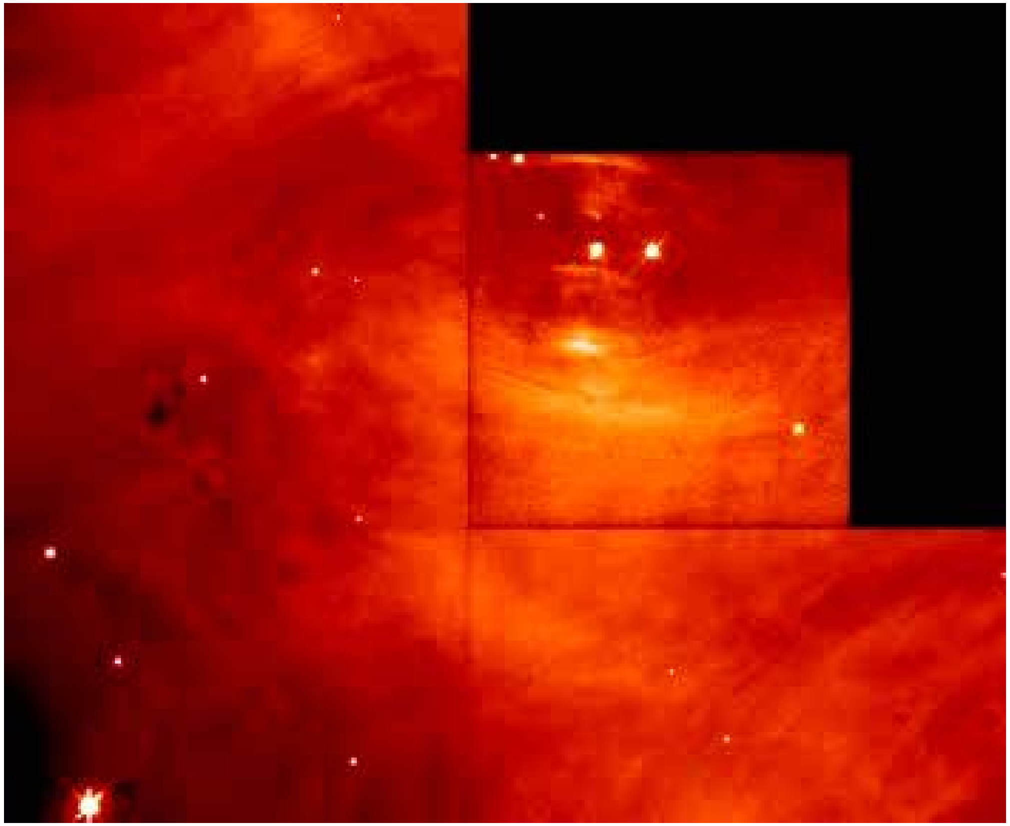




コロナ質量放出（CME）
（SOHO／LASCO，可視光／人工日食）

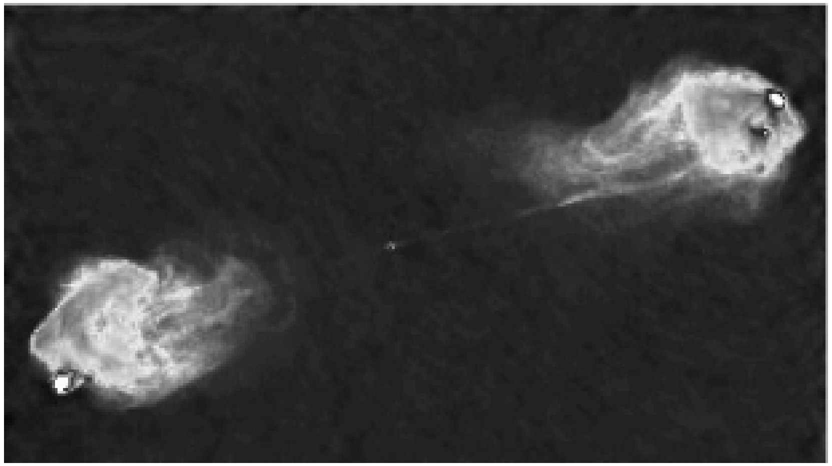


かに星雲中の波
(HST)



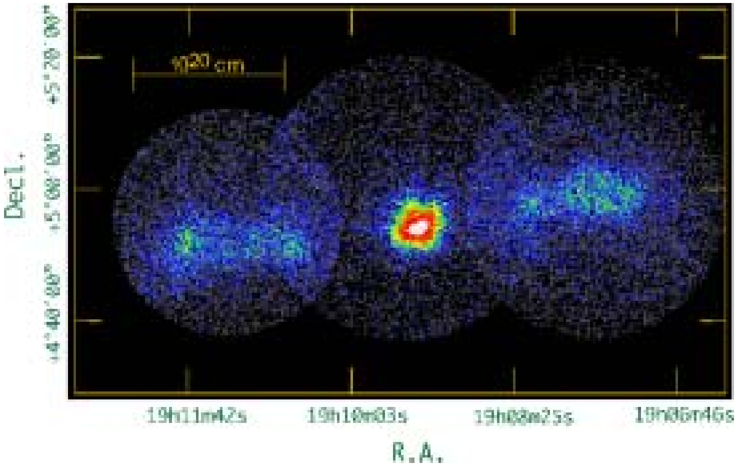
(Chandra)

astrophysical jets



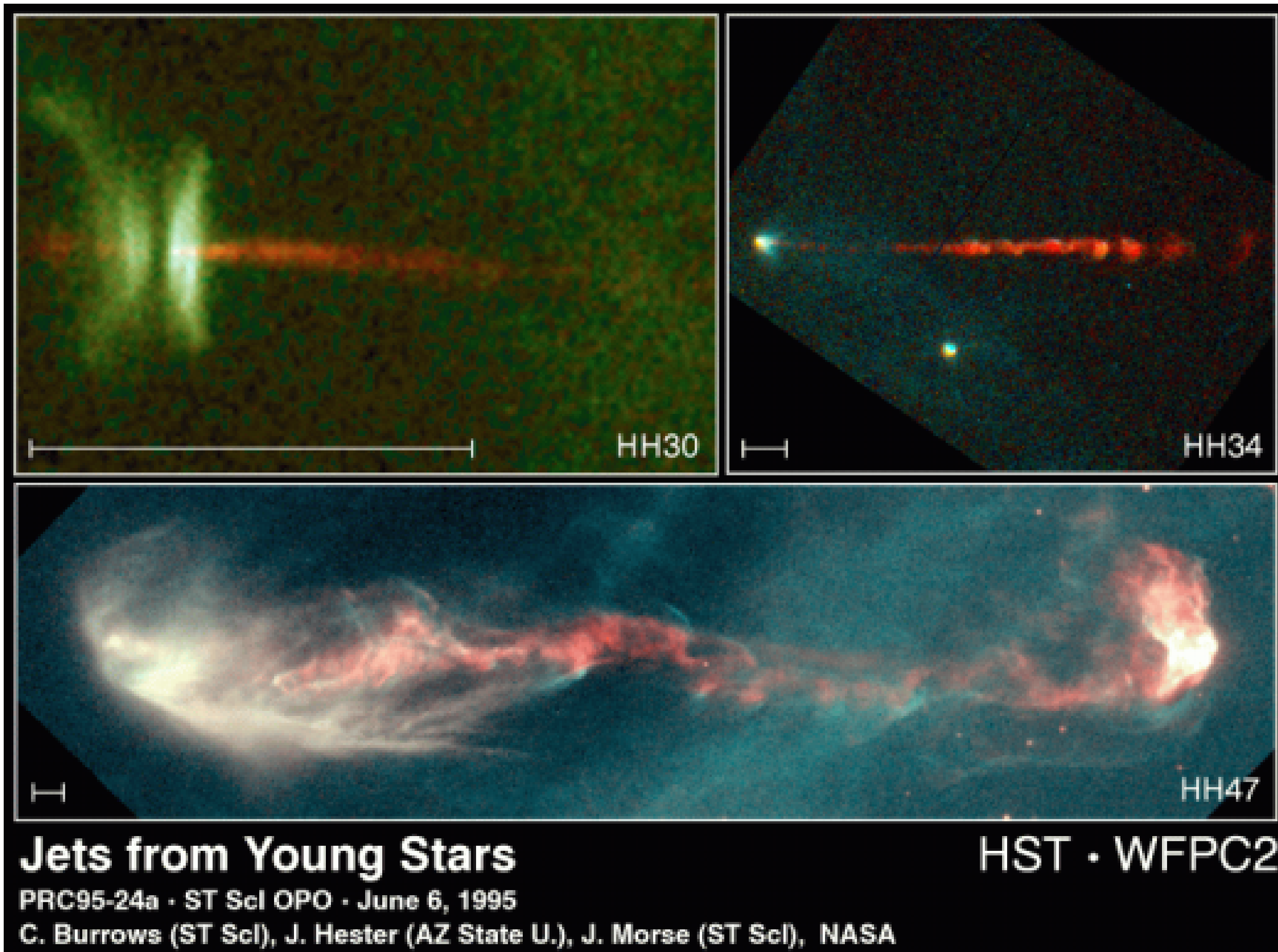
Protostellar jet (HH 1/2)

AGN jet (Cyg A)



Close binary system (SS433)

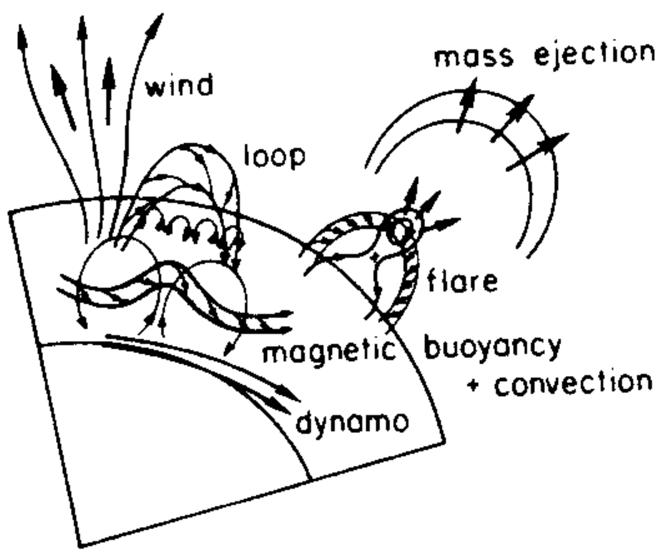
宇宙ジェットと降着円盤
(原始星ジェット)



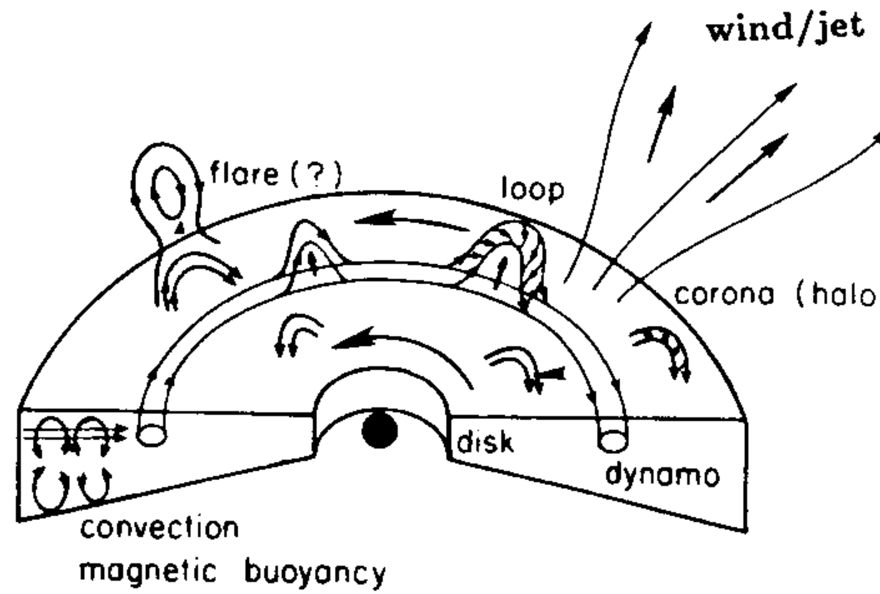
天体MHD現象共通の問題

- 磁場生成　　ダイナモ　（ＭＨＤ乱流）
- 構造形成ーループ、磁気圏、星間雲
  ＭＨＤ不安定性
- プラズマ加熱　　磁気リコネクション
  ＭＨＤ乱流／shock／non-MHD
  （非定常ーフレア、定常ーコロナ）
- プラズマ加速　　磁気遠心力／磁気圧、ガス圧、輻射圧
  （非定常ーコロナ質量放出／ジェット、
  定常ー天体風／ジェット）
- 非熱的粒子　　粒子加速 (non-MHD)

天体MHD基礎過程



(stars)



(disks)

天体MHD現象の共通点
(磁場を散逸させるのは、きわめて困難)

磁気拡散時間
(電流散逸時間)

$$t_D = L^2/\eta \approx 10^{14} L_9{}^2 T_6{}^{3/2} \ s$$

$$\eta = \eta_{Spitzer} \approx 10^4 T_6{}^{-3/2} \ cm^2/s$$

フレア発生時間

$$t_{flare} = 10^2 - 10^3 \sec$$

Alfven時間

$$t_A = L/V_A = 10 \sec$$

磁気レイノルズ数

$$R_m = t_D/t_A \approx 10^{13} >> 1$$

MHD近似

- 流体近似
  特徴的長さ＞＞平均自由行程、または
  イオンのラーモア半径
- ゆっくりした現象（変位電流無視＝非相対論）
  特徴的時間＞＞衝突時間、または
  イオンのラーモア周期
- 準中性
  粒子数密度＞＞Goldreich-Julian 密度
  (n = div (v x B)/e)

太陽コロナ·プラズマの特徴的長さ

- ラーモア半径

$$r_{Li} = \frac{m_i vc}{eB} \approx 10cm\left(\frac{B}{100G}\right)^{-1}\left(\frac{T}{10^6 K}\right)^{1/2}$$

- 平均自由行程

$$l_{mfp} = \frac{1}{n}\left(\frac{kT}{e^2}\right)^2 \approx 10^8 cm\left(\frac{T}{10^6 K}\right)^2\left(\frac{n}{10^9 cm^{-3}}\right)^{-1}$$

- フレアのサイズ $r_{flare} \approx 10^9 cm$

フレア・プラズマ（１０＾７K）における熱伝導の重要性

$$t_{cond} = \frac{3nkL^2}{\kappa_0 T^{5/2}} \approx 1.4 \left(\frac{n}{10^9 cm^{-3}}\right)\left(\frac{L}{10^9 cm}\right)^2 \left(\frac{T}{10^7 K}\right)^{-5/2} \text{ sec}$$

$$t_{rad} = \frac{3kT}{nQ(T)} \approx 4\times 10^4 \left(\frac{n}{10^9 cm^{-3}}\right)^{-1} \left(\frac{T}{10^7 K}\right)^{3/2} \text{ sec}$$

$$t_A = \frac{L}{V_A} \approx 10 \left(\frac{L}{10^9 cm}\right)\left(\frac{n}{10^9 cm^{-3}}\right)^{1/2} \left(\frac{B}{10G}\right)^{-1/2} \text{ sec}$$

- **フレア・プラズマ**（T〜10^7K)**では熱伝導の時間スケールは、**Alfven **時間より短い＝＞**implicit treatment **の必要性**

2. 基礎方程式
電磁流体(MHD)方程式

未知数8個:

密度(ρ)、

速度ベクトル(v)、

磁場ベクトル(B)

圧力(p)

方程式8個:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0,$$

$$\rho \frac{\partial v}{\partial t} + \rho (v \cdot \nabla) v + \nabla p = \frac{1}{c} J \times B + \rho g,$$

$$\frac{\partial B}{\partial t} - \nabla \times (v \times B) = -c \nabla \times (\eta J),$$

$$\rho \frac{De}{Dt} + p \nabla \cdot v = \eta |J|^2$$

where

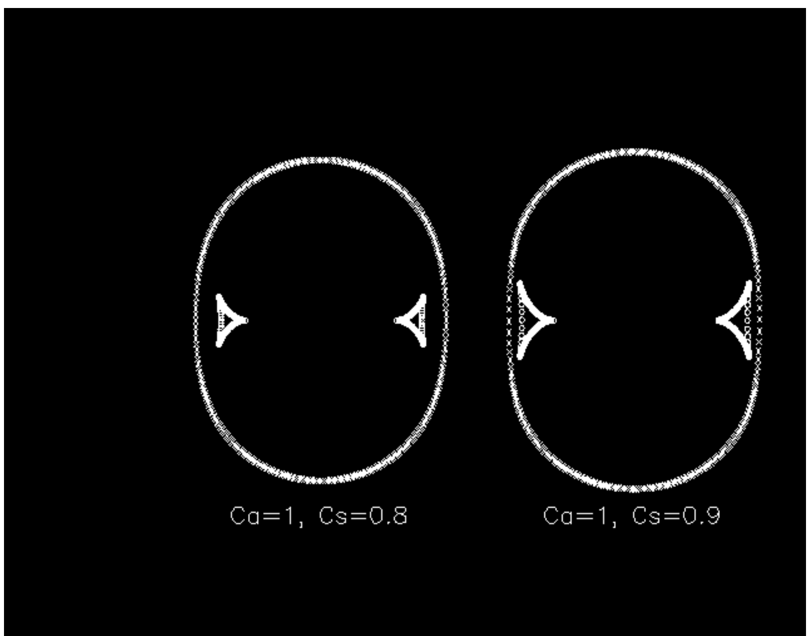
$$J = c \nabla \times B / 4\pi, \qquad e = p / [\rho (\gamma - 1)],$$

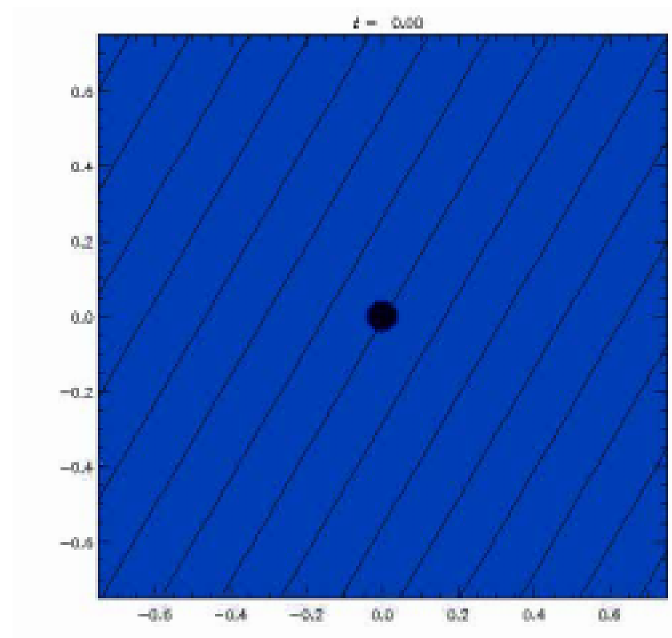
$$D/Dt = \partial / \partial t + (v \cdot \nabla) v$$

MHDの難しさの根源
＝電磁流体波(Alfven, fast, slow)

$$\omega^2 - k^2 {V_A}^2 \cos^2\theta = 0$$

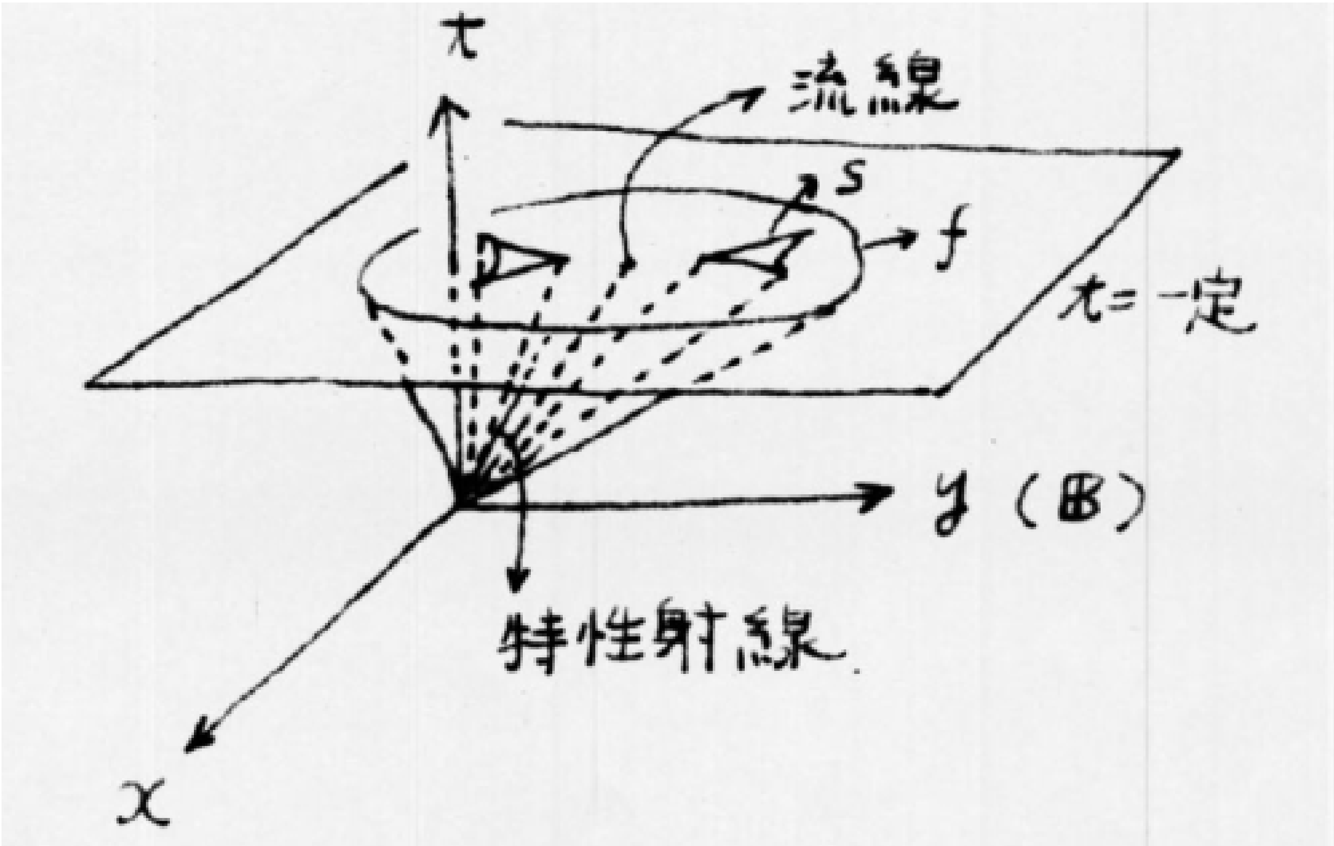
$$\omega^4 - ({C_s}^2 + {V_A}^2)k^2\omega^2 + 4{C_s}^2{V_A}^2k^4\cos^2\theta = 0$$





Group velocity diagram $v_g = \partial\omega / \partial k$

MHD wave 特性曲面



２次元： fast　＋－, slow　＋－, **流線＝５本の射影特性曲線**

２．５次元／３次元：

fast ＋－, Alfven ＋－, slow ＋－, **流線＝７本の射影特性曲線**

Difficulties in Numerical Astrophysical MHD

- Why difficult ?
- because there is gravity (self-gravity, external gravity)

1. Large dynamic range in density, gas pressure, and Alfven speed
2. Wave amplification through vertical propagation
3. Various instabilities driven by gravitational energy

– Boundary condition is most difficult

1. Large dynamic range in density, gas pressure, and Alfven speed

- For example, in the solar atmosphere, the density decreases from the photosphere to the corona by more than 7 ~ 9 orders of magnitude. Alfven speed

$$V_A = B / \sqrt{4\pi\rho}$$

increases rapidly with height.

- Hence we need small grid size (and thus many grid points in vertical directions) and short time step due to CFL condition

$$\Delta t < \Delta z / (V_A{}^2 + C_s{}^2 + V^2)^{1/2}$$

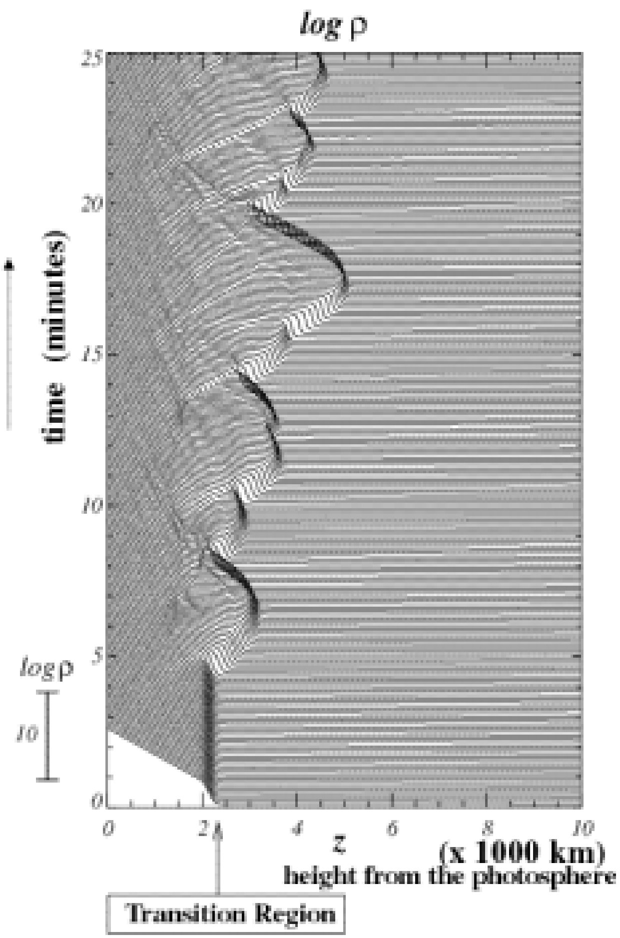
2. Wave amplification through vertical propagation

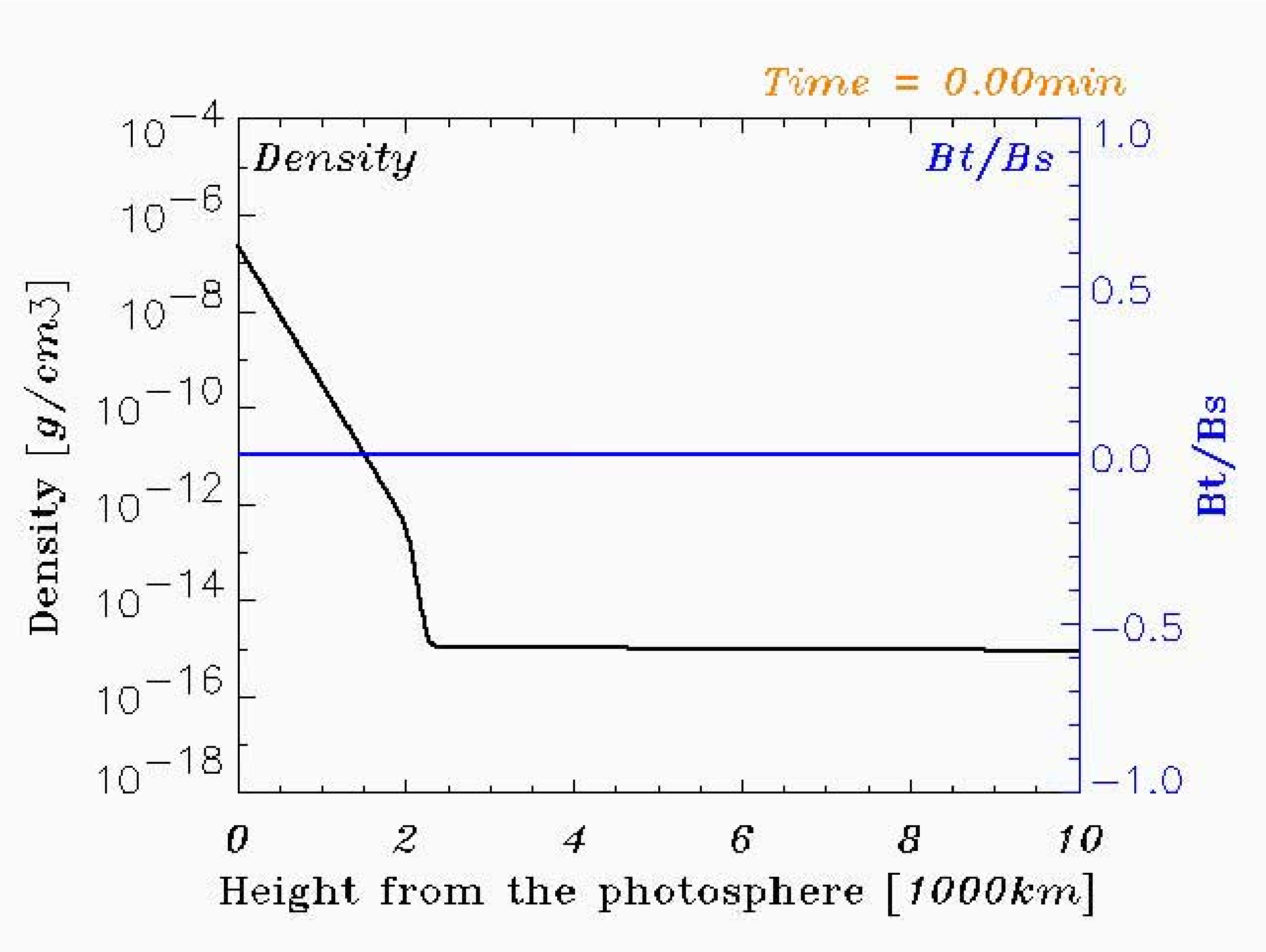
- The amplitude of MHD wave rapidly increases with height when it propagates upward. For example, the amplitude of slow mode MHD wave propagating along vertical flux tube increases as

$$V_{\parallel} \propto \rho^{-1/2} A^{-1/2}$$

- Hence even small amplitude wave at the bottom quickly become large amplitude wave to form shock and influence upper layers significantly.

Alfven wave model of spicules:
numerical simulation (Kudoh-Shibata 1999)



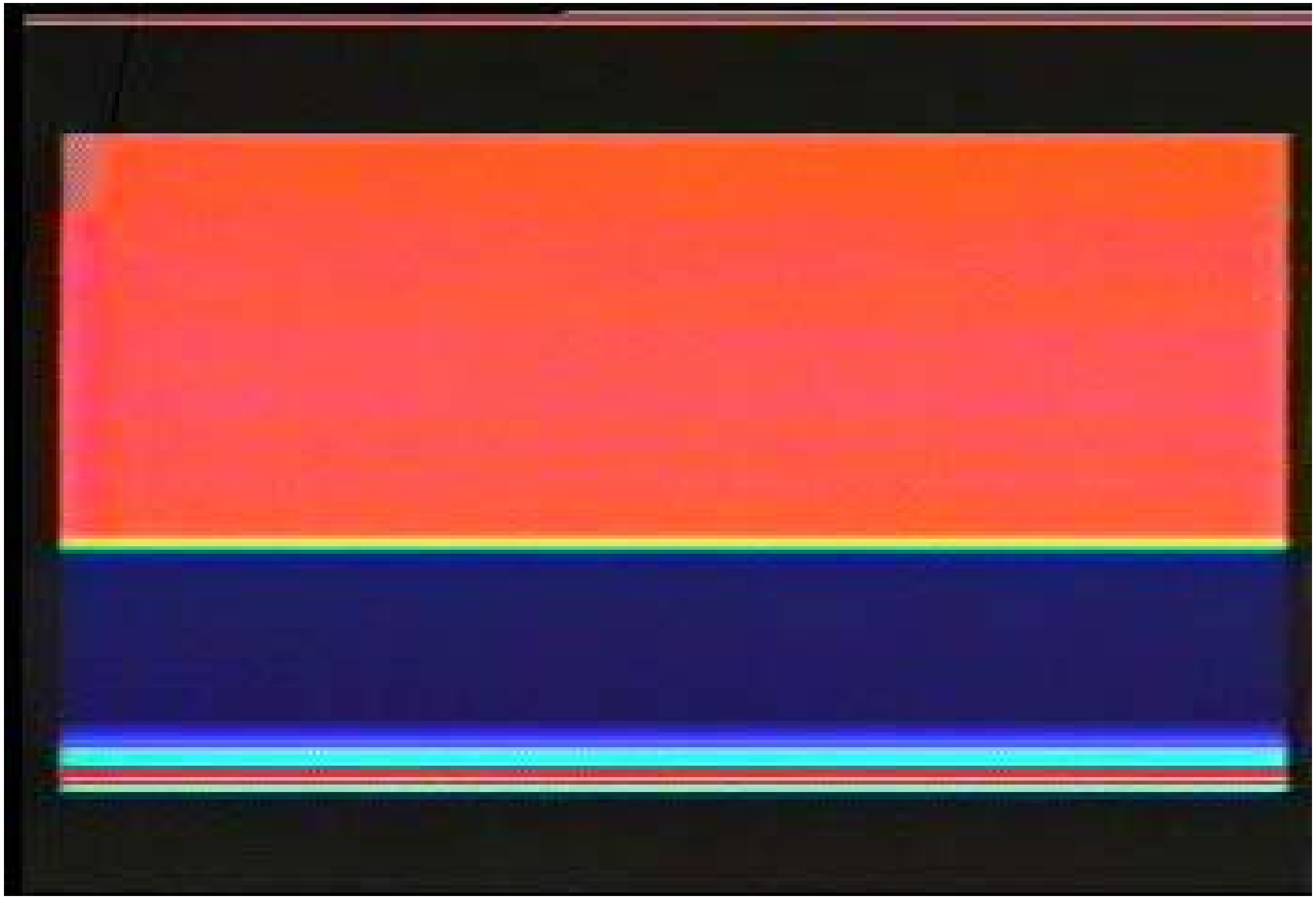


3. Various instabilities driven by gravitational energy

- Various instabilities occur in a gravitationally stratified gas layer, e.g.,
  - convective instability, Rayleigh-Taylor instability, Magnetic buoyancy instability, Parker instability, etc
- These instabilities generate MHD waves and electric currents, which are the source of energy to heat the corona and flares.

Solar emerging flux due to Parker instability

(Shibata et al. 1989, 1990)



3. Numerical method

- Main Newtonian MHD codes in our group
  - modified Lax-Wendroff code
    (originally developed in 1978 by myself, and refined and extended by Dr. Matsumoto, Dr. Yokoyama)
    simple, fast, applicable to many MHD problems, but often unstable and suffers from various numerical errors
  - CIP-MOCCT code
    (developed in 1995 by Dr. Kudoh)

- Note: Higher order Godunov scheme is becoming popular even in MHD code (Balsara,Ryu,Hanawa,Sano&Inutsuka,,,,)

CIP scheme

- A universal solver for hyperbolic equations by CIP(Cubic Interpolated Pseudoparticle/Propagation)
- Developed by
  Prof. T. Yabe (Tokyo Institute of Technology)
  - Yabe and Aoki (1991) Computer Physics Communications, 66, 219-232
- Good at handling contact discontinuity
- Can treat all kind of matter (gas, fluid, solid) simultaneously
- Can also be applied to Vlasov equation

See Ogata's poster

Basic concept of CIP scheme

- We want to solve advection equation

$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x} = 0$$

- Exact solution is f(x,t)=f(x-ut,0) if u=constant.

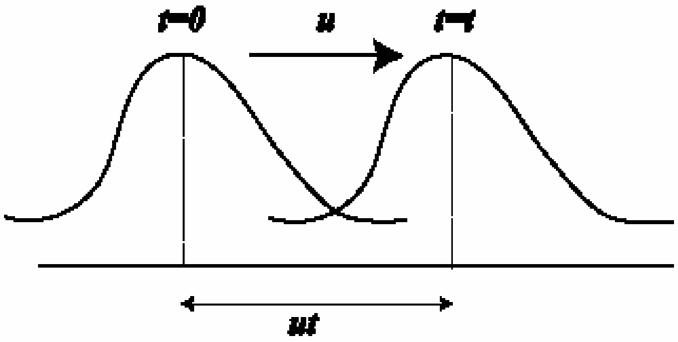


図 1: 速度一定の時の波動方程式の時刻 t での解．単に，$t=0$ の形を ut だけ移動したもの．

Cubic interpolation

- CIP method uses cubic interpolation to determine the profile between i-1 and i

$$F_i(x) = a_i(x - x_i)^3 + b_i(x - x_i)^2 + f_i^{n\prime}(x - x_i) + f_i^n$$

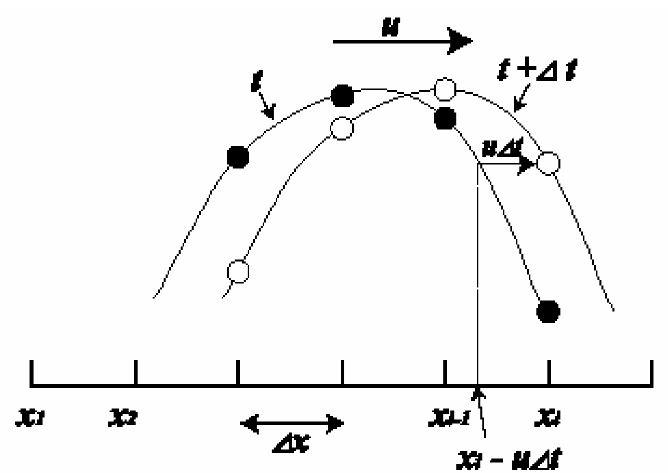


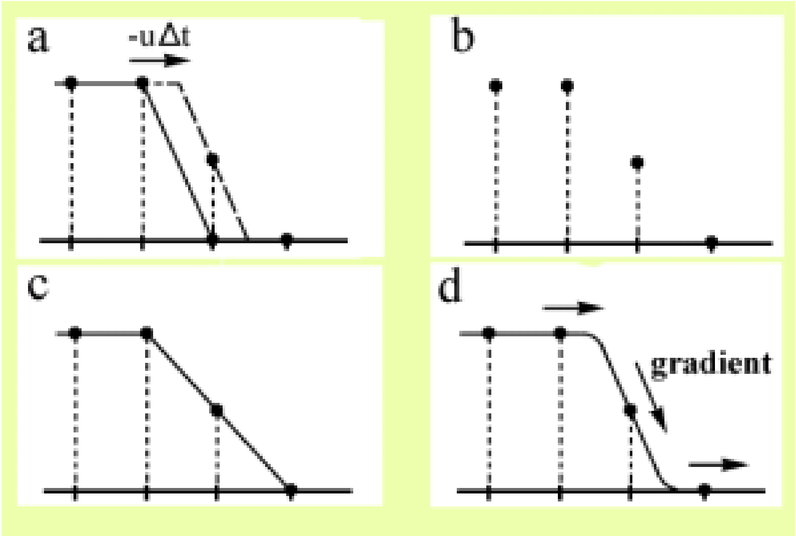
図 2: 離散的に与えられた f. 時間 Δt の間に, $f(x)$ は, 形を $u\Delta t$ だけ移動する.

Advection of gradient

- CIP scheme utilize advection of gradient

$$\frac{\partial f'}{\partial t} + u\frac{\partial f'}{\partial x} = 0$$

to determine a_i and b_i



CIP 法では，x_{i-1} と x_i の 2 点の値を 3 次関数で補間する．x_{i-1} と x_i の区間の関数を $F_i(x)$ とすると，

$$F_i(x) = a_i(x - x_i)^3 + b_i(x - x_i)^2 + \acute{f}_i^n(x - x_i) + f_i^n \tag{11}$$

ここで，$\acute{f}$ は f の x 微分である．今，関数 F_i が隣の区間（x_{i-2} と x_{i-1} の間の区間）の関数 F_{i-1} と x_{i-1} において滑らかにつながっていることを要請する．すなわち，関数と一階微分が連続であることを要請すると

$$F_i(x_{i-1}) = F_{i-1}(x_{i-1}) \tag{12}$$

$$\frac{dF_i(x_{i-1})}{dx} = \frac{dF_{i-1}(x_{i-1})}{dx} \tag{13}$$

となる．この 2 式より，

$$a_i = \frac{\acute{f}_i^n + \acute{f}_{i-1}^n}{\Delta x^2} - \frac{2(f_i^n - f_{i-1}^n)}{\Delta x^3} \tag{14}$$

$$b_i = \frac{3(f_{i-1}^n - f_i^n)}{\Delta x^2} + \frac{2\acute{f}_i^n + \acute{f}_{i-1}^n}{\Delta x} \tag{15}$$

CIP 法では f'^n も f^n と同様に時間発展の解として求めることにする．波動方程式 (7) を u が一定として空間で微分すると，

$$\frac{\partial f'}{\partial t} + u\frac{\partial f'}{\partial x} = 0 \tag{16}$$

となり，f' は f と同じ波動方程式に従う．よって，f' にも式 (10) を適用することができる．したがって，時刻 Δt だけ進んだ値 f^{n+1} と f'^{n+1} は

$$f_i^{n+1} = F(x_i - u\Delta t) = a_i\xi^3 + b_i\xi^2 + f_i'^n\xi + f_i^n \tag{17}$$

$$f_i'^{n+1} = \frac{dF(x_i - u\Delta t)}{dx} = 3a_i\xi^2 + 2b_i\xi + f_i'^n \quad . \tag{18}$$

のように求めることができる．ここで，

$$\xi = -u\Delta t \tag{19}$$

である．初期条件として，f_i^0 と $f_i'^0$ を与えれば，式 (17) と (18) を用いて f_i の離散的な時間発展を求めることが出来る．

図3

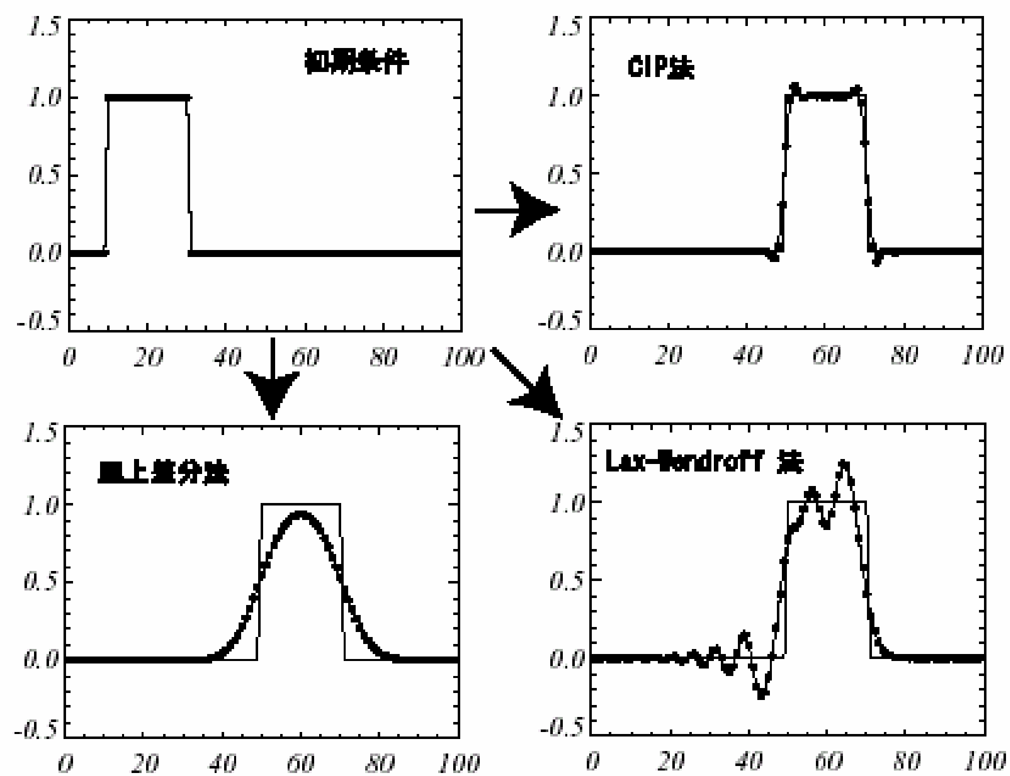


図 3: 矩形波の伝播．$u = 1$，$\Delta x = 1$，$\Delta t = 0.2$ で 200 ステップ計算した結果である．実線が厳密解．黒丸と点線が計算結果．

図4

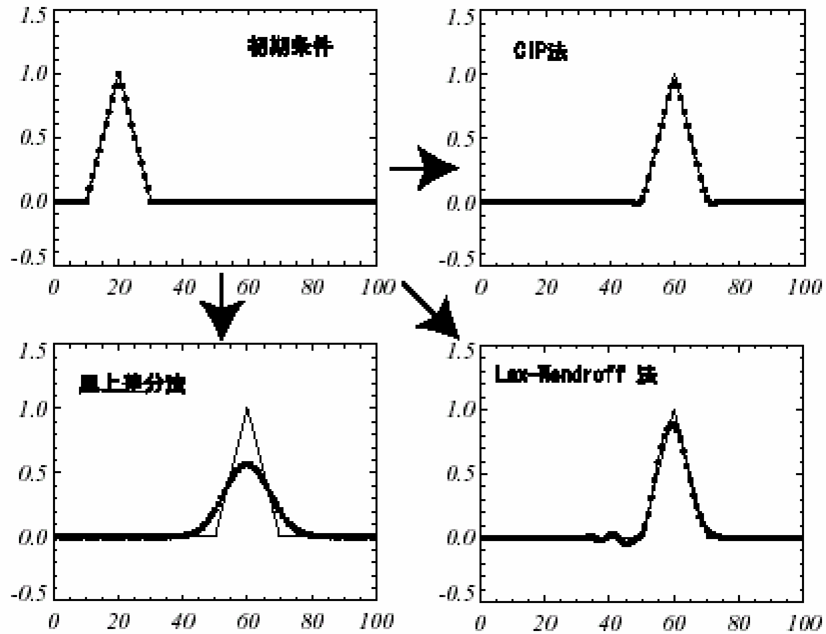
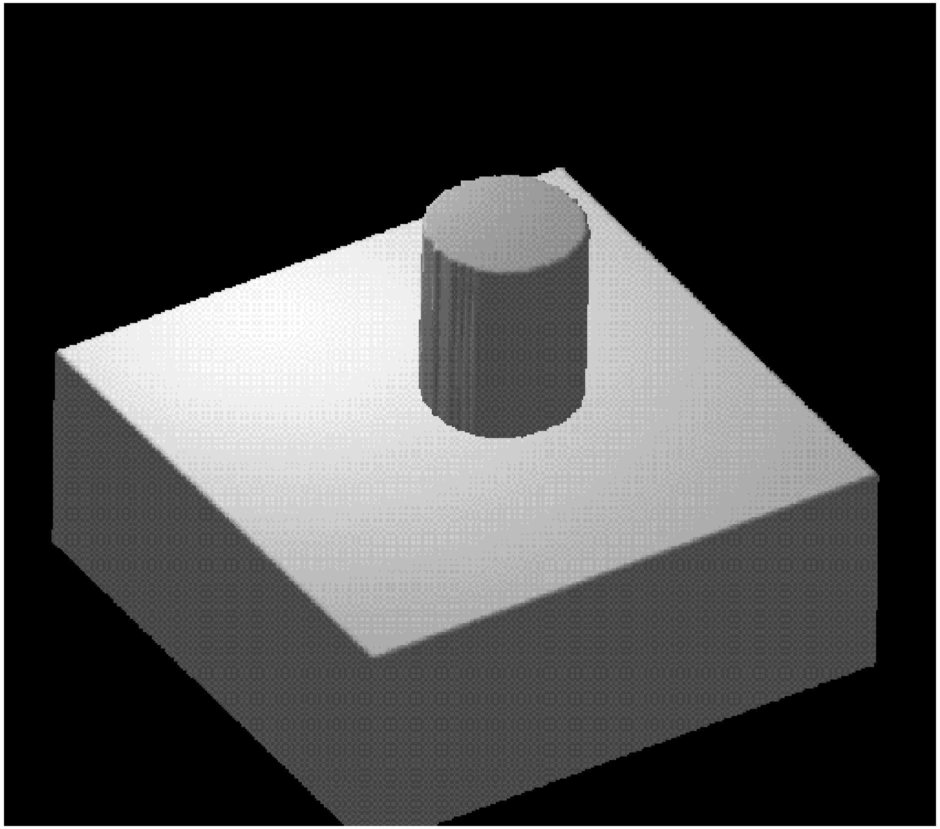


図 4: 三角波の伝播．$u = 1$，$\Delta x = 1$，$\Delta t = 0.2$ で 200 ステップ計算した結果である．実線が厳密解．黒丸と点線が計算結果．

Example 1

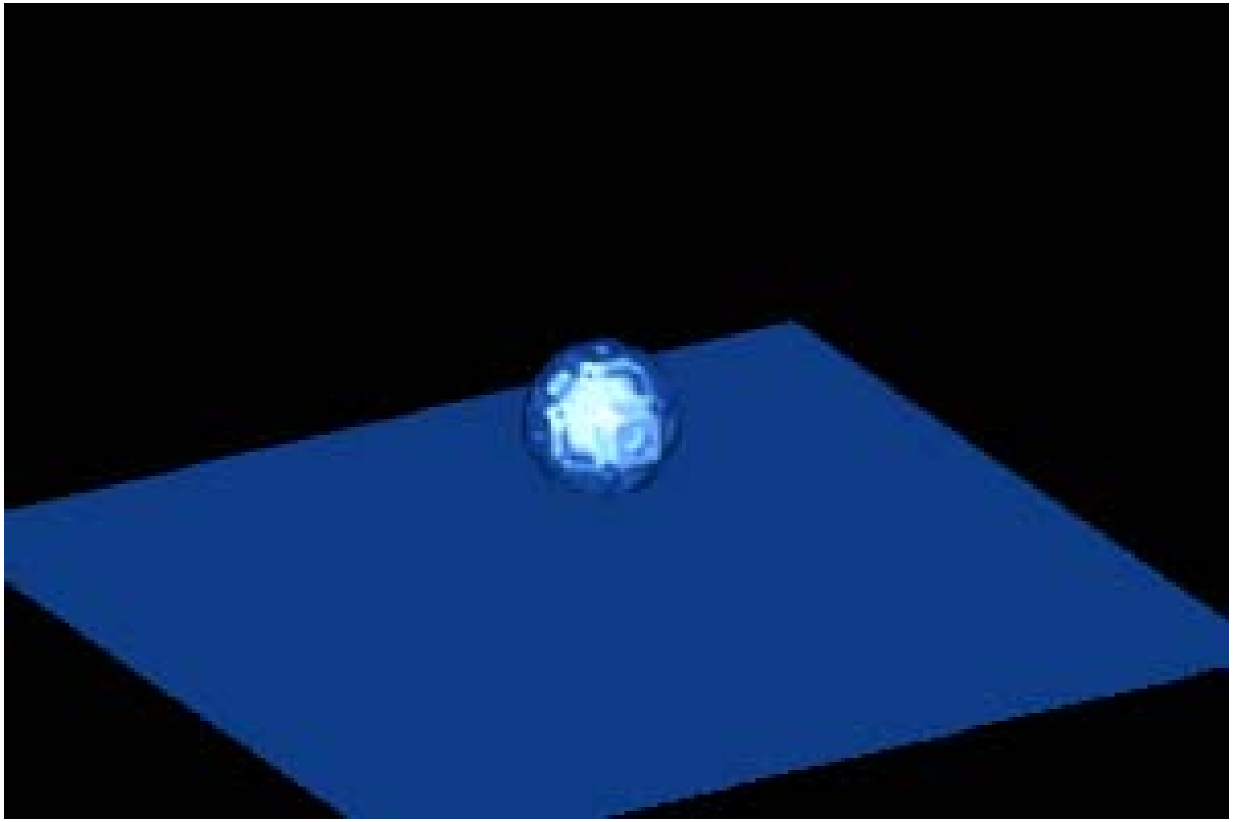
Simulation of a log slamming on the water surface. Moving body is captured with fixed grid system (by Xiao)

150 x 150 x 150



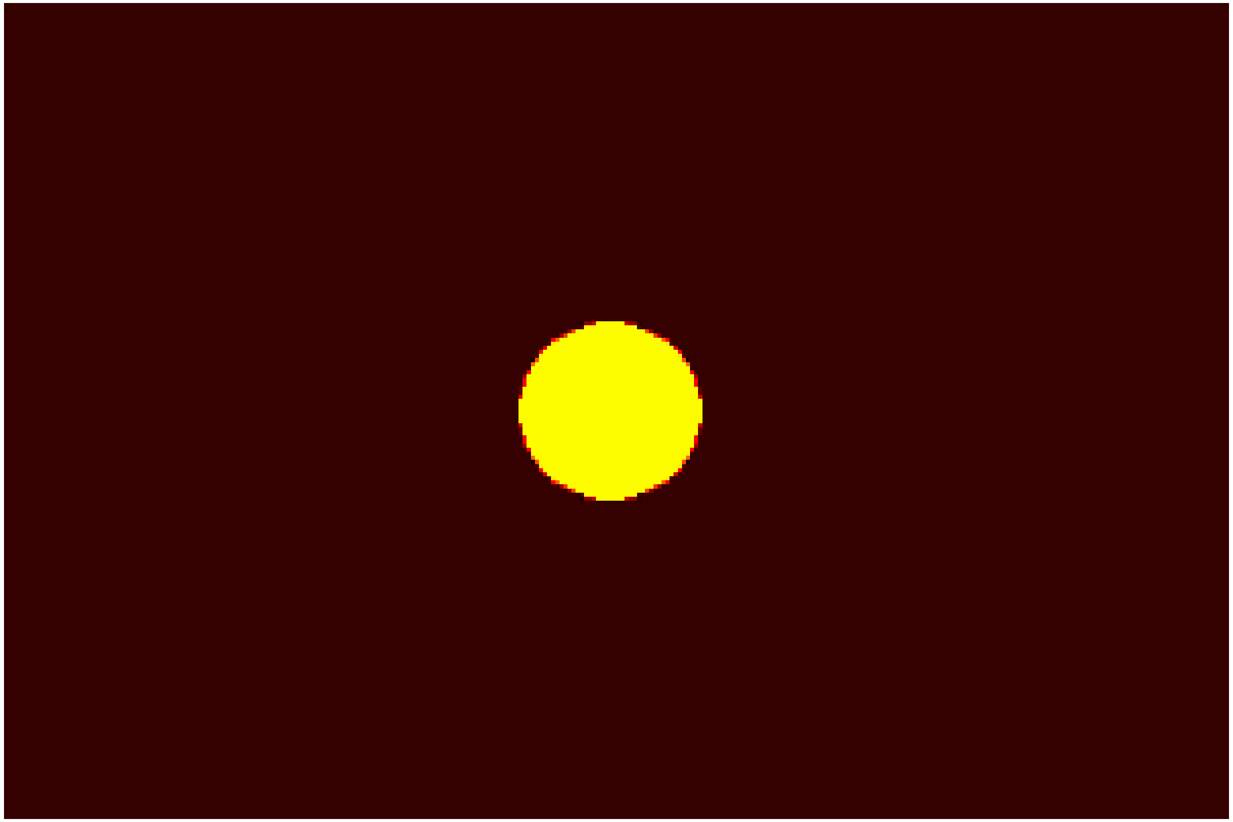
Example 2

(simulation of milk crown on 100 x 100 x 35 grids: Yabe et al.)



Example 3

Comet Shoemaker-Levy 9 on entry into Jovian atmosphere (Yabe et al. 1994)



CIP-MOCCT scheme

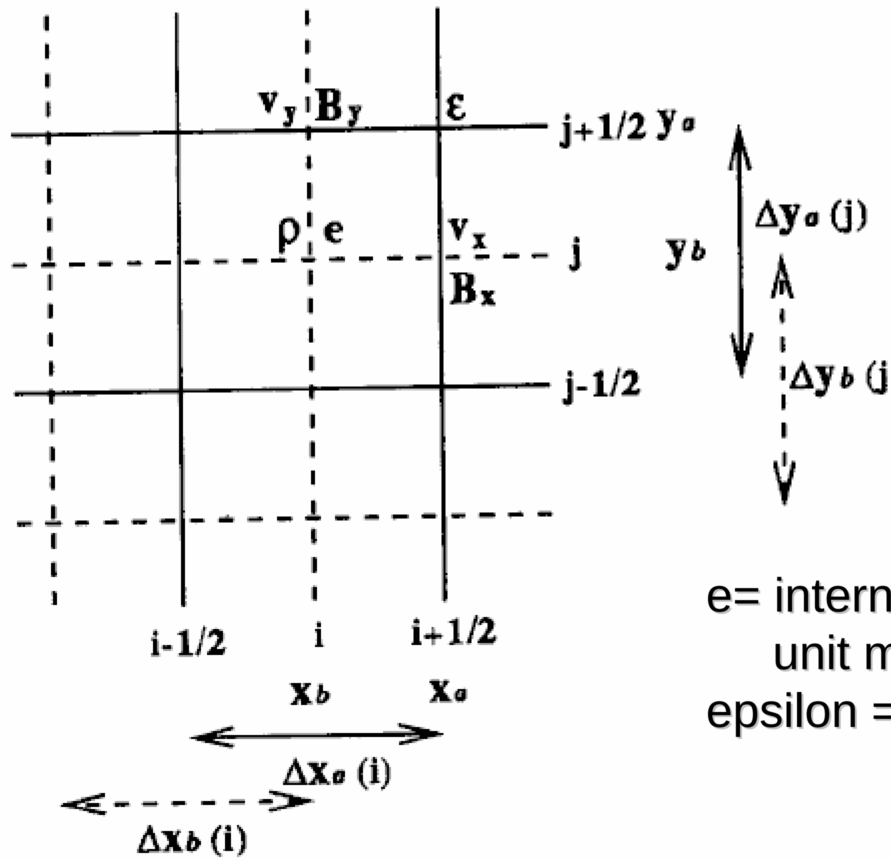
- Developed by Kudoh, Matsumoto, Shibata (1999) Computational Fluid Dynamics Journal 8, 56-68
- For astrophysical MHD problems
- Fluid part => CIP scheme
- Magnetic field part => MOCCT scheme
  (Stone and Norman 1992,
  Evans and Hawley 1988)

MOCCT scheme

- CT (Constrained-Transport) scheme (Evans-Hawley 1988)
  - satisfy divergence free condition (div B =0)
- MOC (Method of Characteristics) scheme (Stone-Norman 1992)
  - stable for Alfven wave

MOC−CT： (1) CTスキーム

(Evans & Hawley 1988)



e= internal energy per unit mass

epsilon = electric field

Fig.11: Centering of variables. The density and internal energy density are zone centered, while x- and y- components of velocity and magnetic field are face centered.

CT スキーム : div B=0 を満たすように induction eq. を解く

$$\frac{\partial B_x}{\partial t} = -\frac{\partial \epsilon}{\partial y}, \quad \text{and} \quad \frac{\partial B_y}{\partial t} = \frac{\partial \epsilon}{\partial x},$$

respectively. The components of magnetic field are directly advanced by the the finite difference;

$$\frac{1}{\Delta t}[B^{n+1}_{x(i+1/2,j)} - B^{n}_{x(i+1/2,j)}] = -\frac{1}{\Delta y_{a(j)}}[\epsilon_{(i+1/2,j+1/2)} - \epsilon_{(i+1/2,j-1/2)}], \quad (27)$$

$$\frac{1}{\Delta t}[B^{n+1}_{x(i-1/2,j)} - B^{n}_{x(i-1/2,j)}] = -\frac{1}{\Delta y_{a(j)}}[\epsilon_{(i-1/2,j+1/2)} - \epsilon_{(i-1/2,j-1/2)}], \quad (28)$$

$$\frac{1}{\Delta t}[B^{n+1}_{y(i,j+1/2)} - B^{n}_{y(i,j+1/2)}] = \frac{1}{\Delta x_{a(i)}}[\epsilon_{(i+1/2,j+1/2)} - \epsilon_{(i-1/2,j+1/2)}], \quad (29)$$

$$\frac{1}{\Delta t}[B^{n+1}_{y(i,j-1/2)} - B^{n}_{y(i,j-1/2)}] = \frac{1}{\Delta x_{a(i)}}[\epsilon_{(i+1/2,j-1/2)} - \epsilon_{(i-1/2,j-1/2)}]. \quad (30)$$

Equation $[(27)\ \times\Delta y_{a(j)} - (28)\ \times\Delta y_{a(j)} + (29)\ \times\Delta x_{a(i)} - (30)\ \times\Delta x_{a(i)}]\ \times\Delta t$ shows

$$
\begin{aligned}
&[B^{n+1}_{x(i+1/2,j)} - B^{n}_{x(i+1/2,j)} - B^{n+1}_{x(i-1/2,j)} \\
&\quad + B^{n}_{x(i-1/2,j)}]\Delta y_{a(j)} + [B^{n+1}_{y(i,j+1/2)} - B^{n}_{y(i,j+1/2)} \\
&\quad - B^{n+1}_{y(i,j-1/2)} - B^{n}_{y(i,j-1/2)}]\Delta x_{a(i)} = 0. \qquad (31)
\end{aligned}
$$

Therefore,

$$
\frac{B^{n+1}_{x(i+1/2,j)} - B^{n+1}_{x(i-1/2,j)}}{\Delta x_{a(i)}} + \frac{B^{n+1}_{y(i,j+1/2)} - B^{n+1}_{y(i,j-1/2)}}{\Delta y_{a(i)}}
$$

$$
= \frac{B^{n}_{x(i+1/2,j)} - B^{n}_{x(i-1/2,j)}}{\Delta x_{a(i)}} + \frac{B^{n}_{y(i,j+1/2)} - B^{n}_{y(i,j-1/2)}}{\Delta y_{a(j)}}. \qquad (32)
$$

(2)　MOC スキーム

(Stone & Norman 1992)：

Alfven wave を精度良く解く

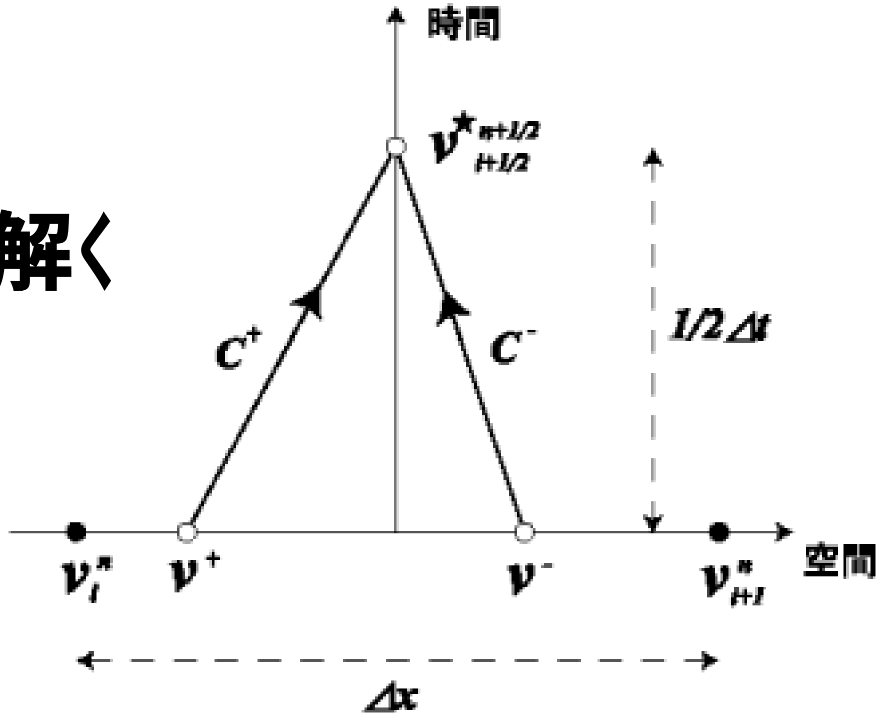


図 2: 1 次元時空のダイアグラム.

$$\varepsilon = -(v_x^* B_y^* - v_y^* B_x^*)$$

$$(v_y^* - v_y^+) - \frac{1}{\sqrt{4\pi\rho^+}}(B_y^* - B_y^+) = 0, \qquad (38)$$

$$(v_y^* - v_y^-) + \frac{1}{\sqrt{4\pi\rho^-}}(B_y^* - B_y^-) = 0, \qquad (39)$$

CIP-MOCCT scheme

(Kudoh, Matsumoto, Shibata, 1999, CFDJ 8, 56)

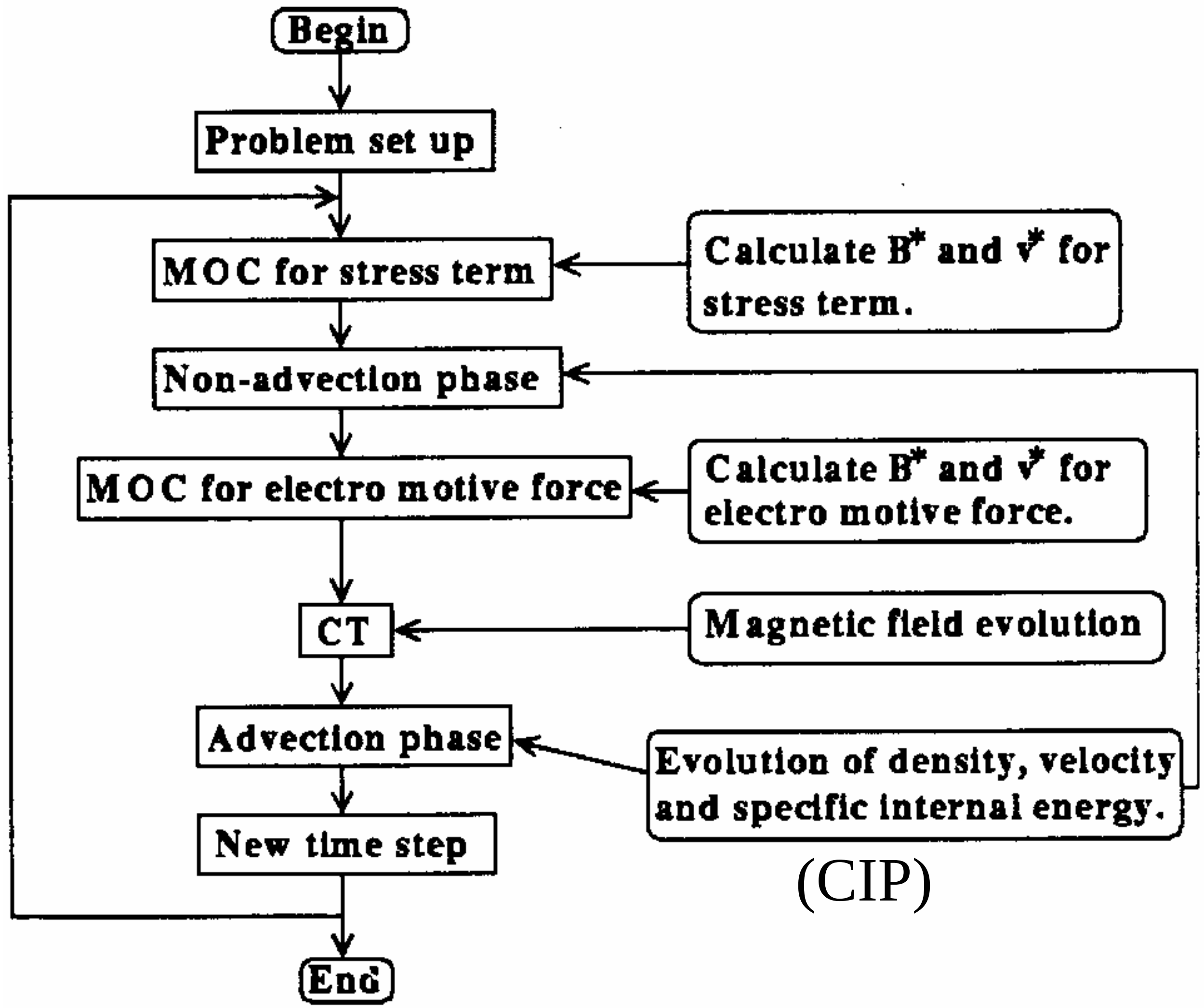
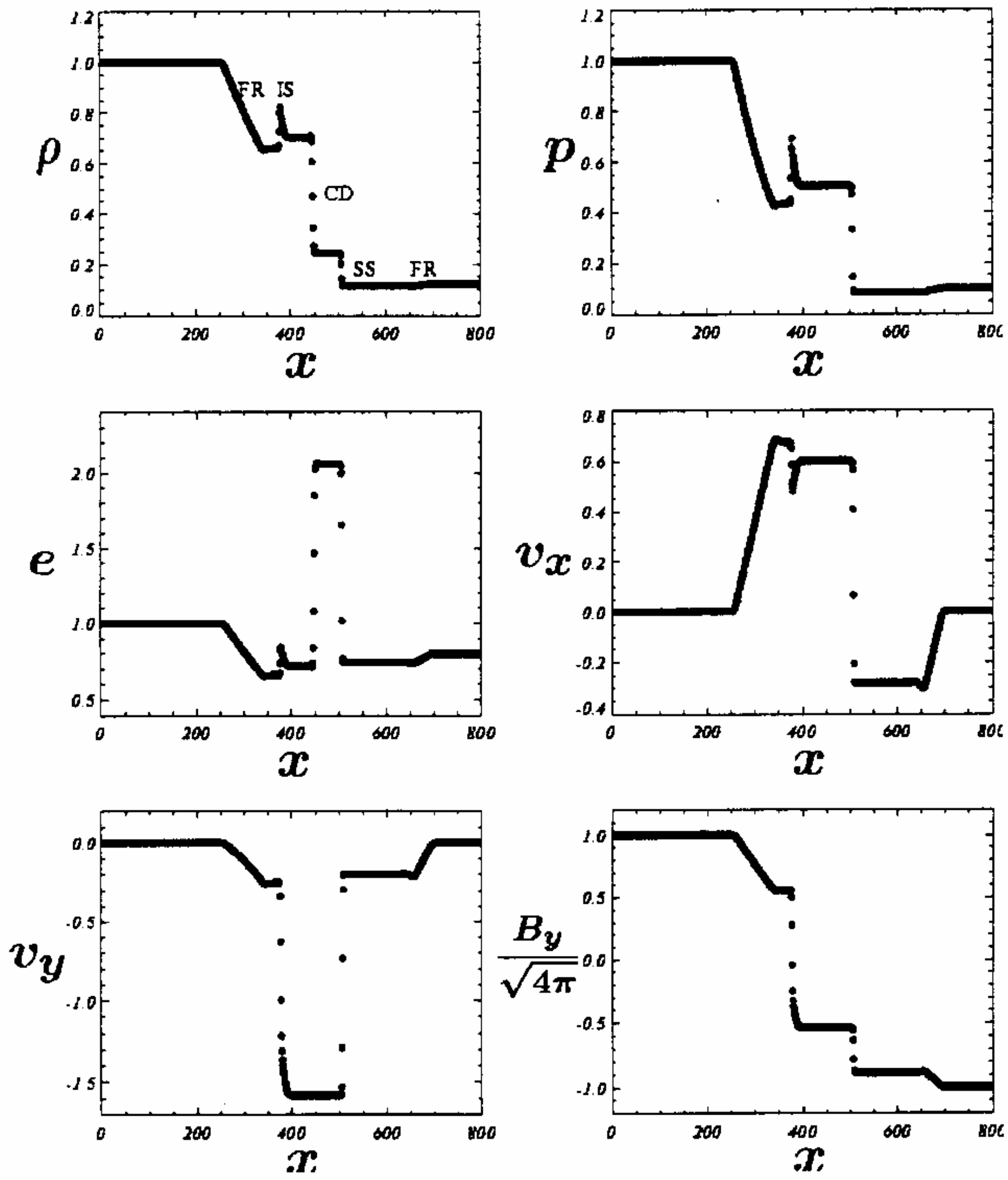
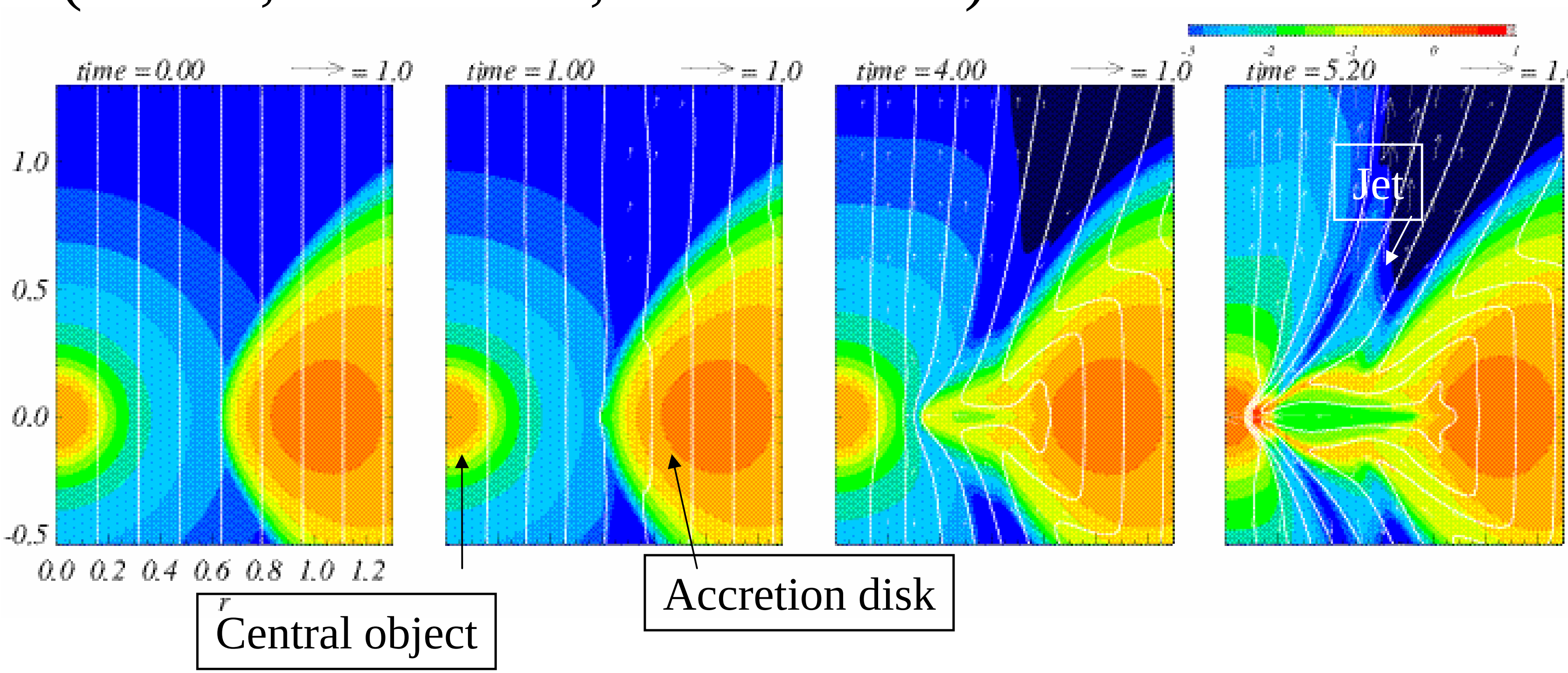


Fig.1: Schematic chart of our scheme

MHD shock tube (Brio and Wu)

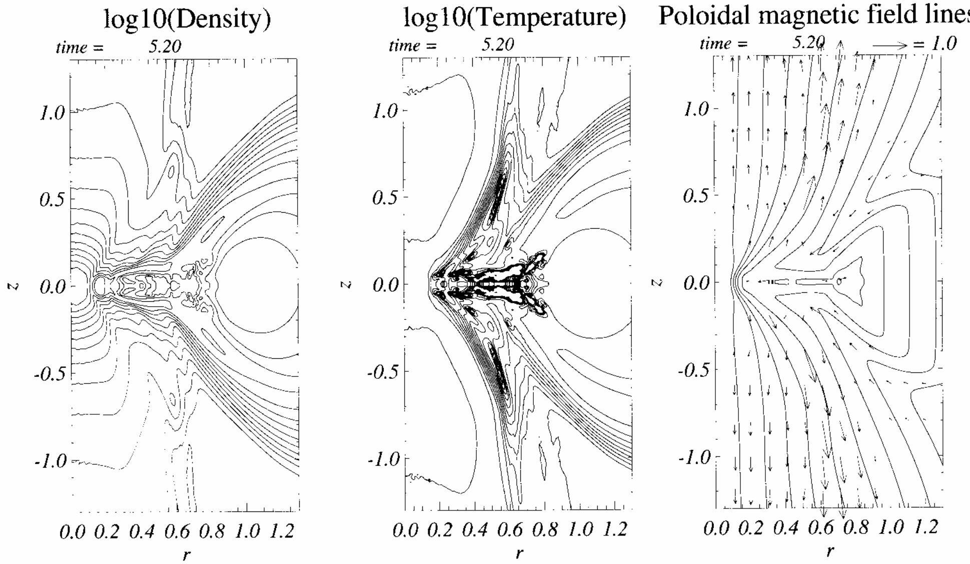


Application of CIP-MOC code to Magnetically driven jet from accretion disk (Kudoh, Matsumoto, Shibata 1998)

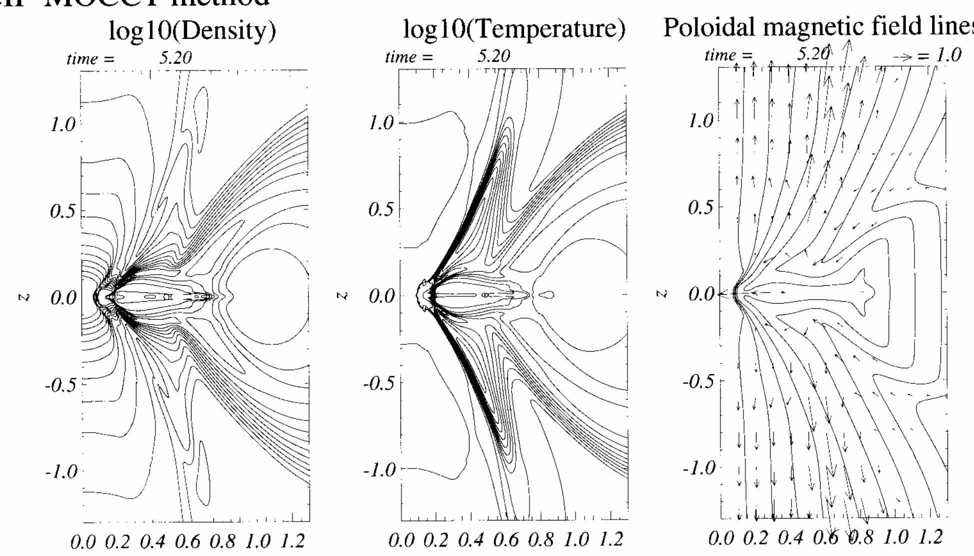


Jet velocity ~ Kepler velocity

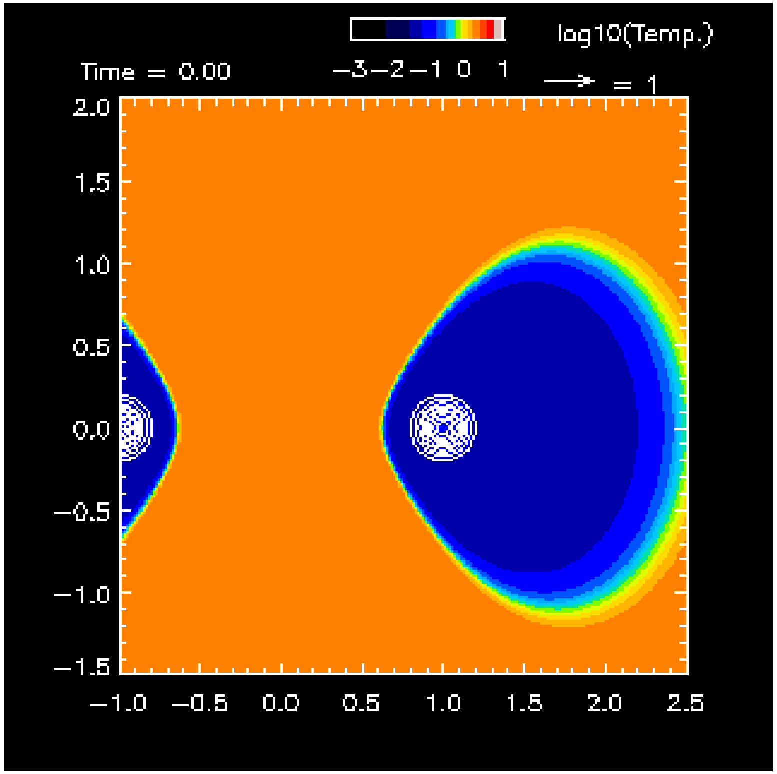
modified Lax-Wendroff method



CIP-MOCCT method



MHD turbulence driven by magnetorotational instability (Kudoh, Matsumoto, Shibata 2002)



Summary of Merits of CIP-MOCCT scheme

- To solve contact discontinuity with high accuracy
- Applicable to either non-conservative or conservative equations
- Applicable to any fluid with complicated physics, such as gas+fluid+solid, etc.
- Applicable to very low beta plasma
  (gas pressure << magnetic pressure)
- Simple and fast

See Ogata's poster for astrophysical application

最新研究のレビュー

- 磁気リコネクション
- 太陽フレア
- 宇宙ジェット
- 降着円盤

磁気リコネクション

磁気リコネクションの基本問題：Reconnection rate　は何が決めているか？

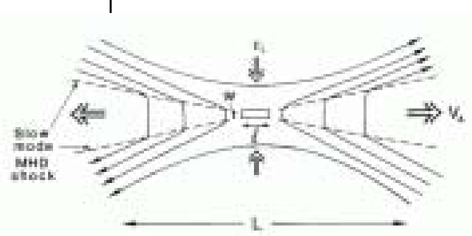
- Magnetic flux reconnected per unit time

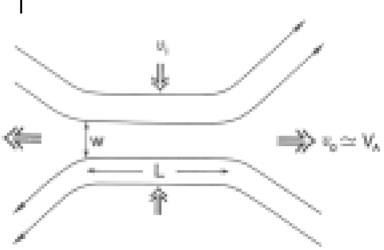
$$M_A = \frac{d\Phi / dt}{V_A B_0} = \frac{E}{V_A B_0} = \frac{\eta J}{V_A B_0} = \frac{V_{in}}{V_A}$$

$$t_{rec} = L / V_{in} = t_A M_A^{-1}$$

磁気リコネクションの基本問題をめぐる激しい論争

•	spontaneous	driven （境界条件）
Petschek	Ugai-Tsuda(1977) Scholer(1989) **Yokoyama-Shibata(1994)**	Sato-Hayashi(1979) Priest-Forbes(1986)
Sweet-Parker		Biskamp(1986)





Sato-Hayashi (1979)

Strong inflow is assumed at the external boundary, which drives reconnection.
=>driven reconnection

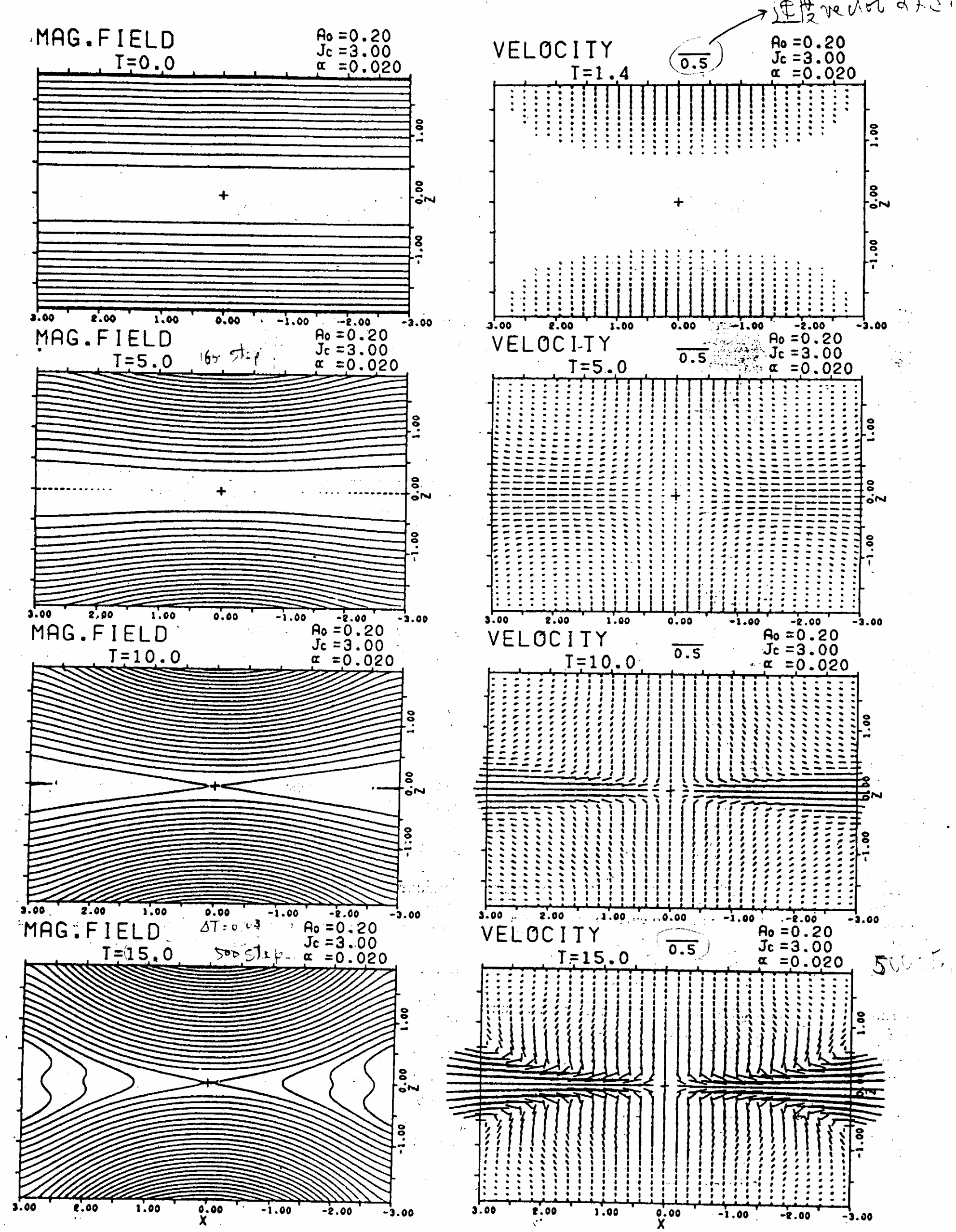
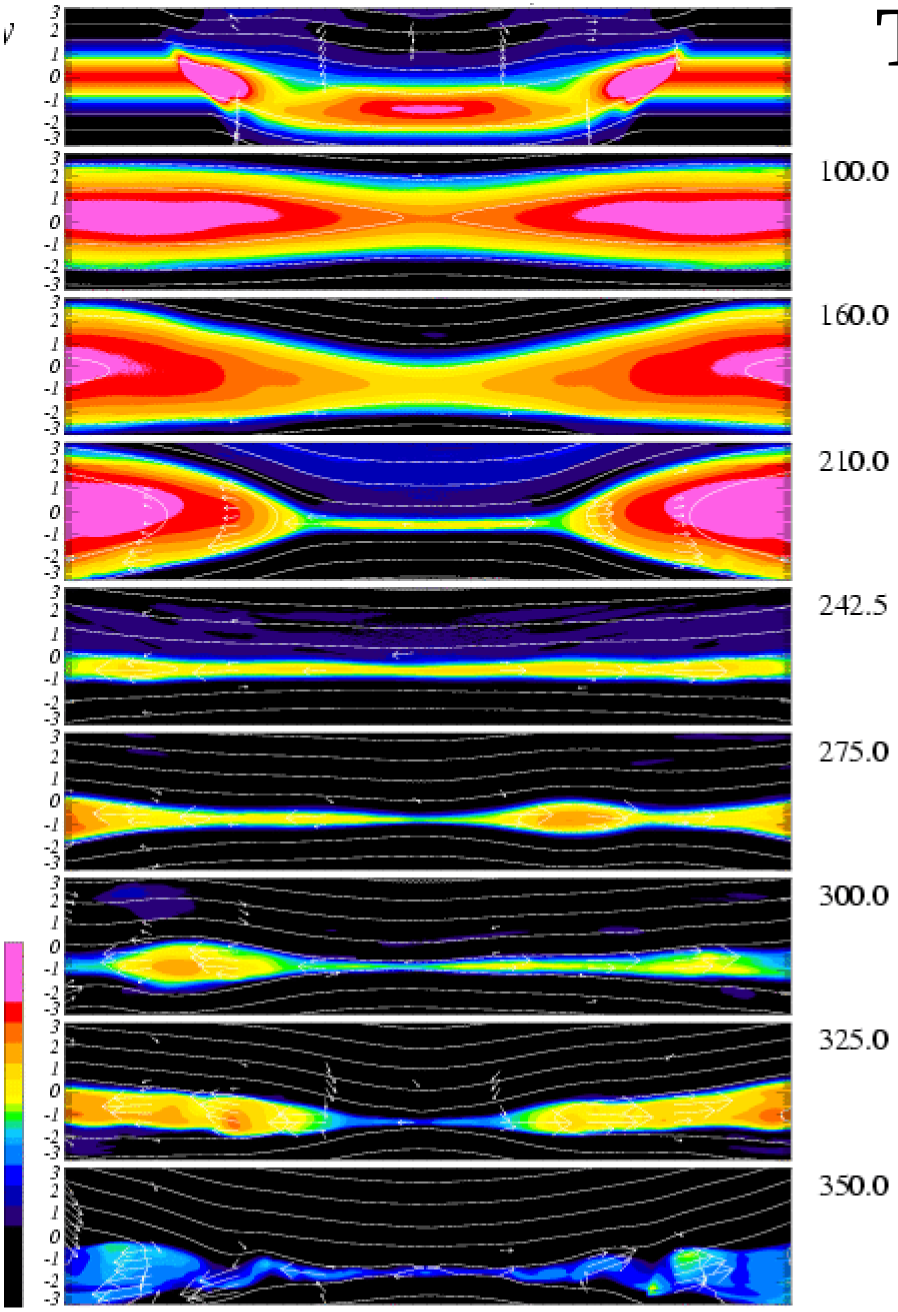
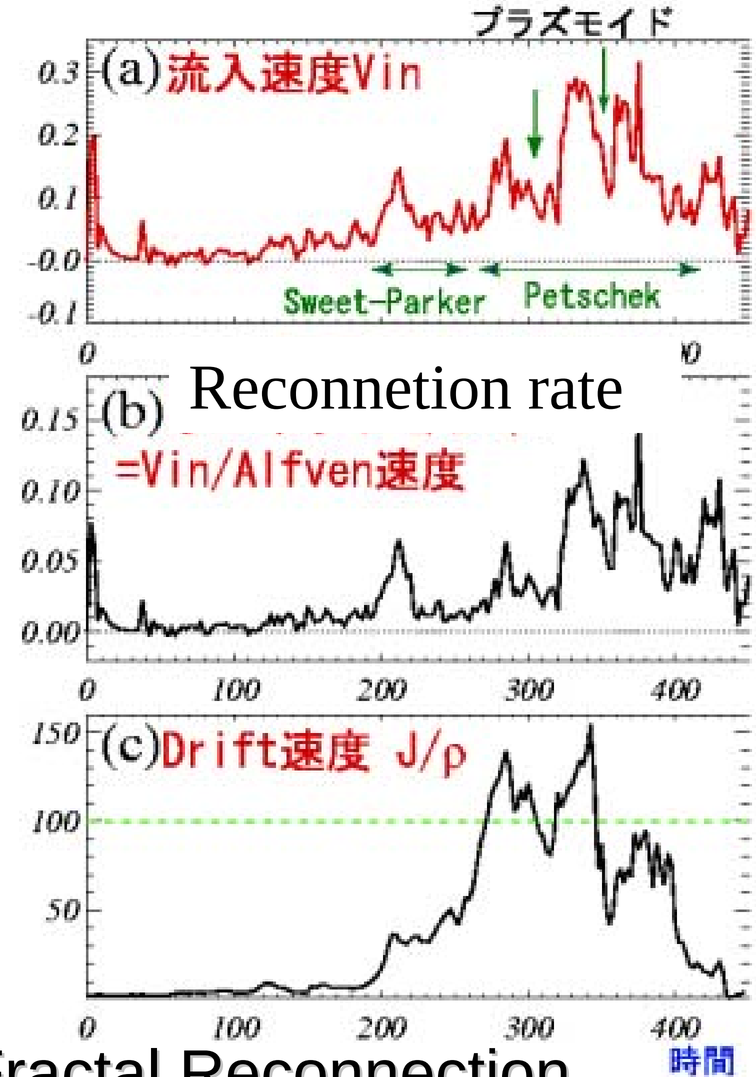


FIG. 1. Computer plots of reconnecting magnetic field lines, or equivector potential lines (left) and plasma flow vectors (right). Note evidence of fast mode expansion in the upstream region, i.e., cusp-like flow direction change, in the bottom right panel (T=15.0).

Tanuma et al. (2001) ApJ



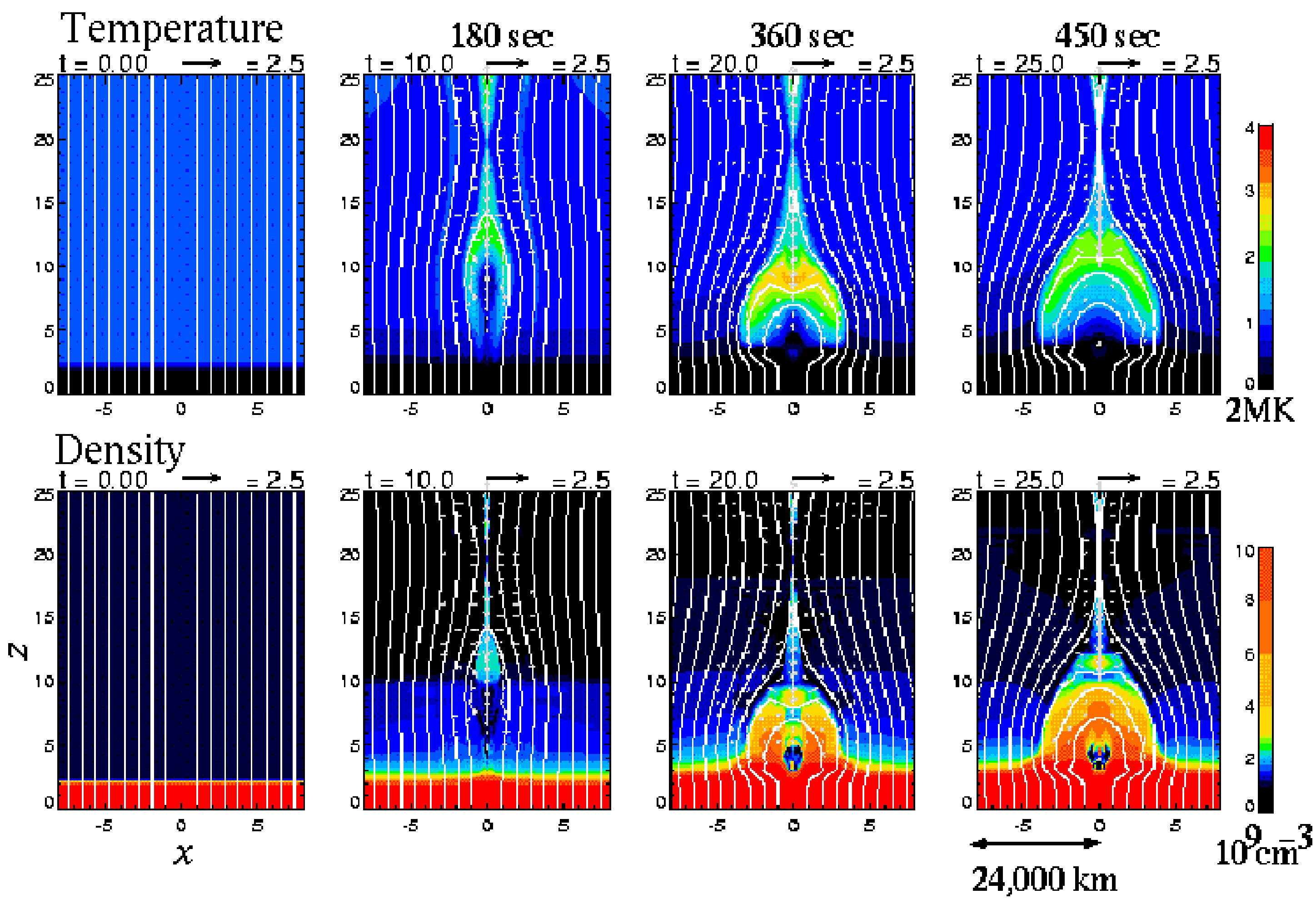


Fractal Reconnection
(Shibata and Tanuma 2001)

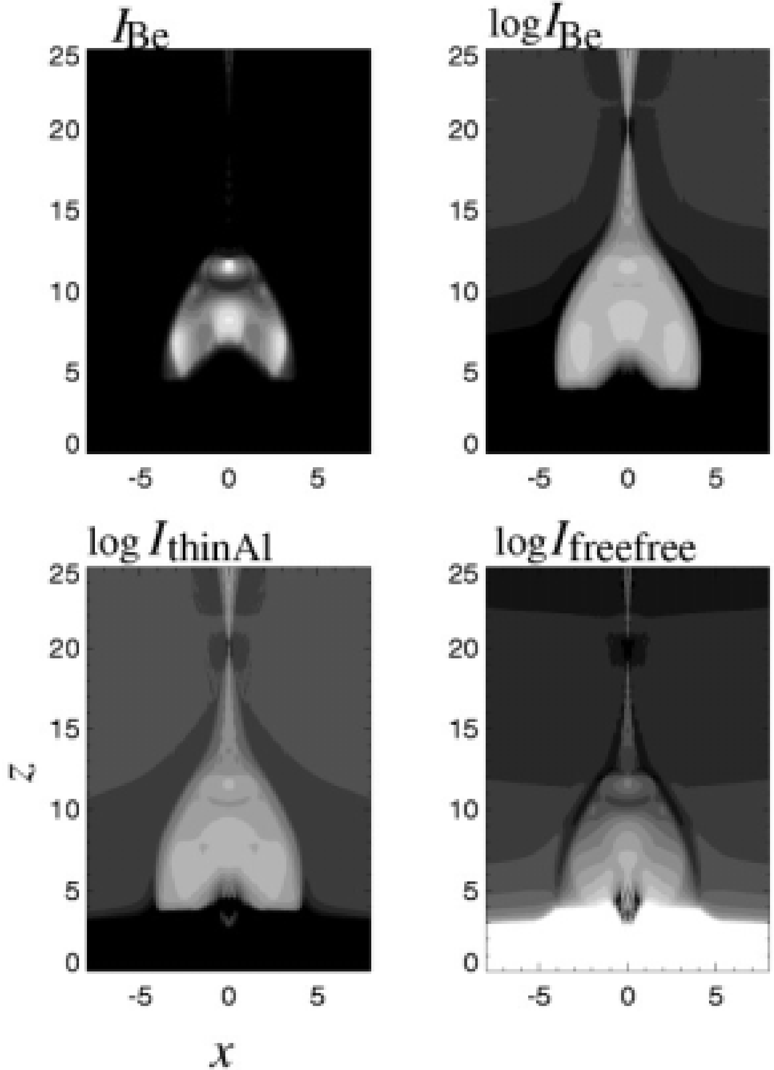
太陽フレア

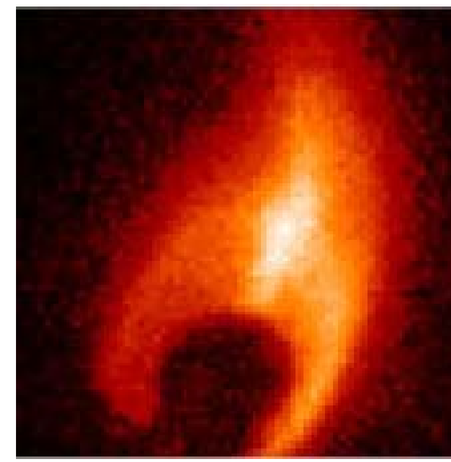
2D MHD Simulation of Reconnection with Heat Conduction

(Yokoyama and Shibata 1998, 2001)

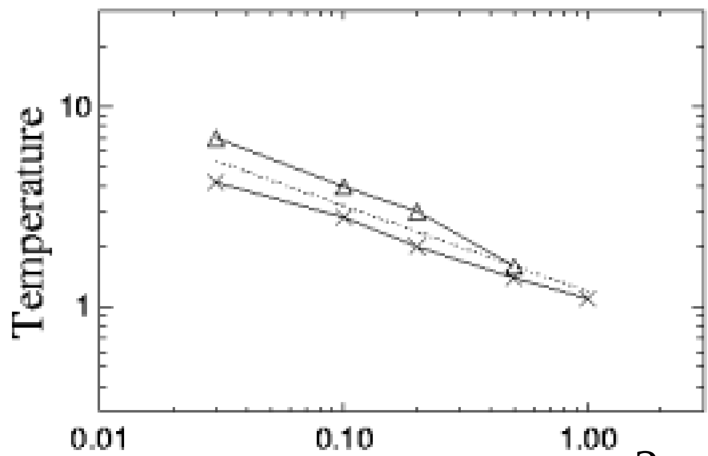


観測的可視化
(理論的に予想されるフレアX線像)

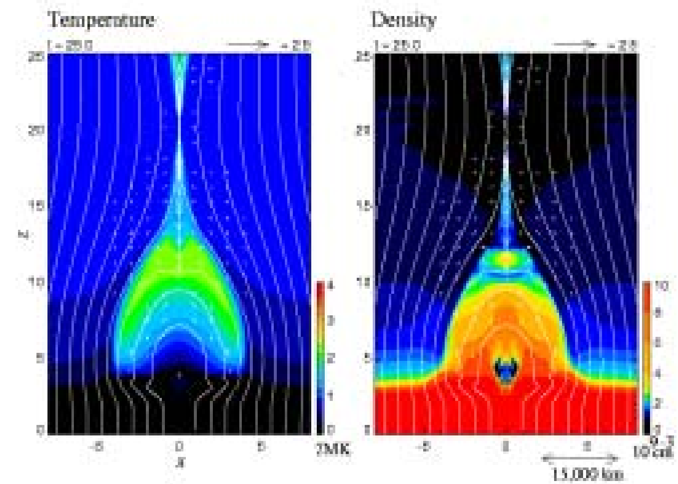




フレア温度の scaling law　の発見 (Yokoyama and Shibata 1998)



$\beta \propto B^{-2}$



$$T \propto B^{6/7} L^{2/7}$$

フレアの温度は何で決まっているか？

- 磁気リコネクション加熱＝熱伝導冷却のバランスで決まる (Yokoyama and Shibata 1998, 2001)

$$B^2 V_A / 4\pi = \kappa T^{7/2} / 2L$$

$$T \propto B^{6/7} L^{2/7}$$

宇宙ジェット

宇宙ジェットの速度は何が決めているか？

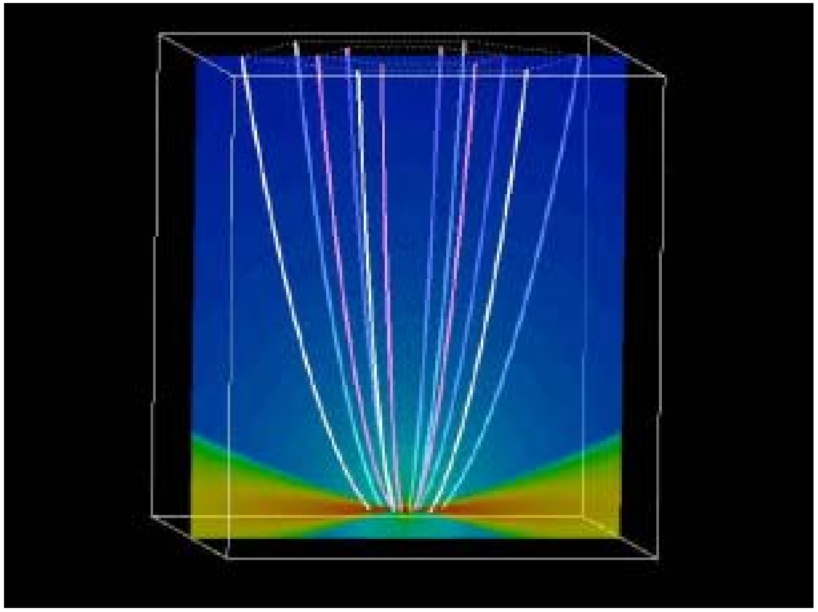
- Many MHD simulations
  - Shibata and Uchida 1986, 1987, 1990, Stone and Norman 1994, Matsumoto et al 1996, Hirose et al. 1997, Kudoh et al. 1998, Ustyugova et al. 1996, …

confirmed that

Jet velocity ~

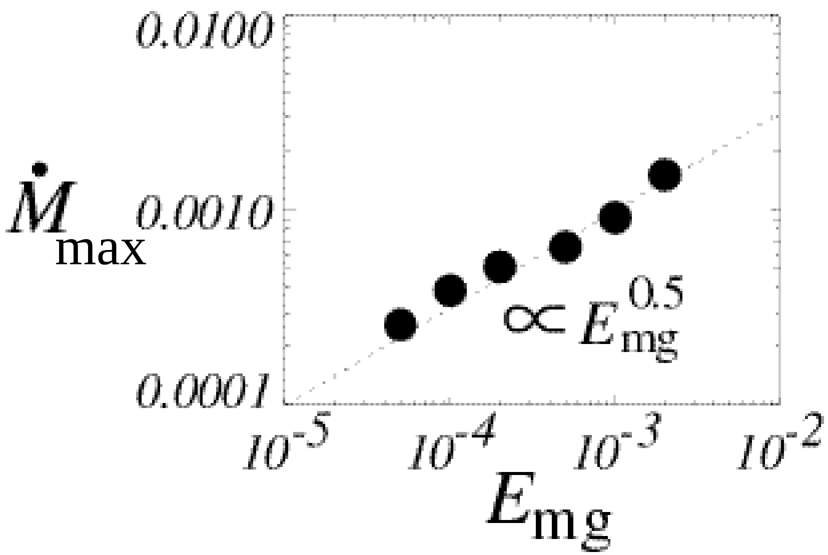
Kepler velocity

Why ?

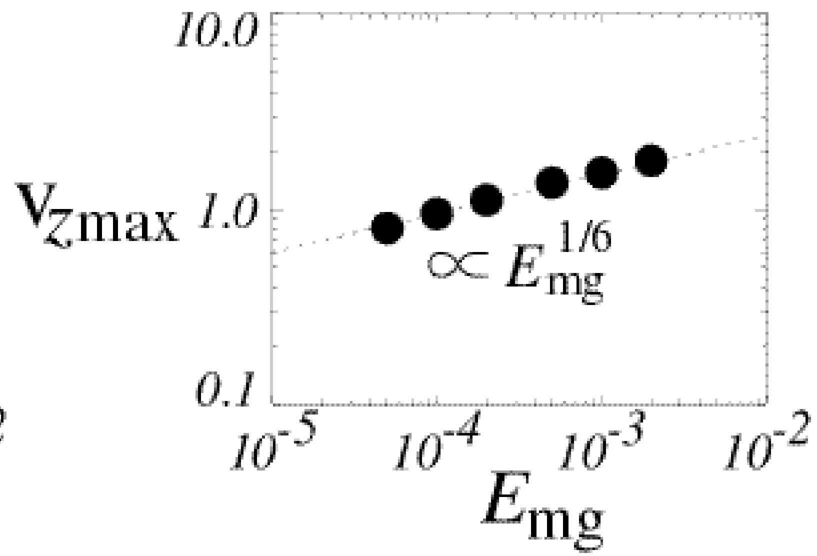


Mass flux and Jet velocity
(Kudoh et al. 1998 for thick disk case)

Mass flux



Jet velocity／Vk



$$E_{mg} = \left(\frac{V_A}{V_K} \right)^2 \propto B_p^2$$

Kato, S. X et al. 2002
(for thin disk case)

Summary of Characteristics of non-relativistic MHD Jets from Accretion Disks

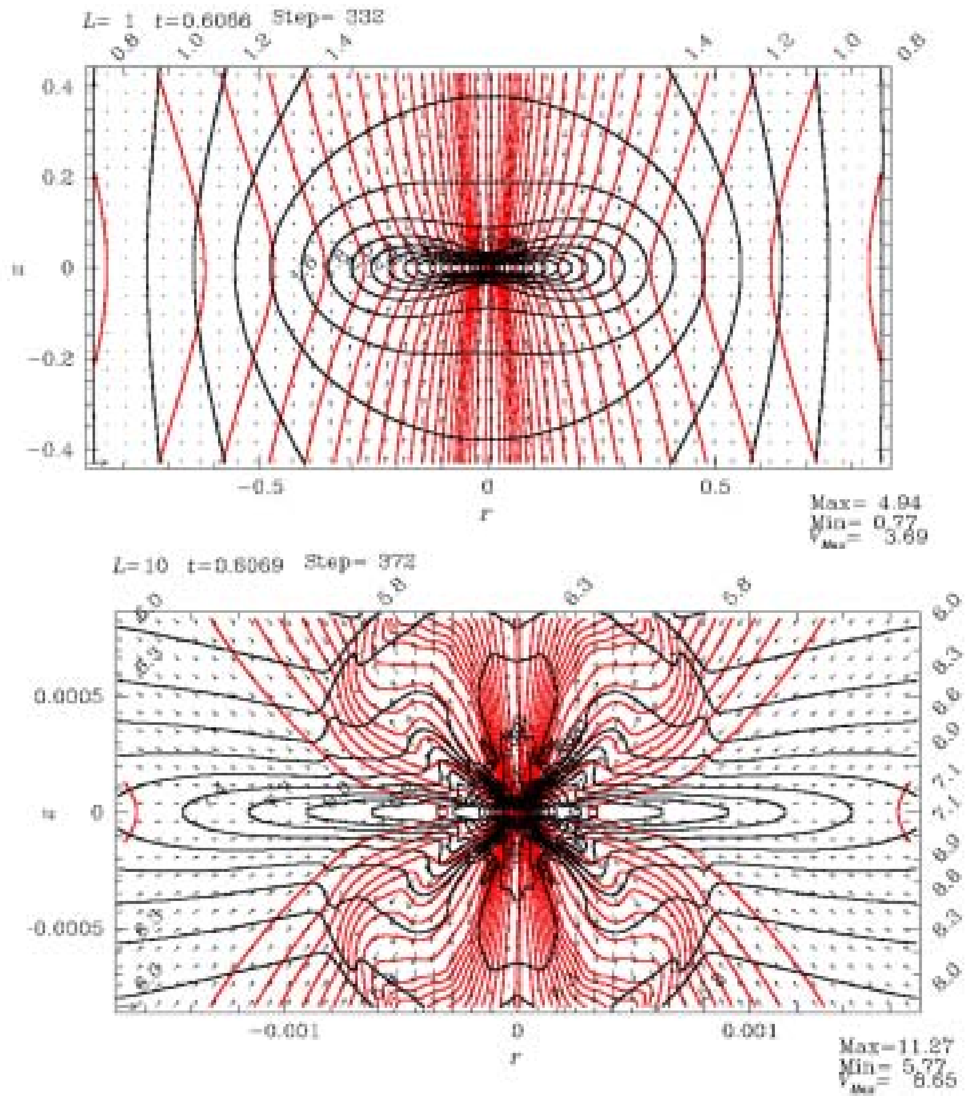
acceleration	centrifugal	magnetic pressure
Poloidal field	strong	weak
Mag. Field config.	straight	highly twisted
Mass flux	$\rho C_s r^2$	$\rho C_s r^2 \frac{B_p}{B_\varphi}$
Jet velocity	$V_k \left(\frac{V_A^2}{C_s V_k} \right)^{1/3}$	$V_k \left(\frac{V_A}{C_s} \right)^{1/3}$
Range of application	$0.01 < E_{mg} < 1$	$E_{mg} < 0.01$

$E_{mg} = \text{mag energy/grav energy}$

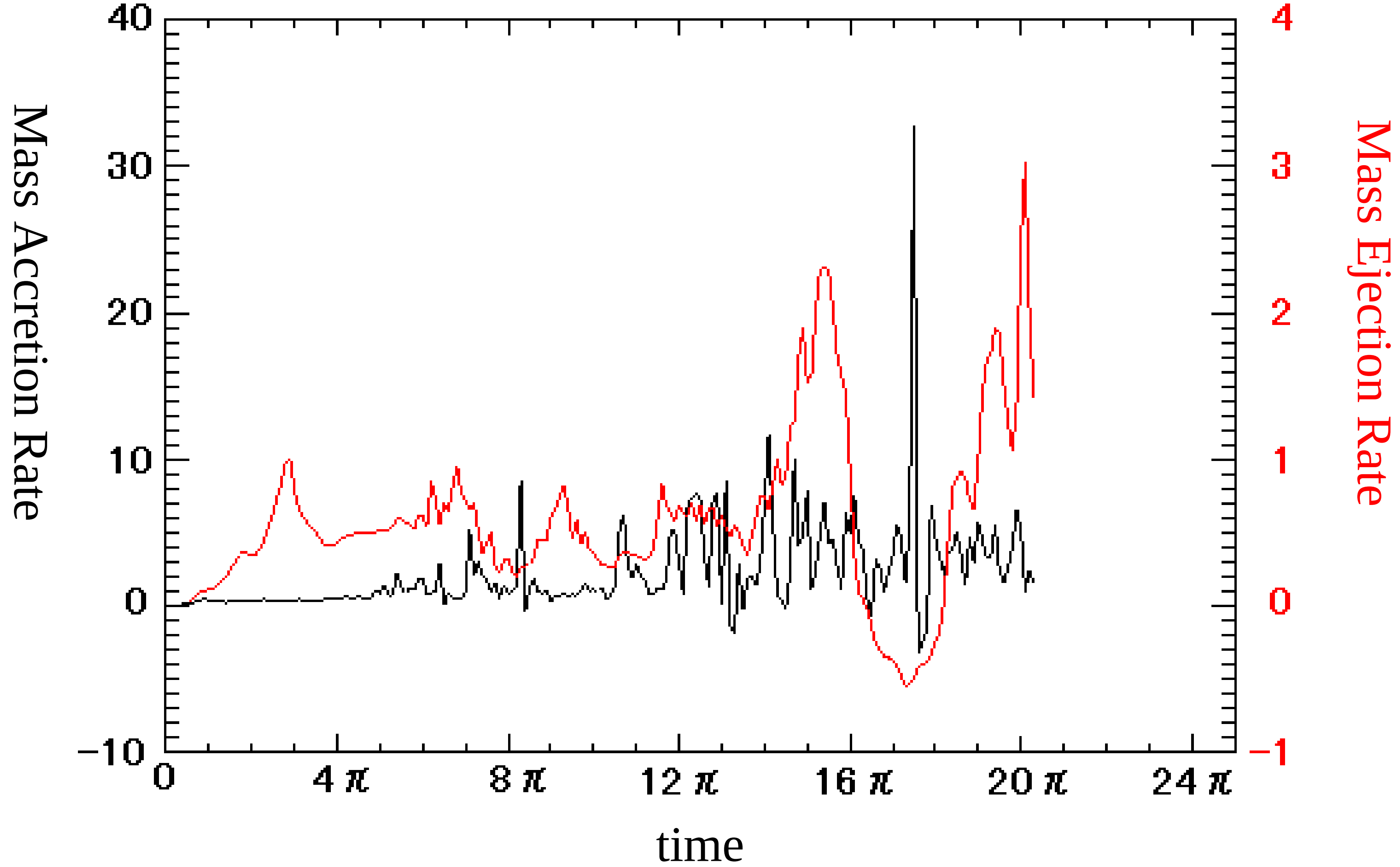
(Kudoh & Shibata)

Tomisaka (2002) ApJ **575, 306**

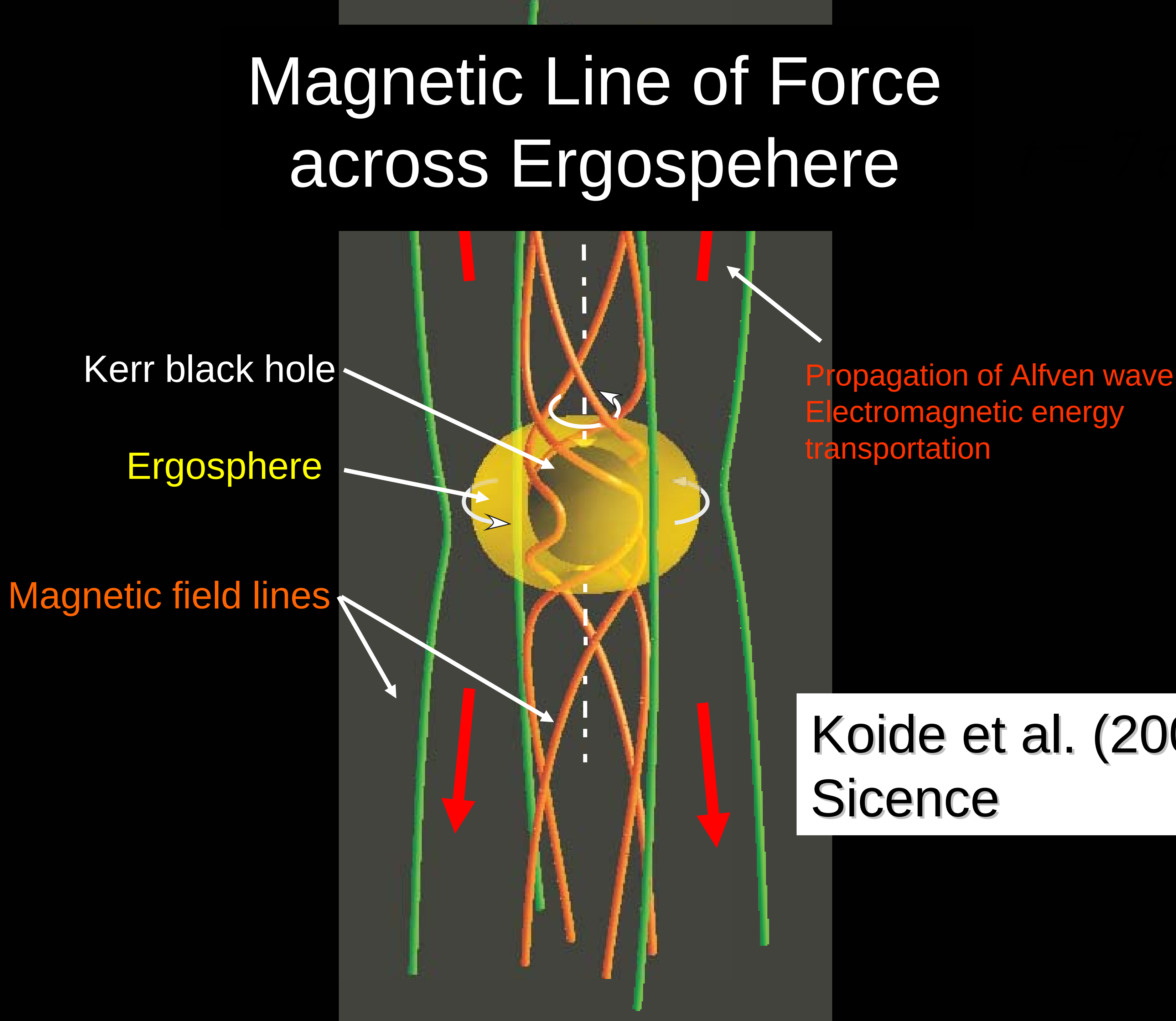
- After adiabatic core is formed, outflow start to be ejected
- In the case of strong magnetic field (beta ~ 1), outflow is accelerated by centrifugal force plus magnetic pressure force, but in the weak field case, outflow becomes more turbulent, and is accelerated by turbulent magnetic pressure



Intermittent Accretion and Ejection
(K. Sato: poster)   (see also Kuwabara)



Magnetic Line of Force across Ergospehere



Koide et al. (2002) Sicence

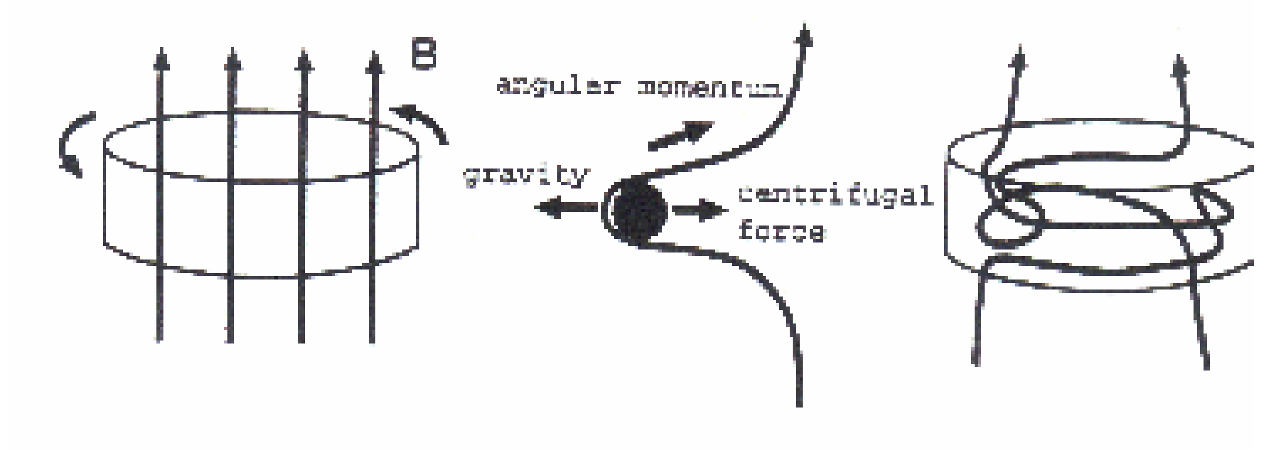
降着円盤

Magneto-rotational instability

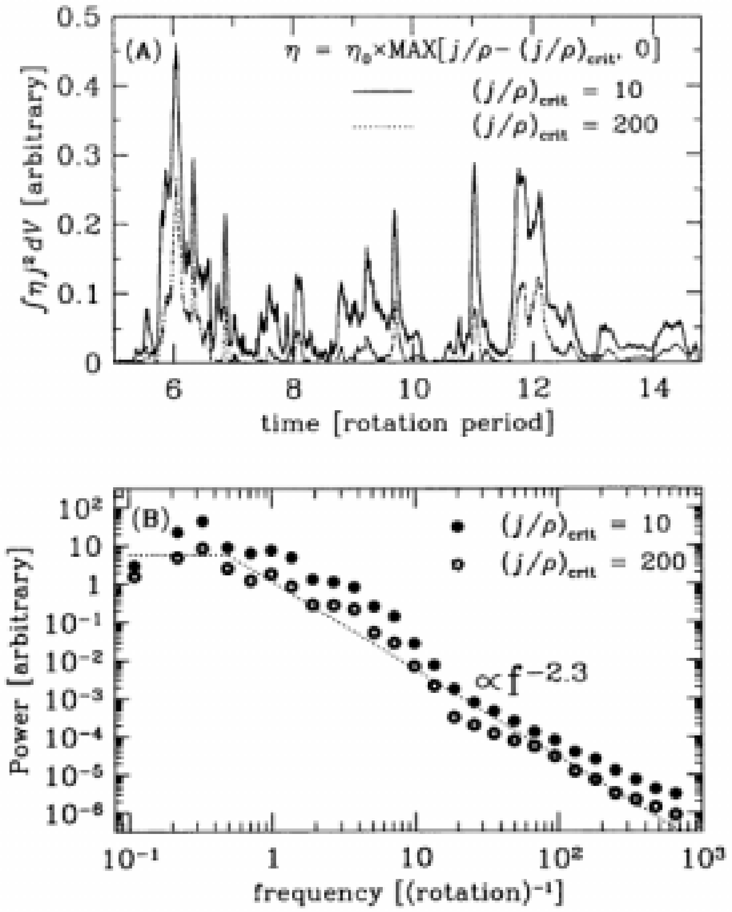
- Balbus-Hawley (1991)
- [Chandrasekhar (1961), Velikhov (1959)]
- Explains **α** viscosity of accretion disks

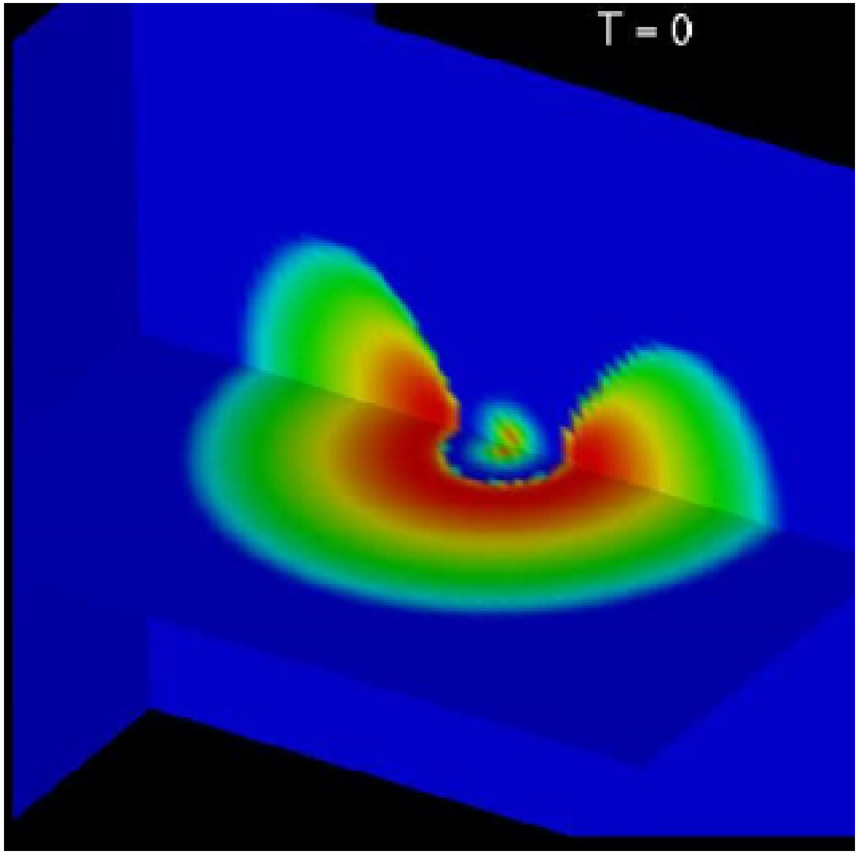
(Hawley-Balbus 1991, Hawley et al. 1995,

Brandenburg et al. 1995, Matsumoto-Tajima 1995)

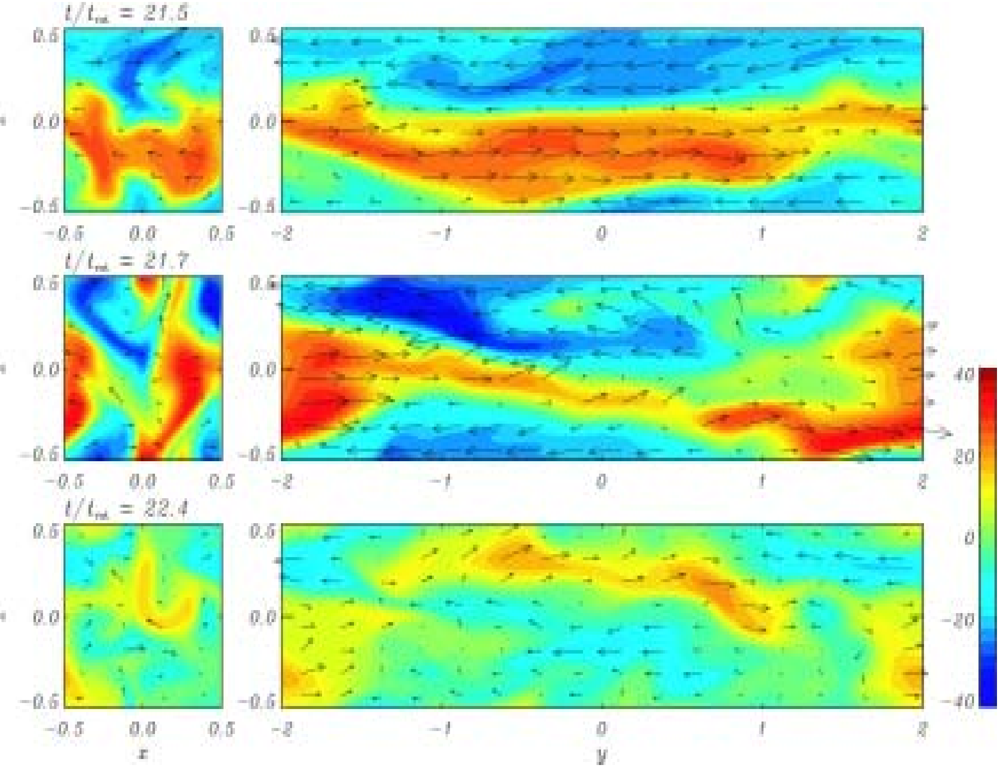


Time variability of 3D magnetized accretion disk (Kawaguchi et al. 1999, Machida et al. 2001 Hawley et al. 2001, Stone et al. 2001)



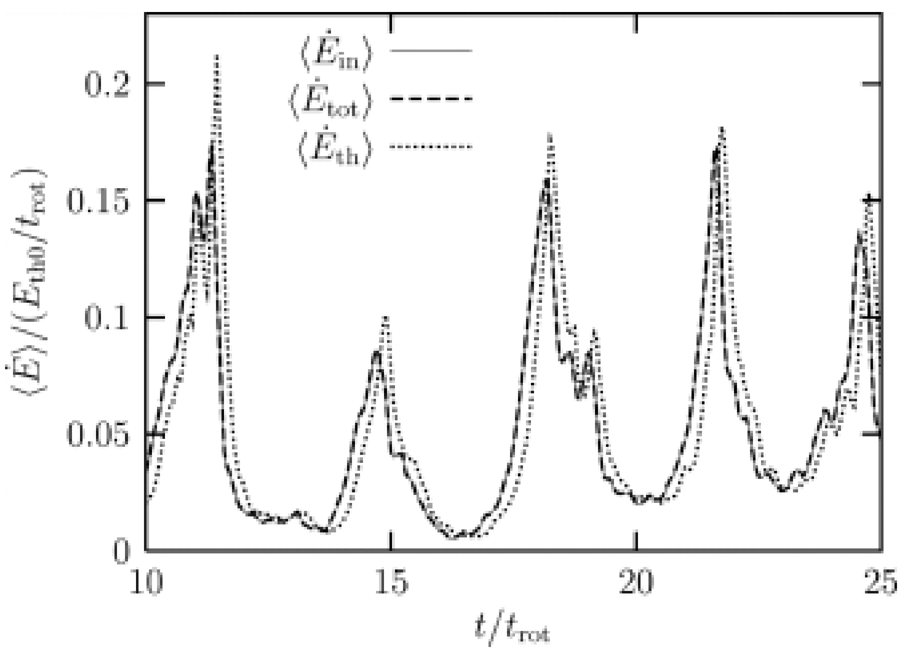


Sano and Inutsuka (2001) ApJ 561, L179



- Local simulation of accretion disk
- Saturation of magnetorotational Instability

=> Reconnection



今後の課題

- 物理･天体物理
  - 磁気リコネクションの基本問題
    3D tearing instability の非線形発展
    ＝＞ フラクタル？ 乱流？
  - MHD＋additional physics
    (e.g., heat conduction, cosmic ray,,,)
  - ねじれた磁束管の浮上にともなう３次元リコネクション (太陽フレアのモデル)
  - ３次元MHDジェット (安定性、コリメーション、
    リコネクション)
  - 降着円盤 (MRI saturation mechanism,
    ダイナモ)

今後の課題（続）

- **数値**MHD
  - CIP-MOCCT code **をあらゆる**MHD**問題に適用してみる**　（e.g., **一般相対論的**MHD**コード**）
  - **多階層統合コードー**Adaptive mesh refinement
  - MHD**＋プラズマ粒子**／Vlasov**統合コード**