

総研大物理科学研究科天文科学専攻
シミュレーション天文学

星間ガスから星への進化

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分子雲

^{13}CO

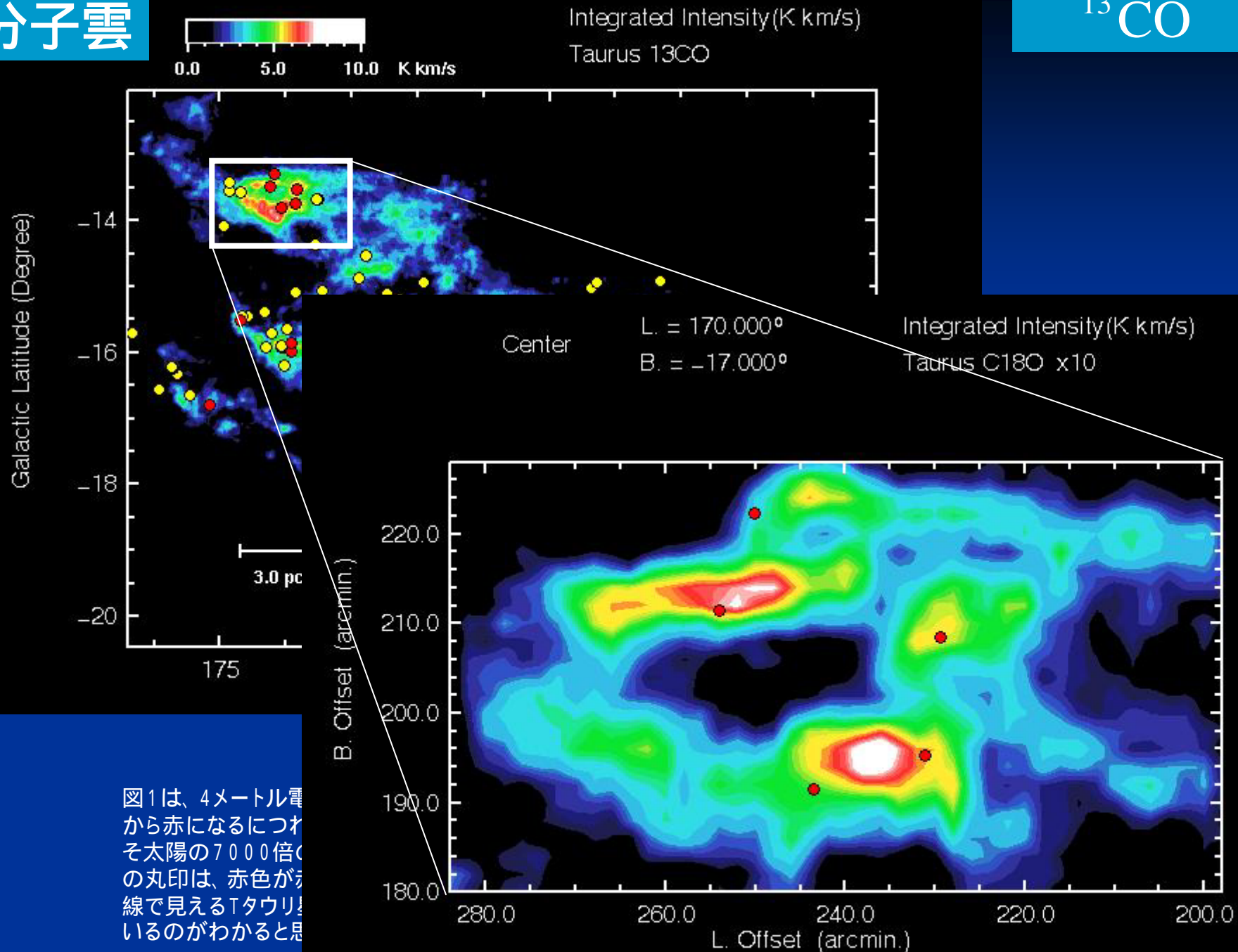
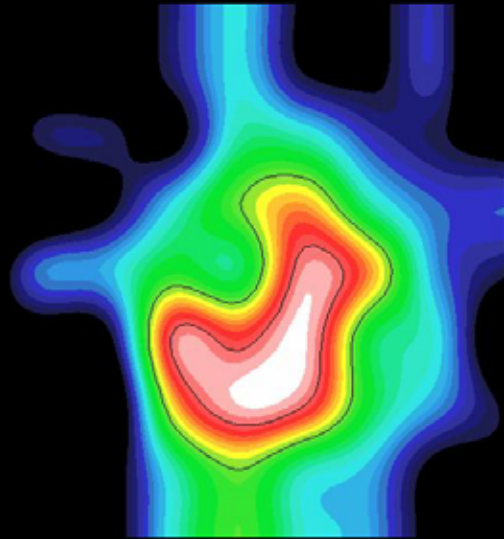
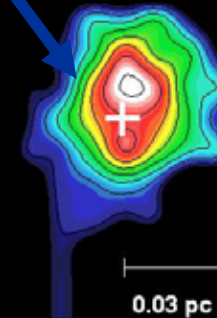


図1は、4メートル電波望遠鏡による観測結果から赤になるにつれて密度が高くなることを示している。その太陽の7000倍の密度を持つ。赤色の丸印は、赤色が最も濃くなる場所を示している。赤線で見えるTaurus AとBの位置がわかる。



星なしコア

赤外線星



星ありコア

右図には赤外線で見えるうまれたばかりの星(十字印)があるけれど、左図にはそれがありません。また左図の分子雲の濃いところ(分子雲コア)は、右図よりも広がっています。星は、左図のような星の「たまご」が、自分たちの重力によってちじんでガスがさらに集まり、その中でうまれると考えられます。(名大A研ホームページ)

典型的星なしコア (prestellar core)

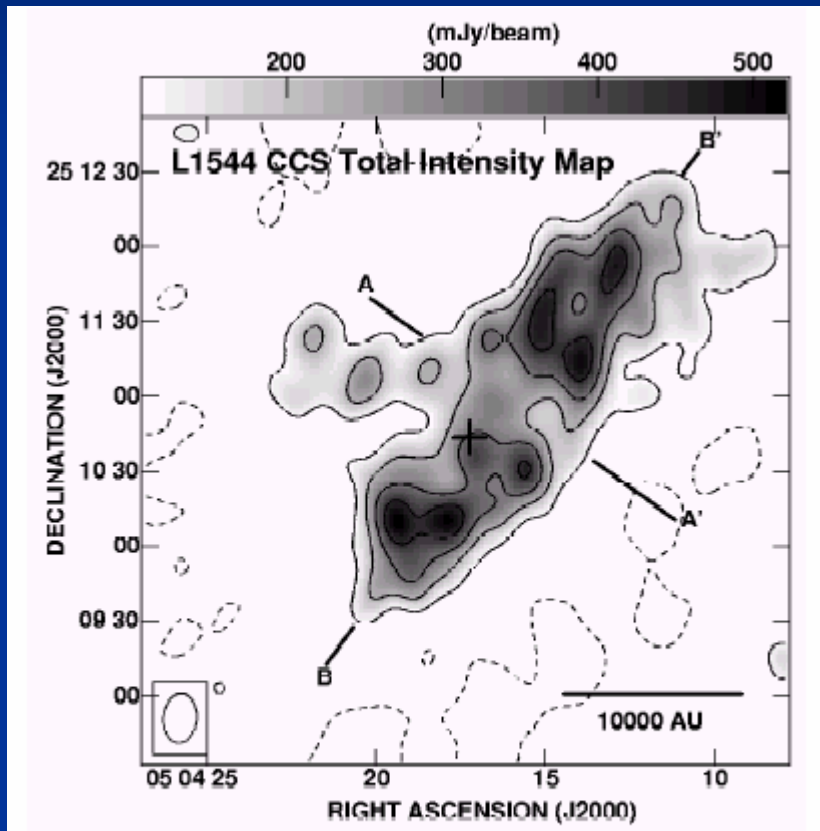
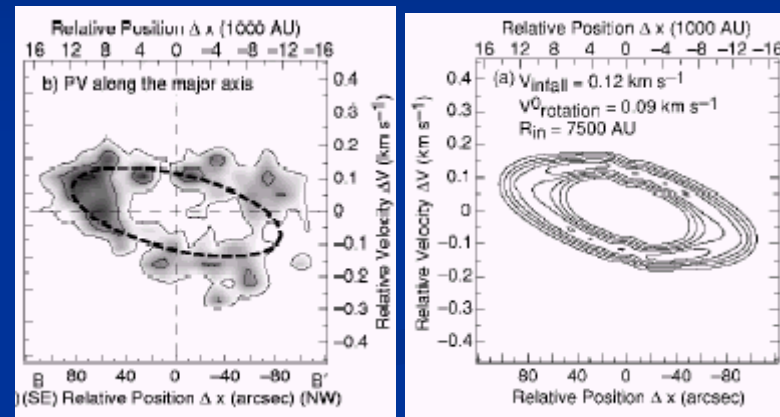


FIG. 1.—CCS total intensity map observed with the BIMA array. The contour spacing is 2σ , starting at $\pm 2\sigma$ with $1\sigma = 55 \text{ mJy beam}^{-1}$. The cross indicates the peak position of the $800 \mu\text{m}$ continuum emission (Ward-Thompson et al. 1994).

観測とモデル



$$V_{rot} = V_{rot}^0 (R / R_{out})$$

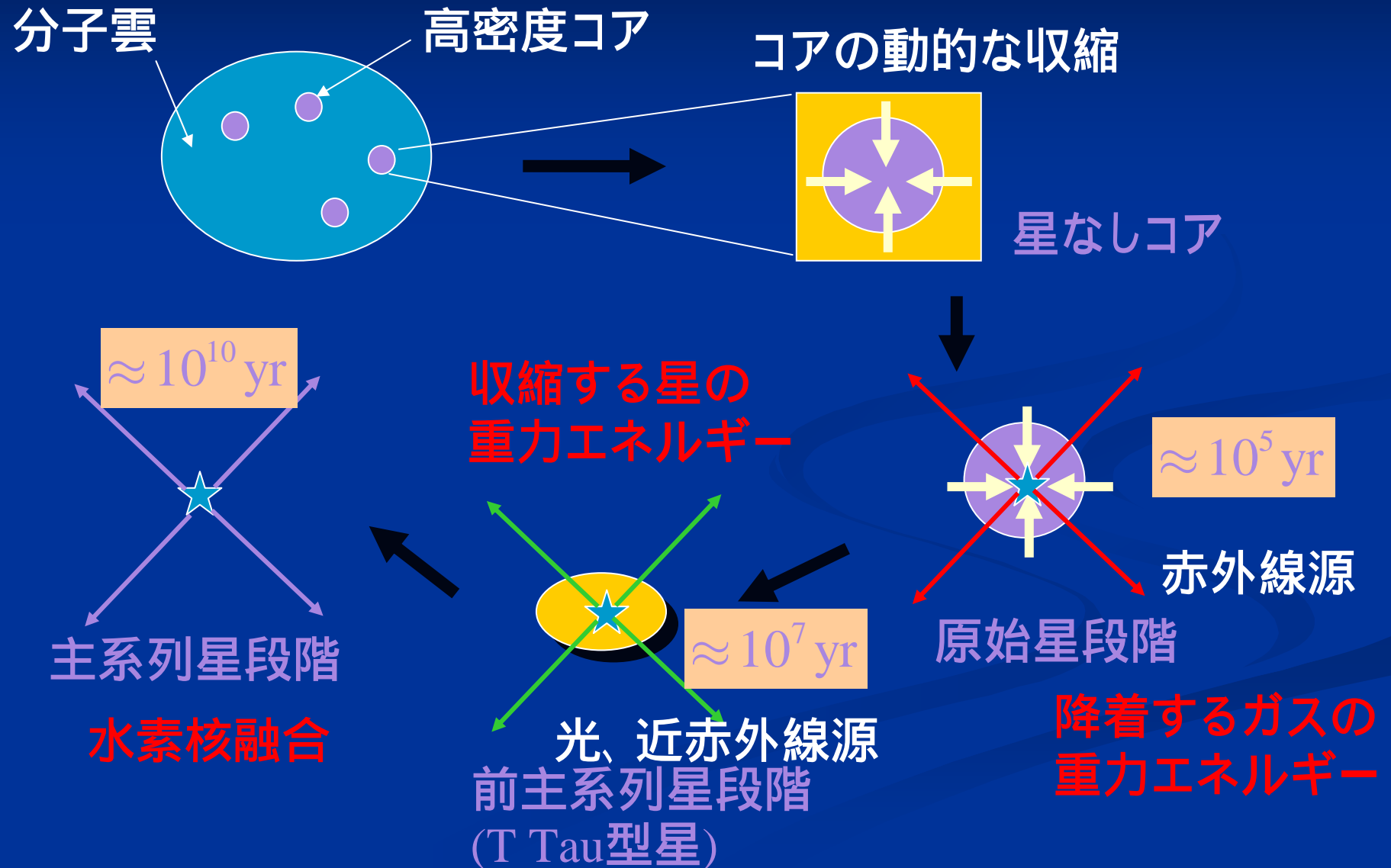
$$V_{rot}^0 = 0.09 \text{ km s}^{-1}$$

$$V_{infall} = 0.12 \text{ km s}^{-1}$$

Ohashi et al. 1999 ApJ, 518, L41

星形成の概念図

太陽質量程度の星の形成過程



力学平衡解

- 温度 T (等温音速 c_s)、外圧 P_0 の元にある球状

ガス $-\frac{d\rho c_s^2}{dr} - \rho g = 0$

圧力 重力

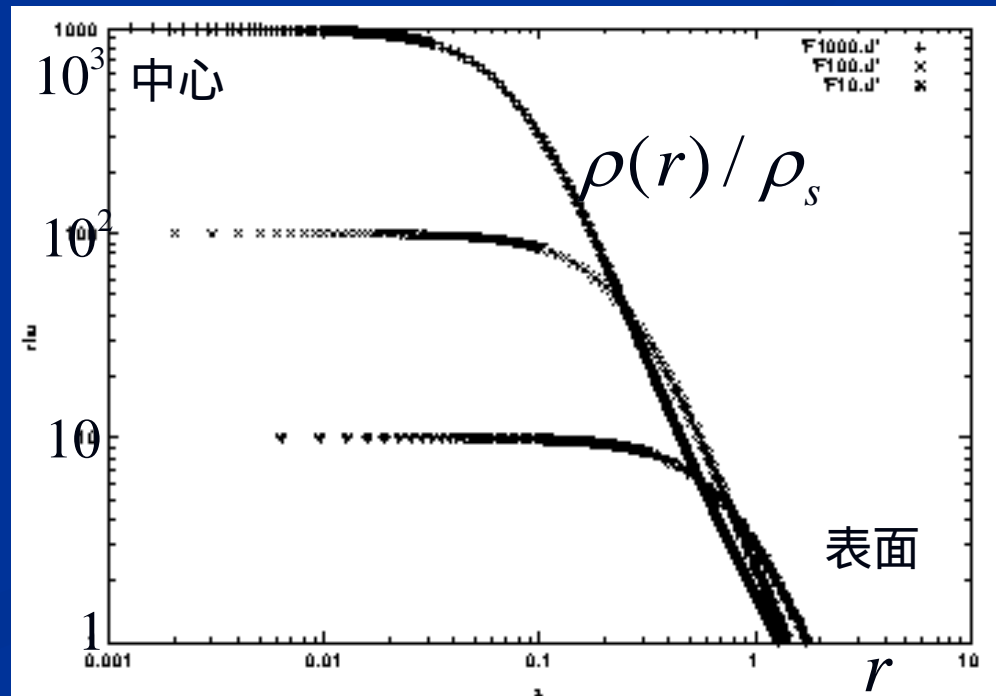
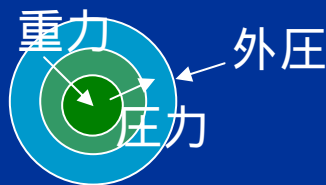
$$g = -\frac{GM_r}{r^2} = -\frac{4\pi G \int_0^r \rho r^2 dr}{r^2}$$

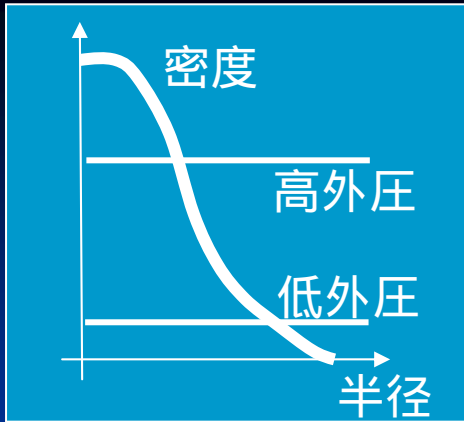
ガウスの定理

規格化 $\rho = \rho_s f; r = \frac{c_s}{\sqrt{4\pi G \rho_s}} \xi$

$$-\frac{df}{d\xi} - \frac{\int_0^\xi f \xi^2 d\xi}{\xi^2} = 0,$$

境界条件 $\xi = 0, f = f_c, \frac{df}{d\xi} = 0$





圧力-密度関係と安定性

S不安定平衡 ■ 力学平衡VS非平衡

$$M_{cl} = M_{cl}(\rho_c, p_{ext})$$

$$\left(\frac{\partial M_{cl}}{\partial p_{ext}}\right)_{\rho_c} \cdot \left(\frac{\partial p_{ext}}{\partial \rho_c}\right)_{M_{cl}} \cdot \left(\frac{\partial \rho_c}{\partial M_{cl}}\right)_{p_{ext}} = -1$$

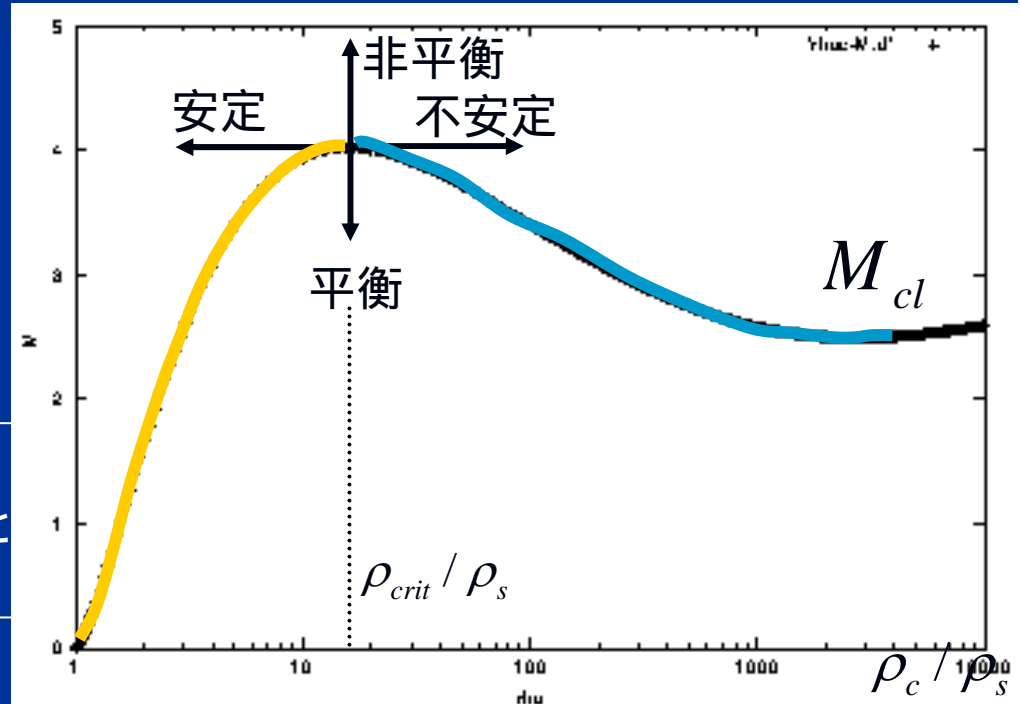
$$\left(\frac{\partial M_{cl}}{\partial p_{ext}}\right)_{\rho_c} < 0 \text{ ㊦ え}$$

$$\left(\frac{\partial p_{ext}}{\partial \rho_c}\right)_{M_{cl}} \cdot \left(\frac{\partial \rho_c}{\partial M_{cl}}\right)_{p_{ext}} > 0$$

外圧
増すと
収縮
安定

$$\left(\frac{\partial M_{cl}}{\partial \rho_c}\right)_{p_{ext}} > 0 \text{ なら } \left(\frac{\partial \rho_c}{\partial p_{ext}}\right)_{M_{cl}} > 0$$

$$\left(\frac{\partial M_{cl}}{\partial \rho_c}\right)_{p_{ext}} < 0 \text{ なら } \left(\frac{\partial \rho_c}{\partial p_{ext}}\right)_{M_{cl}} < 0 \text{ 不安定}$$



密度比<20

観測例

•孤立した暗黒星雲の密度分布

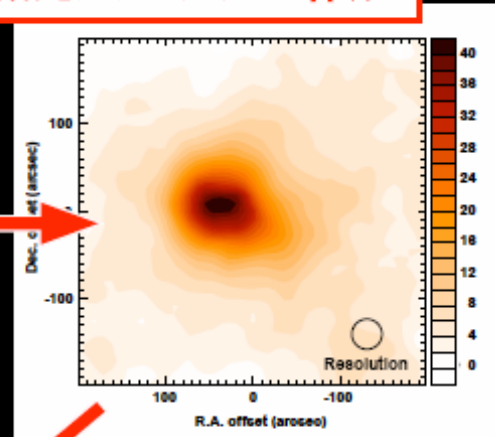
•力学平衡解に近い?

本研究の概要：解析の流れ

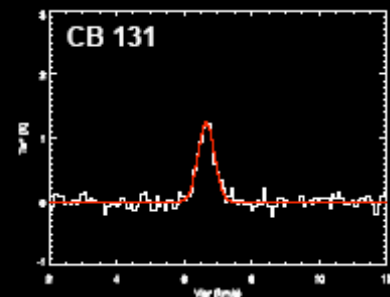
近赤外イメージング



減光量マップの作成

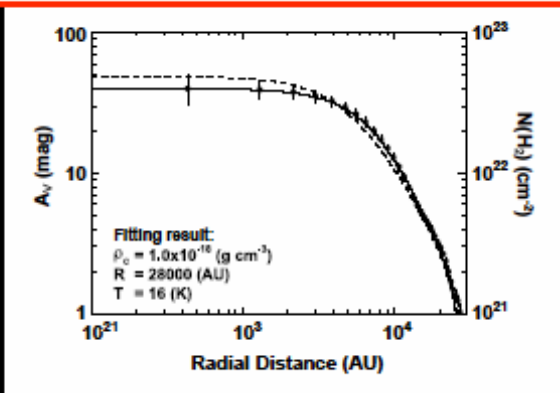


ライン幅測定(電波)



コアの実効的溫度(乱流込み)を測定

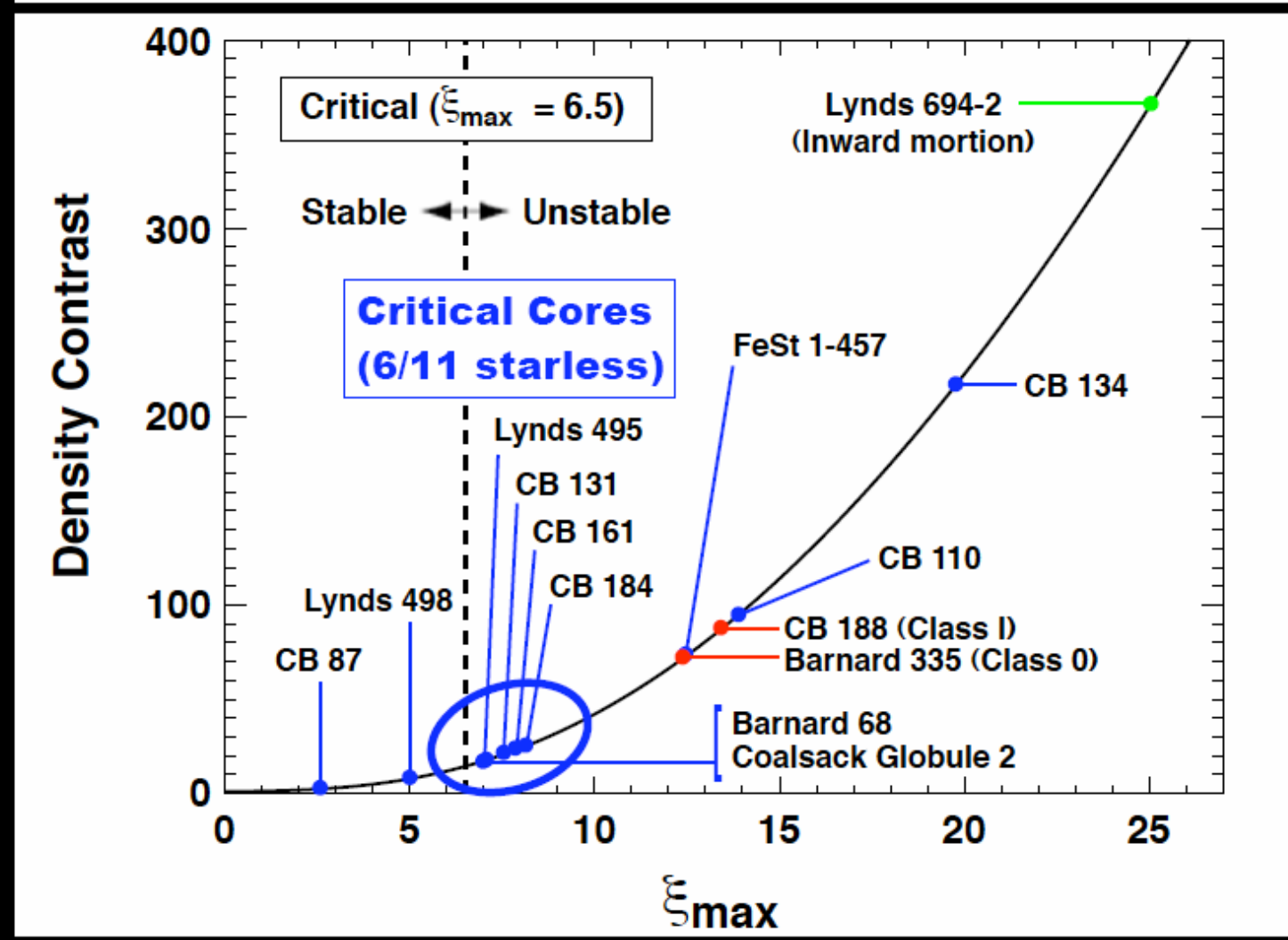
柱密度プロファイル+モデルフィット



コアの物理的性質の決定
(密度構造、サイズ、質量、温度、
力学的安定性...)

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立松健一³ 1.総研大/ALMA準備室、2.東京大学、3.国立天文台

議論(2) / グロビュールの密度構造と力学的安定性 /



ビリアル定理

- ビリアル定理から、球状の雲が力学平衡状態にある条件が決められる。
- 運動方程式に \mathbf{r} を内積して雲全体にわたって体積積分すると、

$$\rho \frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p - \rho \nabla \phi + \frac{1}{4\pi} (\nabla \times \mathbf{B}) \times \mathbf{B}$$

- ビリアル関係式

$$\frac{1}{2} \frac{d^2 I}{dt^2} = 2(T - T_0) + M + W$$

- 慣性モーメント

$$I = \int \rho r^2 dV = \int r^2 dM$$

- 運動エネルギー

$$T = \int \left[\frac{3}{2} p_{th} + \frac{1}{2} \rho v^2 \right] dV = \frac{3}{2} \bar{P} V_{cl}$$

- 表面圧力項

$$T_0 = \int_S P_{th} \mathbf{r} \cdot \mathbf{n} dS = \frac{3}{2} P_0 V_{cl}$$

- 磁場項

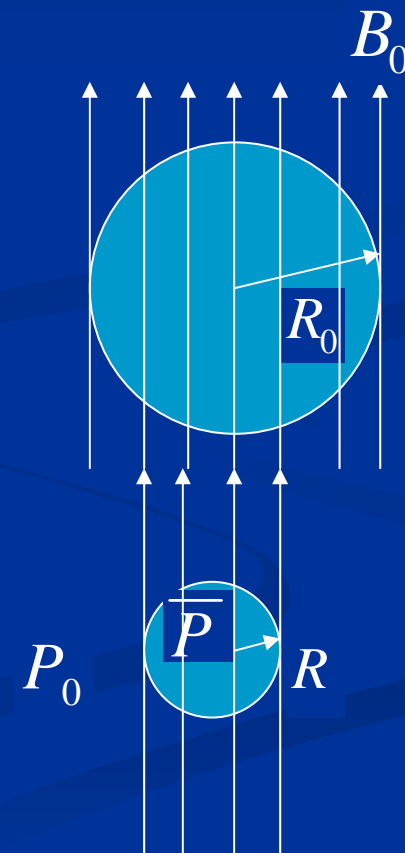
$$M = \int \frac{B^2}{8\pi} dV + \int_S (\mathbf{r} \cdot \mathbf{B}) \mathbf{B} \cdot \mathbf{n} dS - \int_S \frac{B^2}{8\pi} \mathbf{r} \cdot \mathbf{n} dS$$

$$\approx \int \frac{B^2 - B_0^2}{8\pi} dV \approx \frac{1}{6\pi^2} \int \left[\frac{\Phi_B^2}{R} - \frac{\Phi_B^2}{R_0} \right]$$

$$\Phi_B = \pi R_0^2 B_0$$

- 重力項

$$W = - \int \rho \mathbf{r} \cdot \nabla \phi dV = - \frac{3}{5} a \frac{GM^2}{R}$$



8 Virial Analysis

Hydrodynamic equation of motion using the Lagrangean time derivative [eq.(8)] is

$$\rho \frac{dv}{dt} = -\nabla p - \rho \nabla \Phi. \quad (119)$$

For simplicity, consider a spherical symmetric configuration. The equation of motion is expressed as

$$\rho \frac{dv}{dt} = -\frac{\partial p}{\partial r} - \rho \frac{\partial \Phi}{\partial r}. \quad (120)$$

Multiplying radius r to the equation and integrating by the volume $dV = 4\pi r^2 dr$ over a volume from $r = 0$ to $r = R$, we obtain the Virial relation as

$$\frac{1}{2} \frac{d^2 I}{dt^2} - 2T = 3(\gamma - 1)U + W, \quad (121)$$

where

$$I = \int \rho r^2 dV = \int r^2 dM, \quad (122)$$

is an inertia of the cloud, and T and U are, respectively, the kinetic and thermal energies as

$$T = \int \frac{1}{2} \rho v^2 dV = \int \frac{1}{2} v^2 dm, \quad (123)$$

$$U = \int \frac{p}{\gamma - 1} dV. \quad (124)$$

Further,

$$W = - \int \rho \frac{GM_r}{r} dV = - \int \frac{GM_r}{r} dm, \quad (125)$$

is a gravitational energy.

Since

$$r \frac{dv}{dt} = \frac{1}{2} \frac{d^2 r^2}{dt^2} - u^2, \quad (126)$$

the lefthand-side of equation (120) is rewritten as

$$\begin{aligned} \int_0^R \rho r \frac{dv}{dt} 4\pi r^2 dr &= \int_0^R \left(\frac{1}{2} \frac{d^2 r^2}{dt^2} - u^2 \right) \rho 4\pi r^2 dr, \\ &= \frac{1}{2} \frac{d^2}{dt^2} \int_0^R r^2 dm - \int_0^R v^2 dm \\ &= \frac{1}{2} \frac{d^2 I}{dt^2} - 2T, \end{aligned} \quad (127)$$

where we used equation (122) and (123)

On the other hand, the first term of the rhs of equation (120) becomes

$$\begin{aligned}
 - \int_0^R r \frac{dp}{dr} 4\pi r^2 dr &= - \left\{ [4\pi r^3 p]_0^R - 3 \int_0^R 4\pi r^2 p dr \right\}, \\
 &= 3 \int_0^R p dV, \\
 &= 3(\gamma - 1)U.
 \end{aligned} \tag{128}$$

To derive this equation, we have assumed the pressure diminishes at a radius $r = R$ and the surface pressure term does not appear in the final expression. This is valid for an isolated system.

The last term of the rhs of equation (120) is written as

$$- \int_0^R r \rho \frac{d\Phi}{dr} 4\pi r^2 dr = - \int_0^R \rho \frac{Gm_r}{r^2} 4\pi r^2 dr, \tag{129}$$

where we used equation(65). This is rewritten as

$$\begin{aligned}
 - \int_0^R \rho \frac{Gm_r}{r^2} 4\pi r^2 dr &= \int_0^R -\frac{Gm_r}{r} dm \\
 &= W,
 \end{aligned} \tag{130}$$

where $m_r = \int_0^r dm$. The energy $+\frac{Gm_r}{r}$ per unit mass is necessary for a gas element is moved from r , inside which mass m_r is contained, to the infinity. Adding the energy $+\frac{Gm_r}{r} dm$ for all the gas, the potential energy is obtained. In the case of a star composed of uniform density ρ_0 ,

$$W = -\frac{3}{5} \frac{GM^2}{R}, \tag{131}$$

where $M = 4\pi R^3 \rho_0/3$.

To obtain a condition of mechanical equilibrium, we assume $d^2 I/dt^2 = 0$. Equation (121) becomes

$$2T + 3(\gamma - 1)U + W = 0. \tag{132}$$

Assuming the system is static $v = 0$, the above equation reduces to

$$3(\gamma - 1)U + W = 0. \tag{133}$$

B = 0 の場合 (ジーンズ質量)

$$\frac{1}{2} \frac{d^2 I}{dt^2} = 2(T - T_0) + W$$

- 平衡条件

$$4\pi \bar{P} R^3 - 4\pi P_0 R^3 - \frac{3}{5} a \frac{GM^2}{R} = 0$$

- 等温を仮定

$$\bar{P} = c_s^2 \bar{\rho} = c_s^2 \frac{3M}{4\pi R^3}$$

- 外圧に関する条件

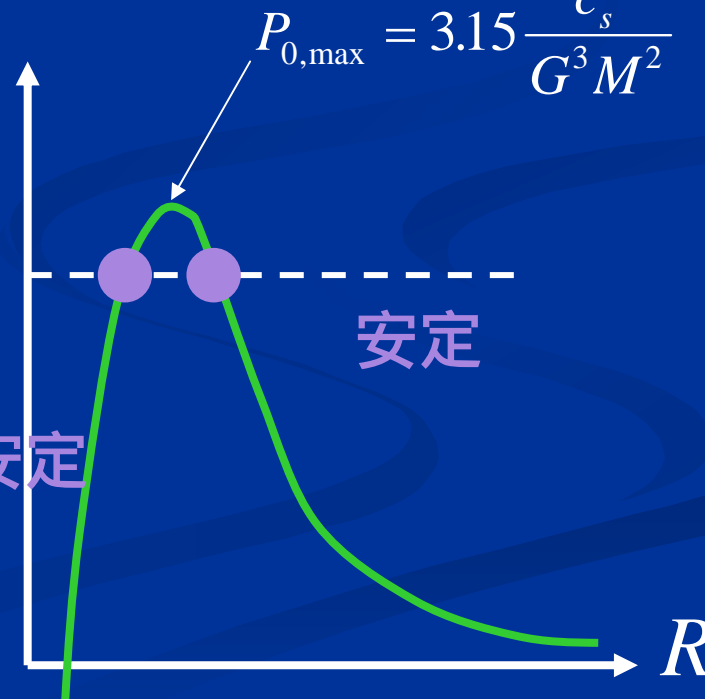
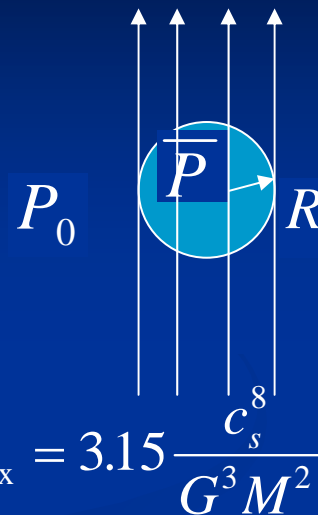
$$P_0 = \frac{3c_s^2 M}{4\pi R^3} - \frac{3aGM^2}{20\pi R^4}$$

- 高外圧 高内圧 重力 P_0

- ジーンズ質量

- ある外圧、温度の元で 不安定
支えられる最大質量

$$M < M_J = 1.77 \frac{c_s^4}{G^{3/2} P_0^{1/2}}$$



電磁流体力学の基礎方程式

- プラズマを電気伝導性を持つ連続物質と考える。
- 変位電流を無視: マックスウエル方程式
 - アンペールの法則 $\text{rot}\mathbf{B}=(4\pi/c)\mathbf{j}$
 - ファラデーの法則 $\text{rot}\mathbf{E}=-\mathbf{d}\mathbf{B}/\text{d}t$
- ローレンツ力
 - $\mathbf{j}\times\mathbf{B}/c=-\text{grad}\mathbf{B}^2/8 + \mathbf{B}\text{grad}\mathbf{B}/4$
- オームの法則
 - $\mathbf{J}=\sigma(\mathbf{E}+\mathbf{v}\times\mathbf{B}/c)$
- 磁場の誘導方程式
 - $\text{d}\mathbf{B}/\text{d}t=\text{rot}(\mathbf{v}\times\mathbf{B})+(c^2/4\pi)\text{grad}\mathbf{B}^2$

MHD基礎方程式

B.1 Magnetohydrodynamics

Here, we derive the basic equations of magnetohydrodynamics. Differences from hydrodynamics are the Lorentz force in the equation of motion and the induction equation of magnetic field. The Lorentz force is written as

$$\mathbf{j} \times \mathbf{B} = \frac{1}{4\pi} (\nabla \times \mathbf{B}) \times \mathbf{B}, \quad (\text{B.1})$$

where we used the Ampere's law $\nabla \times \mathbf{B} = (4\pi/c)\mathbf{j}$ and the displacement current is ignored. Thus, the equation of motion becomes as

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + (\nabla \cdot \mathbf{v})\mathbf{v} \right) = -\nabla p - \rho \nabla \psi + \frac{1}{4\pi} (\nabla \times \mathbf{B}) \times \mathbf{B}, \quad (\text{B.2})$$

in the Eulerian form.

The Faraday's law $\nabla \times \mathbf{E} = -(1/c)(\partial \mathbf{B}/\partial t)$ and the Ohm's law $\mathbf{j} = \sigma(\mathbf{E} + \mathbf{v} \times \mathbf{B}/c)$ (σ is the electric conductivity) lead the induction equation of the magnetic field as

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) - \frac{c^2}{4\pi} \nabla \times \frac{\nabla \times \mathbf{B}}{\sigma}. \quad (\text{B.3})$$

The factor $c^2/4\pi\sigma$ is the coefficient of magnetic diffusibility. When we assume the electric conductivity $\sigma \rightarrow \infty$, diffusive MHD equation, equation(B.3), reduces to the ideal MHD equation as

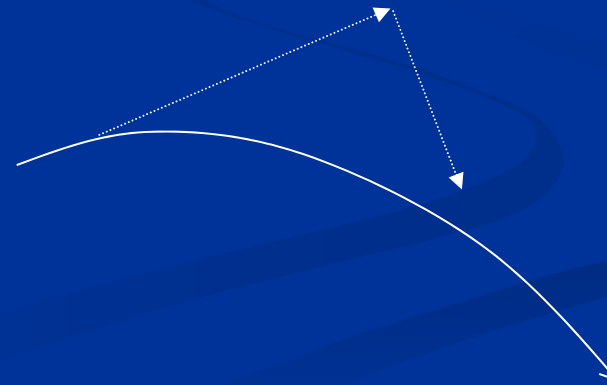
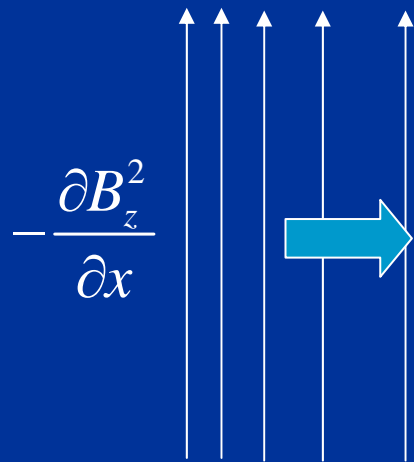
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}). \quad (\text{B.4})$$

磁場による力

- ローレンツ力: 磁場に垂直方向の力

$$\frac{\mathbf{j} \times \mathbf{B}}{c} = \frac{1}{4\pi} (\text{rot } \mathbf{B}) \times \mathbf{B} = -\frac{1}{8\pi} \text{grad} B^2 + \frac{1}{4\pi} \mathbf{B} \cdot \nabla \mathbf{B}$$

- 磁気圧と磁気張力



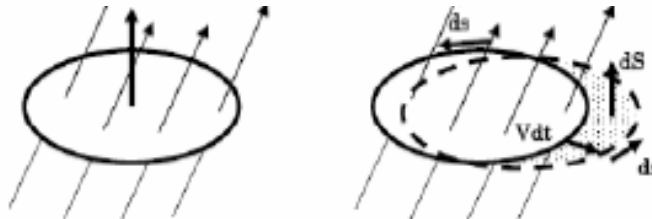
ガスへの凍結

B.1.1 Flux Freezing

An important nature of the ideal MHD is derived from equation (B.4), that is, the matter and the magnetic field is coupled with each other. Consider a gas parcel threaded with the magnetic field B . The magnetic flux anchored to the gas parcel $\Phi_B \equiv \int B \cdot dS$ is changes

$$\text{磁束} \quad \frac{d\Phi_B}{dt} = \frac{d}{dt} \int B \cdot dS = \int \frac{\partial B}{\partial t} \cdot dS + \int B \cdot v \times ds, \quad (\text{B.5})$$

where $s = \partial S$. The first term of the lhs of the equation comes from a time derivative of the magnetic flux density, while the last term represents the change of the integral region due to gas motion (see



磁場を横切って流体が移動することはない。

Figure B.1: The change of flux anchored to a surface dS . One part of the change comes from the temporal change in magnetic flux density. The other comes from the change of the boundary of the surface due to gas motion. Time variation of the area is given by $v dt \times ds$.

Fig.B.1). ($dS = v \times ds$) Using the Stokes' theorem $\int \nabla \times A \cdot dS = \int A \cdot ds$, the last term is reduced to $\int B \times v \cdot ds = \int \nabla(B \times v) \cdot dS$. Finally, we obtain

$$\frac{d\Phi_B}{dt} = \int \left[\frac{\partial B}{\partial t} - \nabla(v \times B) \right] \cdot dS = 0, \quad (\text{B.6})$$

where we used equation (B.4). This means that the magnetic flux anchored to a gas parcel does not change in the ideal MHD regime.

磁場が存在する場合

$$\frac{1}{2} \frac{d^2 I}{dt^2} = 2(T - T_0) + M + W$$

- 星間雲を貫く磁束 $\Phi_B \equiv B_0 \pi R_0^2$ が一定
- 磁場の項 $\int B^2 dV \approx \frac{\Phi_B^2}{R} \propto \frac{GM^2}{R}$ 重力の項
- 初期に磁場が収縮を止められなければ、その後も収縮を止めることは出来ない。
- 平衡条件

$$4\pi \bar{P} R^3 - 4\pi P_0 R^3 - \frac{3G}{5R} (M^2 - M_\Phi^2) = 0$$

$$\frac{3GM_\Phi^2}{5R} = \frac{\Phi_B^2}{3\pi^2 R}$$

■ 準臨界雲

$$M < M_{\Phi} \quad M_{\Phi} < M < M_{cr}$$

■ 超臨界雲

$$M > M_{\Phi}$$

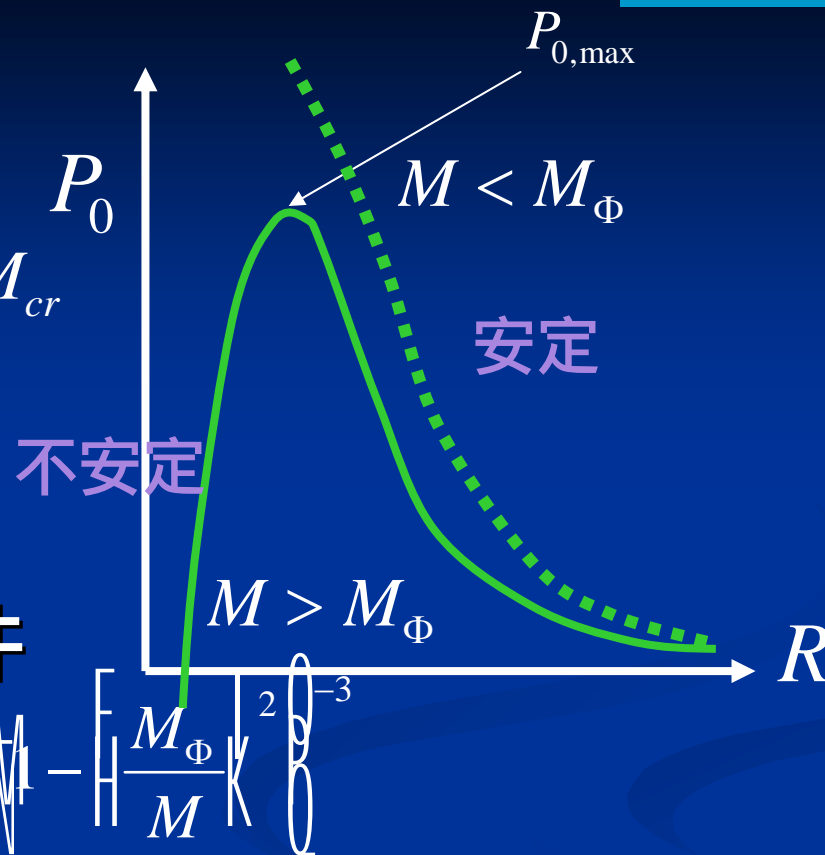
$$M > M_{cr}$$

■ 外圧に関する条件

$$P_0 < P_{0,max} = 3.15 \frac{c_s^8}{G^3 M^2}$$

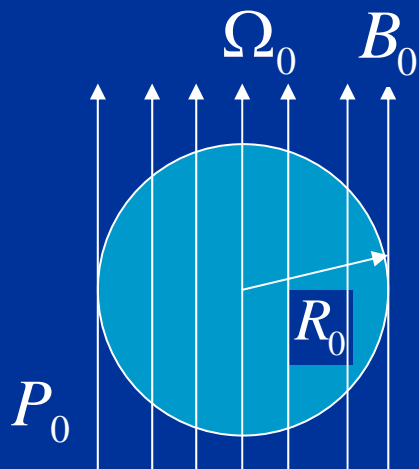
■ ジーンズ質量

$$M < M_{cr} = 1.77 \frac{c_s^4}{G^{3/2} P_0^{1/2} \left[1 - (M_{\Phi}/M) \right]^{3/2}}$$

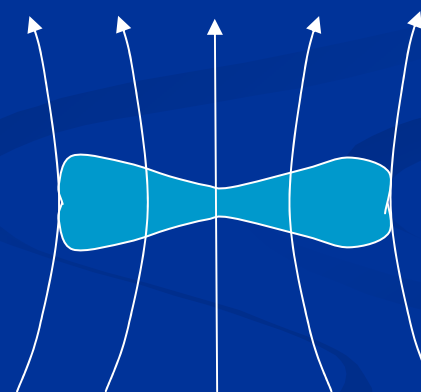


磁気静水圧平衡

{	$\mathbf{B} = \text{rot } \mathbf{A}$	ベクトルポテンシャル Grad-Shafranov 方程式 磁場に垂直方向のつりあい
	$\mathbf{g} = -\text{grad } \phi$	重力ポテンシャル Poisson 方程式



平衡形状



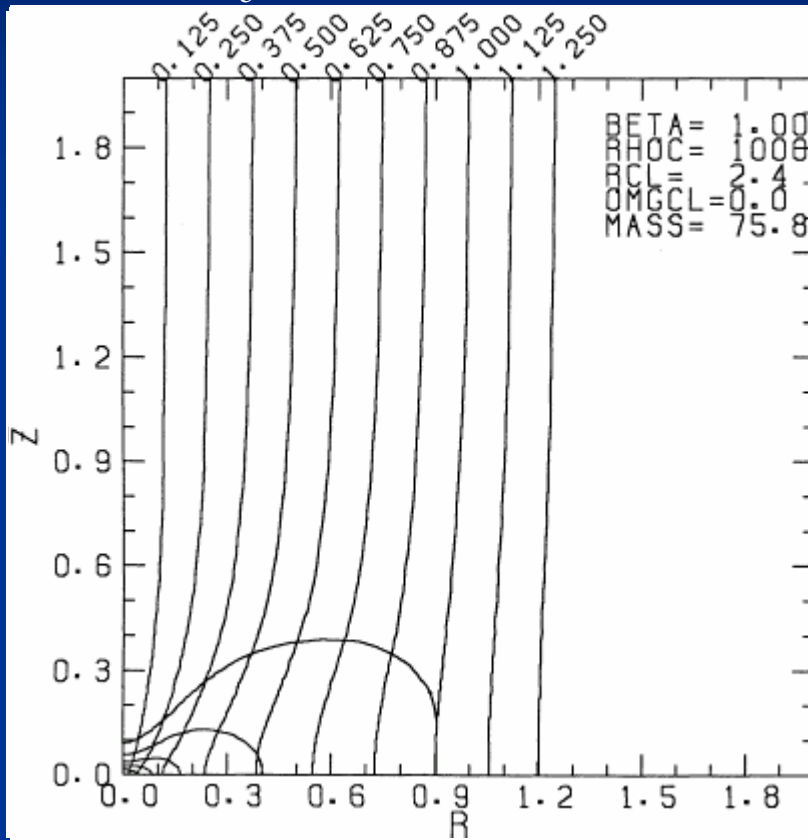
磁束管内の質量と角運動量を保存

≈ プラズマの閉じ込め

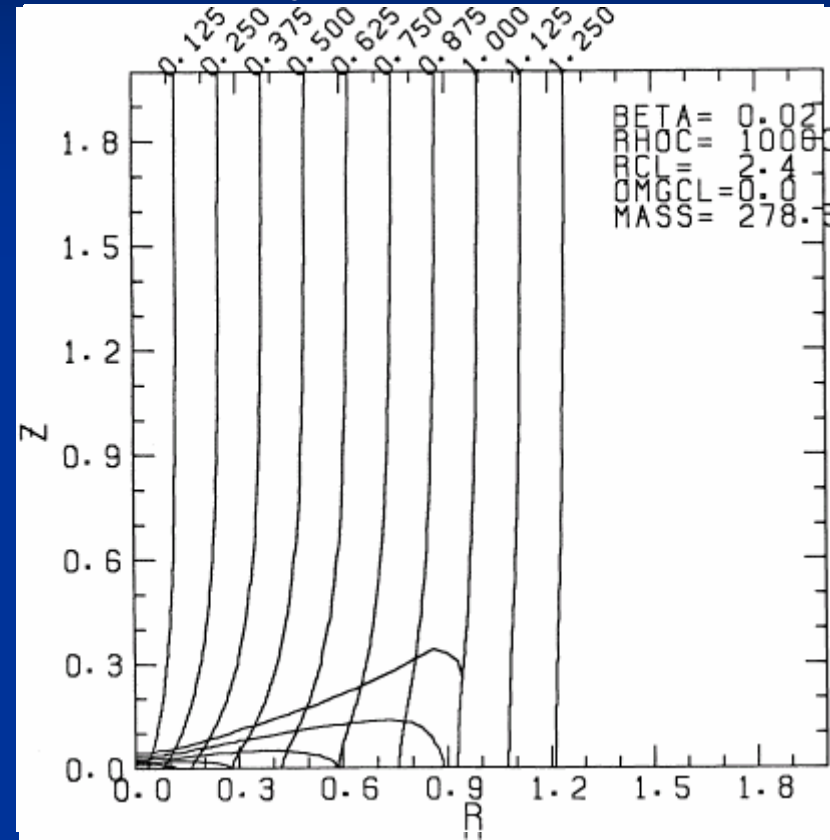
中心密度の異なる一連の解(外圧、磁束 = 一定)

$$\rho_c : 2 \Rightarrow 10^3$$

$$\rho_c : 2 \Rightarrow 10^3$$



$$\beta = 1$$



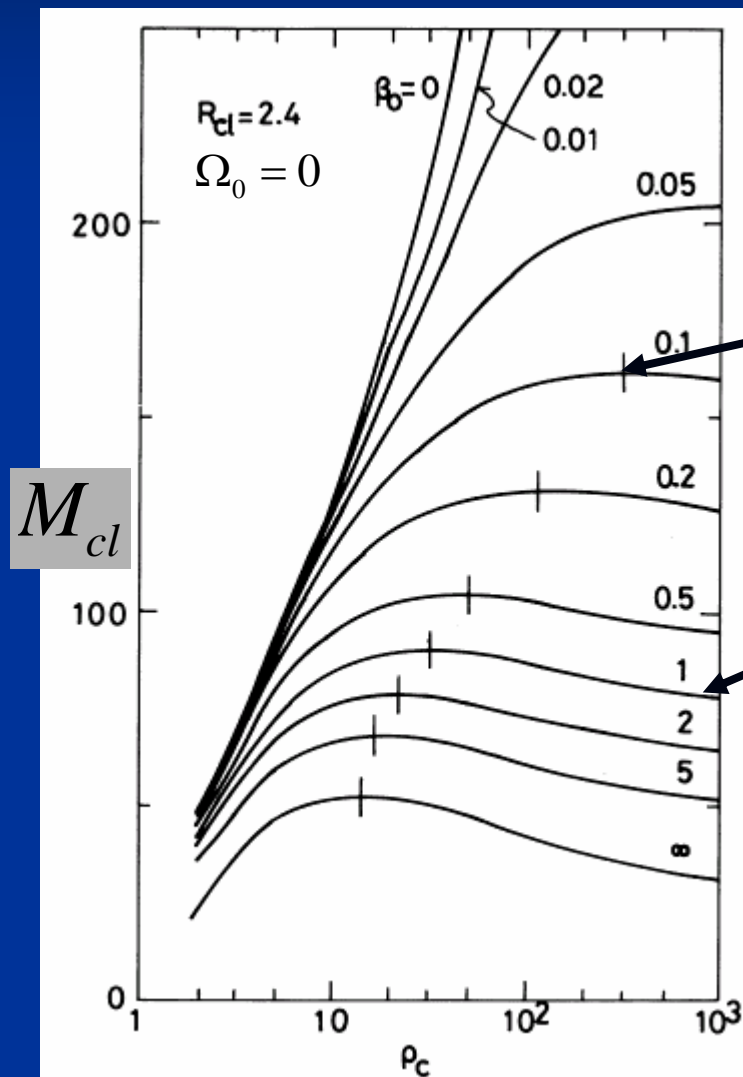
$$\beta = 0.02$$

最大質量

$$M_{cl} \approx \Phi_B / 2\pi\sqrt{G}$$

星間雲を貫く磁束

$$\Phi_B = \pi R^2 B$$



最大質量


$\Phi_B = \text{const}$

磁場は自己重力を支えることができる

$$\rho_c / \rho_s$$

磁場が存在する場合

$$\frac{1}{2} \frac{d^2 I}{dt^2} = 2(T - T_0) + M + W$$

- 星間雲を貫く磁束 $\Phi_B \equiv B_0 \pi R_0^2$ が一定
- 磁場の項 $\int B^2 dV$  $\frac{GM^2}{R}$ 重力の項
- 初期に磁場が収縮を止められなければ、その後も収縮を止めることは出来ない。
- 平衡条件 $4\pi \bar{P} R^3 - 4\pi P_0 R^3 - \frac{3G}{5R} (M^2 - M_\Phi^2) = 0$



$$\frac{3GM_\Phi^2}{5R} = \frac{\Phi_B^2}{3\pi^2 R}$$

■ 準臨界雲

$$M < M_{\Phi} \quad M_{\Phi} < M < M_{cr}$$

■ 超臨界雲

$$M > M_{\Phi}$$

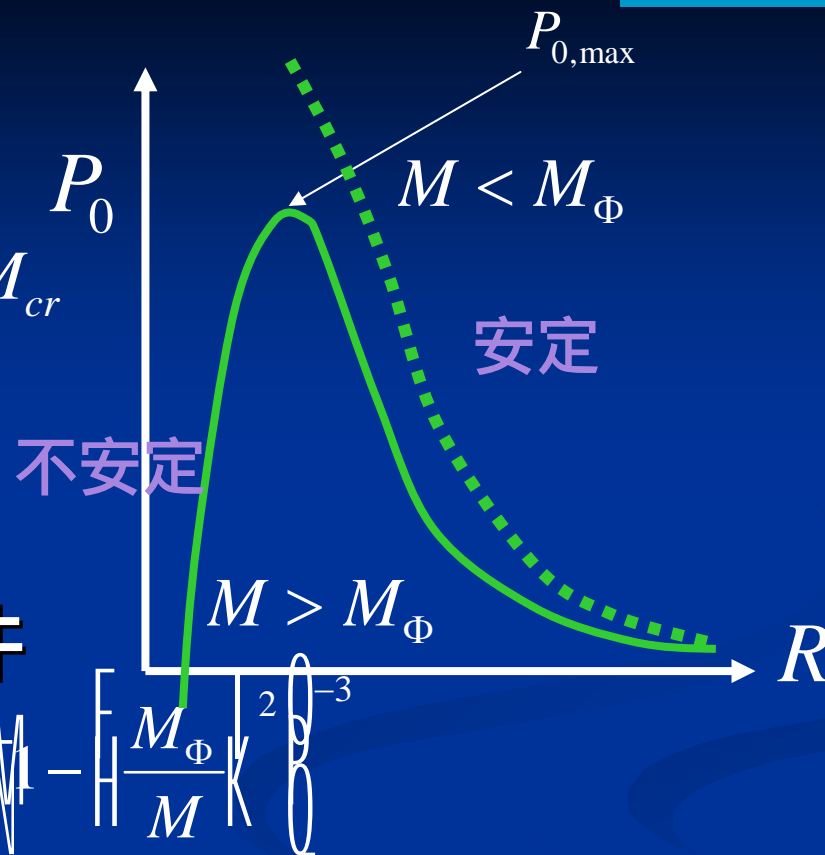
$$M > M_{cr}$$

■ 外圧に関する条件

$$P_0 < P_{0,max} = 3.15 \frac{c_s^8}{G^3 M^2}$$

■ ジーンズ質量

$$M < M_{cr} = 1.77 \frac{c_s^4}{G^{3/2} P_0^{1/2} \left[1 - (M_{\Phi}/M) \right]^{3/2}}$$



■ 超臨界雲

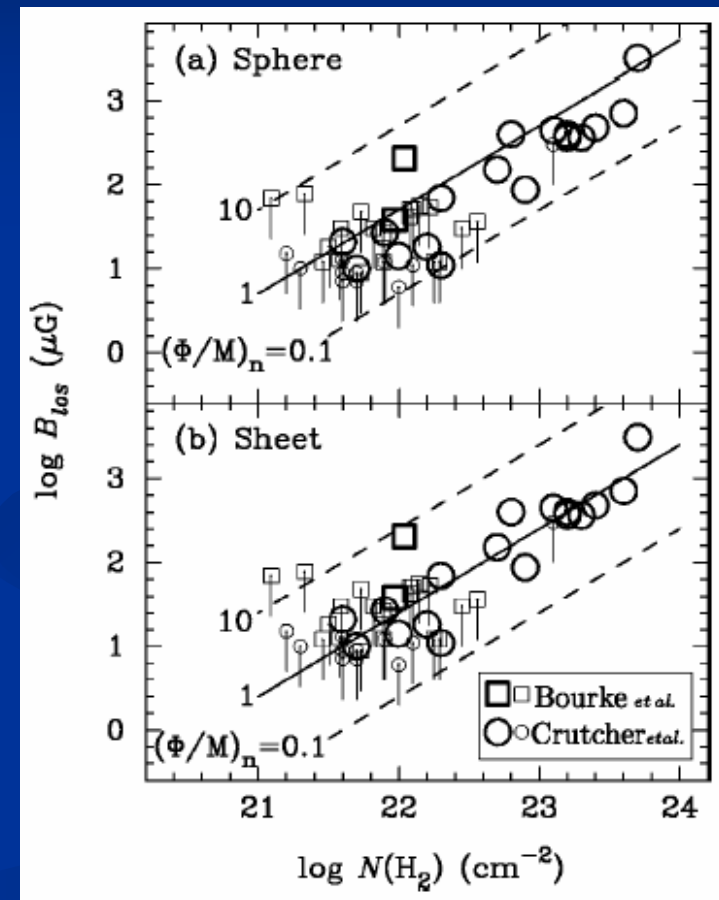
$$M_{cl} > \Phi_B / 2\pi\sqrt{G}$$

■ 動的收縮

■ 準臨界雲

$$M_{cl} < \Phi_B / 2\pi\sqrt{G}$$

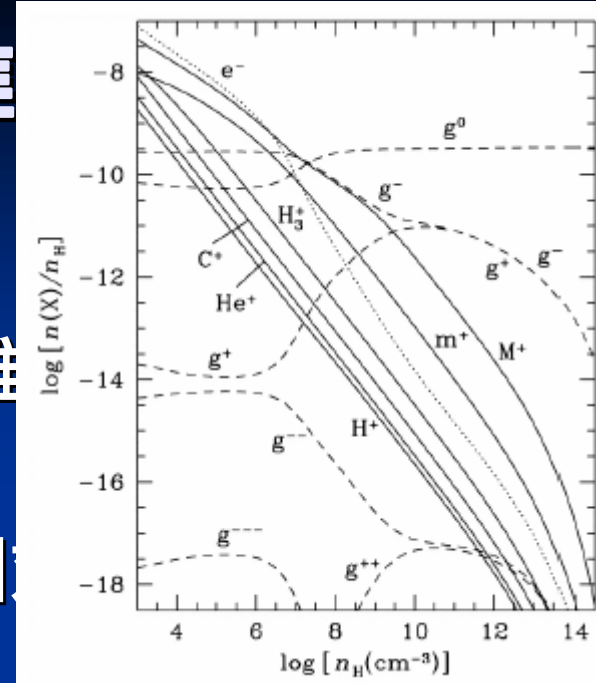
■ 準靜的進化



プラズマ・ドリフトによる準

■ プラズマ・ドリフト

- イオン、電荷を帯びたダスト：電離凍結
- 中性分子、ダスト：イオンなどと相

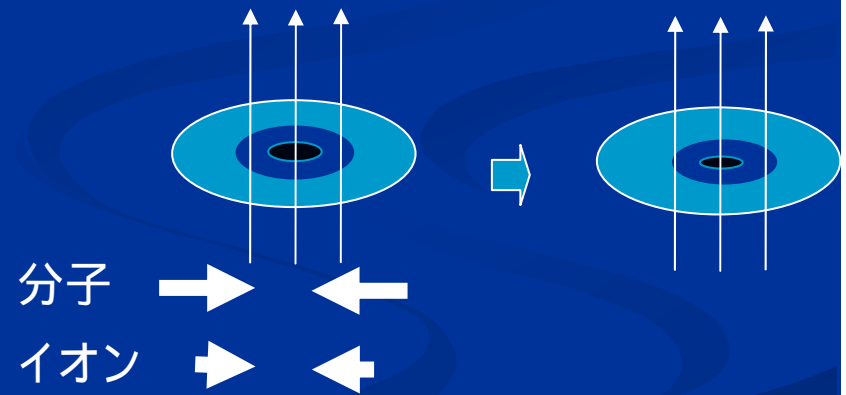


- ほぼ力学平衡状態
- 磁束/質量比の進化

$$\tau_d = \frac{R}{|\mathbf{v}_i - \mathbf{v}_n|} = \frac{4\pi\alpha\rho_i\rho_n R}{(\nabla \times \mathbf{B}) \times \mathbf{B}}$$

$$\approx \frac{4\pi\alpha\rho_i\rho_n R^2}{B^2}$$

$$= 25\text{Myr} \left(\frac{B}{3\mu\text{G}} \right)^{-2} \left(\frac{n}{10^2\text{cm}^{-3}} \right)^2 \left(\frac{R}{1\text{pc}} \right)^2 \left(\frac{x}{10^{-6}} \right)$$



プラズマ・ドリフトによる準静的進化

- 平衡状態から出発し、磁束管間のガスの移動を追跡。それに応じた平衡解をつなぐ 準静的進化
- 中心部で質量/磁束比が増大。
- 超臨界に達した段階で、動的進化に移行する。

