乱流磁場と
相対論的磁気流体風

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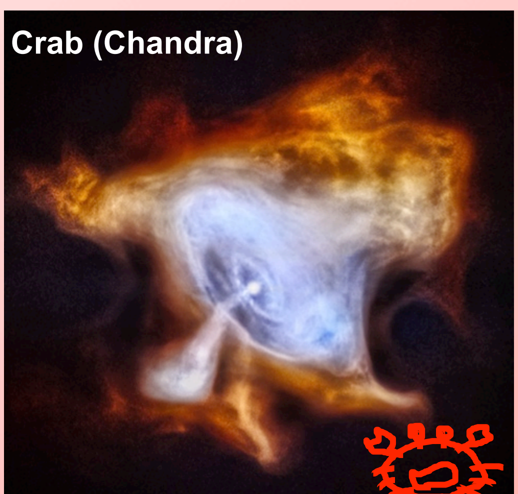
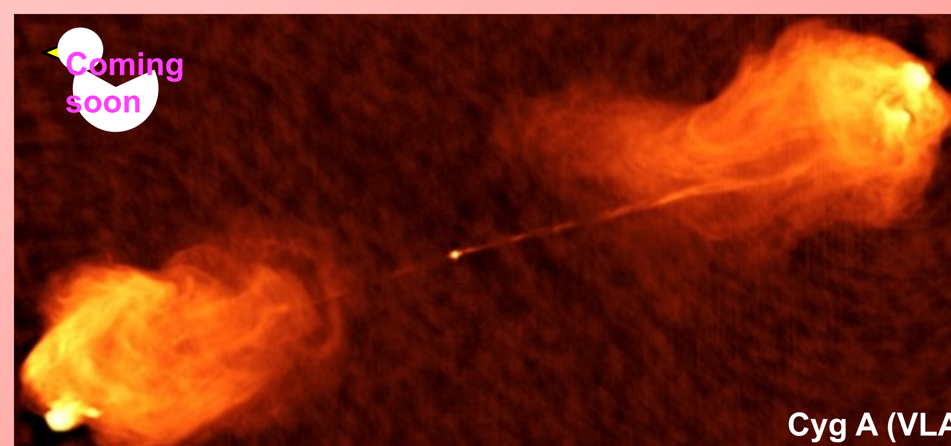
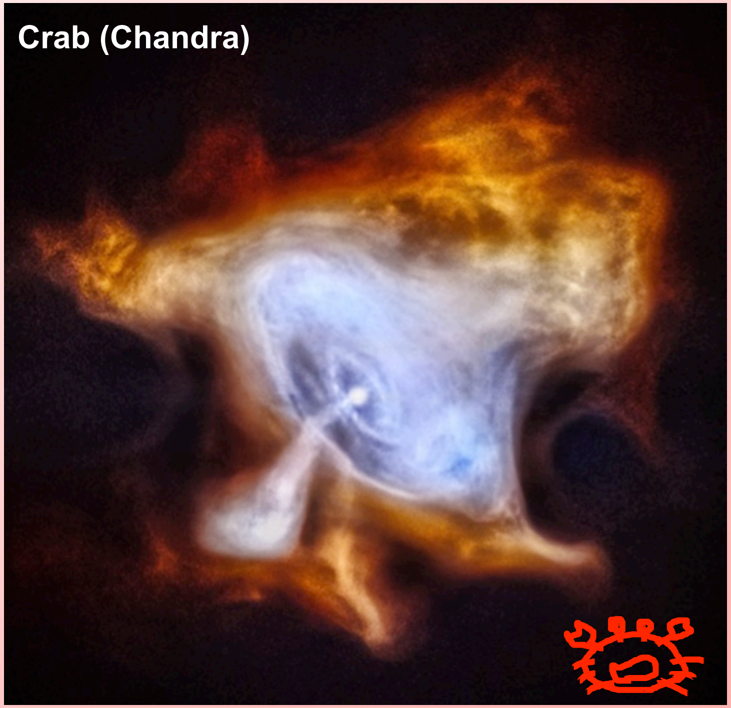


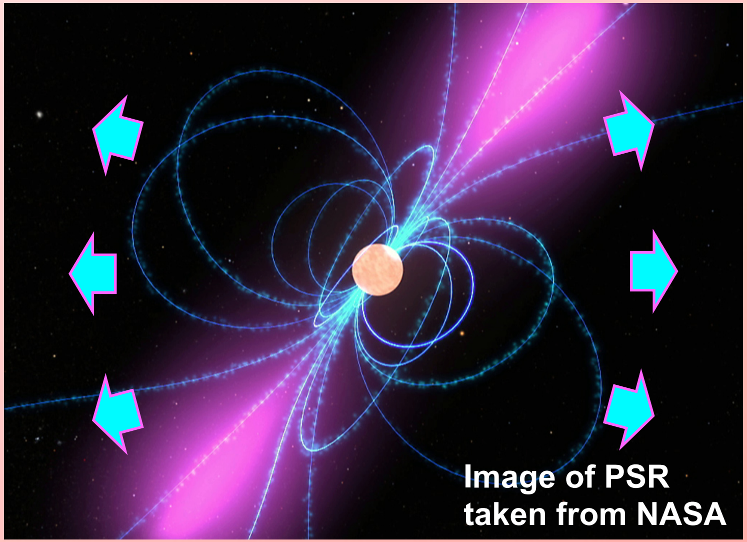


Introduction

Pulsar Winds

- Powered by pulsar = NS.
- Relativistic plasma outflow.
- High energy (non-thermal) emission.
- Non-spherical (jet-torus structure).



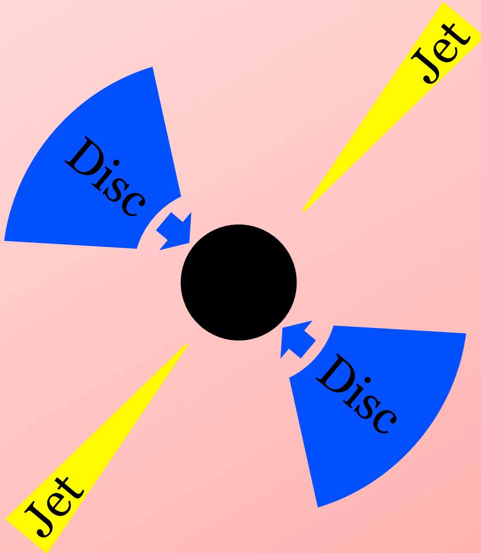


- Rotation power of pulsar ← period decrease
- $\Gamma_{wind} \gg 1$ ← relativistically hot PWN emission
- $e^{\pm}$ plasma ← high emission efficiency of PWN
- Magnetized plasma ← synchrotron emission

Relativistic Jet

- Powered by NS or BH.
- Relativistic plasma outflow.
- High energy (non-thermal) emission.
- Bipolar jets from engine.

Common astrophysical phenomena phenomena in AGN, microquasar, & GRB



- Gravitational energy (inflow -> outflow)

Same as pulsar wind

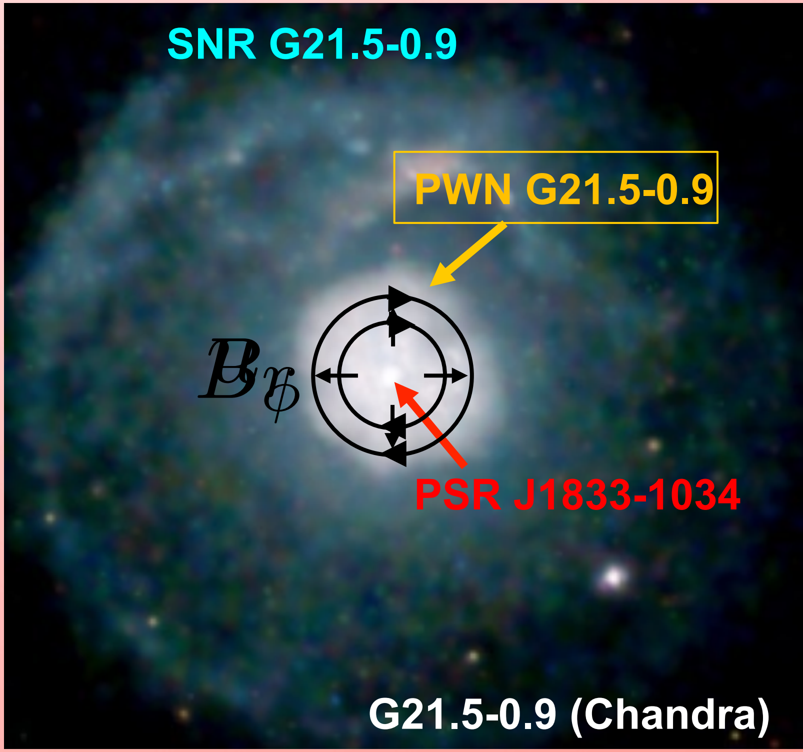
- Rotation powered?
- Role of magnetic field?
- How to accelerates to relativistic flow?
- How to collimate jets?

Motivation

KC model

Kennel & Coroniti (1984a, b) (c.f., Rees & Gunn 1974)
⇒ 1D static MHD model of PWN

- **Cold magnetized e± wind** from the central pulsar.
- **Standing strong** termination shock.
- A PWN is a post-shock pulsar wind.
- **Steady & spherical** system.
- Nebular flow is **pure radial flow**.
- Nebular B-field is **pure toroidal**.
- A PWN is an **ideal MHD flow**.



- Broadband emission by shock-accelerated non-thermal particles.

System dynamics is controlled by magnetization of pulsar wind:

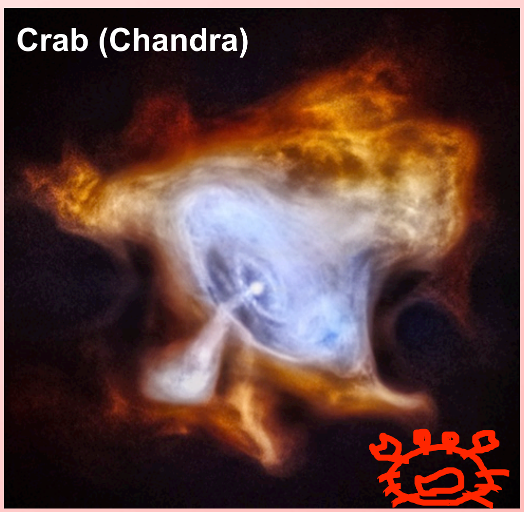
σ = Poynting / particle energy flux

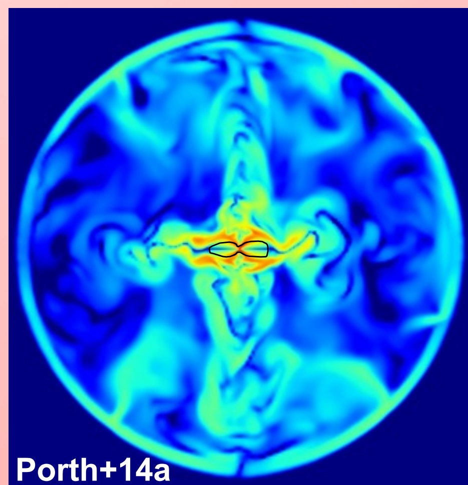
Beyond KC model to resolve σ-problem

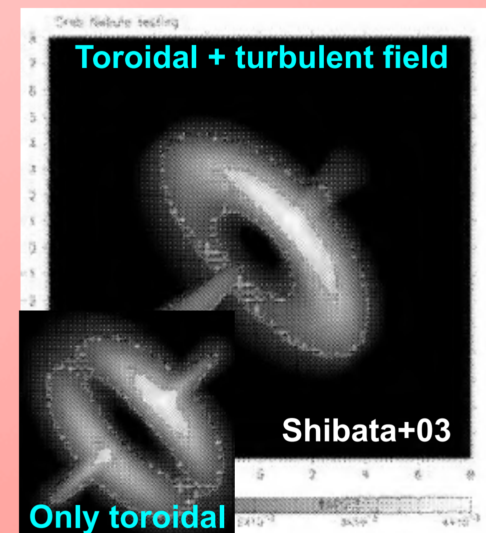
Efforts to $\sigma \ll 1$ in wind region have not been accomplished

KC model = 1D ideal MHD with B_φ

1D? | Ideal MHD? | Toroidal B-field?







3D effects (turbulence) & B-field dissipation (non-ideal MHD)

Basic Equations

Extend KC model by adding phenomenological terms which represent **radiation** loss, **turbulent** magnetic field, & magnetic **dissipation**.

TTT18ApJ

Eq. of continuity

$$\langle \nabla_\mu (n u^\mu) \rangle = 0,$$

Conservation of total energy

$$\langle \nabla_\mu T^{\mu t} \rangle = -\gamma \frac{\Lambda_{\rm rad}}{c},$$

Conservation of fluid internal energy

$$-\langle u_\nu \nabla_\mu T^{\mu\nu}_{\rm FL} \rangle = \frac{\delta b^2/2}{\tau_{\rm diss}} - \frac{\Lambda_{\rm rad}}{c},$$

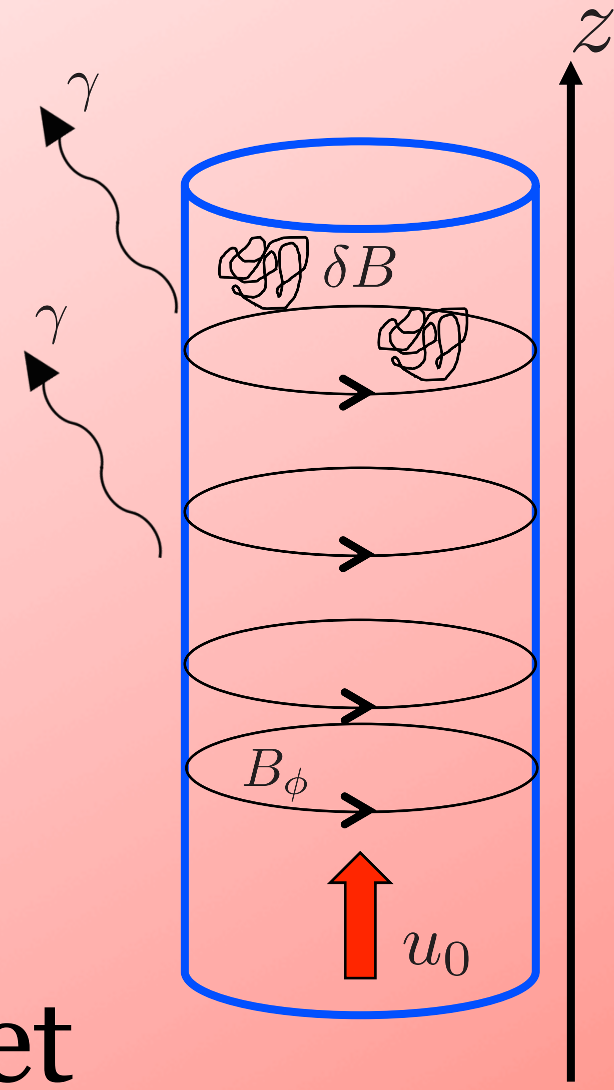
Induction equation for (mean) toroidal field + turbulent field

$$\frac{1}{2}\langle \bar{b}_\mu e^{\mu\nu\alpha\beta} \nabla_\nu F_{\alpha\beta} \rangle = -\frac{\bar{b}^2/2}{\tau_{\rm conv}},$$

$$\frac{1}{2}\langle \delta b_\mu e^{\mu\nu\alpha\beta} \nabla_\nu F_{\alpha\beta} \rangle = \frac{\bar{b}^2/2}{\tau_{\rm conv}} - \frac{\delta b^2/2}{\tau_{\rm diss}}.$$

Steady & spherical symmetry

A Model of Cylindrical Jet



Basic Equations

TTT18の乱流磁場入りの相対論的MHD modelを採用。
radiation loss, **turbulent** magnetic field, & magnetic **dissipation**.

Eq. of continuity

$$\langle \nabla_\mu (n u^\mu) \rangle = 0,$$

Conservation of total energy

$$\langle \nabla_\mu T^{\mu t} \rangle = -\gamma \frac{\Lambda_{\rm rad}}{c},$$

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定常な円柱状ジェットを考える

Cylinder Jet再考

一次元定常流は加速しない ⇔ 一次元定常流は膨張しない

$$(\beta^2 - \beta_{\rm c}^2)\frac{du}{dz} = \frac{8u}{3r}\frac{p}{\epsilon}, \quad \epsilon = w + \bar{b}^2$$

TTT18ではCrab Nebula内での乱流磁場の生成による減速を考えた

$$(\beta^2 - \beta_{\rm c}^2)\frac{du}{dz} = \frac{8u}{3r}\frac{p}{\epsilon} + \frac{\Lambda_{\rm rad}}{3c} + \frac{\bar{b}^2}{3c\tau_{\rm conv}}$$

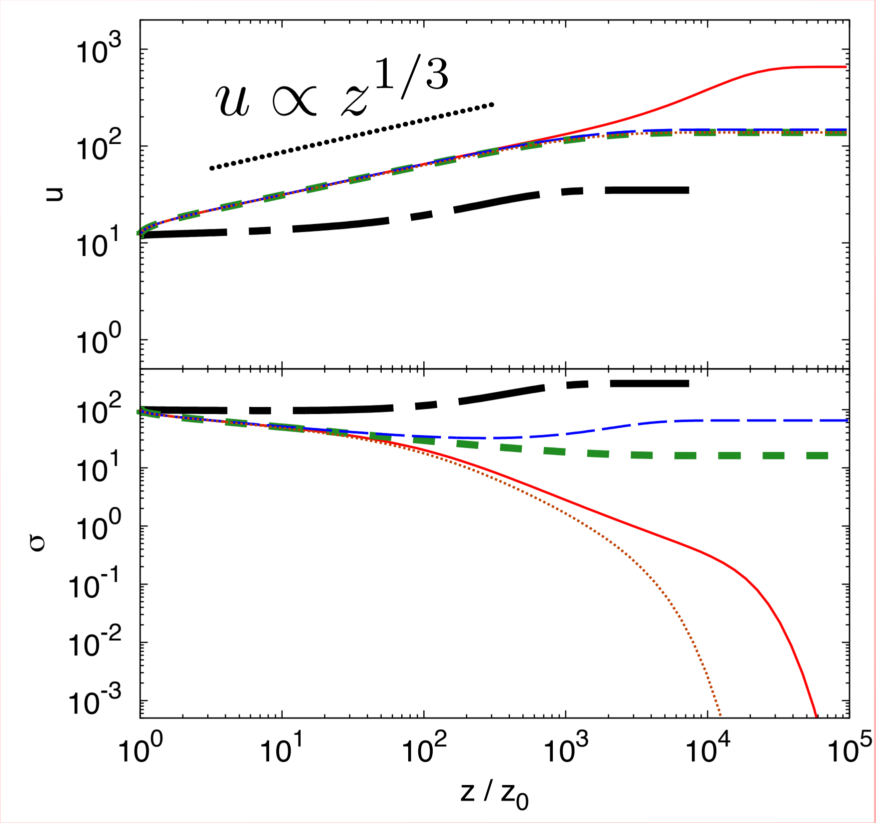
希薄化加速とは別のメカニズム

Results u & σ

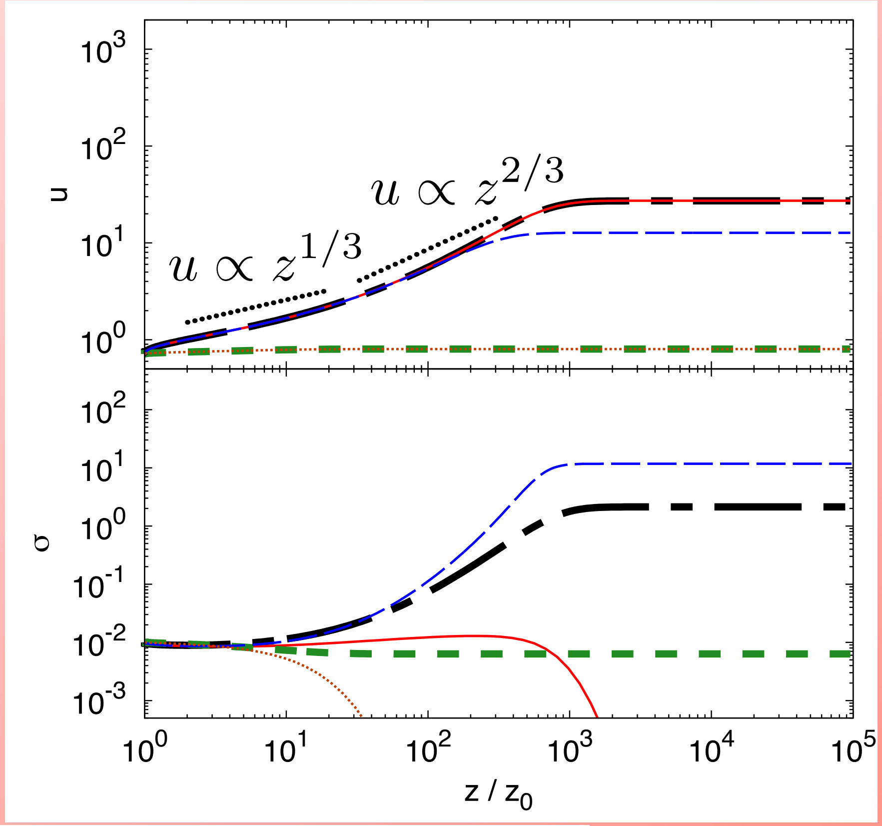
固有系でz_{diss}, z_{conv}が一定

	黒	赤	緑	青	茶
$\tilde{z}_{\mathrm{conv}}$	10^{10}	10	10	10	10
$\tilde{z}_{\mathrm{diss}}$	10^{10}	10	10^{10}	10^{10}	10
$\tilde{z}_{\mathrm{cool}}$	10	10	10^{10}	10	10^{10}

High-σ flow: $\sigma_0 = 10^2$



Low-σ flow: $\sigma_0 = 10^{-2}$



$$(n_0, u_0, w_0, b_0, \delta b_0) = (\gamma_{\mathrm{max}} = 10^4, u_{\mathrm{c}} + \delta u, 1.0, \sigma_0, 0.0)$$

$$w_0 \left[\frac{L_0}{A_0 c u_0 \gamma_0 (1 + \sigma_0)} \right]$$

L_0(全光度), A_0(断面積), z_0(初期位置)で系が定まる。

Summary

一次元流の加速

- 乱流磁場の生成、散逸をモデル化した非MHD方程式系 c.f., STTT18
- 球対称系と同じ $u \propto z^{1/3}$が得られる。 c.f., Drenkhan02
- 散逸+放射冷却を加えることでより加速する。
- 磁場変換、磁場散逸、冷却はそれぞれ違う加速の仕方を示す。
- Total energyが同じ場合、high-σ_0 flowの方が(粒子が少ない分)速くなれる。

Further studies

- 安定なcylinder jetのτ_{conv}をどう評価するのか?
  - Spine-sheath構造でも本当に安定?