コンパクト天体の磁場構造とその活動性

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早稲田大学理工学術院

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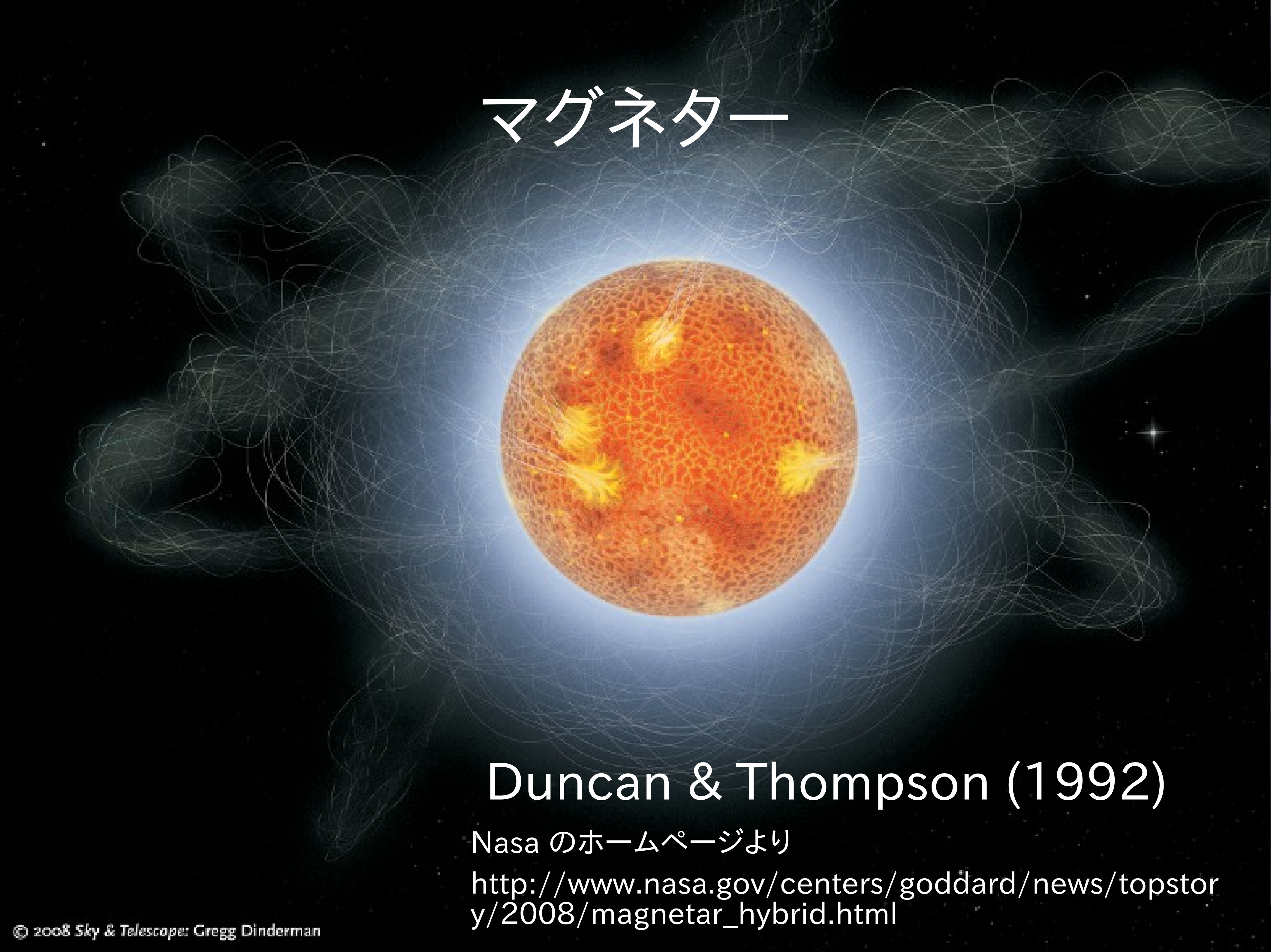
コンパクト天体の活動性と磁気的性質

星の外部の磁場構造

星の内部の磁場構造

動機づけ
（モチベーション）

マグネター



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Duncan & Thompson (1992)

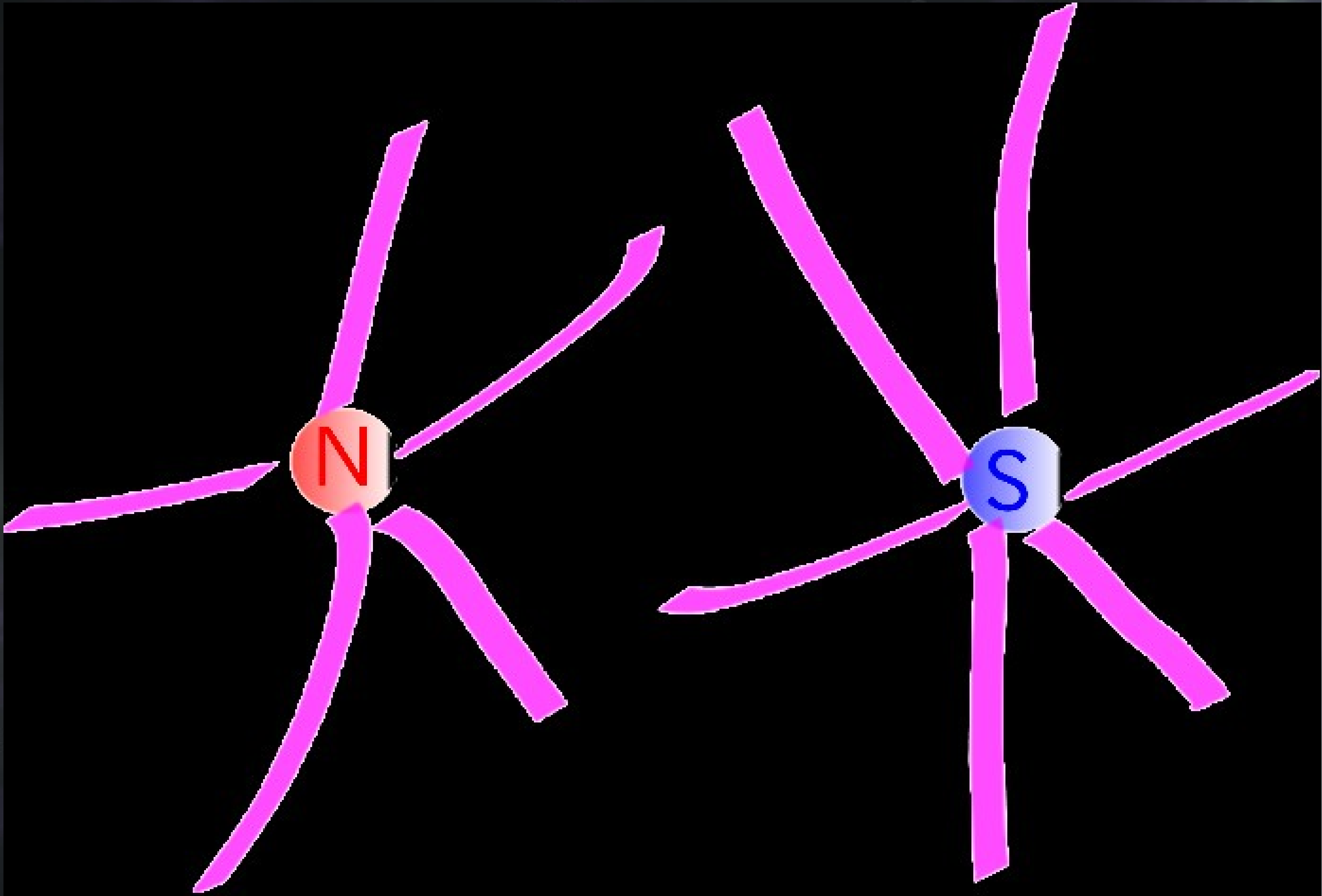
Nasa のホームページより

http://www.nasa.gov/centers/goddard/news/topstory/2008/magnetar_hybrid.html

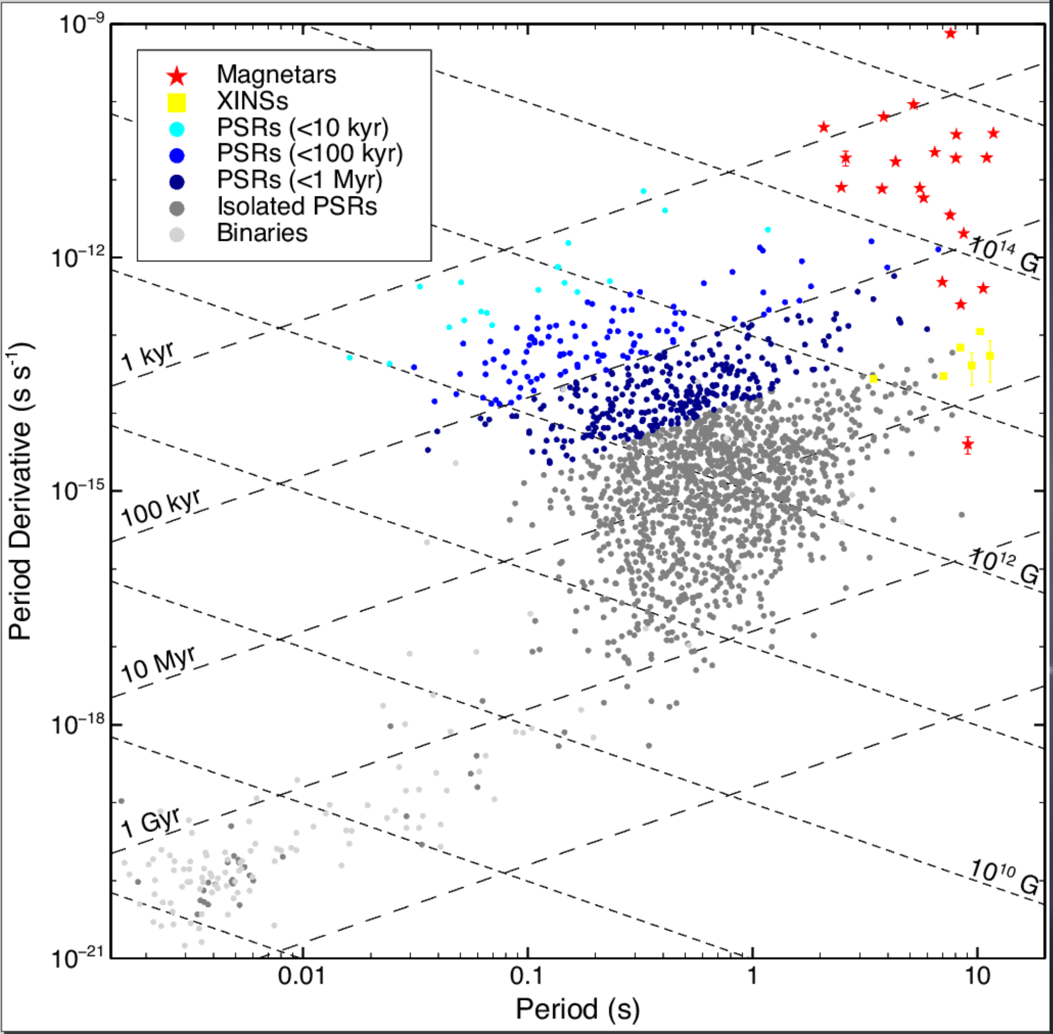
マグネター

SGR 1900+14 (Spitzer Space Telescope)

Wikipedia より


N
S

スピンダウンが大きい



磁気双極子放射

$$L = \frac{1}{6} B_1^2 \frac{r_s^6 \Omega_0^4}{c^3} \sin^2 \chi_1$$

を仮定すると磁場は

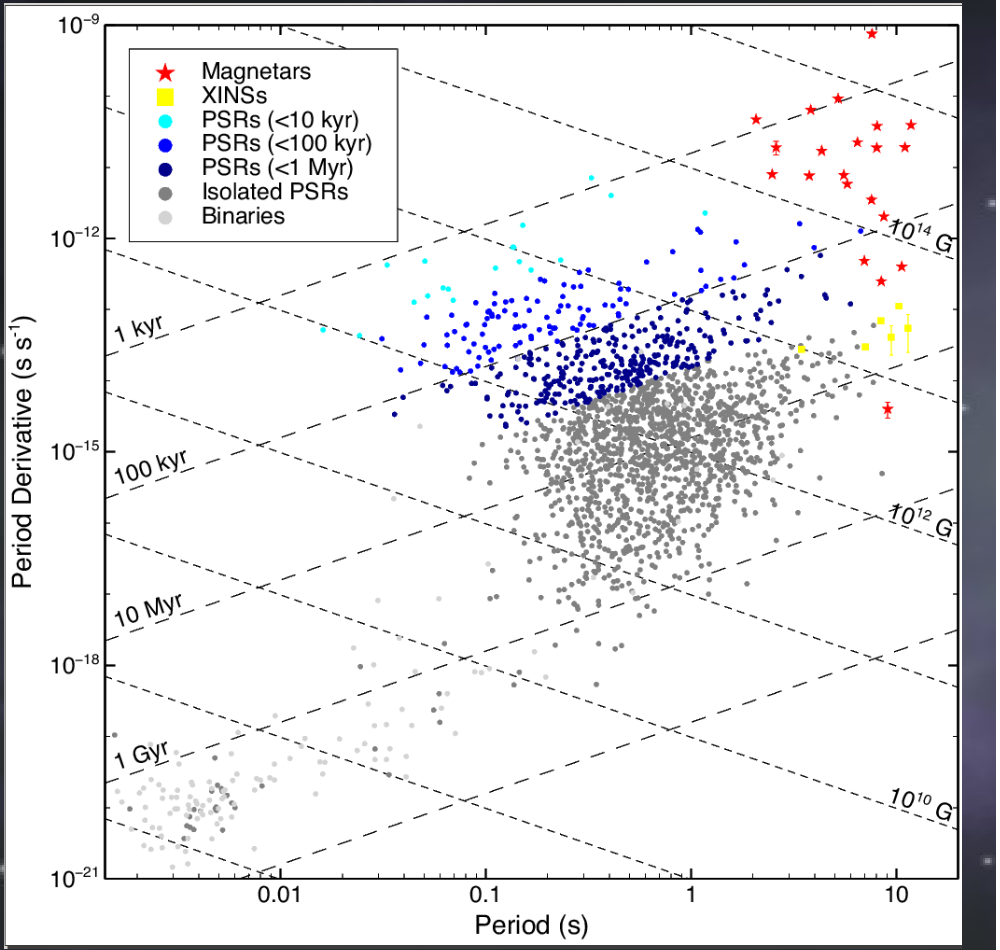
$$B_s \sim 10^{15}\mathrm{G}(P\dot{P}_{10})^{1/2}$$

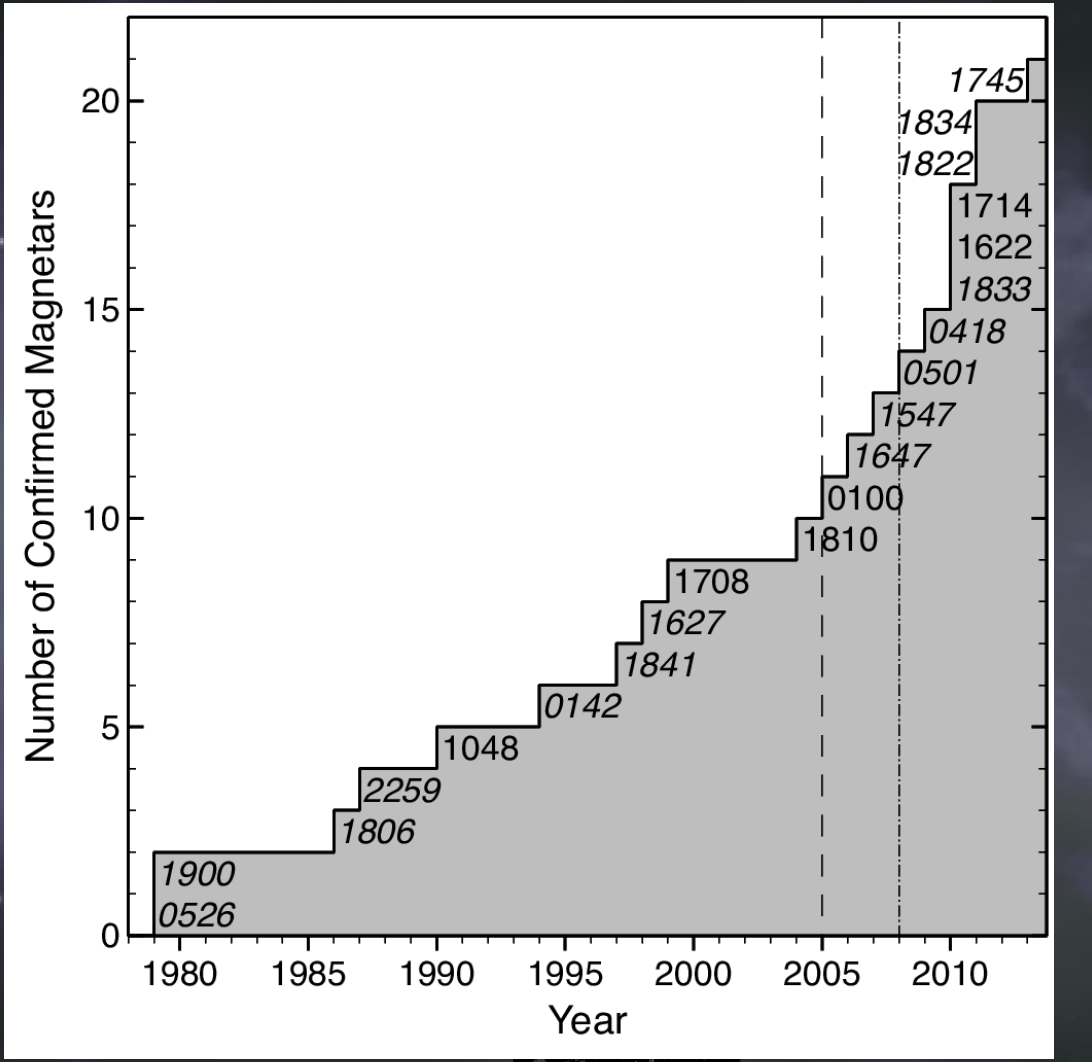
- Olausen & Kaspi（2013）

マグネター

Wikipedia より

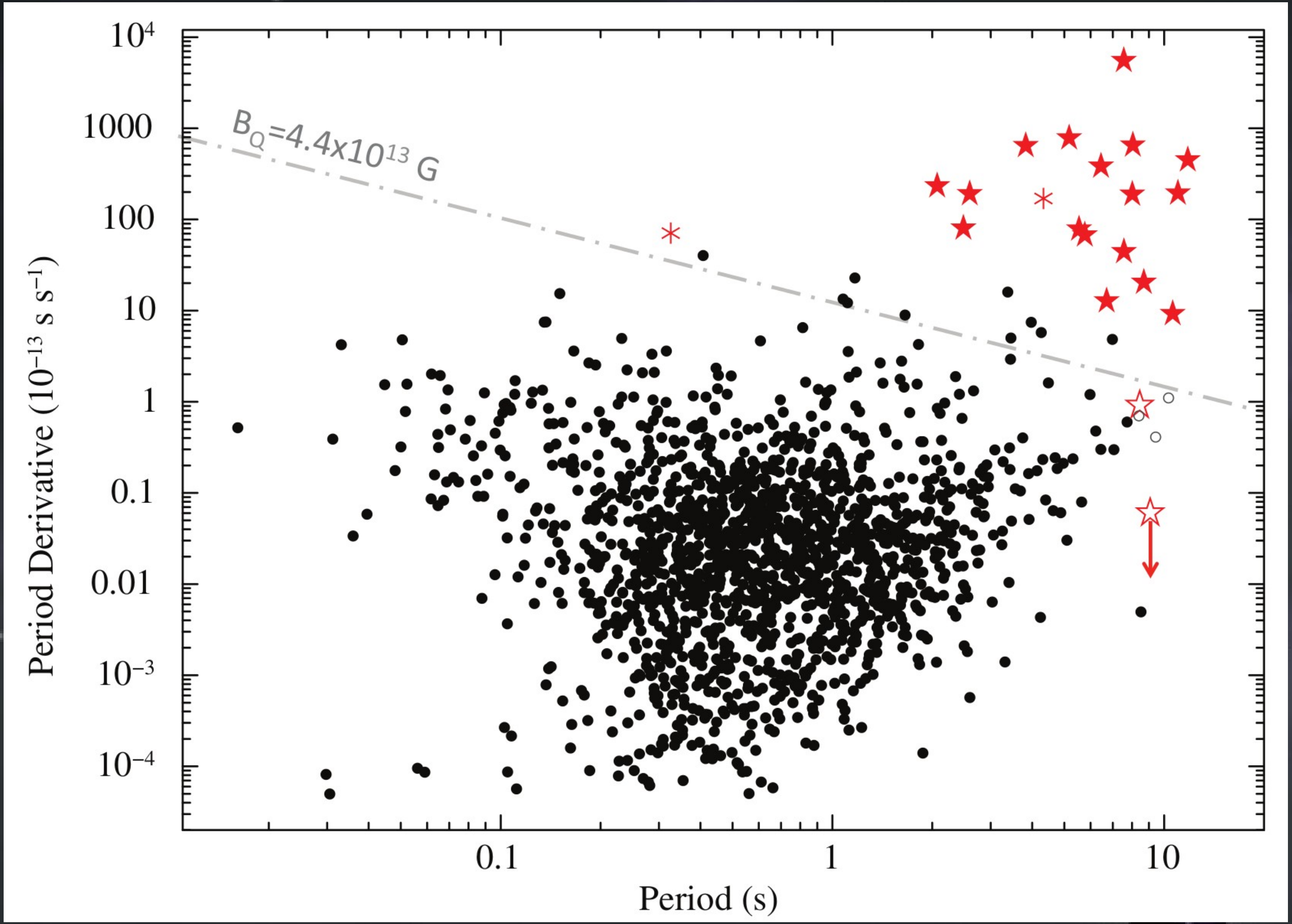
発見されたマグネターの数





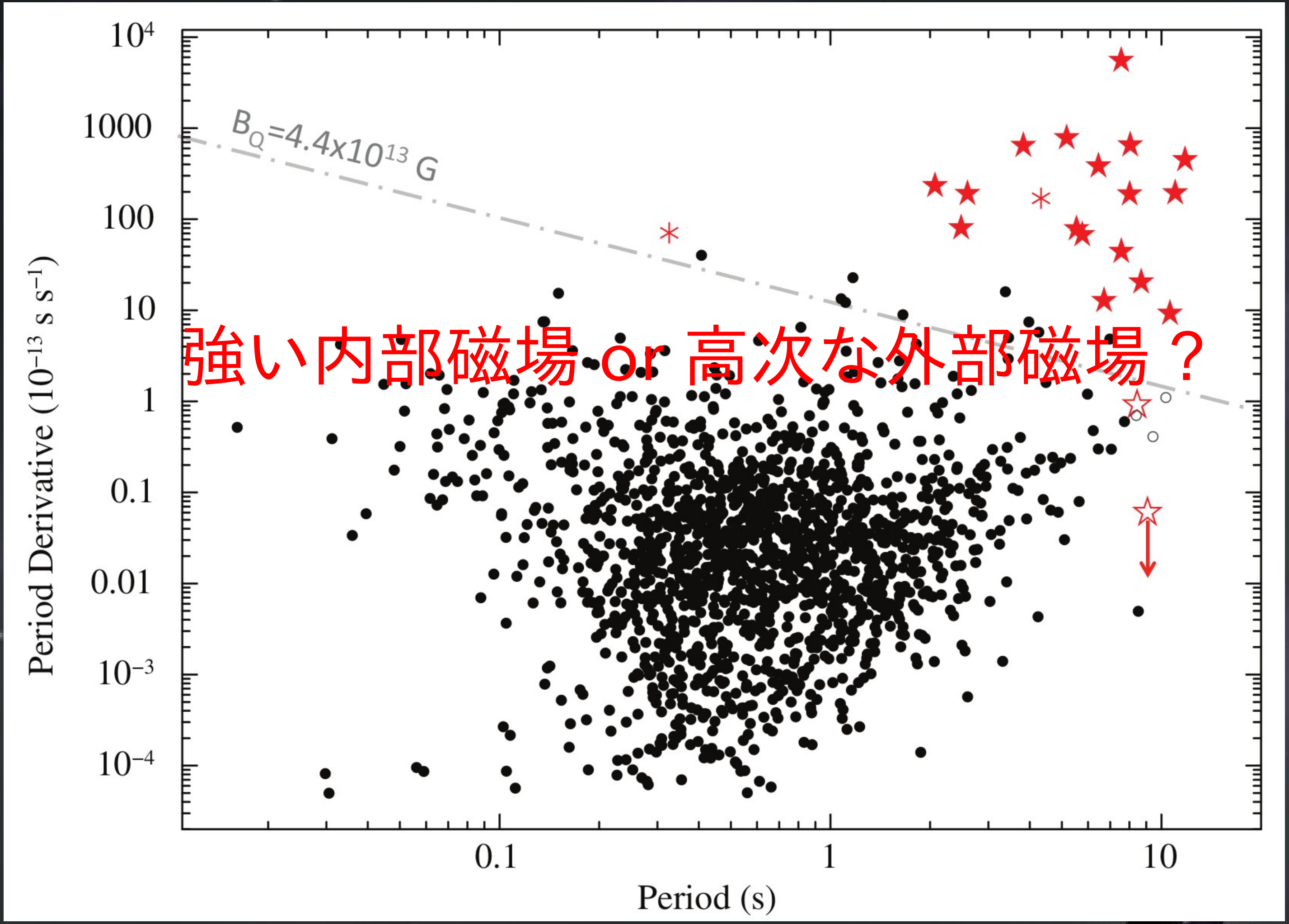
- Olausen & Kaspi（2013）

磁場の弱いマグネター



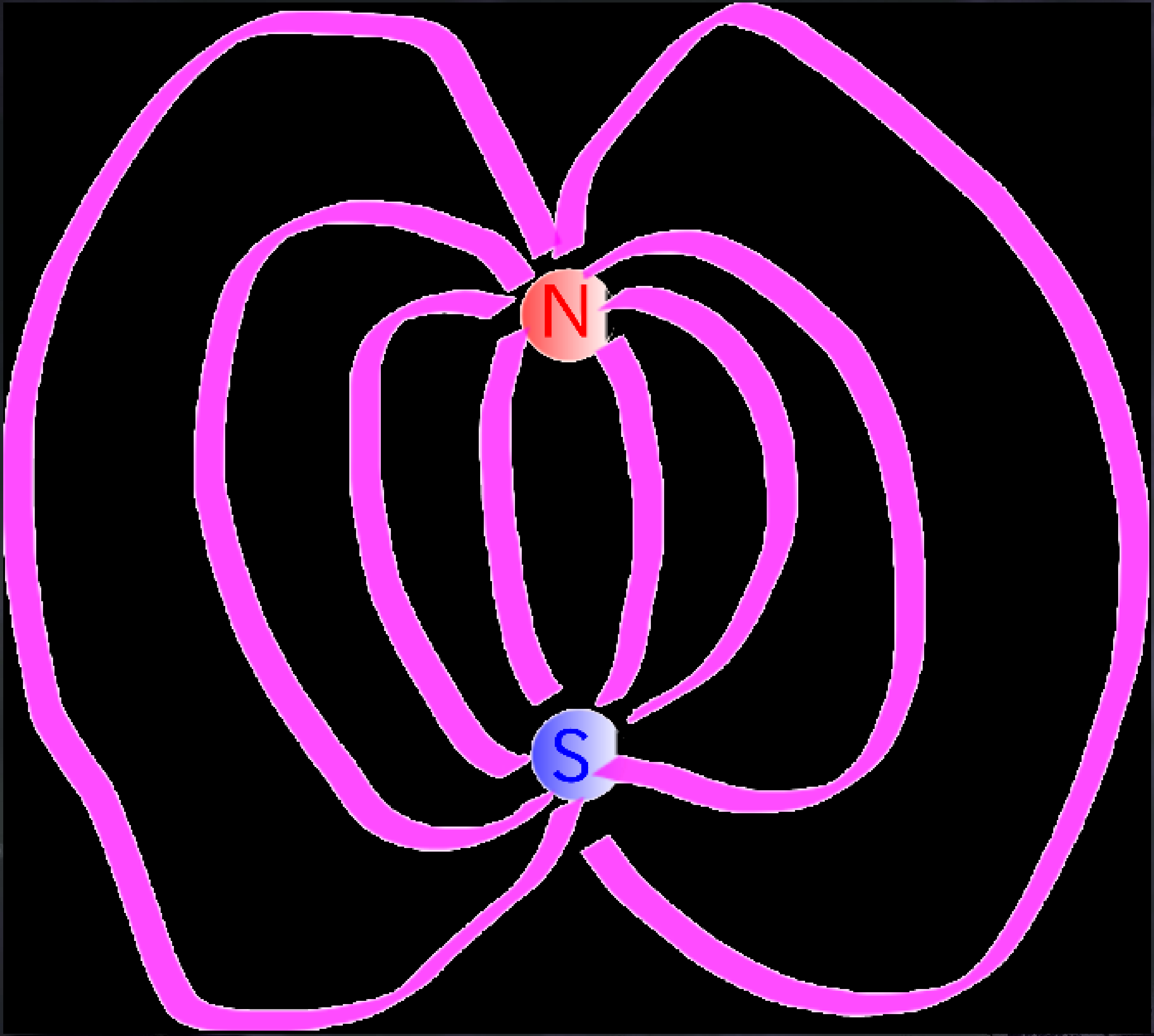
- Rea et al. (2010; 2012)

磁場の弱いマグネター



強い内部磁場 or 高次な外部磁場？

- Rea et al. (2010; 2012)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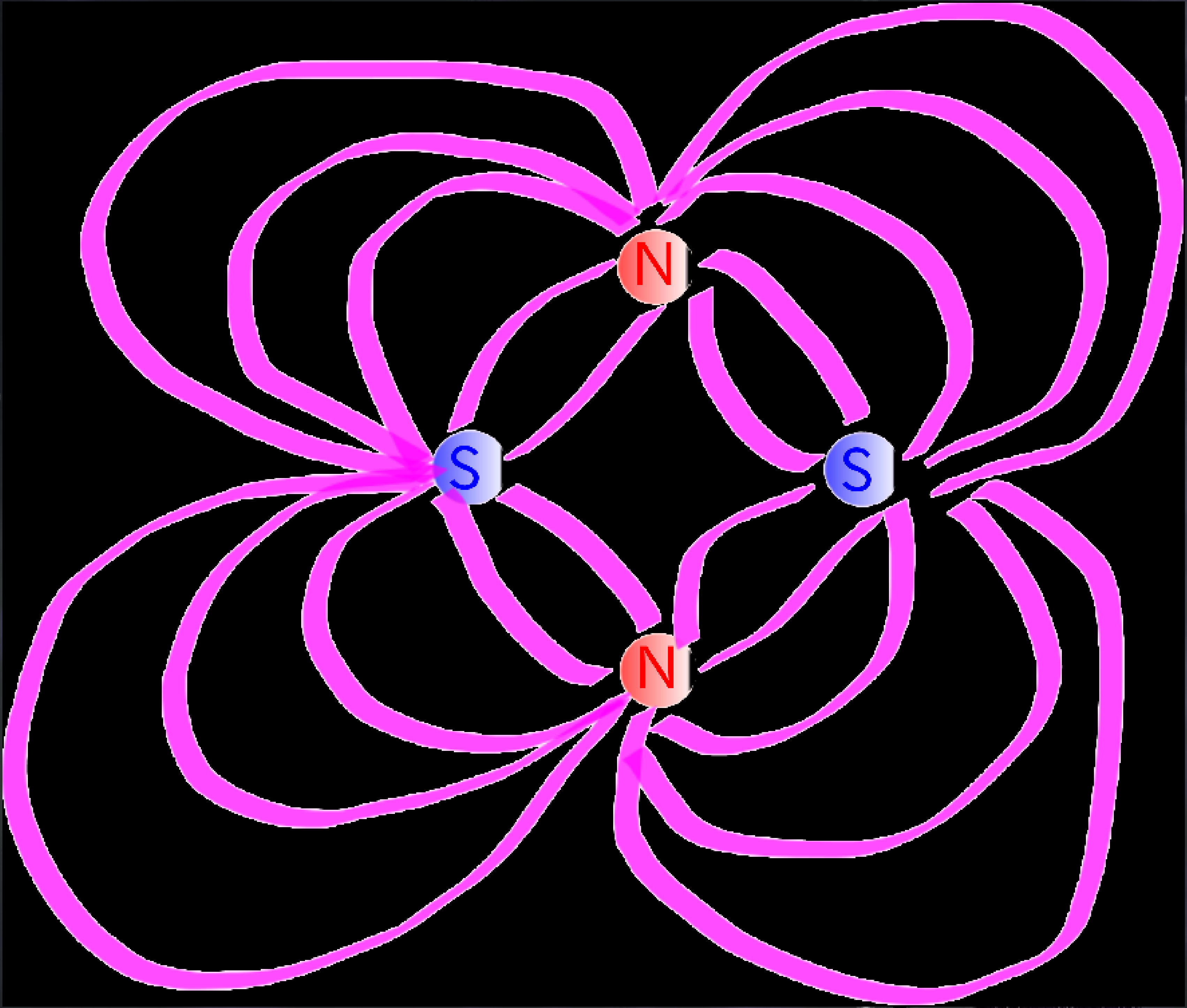
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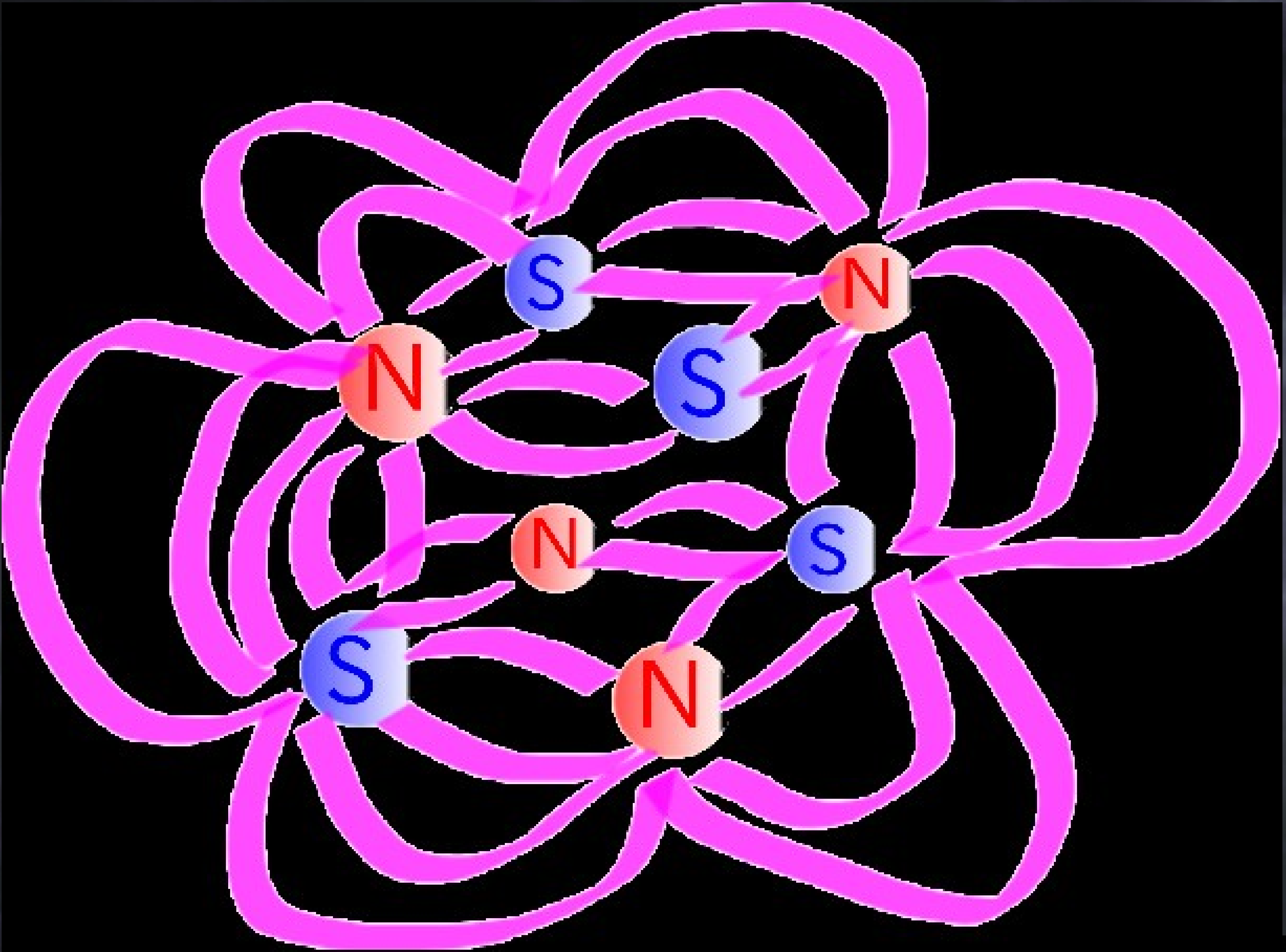
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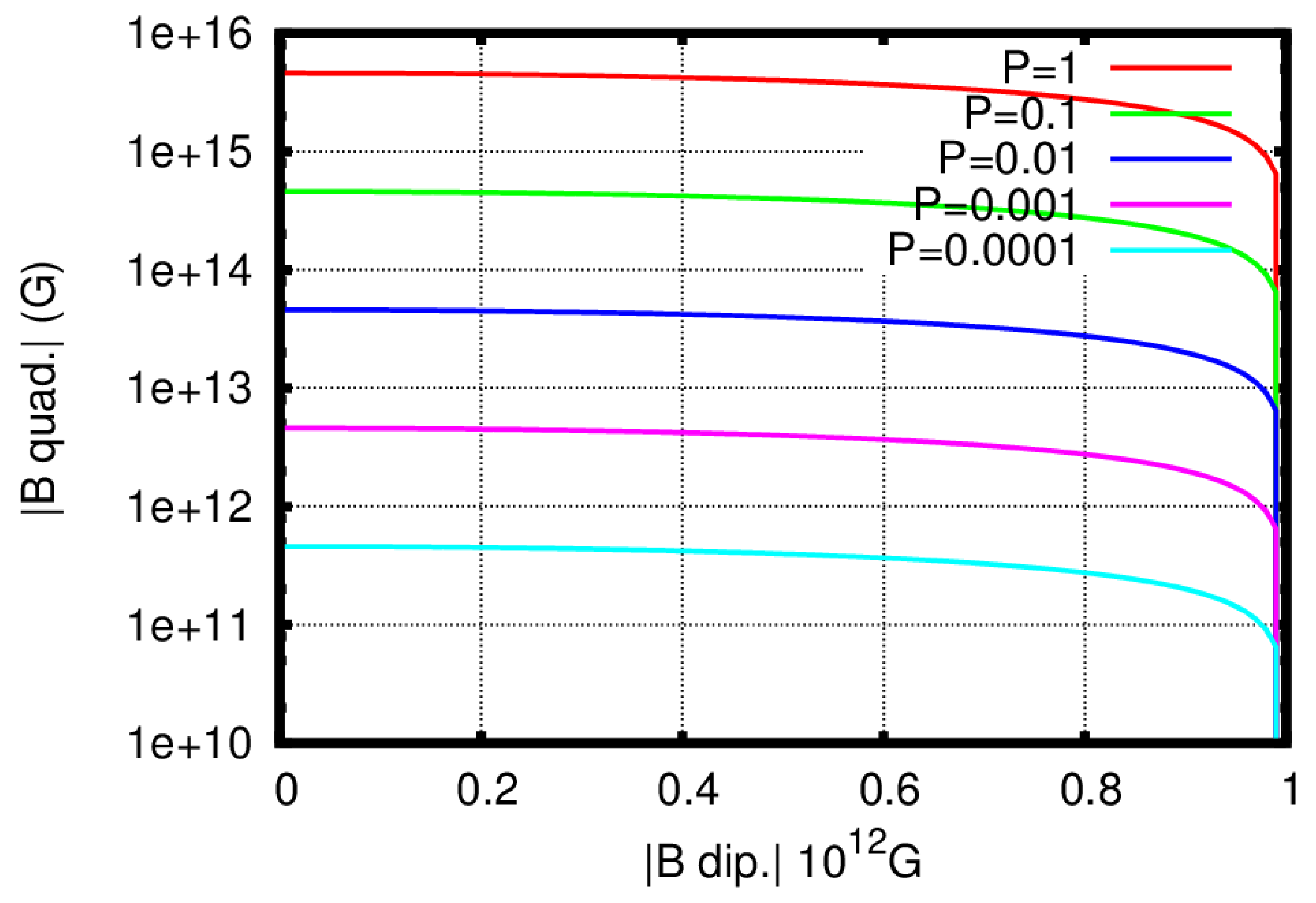
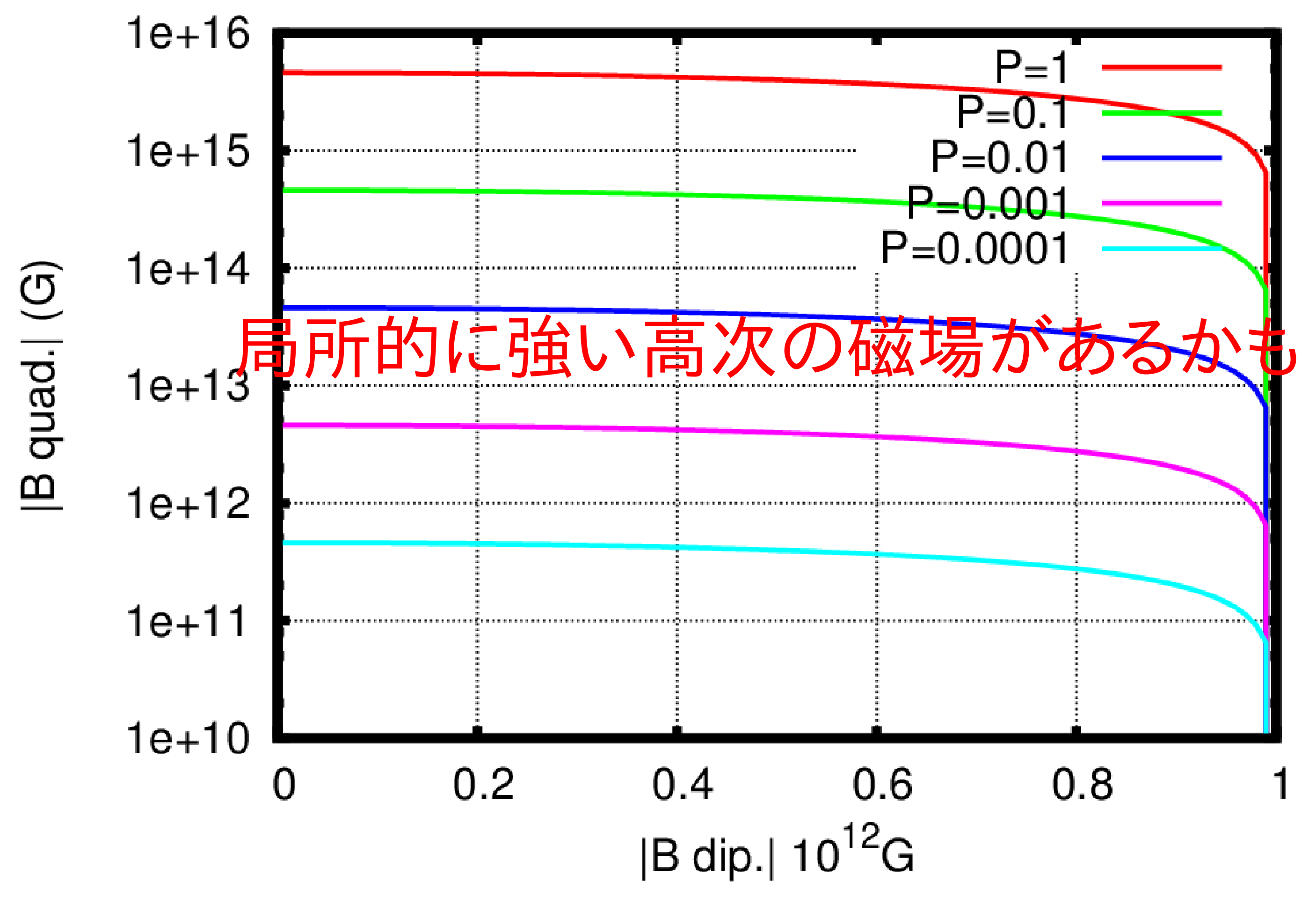
磁気四重極子放射



$$L = \frac{1}{6} B_1^2 \frac{r_s^6 \Omega_0^4}{c^3} \sin^2 \chi_1 + \frac{1}{360} B_2^2 \frac{r_s^8 \Omega_0^6}{c^5} \sin^2 2\chi_2 + \frac{8}{45} B_2^2 \frac{r_s^8 \Omega_0^6}{c^5} \sin^4 \chi_2,$$

- Kojima & Kato (2011)

磁気四重極子放射

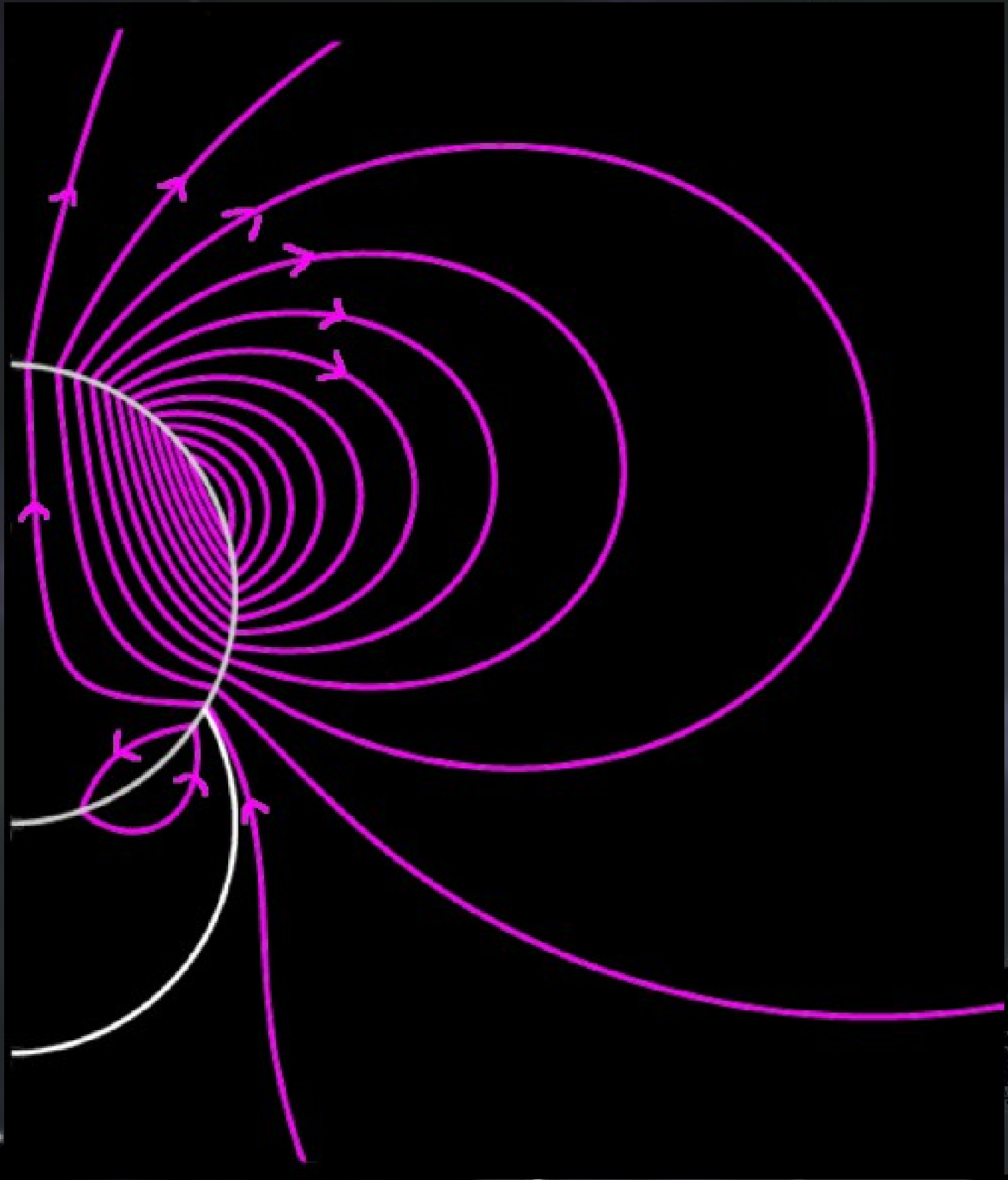


局所的に強い高次の磁場があるかも

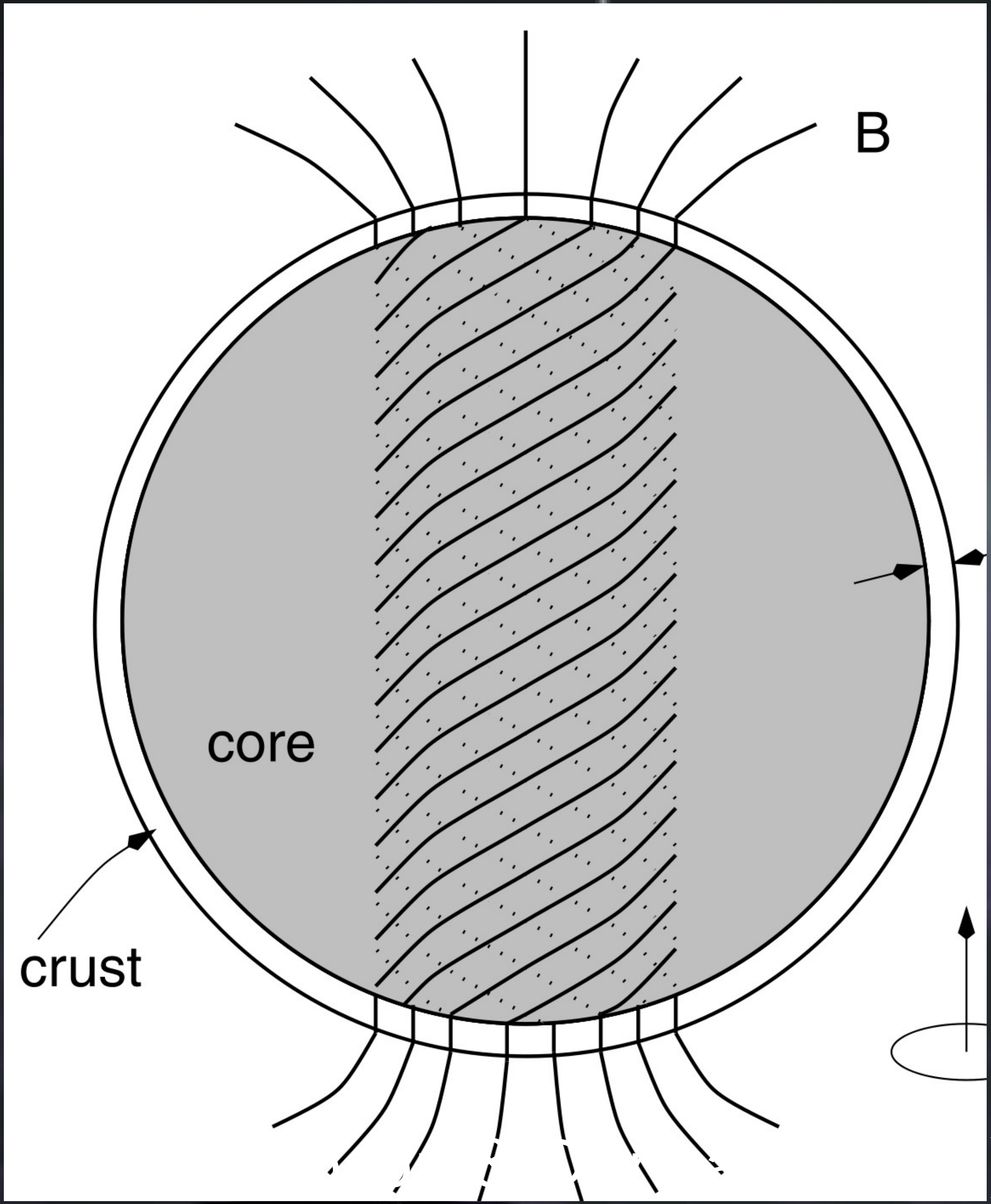
$$L = \frac{1}{6} B_1^2 \frac{r_s^6 \Omega_0^4}{c^3} \sin^2 \chi_1 + \frac{1}{360} B_2^2 \frac{r_s^8 \Omega_0^6}{c^5} \sin^2 2\chi_2 + \frac{8}{45} B_2^2 \frac{r_s^8 \Omega_0^6}{c^5} \sin^4 \chi_2,$$

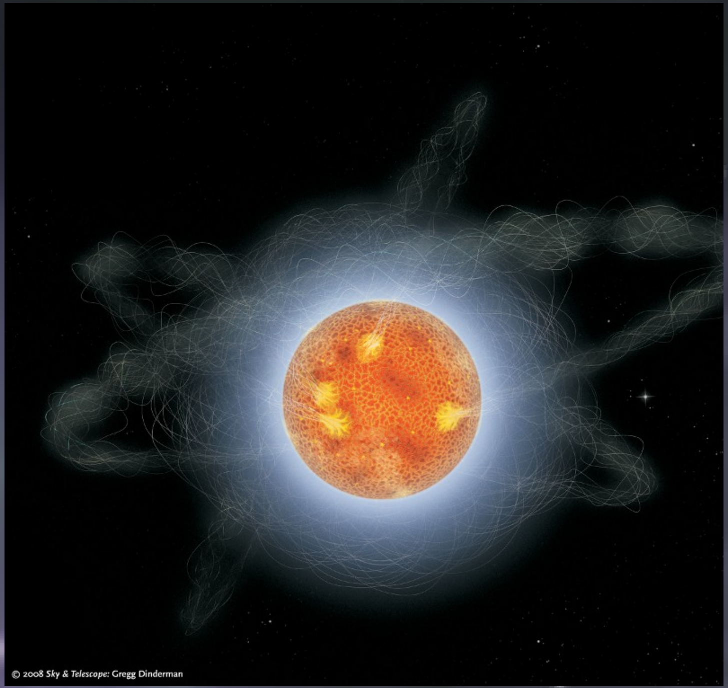
- Kojima & Kato (2011)

双極子 + 四重極子磁場



マグネター




© 2008 Sky & Telescope: Gregg Dinderman

- Duncan & Thompson (1992)
- Thompson & Duncan (1995,1996)

)

マグネター(中性子星)の磁場

- 化石磁場
- (差動)回転による増幅 (ダイナモ, MRI)
  - Thompson & Duncan (1992), Sawai & Yamada (2014) , Kiuchi et al. (2014)
- クラスト内部の熱磁気効果
  - Blandford et al. (1983)
  - Ho, Blandford, & Hernquist (2004)
- 強磁性
  - Makishima et al. (1999); Tatsumi (2000); Eto, Hashimoto & Hatsuda (2013)

磁場の起源は？

化石

磁石

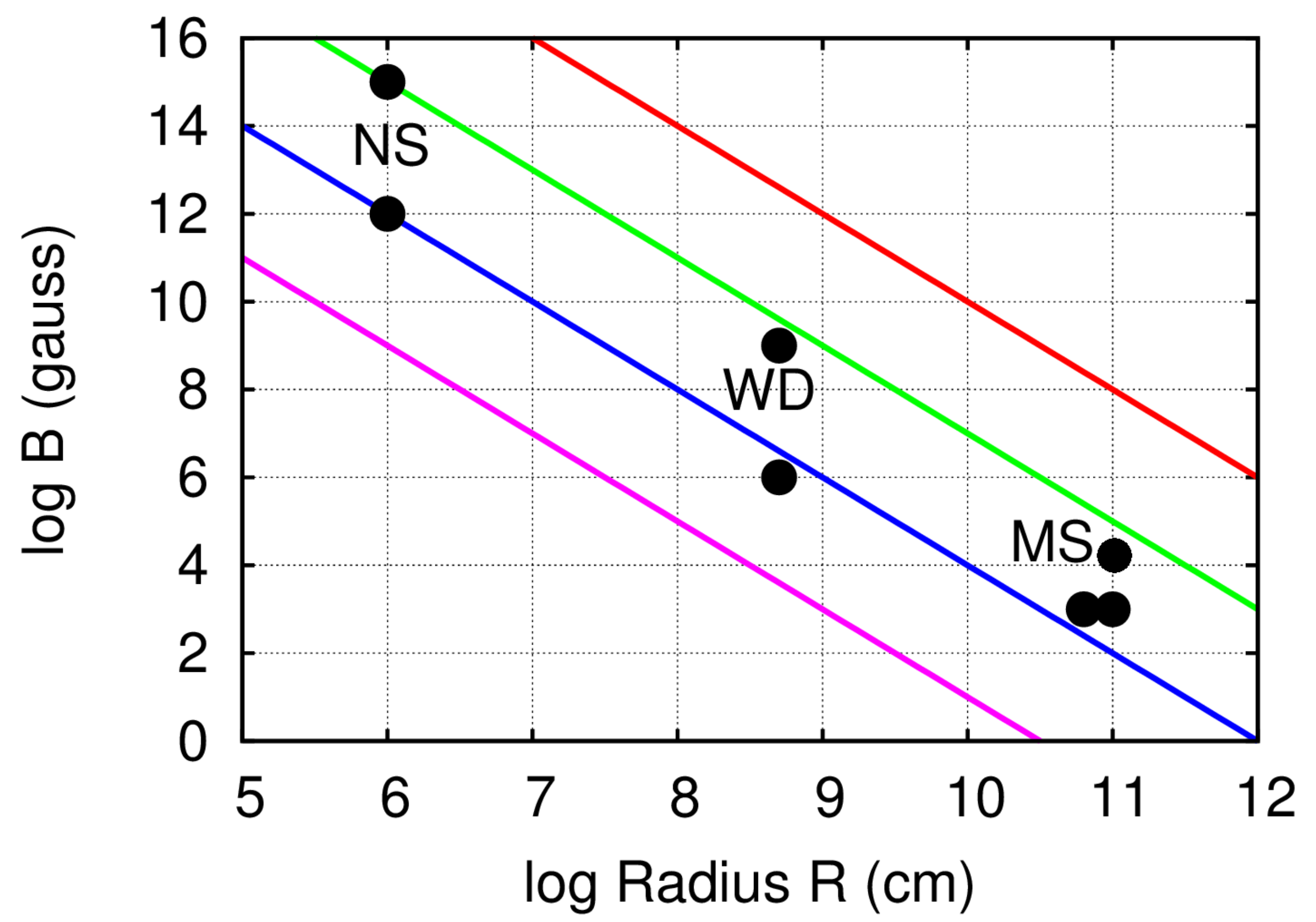
ダイナモ

様々な天体の磁場

- 太陽(黒点) :10^3 G
- Ap /Bp star :10^2 ～ 10^4 G
- B / O star :10^2 ～ 10^3 G
- 強磁場白色矮星 :10^6 ～ 10^9 G
- 中性子星 :10^9 ～ 10^13 G
- マグネター :10^14 ～10^16 G

磁束の保存

$$\frac{\mathcal{M}}{|W|} \sim \frac{B_s^2 R^3}{8\pi} \Big/ \frac{GM^2}{R} \sim \frac{B_s^2 R^4}{M^2}.$$



磁束の保存

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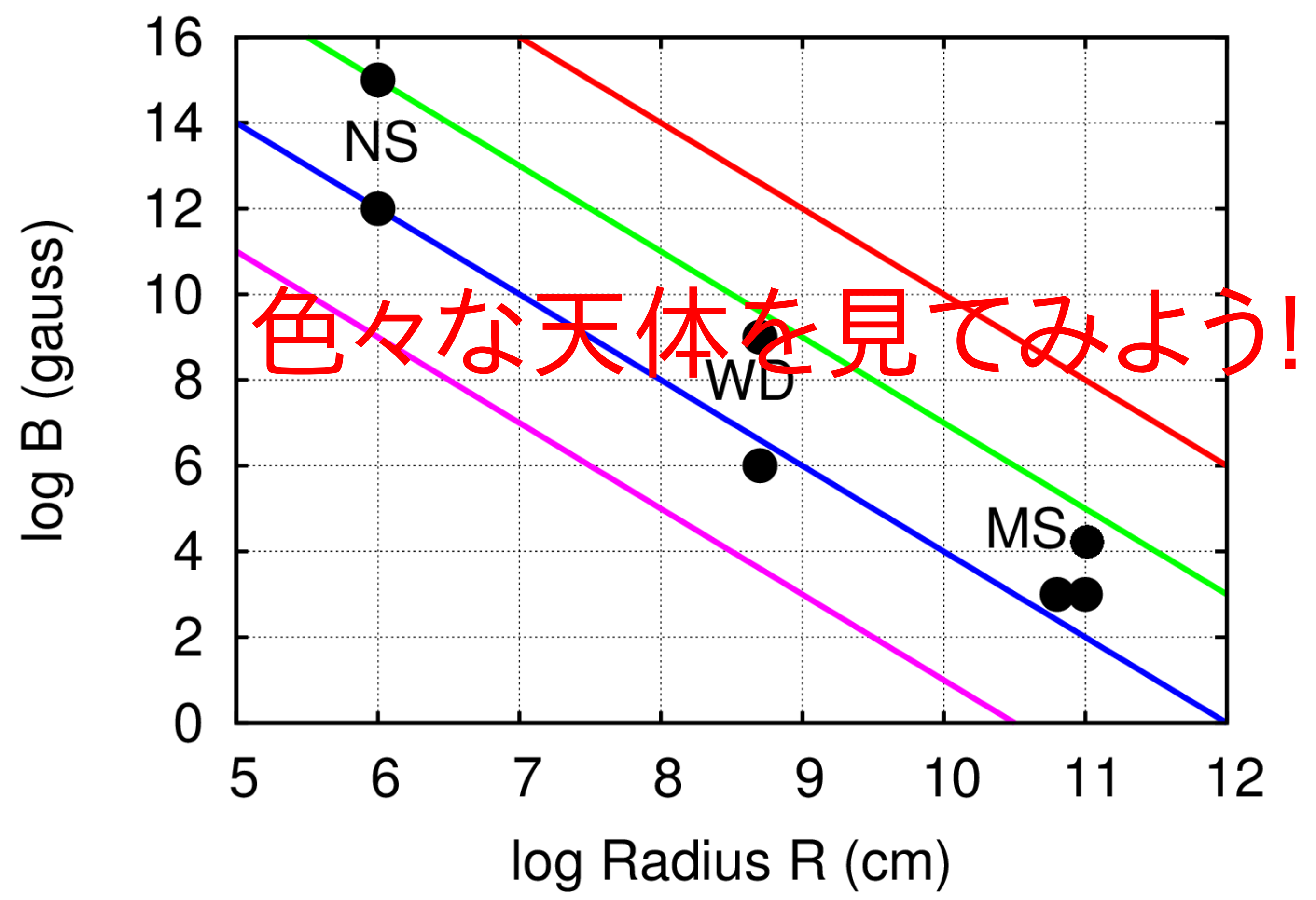
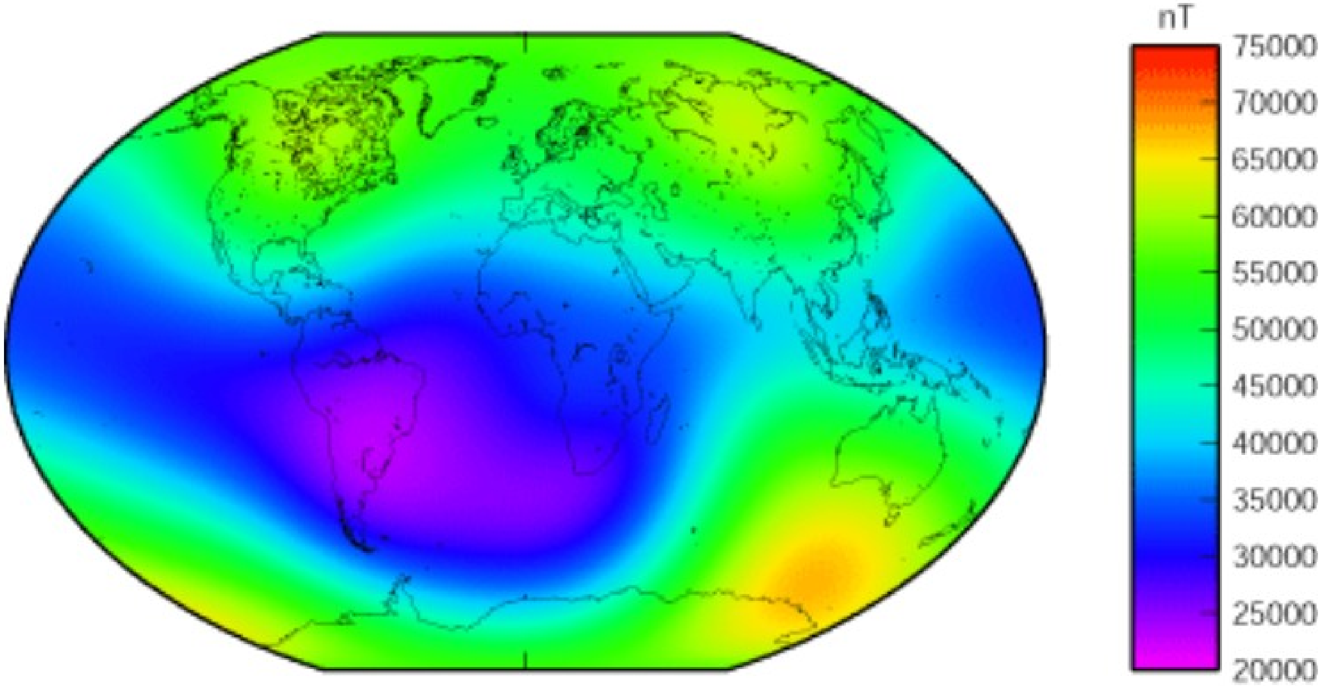


色々な天体を見てみよう!

星の外部磁場構造

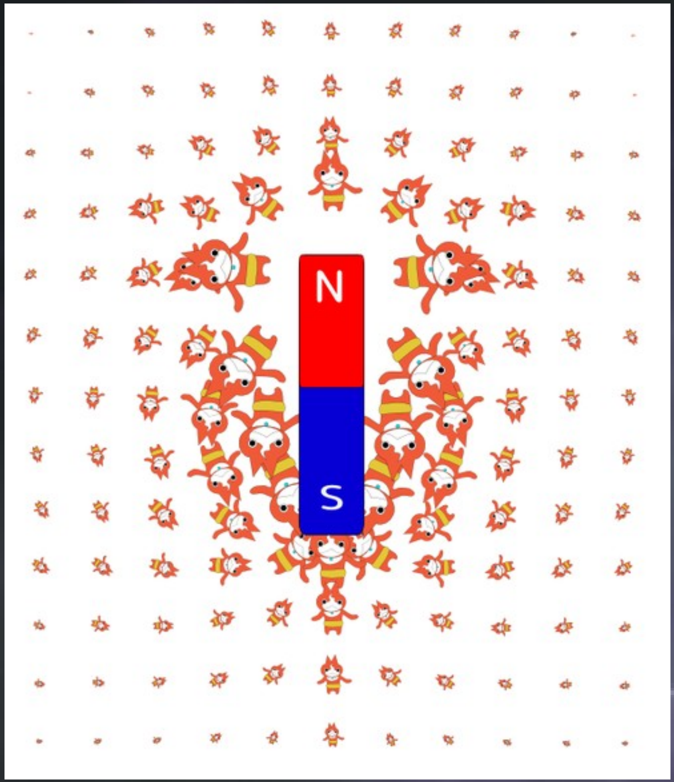
地磁気構造

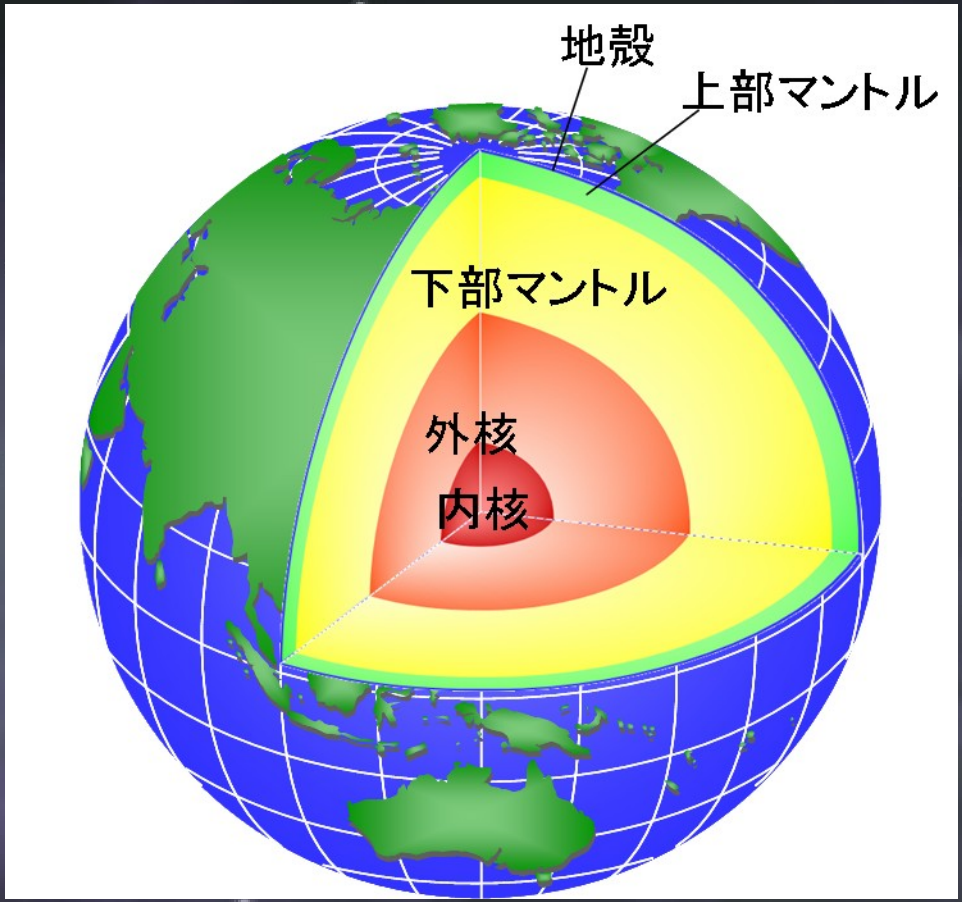


ー地表の磁場強度分布図　（全磁力2000年）ー

地磁気観測所のページより

地磁気の起源は？





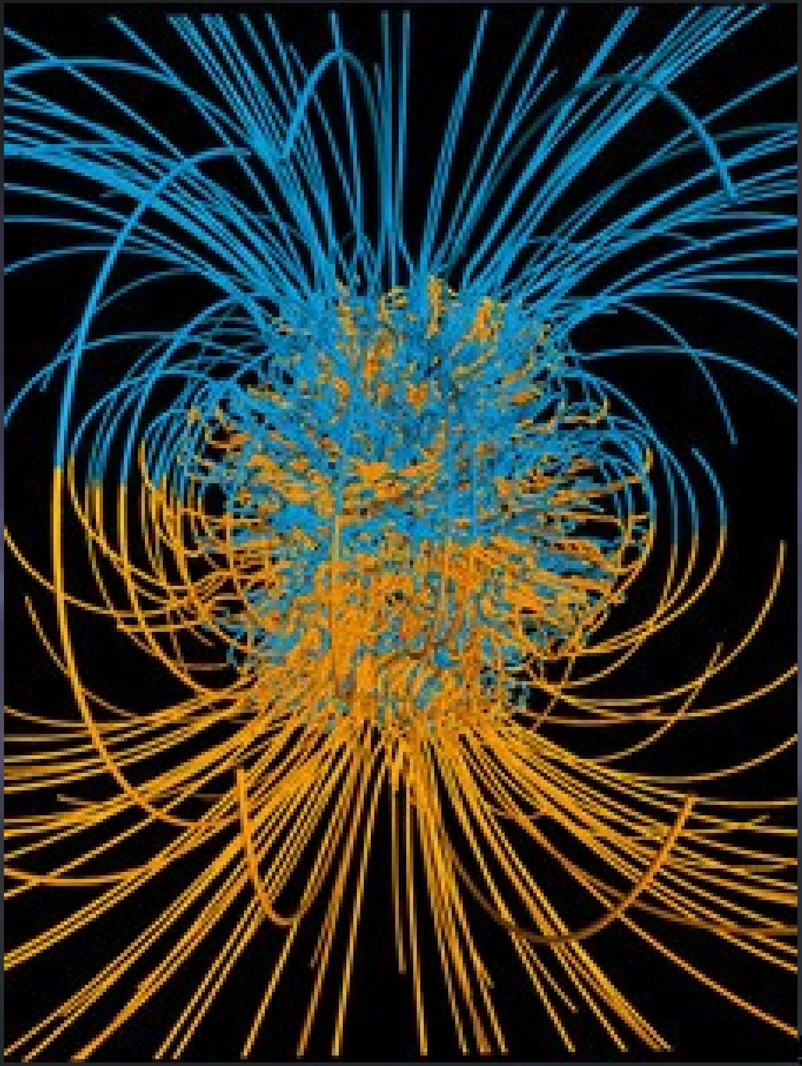
磁石

(磁化した地殻や岩石)

コアダイナモ

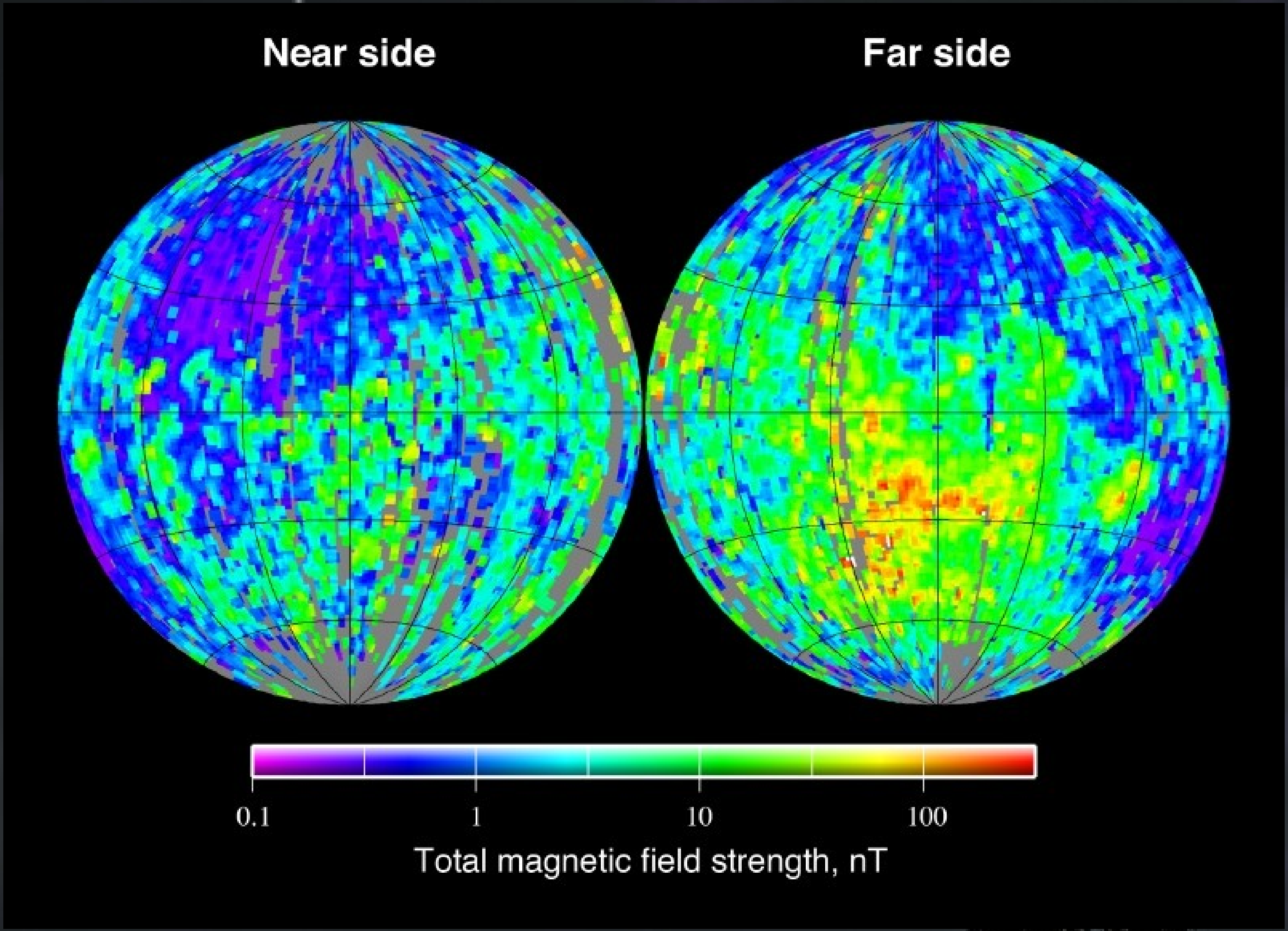
http://www.sci.hokudai.ac.jp/mineral/index.php/
%E7%A0%94%E7%A9%B6%E7%B4%B9%E4%BB%8B

地球ダイナモシミュレーション



Probing the Geodynamo（SCIENTIFIC AMERICAN April 2005）

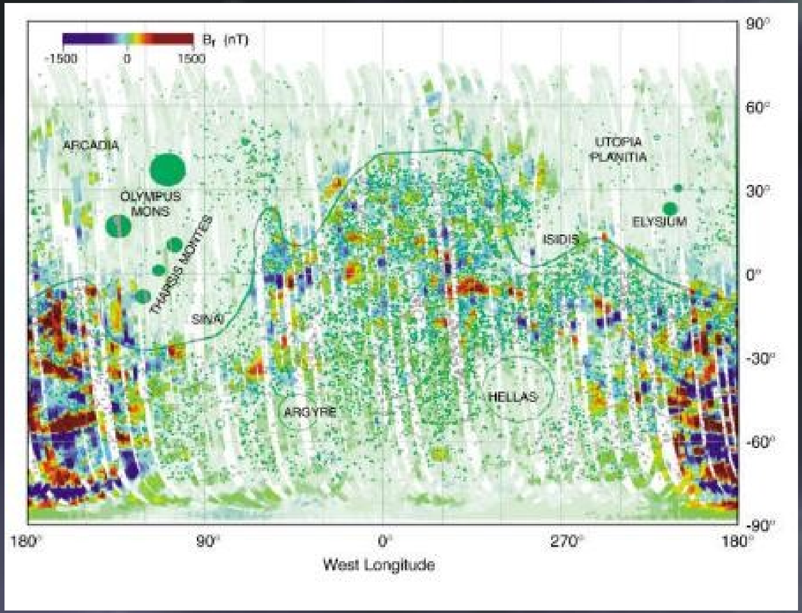
月の磁場



残留磁場？　(©Mark A. Wieczorek)

惑星磁場

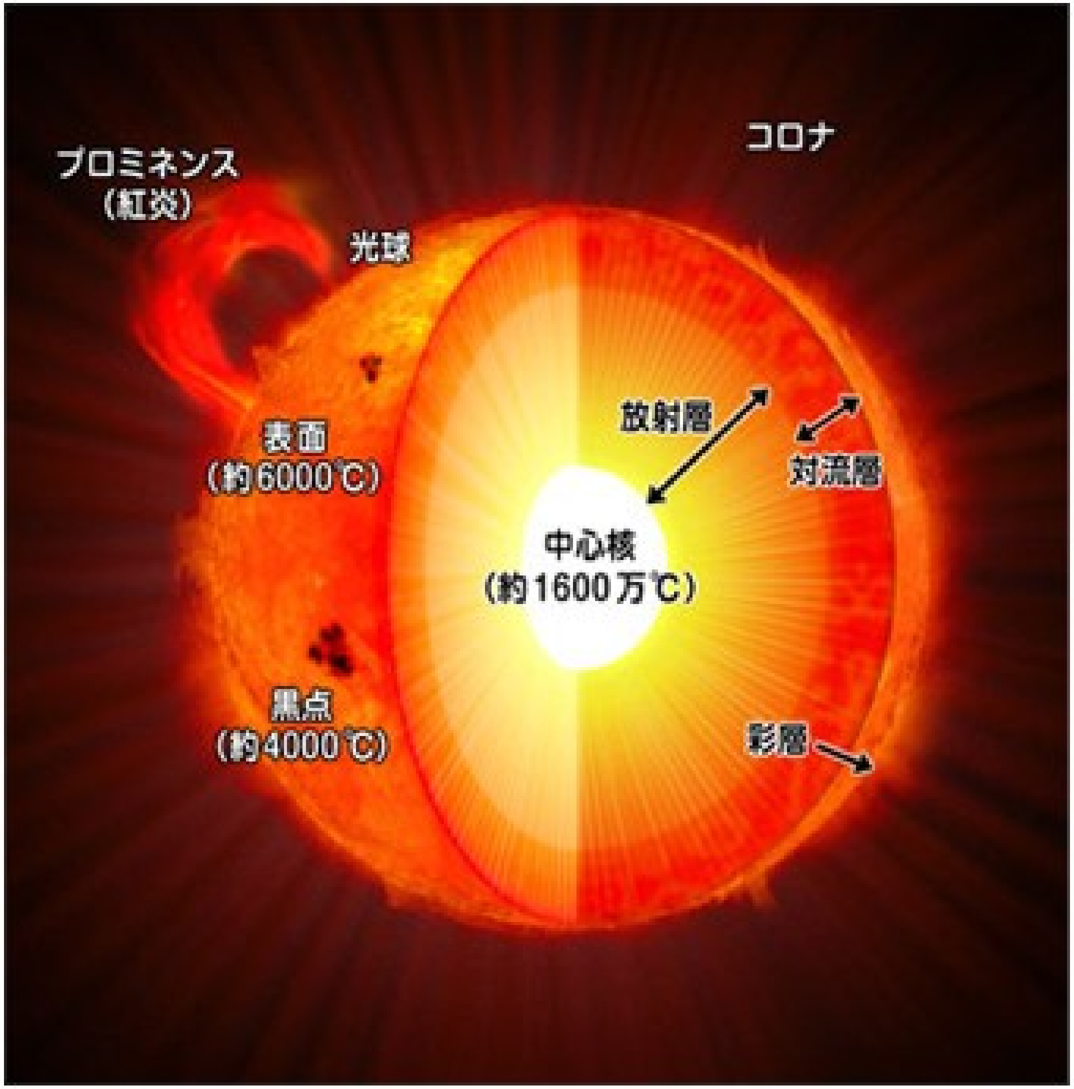
- 水星：ダイナモ?
- 金星：磁場なし？
  - (自転が遅い～243日から?)
- 火星
  - 残留磁気と縞模様
- 木星
  - 10G程度で磁気圏も持つ
  - 金属水素のマントルにおける導電物質の対流活動?



マーズ･グローバル･サーベイヤー探査機

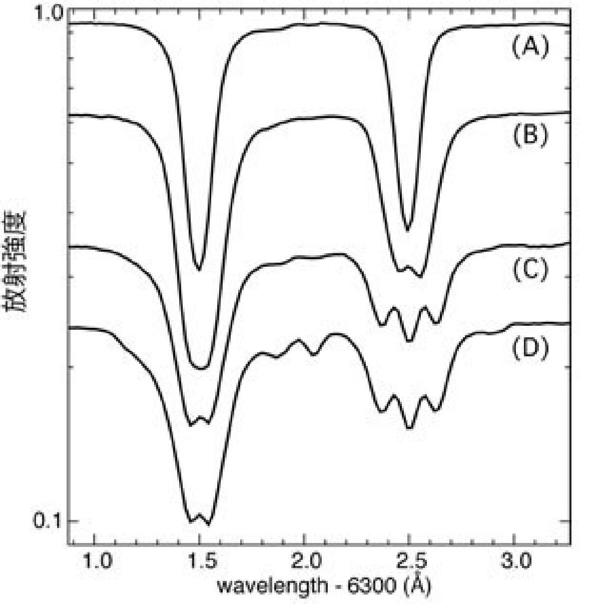
オーロラ　JAXAより

太陽

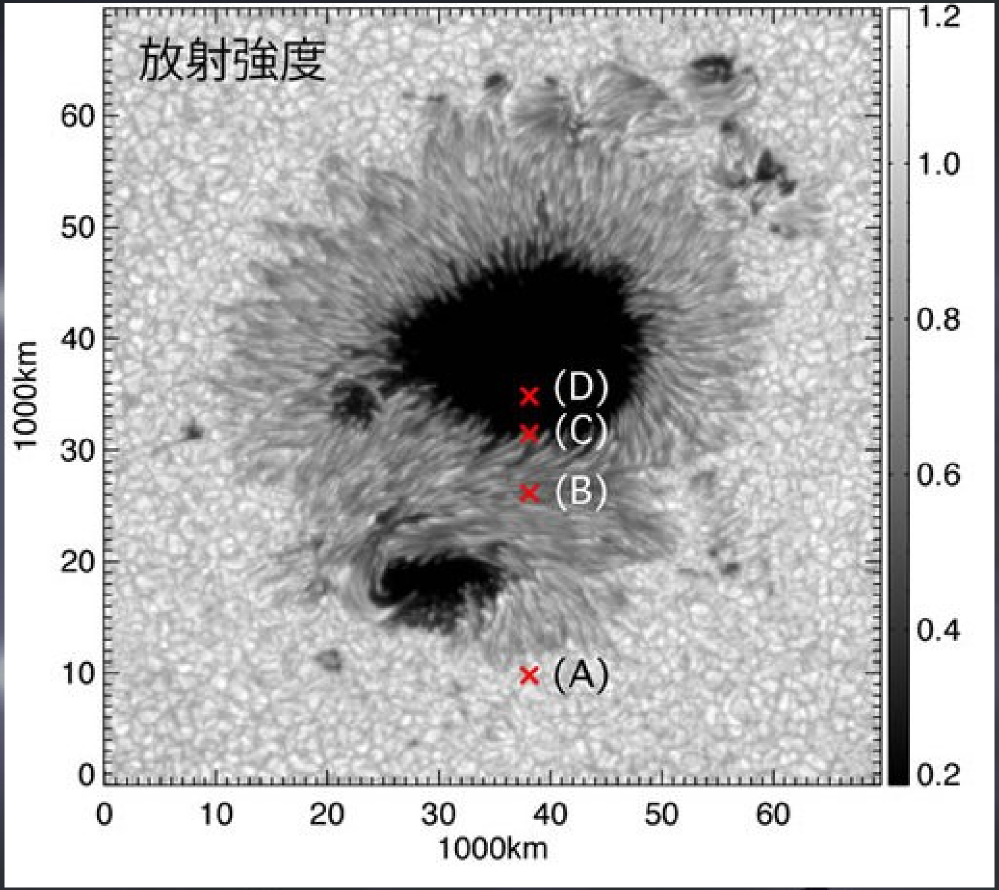


太陽の内部構造　提供: 独立行政法人科学技術振興機構 理科ねっとわーく

ゼーマン効果



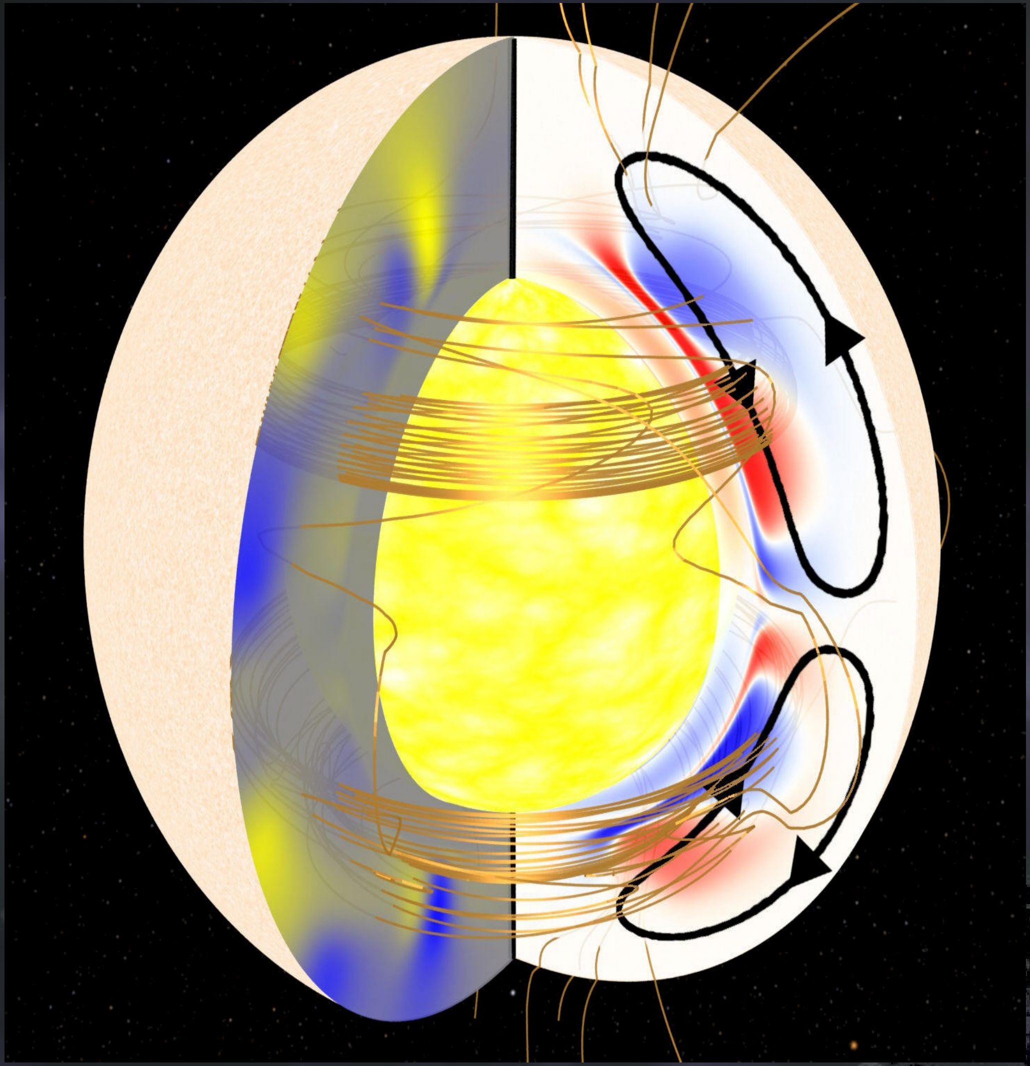
鉄の吸収線



勝川行雄　太陽磁場を測る より

http://prc.nao.ac.jp/extra/uos/ja/no06/

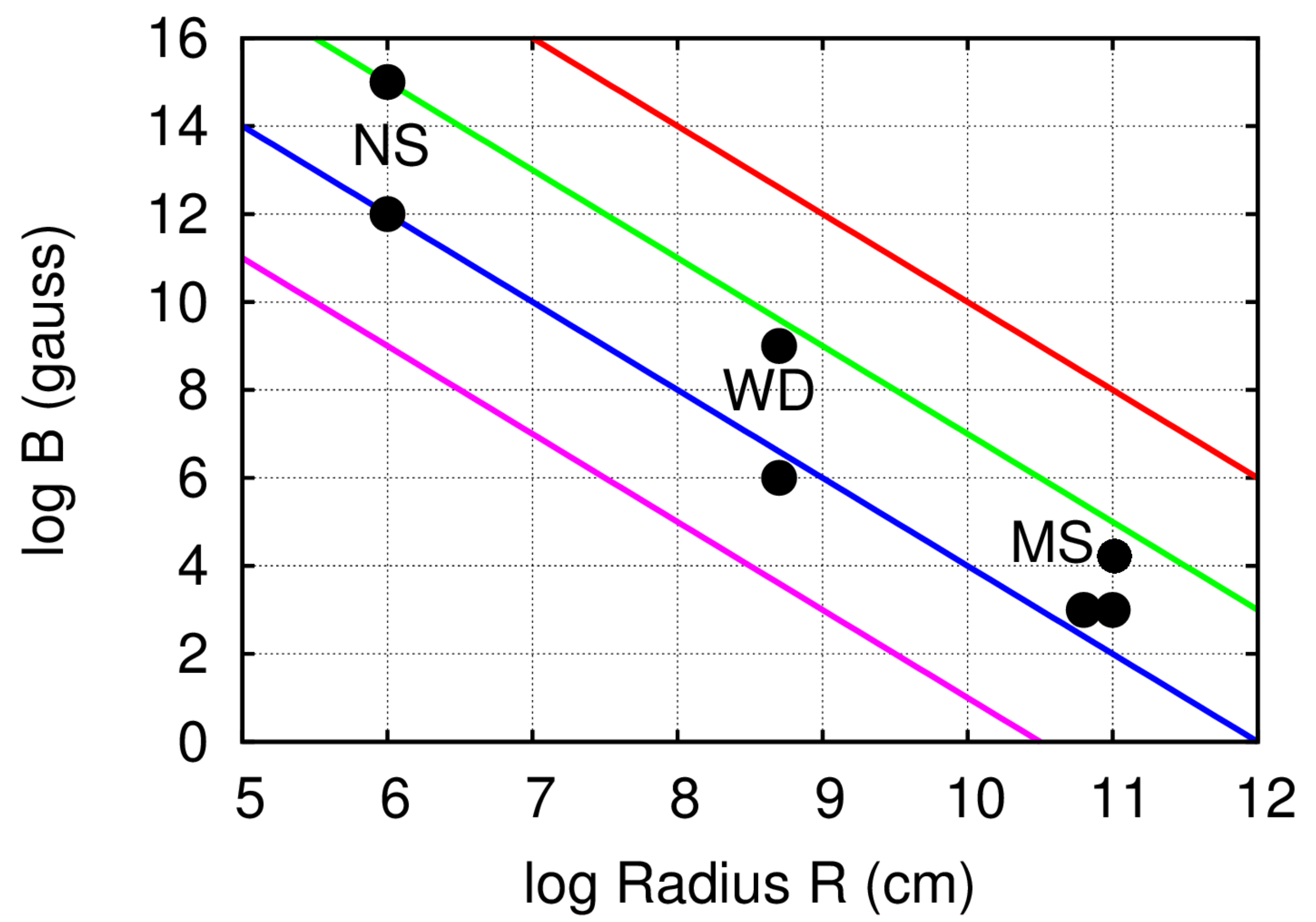
対流層でのダイナモ



恒星磁場

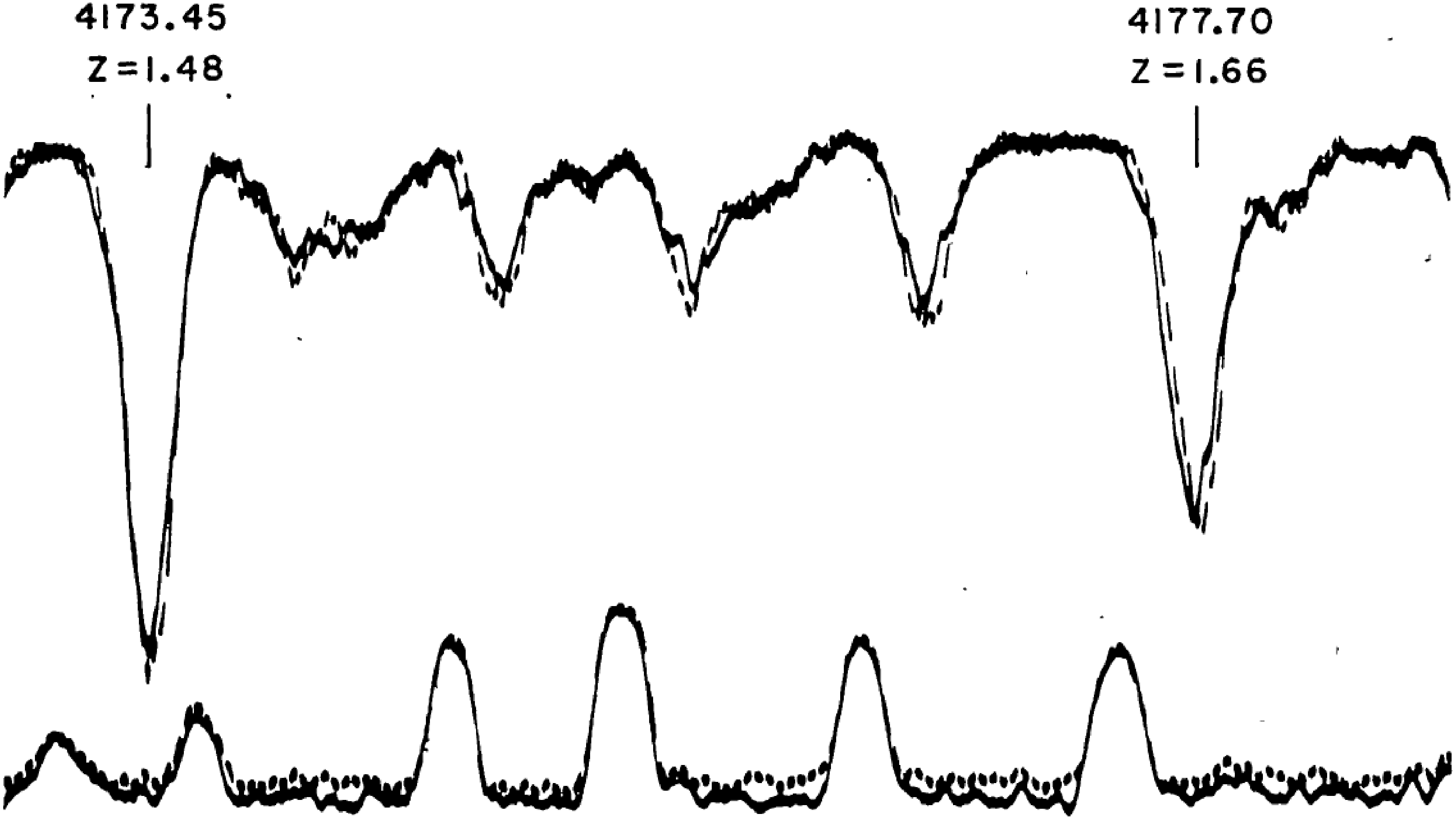
磁束の保存

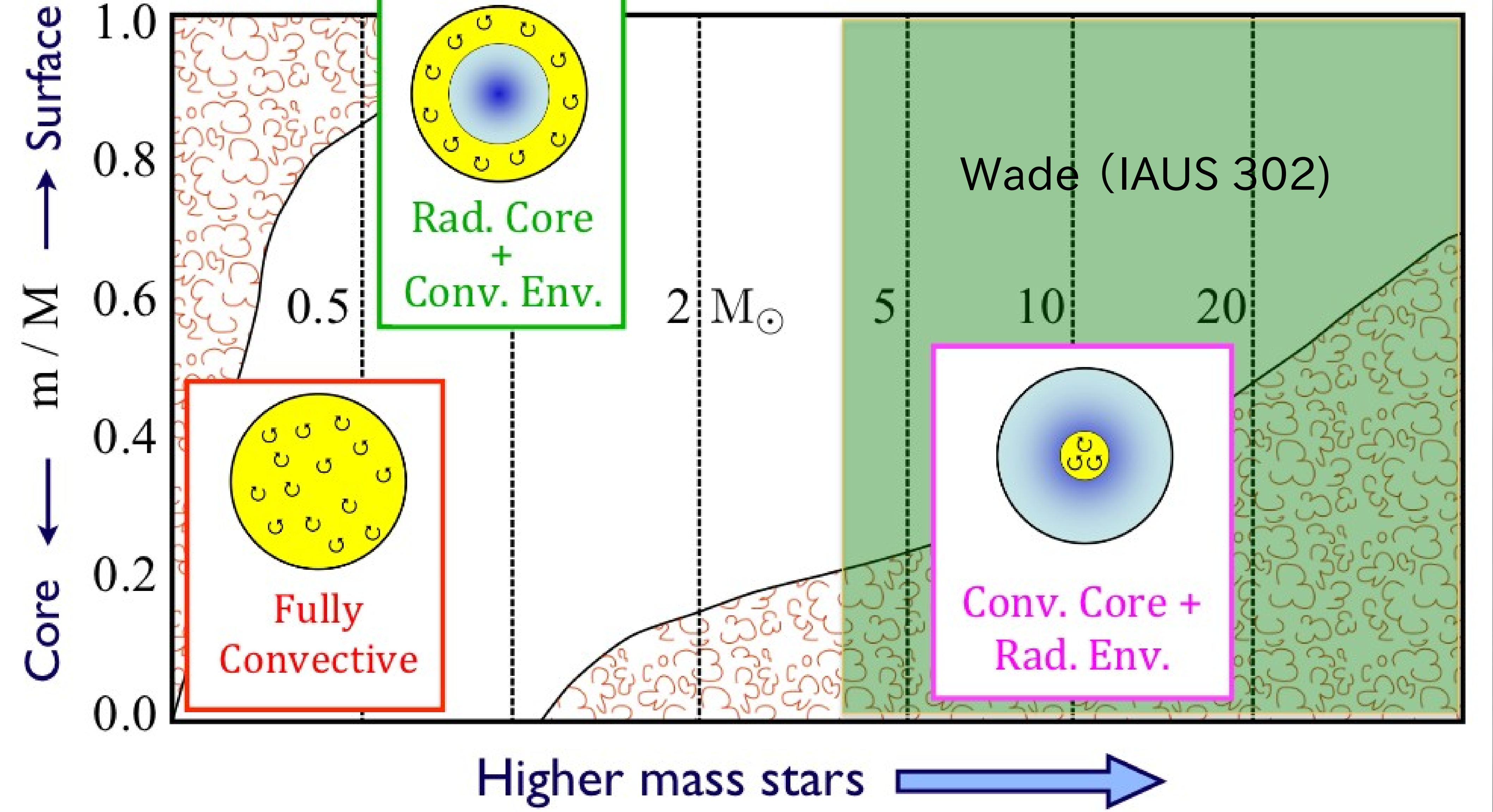
$$\frac{\mathcal{M}}{|W|} \sim \frac{B_s^2 R^3}{8\pi} \Big/ \frac{GM^2}{R} \sim \frac{B_s^2 R^4}{M^2}.$$



恒星の磁場

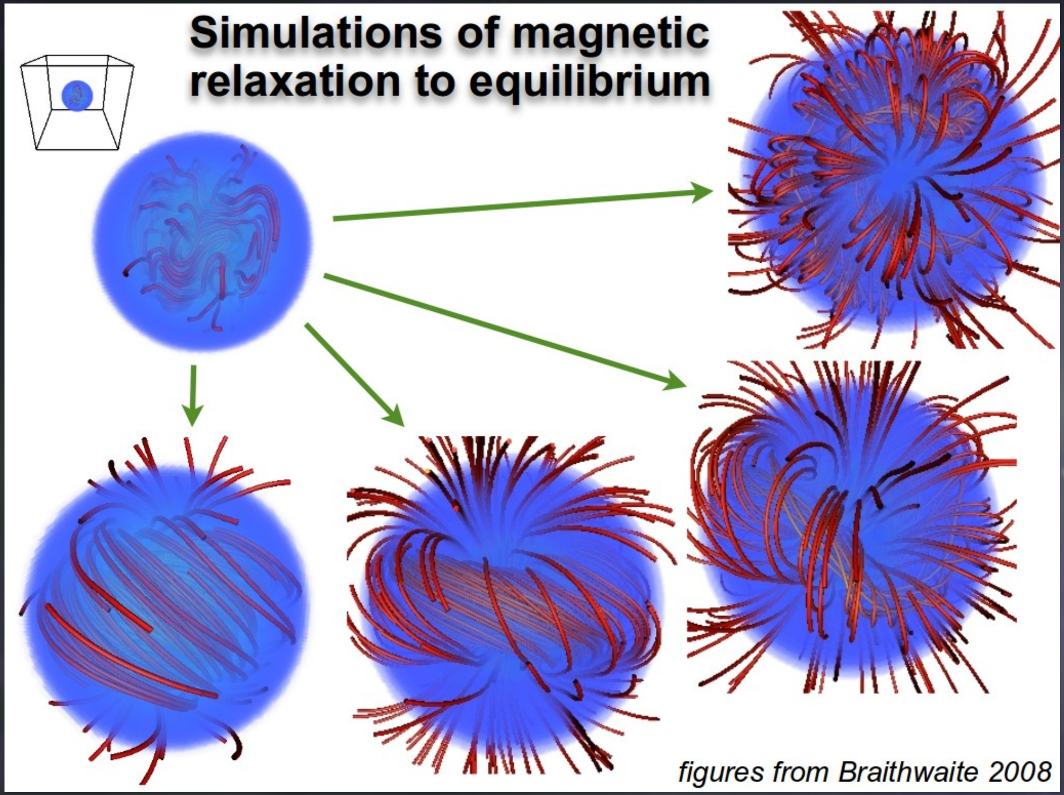
- Babcock (1947)：太陽以外の恒星(Ap星)で磁場発見



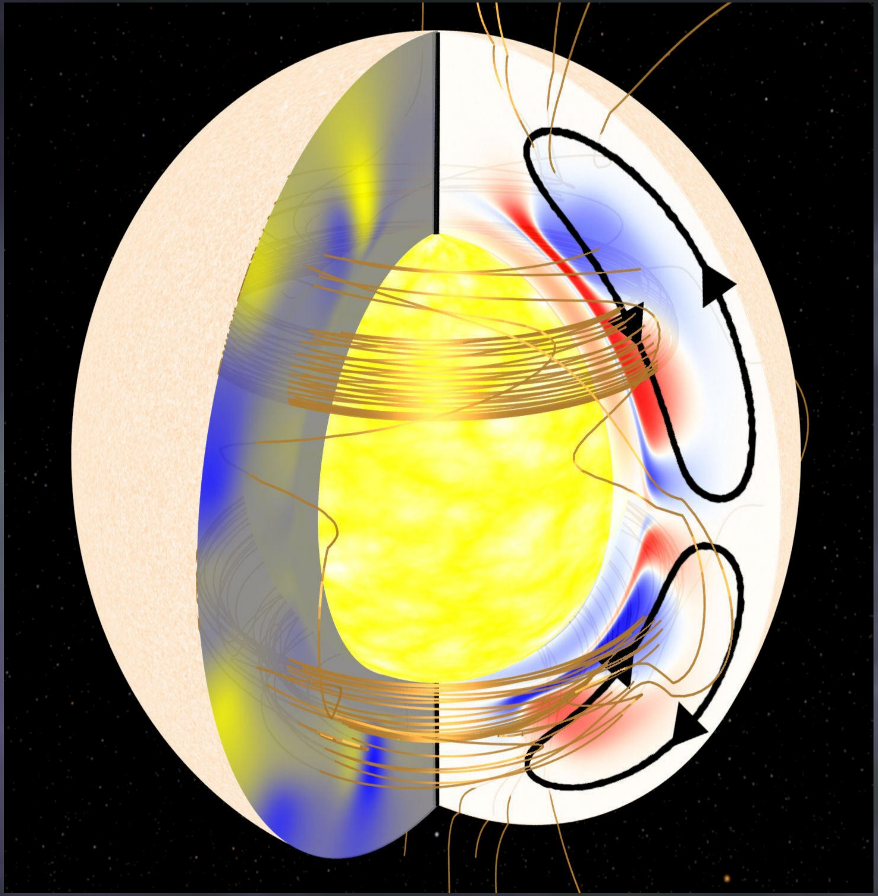


Wade (IAUS 302)

恒星の磁場の起源は？



figures from Braithwaite 2008



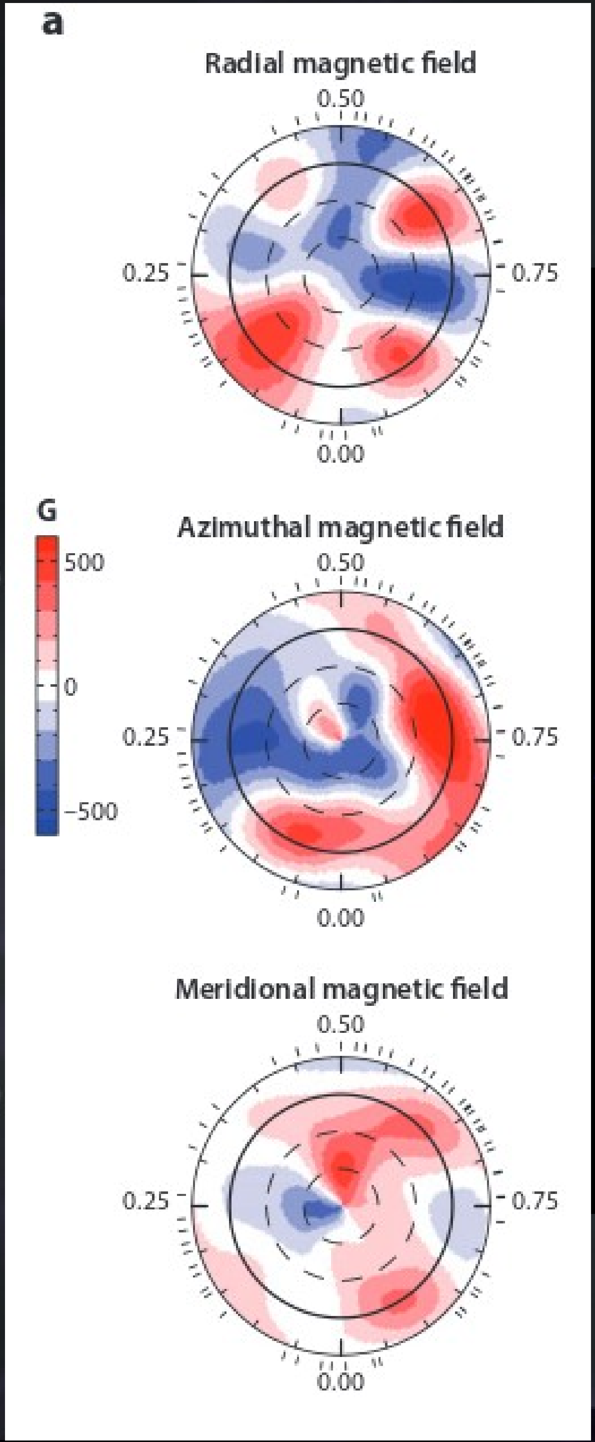
- 化石

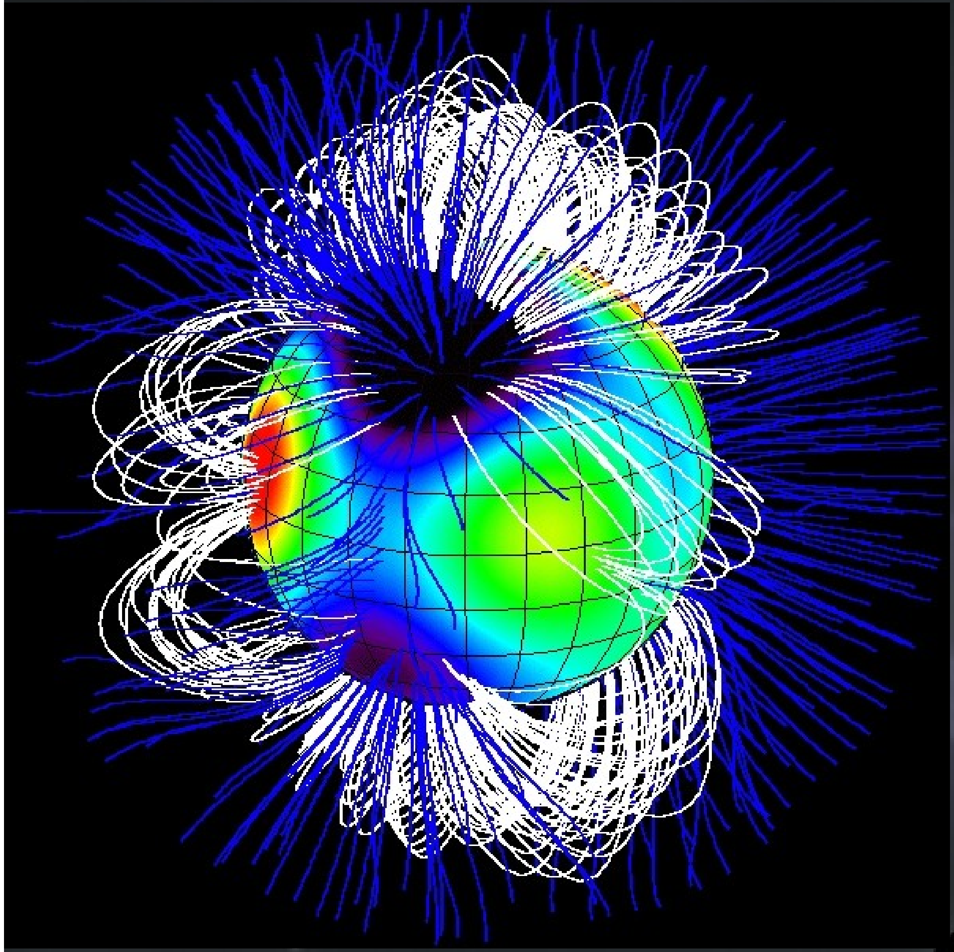
ダイナモ

定常的な構造

周期的に変動

恒星の磁場





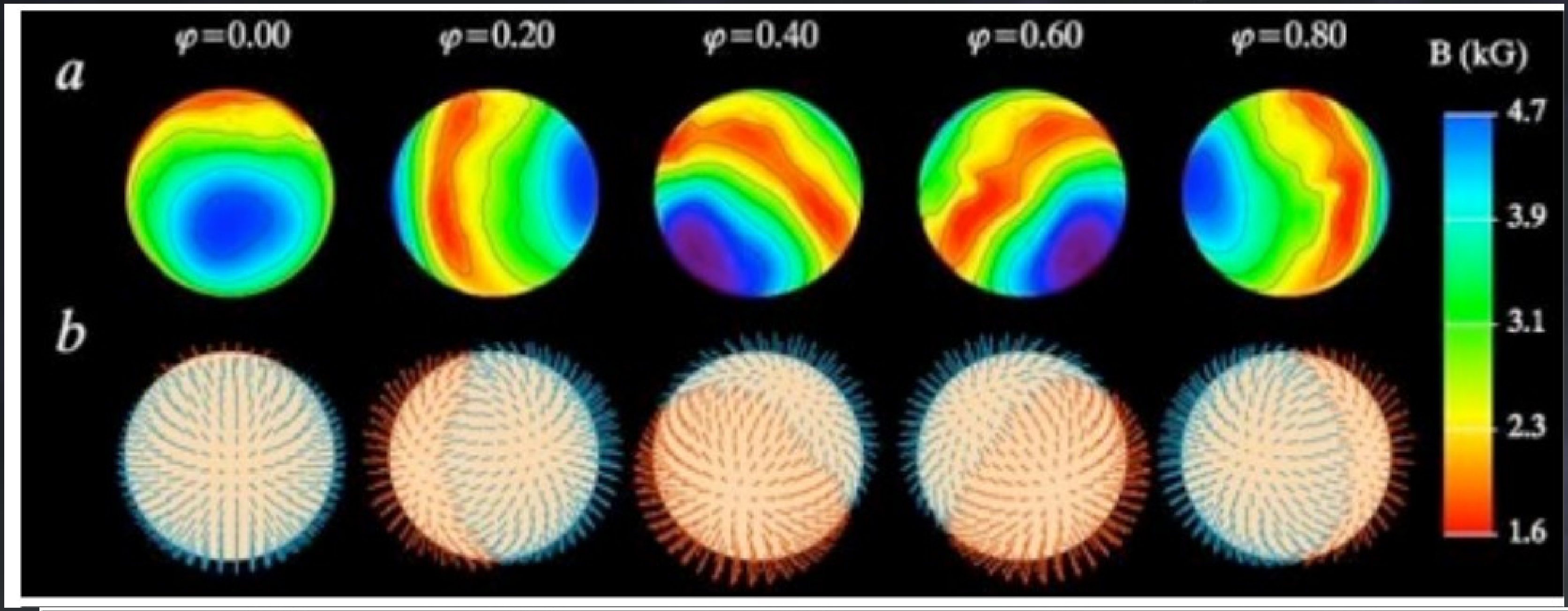
～500 G

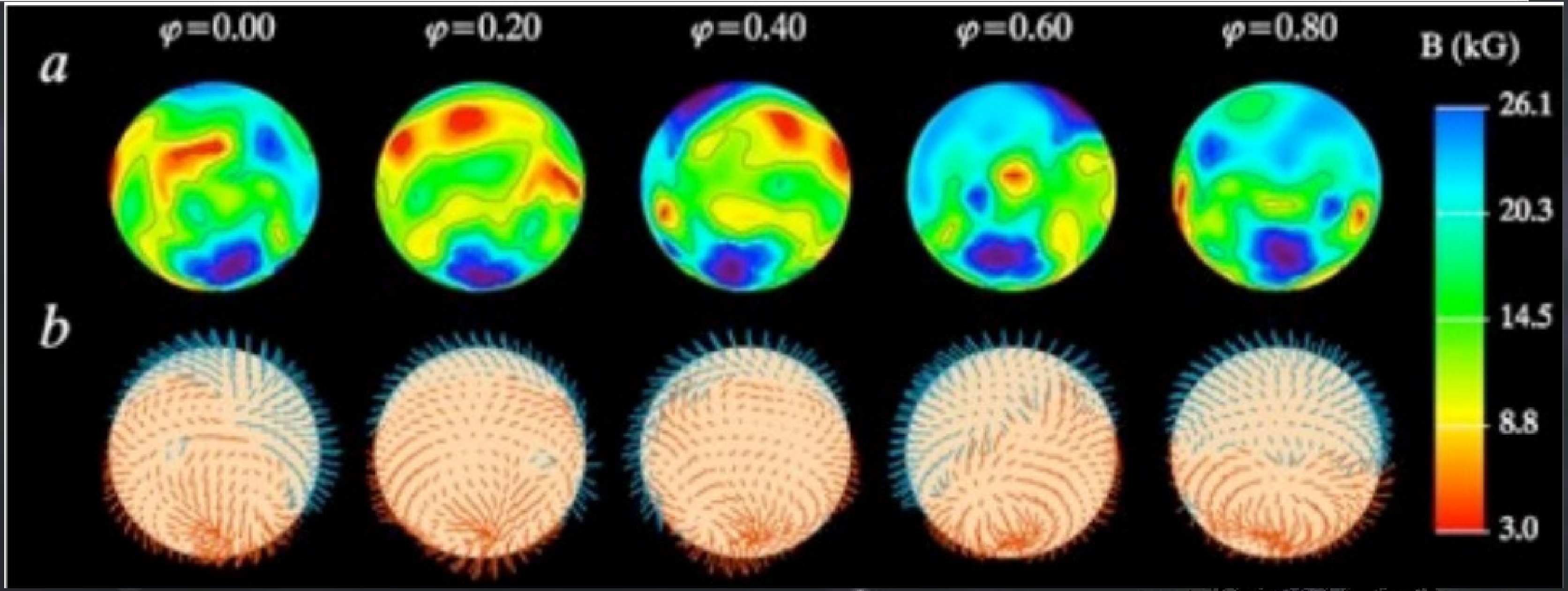
さそり座タウ星(B星)の表面磁場
(cf, Donati et al. 2006;
Donati & Landstreet 2009)

恒星磁場

- A, B, O 型星の10% 程度は200G ～30000G程度の強い磁場を持つ
  - 残り 90 % はおそらく弱い磁場を持つ
- 放射層の化石磁場
  - コアダイナモ磁場
- 比較的双極子的な磁場と複雑な磁場

B～4700G α2 CVn(Kochukhov et al 2002)

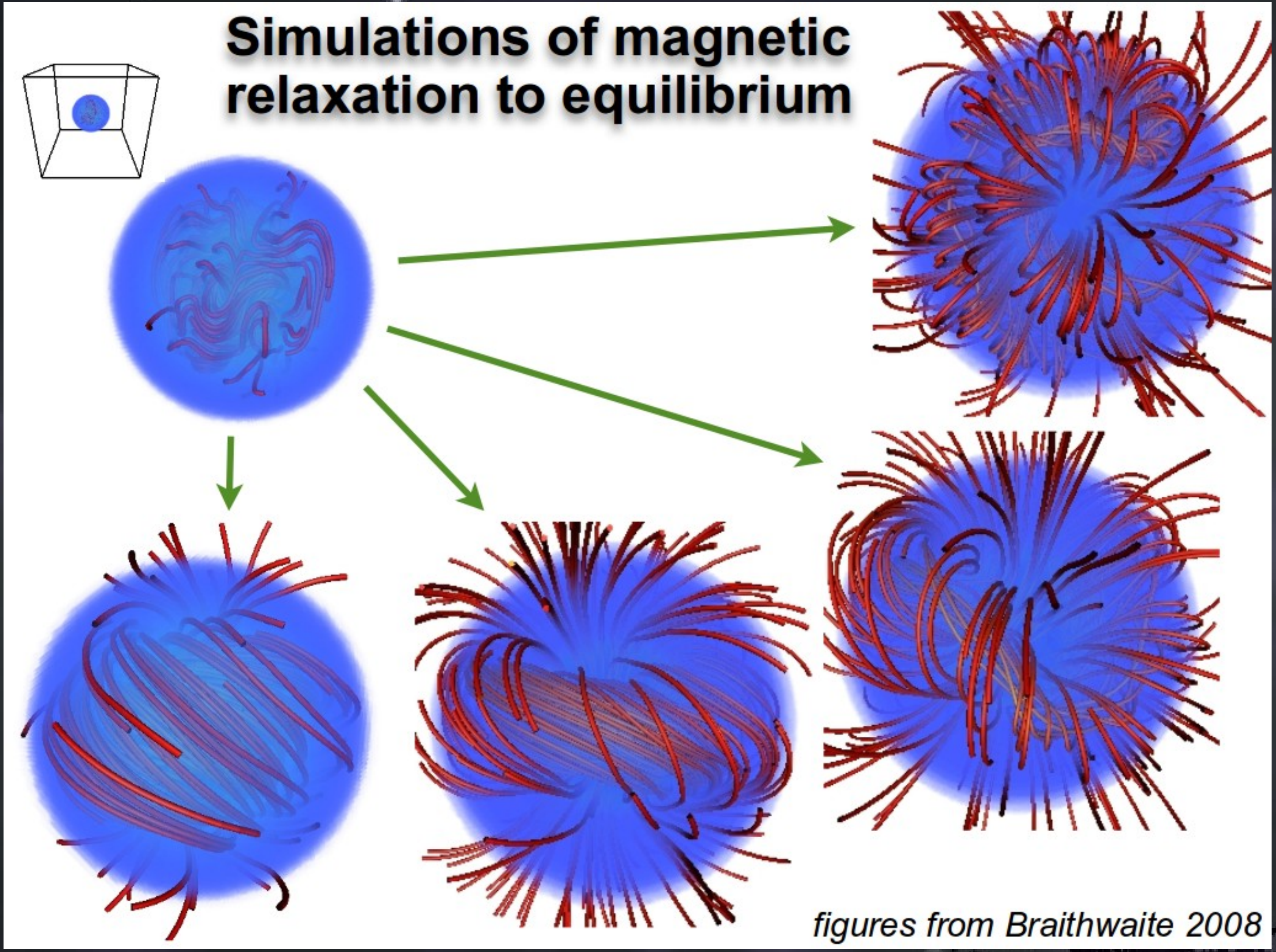




B～ 26000G 53 Cam (Kochukhov et al 2002)

化石磁場

- 初期磁場の違いで磁場構造が変わる？(Braithwaite 2008)

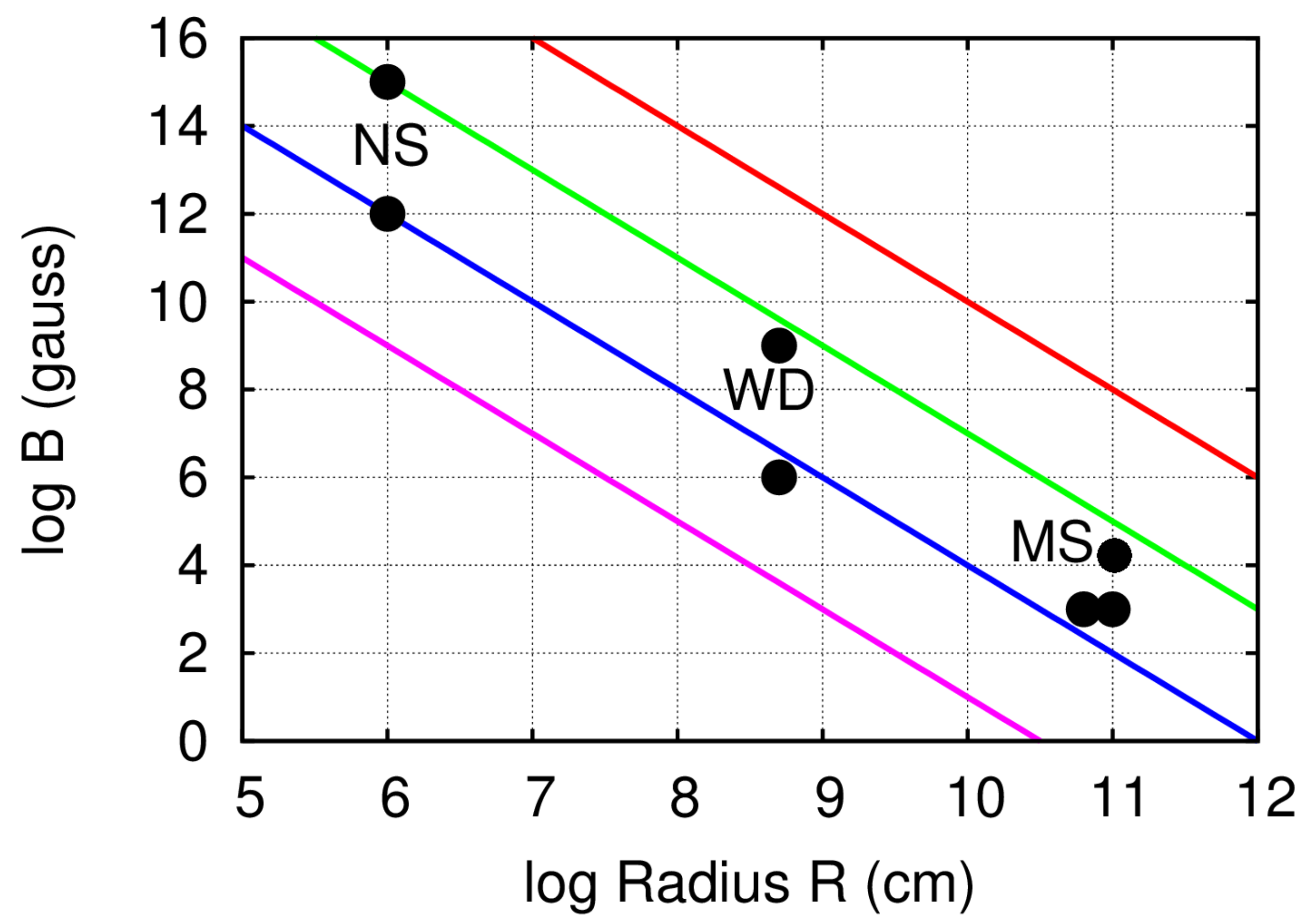


figures from Braithwaite 2008

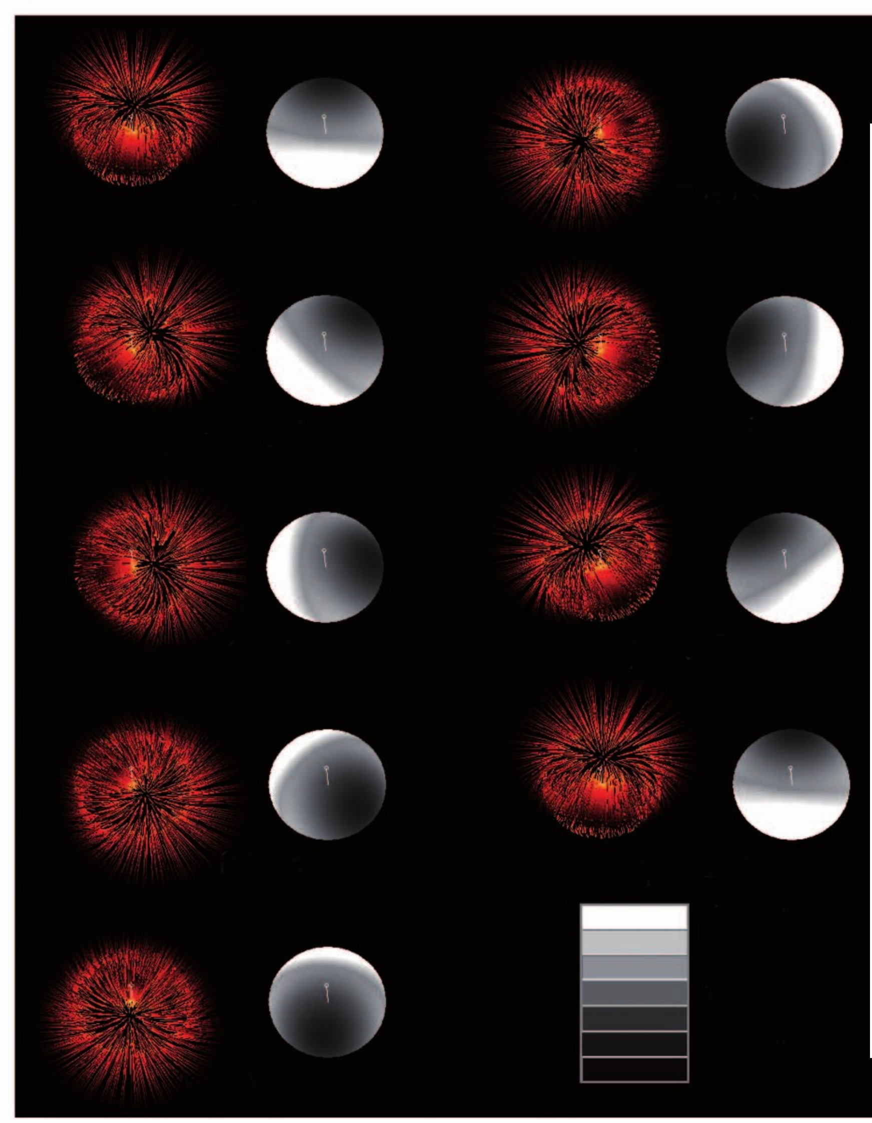
白色矮星

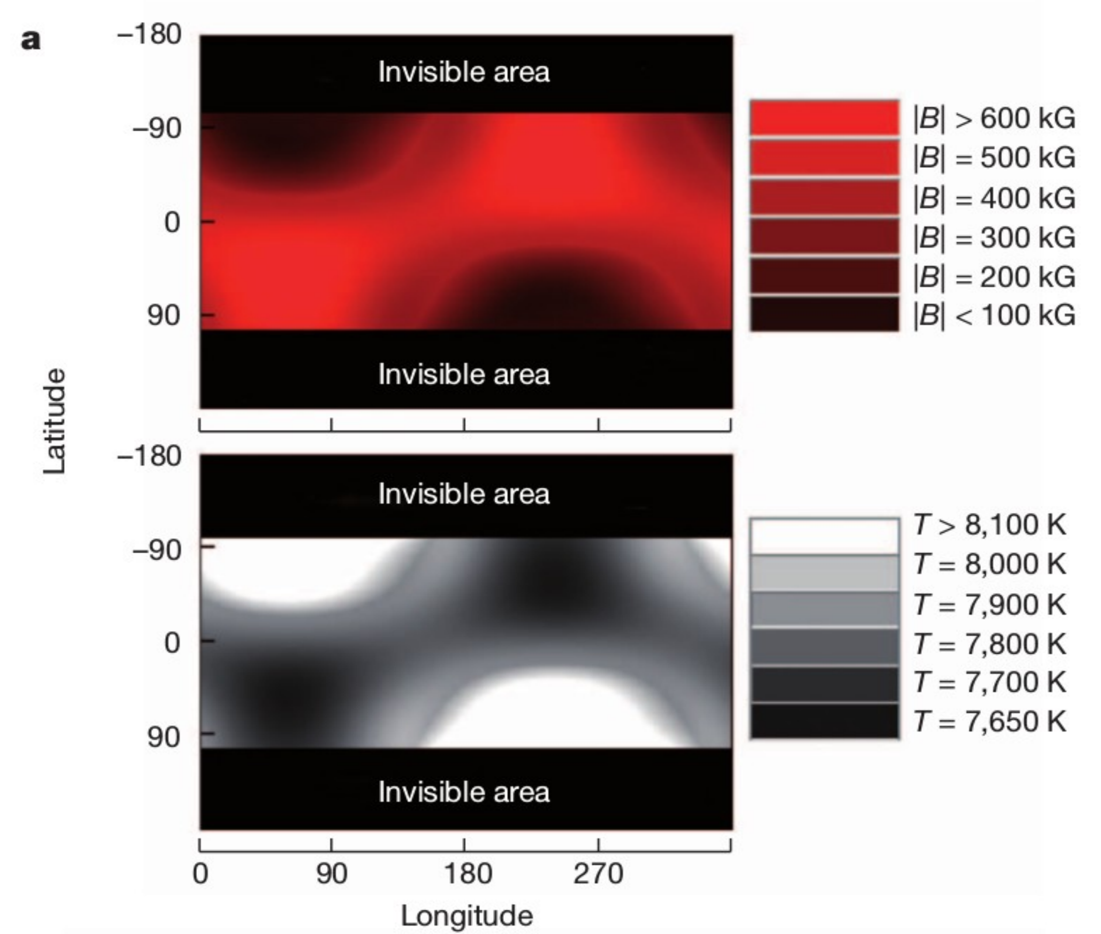
磁束の保存

$$\frac{\mathcal{M}}{|W|} \sim \frac{B_s^2 R^3}{8\pi} \Big/ \frac{GM^2}{R} \sim \frac{B_s^2 R^4}{M^2}.$$



白色矮星(WD 1953-011)の表面磁場





- Valyavin et al. (2014, nature)

強磁場白色矮星

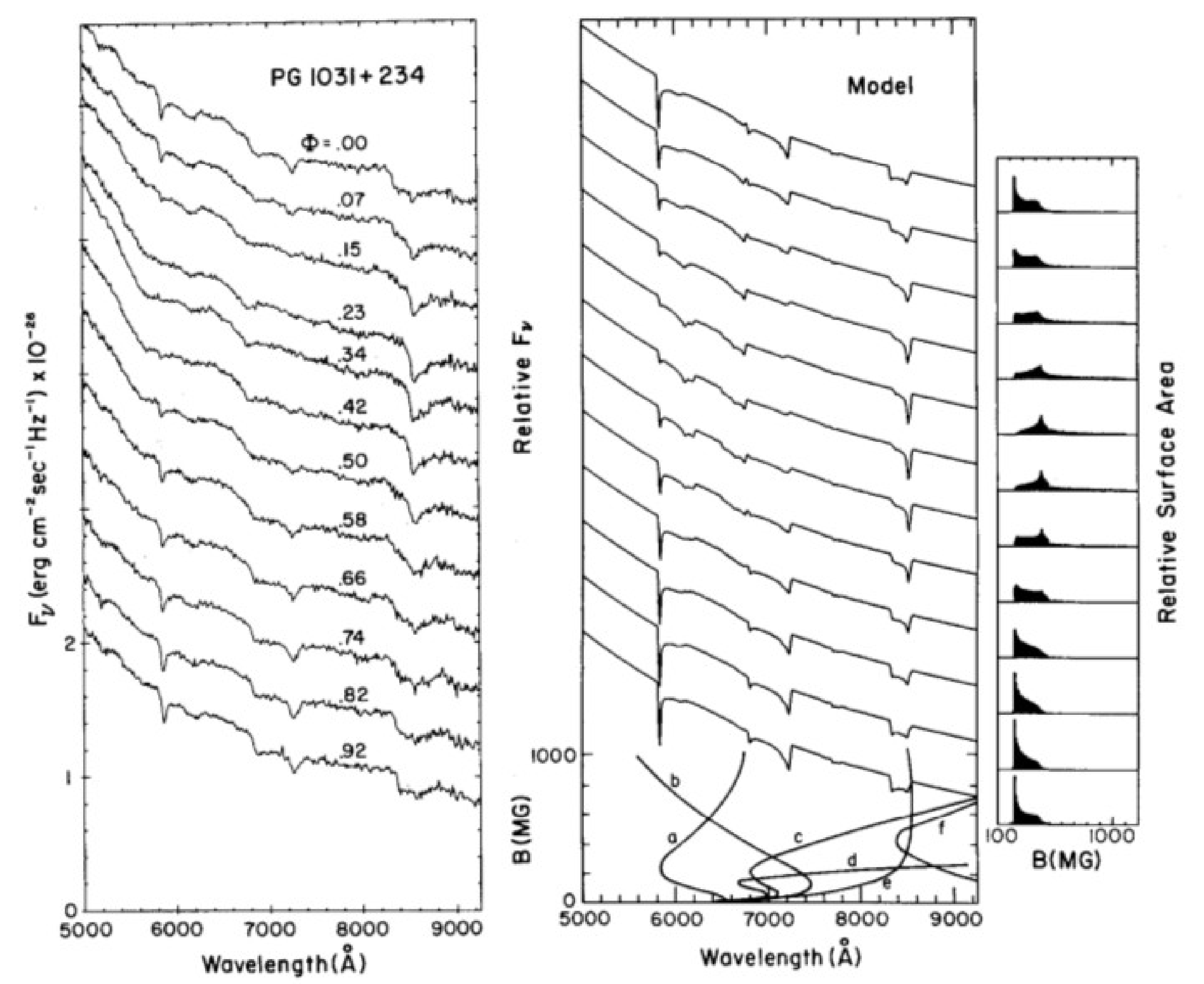
Wickramasinghe
& Ferrario (2000)

- 単星か連星(激変星)
- 10^6 G (1M G) 以上の強磁場を持っているものがいる
  - 最大で～10^9 G (1000M G)程度の磁場！

- 一定の割合が強磁場白色矮星
  - 単星 ～10％ (Liebert et al. 2005)
  - 連星 激変星 ～25％
  - detached ～ 0 ％ Silvestri et al.(2007)

例外 Parsons et al. (2013)

PG 1031+234 (～1000MG, ～3.4 hr)



- Off-centered dipole(比較的複雑な磁場)

Latter et al. (1987).

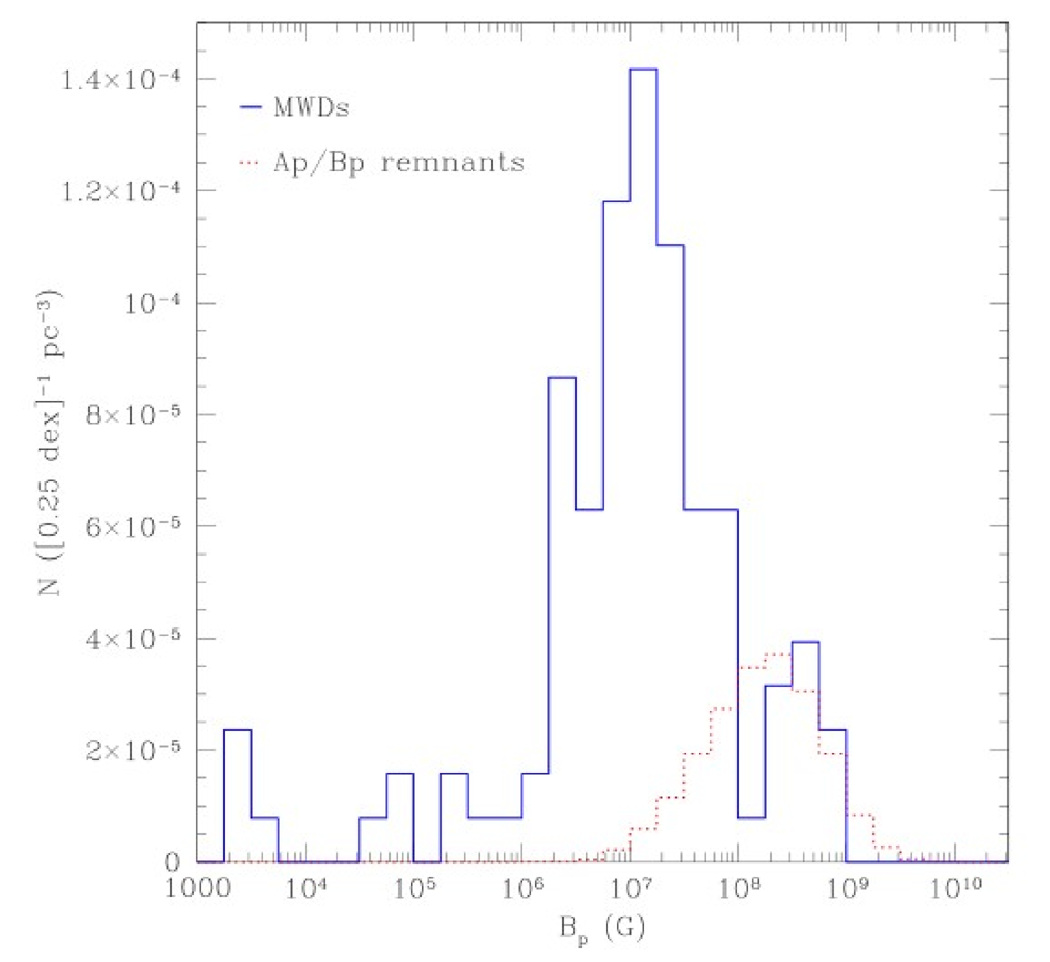
白色矮星の磁場の起源は

- 単星：自転が遅い、質量が大きい

↓

- 化石磁場
  - Ap/Bp star の磁束が保存
- ダイナモ
  - 共通外層時に軌道エネルギーで磁場を増幅
- 白色矮星の合体(DD)
  - 磁場を増幅(MRI)+質量大+回転速い
- 別の何か？

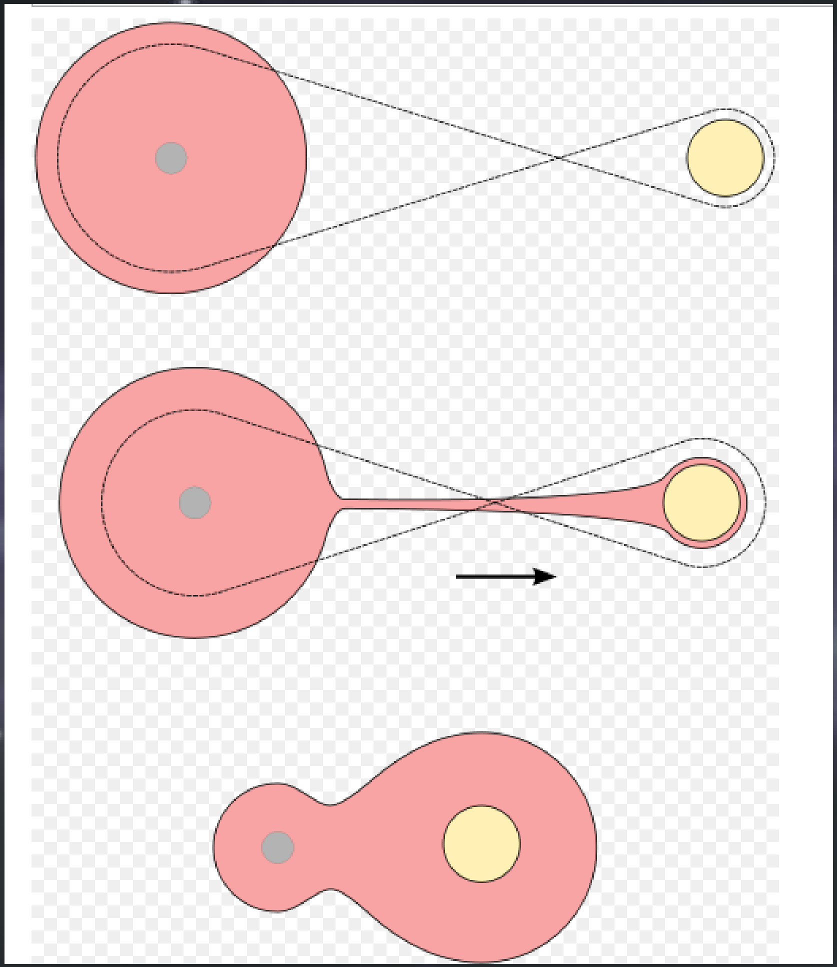
化石磁場



- 数が合わない？（Kawka & Vennes 2004)

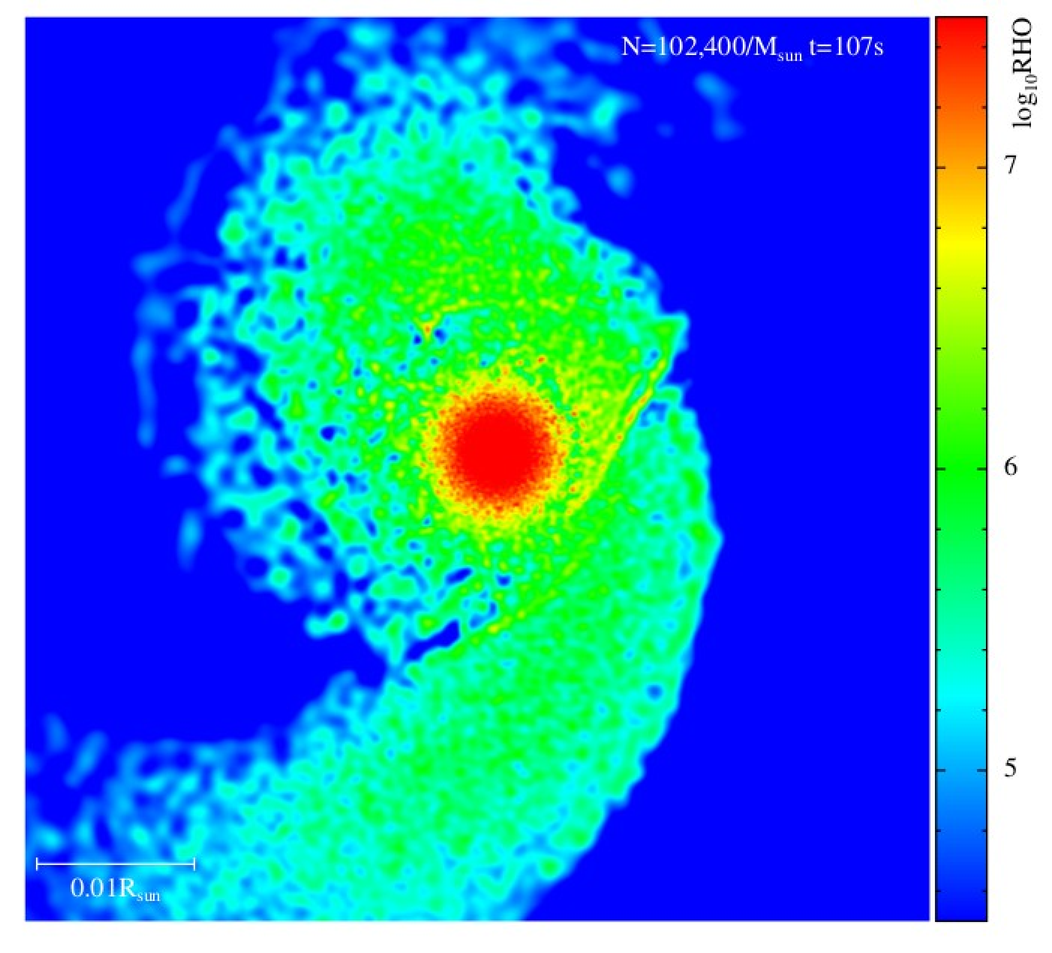
共通外層時におけるダイナモ

Tout et al. (2008); Potter & Tout (2010)

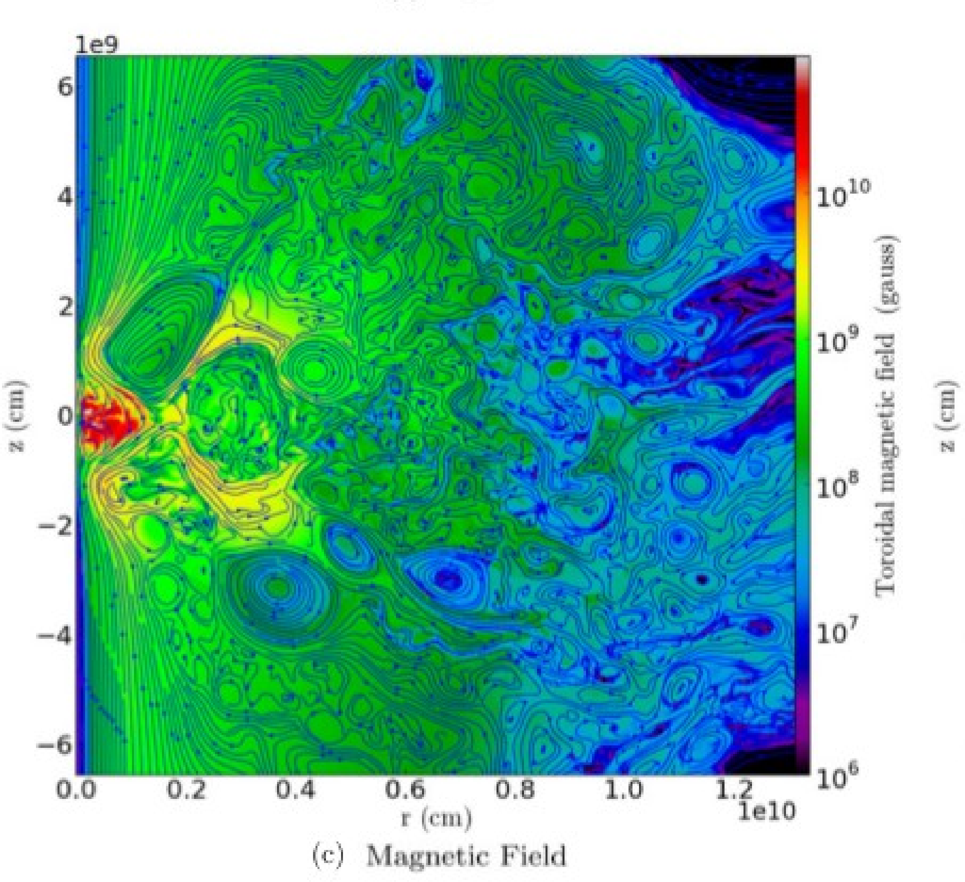


- 強磁場はできるが・・・

DD model



Sato et al. (2014)



Garca-Berro et al. (2012); Ji et al. (2013),

- MRIで増幅?

白色矮性の磁場の起源は？

化石

ダイナモ

星の外側の磁場のまとめ

- 大局的には双極子磁場
  - しかし局所的には高次の磁場でもっと複雑

- 磁場の由来は化石･磁石･ダイナモの3つ
  - それぞれ表面磁場に特徴が現れる

そして内側へ

星の内部の磁場構造

初期の理論的な研究

- Babcock (1949)：太陽以外の恒星(Ap star)で磁場発見

↓

Chandrasekhar らによる初期の論理的研究

- Chandrasekhar & Fermi (1953)
- Ferraro (1954)
- Chandrasekhar (1956)
- Chandrasekhar & Prendergast (1956)
- Prenderagst (1956)
- Woltjer (1959a, b; 1960)

磁場の強さの最大値

Chandrasekhar & Fermi 1953

- Virial 定理と星のエネルギーが負という条件から

$$B/|W| < 1$$

$$B/|W| \sim (B_s^2 R^3/8\pi)(GM^2/R)^{-1}$$

$$1 \sim (\frac{B_s}{10^{18}G})^2(\frac{R}{10^6\mathrm{cm}})^4(\frac{M}{1.4M_\odot})^{-2}$$

電流と磁場

- 電流を与えて磁場構造を求める

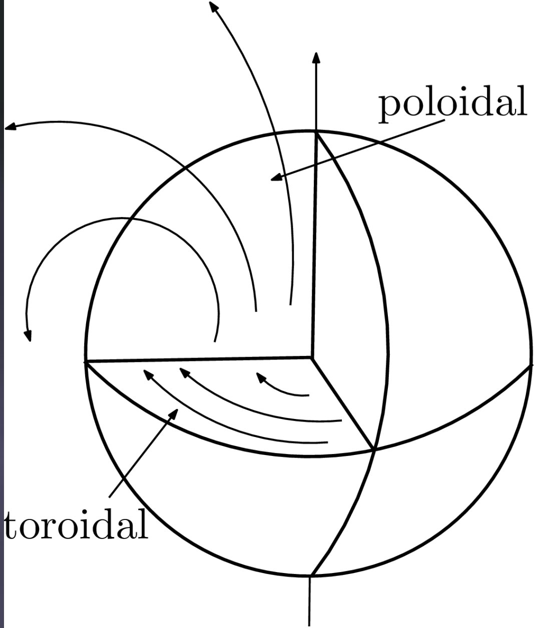
磁場構造の求め方

1.

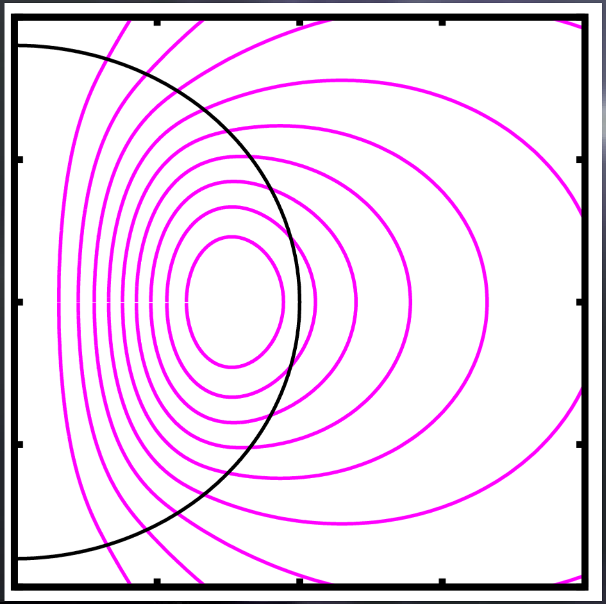
$$\frac{\partial}{\partial t} = 0 \qquad \frac{\partial}{\partial \varphi} = 0$$

$$\boldsymbol{B} = \frac{1}{r\sin\theta}\nabla\Psi(r,\theta)\times\boldsymbol{e}_\varphi + \frac{I(r,\theta)}{r\sin\theta}\boldsymbol{e}_\varphi$$

2.



3.



4.

$$4\pi\frac{\boldsymbol{j}}{c} = \nabla\times\boldsymbol{B}.$$

$$\Delta^*\Psi = -4\pi r\sin\theta\frac{j_\varphi}{c}.$$

$$\Delta^* = \left(\frac{\partial^2}{\partial r^2} + \frac{1}{r^2}\frac{\partial^2}{\partial\theta^2} - \frac{1}{r^2}\frac{\cos\theta}{\sin\theta}\frac{\partial}{\partial\theta}\right).$$

可積分条件とトロイダル電流密度

$$\frac{1}{\rho}\nabla p = -\nabla\phi_g + R\Omega^2\boldsymbol{e}_R + \frac{1}{\rho}\left(\frac{\boldsymbol{j}}{c}\times\boldsymbol{B}\right)$$

$$\rightarrow \frac{\boldsymbol{j}}{c} = \frac{1}{4\pi}\frac{d\kappa(\Psi)}{d\Psi}\boldsymbol{B} + \rho r\sin\theta\mu(\Psi)\boldsymbol{e}_\varphi$$

$$\frac{1}{\rho}\nabla p = -\nabla\phi_g - \frac{1}{2}\nabla|\boldsymbol{v}|^2 + \boldsymbol{v}\times\boldsymbol{\omega} + \frac{1}{\rho}\left(\frac{\boldsymbol{j}}{c}\times\boldsymbol{B}\right)$$

$$\rightarrow \frac{\boldsymbol{j}}{c} = \left[\kappa'(\Psi) + Rv_\varphi Q''(\Psi)\right]\frac{\boldsymbol{B}}{4\pi} + Q'(\Psi)\frac{\boldsymbol{\omega}}{4\pi} + \rho R\left[\mu(\Psi) + Rv_\varphi\Omega'(\Psi)\right]\boldsymbol{e}_\varphi$$

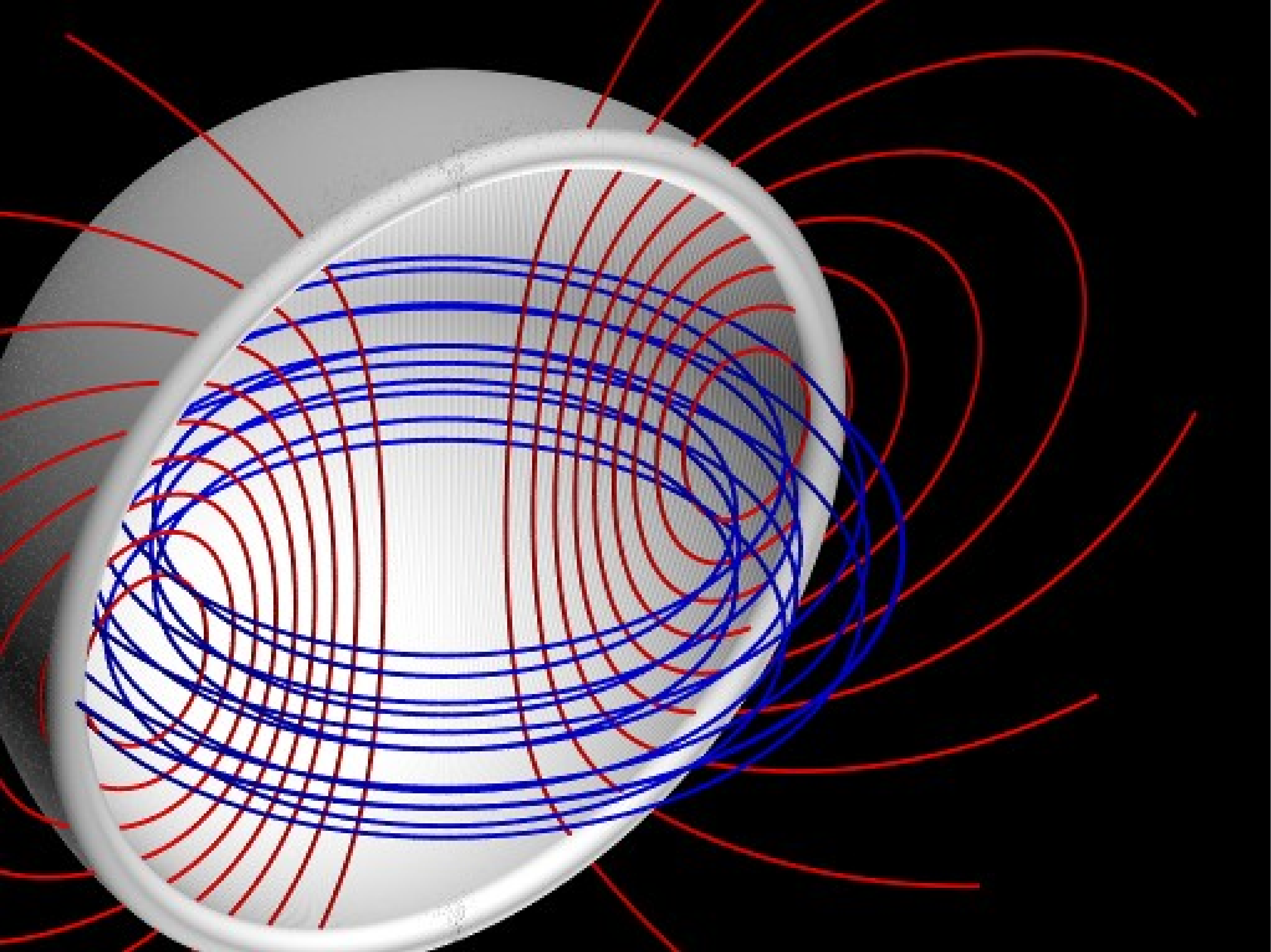
$$\frac{\boldsymbol{j}}{c}\times\boldsymbol{B} = 0$$

$$\nabla\times\left[\frac{c}{4\pi e n_e}\boldsymbol{B}\times(\nabla\times\boldsymbol{B})\right] = 0.$$

$$\rightarrow \frac{\boldsymbol{j}}{c} = \frac{1}{4\pi}\frac{d\kappa(\Psi)}{d\Psi}\boldsymbol{B}$$

$$\rightarrow \frac{\boldsymbol{j}}{c} = \frac{1}{4\pi}\frac{d\kappa(\Psi)}{d\Psi}\boldsymbol{B} + n_e r\sin\theta S(\Psi)\boldsymbol{e}_\varphi$$

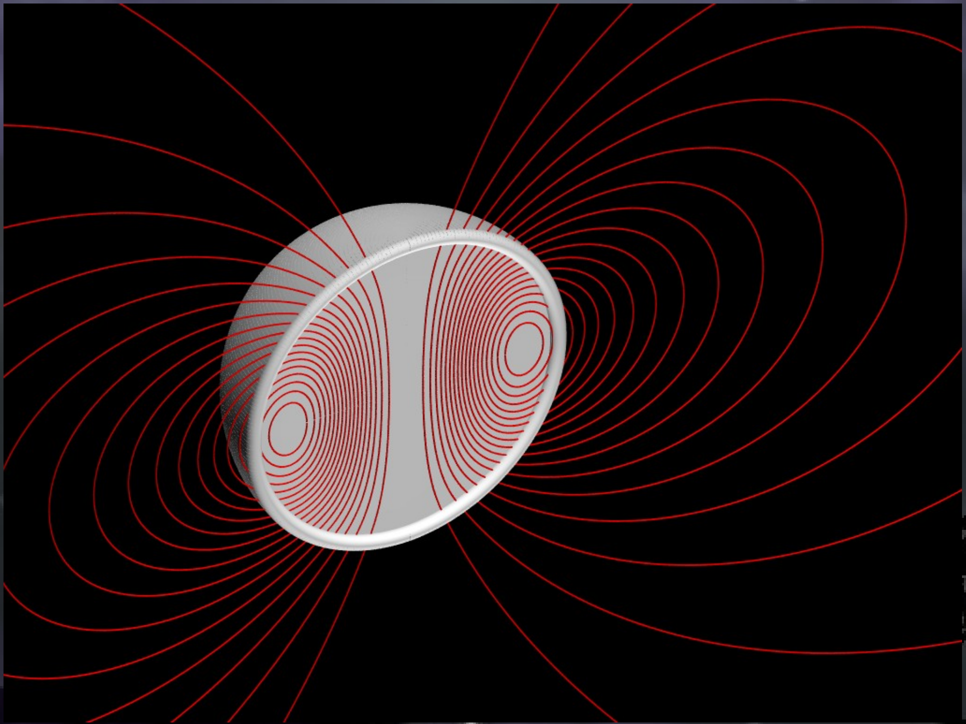
cf. Lovelace et al. (1986); Fuisawa et al.(2013), Fujisawa & Kisaka(2014)
Gourgouliatos et al. (2013)



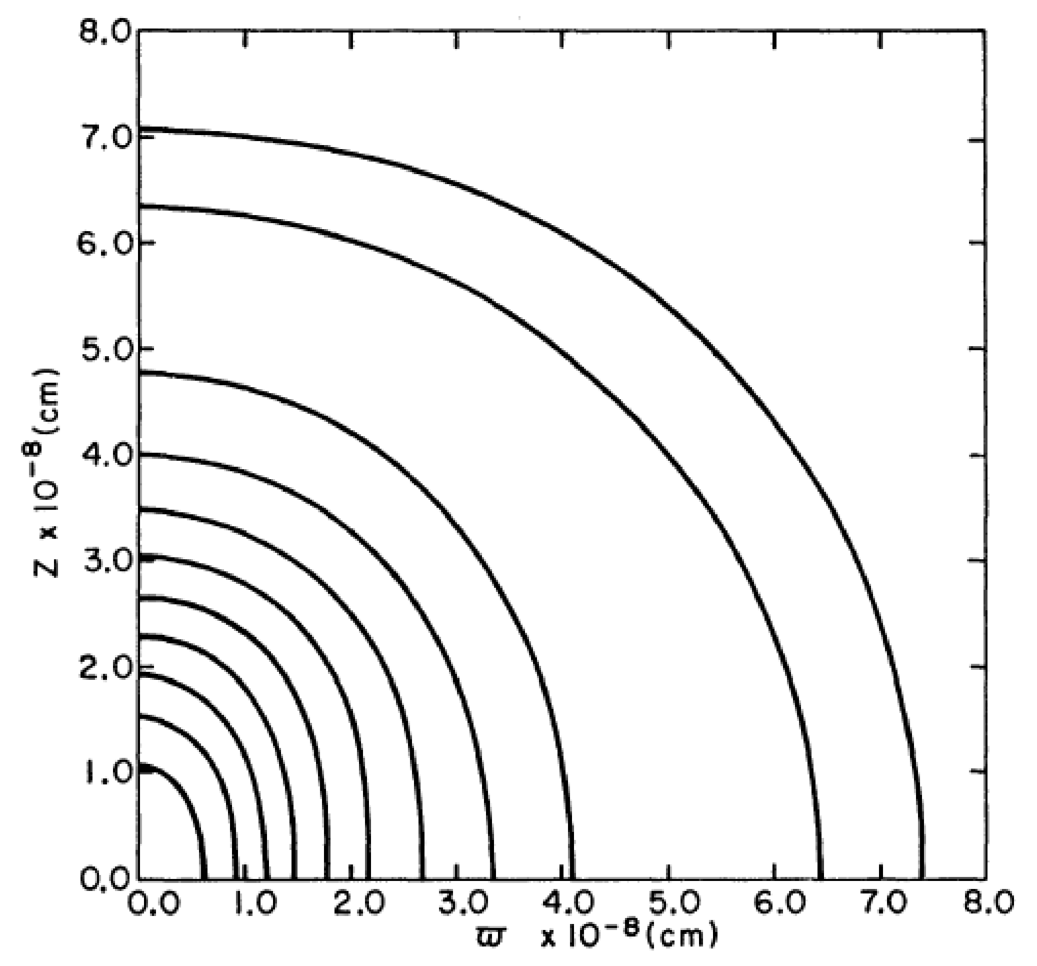
A型星の内部磁場 (Ferraro 1954)

$$\frac{\partial^2 U}{\partial r^2}+\frac{\sin\ \theta}{r^2}\frac{\partial}{\partial\theta}\left(\frac{1}{\sin\ \theta}\frac{\partial U}{\partial\theta}\right)=\kappa r^2\sin^2\ \theta\,.$$

- 星内部の定常的な磁場構造とその時の歪みを計算

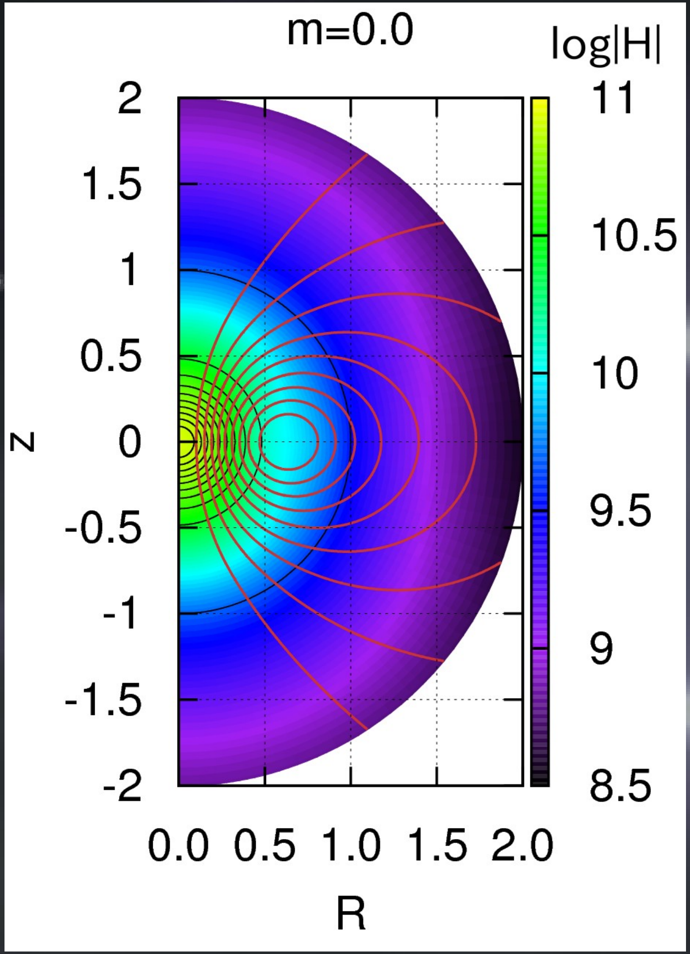


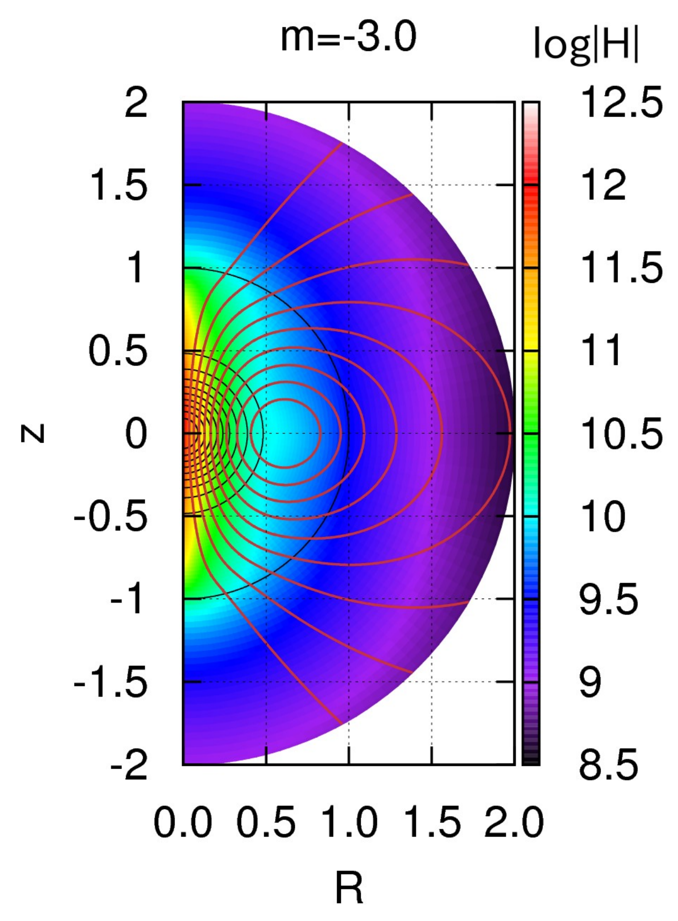
強磁場白色矮星の内部構造1



Ostriker & Hartwick (1968)

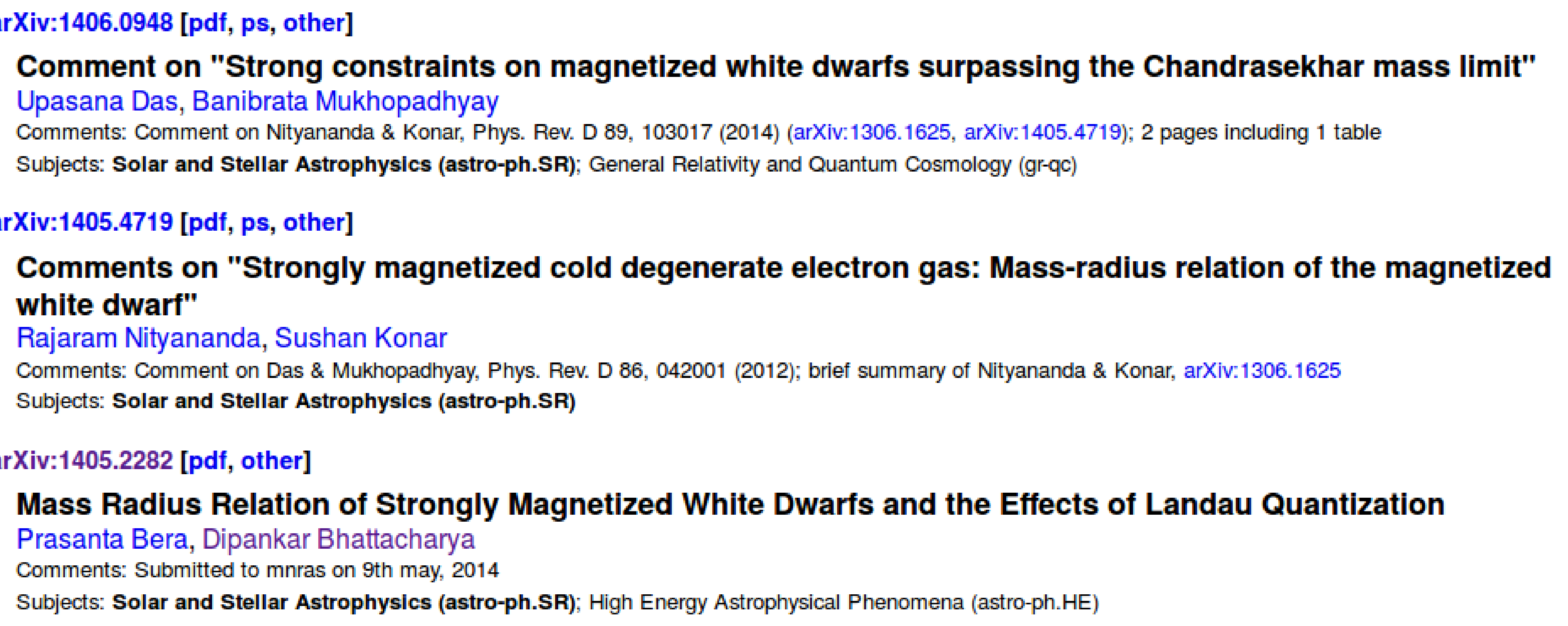
強磁場白色矮星の内部構造2





Fujisawa et al. (2012)

強磁場白色矮星インドの乱1



rXiv:1406.0948 [pdf, ps, other]

Comment on "Strong constraints on magnetized white dwarfs surpassing the Chandrasekhar mass limit"

Upasana Das, Banibrata Mukhopadhyay

Comments: Comment on Nityananda & Konar, Phys. Rev. D 89, 103017 (2014) (arXiv:1306.1625, arXiv:1405.4719); 2 pages including 1 table

Subjects: **Solar and Stellar Astrophysics (astro-ph.SR)**; General Relativity and Quantum Cosmology (gr-qc)

rXiv:1405.4719 [pdf, ps, other]

Comments on "Strongly magnetized cold degenerate electron gas: Mass-radius relation of the magnetized white dwarf"

Rajaram Nityananda, Sushan Konar

Comments: Comment on Das & Mukhopadhyay, Phys. Rev. D 86, 042001 (2012); brief summary of Nityananda & Konar, arXiv:1306.1625

Subjects: **Solar and Stellar Astrophysics (astro-ph.SR)**

rXiv:1405.2282 [pdf, other]

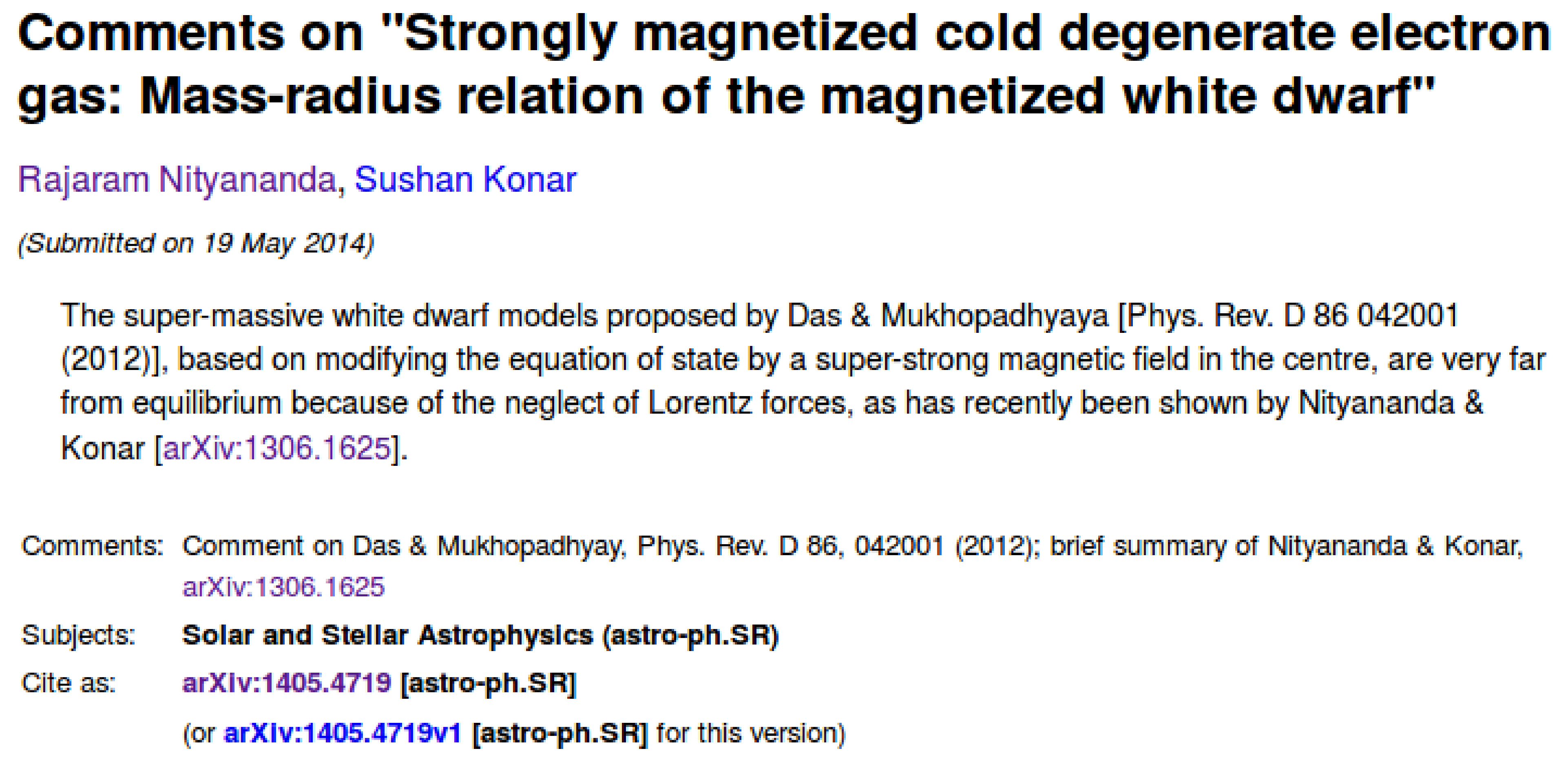
Mass Radius Relation of Strongly Magnetized White Dwarfs and the Effects of Landau Quantization

Prasanta Bera, Dipankar Bhattacharya

Comments: Submitted to mnras on 9th may, 2014

Subjects: **Solar and Stellar Astrophysics (astro-ph.SR)**; High Energy Astrophysical Phenomena (astro-ph.HE)

強磁場白色矮星インドの乱2



Comments on "Strongly magnetized cold degenerate electron gas: Mass-radius relation of the magnetized white dwarf"

Rajaram Nityananda, Sushan Konar

(Submitted on 19 May 2014)

The super-massive white dwarf models proposed by Das & Mukhopadhyaya [Phys. Rev. D 86 042001 (2012)], based on modifying the equation of state by a super-strong magnetic field in the centre, are very far from equilibrium because of the neglect of Lorentz forces, as has recently been shown by Nityananda & Konar [arXiv:1306.1625].

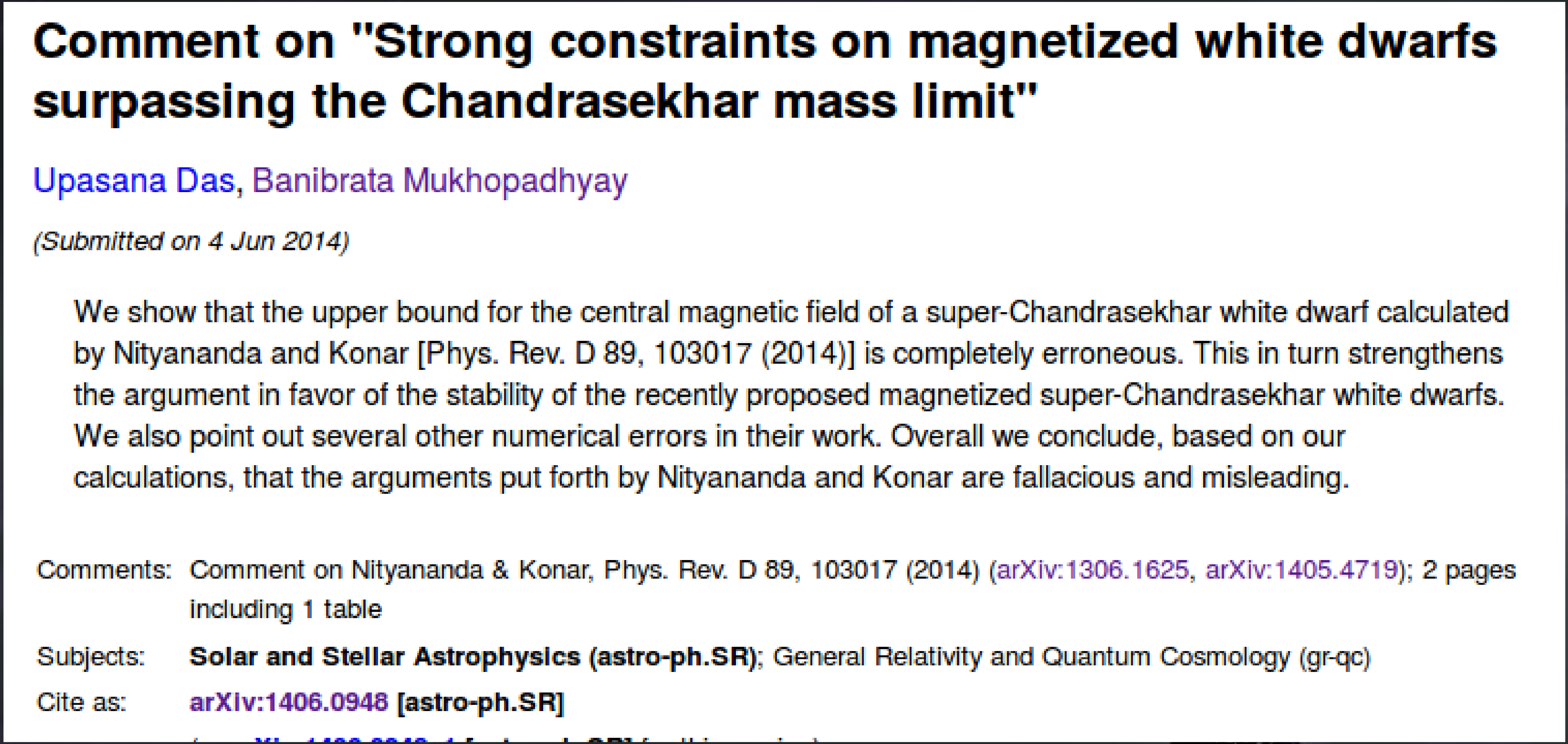
Comments: Comment on Das & Mukhopadhyay, Phys. Rev. D 86, 042001 (2012); brief summary of Nityananda & Konar, arXiv:1306.1625

Subjects: **Solar and Stellar Astrophysics (astro-ph.SR)**

Cite as: **arXiv:1405.4719 [astro-ph.SR]**

(or **arXiv:1405.4719v1 [astro-ph.SR]** for this version)

強磁場白色矮星インドの乱3



Comment on "Strong constraints on magnetized white dwarfs surpassing the Chandrasekhar mass limit"

Upasana Das, Banibrata Mukhopadhyay

(Submitted on 4 Jun 2014)

We show that the upper bound for the central magnetic field of a super-Chandrasekhar white dwarf calculated by Nityananda and Konar [Phys. Rev. D 89, 103017 (2014)] is completely erroneous. This in turn strengthens the argument in favor of the stability of the recently proposed magnetized super-Chandrasekhar white dwarfs. We also point out several other numerical errors in their work. Overall we conclude, based on our calculations, that the arguments put forth by Nityananda and Konar are fallacious and misleading.

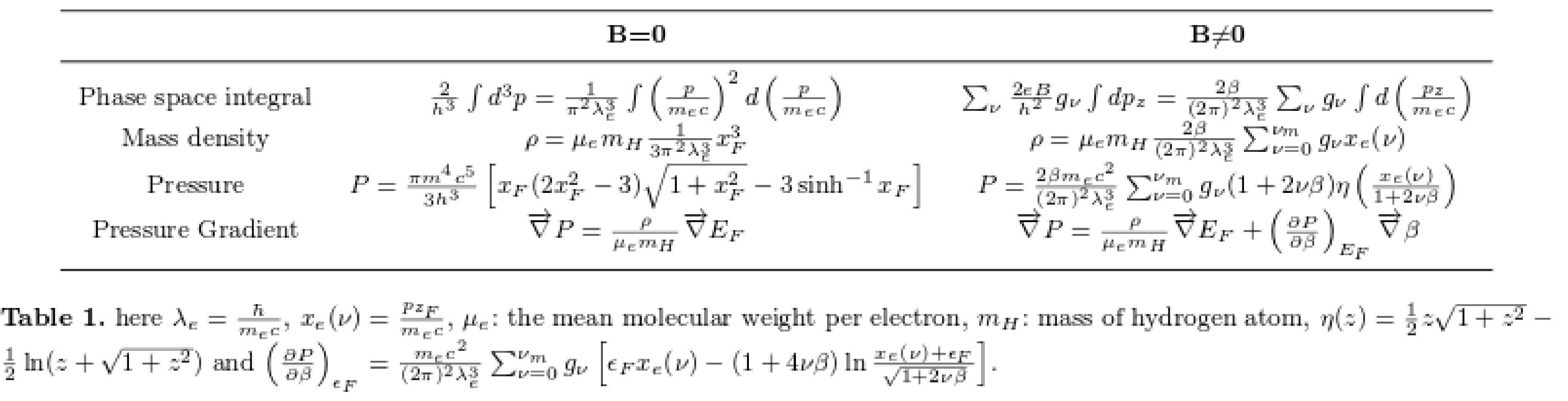
Comments: Comment on Nityananda & Konar, Phys. Rev. D 89, 103017 (2014) (arXiv:1306.1625, arXiv:1405.4719); 2 pages including 1 table

Subjects: **Solar and Stellar Astrophysics (astro-ph.SR)**; General Relativity and Quantum Cosmology (gr-qc)

Cite as: **arXiv:1406.0948 [astro-ph.SR]**

強磁場白色矮星の内部構造3

Mass Radius Relation of Strongly Magnetized White Dwarfs and the Effects of Landau Quantization



	B=0	B≠0
Phase space integral	$\frac{2}{h^3}\int d^3p = \frac{1}{\pi^2\lambda_e^3}\int\left(\frac{p}{m_e c}\right)^2 d\left(\frac{p}{m_e c}\right)$	$\sum_\nu \frac{2eB}{h^2} g_\nu \int dp_z = \frac{2\beta}{(2\pi)^2\lambda_e^3}\sum_\nu g_\nu \int d\left(\frac{p_z}{m_e c}\right)$
Mass density	$\rho = \mu_e m_H \frac{1}{3\pi^2\lambda_e^3} x_F^3$	$\rho = \mu_e m_H \frac{2\beta}{(2\pi)^2\lambda_e^3}\sum_{\nu=0}^{\nu_m} g_\nu x_e(\nu)$
Pressure	$P = \frac{\pi m^4 c^5}{3h^3}\left[x_F(2x_F^2 - 3)\sqrt{1+x_F^2} - 3\sinh^{-1} x_F\right]$	$P = \frac{2\beta m_e c^2}{(2\pi)^2\lambda_e^3}\sum_{\nu=0}^{\nu_m} g_\nu (1+2\nu\beta)\eta\left(\frac{x_e(\nu)}{1+2\nu\beta}\right)$
Pressure Gradient	$\vec{\nabla} P = \frac{\rho}{\mu_e m_H}\vec{\nabla} E_F$	$\vec{\nabla} P = \frac{\rho}{\mu_e m_H}\vec{\nabla} E_F + \left(\frac{\partial P}{\partial \beta}\right)_{E_F}\vec{\nabla}\beta$

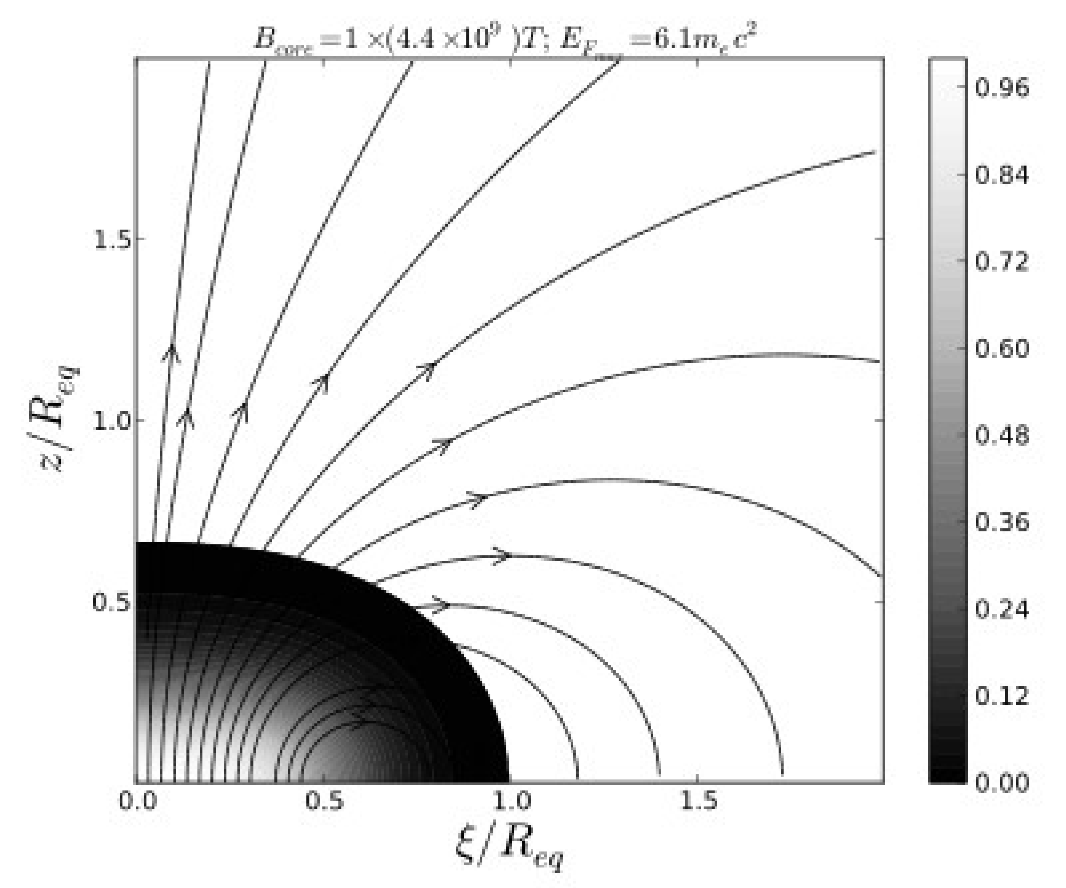
Table 1. here $\lambda_e = \frac{\hbar}{m_e c}$, $x_e(\nu) = \frac{p_{z_F}}{m_e c}$, μ_e: the mean molecular weight per electron, m_H: mass of hydrogen atom, $\eta(z) = \frac{1}{2}z\sqrt{1+z^2} - \frac{1}{2}\ln(z+\sqrt{1+z^2})$ and $\left(\frac{\partial P}{\partial \beta}\right)_{\epsilon_F} = \frac{m_e c^2}{(2\pi)^2\lambda_e^3}\sum_{\nu=0}^{\nu_m} g_\nu \left[\epsilon_F x_e(\nu) - (1+4\nu\beta)\ln\frac{x_e(\nu)+\epsilon_F}{\sqrt{1+2\nu\beta}}\right]$.

Lai & Shapiro (1991).

Bera & Bhattacharaya (2014)

強磁場白色矮星の内部構造3

Mass Radius Relation of Strongly Magnetized White Dwarfs and the Effects of Landau Quantization



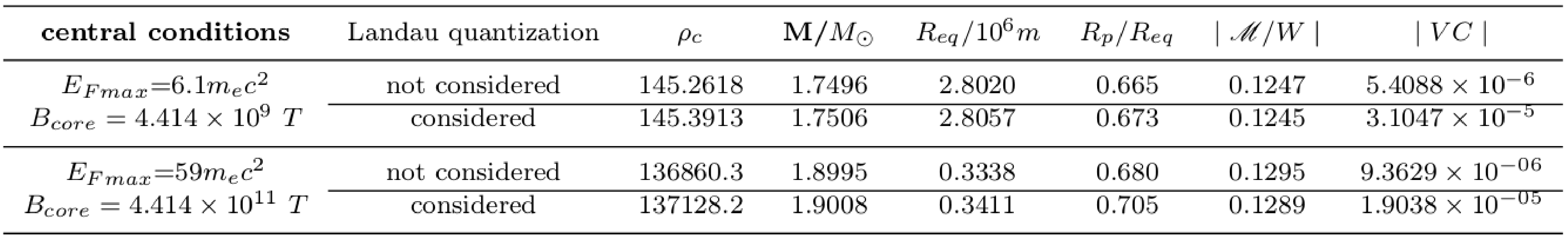
Lai & Shapiro (1991).

Bera & Bhattacharaya (2014)

強磁場白色矮星の内部構造3

Mass Radius Relation of Strongly Magnetized White Dwarfs and the Effects of Landau Quantization

Submitted to mnras on 9th may, 2014

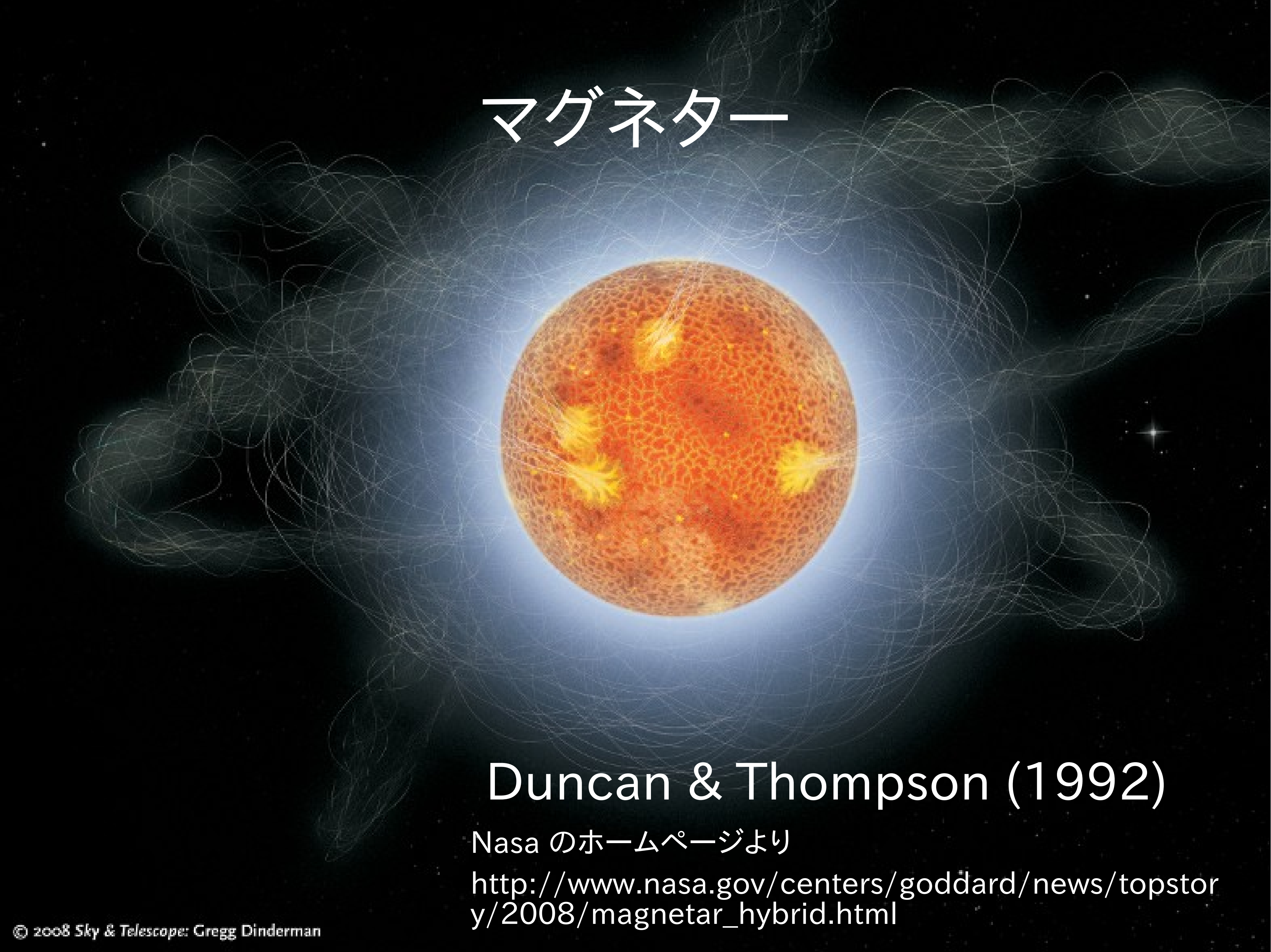


central conditions	Landau quantization	ρ_c	$\mathbf{M}/M_\odot$	$R_{eq}/10^6m$	R_p/R_{eq}	$\mid \mathscr{M}/W \mid$	$\mid VC \mid$
$E_{Fmax}=6.1m_ec^2$ $B_{core} = 4.414\times10^9\ T$	not considered	145.2618	1.7496	2.8020	0.665	0.1247	5.4088×10^{-6}
	considered	145.3913	1.7506	2.8057	0.673	0.1245	3.1047×10^{-5}
$E_{Fmax}=59m_ec^2$ $B_{core} = 4.414\times10^{11}\ T$	not considered	136860.3	1.8995	0.3338	0.680	0.1295	9.3629×10^{-06}
	considered	137128.2	1.9008	0.3411	0.705	0.1289	1.9038×10^{-05}

質量は大きくなるが、磁場も非常に大きい

Bera & Bhattacharaya (2014)

マグネター



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Duncan & Thompson (1992)

Nasa のホームページより

http://www.nasa.gov/centers/goddard/news/topstory/2008/magnetar_hybrid.html

磁場のタイムスケール

- 1:ダイナミカルタイムスケール

$$t_A = \sqrt{4\pi\rho}R/B$$
$$\sim 0.1s\left(\frac{\rho}{10^{15}g/\mathrm{cm}^3}\right)^{1/2}\left(\frac{R}{10^6\mathrm{cm}}\right)\left(\frac{B}{10^{15}\mathrm{G}}\right)^{-1}$$

- 2:　永年タイムスケール
  - Ambipolar 拡散 (100yr ～ ?)
  - Hall 効果 (10^5 yr ～)
  - Ohm 散逸 (～ 10^7 yr ～)

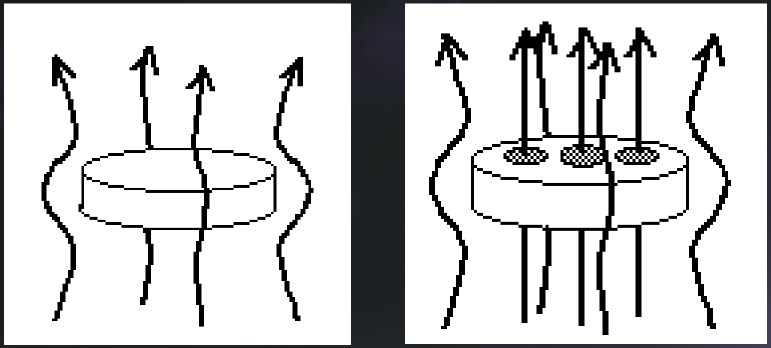
定常と永年進化

様々な定常解

- ニュートン重力
  - Tomimura & Eriguchi (2005)
  - Yoshida & Eriguchi (2006)
  - Yoshida et al. (2006)
  - Haskell et al. (2008)
  - Kiuchi & Kotake (2008)
  - Lander & Jones (2009)
  - Fujisawa et al. (2012)
- GR
  - Ioka & Sasaki (2003, 2004)
  - Ciolfi et al. (2009, 2010)
  - Yoshida et al. (2012)
  - Ciolfi & Rezzolla (2013)
  - Pili et al. (2014)
  - Uryu et al. (2014)
- 二流体(超伝導体)
  - Lander et al. (2012)
  - Glampedakis et al. (2012)
  - Lander (2013a,b)
- Hall equilibria
  - Gourgouliatos et al. (2013)
- Star + magnetosphere
  - Glampedakis et al. (2013)
- Core + Hall equilibrium crust +magnetosphere
  - Fujisawa & Kisaka (2014)

第二種超電導の磁場構造

Lander (2013a,b)



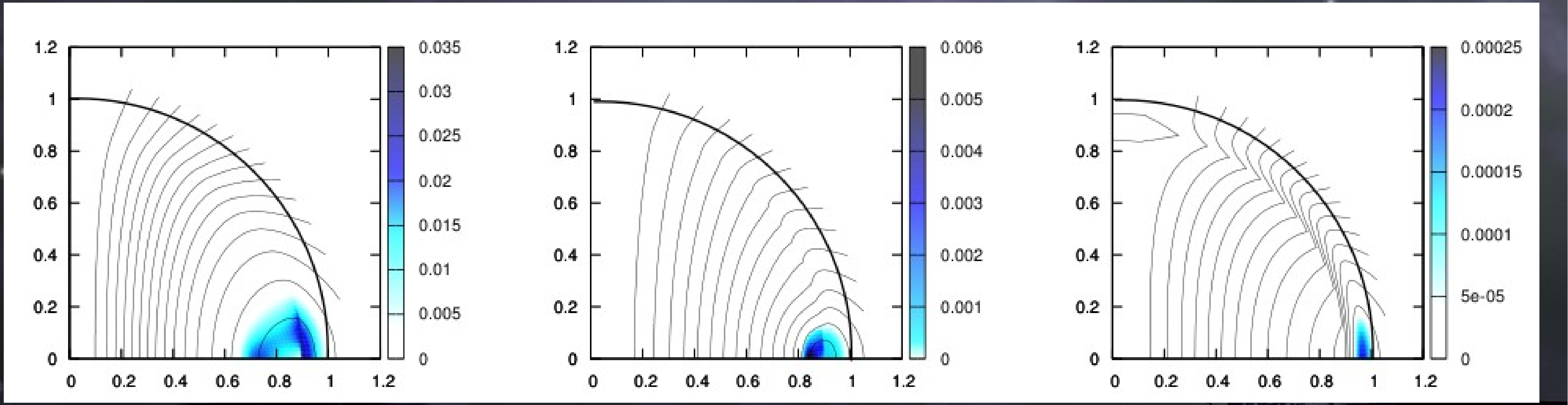
$$\mathfrak{F}_{mag} = -\frac{1}{4\pi}\left[\mathbf{B}\times(\nabla\times\mathbf{H}_{c1}) + \rho_{\rm p}\nabla\left(B\frac{\partial H_{c1}}{\partial\rho_{\rm p}}\right)\right],$$

$$\mathbf{H}_{c1} \quad = \quad H_{c1}\hat{\mathbf{B}}$$

$$H_{c1} \quad = \quad h_c\rho_{\rm p}/\varepsilon_*$$

Hc1 〜 10^15G
Hc2 〜 10^16G

(Glampedakis et al.2011)



中性子星の内部

Baym et al. (1969a,b)

- コア部の電気伝導度が非常に高い

$$\sigma \sim 1.5 \times 10^{29}\mathrm{s}^{-1} \;\; (\mathrm{T} = 10^{8}\mathrm{K}, \rho = 10^{13}\mathrm{g\ cm}^{-3})$$

- Ohm散逸のタイムスケールは宇宙年齢

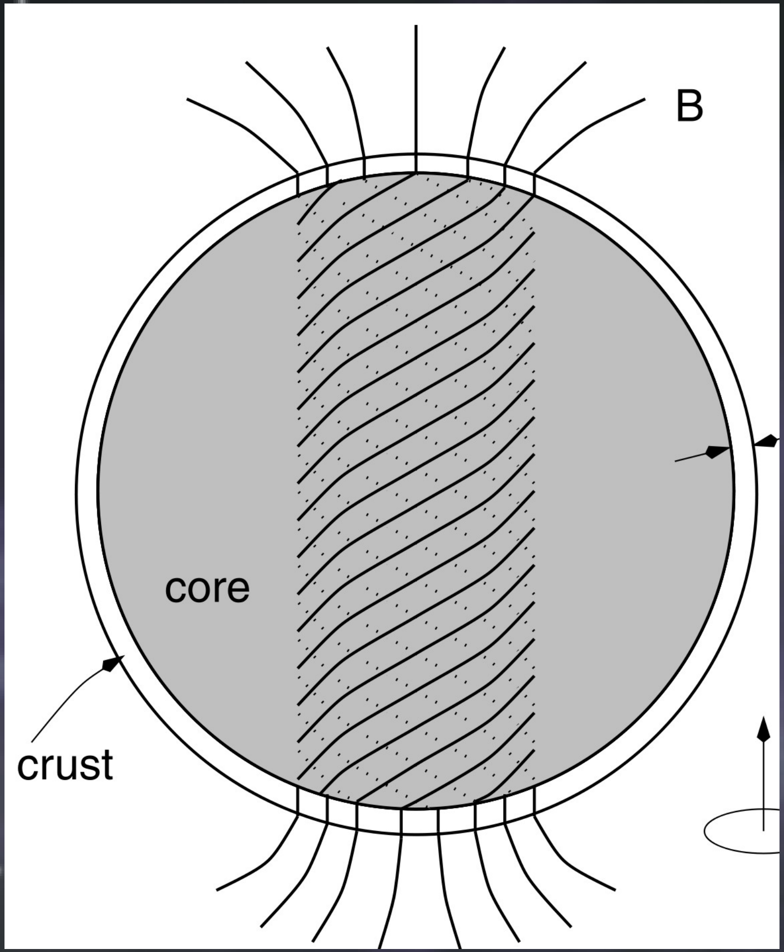
$$t_d \sim \frac{4\pi\sigma L^2}{c^2} \sim 10^{13}\mathrm{yr}$$

- マイスナー効果のタイムスケールも長い

$$t_m = t_d \left(\frac{B}{H_c}\right)^2 \sim 10^{7}\mathrm{yr}$$

$H_c \sim 10^{15}\mathrm{G}$

コア磁場とクラスト磁場



- Thompson & Duncan (2001)
- Thompson et al. (2002)
- Beloborodov & Thompson (2007)

クラストでのOhmic decay

$$t_{\mathrm{ohm.}} \sim \frac{4\pi\sigma_0 L^2}{c^2}$$

$$t_{\mathrm{Ohm}} \sim 5.0 \times 10^7 \left(\frac{L}{10^5\mathrm{cm}}\right)^2 \left(\frac{\sigma}{10^{25}}\right)\mathrm{yr},$$

- 局所的な磁場、もしくは温度が高くなる必要がある

Hall drift

Naito & Kojima (1994)

$$\tau_{pn} \to 0, \quad \tau_{en} \to \infty$$

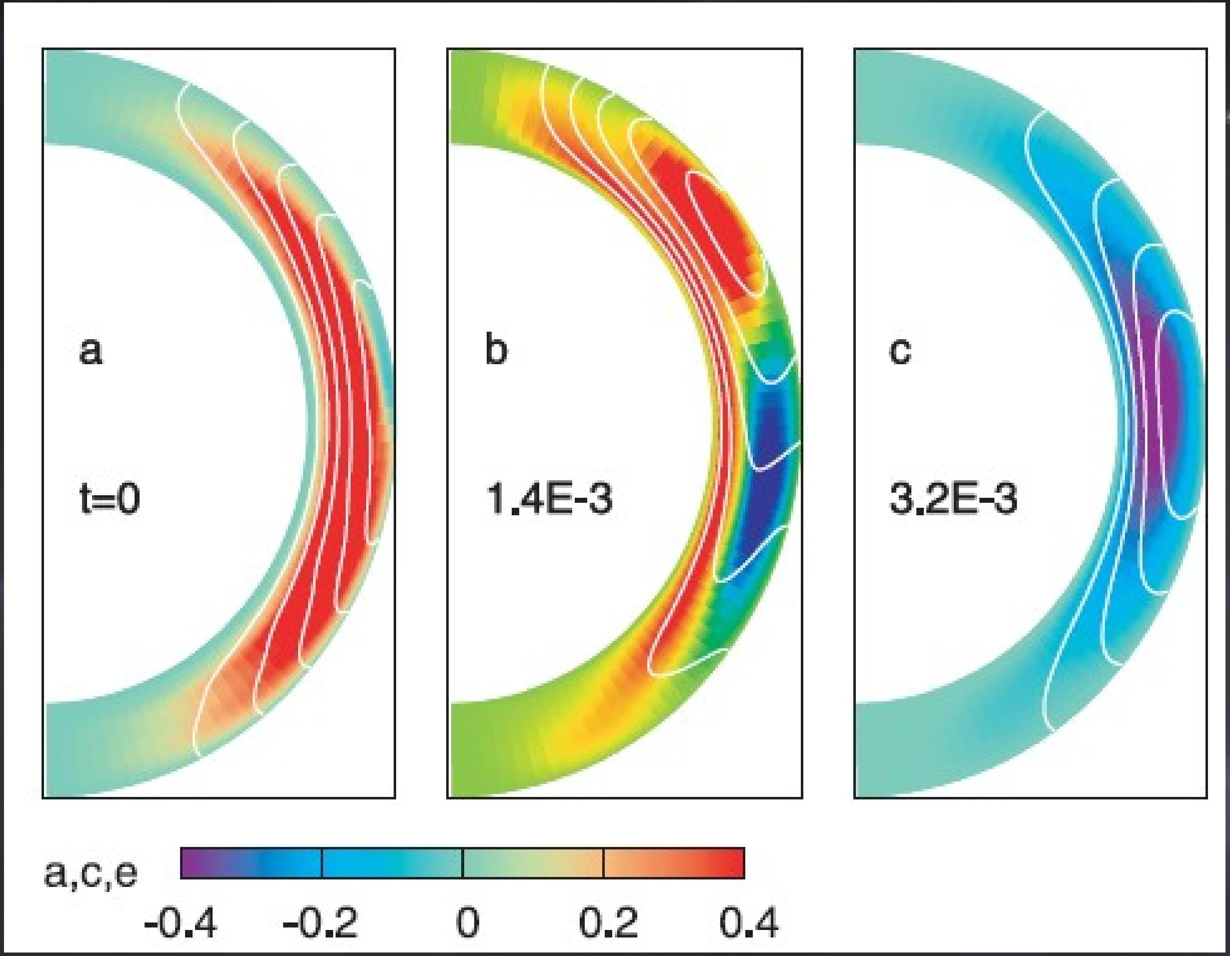
$$\frac{\partial \vec{B}}{\partial t} = -\frac{c}{4\pi n_c e}\nabla \times [(\nabla \times \vec{B}) \times \vec{B}] + \frac{c^2}{4\pi\sigma_0}\Delta\vec{B}$$

$$t_{\mathrm{Hall}} \sim 5.0 \times 10^5 \left(\frac{B}{10^{15}\mathrm{G}}\right)^{-1} \left(\frac{L}{10^5\mathrm{cm}}\right)^2 \left(\frac{\rho}{10^{14}\mathrm{g/cm^3}}\right) \mathrm{yr},$$

$$\mathcal{R}_m \equiv \frac{t_{Ohm}}{t_{Hall}} = \frac{\sigma B}{ecn_e} = 100 - 1000 \left(\frac{B}{10^{15}\mathrm{G}}\right)\left(\frac{\sigma}{10^{25}}\right)$$

- マグネターのクラストではよく効く！

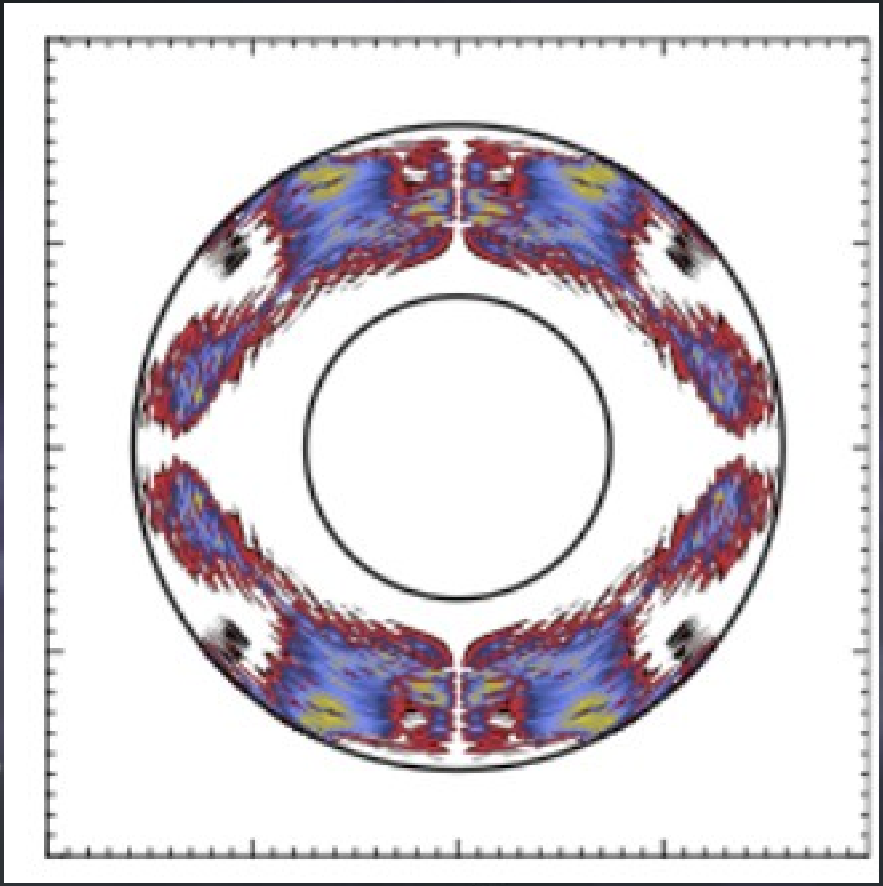
Hall MHD シミュレーション



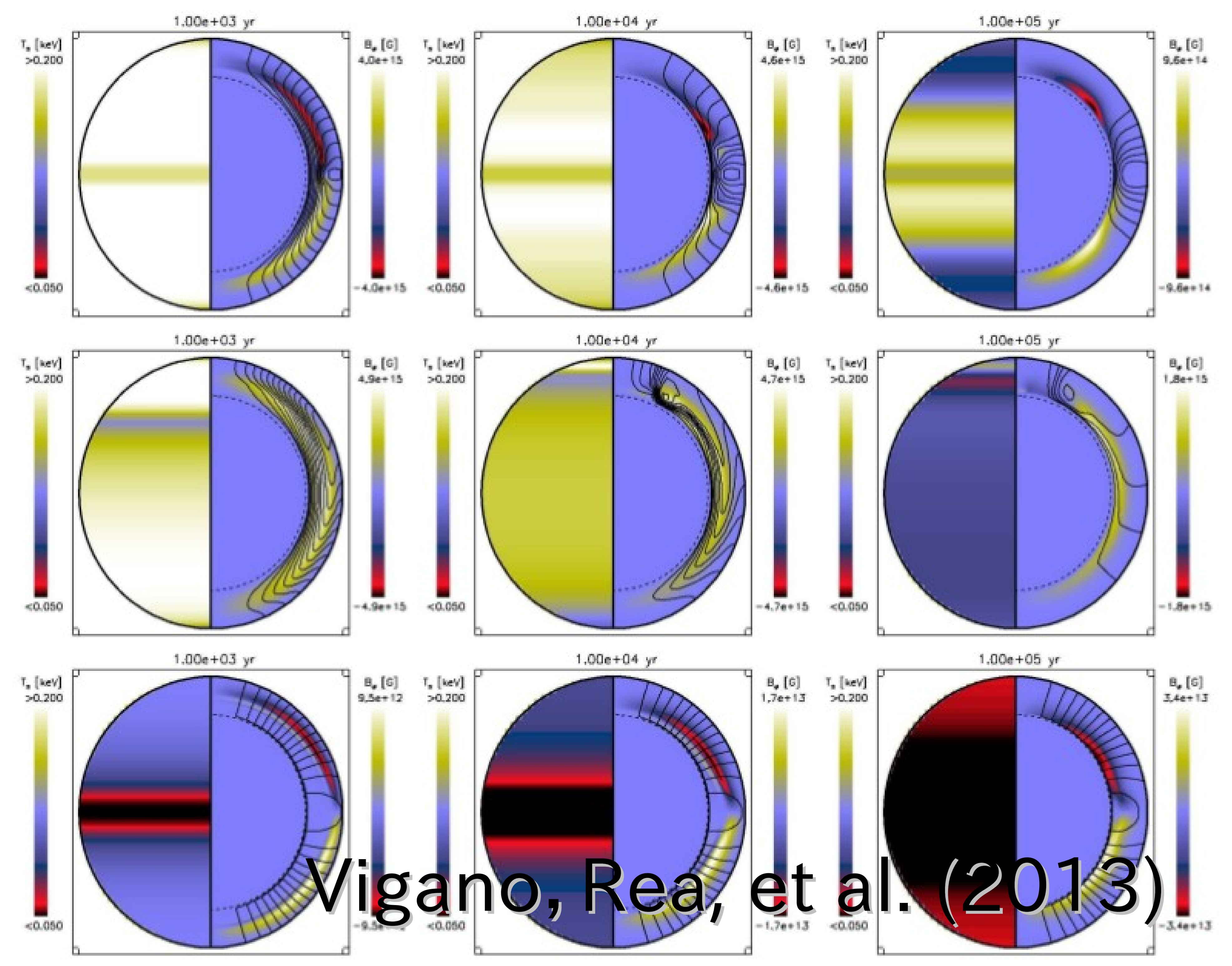
Kojima & Kisaka (2012)

トロイダル磁場が高次の磁場になり散逸を促進

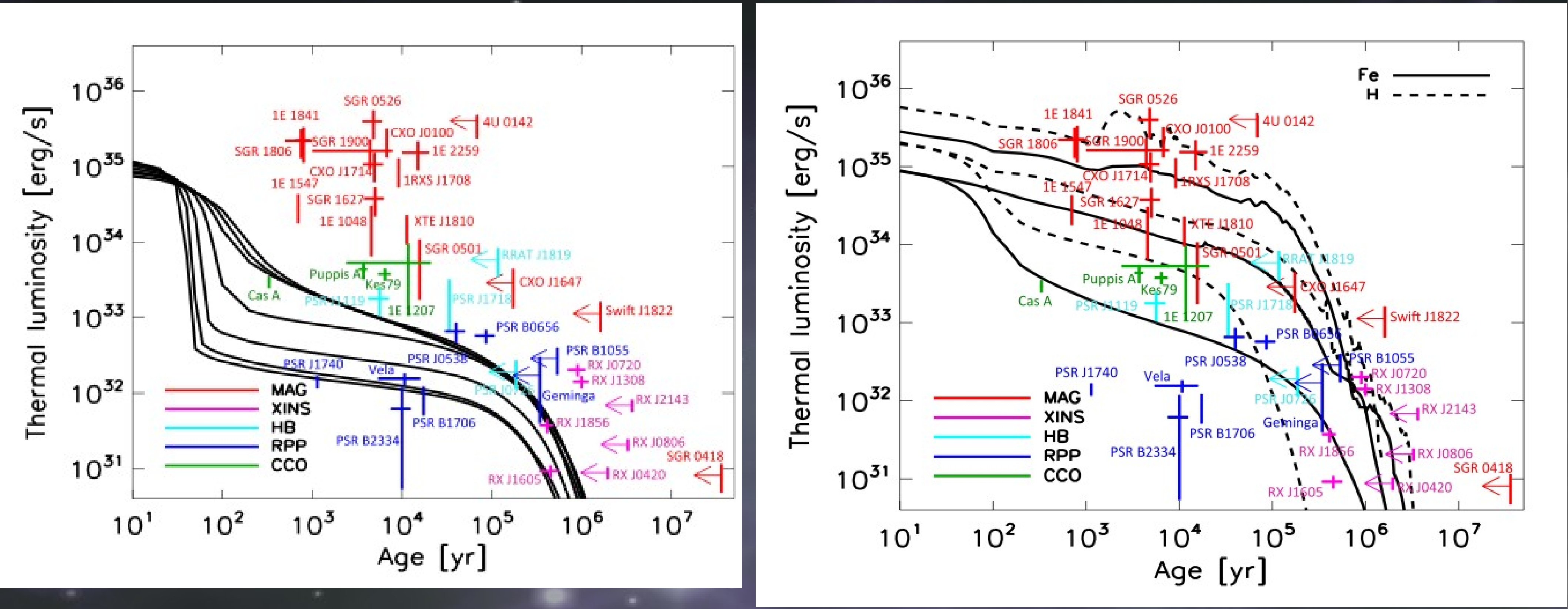
クラストの歪みとエネルギー解放



Perna & Pons (2011)



Vigano, Rea, et al. (2013)


Thermal luminosity [erg/s]
Age [yr]
10^{31}
10^{32}
10^{33}
10^{34}
10^{35}
10^{36}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
MAG
XINS
HB
RPP
CCO
Fe
H
SGR 0526
1E 1841
SGR 1806
SGR 1900
CXO J0100
4U 0142
1E 2259
CXO J1714
1RXS J1708
1E 1547
SGR 1627
1E 1048
XTE J1810
SGR 0501
RRAT J1819
CXO J1647
Puppis A
Kes79
Cas A
PSR J1119
1E 1207
PSR J1718
Swift J1822
PSR B0656
PSR B1055
PSR J0538
PSR J1740
Vela
PSR J0726
Geminga
RX J0720
RX J1308
RX J2143
RX J1856
PSR B1706
PSR B2334
RX J0806
SGR 0418
RX J1605
RX J0420

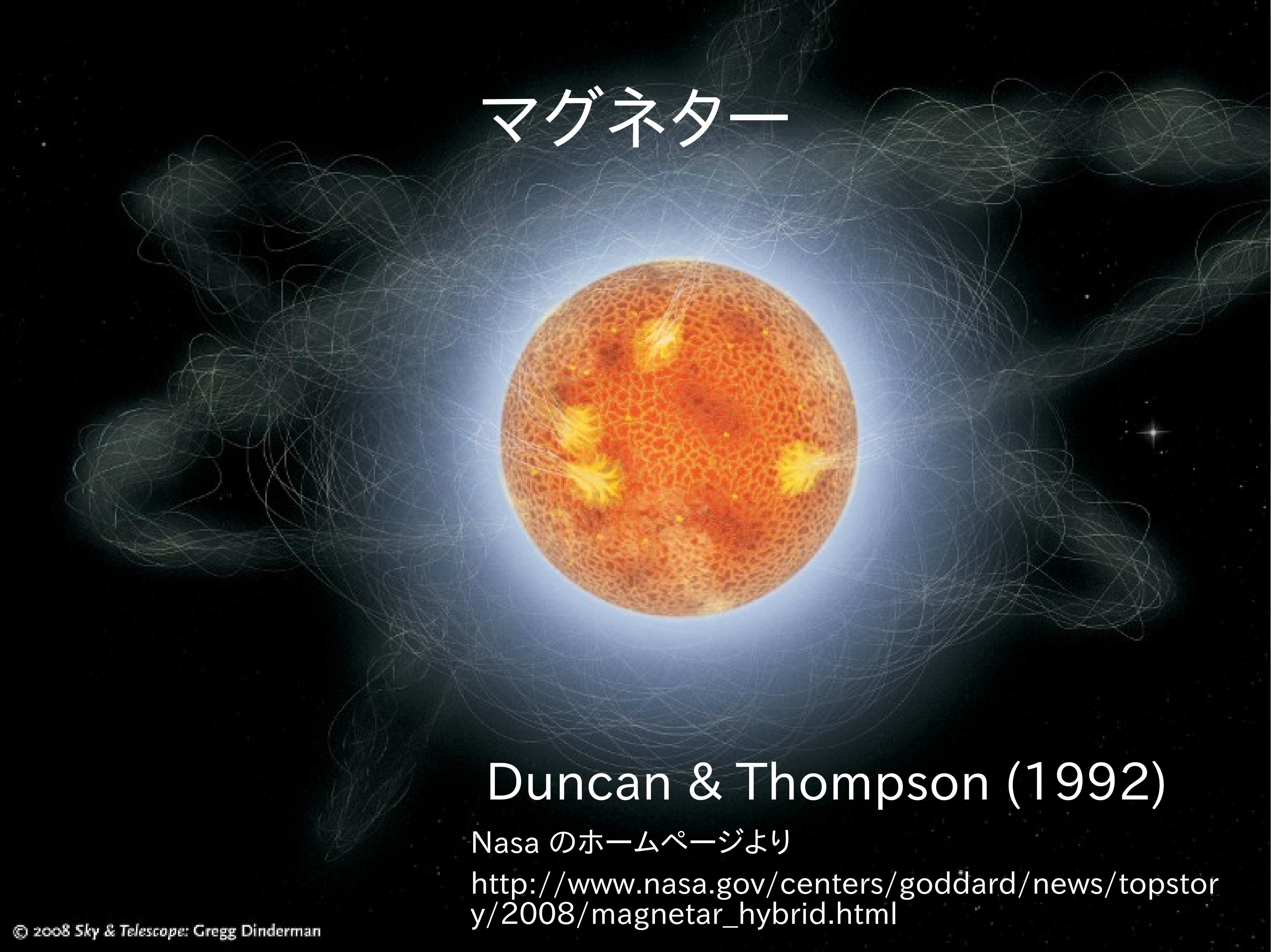
磁場なし　：　磁場あり

Magnetic field configurations of a magnetar throughout its interior and exterior -- core, crust and magnetosphere

Kotaro Fujisawa & Shota Kisaka (2014)

arXiv:1409.4547

マグネター



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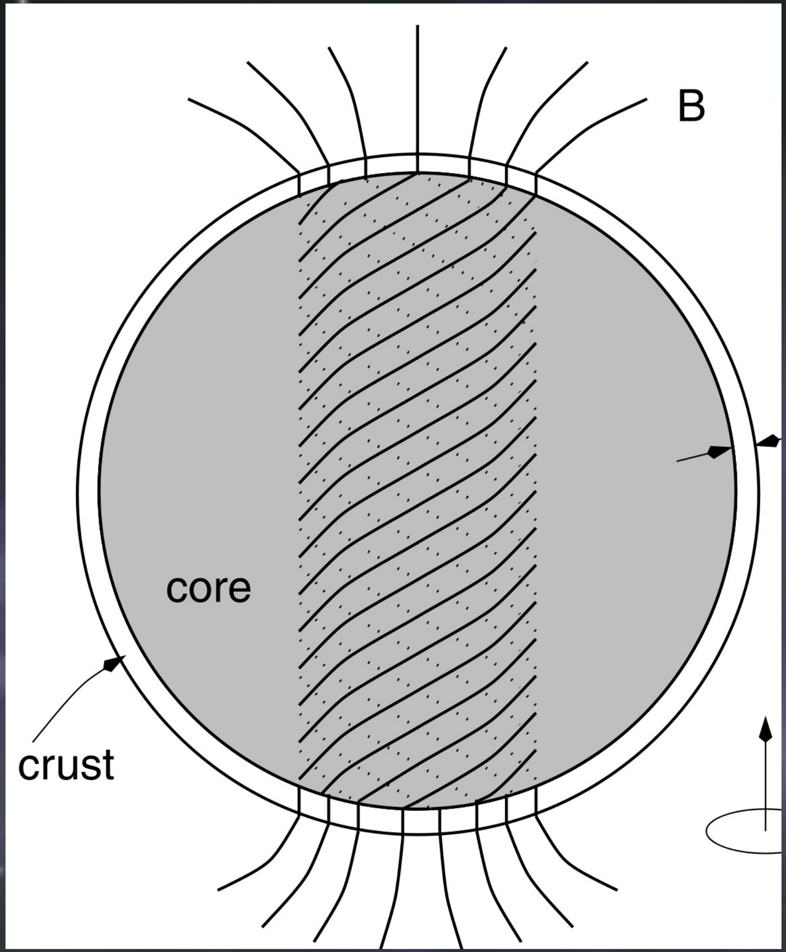
Duncan & Thompson (1992)

Nasa のホームページより

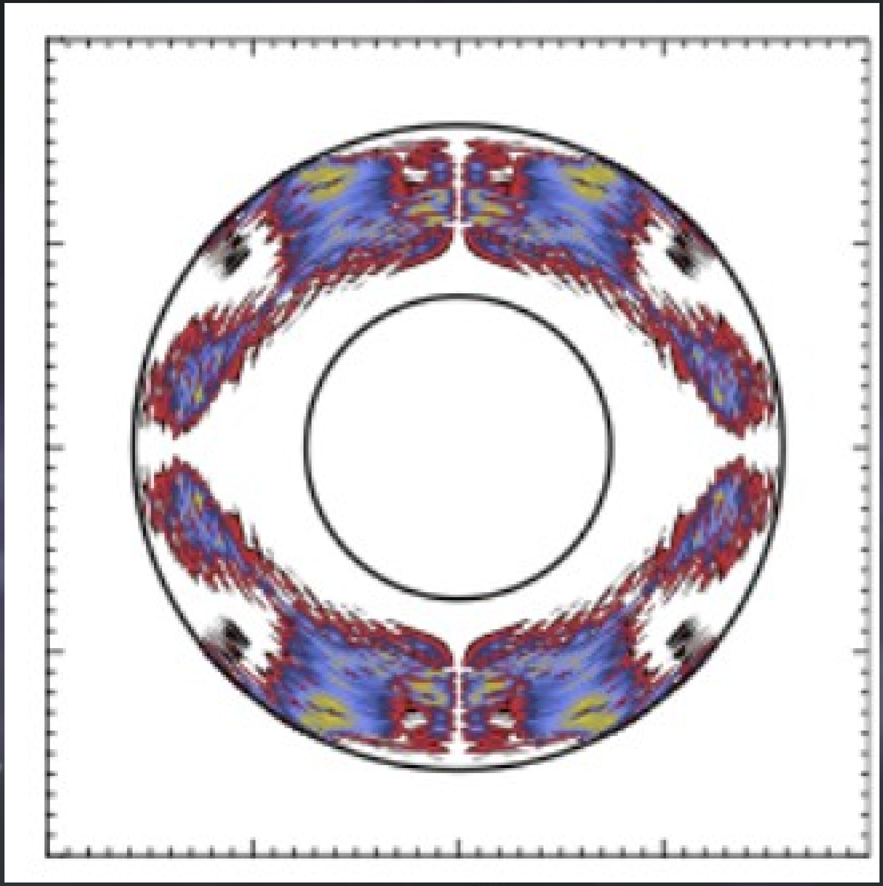
http://www.nasa.gov/centers/goddard/news/topstory/2008/magnetar_hybrid.html

ねじれたコア磁場とエネルギー解放



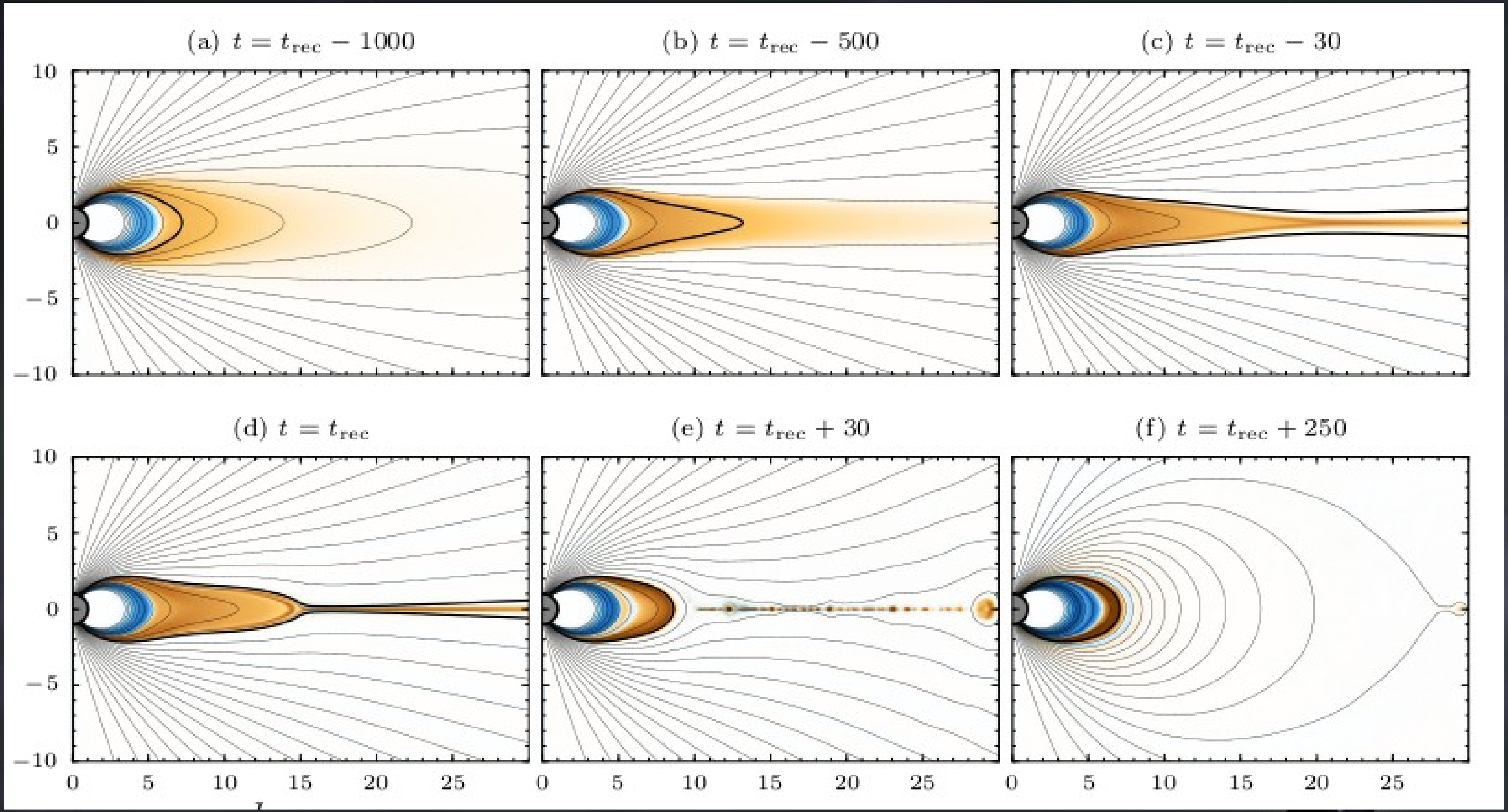
- Thompson & Duncan (2001)
- Thompson et al. (2002)
- Beloborodov & Thompson (2007)

クラストの歪みとエネルギー解放



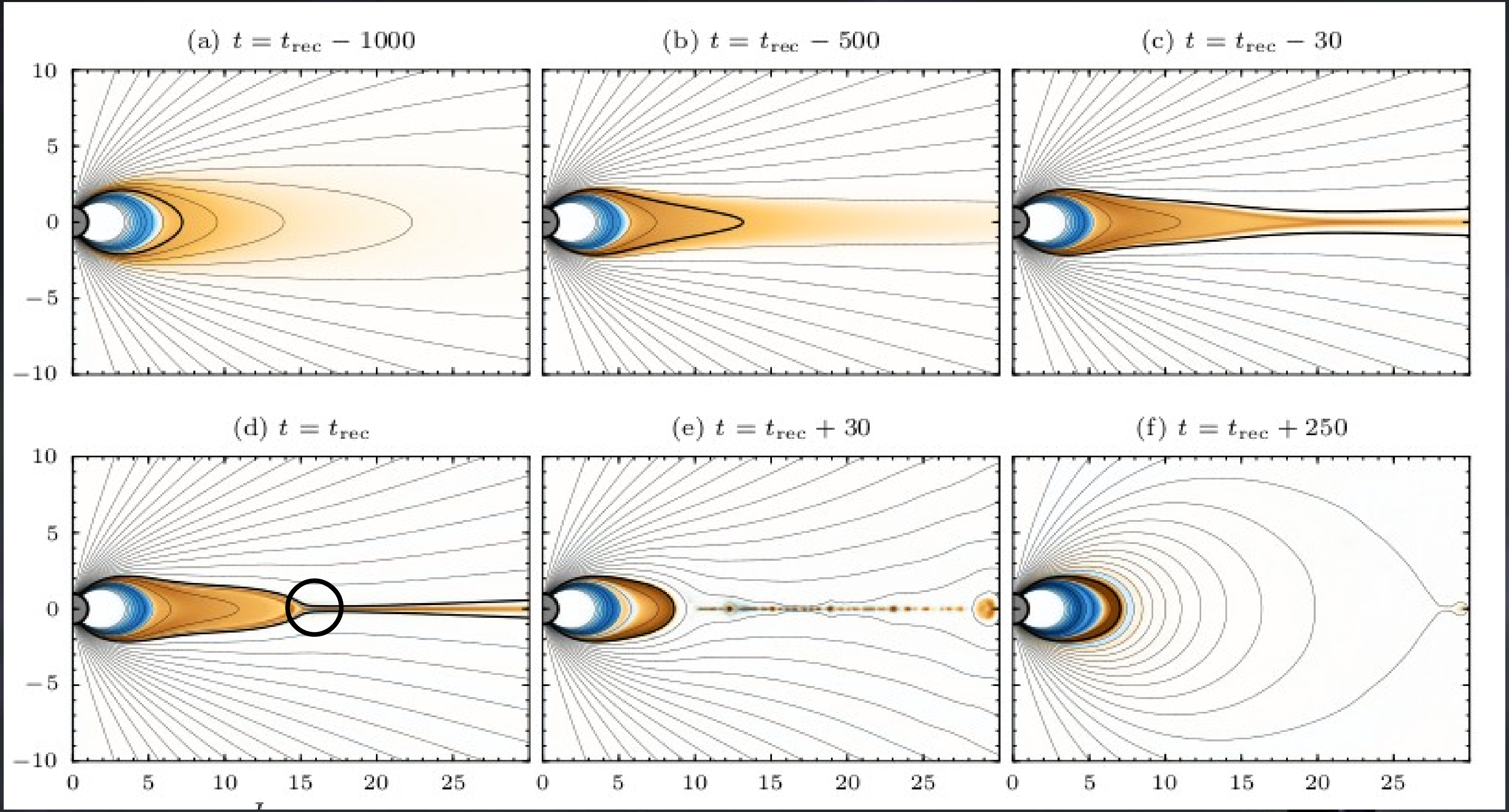
Perna & Pons (2011)

ねじれた磁気圏磁場とエネルギー解放



Parfrey et al. (2013)

ねじれた磁気圏磁場とエネルギー解放



Parfrey et al. (2013)

Hall MHD Equilibrium state

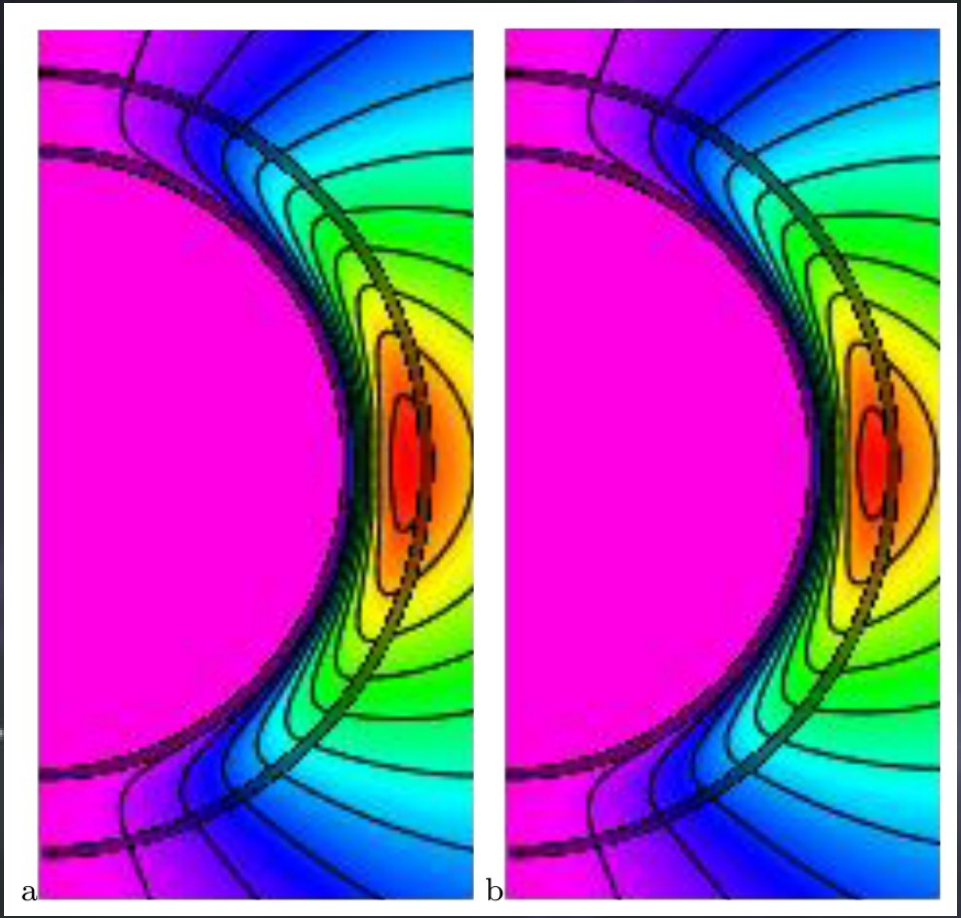
$$\frac{\partial}{\partial t}\boldsymbol{B} = -\nabla \times \left(\frac{c^2}{4\pi\sigma} \nabla \times \boldsymbol{B} \right) + \nabla \times \left[\frac{c}{4\pi e n_e} \boldsymbol{B} \times (\nabla \times \boldsymbol{B}) \right].$$

⇓

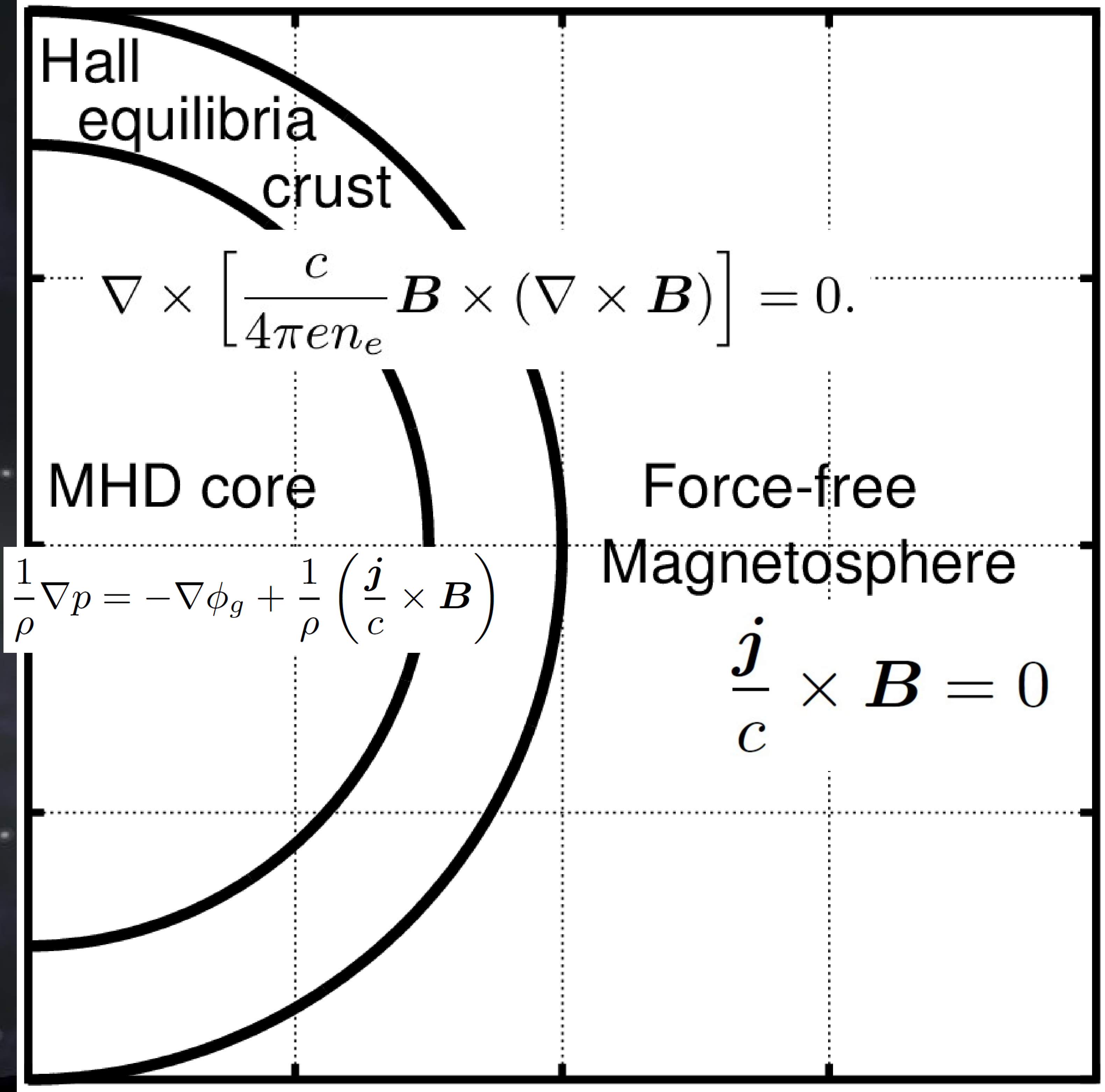
$$\nabla \times \left[\frac{c}{4\pi e n_e} \boldsymbol{B} \times (\nabla \times \boldsymbol{B}) \right] = 0.$$

- Hall drift が非常に強く, Hall 効果がとまる極限的な状態.

Hall 定常の計算



- Gourgouliatos et al. (2013)



Hall equilibria

crust

$$\nabla \times \left[\frac{c}{4\pi e n_e}\boldsymbol{B} \times (\nabla \times \boldsymbol{B})\right] = 0.$$

MHD core

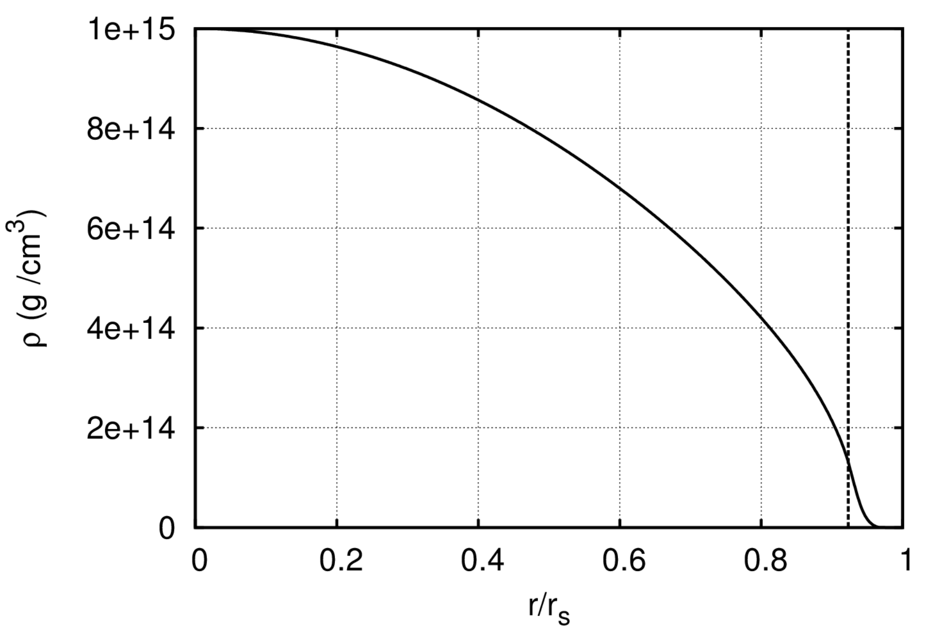
$$\frac{1}{\rho}\nabla p = -\nabla\phi_g + \frac{1}{\rho}\left(\frac{\boldsymbol{j}}{c} \times \boldsymbol{B}\right)$$

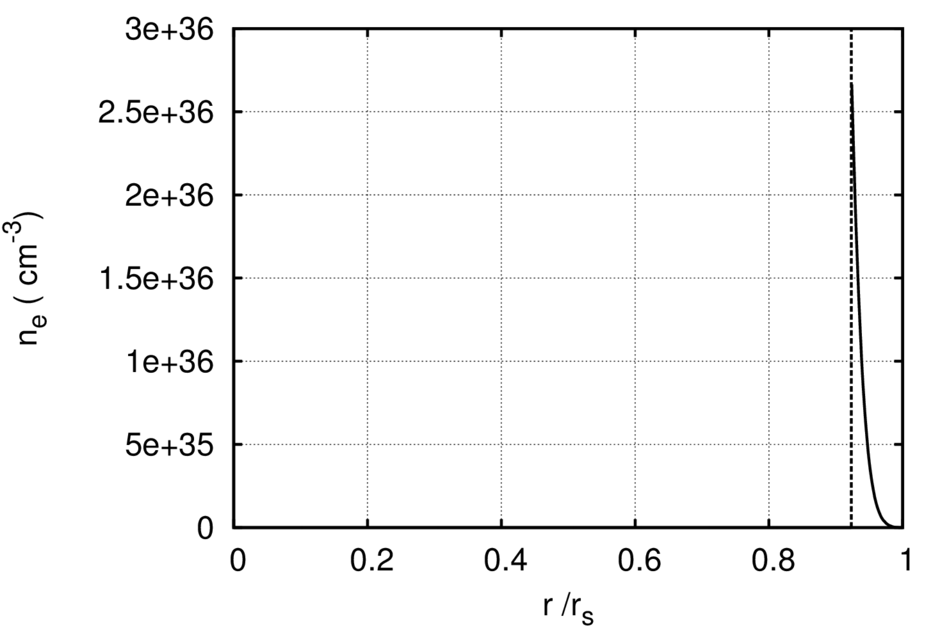
Force-free Magnetosphere

$$\frac{\boldsymbol{j}}{c} \times \boldsymbol{B} = 0$$

マグネターのモデル

- 質量 ～ 1.4 solar mass
- 半径 ～ 13 km
    - SLy. EOS (Douchin & Haensel 2001)

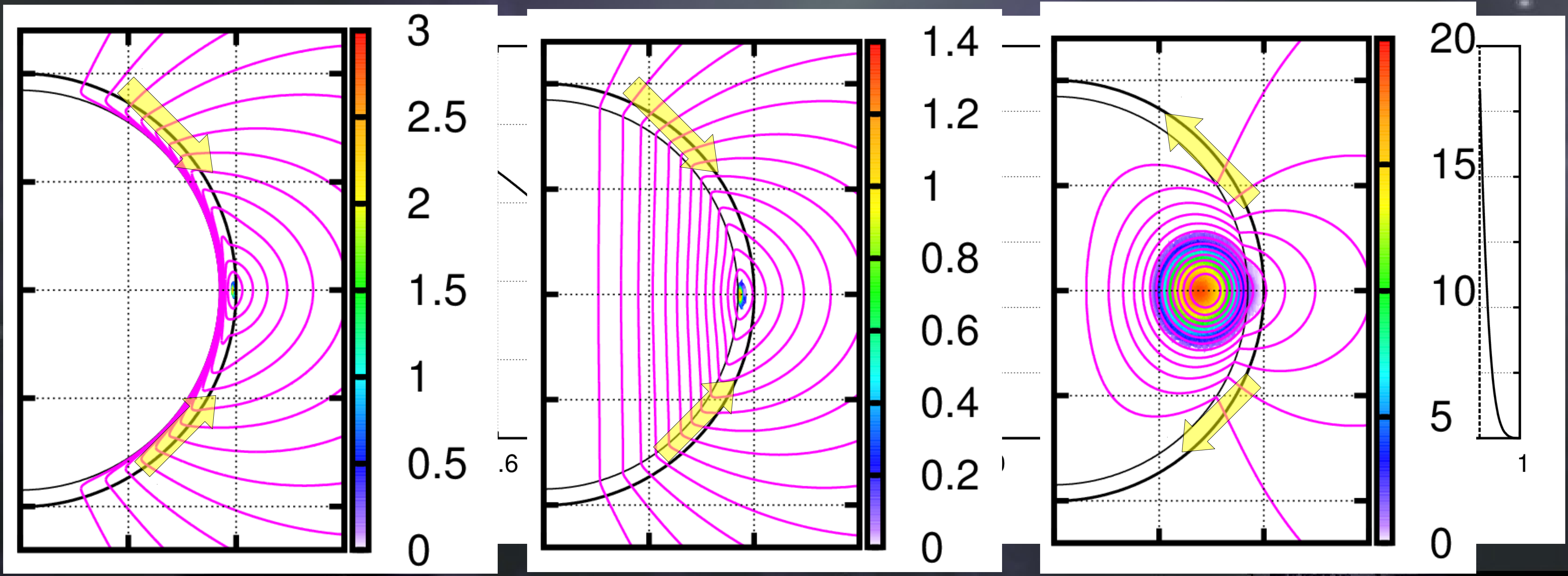




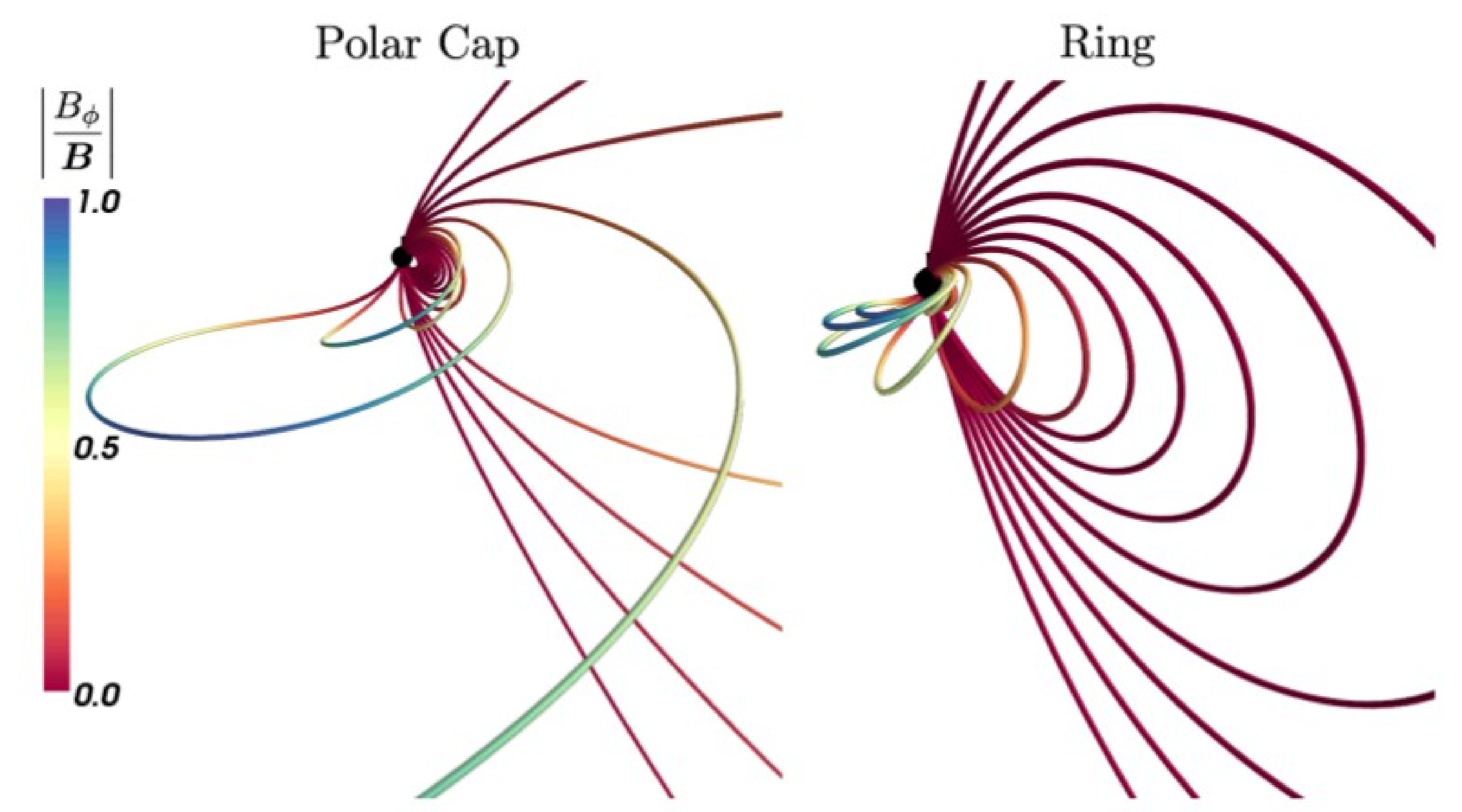
様々な内部磁場モデル

Fujisawa & Kisaka (2014)

- 質量 ～ 1.4 solar mass
- 半径 ～ 1.3 km
  - SLy. EOS (Douchin & Haensel 2001)

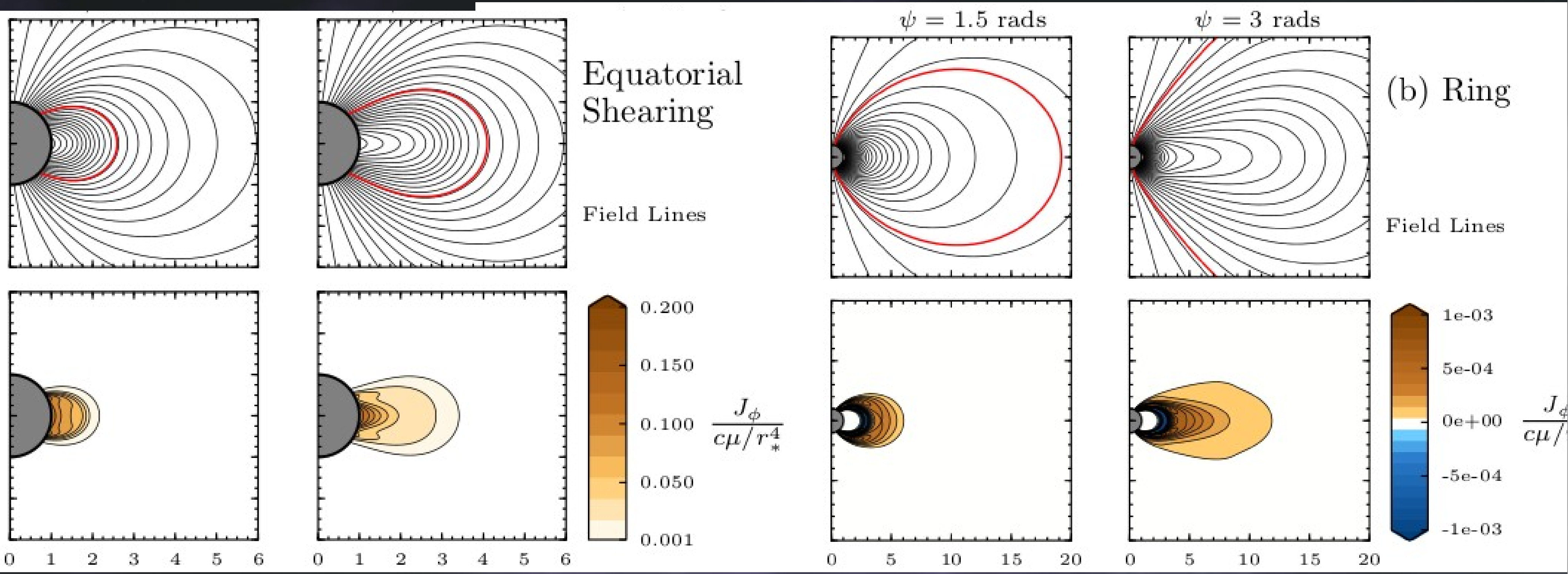


磁気圏内部のねじれ磁場



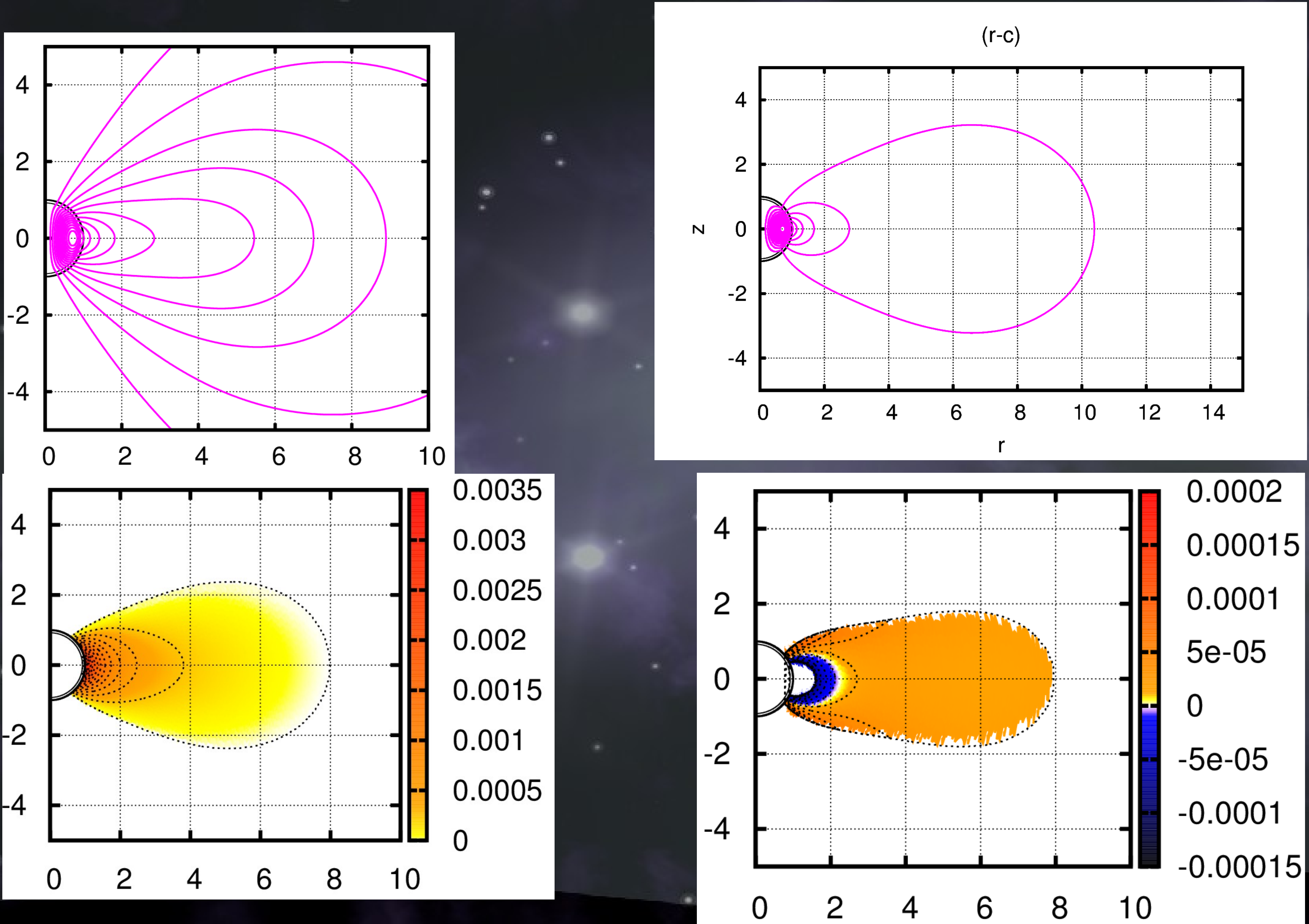
- Parfrey et al. (2013)

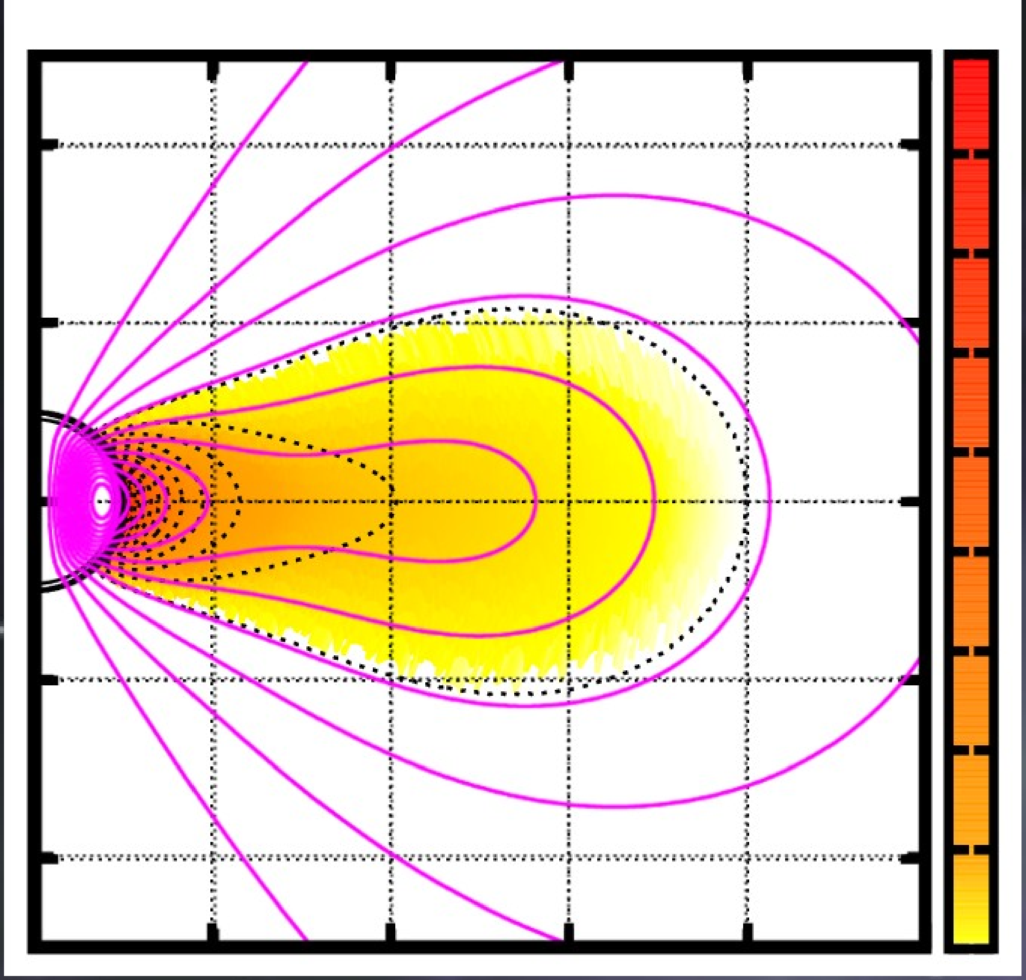
磁気圏のねじれのモデル



- Parfrey et al. (2013)

磁気圏にねじれた磁場を伴っている時

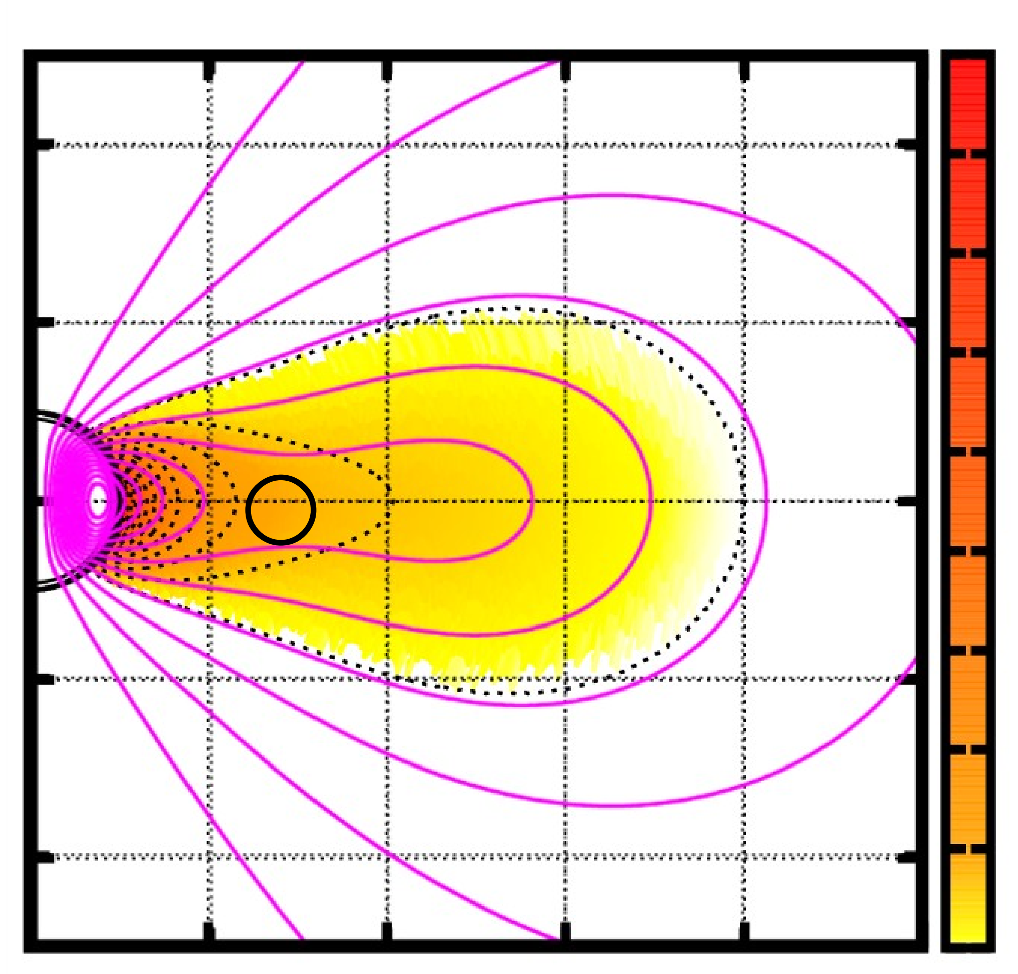




X-point 構造

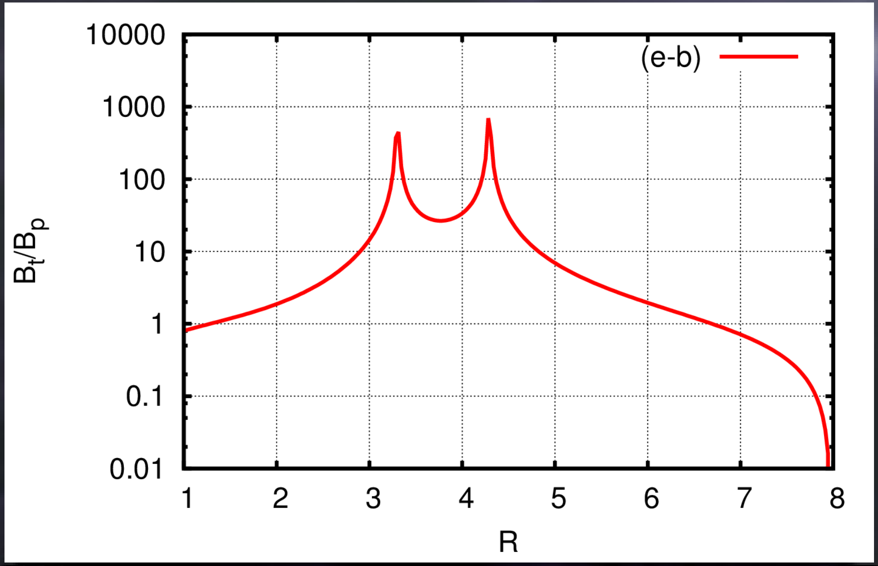
- X-point な磁場構造が磁気圏に出現

X-point 構造

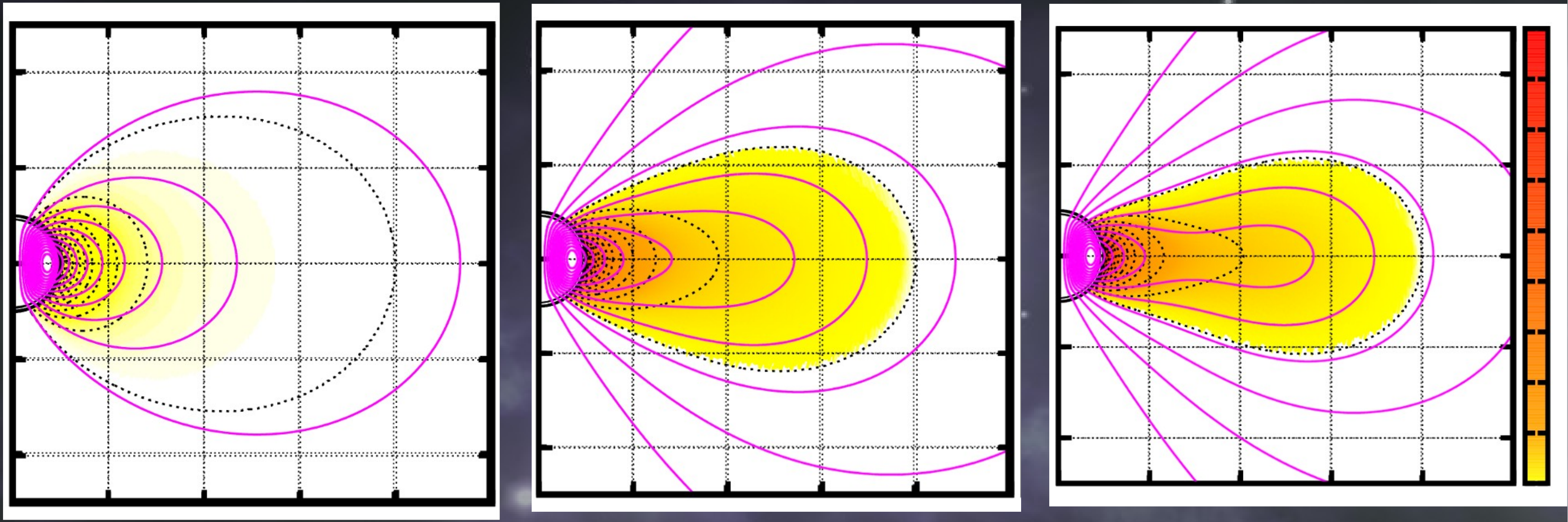


- X-point な磁場構造が磁気圏に出現

  →リコネクションを起こしてエネルギーを解放しうる

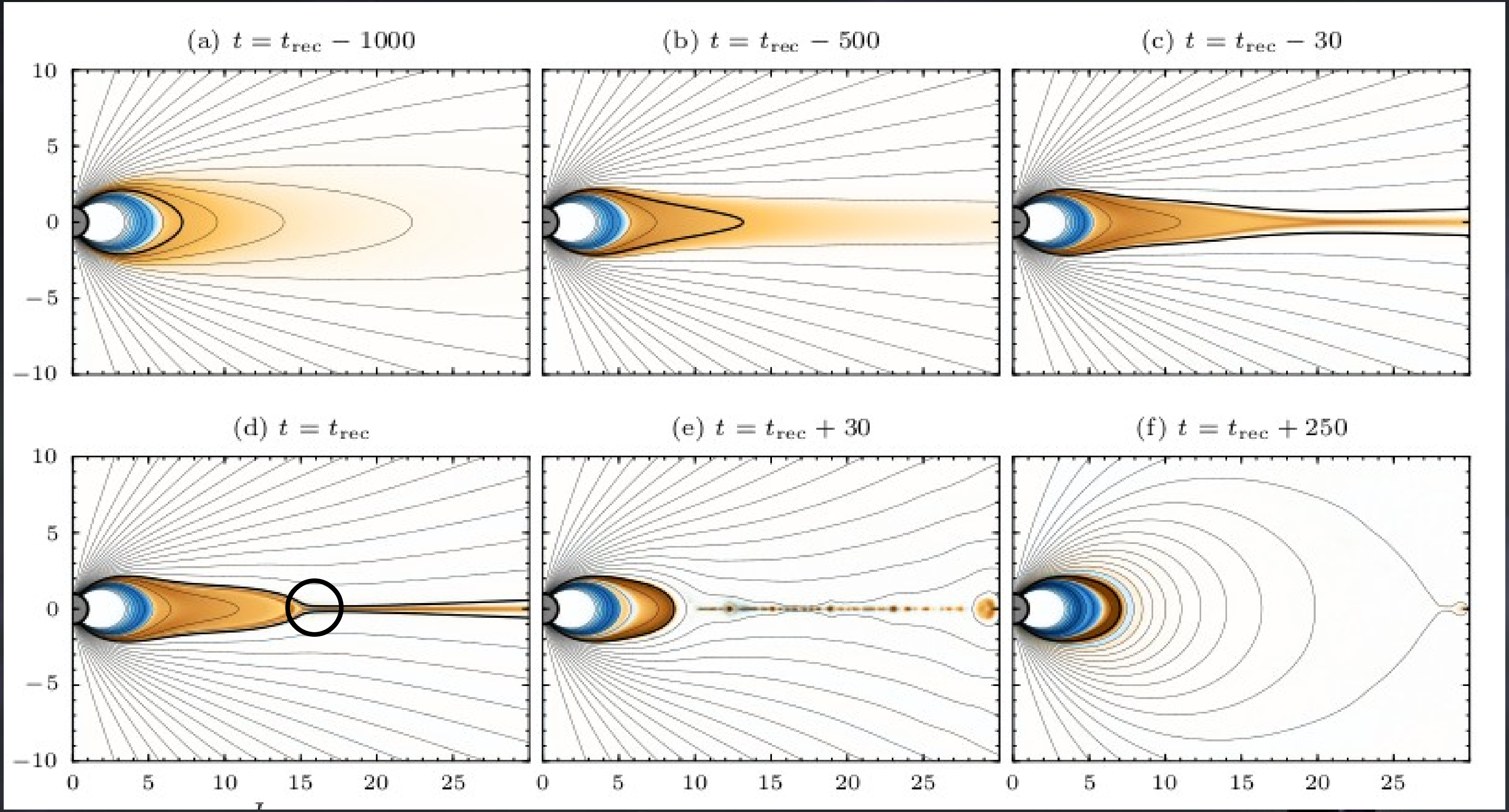


X-point 構造の形成1



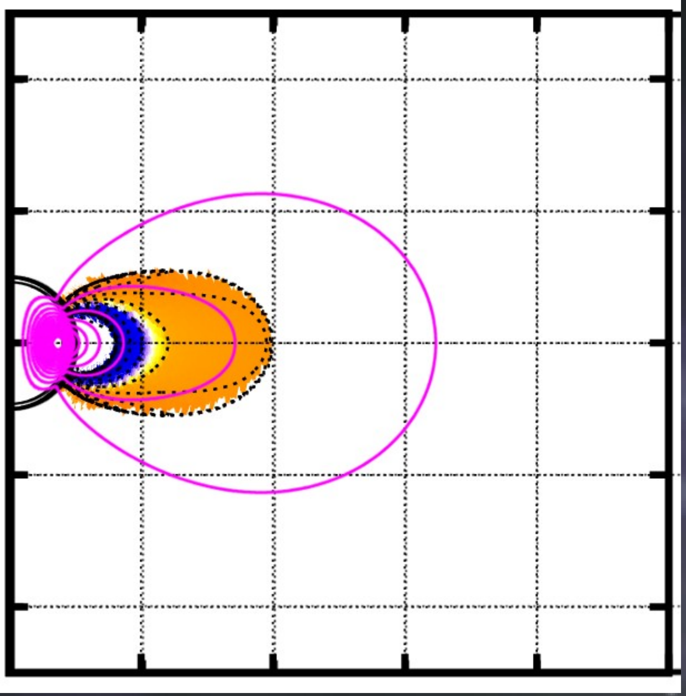
- ねじれが強くなると生じる.

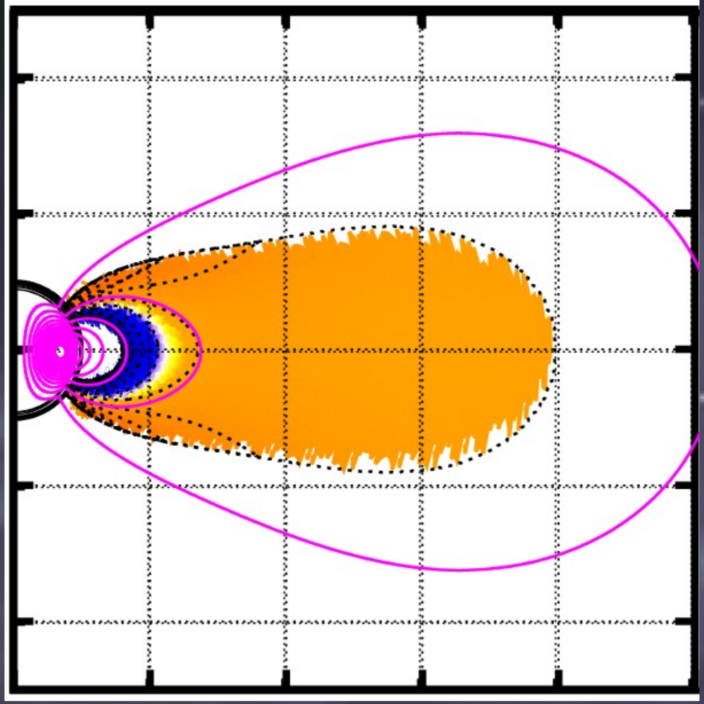
ねじれた磁気圏磁場とエネルギー解放

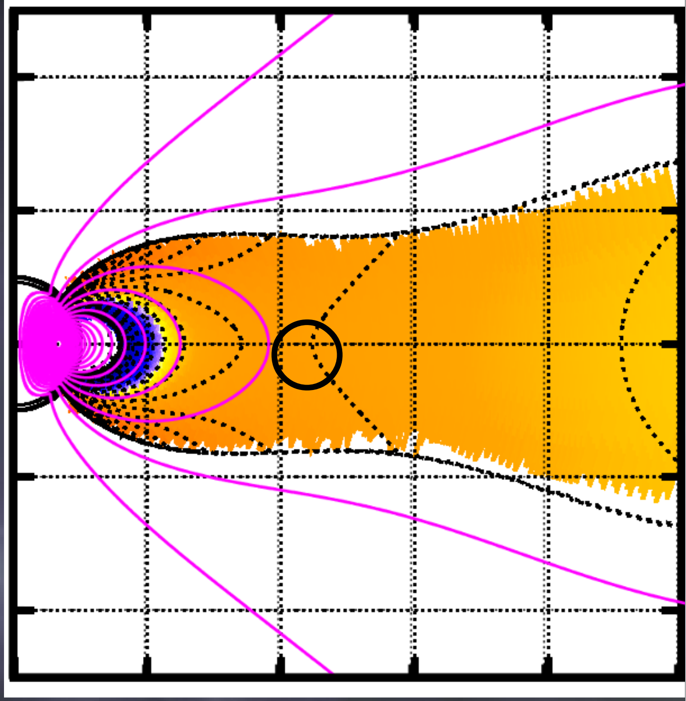


Parfrey et al. (2013)

X-point 構造の形成2

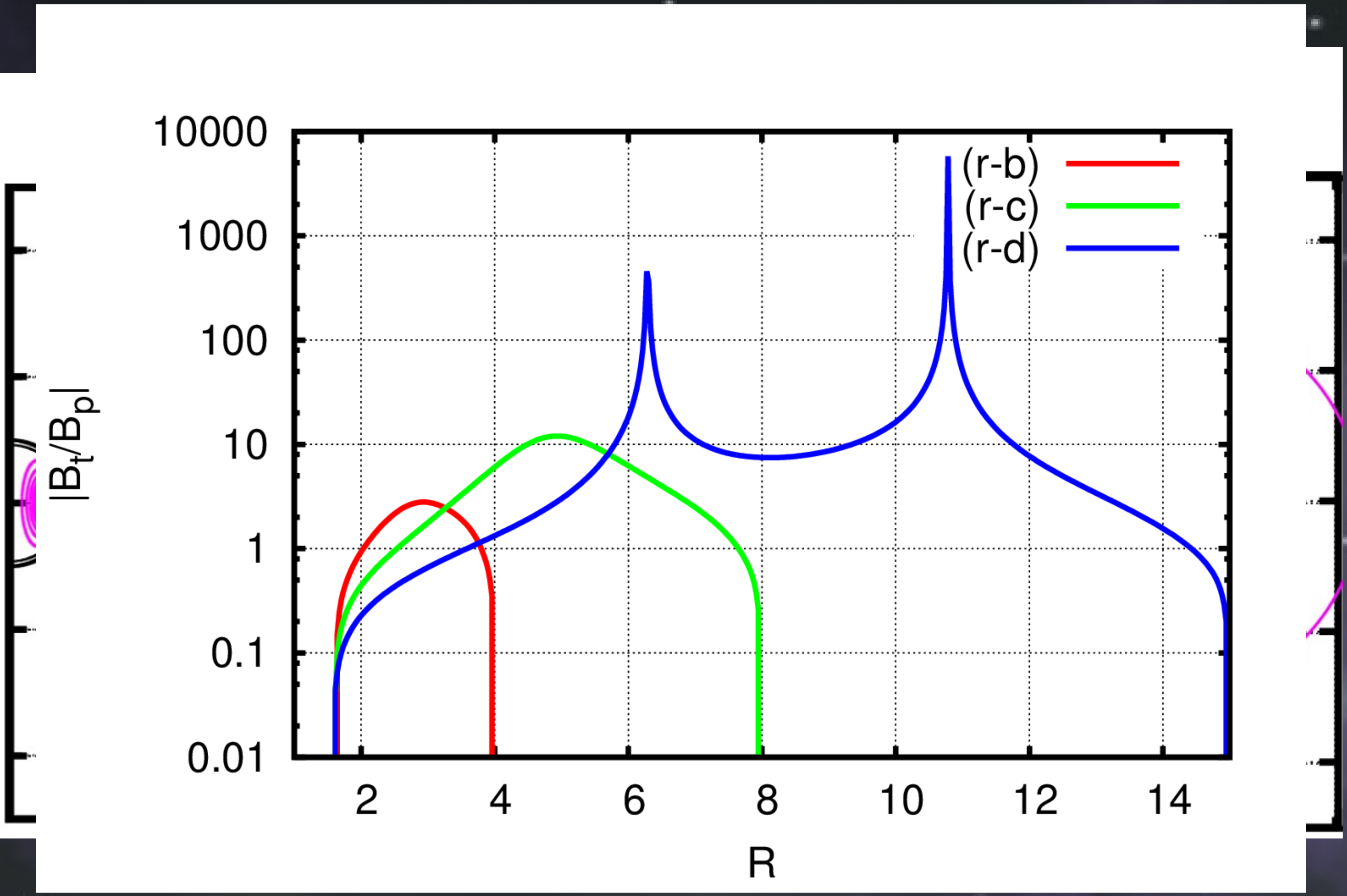

(r-b)

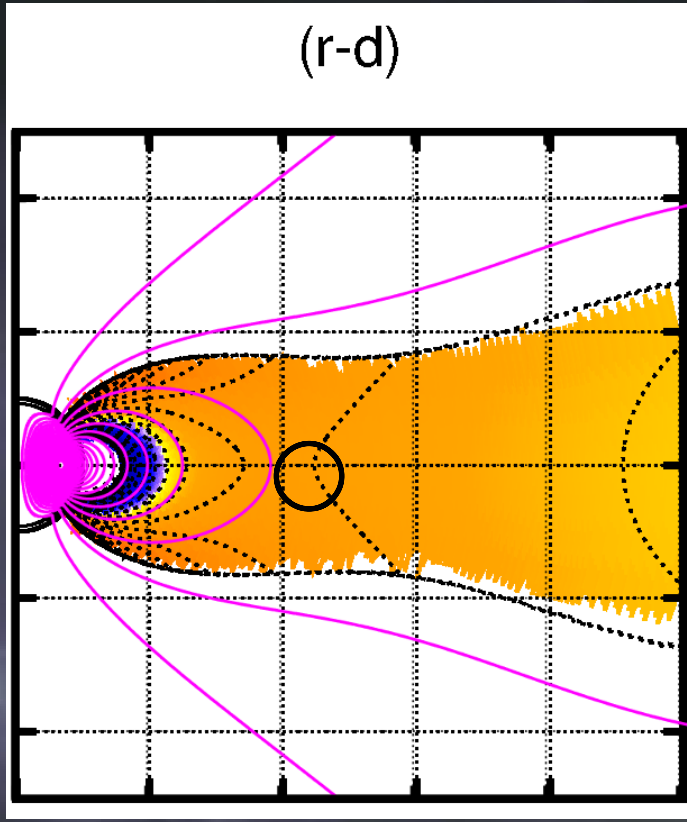

(r-c)


(r-d)

- ねじれ(の根元の部分)が大きくなると生じる.

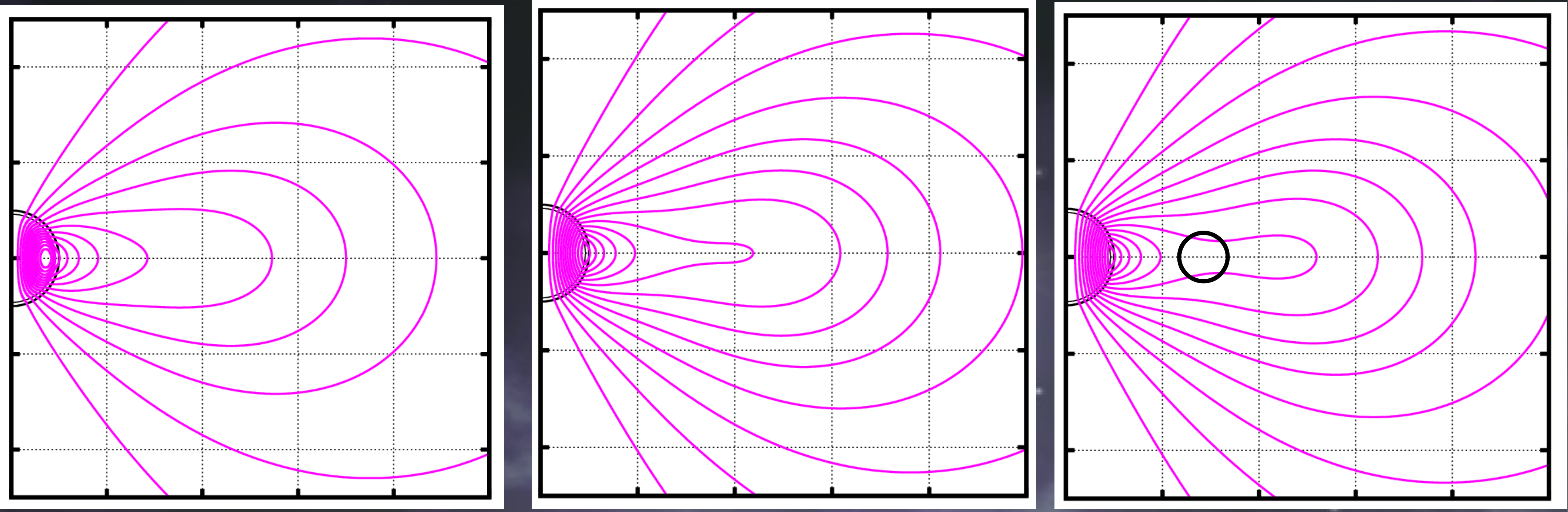
X-point 構造の形成2





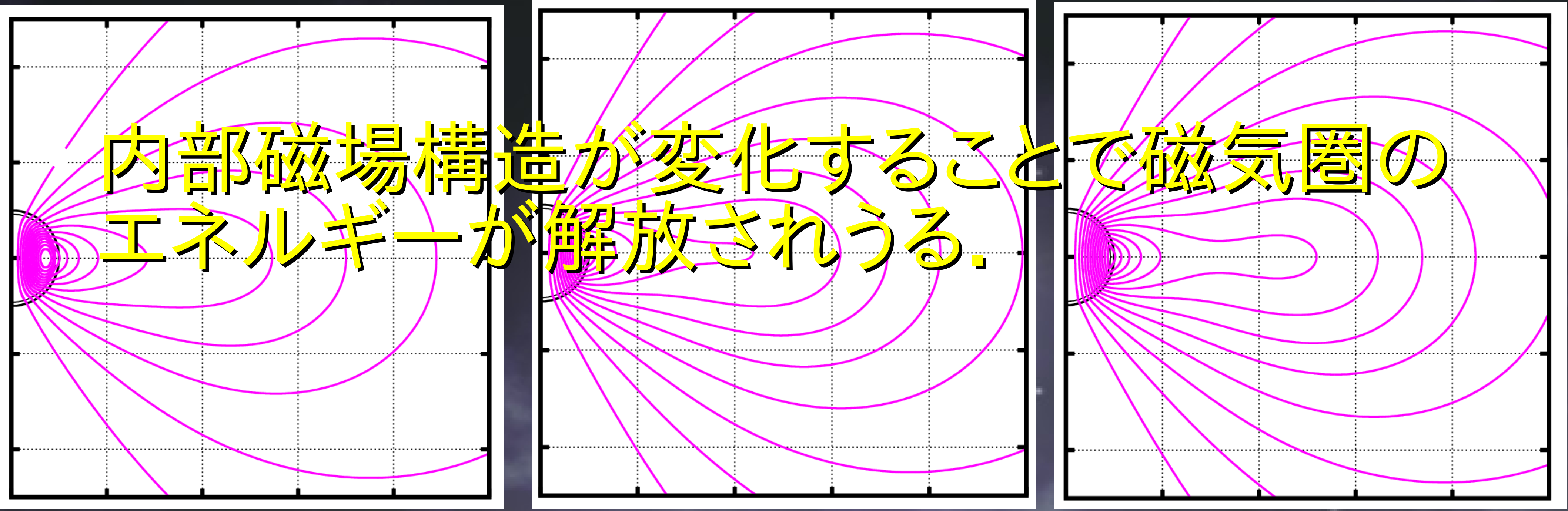
- ねじれ(の根元の部分)が大きくなると生じる.

X-point 構造の形成3



- コア·クラスト間の表面電流を変化させると生じる.

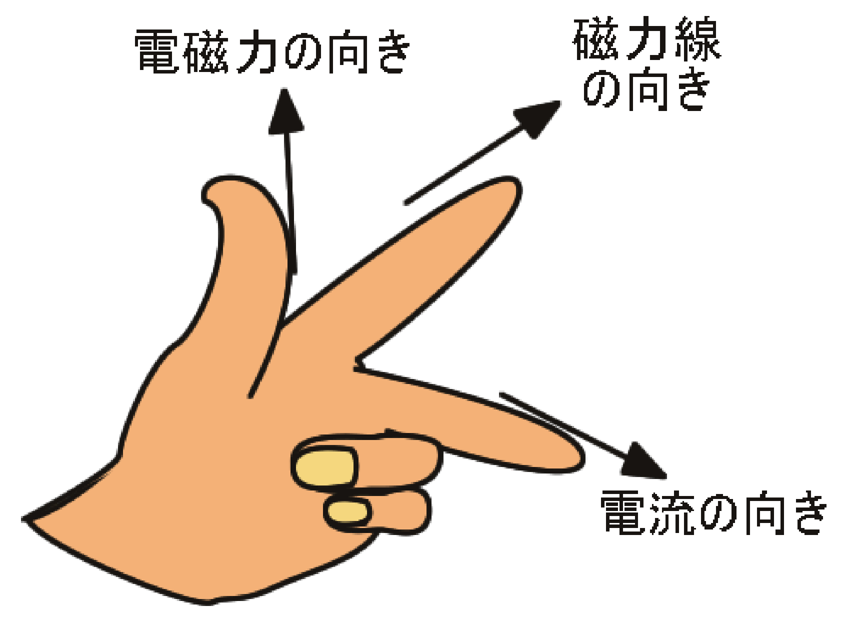
X-point 構造の形成3



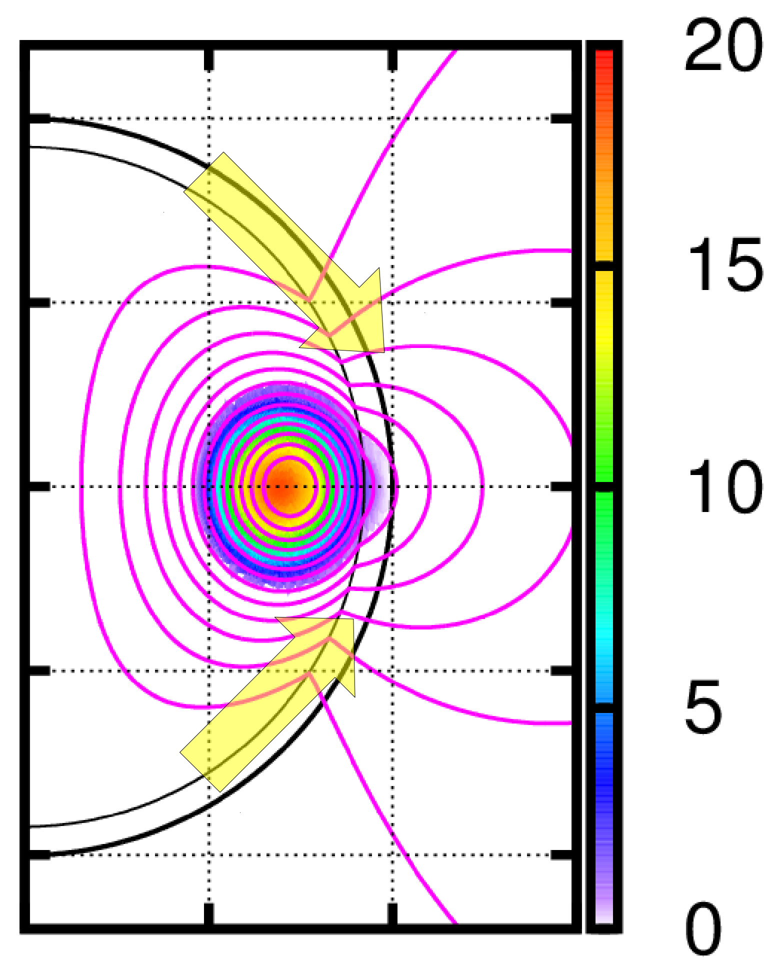
内部磁場構造が変化することで磁気圏のエネルギーが解放されうる.

- コア･クラスト間の表面電流(クラスト底面への圧力)を変化させると生じる.

コア・クラスト磁場



Bϕ/B_s



矢印のような力をかけると磁気圏に
X-pointが生じる

まとめ

- コア･クラスト･磁気圏の定常的な磁場構造を計算した.
- 星(クラスト)の歪み方によって星外部の定常的な磁場構造が変化することが分かった.
- コア･クラストでの磁場構造の変化によってX-point構造が形成されることが明らかになった.
    - 星内部の状態の変化によって磁気圏のエネルギーを間接的に解放!

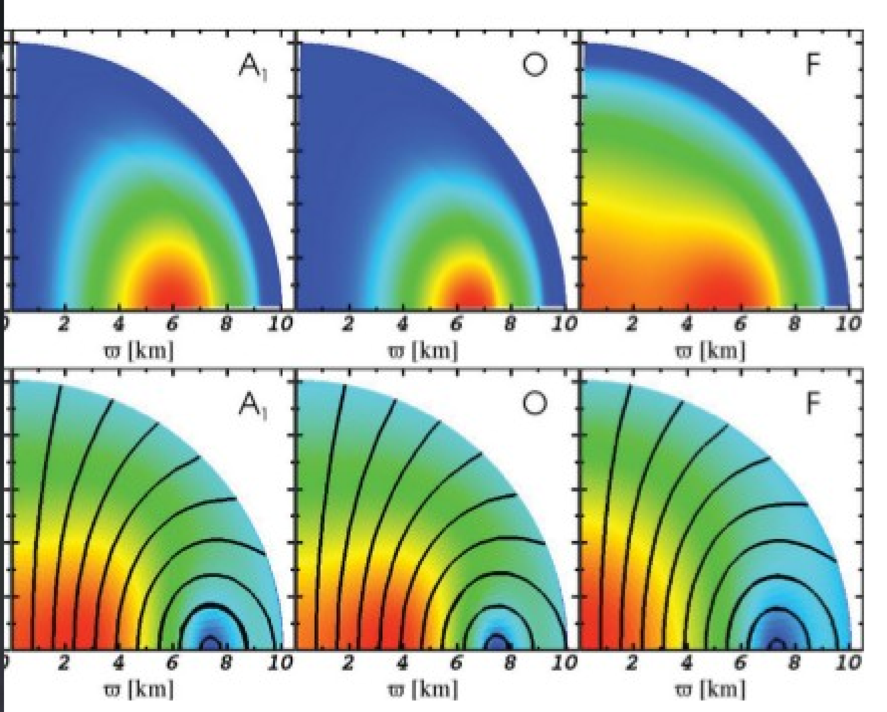
様々な内部磁場や外部磁場の理論計算が行えるようになった.

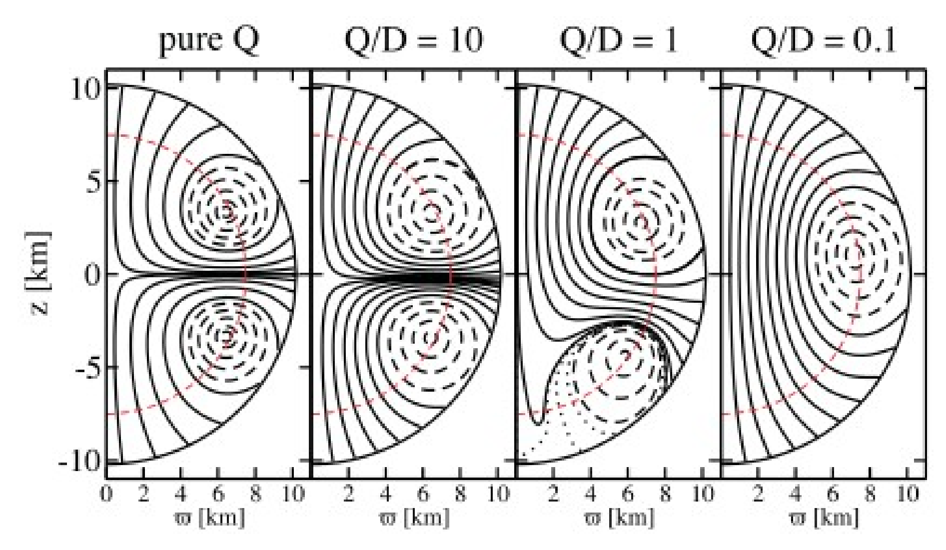
⇒　観測可能性を考える！

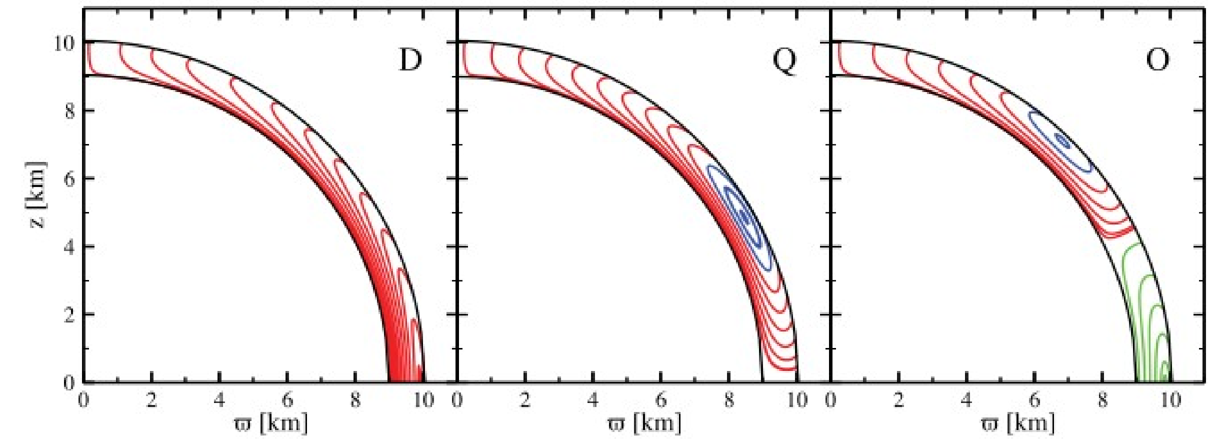
内部磁場の観測可能性

- 磁場の永年進化と観測の比較
  - Vigano et al. (2013), Yasutake et al. (2014)
- ジャイアントフレアのQPOと磁場構造
  - Gabler et al. (2013)
- 磁場による歪みと重力波 (Cutler 2002)
  - Haskell et al. (2008, 2013)
  - Ciolfi et al. (2009, 2010)
  - Makishima et al. (2014)
    SGRBとマグネターと重力波
  - Rowlinson et al. (2013)
  - Dall'Osso et al. (2014)

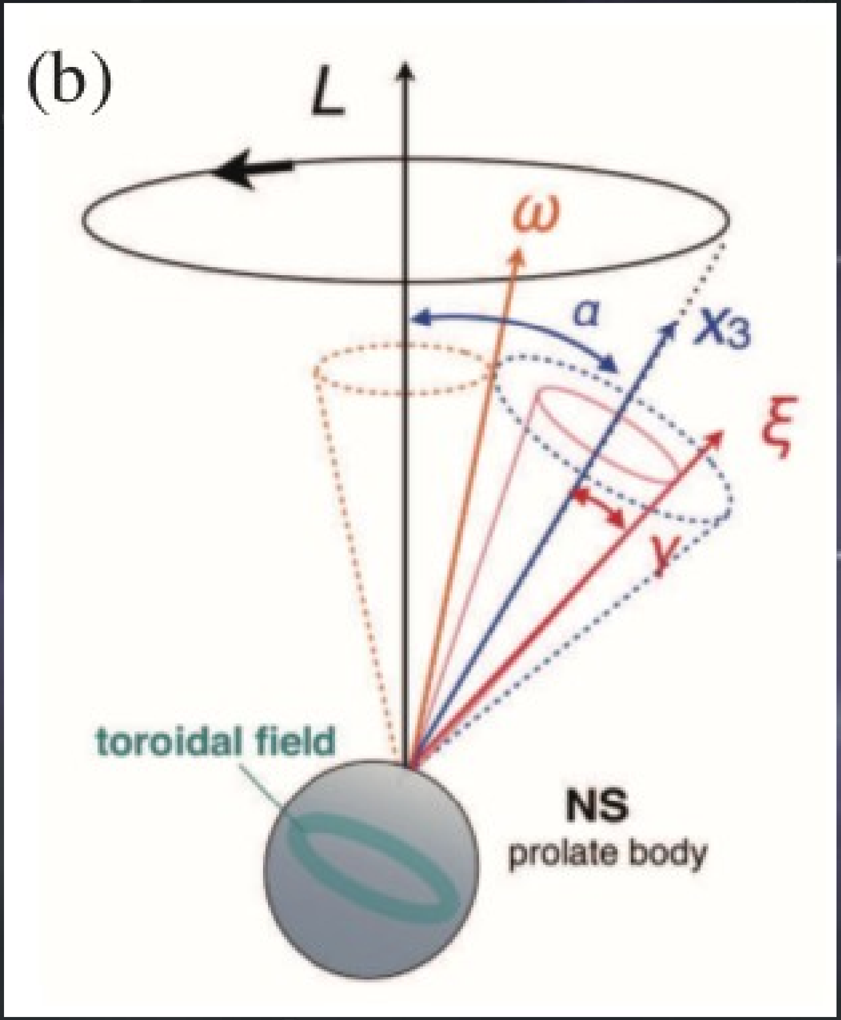
•Gabler et al. (2013)





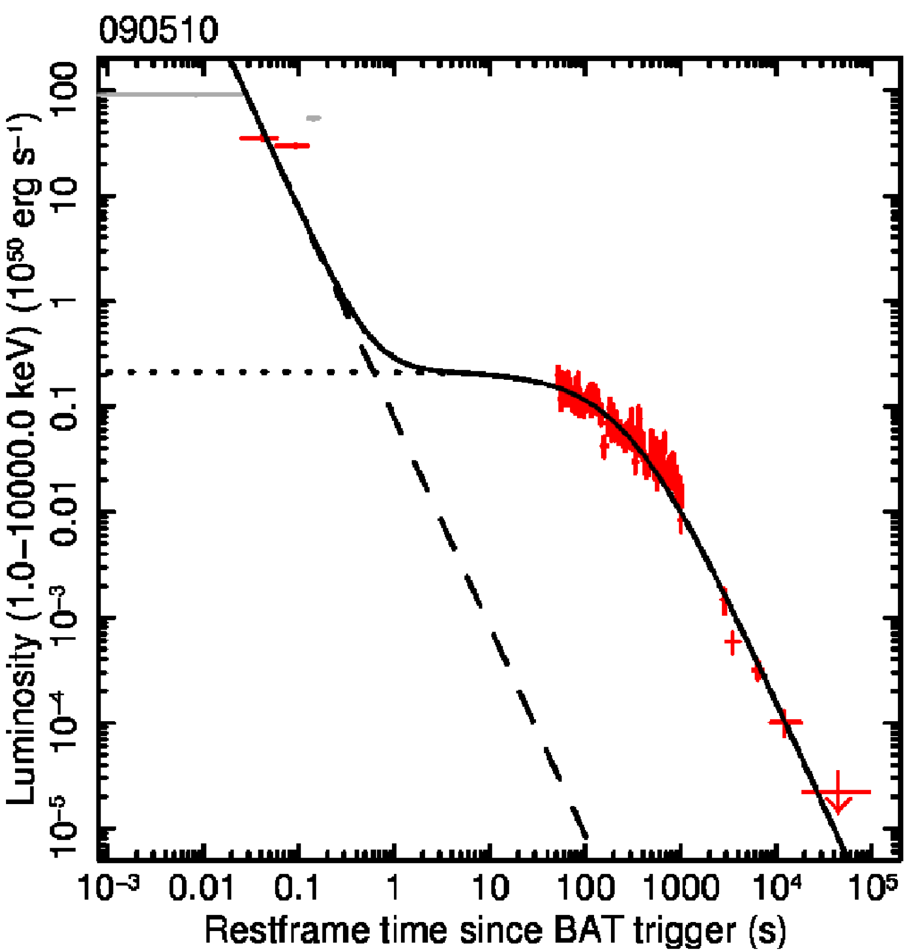


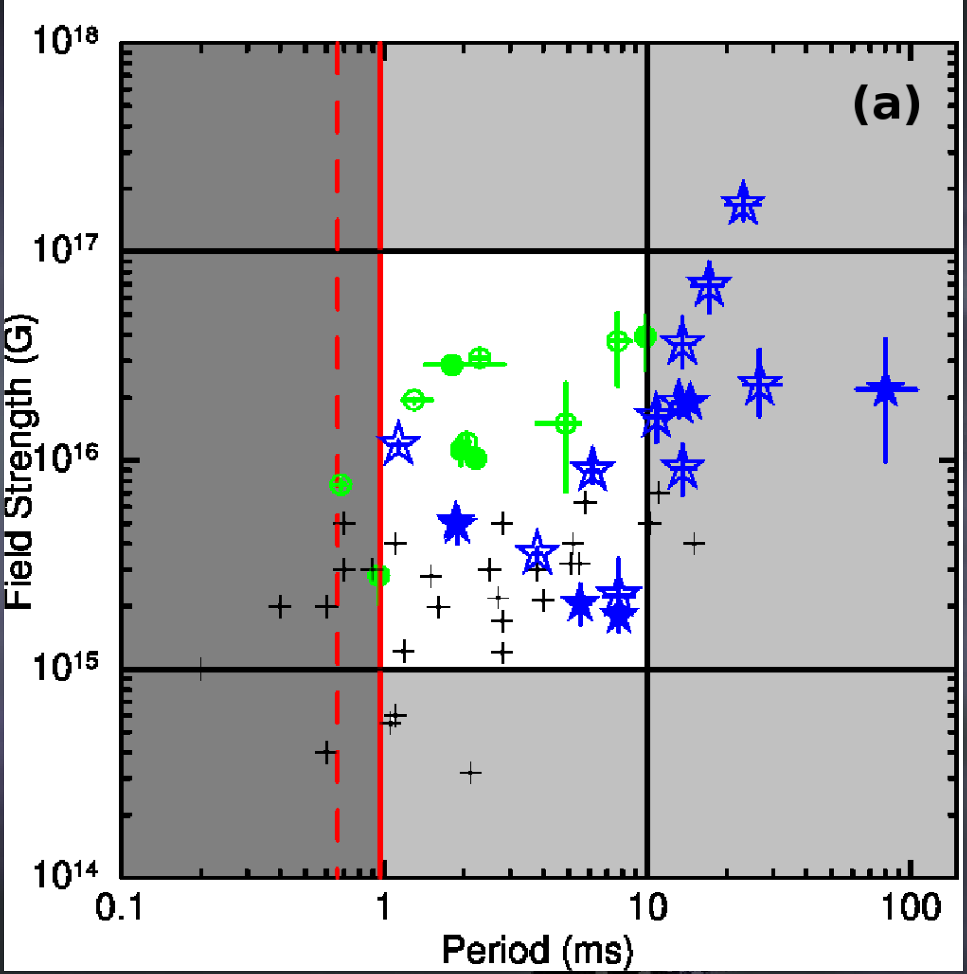
Makishima et al. (2014)



強いトロイダル磁場で扁長に。

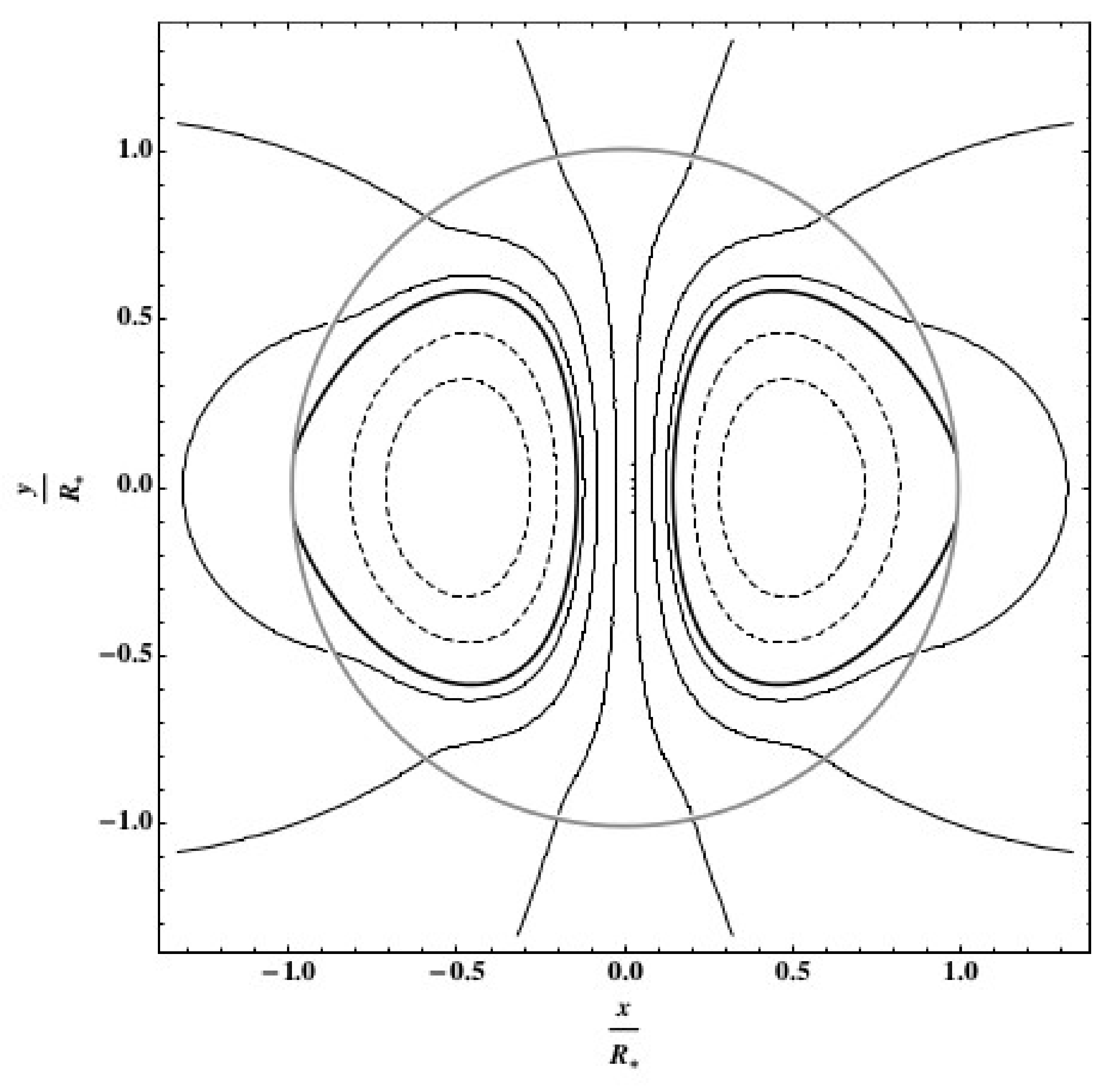
Rowlinson et al. (2013)



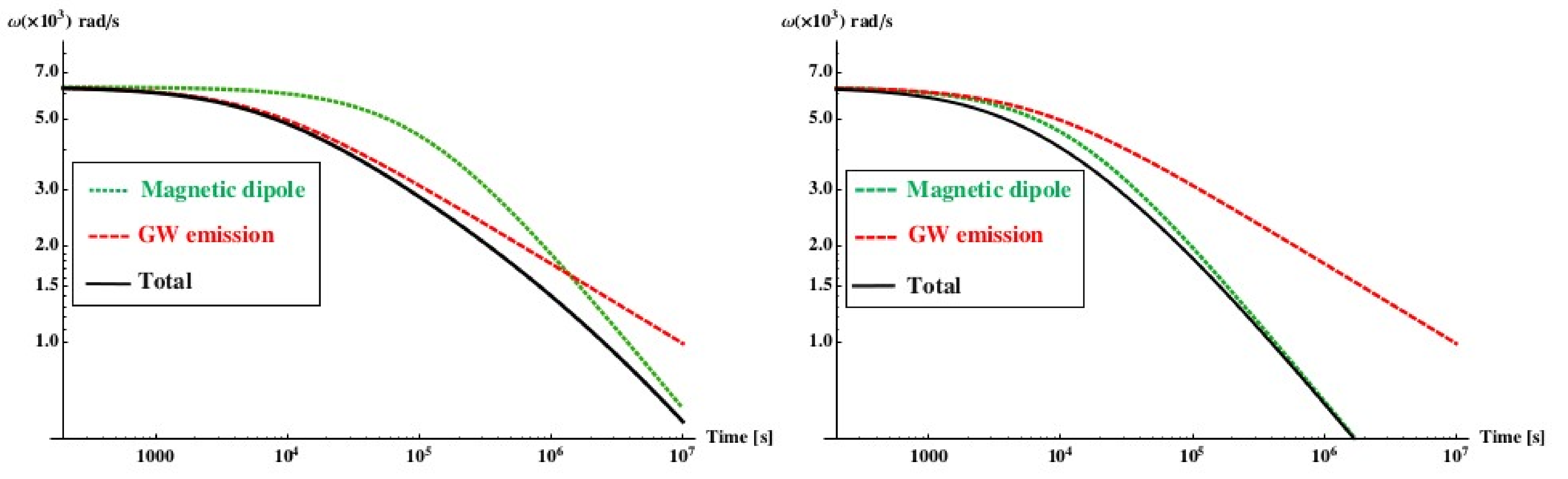


- SGRBのライトカーブをフィッティング

Dall'Osso et al. (2014)



Dall'Osso et al. (2014)



$$L = \frac{1}{6} B_1^2 \frac{r_s^6 \Omega_0^4}{c^3} \sin^2 \chi_1$$

$$\dot{E}_{\mathrm{GW}} = -\frac{2}{5}\frac{G(I\epsilon_{\mathrm{B}})^2}{c^5}\omega_s^6 \sin^2\chi\,(1+15\sin^2\chi)$$

$$\dot{\omega}_s = -\frac{B_{\mathrm{dip}}^2 R^6}{6Ic^3}\omega_s^3 - \frac{32}{5}\frac{GI\epsilon_{\mathrm{B}}^2}{c^5}\omega_s^5$$

まとめ

- 地球や惑星、太陽をはじめ多くの星が観測可能な磁場を持っている
  - 磁場の起源は、化石・磁石・ダイナモの3つ
  - 白色矮星の磁場
- 観測できない内部磁場は理論的に求める必要がある
  - QPOや磁場・熱の永年進化，重力波を駆使して内部磁場を「観測」する

→小嶌さんの講演へ続く

We are magnetic friends!