Convective dynamos in protoneutron stars

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PHAROS & CoCoNut Meeting 2018:
Magnetic field formation and evolution in neutron stars

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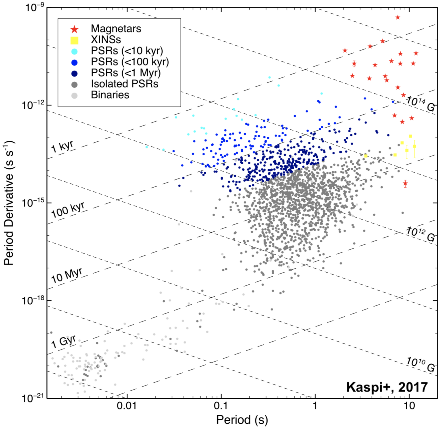
The $P - \dot{P}$ diagram



Magnetars

- galactic X-ray sources (bursts, outbursts, flares)
- ~ 30 objects ($\overset{?}{\gtrsim} 10\,\%$ of the young NS population)
- ~ 10 associated with standard SNRs

The dipolar model

- magnetic field intensity $B \propto \sqrt{\dot{P}P} \sim 10^{15}\,\mathrm{G}$
- spindown time scale $\tau_c \propto P\dot{P}^{-1} \sim 10^3\,\mathrm{yr}$

What the origin of such strong magnetic fields ?

Possible scenario

1. fossil field
2. *in-situ* amplification
   - MRI (next talk by Alexis Reboul-Salze)
   - convective dynamo: Thompson & Duncan (1993)

What the origin of such strong magnetic fields ?

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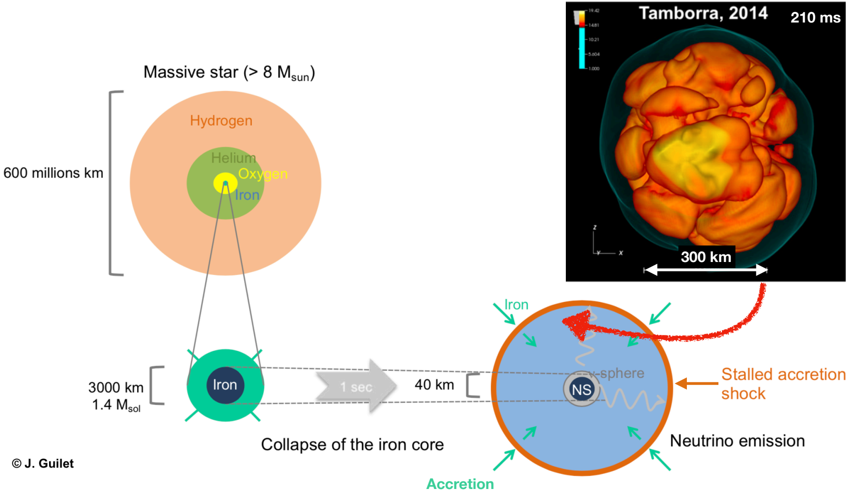
Implications

About 1000 articles on magnetars dealing with

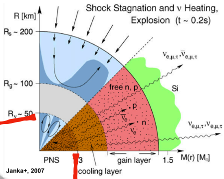
- superluminous SNe
- FRBs (Margalit 2018, *Unveiling the Engines of Fast Radio Bursts, Super-Luminous Supernovae, and Gamma-Ray Bursts*)
- . . . see talk by Matteo Bugli

Core collapse of a massive star

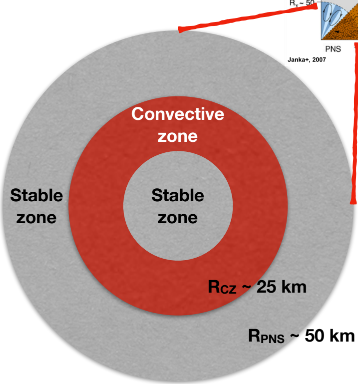


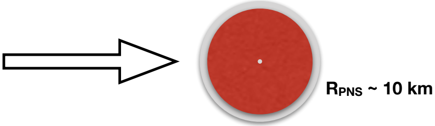
Protoneutron star structure . . . and evolution

t = 0.2 s



t = 7 s



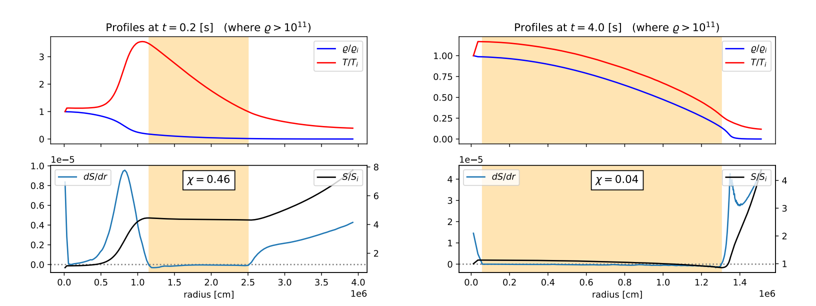


Ledoux criterion

$$\frac{dS}{dr} + \left(\frac{\partial S}{\partial Y_l}\right)_{P,\rho} \frac{dY_l}{dr} < 0$$

Determining the extent of the convective zone

27 $M_\odot$ 1D model from T. Janka's group (MPA)



Methods

1. stability determined according to the Schwarzschild criterion
2. deduce the shell geometry and the background profile $(\tilde{T}, \tilde{\varrho})$

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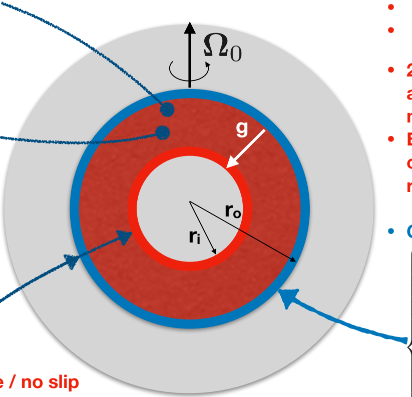
Requirements and simplification hypothesis

Input:
- Temperature profile
- Density profile

Transport coefficients:
- Kinematic viscosity ν
- Thermal diffusivity κ
- Magnetic diffusivity η



Boundary conditions:
- **Mechanical:** stress-free / no slip
- **Thermal:** fixed entropy flux
- **Magnetic:** perfect conductor ($B_{//}$) / pseudo-vacuum ($B_{\perp}$)

Hypothesis:
- Spherical geometry
- Adiabatic stratification
- Low Mach convection
- 2nd order diffusion approximation for the neutrino transport
- Electrical conductivity of degenerate, relativistic electrons
- Orders of magnitude

$$\begin{cases} \Phi_o \sim 10^{52}\,\mathrm{erg/s} \\ r_o \sim 25\,\mathrm{km} \\ T_o \sim 10^{11}\,\mathrm{K} \\ \varrho_o \sim 10^{13}\,\mathrm{g/cm^3} \\ \nu_o \sim 10^{10}\,\mathrm{cm^2/s} \\ \kappa_o \sim 10^{12}\,\mathrm{cm^2/s} \\ \eta_o \sim 10^{-3}\,\mathrm{cm^2/s} \end{cases}$$

The anelastic approximation (sound-proof approximation)

$$\nabla \cdot (\tilde{\varrho}\mathbf{u}) = 0$$

$$\frac{D\mathbf{u}}{Dt} = -\boldsymbol{\nabla}\left(\frac{p}{\tilde{\varrho}}\right) - \frac{2}{E}\mathbf{e}_z \times \mathbf{u} - \frac{Ra}{Pr}\frac{d\tilde{T}}{dr}S\mathbf{e}_r + \frac{1}{EPm}\frac{1}{\tilde{\varrho}}(\boldsymbol{\nabla} \times \mathbf{B}) \times \mathbf{B} + \mathbf{F}_\nu$$

$$\frac{DS}{Dt} = \frac{1}{Pr\tilde{\varrho}\tilde{T}}\nabla \cdot \left(\kappa\tilde{\varrho}\tilde{T}\boldsymbol{\nabla}S\right) + \frac{Pr}{Ra\tilde{\varrho}\tilde{T}}\left(\frac{\eta}{Pm^2 E}(\nabla \times \mathbf{B})^2 + Q_\nu\right)$$

$$\frac{\partial\mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) - \frac{1}{Pm}\nabla \times (\eta\nabla \times \mathbf{B})$$

$$\nabla \cdot \mathbf{B} = 0$$

Jones+11,14

Units and control parameters

MagIC pseudo-spectral code: chosen units

$$[d] = r_o - r_i\,, \quad [t] = \frac{d^2}{\nu_o}\,, \quad [B] = \sqrt{\Omega \varrho_o \mu_0 \eta_o}$$

$$[S] = d \left.\frac{\partial S}{\partial r}\right|_{r_o}\,, \quad [T] = T_o\,, \quad [\varrho] = \varrho_o$$

4 dimensionless control parameters

$$E = \frac{\nu_o}{\Omega d^2}, \quad Pr = \frac{\nu_o}{\kappa_o}, \quad Pm = \frac{\nu_o}{\eta_o}, \quad Ra = \frac{T_o d^3 \left.\frac{\partial S}{\partial r}\right|_{r_o}}{\nu_o \kappa_o}, \quad Ra_c = f(E, Pr)$$

Scaling the results

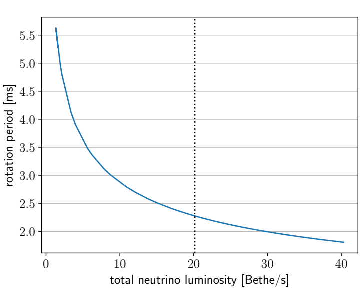
$$Ra^* = \frac{E^3}{Pr^2} Ra = \frac{\Phi_o}{4\pi r_o^2 \varrho_o \Omega^3 d^3} \implies \Omega \xrightarrow{E} \nu_o \xrightarrow{Pr,Pm} \kappa_o, \eta_o$$

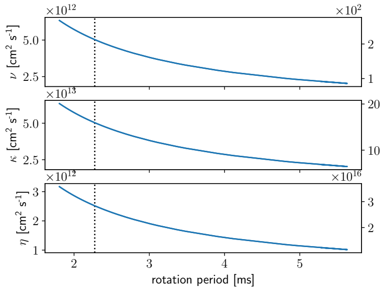
Parameter space achievable in numerical simulations

Typical parameters

Input: $E \sim 10^{-3},\ \mathrm{Pr} = 0.1,\ Ra/Ra_c \sim 10,\ Pm = \mathcal{O}(1) \ll 10^{14}$

Output: $Rm = \frac{Ud}{\eta} \lesssim \mathcal{O}(10^2) \ll 10^{17},\quad 10^{-1} \lesssim Ro = \frac{U}{\Omega d} \lesssim 10^1$





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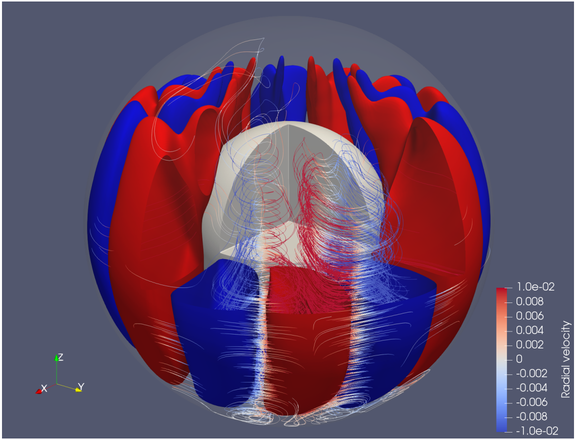
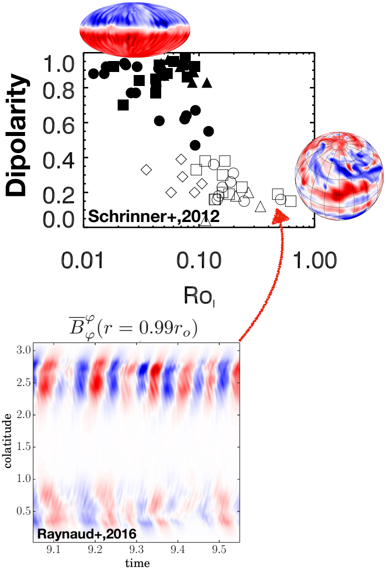
The onset of convection



Isosurfaces of v_r and velocity streamlines

(Numerical) stellar & planetary dynamos : simplified overview



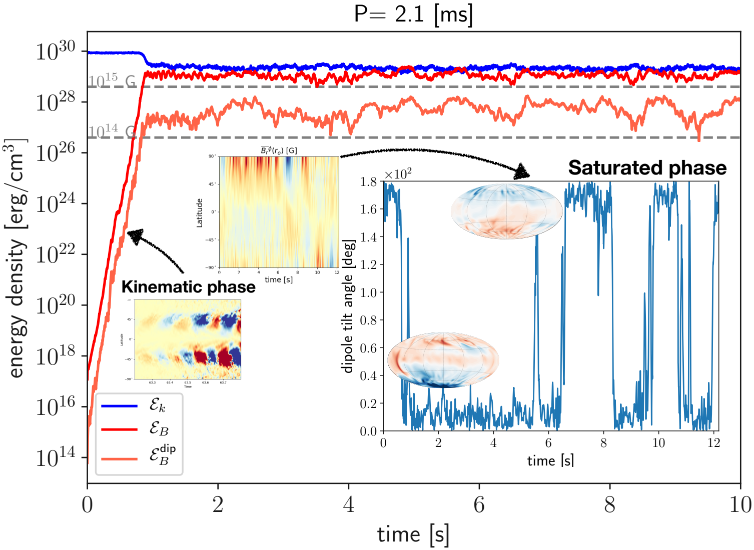
Dichotomy between:

1. **Dipolar dynamos:** axisymmetric, stationary
2. **Multipolar dynamos:** non axisymmetric, oscillatory

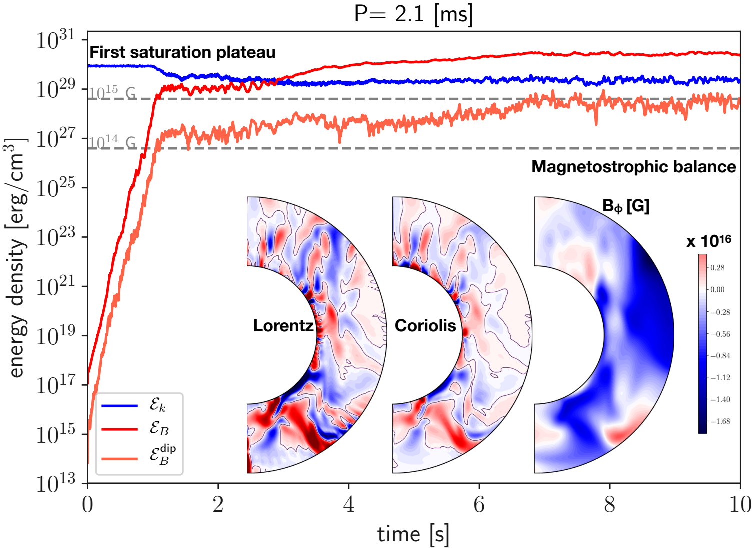
- Ω-effect at work for oscillatory dynamos
- with stress-free b.c., bi-stable behaviour

Christensen+06, Gastine+[12,13], Schaeffer+17, Schrinner+[12,14], Raynaud+[14,15,16], Strugarek+[17,18], Duarte+18, Dormy+18

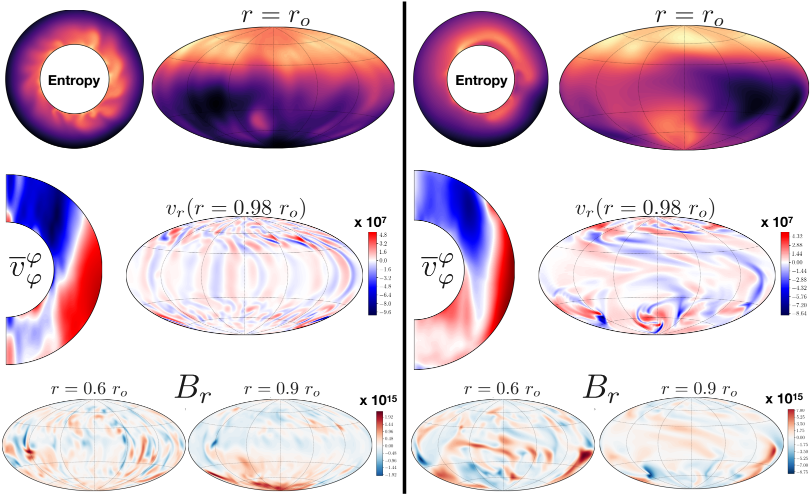
Oscillatory dynamo with chaotic reversals of the surface dipole



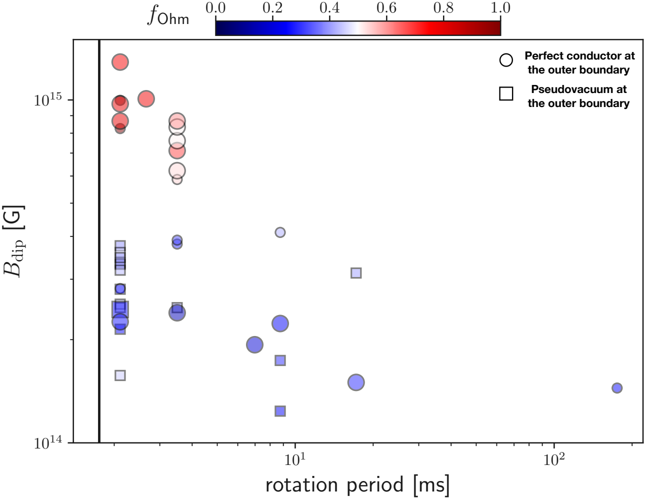
Strong field regime (stationary)



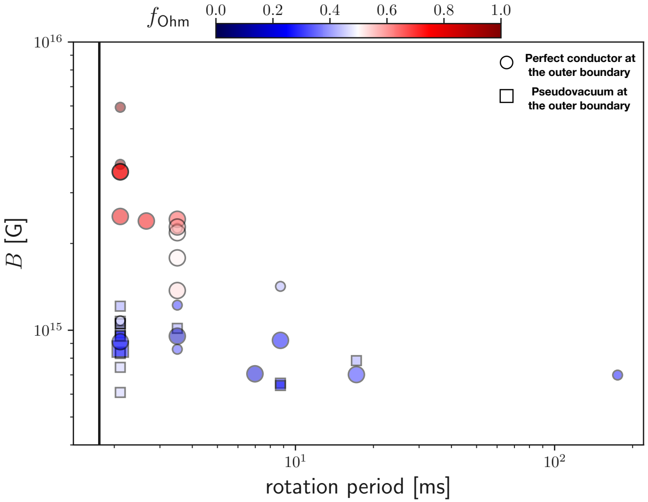
Weak vs. strong field



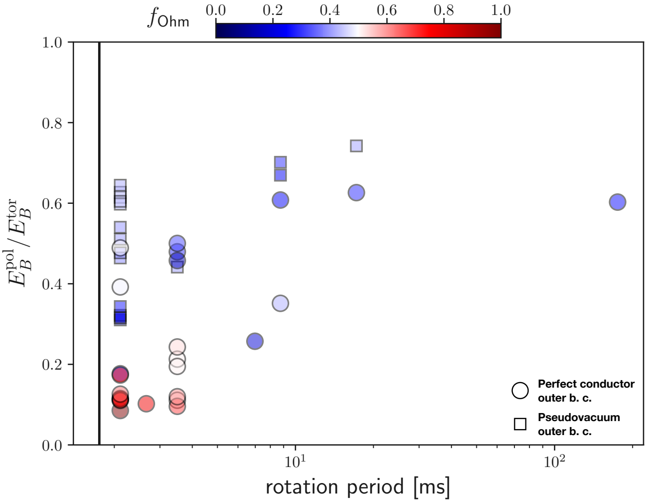
Dipole intensity



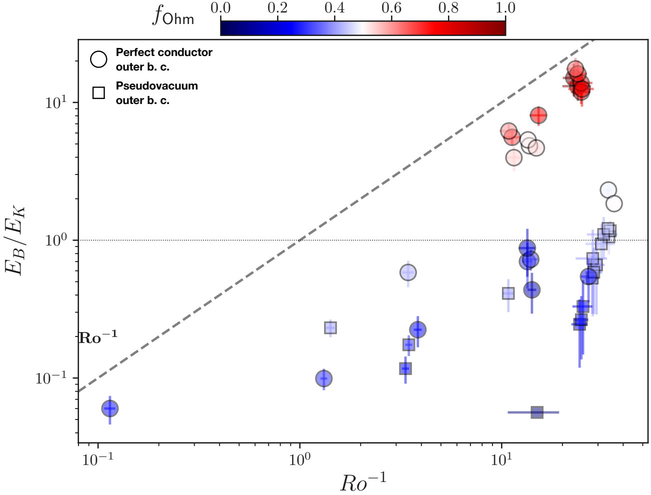
Magnetic energy density



Ratio poloidal/toroidal magnetic energy



Magnetic/kinetic energy scaling



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Conclusions

These first protoneutron star dynamos are

1. "compatible" with observational constraints on the dipole field strength ($\geq 10^{14}$ G)
2. non dipole dominated, Ω-effect driven (differential rotation)

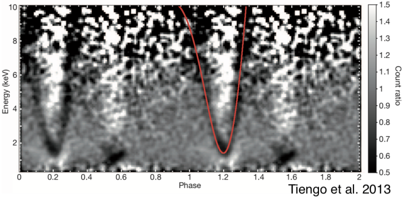
The saturated state is

1. strongly sensitive to the outer magnetic boundary condition: magnetostrophic balance (Coriolis - Lorentz) favoured with perfect conductor b. c. at low Rossby number
2. weakly sensitive to the interior model (various diffusivity profiles)

Some perspectives

Observations: field topology

- Tiengo+13: phase dependent absorption features $\Longrightarrow$ small scale surface field
- Makishima+18: 55 ks hard X-ray pulse-phase modulation $\Longrightarrow$ $B_T \sim 10^{16}$ G



Tiengo et al. 2013

Modelling

- link with Alexis Reboul-Salze work on the stably stratified region & Matteo Bugli for supernova models
- initial conditions for the subsequent evolution phases: magneto-thermal evolution