The magnetic-field evolution of neutron stars

Many questions, a few answers

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Motivation

- magnetic fields of neutron stars are strongest in the Universe
- crucial part of understanding NSs (and the reason most are even observable)
- generally not as dynamic (internally) as e.g. the Sun
- but evolution drives X-ray bursts, γ-ray flares
- B evolution key to understanding different manifestations of neutron stars
- harder to ignore now: pulsar state-switching, long-period radio sources, low-B magnetars, high-B pulsars...
- shorter timescales suggest we start with crustal field

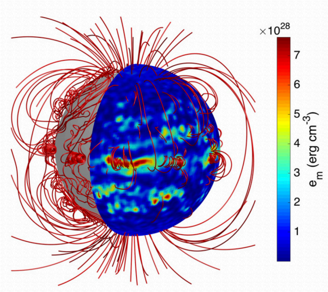
Electron MHD

Magnetic-field evolution in a neutron star crust given by (Goldreich & Reisenegger '92):

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

- first term: Hall drift, second term: Ohmic decay
- electron MHD: in the crust, assume ions static, locked into crustal lattice
- so $\boldsymbol{j} \propto \boldsymbol{v}_\ominus - \boldsymbol{v}_\oplus = \boldsymbol{v}_\ominus$ - electron velocity is the only variable
- ignores interplay with other physics, e.g. thermoelectric effect

- Hall drift does not dissipate field, instead makes small high-B regions; see right (Gourgouliatos+16)
- Ohmic decay dissipates small-scale B more efficiently: so Hall 'helps' it



Beyond the usual eMHD

- Field evolution has come a long way in the last 15 years
- Most work focusses on the crust alone: timescales seem most relevant, connects to exterior and observations
- Some talks on this, so will be brief (Sorry: no references here)
- now 3D, coupled with thermal evolution, helps to unify different 'kinds' of neutron star
- Do we need to do anything more than just refine eMHD?

What's left to do?

The impressive progress in eMHD evolutions is nonetheless built on several barely-questioned assumptions, that might be very restrictive:

- Initial conditions for simulations (and **when** do we start eMHD?)
- Boundary conditions: is $B = 0$ at inner boundary reasonable?
- eMHD works as long as the crustal lattice remains rigid. Does it?
- Is it always safe to neglect the core?

With these, the problem reduces to solving one key equation $\partial_t \boldsymbol{B} = \ldots$ (plus a second for the thermal sector). In principle it is 'clear' ($\neq$ 'easy') to refine this:

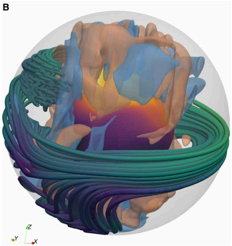
- 3D, better resolution, better numerical methods
- more realistic treatments of microphysics, etc

Relaxing the assumptions, however, we have to confront significant new ambiguities and poorly understood neutron-star physics...

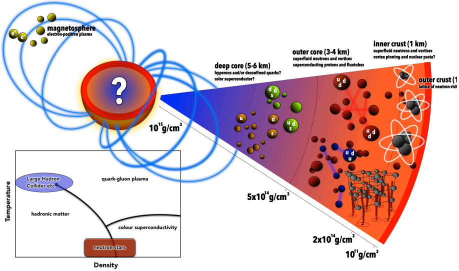
Neutron-star birth: dynamos briefly

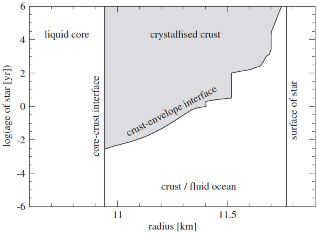
- To understand what magnetic field will be present when crustal evolution starts, need to look at phase before crust formation
- Some sort of dynamo amplifies B shortly after birth (converting turbulent kinetic energy to magnetic energy)
- Recent work simulating neutron-star dynamo, essentially 'usual' stellar dynamo with NS parameters (e.g. Raynaud+20)
- Now implemented as initial configurations for eMHD evolutions (Dehman+23, Igoshev talk); not same as simple poloidal dipole field

- Resulting magnetic field strongly dependent on nature of dynamo
- Worrying possibility: neutron-star dynamos (high Pm) are qualitatively different from others and need a different treatment (Lander'21)



Material changes to the neutron star

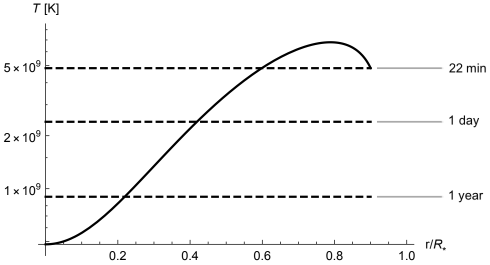




- what does ‘time=0’ in an eMHD evolution mean?
- **very** gradually the crust forms, from the inside out
- core superconductivity starts **minutes** after birth
- but process continues for $\sim 10^2 - 10^6$ yr
- neither process is instantaneous!

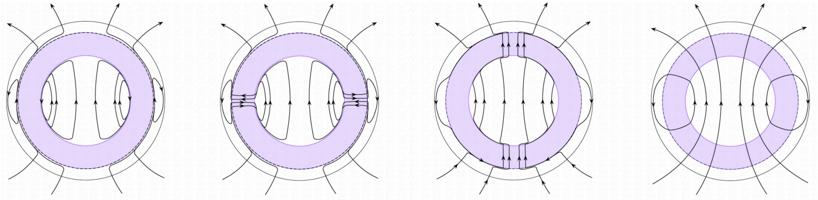
The 'Meissner' inner boundary

- For simplicity, often take $B = 0$ at crust-core boundary
- Wrongly assumed to be the expected result of core superconductivity
- superconducting region expands on cooling timescale (Ho+17)
- 'Meissner effect' means minimum-energy state is $B = 0$, but tells us nothing about how/if we can get there
- worth a closer look...



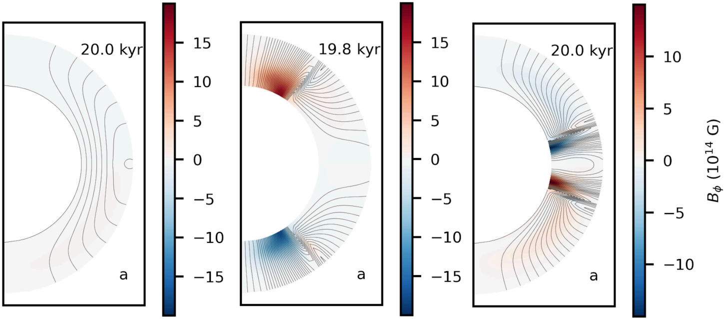
Expelling core field: fluid motions plus reconnection

- How can Meissner effect be realised? Not (necessarily) by field decay
- can 'cut' angular field lines to make $B = 0$ region, but not radial ones ($\nabla \cdot \boldsymbol{B} = 0$ condition)
- process limited by continuity of B_r, flux conservation
- Combination of fluid motions at onset, then reconnection
- Full expulsion only for $10^{12} \lesssim B[\mathrm{G}] \lesssim 10^{14}$
- Even in this range, if reconnection inefficient, leaves 'holes' in $B = 0$ region where field penetrates (hole size $\propto B$) (Lander, in prep)



Holes in the boundary: qualitatively new phenomena

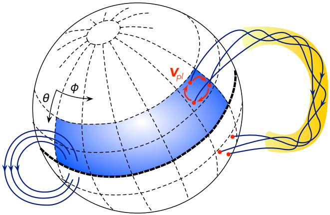
- When crustal field continues into core, evolution slower/smoother than for $B = 0$ boundary (Vigano+13)
- Expect similar for 'hole' boundary condition?
- actually see shearing between two domains, sharp features in B
- new: 'plasmoids' seem to be expelled in region above edge of 'hole'
- could power late re-activation of a magnetar? (Lander, Gourgouliatos +, in prep)



Build-up of crustal stress and failure

- Electric current is fundamental physical quantity $\boldsymbol{j} \propto \boldsymbol{v}_\ominus - \boldsymbol{v}_\oplus \propto \nabla \times \boldsymbol{B}$
- So magnetism is fundamentally a two-fluid (or more) problem
- But can often avoid this, e.g. eliminate $\boldsymbol{j}$ in favour of $\boldsymbol{B}$ in usual MHD
- eMHD: ions trapped in crustal lattice, electrons mobile, neglect $v_\oplus \ll v_\ominus$
- but stresses τ build as B evolves away from initial unstressed state
- eventually exceed elastic yield stress $\tau_{el} \implies$ crust must 'break' $\implies v_\oplus$ suddenly becomes non-negligible

- in fact, **need** $v_\oplus \neq 0$ for magnetar bursts anyway
- expect failure to be 'commonplace' for $B^2/8\pi \sim \tau_{\rm el} \implies B \sim 10^{14}$ G
- need to be quantitative: criterion for crustal failure, criterion for post-failure dynamics

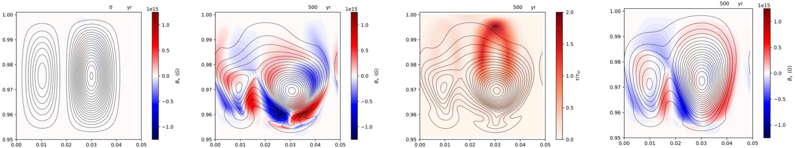


Magnetoplastic evolutions

- failure probably plastic/ductile not brittle (Jones'03)
- then appropriate to use von Mises criterion; contract tensorial stress components, compare with scalar yield stress

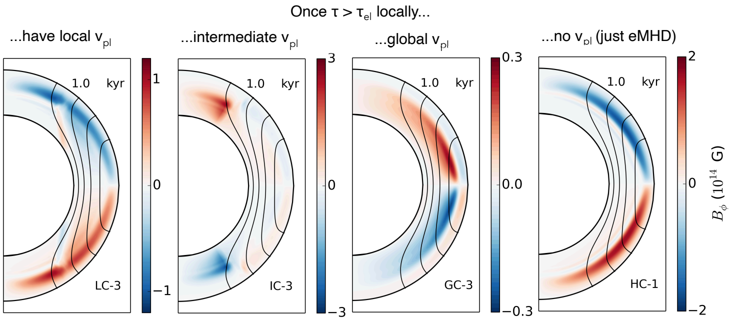
$$\tau_{\rm el} \leq \sqrt{\tfrac{1}{2}\tilde{\tau}_{ij}\tilde{\tau}_{ij}} = \frac{1}{4\pi}\sqrt{\tfrac{1}{3}B_0^4 + \tfrac{1}{3}B_{\rm now}^4 + \tfrac{1}{3}B_0^2 B_{\rm now}^2 - (\boldsymbol{B}_0\cdot\boldsymbol{B}_{\rm now})^2}$$

- monitoring this, see that yielding happens early, eMHD then not valid (Lander&Gourgouliatos'19)
- solve to find velocity of plastic flow $\boldsymbol{v}_{pl}$
- add new advection term $\nabla\times(\boldsymbol{v}_{pl}\times\boldsymbol{B})$ to evolution
- plastic flow often (partially) counteracts Hall term



initial B | eMHD | τ from eMHD | eMHD+plastic

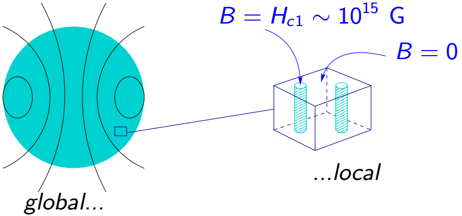
Global vs local failure, and SOC



- In local simulation, can assume whole domain fails. Globally?
- No tectonic plates – what sets failure boundaries? (Gourgouliatos&Lander'21)
- Existence of giant flares plus burst statistics $\Longrightarrow$ self-organised criticality
- Crustal cellular automaton model gives qualitative explanation (Lander'23)
- localised failures and small coronal twists: X-ray and radio bursts
- points to complex stress pattern and localised corona

Evolution in the core

Core evolution: contentious, complex, and thought to be slow. For part/all of core, expect neutrons to be superfluid, and the protons to form a type-II superconductor, which causes B to be quantised into fluxtubes:



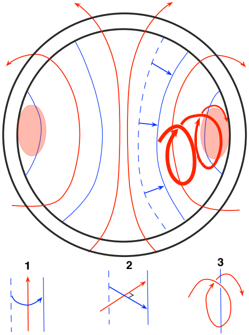
Generally speaking, the action of core-field evolution mechanisms is to:

- dissipate the field (e.g. Ohmic decay)
- advect the field at some velocity $\boldsymbol{v}$: $\partial_t \boldsymbol{B} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B})$

This velocity could be:

- induced by deviations from chemical equilibrium (Ofengeim&Gusakov'18,Moraga+24)
- ambipolar drift velocity (Castillo+20,Vigano+21,Igoshev+23,Skiathas+24)
- fluxtube drift velocity (Jones'91,'06;Glampedakis+11,Graber+15,Bransgrove+18,..)

Vortex-fluxtube interactions



- entrainment effectively magnetises the (neutral) neutron vortices (Sedrakyan&Shakhabasyan'81;Alpar+84)
- find energies of vortex-fluxtube interactions from Ginzburg-Landau theory
- for a vortex to cross a fluxtube, it needs to overcome an energy barrier (Jones 1991):

$$\mathcal{E} \sim \mathbf{B}_n \cdot \mathbf{B}_p$$

- averaging to get macroscopic effect uncertain: vortex tension, turbulence
- interplay between pinning and cutting regimes
- potential coupling of spindown and magnetic-field evolution (Srinivasan+90)
- superconducting equilibrium models (Lander'14,Sur+20) suggest no core pinning if core field $\lesssim 10^{14}$ G

Outlook

Magnetothermal evolution in the crust

- by one definition, field evolution is well understood and advanced
- development of intense 3D patches of field, heating
- connection with exterior
- clear link to magnetars, unification of classes of neutron star

Beyond electron MHD

- new initial conditions now being explored – but dynamos poorly understood
- Inner boundary condition of $B = 0$ needs re-examining: qualitatively affects evolutions
- Crustal failure being pursued, but material physics and failure properties of crust need to be 'guessed'
- Need to understand core-field evolution and crust-core coupling