Internal Magnetic Fields Asteroseismology

Matteo Cantiello ¹,² ¹ CCA, Flatiron Institute ² Princeton University
A New Era for Stellar Physics

Unprecedented synergy between high precision, big data (in particular photometry and astrometry) and theory (in particular asteroseismology and 3D numerical simulations). Together with the advent of open source, community-driven stellar evolution codes like MESA (new instrument paper on the arXiv tomorrow!), this is empowering a better scrutiny of established 1D results. With many exciting surprises…
Top 5 frontier problems in Stellar Astrophysics?

- Mass Loss / Stellar Eruptions
- Common Envelope Evolution / Stellar Mergers

- Angular Momentum Transport in Stellar Interiors (See Jim Fuller’s talk)

- Convective Boundaries

- The Origin of Stellar Magnetism / Stellar Dynamos (This talk)
$S^2_\ell = \frac{c_s^2 \ell (\ell + 1)}{r^2}$
Since mixed modes live both as p-mode (in the envelope) and as g-mode (in the core), if observed at the surface their properties (e.g. rotational splitting) can give information about e.g. rotation rate in different regions of the star!

(Beck et al. 2012, Mosser et al. 2012)
Stars evolve this direction

Stello, MC, JF et al. (Nature 2016)

A puzzle: Depressed Dipolar Modes

Mosser et al. 2012

Stello, MC, JF et al. (Nature 2016)
Mixed Modes interacting with B-Fields?
In the presence of strong B-fields, magnetic tension forces can become comparable to buoyancy

Lorentz Force $\sim$ Buoyancy Force

$B_c = \sqrt{\frac{\pi \rho}{2}} \frac{\omega^2 r}{N}$

Fuller + Cantiello et al. (Science 2015)
Lecoanet, Fuller, MC et al. (2016)
See also Loi & Papaloizou (2017, 2018)

Typical Critical B-field $\sim 10^5$ G
Fraction of stars with strong internal B-fields

From a sample of 3000+ stars

At least 50-60% have strong internal B-fields!

But See also Mosser et al. 2016

Stello, Cantiello, Fuller et al. (Nature 2016)
Convective core dynamos on the MS: $B_{eq} \sim 10^5$ G

Magnetic field topology is complex

Flux conservation can easily lead to $B \sim 10^6$-$10^7$ G on the RG

Stable magnetic configurations of interlocked poloidal+toroidal fields exist in radiative regions

Energy Equipartition

\[ \frac{1}{2} \rho v_{\text{con}}^2 \approx \frac{B_{\text{eq}}^2}{8\pi} \]

Magnetic Flux Freezing & Conservation

\[ B_{\text{RG}} = B_{\text{MS}} \left( \frac{r_{\text{MS}}}{r_{\text{RG}}} \right)^2 \]

MHD Sims: Courtesy of K. Augustson
See Cantiello et al. 2016 for more…
Numerical Simulations

Solving the linearized magneto-Boussinesq equations using DEDALUS

\[
\rho_0 \partial_t u + \nabla p'_{\text{tot}} = g \rho' + \frac{1}{4\pi} \left( B_0 \cdot \nabla B' + B' \cdot \nabla B_0 \right)
\]

\[
\nabla \cdot u = 0
\]

\[
\partial_t \rho' = \frac{\rho_0 N_0^2}{g} e_z \cdot u
\]

\[
\partial_t B' = B_0 \cdot \nabla u - u \cdot \nabla B_0
\]

Lecoanet, Fuller, MC et al. 2017
damp driving

$Lecoanet, Fuller, MC et al. 2017$

$B_c = \sqrt{\frac{\pi \rho}{2} \frac{\omega^2 r}{N}}$

Constant B, variable N
Simulation vs Analytical Theory

IGW perfectly transmitted into Alfvénic Waves. High wavenumber: They dissipate

Next: 3D and more realistic B-field configurations

Lecoanet, Fuller, MC et al. 2017
Opportunities with TESS

Magnetic suppression of g-modes in SPB and Gamma-Dor stars.

Should occur preferentially in late main-sequence stars

Typical Critical B-field required $\sim 10^5$ G

Cantiello, Fuller & Bildsten 2016
Conclusions

Asteroseismology allows to probe for strong magnetic fields in the deep interiors of stars!

Important results:

✴ In the presence of strong internal magnetic fields, g-modes oscillations are affected. Fuller, MC et al. (2015), MC, Fuller & Bildsten (2016), Lecoanet et al. 2017. This process has to occur for fields above a certain threshold.

✴ Strong core B-fields potentially ubiquitous in stars above ~1.5$M_{\text{Sun}}$. Fuller, MC et al. (2015), Stello, MC et al. (2016). *Not* included in stellar evolution.
Thanks!!
What is the Flatiron Institute?
David Spergel
Rachel Somerville
Greg Bryan
Yuri Levin
David Hogg
Will Farr
Phil Armitage
Shirley Ho

+ 30 Postdocs & Research Scientists (~16 more starting in the fall)