Pulsations and Magnetic Fields in Massive Stars

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Massive stars

- Energy / Momentum in ISM
  - Stellar Winds, SNe
- Nucleosynthesis
- Remnants: NS and BHs
  - Magnetars, Pulsars, Long GRBs... Importance of magnetic fields, mass-loss and final angular momentum budget
A biased, incomplete overview

- Magnetic Fields
  - Fossil - Dynamo Generated
  - Impact on angular momentum transport
  - Impact on photometric diagnostics

- Pulsations
  - Solar-like oscillations in massive stars
    - I will talk only about MS stars, but pulsations in later phases might be important (e.g. Talk from Saio)
Magnetic Fields
About 30 magnetic OB stars found (e.g. Donati, Hubrig, Neiner, Petit)

Detection through Zeeman spectral signature

Mostly dipolar, amplitude between 300 G and several kG

Bias toward strong, large scale fields

Origin unclear. Likely Fossil (Wade et al. 2010)

Similar to $A_p/B_p$ stars $\sim$ 5-10% ?
OB stars show puzzling surface phenomena (e.g. DACs, LPV, Wind Clumping, Solar-Like Oscillations, Red Noise, Photometric variability, X-ray emission...)

Some of these phenomena are **ubiquitous**. Therefore can not be explained by large scale fields! (e.g. Schnerr+08)

Small scale / small amplitude fields? (e.g. Cranmer & Owocki 96, Fullerton+96, Kaper+97, Henrichs+05)

(DACs: Kaper, Henrichs et al. 1999)
Origin of B-fields in massive stars

- **Fossil Fields**
  - B-field is produced/retained during star formation
  - Field arranged into a **stable configuration**
    (Braithwaite & Nordlund 2006, Duez et al. 2010)

- **Contemporary Dynamo Action**
  - Configuration of the flow that transforms kinetic energy into magnetic energy. B-field maintained against Ohmic dissipation.
    (Cantiello et al. 2010)
Stable Configurations
Stable Configurations

- Purely poloidal fields are unstable
Purely poloidal fields are unstable

e.g. Flowers & Ruderman 1977
Stable Configurations

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- Purely toroidal fields are unstable

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Stable Configurations

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*e.g.* Flowers & Ruderman 1977

**Tayler Instability**

*e.g.* Spruit 1999
Stable Configurations

- Purely poloidal fields are unstable
- Purely toroidal fields are unstable
- Instability occurs on the Alfven timescale: the field rapidly becomes unobservable

- e.g. Flowers & Ruderman 1977
- Tayler Instability
- e.g. Spruit 1999
Stable Configurations

Dynamo Action in OB stars

- **Dynamo in Convective Core**
  (e.g. MacGregor & Cassinelli 2003, Augustson 2010)

- **Dynamo in Radiative Zone**
  (e.g. Spruit 2002, implemented in stellar evolution codes)

- **Dynamo in Iron Convection Zone**
  (Cantiello et al. 2009, 2010; Cantiello & Braithwaite 2011)
Dynamo in the Iron Convection Zone
Stellar structure

Low Mass stars
- Radiative core
- Convective envelope
  - e.g. 1$M_{\text{Sun}}$

Massive stars
- Convective core
- Radiative envelope
  - e.g. 20 $M_{\text{Sun}}$
Stellar structure

Low Mass stars
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Inside a massive star

Iron bump

He bump

Kappa [cm² g⁻¹]

LOG T [K]

Z=0.02
Z=0.004
Z=0.002
Z=0.001
Z=0.00001
Physics in the FeCZ

(e.g. Lighthill ‘52, Stein ‘67, Edmunds ‘78, Goldreich & Kumar ’90, de Jager et al. ’91)

Cantiello et al. 2009
Sub-surface convective zone

Acoustic and gravity waves
Buoyant magnetic flux tubes
Microturbulence
Clumps
Stellar surface
Radiative Layer
Convective Zone
Radiative Layer

Matteo Cantiello
Near-Surface Convection in Massive Stars
KITP – October 24th 2011

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Pulsations and Magnetic Fields in Massive Stars
IAU GA SpS13 – Beijing 2012
Dynamo Action in FeCZ

Subsurface convection
Rotation + Shear

(Cantiello, Braithwaite, Brandenburg et al. 2010)
Here we assume dynamo action!

Cantiello & Braithwaite '11
Three mechanisms
1) Magnetic Diffusion \( \sim 10^7 \) yr
2) Wind Advection \( \sim 1 \) yr
3) Magnetic Buoyancy \( \sim \) hours

- The amplitude of a self contained magnetic feature scales as \( B \propto \rho^{2/3} \)
- If the field is still anchored to the convection zone plasma can flow through the tube and higher fields can be reached (up to equipartition with thermal pressure) (Cantiello & Braithwaite '11)
A very simple model:
1) Assume hydrostatic equilibrium
2) Assume thermal equilibrium
3) Assume beta >> 1

\[ \beta = \frac{\rho kT}{B^2/8\pi} \]

\[ F_{\text{drag}} = F_{\text{buoyancy}} \]

\[ v^2 \rho l^2 = \Delta \rho g l^3 \]

\[ \frac{v^2}{c_s^2} = \frac{l}{H_p \beta} \]

\[ v_{\text{rise}} \sim c_s \beta^{-1/2} \]

In the models beta ~ 100
Buoyant velocity is ~1/10 of the sound speed

e.g. Acheson (1978)
Magnetic Spot in the Sun
For fields of ~ 100 G emerging at the surface this leads to a temperature increase of ~ 300 K. A hot, bright spot

Cantiello & Braithwaite (2011)
How they would look like?

Spot in a convective star

Spot in a radiative star (?)
High precision photometry

CoRoT: HD 46149 (Degroote et al. 2010)

CNES / David Ducros
Spots in a O8V star?

HD 46149 (Degroote et al. 2010)
Spots in a B0.5IV star?

HD51756 (Papics et al. 2011)
Spots in a B0.5IV star?

HD51756 (Papics et al. 2011)

Near-Surface Convection in Massive Stars

Matteo Cantiello

Pulsations and Magnetic Fields in Massive Stars

IAU GA SpS13 – Beijing 2012
Photometric variability: HRD location

![HRD Diagram with HD51756](image.png)
Effects from B-fields

- **Stellar Surface**
  - Observable surface effects (spots/inhomogeneities...)

- **Stellar Interior**
  - Angular momentum transport
  - Chemical mixing

- **Stellar Wind**
  - Wind anisotropies/inhomogeneities
  - Modified angular momentum loss
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Angular Momentum Transport
Tayler-Spruit dynamo operates in radiation zones (Spruit 2002)

- It requires some differential rotation
- Omega-effect amplifies toroidal component
- Tayler instability closes the dynamo loop (see however Zahn et al. 2007 for some criticism of the Tayler-Spruit dynamo)
- Results in efficient transport of $j$
- Asteroseismic observations can put important constraints on $j$-transport mechanism (see e.g. Eggenberger et al. 2005, 2012)
Spin of compact remnants
(Heger et al. 2005, Suijs et al. 2008)

Core-envelope coupling leads to spin-down of the core
GRB progenitors (Yoon et al. 2005, Woosley & Heger 2006, Cantiello et al. 2007)

Without B-fields too many massive stars would make a GRB

Computed with open source code MESA (mesa.sourceforge.net)
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Magnetic fields can increase wind angular momentum loss
(Weber & Davis 1967, ud-Doula & Owocki 2002)

\[ \dot{J} = \frac{2}{3} \dot{M} \Omega R^2_A \]

Spin-down time measured in Sigma-Ori matches theoretical predictions
(Townsend et al. 2010)

Potentially important for stellar evolution models
(e.g. Meynet et al. 2011)
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\[ M_{\text{ini}}=10M_{\text{Sun}}, \ V_{\text{ini}}=200 \text{ km/s} \] (Meynet et al. 2011)
Pulsations
Solar-like oscillations
Cantiello et al. 2009
Suggest that near-surface convection in hot, massive stars could cause stochastically excited pulsations

Belkacem et al. 2009
Corot detection of solar-like oscillations in the massive star V1449 Aql (B type Star) [However, see Aerts et al. 2011]

Belkacem et al. 2010
Theoretical calculations of stochastically excited modes from sub-surface convection.

Degroote et al. 2010
Corot detection of solar-like oscillations in an O-type star
Solar-like oscillations in O star

HD 46149 (Degroote et al. 2010)
Solar-like oscillations in O star

**Fig. 10.** Échelle diagram of observed frequencies (filled circles, the size of the dot scales with the power). Black circles represent modes with an amplitude above 11.5 ppm, the grey circles are modes with an amplitude above 10.5 ppm. The frequency values of $\ell = 0$ (×) and $\ell = 1$ (+) modes are overplotted for the models of the primary component listed in Table 3 (red symbols denote the 30 $M_\odot$ model, green symbols denote the 34 $M_\odot$ model).

HD 46149 (Degroote et al. 2010)
Photometric variability: HRD location

![HRD Diagram](chart.png)

HD46149 (Degroote+ 2011)
Red Noise
“Red Noise” in O stars

- Variability in the CoRoT photometry of 3 hot O-type stars
- No clear pulsations detected
- Variability of stochastic nature
- Near-surface convection, granulation or wind inhomogeneities

(Blomme et al. 2011)
“Red Noise” in O stars

(Blomme et al. 2011)
Photometric variability: HRD location

HD46150
HD46223 (Blomme+ 2011)
HD46966
Photometric variability: HRD location

- Red Noise
- Spots/Solar-like

Log L vs log $T_{\text{eff}}$

- HD46149 (Degroote + 2010)
- HD51756 (Papics + 2011)
- HD46150
- HD46223 (Blomme + 2011)
- HD46966

Fe convective zone
Photometric variability: HRD location

- HD46149 (Degroote+ 2010)
- HD51756 (Papics+ 2011)
- HD46150
- HD46223 (Blomme+ 2011)
- HD46966
Some open questions

- What is the origin of large scale, large amplitude fields
- Can magnetic fields be amplified in the radiative regions of rotating stars (e.g. Tayler-Spruit)
- Are small-scale surface fields ubiquitous
- Bright spots in massive stars?
- Solar-like oscillations in massive stars
- Interaction of mass-loss and pulsations
谢谢