The Effects of Magnetic Fields on Stellar Structure

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Magnetic fields in stars

- **Low mass stars**: Generate magnetic fields via a dynamo process in their outer convective layers.
- **High mass stars**: Origin of magnetic fields unclear, may be fossil fields retained from a previous event (possibly a merger or interaction with another star).
- Origin and evolution of magnetic fields in both low and high mass stars is an active research area.

Magnetic effects on stellar structure

- **Convection**: A vertical magnetic field inhibits convective motion. This is observed in sunspots (see Fig. 1). Gough & Taylor (1966) derived the magnetic inhibition parameter to describe the effect of magnetic fields on convection:

$$\delta = \frac{B_v^2}{B_v^2 + 4\pi\gamma p_{\rm gas}}$$

- When δ is large, convection is strongly inhibited and vice versa when δ is small. The inhibition of convection occurs in two ways:
  1) Increases the threshold for convection to begin.
  2) Decreases the energy transferred by convection once it does begin.
- **Magnetic pressure**: Magnetic fields exert a pressure on stellar plasma. This pressure can help support the star against gravity.
- These effects have been included in previous stellar evolution models (e.g. Mullan & MacDonald 2001). These works show that magnetic effects inflate the sizes of stars.

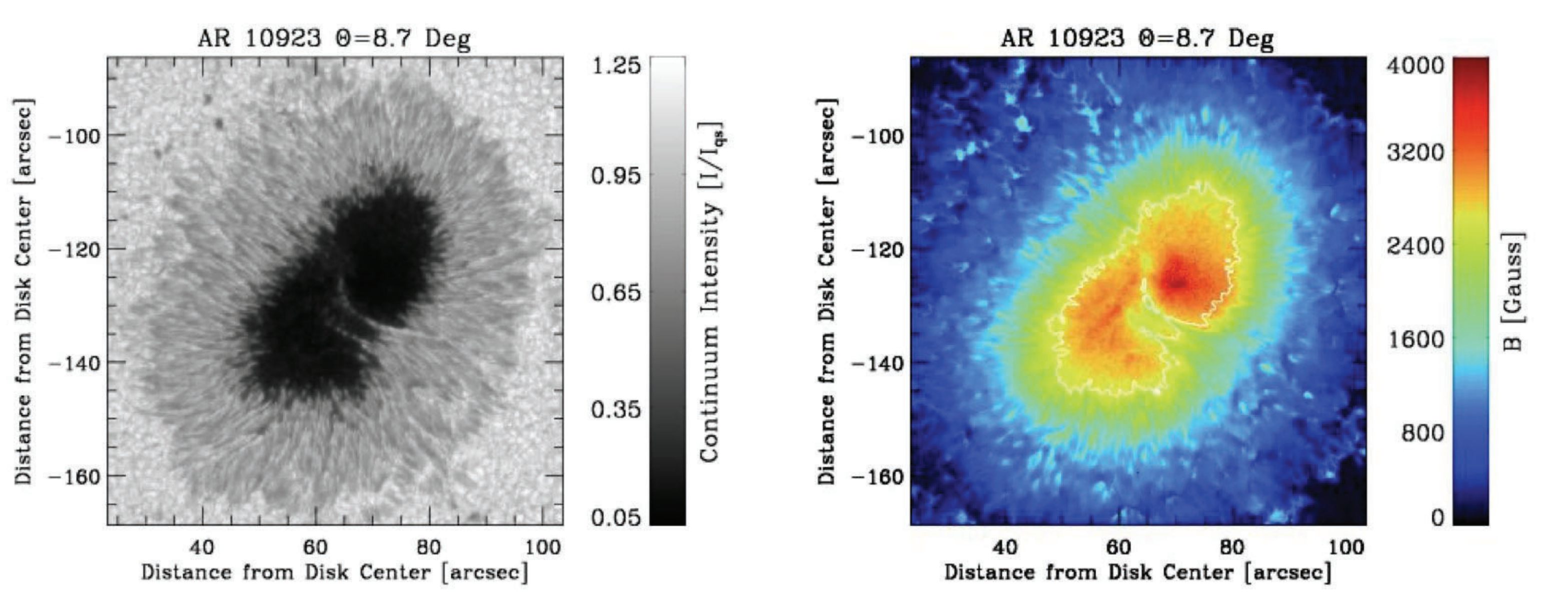


Fig. 1: Brightness (left) and magnetic field strength (right) of a sunspot; low brightness is caused by a vertical magnetic field which inhibits convective motion (Borrero & Ichimoto 2011).

Magnetic field profile

- The internal magnetic field profile is poorly constrained by observations. Current models adopt the following:
  - Keep δ constant in the outer layers of the star. While moving deeper into the star, the magnetic field increases to compensate for the increasing pressure.
  - This continues until the magnetic field reaches a ceiling value, at which the magnetic field remains constant while moving deeper into the star. Typical values for the ceiling field are ~ 10^4 G.

Project goals

The Modules for Experiments in Stellar Astrophysics (MESA) is an open source, detailed 1D stellar evolution code. MESA can be extended to test and study new physics. **The goal of this project is to modify MESA to include the effects of magnetic fields.** We have made much progress, however there is still work to be completed. Below we show two plots that best describe how magnetic fields alter stellar structure.

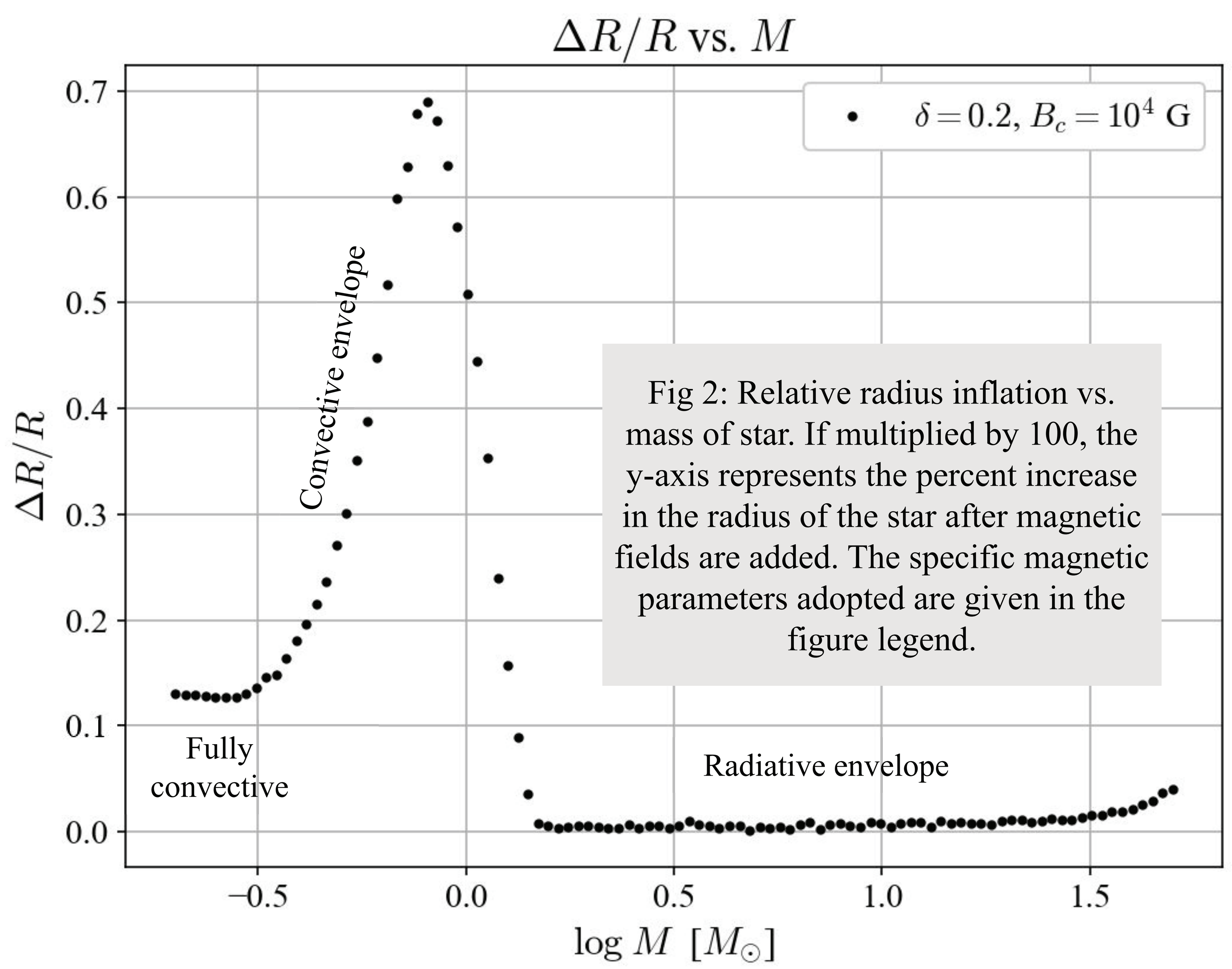


Fig 2: Relative radius inflation vs. mass of star. If multiplied by 100, the y-axis represents the percent increase in the radius of the star after magnetic fields are added. The specific magnetic parameters adopted are given in the figure legend.

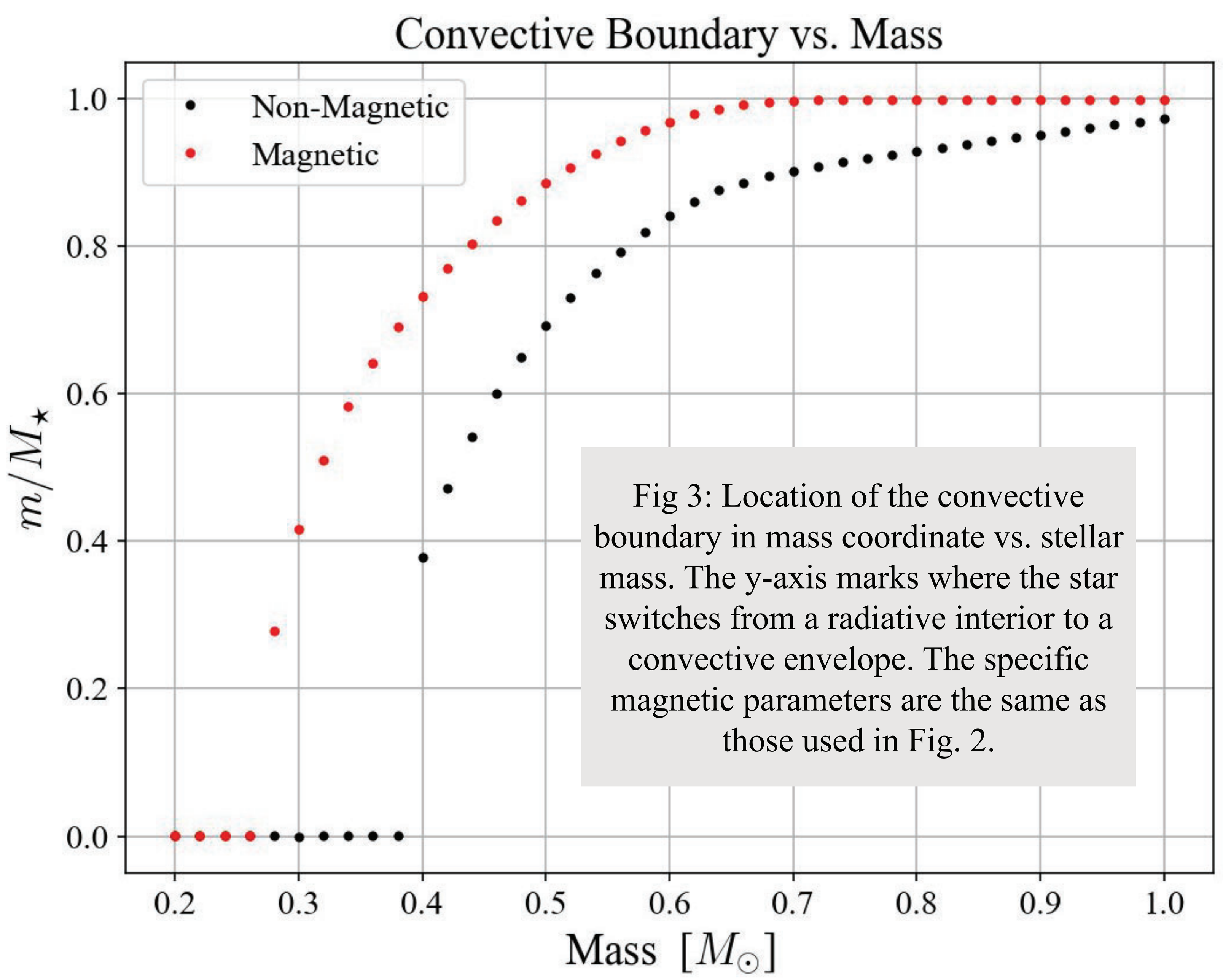


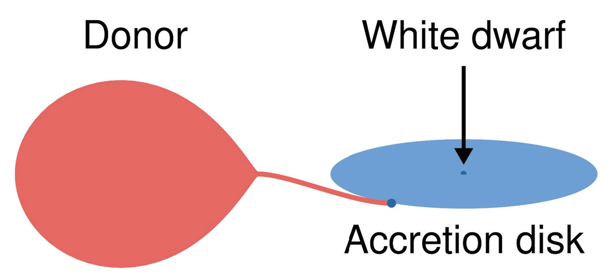
Fig 3: Location of the convective boundary in mass coordinate vs. stellar mass. The y-axis marks where the star switches from a radiative interior to a convective envelope. The specific magnetic parameters are the same as those used in Fig. 2.

Preliminary results

- **Radius inflation:** Magnetic fields inflate stars, causing larger radii compared to non-magnetic stars of the same mass (Fig. 2). This is caused by the inhibition of convection, which dams up energy inside the star, causing it to heat up and expand. This is most pronounced in stars that have outer convective envelopes (≲1.3 $M_\odot$) rather than outer radiative envelopes (see Fig. 2). The curve flattens out on the low mass end, which consists of fully convective stars.
- **Radiative core retention:** Magnetic fields cause stars to retain their radiative cores at lower masses when compared to non-magnetic stars (see Fig. 3). The inflation of the star impacts the structure throughout, which modifies the energy transport in the central regions.

Future work

- We will ultimately apply these magnetic effects to more exotic objects and phases of stellar evolution. Below are two areas we are currently studying:
  - **Cataclysmic variables:** These are close binary stars where a low mass star transfers mass onto a white dwarf star. The white dwarf essentially cannabalizes its companion. The companions are believed to be magnetic, however the magnetic effects on stellar structure are not included in models. The radius inflation would impact how much material is transferred from the companion to the white dwarf.



  - **Convective Kissing Instability:** This is an instability driven by merging convective zones in low mass stars over the course of millions/billions of years. We have not identified a star currently undergoing this phase, however its effects can be observed in large distributions of stars. Attempts to reproduce these observations have been fairly successful, but there are discrepancies. Previous work has shown that reducing the efficiency of convection can bring the models into better agreement with the observations (Boudreaux & Chaboyer 2023). A reduction in convective efficiency can be accomplished with magnetic fields.
- There are plenty of other examples in stellar astrophysics where magnetic fields are important. As observations become more and more refined, we must have a detailed understanding of the impacts of magnetic fields in order to match models with observations.

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