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HIDDEN MAGNETIC FIELDS IN STELLAR INTERIORS PROBED BY ASTEROSEISMOLOGY

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Abstract. Understanding the distribution and evolution of angular momentum is essential for comprehending stellar formation and evolution. Recent missions like CoRoT and Kepler have highlighted flaws in current angular momentum transport models (Mosser et al. 2012; Ouazzani et al. 2019). Magnetic field is a promising candidate to explain the missing transport, and hopefuly solve the issue. Asteroseismology via perturbative methods has recently enabled the first detection and measurements of magnetic fields in stellar interiors (Li et al. 2022). Here, we present an upgrade of the non-perturbative oscillation code ACOR (Ouazzani et al. 2012, 2015) that will fully incorporate stellar rotation and magnetic fields in a two-dimensional framework. This code will allow us to test the existing perturbative methods and tackle the area of strong and complex internal magnetic fields, thereby allowing realistic seismic diagnostics of magnetic fields.

Keywords: Stars, Magnetic Field, Asteroseismology, Rotation, Angular momentum transport

1 Introduction

We present here the latest advancements in the development of the magnetic extension of the code ACOR, referred to as ACOR(Mag) (Adiabatic Code of Oscillation including Rotation and Magnetic field). The original ACOR code computes adiabatic non-radial pulsations of a rotating star using a non-perturbative approach, accounting for both centrifugal deformation and the full Coriolis acceleration. The oscillations are found solving the classical set of oscillation equations, with rotation, as an eigenvalue problem, via a Newton-like method. The angular dependance of the modes is expanded in spherical harmonic series while the radial discretization is handled using a 4th-order finite differences scheme (Scuflaire et al. 2008). A system of coordinates adapted to the star's centrifugal deformation (Bonazzola et al. 1998; Ouazzani et al. 2015) is used to avoid discontinuities and facilitate the implementation of boudary conditions. In Sect 2., we present the magnetohydrodynamic oscillation equations in spheroidal geometry, along with the assumptions made as well as the modifications introduced to incorporate magnetic fields. Finally in Sect 3., we discuss the use of *SymPy**, a python library for symbolic computation, allowing us to overcome the complexity of the problem imposed by the equations, while providing great adaptability to various assumptions.

2 Underlying equations and usage of ACOR(Mag)

The system of equations to be solved is the same as in ACOR, with the inclusion of the terms related to the Lorentz force in the momentum equation and the additional induction equation. The following assumptions have been made: the star's hydrostatic structure is axisymmetric, the magnetic field is aligned with the rotation axis and independent of the azimuthal angle, and the structural deformation due to the magnetic field is neglected. Under these assumptions, the system of equations becomes more complex, expanding from 4 to 8 radially differentiated equations. To run ACOR(Mag), the user will need an equilibrium MHD structure, which will be used as input for the code. Initially, we will introduce a simplified steady magnetic field that will be integrated into an already-computed equilibrium hydrodynamic structure. The ultimate goal is to use fully realistic MHD simulations as the input structure.

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*`https://www.sympy.org/en/index.html`

3 Automations with SymPy

Due to the complexity of the problem involving MHD equations, spectral decomposition using spherical harmonics, and spheroidal coordinates, formulating the equations proved to be more challenging than initially anticipated. To overcome these difficulties, I decided to use *SymPy*, a Python library for symbolic computation, and successfully automated the various processes required for deriving the set of equations. This process is summarized in Figure 1. I developed Python routines to automate these steps, transforming the set of equations into the symbolic matrix we aim to solve. A Fortran file is then generated from this matrix and used as input for ACOR(Mag) to numerically compute the various matrix coefficients. This approach offers several advantages : greater flexibility and adaptability –as the set of equations can be treated as an input–, faster analytical development and code implementation in the long run and an improved error control –allowing for easier comparison and testing of the coefficients–.

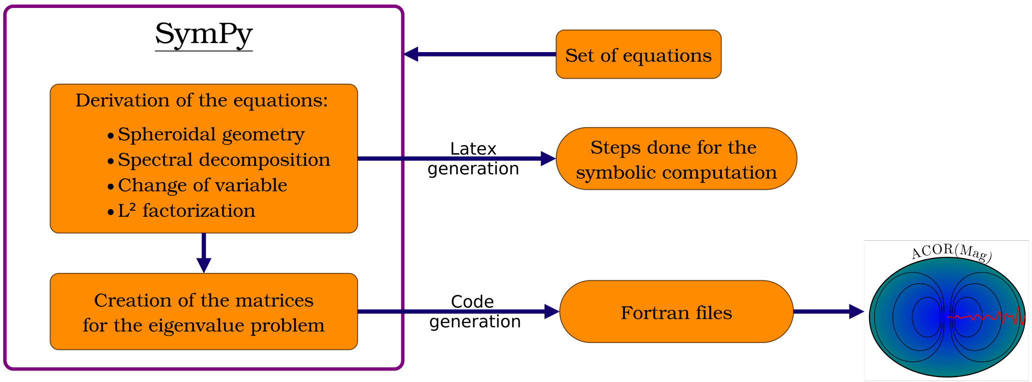

Fig. 1. Diagram of the automation process using

4 Conclusions

We described here the initial steps of the development of a 2D oscillation code designed to account for the full effects induced by rotation and magnetic field simultaneously. The routines developed using *SymPy* have enabled faster analytical development and code implementation, while also improving error control. This will make it easier to test the assumptions made by current methods (Loi (2021); Dhouib et al. (2022)) for different topologies. Then, it is planned to tackle the regime of strong fields as well as to compare the theoretical frequencies with the observed ones from the *Kepler* mission to develop magneto-asteroseismic diagnostics.

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