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IMPACT OF LARGE-SCALE MAGNETIC FIELDS ON SOLAR STRUCTURE

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Abstract. We here focus on the impact of large-scale magnetic fields on the solar structure from its core up to its surface by treating semi-analytically the Magneto-HydroStatic (MHS) equilibria of a self-gravitating spherical shell. Then, the modifications of the internal structure of the Sun introduced by such a field are deduced, and the resulting multipolar gravitational moments are obtained.

1 Introduction

With the ongoing development of the Sun-Earth interaction studies and the coming launch of Picard, it is of primordial importance to get a better understanding of the processes which are at the origin of the solar variability. In particular, since the tachocline can play an important role on the generation of the large-scale magnetic field in the innermost layers of the Sun, conversely the proper modeling of the internal magnetic field can improve our understanding of the fundamental phenomena acting in this region. We here depict how a large-scale magnetic field can have an impact on the solar structure. For this purpose, we consider an internal magnetic field confined below the convection zone by solving a non force-free magneto-hydrostatic (MHS) equilibrium, using a Grad-Shafranov approach. A pertubative treatment is then performed on a solar model, allowing us to derive the amplitude of the fluctuations over the gravitational potential and the thermodynamic quantities at the surface of the Sun for an internal field with a 7MG strength, which is the upper limit proposed by Friedland & Gruzinov (1991) to adjust it to present observables.

2 Formalism

The magnetic field configuration is derived for a field which is assumed to be axisymmetric, in magneto-hydrostatic equilibrium and non force-free following the formalism presented in these proceedings by Duez *et al.* (to which we will refer hereafter as Paper I). The main difference lies in the change of boundary conditions: here the field is assumed to be confined below the convection zone ($r \leq R_b$, where R_b is the radiation-convection border), and the equilibrium modeled is thus similar to the one reached in a spheromak experiment as the toroidal field vanishes at the boundary. However, the main differences with spheromaks experiments where magnetohydrodynamic instabilities tend to reorganize the plasma towards a force-free state are that the Lorentz force does not vanish here and that $\beta \gg 1$ ($\beta = P_{\rm gas}/P_{\rm mag}$). This non force-freeness induces perturbations on the structural quantities by modifying the hydrostatic balance that will be quantified.

2.1 Magnetic field topology

The magnetic field is derived as in Paper I, to the exception of the Green's function which are modified owing to the new boundary conditions according to $g_l(r,r') = \frac{1}{(2l+3)}\left[\frac{r'^{l+2}}{R_b^{2l+3}} - \frac{1}{r'^{l+1}}\right] r^l$ if $r < r'$ or $g_l(r,r') = \frac{1}{(2l+3)}\left[\frac{r^l}{R_b^{2l+3}} - \frac{1}{r^{l+3}}\right] r'^{l+2}$ if $r > r'$; thus the flux function Ψ vanishes at $r = R_b$ and so does the magnetic field.

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2.2 *Perturbation of the structural quantities*

A first-order perturbative treatment is performed in the high-β regime to highlight the structural modifications associated with the adjustment of the hydrostatic equilibrium due to the magnetic field. Our complete study (Duez *et al.*, 2008) has shown that as a first approximation, the only perturbation to take into account is the one arising from the introduction of the Lorentz force which is assumed to be weak compared with the gravitational field and with the gaseous pressure gradient. The equation for the perturbation of the gravific potential is derived following Mathis *et al.* (2008). First, we expand all the quantities X (the gravific potential, the density, the pressure, the temperature) around the non-magnetic state X_0 as $X(r,\theta) = X_0(r) + \sum_{l\geq 0} \widehat{X}_l(r) P_l(\cos\theta)$. Next, the components of the Lorentz force (resp. radial and latitudinal) are projected on the Legendre polynomials:

$$F_{\mathcal{L},r}(r,\theta) = \sum_l \mathcal{X}_{\boldsymbol{F}_{\mathcal{L}};l}(r)\, P_l(\cos\theta) \qquad F_{\mathcal{L},\theta}(r,\theta) = -\sum_l \mathcal{Y}_{\boldsymbol{F}_{\mathcal{L}};l}(r)\, \partial_\theta P_l(\cos\theta)\,. \tag{2.1}$$

The equation ruling the amplitude of the gravific potential perturbation induced by the magnetic field ($\widehat{\phi}_l$) is then given by

$$\frac{1}{r}\frac{\mathrm{d}^2}{\mathrm{d}r^2}\left(r\widehat{\phi}_l\right) - \frac{l(l+1)}{r^2}\widehat{\phi}_l - \frac{4\pi G}{g_0}\frac{\mathrm{d}\rho_0}{\mathrm{d}r}\widehat{\phi}_l = \frac{4\pi G}{g_0}\left[\mathcal{X}_{\boldsymbol{F}_{\mathcal{L}};l} + \frac{\mathrm{d}}{\mathrm{d}r}\left(r\mathcal{Y}_{\boldsymbol{F}_{\mathcal{L}};l}\right)\right] \tag{2.2}$$

while the perturbations of density ($\widehat{\rho}_l$) and of pressure ($\widehat{P}_l$) are obtained: $\widehat{\rho}_l = \frac{1}{g_0}\left[\frac{\mathrm{d}\rho_0}{\mathrm{d}r}\widehat{\phi}_l + \mathcal{X}_{\boldsymbol{F}_{\mathcal{L}};l} + \frac{\mathrm{d}}{\mathrm{d}r}\left(r\mathcal{Y}_{\boldsymbol{F}_{\mathcal{L}};l}\right)\right]$ and $\widehat{P}_l = -\rho_0\widehat{\phi}_l - r\mathcal{Y}_{\boldsymbol{F}_{\mathcal{L}};l}$. Finally, it is interesting to get diagnosis from the stellar radius variation induced by the magnetic field. The definition of the radius of an isobar is then given by: $r_P(r,\theta) = r\left[1 + \sum_{l\geq 0} c_l(r) P_l(\cos\theta)\right]$ where $c_l = -\frac{1}{r}\frac{\widehat{P}_l}{\mathrm{d}P_0/\mathrm{d}r} = \frac{\rho_0}{\mathrm{d}P_0/\mathrm{d}r}\left(\frac{1}{r}\widehat{\phi}_l + \frac{\mathcal{Y}_{\boldsymbol{F}_{\mathcal{L}};l}}{\rho_0}\right)$.

3 Results

Results for the normalized perturbations in gravitational potential $\tilde{\Phi}_l$, density $\tilde{\rho}_l$, pressure $\tilde{P}_l$ (where $\widetilde{X}_l = \widehat{X}_l/X_0$), and radius c_l are shown in Fig. 1 (for the modes $l=0$ and $l=2$) for a field's strength of $B_0 = 7\,\mathrm{MG}$. Using the continuity of ϕ at the surface (at $r = R_\odot$), we derive the expression to evaluate the gravitational multipolar moments : $J_l = \left(\frac{R_\odot}{GM_\odot}\right)\widehat{\phi}_l\,(r = R_\odot)$. The surface values are $\tilde{\rho}_0 = -1.67\times 10^{-1}$, $\tilde{P}_0 = -5.91\times 10^{-1}$, $c_0 = -1.17\times 10^{-4}$, $J_0 = 1.17\times 10^{-4}$; $\tilde{\rho}_2 = 2.92\times 10^{-3}$, $\tilde{P}_2 = 1.03\times 10^{-2}$, $c_2 = 2.04\times 10^{-6}$ and $J_2 = -2.05\times 10^{-6}$ which means that the configuration associated with such a dipolar magnetic field is prolate.

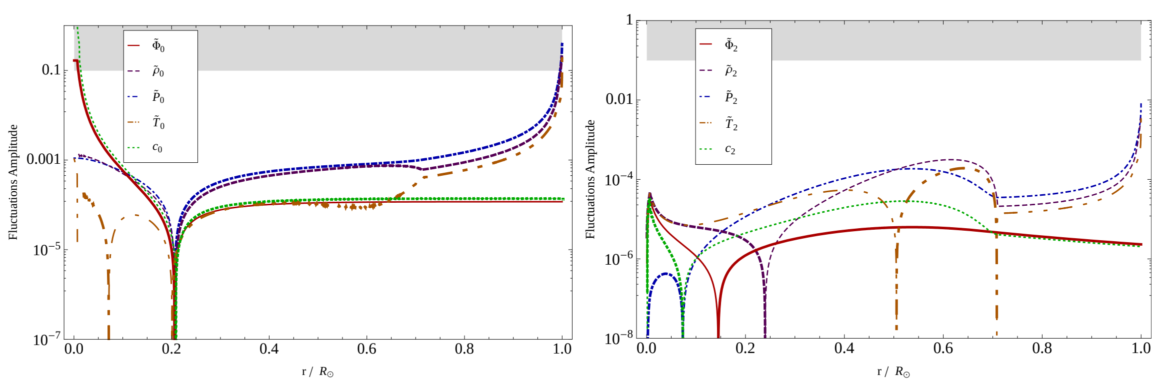

Fig. 1. Normalized modal fluctuations with $l=0$ (**Left**) and $l=2$ (**Right**) in gravitational potential, density, pressure, temperature and radius, for a dipolar field buried in the solar radiation zone with a strength of $B_0 = 7\,\mathrm{MG}$.

References

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