*Dynamics of Solar and Stellar Convection Zones and Atmospheres*
*Proceedings IAU Symposium No. 365, 2024*
*A. V. Getling & L. L. Kitchatinov, eds.*
doi:10.1017/S1743921323004994

# Effects of small-scale magnetic fields in the photosphere on surface effects for solar-like stars

**Guifang Lin**[1,2,5], **Yan Li**[1,2,3,4,5], **Jie Su**[1,2,3,5], **Tao Wu**[1,2,3,5] and **Yuetong Wang**[1,2,5]

[1]Yunnan Observatories, Chinese Academy of Sciences, Kunming 650216, P. R. China

[2]Key Laboratory for the Structure and Evolution of Celestial Objects, Chinese Academy of Sciences, P. R. China

[3]Center for Astronomical Mega-Science, Chinese Academy of Sciences, Beijing, 100012, P. R. China

[4]University of Chinese Academy of Sciences, Beijing 100049, P. R. China

[5]International Centre of Supernovae, Yunnan Key Laboratory, Kunming 650216, P. R. China

**Abstract.** Magnetic fields are important physics in stellar evolutionary theory, which seriously affects the stellar structure and evolutionary statues. The small-scale magnetic fields in the photosphere are ubiquitous, and float on the stellar surface, which usually couple with the acoustic waves, affecting the propagation of the acoustic waves. Considering the effect of the magnetic fields in the stellar photosphere on the oscillation frequencies, we calculate the asteroseismology for solar-like star KIC 11295426 and KIC 10963065. We obtain the stellar fundamental parameters, especially the strength of small-scale magnetic fields in the stellar photosphere. We find that the small-scale magnetic fields in the stellar photosphere may obviously improve the agreement between the observations and the theoretical models for two stars. The magnetic strength for KIC 11295426 and KIC 10963065 from asteroseismology are in agreement with the stellar period-activity relation.

**Keywords.** Asteroseismology, Solar-like stars:oscillations, stars:atmosphere, magnetic fields

## 1. Introduction

Over the past decades, many space telescope (i.e. MOST, CoRoT, Kepler, K2 and TESS) have observed more and more uninterrupted high-precision photometric data of solar-like stars and red giant stars (e.g. Koch et al. 2010; Howell et al. 2014). This will facilitate better constraining stellar parameters and deeper exploring the stellar inner structure (e.g. Soriano & Vauclair 2008; Beck et al. 2012; Bellinger et al. 2019).

Due to the complex surface structure of the sun, there was a systematical offset between the observed oscillation frequencies and the theoretical ones (Christensen–Dalsgaard et al. 1988; Dziembowski et al. 1988), which was independent on the spherical degree $\ell$ and increased with the frequencies. This is known as the near-surface effect of solar p-mode oscillations. Until now, we have not fully understood the physics of the near-surface effect.

In order to eliminate the systematical offset, many researchers have used the different numeric fitting formulae to correct the frequencies. They used the form of single power law or the form of $\nu^3/I$ and $\nu^{-1}/I$ to correct the frequencies (Kjeldsen et al. 2008; Ball & Gizon 2014). On the side of stellar structure, the averaged structure of 3D hydrodynamical simulation are used to replace the stellar surface structure (Ball et al. 2016; Houdek et al. 2017; Schou & Birch 2020). They considered the physical effects of non-adiabaticity and turbulent pressure, and got the frequency deviations with $\leq 3\mu$Hz for the sun. Considering the magnetic pressure in the quiet solar photosphere, Li et al. (2021) found that the solar p-mode oscillations were reflected at the magnetic-arch splicing layer. They got the smallest systematical deviations to date between the observed and theoretical frequencies.

The small-scale magnetic field in the photosphere is very important. It couples with the acoustic waves, and may affect the propagation of the acoustic waves (Rosenthal et al. 2002; Bogdan et al. 2003). In our work, based on Li et al. (2021), we mainly focus on the effects of the small-scale magnetic field in the photosphere on the p-mode oscillations frequencies for the solar-like stars. Considering the magnetic fields in the photosphere, we construct the stellar models for the solar-like star KIC 11295426 and KIC 10963065.

## 2. Stellar model with small-scale magnetic fields

We use MESA evolutionary code, version r-10398 to construct the stellar structure (e.g. Paxton et al. 2018). We adopt the GS98 (Grevesse & Sauval 1998) chemical composition and the OPAL opacity tables from Iglesias & Rogers (1996). In the stellar evolutionary models, the convection is treated as the standard mixing length theory (Böhm-Vitense 1958), and the convective overshooting is not considered. We also include the element diffusion. We use the "adipls" package (Christensen–Dalsgaard 2008) in MESA to solve the adiabatic oscillation equations and get the theoretical p-mode oscillations frequencies.

Based on Li et al. (2021), we consider the effects of magnetic fields in the Eddington gray-atmosphere model. We use the unified $T-\tau$ relation (Li et al. 2021). In the Hopf-like function $q(\tau)$, we add a term to account for the effects of magnetic fields:

$$q(\tau) = q_{\rm ori}(\tau) + a\exp(-b\sqrt{\tau}) \tag{1}$$

In the Eddington gray-atmosphere model, $q_{\rm ori}$ is 2/3. Parameter $a$ represents the magnetic strength and $b$ determines the location of the magnetic-arch splicing layer. For the reflected standing waves, we adopt the surface mechanical boundary condition as $P^{'} = 0$. For more details, please refer to Li et al. (2021).

We apply this method to two solar-like stars: KIC 11295426 and KIC 10963065. These two stars are host stars with a few transiting planets (Gilliland et al. 2013; Marcy et al. 2014). Using Kepler short cadence data, we compare the theoretical p-mode frequencies with observed 38 mode frequencies for KIC 11295426 and 44 ones for KIC 10963065 identified from Davies et al. (2016). We use the value of $\chi^2$ which is defined as the average of squared differences between the observed and theoretical frequencies weighted by the observational errors to evaluate the matching goodness. The $\chi^2$-minimization model is used as the best-fit model.

## 3. Asteroseismology analysis

In our models, in order to reduce the amount of calculations, we use a method of loop calculation to get a self-consistent magnetic parameters $a$ and $b$. We use the internal structure of the models without magnetic fields to constrain the initial fundamental parameters by comparing the ratios of small- to large- separations between the observed and theoretical ones. Using the initial fundamental parameters, we can get the values of $a$ and $b$. Using the determined values of $a$ and $b$, we calculate the stellar structure and evolution of the models with magnetic fields and get the $\chi^2$-minimization model. Through the iterative calculations, when the initial input fundamental parameters are the same with the ones of $\chi^2$-minimization model, the values of $a$ and $b$ are adopted as

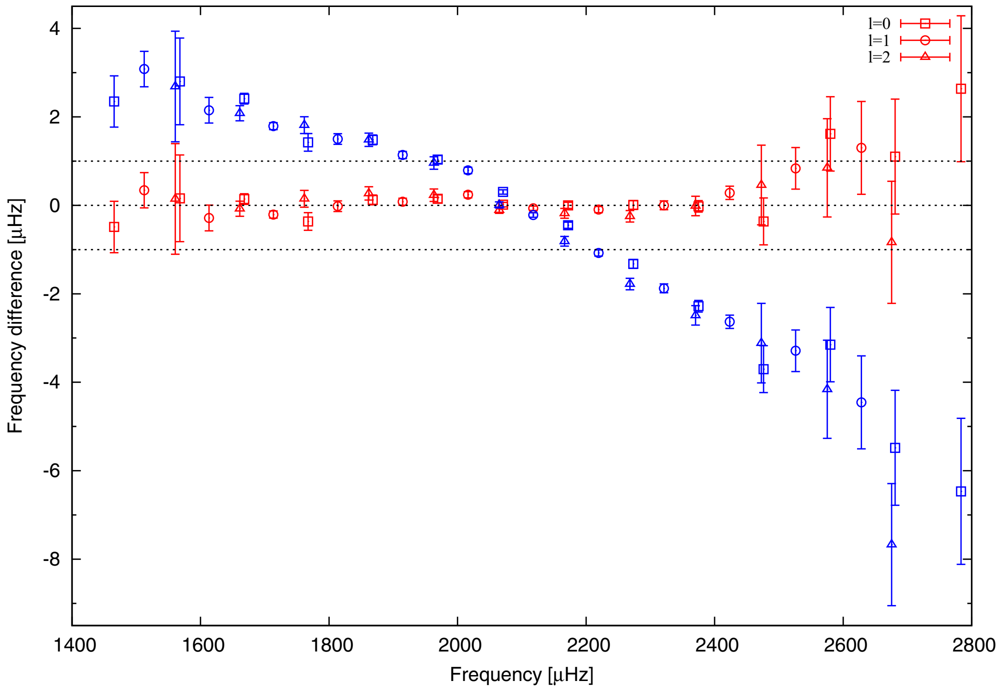


**Figure 1.** The frequency differences between observations and best-fit model with (open red points) and without magnetic fields (open blue points) for KIC 11295426. The horizontal dotted lines represent $y = 0, \pm 1\mu$Hz.

the optimal ones. For KIC 11295426, the optimal magnetic parameters $a$ and $b$ are 280 and 70, respectively, and the ones for KIC 10963065 are 480 and 54.

For KIC 11295426, the parameters of the best-fit model with magnetic fields and minimum $\chi^2$ are $M = 1.09M_\odot$, $Z_{\rm init} = 0.0255$, $\alpha_{\rm MLT} = 1.78$. The corresponding differences between the observed frequencies and the theoretical ones are shown in Fig. 1. The fundamental parameters of the best-fit model with magnetic fields for KIC 10963065 are $M = 1.095M_\odot$, $Z_{\rm init} = 0.015$, $\alpha_{\rm MLT} = 1.72$. The corresponding frequencies differences are shown in Fig. 2. From our results, we can find that except for a few higher frequencies, the most frequency differences of the best-fit models with magnetic fields for two solar-like stars are less than $1\mu$Hz. In other words, the most frequencies of the best-fit models with magnetic fields are all in agreement with the observed ones. The frequencies for the models without magnetic fields deviate systematically and significantly from the observation. This means that the small-scale magnetic fields in the photosphere can obviously reduce the systematical deviations between the observed frequencies and the theoretical ones.

In addition, according to the values of optimal magnetic parameters $a$ and $b$ for the two solar-like stars, using the relationship that gas pressure equals to magnetic pressure (Rosenthal et al. 2002; Cally 2007), we independently derive the strength of small-scale magnetic fields in the photosphere for KIC 11295426 and KIC 10963065. The magnetic strength for KIC 11295426 is about 89 G and the one for KIC 10963065 is about 127 G. Through the spectroscopy observations, KIC 11295426 is a relatively slower rotating star (Gilliland et al. 2013) than the sun, while KIC 10963065 is a faster rotating star with rotation period 12.5 days (Suto et al. 2019). Although the magnetic strength for KIC 11295426 is very close to the one of the sun (Li et al. 2021), the magnetic strength of the two solar-like stars are in agreement with the stellar period-activity relation.

https://doi.org/10.1017/S1743921323004994 Published online by Cambridge University Press

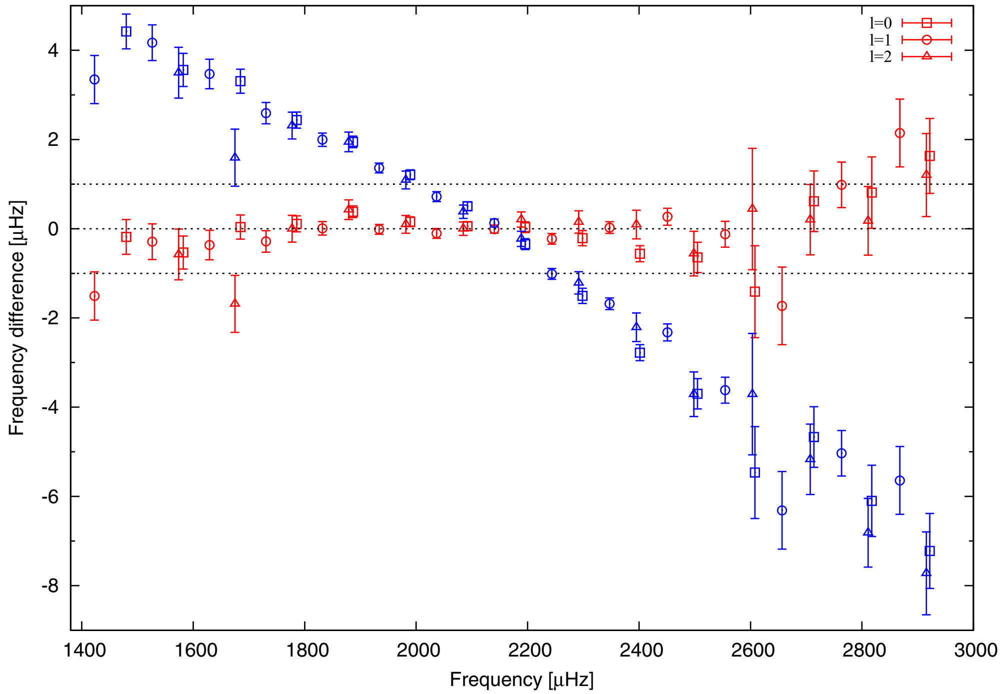


**Figure 2.** The frequency differences between observations and best-fit model with (open red points) and without magnetic fields (open blue points) for KIC 10963065.

## 4. Summary and discussion

Due to the convective shell for the solar-like stars, the stellar surface structure is very complex. This results in a systematic deviation between the observation frequencies and the theoretical ones. By considering the effects of small-scale magnetic fields in the photosphere on stellar oscillation frequencies, we calculate the asteroseismology for KIC 11295426 and KIC 10963065.

We consider magnetic pressure with two parameters $a$ and $b$ in the stellar Eddington gray-atmosphere model, and construct the asteroseismic models with magnetic fields. We derive the stellar fundamental parameters for the two solar-like stars KIC 11295426 and KIC 10963065. The results are consistent with other results from spectroscopic observations and the other theoretical models (e.g. Gilliland et al. 2013; Marcy et al. 2014; Silva Aguirre et al. 2015; Kayhan et al. 2019).

We find that magnetic fields in the photosphere obviously reduces the frequency deviations between observations and the best-fit model with minimum $\chi^2$. The small-scale magnetic fields in the photosphere only change the stellar surface structure. The improvement on the systematical offset between observation and the best-fit models is mainly due to the effect of magnetic field on the stellar surface physics. In addition, using the asteroseismology, we independently derive the magnetic strength for the two solar-like stars. Compared with the one of the sun, the magnetic strength for KIC 11295426 and KIC 10963065 are consistent with the stellar period-activity relation.

**Acknowledgement** This research is supported in part by the National Key R&D Program of China (Grant No. 2021YFA1600400/2021YFA1600402), by the B-type Strategic Priority Program No. XDB41000000 funded by the Chinese Academy of Sciences (CAS), by the National Natural Science Foundation of China (NSFC) under grants 12133011, 12288102 and 11833006, and supported by International Centre of Supernovae, Yunnan Key Laboratory (No. 202302AN360001).

https://doi.org/10.1017/S1743921323004994 Published online by Cambridge University Press

## References

Ball, W. H., Beeck, B., Cameron, R. H., & Gizon, L. 2016, *A&A*, 592, 159
Ball, W. H., & Gizon, L. 2014, *A&A*, 568, A123
Beck, P. G., Montalban, J., Kallinger, T., *et al.* 2012, *Nature*, 481, 55
Bellinger, E. P., Basu, S., Hekker, S., & Christensen–Dalsgaard, J. 2019, *ApJ*, 885, 143
Bogdan, T. J., Carlsson, M., Hansteen, V. H., *et al.* 2003, *ApJ*, 599, 626
Böhm-Vitense, E. 1958, *Z. Astrophys.*, 46, 108
Cally, P. S. 2007, *Astron. Nachr.*, 328, 286
Christensen–Dalsgaard, J. 2008, *Ap&SS*, 316, 113
Christensen–Dalsgaard, J., Däppen, W., & Lebreton, Y. 1988, *Nature*, 336, 634
Davies, G. R., Silva Aguirre, V., Bedding, T.R., *et al.* 2016, *MNRAS*, 456, 2183
Dziembowski, W. A., Paterno, L., & Ventura, R. 1988, *A&A*, 200, 213
Gilliland, R. L., Marcy, G. W., Rowe, J. F., *et al.* 2013, *ApJ*, 766, 40
Grevesse, N., & Sauval, A. J. 1998, *Space Sci. Rev.*, 85, 161
Houdek, G., Trampedach, R., Aarslev, M. J., & Christensen–Dalsgaard, J. 2017, *MNRAS*, 464, L124
Howell, S. B., Sobeck, C., Haas, M., *et al.* 2014, *PASP*, 126, 398
Iglesias, C. A., & Rogers, F. J. 1996, *ApJ*, 464, 943
Kayhan, C., Yıldız, M., & Celik Orhan, Z. 2019, *MNRAS*, 490, 1509
Kjeldsen, H., Bedding, T. R., & Christensen–Dalsgaard, J. 2008, *ApJL*, 683, L175
Koch, D. G., Borucki, W. J., Basri, G., *et al.* 2010, *ApJL*, 713, L79
Li, Y., Zhang, Q. S., Wu, T., *et al.* 2021, *ApJ*, 916, 107
Marcy, G.W., Isaacson, H., Howard, A.W., *et al.* 2014, *ApJS*, 210, 20
Paxton, B., Schwab, J., Bauer, E. B., *et al.* 2018, *ApJS*, 234, 34
Rosenthal, C. S., Bogdan, T. J., Carlsson, M., *et al.* 2002, *ApJ*, 564, 508
Schou, J., & Birch, A. C. 2020, *A&A*, 638, 51
Silva Aguirre, V., Davies, G. R., Basu, S., *et al.* 2015, *MNRAS*, 452, 2127
Soriano, M., & Vauclair, S. 2008, *A&A*, 488, 975
Suto, Y., Kamiaka, S., & Benomar, O. 2019, *AJ*, 157, 172