Stars and their variability observed from space
C. Neiner, W. W. Weiss, D. Baade, R. E. Griffin, C. C. Lovekin, A. F. J. Moffat (eds)

SHINE BRITE: SHEDDING LIGHT ON STELLAR VARIABILITY THROUGH ADVANCED MODELS

D. Fabbian[1], F. Kupka[2], D. Krüger[1,2,3], N. M. Kostogryz[2] and N. Piskunov[4]

Abstract. The correct interpretation of the large amount of complex data from next-generation (in particular, space-based) observational facilities requires a very strong theoretical underpinning. One can predict that, in the near future, the use of atmospheric models obtained with three-dimensional (3-D) radiation magneto-hydrodynamics (RMHD) codes, coupled with advanced radiative transfer treatment including non-local thermodynamic equilibrium (non-LTE) effects and polarisation, will become the norm. In particular, stellar brightness variability in cool stars (i.e., spectral types F– M) can be caused by several different effects besides pulsation. In this review we have briefly discussed some published results, and mentioned aspects of recent progress. It then attempted to peek into what the future may hold for understanding this important aspect of the lives of stars.

Keywords: Method: magnetohydrodynamics (MHD), radiative transfer, stars: variables: general

1 Introduction

Numerical radiation (magneto-)hydrodynamic simulations of stellar atmospheres provide a strong basis for a multitude of studies of different aspects of (in particular) cool stars. One of the topics of great interest is understanding why many – if not all – of them undergo some amount of variation in their brightness with time. Owing to its proximity, one particularly well-studied case is that of the Sun. However, because its periodic brightness variation is small (about 0.1%) and has a relatively long period of 11 years, it was discovered only relatively recently compared to the variations observed in other stars (intrinsic variables such as pulsating, eruptive or cataclysmic/explosive stars, or extrinsic variables such as eclipsing or rotating stars), which in some cases have been known for many centuries.

In this contribution we have provided a very brief discussion of some recent results of interest, and some conclusions.

2 Discussion

"Box in a star" numerical simulations of stellar atmospheres, based on solving the (numerical) radiation (magneto-)hydrodynamics equations, aim at reproducing and understanding features of (magneto-)convection as observed by ground- and space-based instruments.

These type of simulations are well-tested, and are capable of reproducing observations such as solar granulation and stellar spectral lines. Moreover, they are useful for gaining physical insight into convective heat transport and the interaction of convection with pulsation modes.

***Figure 1 shows the temperature for a snapshot from the ~ 21 solar h of statistically-stable evolution of a solar-like simulation of ~ 3.7 Mm vertical extent and of 6.0 Mm extent in each horizontal direction.

Improvements in the treatment of radiative transfer and in the starting input for the modelling have recently been implemented in the code, plus the possibility of using, where appropriate, the (non-grey, 3-D) Eddington approximation for faster calculations (see, e.g., Krüger et al. (2019); Kupka (2018); Kostogryz et al. (2019)).

The ANTARES code has recently been applied successfully by our group to perform long-duration 3-D simulations of solar and stellar convection, for studying p-mode excitation and damping processes. The spectral

[1] Georg-August-Universität Göttingen, Institut für Astrophysik, Friedrich-Hund-Platz 1, D-37077 Göttingen, Germany
[2] MPI für Sonnensystemforschung, Justus-von-Liebig-Weg 3, D-37077 Göttingen, Germany
[3] Universität Wien, Fakultät für Mathematik, Oskar-Morgenstern-Platz 1, A-1090 Wien, Austria
[4] Uppsala University, Department of Physics and Astronomy, Regementsvägen 1, SE-752 37 Uppsala, Sweden

© Stars from Space

power of vertical velocity in the solar granulation simulation performed with this code shows eigenmode frequencies with the correct shape. Scaling has to be carried out to account for the limited size and depth coverage of the simulated model (i.e., for the relative shallowness of the "box in a star" geometry compared to the whole star).

Apart from the necessary scaling, it is important (as presented by F. Kupka, [PAGE]) that the 3-D hydrodynamical simulations have sufficient spatial and temporal resolution, spatial vertical and horizontal extent and time duration, for successful application to asteroseismology studies such as excitation and damping of solar-like p-modes. In particular (as is the case for our simulations) they must be able to describe well the properties of the superadiabatic layer, one of the crucial aspects for matching observed p-mode characteristics (*viz.*,frequency, amplitude and line shapes) in the power spectra of solar-like oscillating stars. It will of course be interesting to see MHD models applied for this purpose in the future for understanding the influence of magnetism on stellar atmospheric plasma, as discussed briefly below.

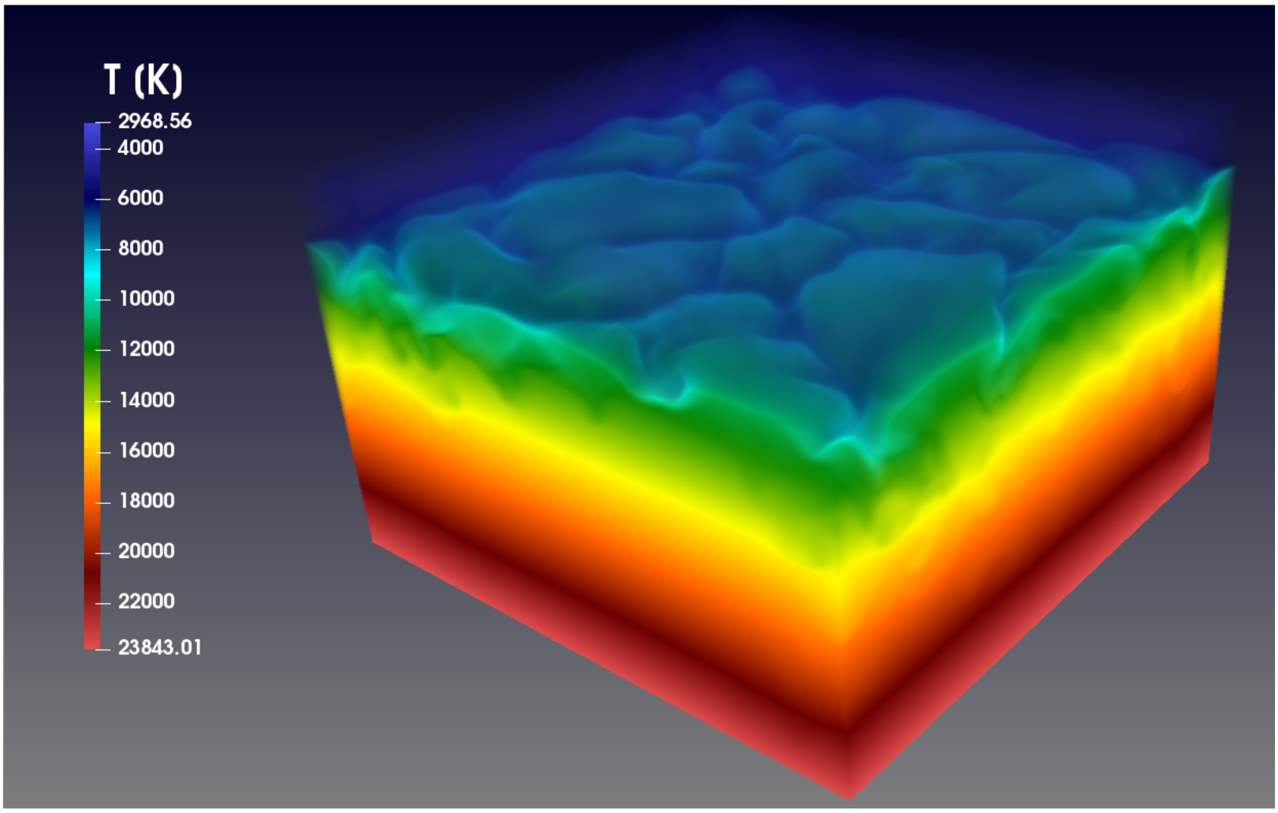

Fig. 1. Temperature (in K units) for a snapshot of the solar-like simulation "SLOPMD1" performed with the code ANTARES and visualised using ParaView (`https://www.paraview.org/`). This is the snapshot used as input to obtain the synthetic spectrum shown in Fig. 3.

Brightness variations observed in the light curve of different stars can, however, at least in part, be caused by processes other than solar-like oscillations (i.e., those excited by convective motions).

Granulation is the clearest visual manifestation of the process of convection at the surface of stars. Owing to the stochastic nature of convection, the granulation pattern produces micro-variations of the emerging radiation with time. Once p-mode oscillations (manifested as discrete peaks) are removed from the solar power spectrum, for example, it is mostly this granulation signal (the so-called "granulation background") which is left.

One sub-category of cool stars is particularly interesting, namely, stars on the main sequence and broadly similar to the Sun (spectral types F–K), so-called solar-type stars. The variability of their magnetic activity has recently been reviewed e.g. in Fabbian et al. (2017).

For the Sun, observations show a steeply-decreasing granular signal power at high frequencies ($\sim 1-8$ mHz), while the roughly constant power around ~ 0.2 mHz is followed by a rise with decreasing frequencies below ~ 0.1 mHz, caused by solar magnetic activity. Using the CO^5BOLD code, Ludwig et al. (2009) showed that atmospheric models from 3-D radiation hydrodynamic (RHD) simulations, while able to reproduce the power spectrum of granulation-related brightness fluctuations at intermediate and high frequencies reasonably well, contain (as to be expected, being representative of the pure non-magnetic case) less power at low frequencies than in the observational data. They found a puzzling discrepancy with the observed granulation background for F-type dwarfs, in that it was only after scaling the power and frequency of their predicted granulation-related brightness fluctuations to account (e.g.) for possible uncertainties in stellar parameter determinations, and after adding an *ad hoc* power-law magnetic activity signal, that the mismatch could be resolved – at least to a significant extent. The authors then performed 2-D RMHD solar simulations, assuming different levels of initial magnetic field strength. They found that observations have a low level of granulation-related brightness fluctuations around 1 mHz compared to their 2-D RMHD predictions. By virtue of the very similar topology of granular flows among solar-type stars, they made the hypothesis that the rise at low frequency in the temporal power spectrum of F-type dwarfs may be an indication of some type of magnetic activity in those stars too, analogous to what was hinted in the case of observational data for the Sun. However, their 2-D results – see their derived temporal power spectra of resulting emergent intensity in Fig. 2 – exclude local dynamo action in the granular flow as the source of magnetism producing the mismatch between predictions and observations. That leaves the existence of a ubiquitous, larger-scale magnetic field of several hundred G (though not yet detected by observations) as the only plausible cause able to affect the dynamics of granulation to an extent of the order needed to reduce the predicted brightness fluctuations to the observed low level.

It remains to be seen if switching to RMHD simulations in 3-D, for solar-type stars that have very precise stellar parameter determinations, can clarify the appearance of the brightness fluctuations power spectra for solar-type stars other than the Sun, or whether observations will confirm the presence of a strong magnetic field organised on a larger scale, or whether other explanations may be required.

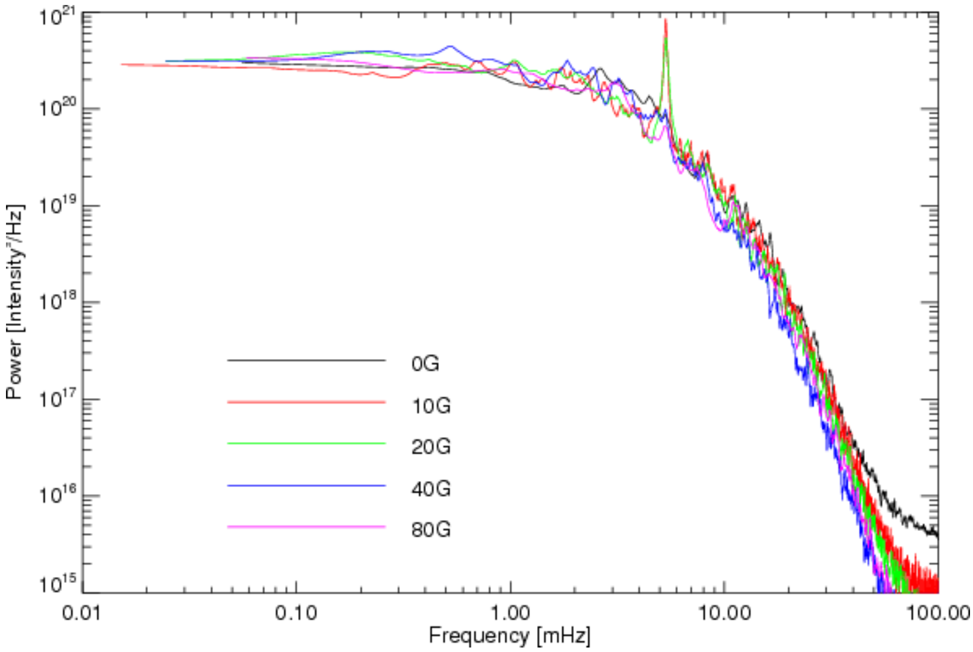

Fig. 2. Temporal power spectra of the horizontally-averaged vertically-emergent intensity of different MHD runs (solid curves in different colours) with solar atmospheric parameters (image adapted from Fig. 5 of Ludwig et al. (2009)).

Tools for calculating the synthetic spectrum on the basis of the multi-dimensional stellar photosphere simulations enable one to compare with, and check against, observations. Figure 3 gives an example of a synthetic spectrum computed on the basis of a solar granulation model, from an ANTARES radiation hydrodynamic photospheric simulation having "Model S" Christensen-Dalsgaard et al. (1996) as its starting input model and then relaxed as described by Kupka & Muthsam (2017).

Fabbian et al. (2010, 2012); Fabbian & Moreno-Insertis (2015) showed that the presence of magnetic fields can have a significant effect on the formation of Fe and O spectral lines in 3-D MHD solar simulations, affecting their profiles and intensities and thence the photospheric chemical abundances inferred from a fit to the observations.

Some spectral lines are particular sensitive to the level of solar and stellar activity (see, e. g., Vitas et al. (2009)).

Concerning the Sun, very recently Criscuoli et al. (2019) performed a thorough study comparing the results of different commonly-employed radiative transfer codes. They showed the importance of being aware of the

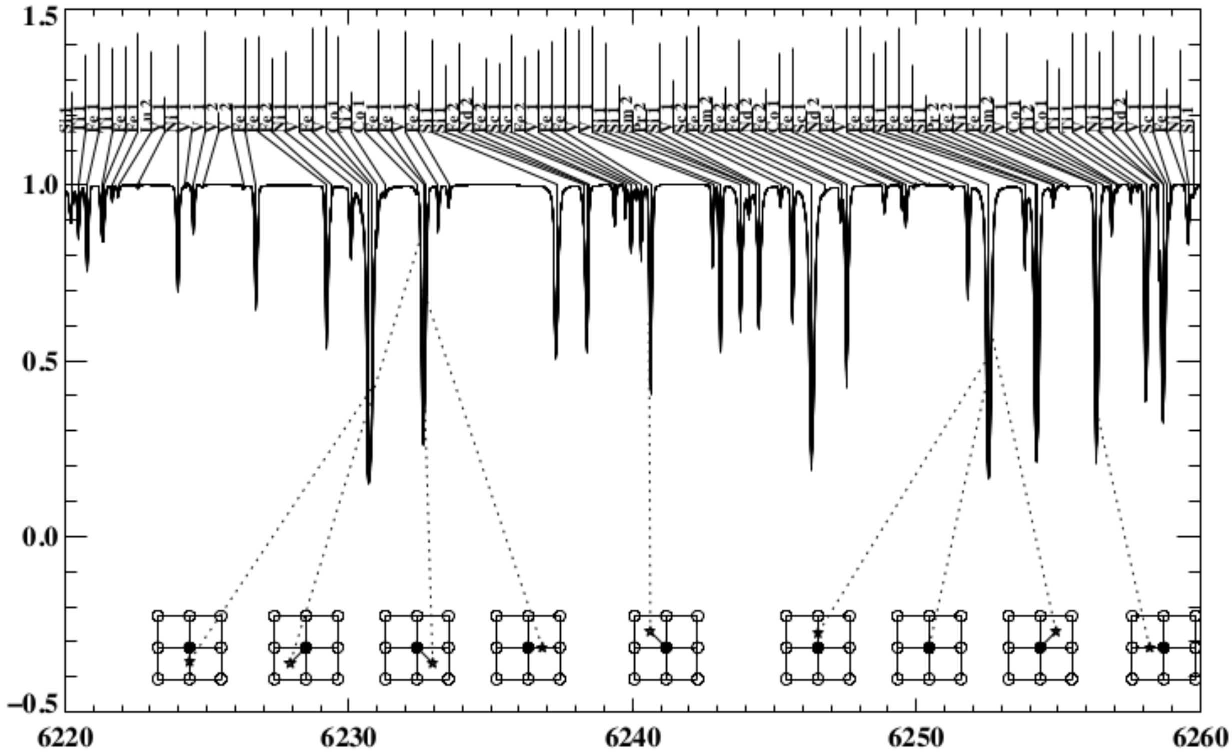

Fig. 3. Disk-centre intensity for the synthetic spectrum obtained for the region $\lambda\,6220$–$6260\,\text{Å}$, based on a 3-D RHD solar simulation performed with the ANTARES code. The calculation used as input the snapshot shown in Fig. 1.

relevant techniques, approximations and uncertainties involved, for explaining the subtle differences they found between the synthetic quiet-Sun spectra in order to reproduce well the solar irradiance measurements and to understand which features contribute the most to solar variability.

An effort on the part of theoretical and experimental physicists to achieve more accurate atomic and molecular data is of particular help. Databases listing their most recent data and compilations, e.g. VALD3 (the current version of the VALD online database, as described in Pakhomov et al. (2017)) are of great help for improving atmospheric and spectral synthesis modelling, and should be strongly supported by the stellar astrophysical community.

3 Conclusions

In this review we have discussed briefly some issues related to understanding stellar brightness variability. Cool stars show variability with periods ranging from very short to very long time-scales, with variations of different types often overlapping so the physical causes of their different variations are not easy to disentangle. One main point is that 3-D RMHD stellar atmospheric models, being based on first-principles and updated micro- and macro-physics and being able to withstand demanding tests against observations, are sufficiently well-developed nowadays to be employed in this field as the required input.

That naturally suggests that the application of advanced stellar atmospheric simulations, including the ever-more-complete treatment of relevant physical processes, is one of the main avenues for understanding better this aspect of the lives of stars, and that it will become more widespread and common practice to replace outdated and over-simplified modelling restricted to the limitations of one-dimensional, plane-parallel, static, gray atmospheres that neglect scattering and magnetic fields.

DF, FK, and DK gratefully acknowledge support by the Austrian Science Fund (FWF) through project P29172-N27, and they also thank the Vienna Scientific Cluster VSC-3 (project 70950) and the Faculty of Mathematics at the University of Vienna for granting computing resources. FK acknowledges partial support through the European Research Council Synergy Grant WHOLE SUN #810218. NMK is supported by the German space agency (Deutsches Zentrum für Luft- und Raumfahrt) under PLATO Data Center grant 50OO1501.

References

Christensen-Dalsgaard, J., Dappen, W., Ajukov, S. V., et al. 1996, Science, 272, 1286

Criscuoli, S., Rempel, M., Haberreiter, M., et al. 2019, Sol. Phys., *accepted*

Fabbian, D., Khomenko, E., Moreno-Insertis, F., & Nordlund, Å. 2010, ApJ, 724, 1536

Fabbian, D. & Moreno-Insertis, F. 2015, ApJ, 802, 96

Fabbian, D., Moreno-Insertis, F., Khomenko, E., & Nordlund, Å. 2012, A&A, 548, A35

Fabbian, D., Simoniello, R., Collet, R., et al. 2017, AN, 338, 753

Kostogryz, N. M., Kupka, F., Piskunov, N., et al. 2019, Sol. Phys., *in prep.*

Krüger, D., Kostogryz, N., Fabbian, D., & Kupka, F. 2019, in Journal of Physics Conference Series, Vol. 1225, Journal of Physics Conference Series, 012017

Kupka, F. 2018, in Astronomy in Focus, IAU Focus Meeting FM9, XXXth IAU GA, Vienna (Austria), ed. G. Kopp & A. Shapiro, Vol. 1, *in press*

Kupka, F. & Muthsam, H. J. 2017, Living Reviews in Computational Astrophysics, 3, 1

Ludwig, H. G., Samadi, R., Steffen, M., et al. 2009, A&A, 506, 167

Pakhomov, Y., Piskunov, N., & Ryabchikova, T. 2017, ASPCS, Vol. 510, VALD3: Current Developments (San Francisco: ASP), 518

Vitas, N., Viticchiè, B., Rutten, R. J., & Vögler, A. 2009, A&A, 499, 301