

# Stellar differential rotation in theory and observation

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Stellar differential rotation is intimately related to the stellar magnetic dynamo and, thus, to stellar activity. In recent years, significant progress in the measurement of differential rotation on the basis of Doppler imaging techniques and the availability of space-based long-term photometry has been achieved. Similarly, simulations incorporate ever more details of the complexity of convective zones. While some aspects of solar and stellar differential rotation can be explained now, several important questions remain open or controversial. In this splinter session, we discussed the latest observational and theoretical progress in the field of differential rotation.

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## 1 Introduction

The discovery of solar differential rotation is now nearly 400 years old. In the year 1630, it was Christoph Scheiner—a Jesuit priest and scientist—who noticed that sunspots in equatorial vicinity cross the disk faster than those closer to the poles. In 1860, R. C. Carrington carried out intensive sunspot observations and, for the first time, quantified the effect of solar differential rotation (Carrington 1860). Hundreds of studies have followed his pioneering work, and differential rotation has ceased to be a privilege of our Sun. Indeed, it is believed that many—or maybe all—cool stars show it at some level.

While the technique of Doppler Imaging has allowed to measure differential rotation in an increasing number of individual stars (Strassmeier 2009), the *Kepler* and CoRoT space missions have opened a completely new window to explore differential rotation in thousands of stars using both asteroseismology and starspot-induced variability (e.g., Lanza et al. 2011, Frasca et al. 2011).

Differential rotation is intimately related to the stellar magnetic dynamo. Therefore, observations of differential rotation are essential in constraining theoretical dynamo models and understanding the generation and evolution of magnetic fields, which, in turn, are the driving force of stellar activity. As such, the magnetic field is responsible for starspots, chromospheric heating, stellar flares, and X-ray emission—to name but a few. It is now believed that stellar activity influences planetary evolution and habitability (e.g., Lammer et al. 2007), which once more emphasizes the importance of understanding the dynamo.

Although differential rotation has long been known to exist, many of its aspects like its strength, sense, and temporal variability have remained controversial until today (Wöhl et al. 2010). With the new era of space-based photometry just begun and significant progress having been made in the modeling of convection, our splinter session entitled “Differential rotation in theory and observation” has been set up to review and discuss the latest development in the field.

## 2 Measurements of differential rotation

Using the full arsenal of available measurement techniques, including sunspot tracking, Doppler measurements, and p-mode splitting, a complex rotation pattern has been discovered on the solar surface and in its interior. Solar rotation does not even appear to be constant but varies in time. Such complexity can be observed on the Sun due to its proximity. One of our splinter’s goals was to review the current status of differential rotation measurements on other stars.

*Manuel Flores Soriano* (MFS) presented an analysis of “Surface velocity fields on LQ Hya from Doppler imaging”. His analysis is based on about 200 spectra distributed over four months of time. As pointed out by MFS, estimates of differential rotation derived from series of Doppler images remain controversial. In his approach, MFS seeks to derive the strength of differential rotation by spot-center tracking. With this technique—so he concluded—lap-time estimates are in good agreement with theoretical predictions; in particular, MFS juxtaposed his estimate of 140 d with a model prediction of 120–140 d provided by Manfred Küker (see Sect. 3). During the subsequent discussion, MFS explained

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that the main source of uncertainty in his method is the determination of the spot latitude, which remains a common problem in all surface reconstructions.

More measurements of differential rotation, this time based on Zeeman-Doppler-imaging, were presented by *Steven Marsden (SM)*, who reported on the latest outcomes of differential rotation measurements in young, solar-type stars. In his presentation, SM addressed, among others, the questions whether the level of differential rotation is temporally variable and whether it may be related to the length of the magnetic cycle. Differential rotation on cool, young stars is believed to be temporally variable as has, e.g., been shown for the young, ultra-fast rotator AB Dor (Donati, Collier Cameron & Petit 2003). It is speculated that a conversion from kinetic into rotational energy—and vice versa—may be responsible for the observed variability. As pointed out also by SM, magnetic structures as evidenced by Zeeman-Doppler-imaging tend to indicate stronger differential rotation than starspots, which is a likely consequence of different anchoring heights in the stellar atmosphere.

SM reported on a Zeeman-Doppler-imaging survey of six young solar analogs, in which magnetic cycles and differential rotation were searched for. Among the surveyed sources, only one star with a magnetic cycle could be detected. The results presented by SM do not support a direct relation between a high level of differential rotation and a short magnetic cycle. Nonetheless, they show that young stars of late F and G spectral type can show strong levels of differential rotation; in particular, up to ten times the solar value has been measured.

SM noted that differential rotation measurements in IM Peg show a large scatter, which may indicate intrinsic variability, albeit, without a clear trend (cf., Marsden et al. 2007). Therefore, SM cautioned that at least part of the scatter may be explained by yet unaccounted for systematic effects. Along these lines, the subsequent discussion concentrated on the error analysis in differential rotation measurements using Doppler imaging techniques. One questioner asked whether differential rotation could be determined from the light curve alone—an allusion to the new possibilities of spaced-based photometry. While this question remained unanswered at this point, it could be handed right away to the next speaker *Timo Reinhold (TR)*, who works on differential rotation in *Kepler* data.

Similar to R.C. Carrington almost 150 years ago, Starspot modulation can be used to infer differential rotation on the stellar surface (Strassmeier & Bopp 1992, Huber et al. 2010, Ohla et al. 2012, Lanza et al. 1994). This approach is followed by TR, who addressed the question: “Can we find differential rotation in all *Kepler* stars?”. In contrast to Carrington’s early work, TR cannot revert to measurements of the spot location, but has to rely on the light curve alone—however good this might be, his problem remains intricate.

TR presented a detectability study for differential rotation in *Kepler* light curves. His approach is the following:

first, he simulates a spotted stellar surface, second, derives the corresponding light curve, and, finally, tries to recover the input parameters. As of now, his algorithms reliably recover the input rotation period. The second period, which indicates differential rotation, is obtained in 42% of the cases. The subsequent discussion concentrated on whether the limitation of his simulations, in particular, the used spot-size limit, the limited number of spots, and the neglect of spot evolution, will have an effect on resulting determination of differential rotation. TR pointed out that among the most striking light curves observed in the *Kepler* data are those showing a “CoRoT-2A-like beating pattern”. Such photometric behavior is even, as TR noted in response to an audience question, a common feature among the *Kepler* light curves.

An alternative technique to measure differential rotation in light curves is asteroseismology, i.e., the analysis of the stellar pulsation modes. Helioseismology has been immensely successful in exploring the inner structure of the Sun (e.g., Thompson et al. 2003). However, an intensity amplitude of no more than a few times  $10^{-6}$  associated with solar-like oscillations has long been preventing the use of seismology in the study of other stars. With *Kepler*, this now becomes possible. *Rafael Garcia (RG)* presented “Asteroseismic prospects for measuring differential rotation” and latest results. Solar oscillations show typical periods of a few minutes, and the majority of the observed modes are associated with standing p-modes. One of the most important aspects of solar oscillations presented by RG is the so-called “frequency splitting”,  $\delta_{nlm} = \omega_{nlm} - \omega_{nl0}$ , which can be used to infer the internal rotation profile of the stars. As different modes penetrate and, thus, probe different parts of the stellar sphere, nearly the entire rotation profile can be recovered from asteroseismic observations (e.g., Schou, Christensen-Dalsgaard & Thompson 1994).

Exploring the core using asteroseismology remains challenging, because the core has a comparatively small effect on the resulting solar-like oscillation spectrum (Thompson et al. 2003). Nonetheless, RG reported on their recent measurement of red-giant core rotation using mixed modes. These modes behave like acoustic waves in the convection region and gravity waves in the core and occur in evolved stars, so that Beck et al. (2012) could use them to detect an “increasing rotation rate from the surface of the star to the stellar core”.

Furthermore, RG reported on a study of a sample of 190 stars observed by *Kepler* in short cadence, i.e., with a temporal resolution of 1 min. The sample selection was tuned to minimize the effects of stellar activity. Based on their analysis, RG is confident that differential rotation both in radial and surface direction can be inferred from asteroseismic measurements in their sample stars. The audience was keen to get to know whether RG and collaborators can find a relation between radial and surface differential rotation or a relation between red giant differential rotation and that of cool main-sequence stars. While the answer was not given

this time, RG held out the prospect of an answer at Cool Stars 18.

### 3 The theory of differential rotation

The first to present theoretical aspects of differential rotation, was *Manfred Küker* (MK). He set the stage by noting that while the strength of differential rotation is independent of the rotation rate,  $\Omega$ , it does depend on the temperature with  $\delta\Omega = \Omega_{eq} - \Omega_{pole} \sim T^{8.6}$  (see Barnes et al. 2005). Any valid theory of differential rotation has to explain this fact. MK proceeded by introducing model calculations based on the mean-field theory of hydrodynamics. In this approach, small-scale plasma motions are treated by an average, ensuing more tractable computations. Small-scale motions are, however, not entirely eliminated in this picture, but occur in the form of a correlation tensor, which represents the Reynolds stresses. A sketch of the theory may, e.g., be found in Küker & Rüdiger (2008). MK emphasized that, due to stratification and Coriolis forces, his models always produce differential rotation.

MK compared his model predictions to the observed properties of the Sun and concluded that the solar rotation profile is well reproduced including the meridional flow. No model tuning is needed to achieve this agreement. The model predictions do not only match measurements of the Sun, but MK also presented a sample of three other stars for which good agreement between measurement and model prediction has been achieved, namely, CoRoT-2A, V889 Her, and LQ Hya (see MFS's talk, Sect. 2).

In the mean-field model, the sources of differential rotation are the Reynolds stresses and the baroclinic flows, i.e., convection under the influence of Coriolis forces. Besides the prediction of a weak dependence of differential rotation on rotation-rate and a strong correlation with temperature, the model makes a solid statement concerning the sense of differential rotation: it rules out antisolar differential rotation. However, Kitchatinov & Rüdiger (2004) note that the models can produce antisolar differential rotation, if large-scale thermal inhomogeneities or tidal forcing in a binary system are present.

After the talk, a member of the audience pointed out that the number of stars without a detection of differential rotation outnumbers that of detections by a large margin. In reply, Steven Marsden noted that their Doppler images virtually always show differential rotation. Whether or not this fact may be suspicious, as noted by another member of the audience, the fraction of stars showing differential rotation remains an unresolved issue.

Following the discussion, *Allan Sacha Brun* (ASB) continued by presenting model calculations based on the direct three-dimensional simulation of convection using the Anelastic Spherical Harmonic (ASH) code. The models, indeed, reproduce differential rotation with a strong dependence on the temperature at the tachocline.

The models presented by ASB incorporate magnetic fields and show that the level of differential rotation depends on the magnetic field strength. In particular, the presence of a magnetic field hampers differential rotation. Therefore, ASB pointed out that active stars with strong magnetic fields are expected to show weaker differential rotation than inactive stars. In the later discussion the question turned up how this model prediction compares with the observation of young, highly active stars, which do show differential rotation. It was, however, noted that the opposite is observed as well. The origin of such differences, whether they may, e.g., be related to the presence of disks, still needs observational clarification.

In contrast to the mean-field approach presented by MK, the simulations presented by ASB do produce antisolar differential rotation depending on the position in the parameter space.

*Matthew Browning* (MB) elaborated on "Simulations of differential rotation on very low mass stars and its quenching by magnetic fields". Stars with a spectral type later than about M3 become fully convective and, therefore, lack a tachocline, which is an important ingredient in the dynamo models of more massive stars. In spite of the absence of a tachocline, a major fraction of low-mass M-stars shows a high level of activity.

Right at the beginning, MB made a clear statement by formulating three key outcomes of his research: (1) Differential rotation can exist on low-mass stars, (2) its sense depends on various parameters including the rotation rate, and (3) the magnetic field has a crucial effect on differential rotation.

In his simulations, MB finds differential rotation both with solar and antisolar sense. The basic pattern emerging from the simulations is that convection strongly influenced by rotation through the Coriolis force, i.e., a low Rossby number, gives rise to solar differential rotation, while a weak rotational influence leads to antisolar differential rotation (e.g., Browning 2011). An observational verification of this prediction remains challenging, because differential rotation would have to be measured on faint, slowly rotating stars. As noted above, MB finds a strong dependence of differential rotation on the magnetic field, which may even completely quench differential rotation (e.g., Browning 2008). While the dependence of differential rotation on effective temperature in his models has not yet been studied, this point is on his agenda.

*Kyle Augustson* (KA) presented his ASH simulations carried out to analyze "Magnetconvection and differential rotation in F-type stars" (Augustson et al. 2012). KA studied the dependence of differential rotation and magnetic fields in the interior of F-type stars as a function of the rotation rate.

In their models, KA and collaborators, indeed, reproduce large latitudinal variations in angular velocity and temperature. An increased rotation rate ensures stronger differential rotation and is accompanied by a latitudinal tempera-

ture gradient in the deep convection zone. In turn, the meridional circulation is weakened. Moreover, large-scale magnetic structures—dubbed wreaths—where detected, whose likely origin is the  $\Omega$  effect.

Clearly, stellar rotation rates evolve in time and so does differential rotation. Latest progress on this subject was presented by *Jerome Bouvier* (JB), who covered the long-term angular momentum evolution in his presentation “Angular momentum evolution models and their predictions regarding tachocline differential rotation in solar type stars”.

The major processes governing the angular momentum evolution of solar like stars are: star-disk interaction, wind breaking, and core-envelope decoupling. Star-disk interaction dominates the angular momentum transfer primarily before the zero age main-sequence, after which wind breaking takes over to slow down the stars (Bouvier 2008).

A major unknown in the equations remains the angular momentum transfer between the radiative core and the convective envelope parametrized by the core-envelope decoupling timescale. JB presented his finding that the core-envelope decoupling timescale needs to depend on the actual stellar rotation rate to explain the observations: Slow rotators show a high degree of differential rotation between core and envelope, while the opposite is true for fast rotators, in which core-envelope decoupling is a minor issue (Bouvier 2008). The physics behind the internal angular momentum transport still remains unclear.

Finally, *Olivier Do Cao* (ODC) presented a theoretical study of temporal variability and cyclic behavior of differential rotation in his talk entitled “Cycle modulations and torsional oscillations in dynamo models of solar-like stars”. The Sun shows a prominent 11-year sunspot cycle, which is associated with an underlying 22-year magnetic cycle. Doppler measurements have uncovered latitudinal bands of alternating rotation speed on the Sun, so-called torsional oscillations, whose structure also varies with the magnetic cycle.

ODC and collaborators use the STELEM code, to study magnetic cycles in solar-like stars. Observationally, it has been established that the period of these cycles in solar like stars increases with decreasing rotation rate. In a recent study (Do Cao & Brun 2011), ODC and collaborators had already demonstrated that this dependence cannot be reproduced given unicellular meridional circulation. The observations can, however, be reproduced by considering “turbulent pumping”, i.e., magnetic field transport, which does not result from bulk plasma motion, but from radially asymmetric convection. The simulations require that the efficiency of pumping scales quadratically with the stellar rotation rate to reproduce the observations.

In their new simulations, the amount of physics included has been extended to get a more complete and realistic picture of cycles. In particular, nonlinear effects such as the Malkus-Proctor term have been included. The simulations presented by ODC reproduce the solar butterfly diagram and are now capable of producing magnetic cycles.

## 4 Conclusion

In our splinter session, the latest developments in the analysis of differential rotation have been approached both from an observational and a theoretical point of view. While the presented successes give evidence of the swift progress, several important questions remain controversial:

- How ubiquitous is differential rotation? Which stars show differential rotation at what level?
- Is differential rotation temporally variable? If yes, what are the timescales and amplitudes?
- Is antisolar differential rotation realized. If yes, where is its rotational regime?
- How strongly do magnetic fields quench differential rotation?

We would like to thank all speakers, questioners, and listeners for an inspiring and successful splinter session.

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