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Studying solar rotation models with the Toulouse-Geneva evolution code

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Abstract. The rotation evolution of solar-type stars is one of the hottest topics in today's discussions in the realm of stellar astrophysics. Since the photometric and seismic analysis of Kepler targets came out, some issues have appeared regarding the reliability of the widespread age estimation technique known as gyrochronology, especially related to stars older than the Sun. In this work, we initially analyzed the rotation evolution of three different stellar samples. Each one of the samples has ages calculated using a different approach. Moreover, we also included a Maunder minimum candidates sample to look for evidence of modifications in the braking law (Skumanich law) due to changes in the stellar dynamo. We compute the rotation evolution of the Sun using the Toulouse-Geneva evolution code (TGEC) with two different magnetic breaking implementations, both following the Skumanich law on the main sequence. We verified that the sample with ages determined by gyrochronology fits well our models since both gyrochronology and magnetic braking equations follow the Skumanich law. Therefore, this is a control sample. However, the other samples impose challenges to our models, requiring further investigation. We highlight the sample with seismological ages, which seems to deflect from the standard solar rotation evolution model after the age of the Sun. However, questions about the spectroscopic constraints of this sample should be raised.

Resumo. A evolução da rotação de estrelas do tipo solar é um dos tópicos mais quentes nas discussões atuais no campo da astrofísica estelar. Desde que as análises fotométricas e sísmicas dos alvos do Kepler foram realizadas, algumas questões surgiram em relação à confiabilidade da técnica de estimativa de idades conhecida como girocronologia, especialmente no tocante a estrelas mais velhas que o Sol. Neste trabalho, inicialmente analisamos a evolução da rotação de três amostras estelares diferentes. Cada uma delas tem idades calculadas usando uma abordagem diferente. Além disso, também incluímos uma amostra com candidatos ao Mínimo de Maunder para procurar evidências de modificações na lei de frenagem (lei de Skumanich) devido a mudanças no dínamo estelar. Calculamos a evolução da rotação do Sol usando o código de evolução estelar de Toulouse-Genebra (TGEC) com duas implementações diferentes de freio magnético, ambas seguindo a lei de Skumanich na sequência principal. Verificamos que a amostra com idades determinadas pela girocronologia se ajusta bem aos nossos modelos, uma vez que tanto a girocronologia quanto as equações de freio magnético seguem a lei de Skumanich. Portanto, essa é uma amostra de controle. No entanto, as outras amostras impõem desafios aos nossos modelos, exigindo uma investigação mais aprofundada. Destacamos a amostra com idades sismológicas, que parece se desviar do modelo de evolução padrão da rotação solar após a idade do sol. No entanto, devem ser levantadas questões se as restrições dos parâmetros espectroscópicos dessa amostra são adequados.

Keywords. Stars: interiors – Stars: rotation – Stars: magnetic field – Stars: solar-type – Sun: rotation

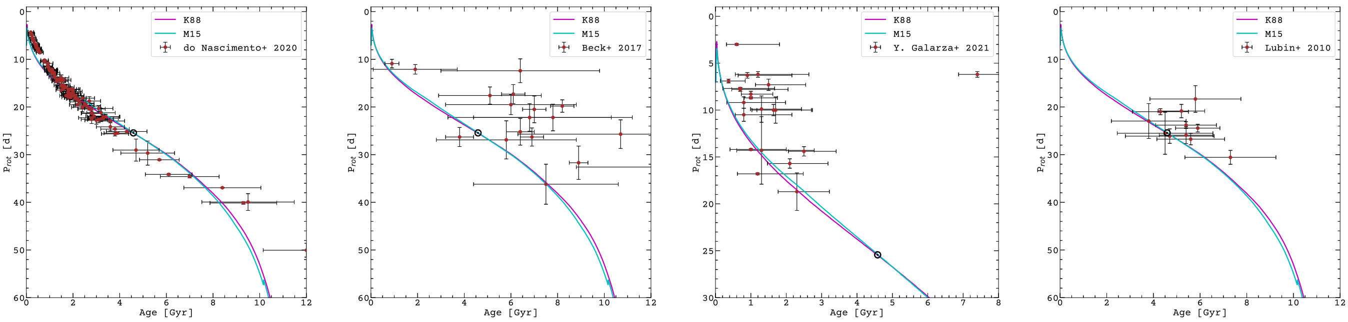
1. Introduction

We may be living in an era of drastic modification in the way we understand stars and their inner workings. A good portion of this revolution is due to the immense amount of data acquired by the CoRoT mission (Baglin et al. 2006) (ESA), and the subsequent Kepler (Borucki 2010) and K2 (Howell 2014) missions (NASA), not to mention the ongoing TESS mission (NASA) (Ricker et al. 2015). The recent findings from the analysis of the high precision, high cadence, light curves observed by the NASA's satellites revealed some unexpected features of the evolution of stars, especially related to their rotation evolution. Some of the conclusion extracted from the photometric data analysis have put under serious stress our present theoretical understandings of how stars behave and evolve, and the problem of how rotation and magnetism are intertwined in the stellar interiors is becoming more and more complicated as new data come out.

In short, the problem we are currently addressing began with a mismatch between the data of young clusters and old field Kepler stars plotted together in a P_{rot} Vs Age diagram. Angus et al. (2015) was incapable of deriving a single gyrochronological relationship when including the Kepler data for old field stars, with seismic ages, together with the already known data from young open clusters. In the following year, van Saders et al. (2016) went a step further and proposed a radical shift in the stellar rotation evolution after the age of the Sun, which, in principal, would explain the anomalous old field Kepler stars, but would seriously compromise the validity of the Skumanich law (Skumanich 1972) and the age estimating technique known as gyrochronology (Barnes 2007). Since this issue continue to be an unresolved problem, we decided to investigate the rotation evolution of different samples of solar analogues and twins using the rotation models of the Toulouse-Geneva Evolution Code (TGEC).

2. Working samples

Aiming at studying how different samples of solar analogues and twins would behave in comparison to our solar rotation evolution tracks, we first selected three samples from the literature that use three different methods of estimating stellar ages. The first one is the sample of a solar analogues by do Nascimento et al. (2020), which is a cross-matched sample between Kepler and Gaia data. It uses gyrochronology as the age estimation method and periods derived from the Kepler light curves. The second sample comes from the work of Beck et al. (2017), which uses ages derived from seismological data and rotation periods also derived from the analysis of Kepler light curves. The third sample we studied is presented in the work of Yana Galarza et al. (2021). The ages are derived using two methods. The first one uses isochrones, together with spectroscopic and photometric data from the targets,



(a) do Nascimento et al. (2020) sample.

(b) Beck et al. (2017) sample.

(c) Yana Galarza et al. (2021) sample.

(d) MM candidates sample (Lubin et al. 2010).

Figure 1: The rotation data points for all samples plotted against the TGEC solar rotation evolution tracks.

while the second method involves Bayesian inference. We chose to use the former in this work (Figure 1- c). The targets were observed by TESS or Kepler (besides the observation from the Gaia satellite), which means that the rotation periods were also estimated using photometric analysis of light curves. Finally, the last sample is composed of Maunder minimum (MM) candidates studied in the work of Lubin et al. (2010). The ages, derived from isochrones, come from the work of Brewer et al. (2016). Besides, we estimated the rotation periods for this sample using the equation of activity calibration defined by Noyes et al. (1984).

3. Physics of the models

The rotation evolution models presented in this work were produced with the Toulouse-Geneva evolution code (TGEC) (Hui-Bon-Hoa 2008; do Nascimento et al. 2009). The models use nuclear reaction rates from the analytical formula of the NACRE compilation (Angulo et al. 1999), while the atomic screening factor used are described by Bahcall et al. (1992). We used the opacity tables from the OPAL OPACITY CODE (Iglesias & Rogers 1996), complemented at low temperature by the molecular opacities of Alexander & Ferguson (1994). For the equation of state (EOS), we use the OPAL 2001 EOS tables (Rogers & Nayfonov 2002). The mixing length theory (MLT) (Böhm-Vitense 1958) is the treatment of convection chosen to compute our models. We use the Eddington relation as the prescription for the integration of the stellar boundary with its atmosphere (gray atmosphere). Finally, the most relevant part to the work developed here is related to the routines that treat the transport of angular momentum. The transport of angular momentum in the radiative zone is treated as an advective-diffusive process, while the convection zone rotate as a solid body (Zahn 1992). We use the prescription laid out in the work of Talon & Zahn (1997) for the vertical transport of angular momentum, and the prescription described in Mathis & Zahn (2004) for the horizontal transport of angular momentum. The prescriptions for the magnetic braking at the surface come from the works of Kawaler (1988) and Matt et al. (2015).

4. Results

First, the sample of do Nascimento et al. (2020) can only serve as a control sample, since our evolution models follow the Skumanick law on the main sequence, as it does, by design, the ages derived by gyrochronology. Therefore, it is natural that we could not identify any relevant disparities between this sample and our models. Then, for the sample of Beck et al. (2017), it is possible to identify a clear divergence from our models for most of the data with ages older than the Sun, which could indicate a decrease in magnetic braking efficiency (van Saders et al. 2016). However, this sample of seismic analogues have a considerable scatter of spectroscopic parameters and should be better constrained before comparing it with the solar rotation evolution model. The next sample, Yana Galarza et al. (2021), is composed of young stars with parameters constrained to be relevant to the rotation evolution of the Sun. We found that a good portion of this sample is above our rotation models and most of these stars are not young enough to be explained by solar rotation models with higher initial angular momentum (Gallet & Bouvier 2015; Amard et al. 2016). Finally, regarding the sample of MM candidates, which had their parameters constrained using the solar proxy definition of Yana Galarza et al. (2021), we found that these targets also diverge from our models in a way that reinforce the hypothesis that those stars are going through a transition in their internal dynamo, leading to a decrease in magnetic braking. The results are shown in Figure 1.

5. Conclusion

The rotation evolution of solar-type stars will continue to be investigated so that we are able to understand in a deeper sense how this fundamental stellar property is intertwined with the magnetic phenomena and how it depends on atmospheric parameters such as metallicity (Amard & Matt 2020). Until we get this relationship right, methods of estimating stellar ages such as gyrochronology are hindered, since we cannot safely determine which group of solar-type stars are not affected by a decrease in magnetic braking (Lorenzo-Oliveira 2019). The mentioned problem with the young stars of Yana Galarza et al. (2021) needs further investigation and the MM sample is going to be key in the development of the discussion related to changes in the dynamo of middle-age solar-type stars.

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