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SEARCHING FOR ANTI-SOLAR DIFFERENTIALLY ROTATING STARS - AN APPLICATION TO THE KEPLER FIELD

Q. Noraz[1], S. N. Breton[1,], A. S. Brun[1,], R. A. García[1,], A. Strugarek[1,], A. R. G. Santos[2], S. Mathur[3] and L. Amard[1,]

Abstract. Over the last decades, anti-solar differential rotation profiles have been found in numerical simulations of convective envelopes of low-mass stars. These profiles are characterized by a slow equator and fast poles (reversed with respect to the Sun), and occur in simulations for high Rossby numbers. At the same time, anti-solar differential rotation profiles have been reported in evolved stars, but never unambiguously observed for solar-type stars on the main sequence. As the Sun ages and spins down, its effective Rossby number increases, which could induce a transition toward an anti-solar regime before the end of the main sequence. Such a rotational transition would have an impact on the large-scale dynamo process and magnetic activity. The detection of anti-solar rotation for main-sequence stars would therefore improve our understanding of the magneto-rotational evolution of solar-type stars.

In this context, we use the Kepler survey in order to identify main-sequence stellar targets that might exhibit an anti-solar differential rotation profile. To do that, we develop a new theoretical formula, motivated by numerical simulations, in order to estimate the fluid Rossby number of solar-like stars from observable quantities. In this development, we take into account structural and metallic aspects. We quantify the fluid Rossby number of 50,656 Kepler targets using the most recent catalog of rotational periods (Santos et al. 2021).

After checking individually each selected target, we obtain a catalog of 22 candidates likely in a state of anti-solar differential rotation. We conclude that promising cool main-sequence stellar candidates for anti-solar differential rotation already exist in the Kepler field, even though their number is small. Future characterization of these stars would increase our understanding of the mechanisms impacting magnetic and rotational evolution of old solar-type stars at high Rossby number.

Keywords: stars, solar-type, rotation, evolution, photometry, Kepler, observations, convection, Rossby

1 Anti-solar differential rotation in solar-type stars

Observations of the Sun show that its rotation is differential, which means that all latitudes do not rotate at the same rate (Scheiner 1630; Carrington 1860). In particular, helioseismology has allowed us to probe the solar interior (Thompson et al. 1996; Howe et al. 2011), indicating that this differential rotation (DR) also varies in radius in the entire convective zone, but is close to being solid within the radiative interior, below 0.7 $R_\odot$. The rotation profile of the Sun is in particular characterized by an equatorial zone of the convective envelope rotating faster than the radiative interior, while the polar regions rotate more slowly than the latter.

The exact mechanism of redistribution of angular momentum leading to such a profile is currently subject to debate in the context of the *Convective Conundrum* (O'Mara et al. 2016, see also Gizon & Birch 2012; Rast 2020; Hotta et al. 2022). However, one result reproduced by the vast majority of global numerical models is the modification of the DR profile as a function of the Rossby number Ro, which is defined by the ratio of the advection term to the Coriolis force in the Navier-Stockes equation (Gastine et al. 2014). In particular, three main regimes are found: cylindrical profiles shaped by the Taylor-Proundman constraint for low Ro, solar type

[1] Département d'Astrophysique/AIM, CEA/IRFU, CNRS/INSU, Univ. Paris-Saclay & Univ. de Paris, 91191 Gif-sur-Yvette, France
[2] Instituto de Astrofísica e Ciências do Espaço, Universidade do Porto, CAUP, Rua das Estrelas, PT4150-762 Porto, Portugal
[3] Instituto de Astrofísica de Canarias (IAC), E-38205 La Laguna, Tenerife, Spain

profiles (fast equator/slow poles) deviating from this constraint for intermediate *Ro*, and finally the appearance of "anti-solar" type profiles (slow equator/fast poles) when *Ro* is high enough (Gilman 1977; Ballot et al. 2007; Kpyl et al. 2011; Guerrero et al. 2013; Brun et al. 2017).

Rotation evolution models (Gallet & Bouvier 2013; Amard et al. 2019; Ahuir et al. 2021) and observations (Skumanich 1972) jointly tend to show that solar-type stars lose angular momentum through their magnetized wind during the main sequence (MS), hence spin down, which by definition increases their Rossby number *Ro*. We wonder therefore if the Sun could experience a regime transition toward an anti-solar rotation profile before the end of its MS, more generally if this can happen for a solar-type star, and if so, if this is something common.

On the one hand, the observational detection of anti-solar rotation profiles have been reported for later evolution stages, like subgiant (Harutyunyan et al. 2016) and giant stars (Strassmeier et al. 2003; Kvri et al. 2017). Although we have to keep in mind that the problem may be degenerate due to spot evolution along one rotation period (Reiners & Schmitt 2002), these detections are considered as robust. On the other hand, there is currently no robust detection of such profile for cool stars on the MS (Reinhold & Arlt 2015; Benomar et al. 2018). The low rotation rate indeed makes their observational characterization particularly difficult and thus high Rossby stars have barely been observed (Donati et al. 2006; Reinhold & Arlt 2015; Shapiro et al. 2020). In that sense, numerical simulations are therefore a powerful tool to first study these possible stars from a theoretical point of view.

From a numerical point of view, the high *Ro* space is however also subject to debate, in particular to discriminate which impact an anti-solar rotation profile would have on the stellar magnetism. Some global 3D studies find anti-solar rotation models producing magnetic cycles (Karak et al. 2015; Viviani et al. 2018, 2019) while others do not (Warnecke 2018; Strugarek et al. 2018; Brun et al. 2022). Recent 2D mean-field studies have nevertheless suggested that the presence of an anti-solar cycle strongly depends on the prescribed dynamo model (Karak et al. 2020; Noraz et al. 2022b). The detection of a cycle on a confirmed anti-solar rotator would therefore be a tremendous constraint on deciphering what type of dynamo is actually acting in slow rotators, and more generally in the Sun and solar-like stars. This study, based on (Noraz et al. 2022a), proposes to look for observational targets, considered as good candidates to be in the anti-solar DR regime, and thus interesting for future characterizations in that sense.

2 Observational Rossby formula and application to the Kepler field

In order to find the candidate stars for anti-solar rotation, we propose to calculate their Rossby number *Ro* in order to select the targets with the highest values. Different definitions of *Ro* and are used in the community (see Appendix B of Brun et al. 2017 or Kpyl 2022). We decide here to consider the *fluid* Rossby number $Ro_{\rm f}$, regularly used to characterize global simulations, in which the anti-solar profiles emerge. It is defined such that $Ro_{\rm f} = \frac{\omega}{2\Omega_*} \simeq \frac{v_{\rm conv}}{2\Omega_* D}$, with ω the vorticity, Ω_* the angular rotation rate, $v_{\rm conv}$ the convective velocity and D a characteristic length scale. First, we propose a development (details available in Noraz et al. 2022a), allowing to calculate $Ro_{\rm f}$ from observable quantities, and taking into account the structural changes happening when considering different masses M_* and metallicity indexes [Fe/H].

Using mixing length theory arguments we can express $v_{\rm conv} \propto (\frac{L_* R_*}{M_*})^{1/3} S(M_*)$, where L_* is the stellar luminosity, R_* the stellar radius and S a structural factor accounting for the convective envelope shrinking when considering higher masses. Homology relations such as $L_* \propto M_*^{m_1}([\mathrm{Fe/H}]+2)^{m_2}$, $R_* \propto M_*^{n_1}([\mathrm{Fe/H}]+2)^{n_2}$ and the assumption $S \propto M_*^{q_1}([\mathrm{Fe/H}]+2)^{q_2}$ allow us to express $v_{\rm conv} \propto M_*^{q_1+(m_1+n_1-1)/3}([\mathrm{Fe/H}]+2)^{q_2+(m_2+n_2)/3}$ as a function of the mass and the metallicity index only. Using the classic relation $L_* = 4\pi R_*^2 \sigma T_{\rm eff}^4$ makes then the link between M_* and the effective temperature $T_{\rm eff}$. Finally, we calibrate indexes m_1, m_2, n_1, n_2, q_1 and q_2 with stellar evolution models of (Amard et al. 2019), which gives us

$$\frac{Ro_{\rm f}}{\mathrm{Ro}_{\rm f,\odot}} = \left(\frac{P_{\rm rot,*}}{\mathrm{P}_{\rm rot,\odot}}\right) \times \left(\frac{T_{\rm eff}}{\mathrm{T}_{\rm eff,\odot}}\right)^{3.29} \times \left(\frac{[\mathrm{Fe/H}]+2}{2}\right)^{-0.31} . \quad (2.1)$$

where we normalize to solar values in order to avoid any dependency on the choice of *Ro* definition.

We then compute the Rossby number of the 50,656 *Kepler* targets available in the recent rotation catalog of Santos et al. (2019, 2021). Because Eq. 2.1 is developed for the MS, and since we want to focus specifically on this evolutionary phase, we do not consider the subgiants targets of the catalog. To exclude them, we parameterize the terminal-age-main-sequence (TAMS) in the Kiel parameter space (surface gravity $\log_{10}$g vs. $T_{\rm eff}$) as a function of metallicity (see Appendix B of Noraz et al. 2022a), and consider targets below these parameterizations within a Kiel diagram only.

To highlight candidates for the anti-solar DR regime, we now select targets with a $Ro_{\rm f}$ value above 1.3, as only anti-solar profiles are observed in numerical models of Brun et al. (2022) which are above this value. We choose to consider $\mathrm{Ro}_{\mathrm{f},\odot} = 0.9$ according to results of the same numerical study, which gives the threshold $Ro_{\rm f}/\mathrm{Ro}_{\mathrm{f},\odot} > 1.44$, and we finally select a list of 99 candidates.

The 99 selected targets are then individually analyzed in order to check that their signals are not polluted by a stellar neighbor or unflagged companion. All checks details are gathered for each selected target with available data in this Github repository. We finally obtain 22 promising targets for hosting anti-solar DR, and illustrate them in Fig. 1.

3 Promising observational candidates for hosting an anti-solar DR profile

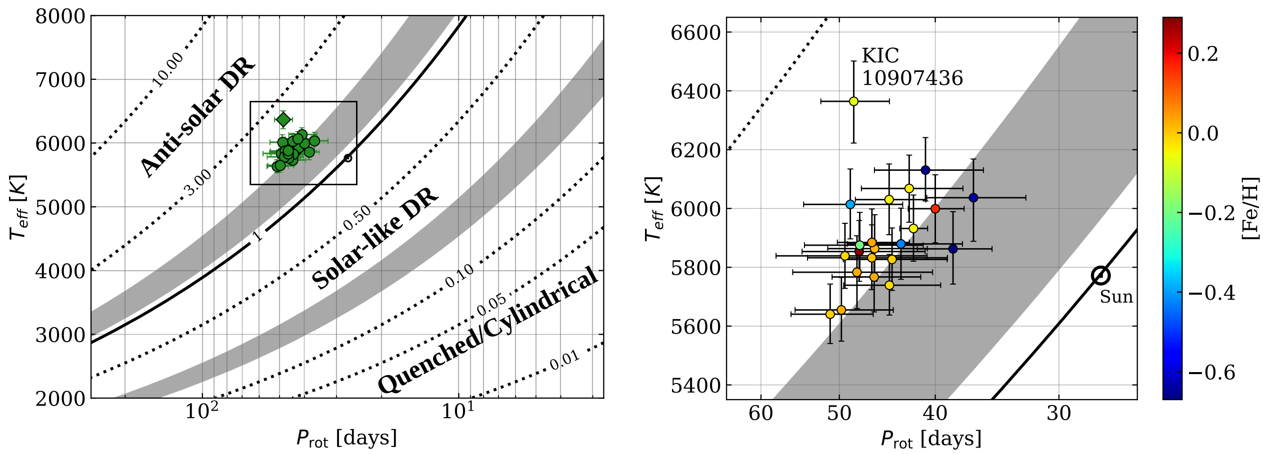

Fig. 1. DR diagram ($T_{\rm eff}$ vs. $P_{\rm rot} = 2\pi/\Omega_*$) in which we described the different DR regimes expected, and delimited by gray transition regions. **Left:** Green points represent the 22 anti-solar promising candidates, for which $Ro_{\rm f}/\mathrm{Ro}_{\mathrm{f},\odot} > 1.44$. Dotted lines represent constant $Ro_{\rm f}/\mathrm{Ro}_{\mathrm{f},\odot}$ values, as deduced from Eq. 2.1 when considering the solar metallicity [Fe/H]=0. The solid black line hence represents the solar value. **Right:** Zoom into the left panel on the anti-solar promising candidates, color-coded by metallicity indexes. Adapted from Noraz et al. (2022a).

In the list of the 22 high Rossby selected stars that are likely to show anti-solar differential rotation, we identify two samples. The first one considers 14 candidates found in the solar metallicity range -0.1<[Fe/H]<+0.1. We provide a list of their stellar parameters in Table 1 of Noraz et al. (2022a), where we highlight KIC 10907436 as the most promising candidate and two other interesting targets, namely the solar analog KIC 7189915 and the seismic target KIC 12117868. We then find 8 other promising candidates in the second samples, when considering other compositions, and for which stellar parameters are given in the second Table of the same study. We thus underline KIC 2161400, which has the highest $Ro_{\rm f}$ value for promising targets out of the solar metallicity range.

4 Conclusions

We conclude that cool main-sequence stellar candidates for anti-solar differential rotation exist in the Kepler sample, but are scarce given the strict selection criteria we considered. We give a list of 22 targets (out of 50,656) that we consider as promising to show anti-solar DR, and detail them in Noraz et al. (2022a).

As the parameter space at high Rossby numbers is still poorly known, both from a numerical and an observational point of view, these new targets open new perspectives and may bring new observational constraints from their future characterization: in particular, on the confirmation or not of anti-solar profiles on the MS, the search for a potential rise of magnetic activity or magnetic flux for this regime (Brandenburg & Giampapa 2018; Brun et al. 2022), or even if such a profile is related to the weakened angular momentum loss observed on old solar-type stars (van Saders et al. 2016; Hall et al. 2021).

KIC 12117868 is particularly interesting for future asteroseismic characterizations, since such techniques allow to quantify the latitudinal rotation contrast, and thus potentially the DR profile regime. However, such confirmations for anti-solar candidates currently require a better signal-to-noise ratio (Benomar et al. 2018), which could be obtained by monitoring a star for a longer time, or by targeting brighter stars. Such targets will be in particular accessible with the future PLATO mission (Rauer et al. 2014). In this context, the PLATO analysis pipeline will integrate Eq. 2.1 for a direct characterization of the Ro_f from observations.

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References

Ahuir, J., Strugarek, A., Brun, A.-S., & Mathis, S. 2021, Astronomy & Astrophysics, 650, A126

Amard, L., Palacios, A., Charbonnel, C., et al. 2019, Astronomy & Astrophysics, 631, A77

Ballot, J., Brun, A. S., & TurckChieze, S. 2007, The Astrophysical Journal, 669, 1190

Benomar, O., Bazot, M., Nielsen, M. B., et al. 2018, Science, 361, 1231

Brandenburg, A. & Giampapa, M. S. 2018, The Astrophysical Journal, 855, L22

Brun, A. S., Strugarek, A., Noraz, Q., et al. 2022, The Astrophysical Journal, 926, 21

Brun, A. S., Strugarek, A., Varela, J., et al. 2017, The Astrophysical Journal, 836, 192

Carrington, R. C. 1860, MNRAS, 20, 254

Donati, J.-F., Howarth, I. D., Jardine, M. M., et al. 2006, Monthly Notices of the Royal Astronomical Society, 370, 629

Gallet, F. & Bouvier, J. 2013, Astronomy & Astrophysics, 556, A36

Gastine, T., Yadav, R. K., Morin, J., Reiners, A., & Wicht, J. 2014, Monthly Notices of the Royal Astronomical Society: Letters, 438, L76

Gilman, P. A. 1977, Geophysical and Astrophysical Fluid Dynamics, 8, 93

Gizon, L. & Birch, A. C. 2012, Proceedings of the National Academy of Sciences, 109, 11896

Guerrero, G., Smolarkiewicz, P. K., Kosovichev, A. G., & Mansour, N. N. 2013, The Astrophysical Journal, 779, 176

Hall, O. J., Davies, G. R., van Saders, J., et al. 2021, Nature Astronomy, 5, 707

Harutyunyan, G., Strassmeier, K. G., Knstler, A., Carroll, T. A., & Weber, M. 2016, Astronomy & Astrophysics, 592, A117

Hotta, H., Kusano, K., & Shimada, R. 2022, The Astrophysical Journal, 933, 199

Howe, R., Larson, T. P., Schou, J., et al. 2011, Journal of Physics: Conference Series, 271, 012061

Karak, B. B., Kpyl, P. J., Kpyl, M. J., et al. 2015, Astronomy & Astrophysics, 576, A26

Karak, B. B., Tomar, A., & Vashishth, V. 2020, Monthly Notices of the Royal Astronomical Society, 491, 3155

Kpyl, P. J. 2022, Transition from Anti-Solar to Solar-like Differential Rotation: Dependence on Prandtl Number

Kpyl, P. J., Mantere, M. J., Guerrero, G., Brandenburg, A., & Chatterjee, P. 2011, Astronomy & Astrophysics, 531, A162

Kvri, Z., Strassmeier, K. G., Carroll, T. A., et al. 2017, Astronomy & Astrophysics, 606, A42

Noraz, Q., Breton, S. N., Brun, A. S., et al. 2022a, Astronomy & Astrophysics, 18

Noraz, Q., Brun, A. S., Strugarek, A., & Depambour, G. 2022b, Astronomy & Astrophysics, 658, A144

O'Mara, B., Miesch, M. S., Featherstone, N. A., & Augustson, K. C. 2016, Advances in Space Research, 58, 1475

Rast, M. P. 2020, in Dynamics of the Sun and Stars, ed. M. J. P. F. G. Monteiro, R. A. Garca, J. Christensen-Dalsgaard, & S. W. McIntosh, Vol. 57 (Cham: Springer International Publishing), 149–161

Rauer, H., Catala, C., Aerts, C., et al. 2014, Experimental Astronomy, 38, 249

Reiners, A. & Schmitt, J. H. M. M. 2002, Astronomy & Astrophysics, 388, 1120

Reinhold, T. & Arlt, R. 2015, Astronomy & Astrophysics, 576, A15

Santos, A. R. G., Breton, S. N., Mathur, S., & Garca, R. A. 2021, The Astrophysical Journal Supplement Series, 255, 17

Santos, A. R. G., Garca, R. A., Mathur, S., et al. 2019, The Astrophysical Journal Supplement Series, 244, 21

Scheiner, C. 1630, Rosa Ursina (ETH-Bibliothek Zrich)

Shapiro, A. I., Amazo-Gmez, E. M., Krivova, N. A., & Solanki, S. K. 2020, Astronomy & Astrophysics, 633, A32

Skumanich, A. 1972, ApJ, 4

Strassmeier, K. G., Kratzwald, L., & Weber, M. 2003, Astronomy & Astrophysics, 408, 1103

Strugarek, A., Beaudoin, P., Charbonneau, P., & Brun, A. S. 2018, The Astrophysical Journal, 863, 35

Thompson, M. J., Toomre, J., Anderson, E. R., et al. 1996, Science, 272, 1300

van Saders, J. L., Ceillier, T., Metcalfe, T. S., et al. 2016, Nature, 529, 181

Viviani, M., Kpyl, M. J., Warnecke, J., Kpyl, P. J., & Rheinhardt, M. 2019, The Astrophysical Journal, 886, 21

Viviani, M., Warnecke, J., Kpyl, M. J., et al. 2018, Astronomy & Astrophysics, 616, A160

Warnecke, J. 2018, Astronomy & Astrophysics, 616, A72