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Report on 3-D simulations of solar-like stars

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Within the Spacelnn project we have conducted a series of 15 3-D MHD simulations of solar–like stars using the MPI code ASH (Anelastic Spherical Harmonics; Brun et al. 2004) on massively parallel computers. To do so we have varied global parameters of the star studied such as mass, aspect ratio and rotation rates but kept those parameters such as to retain a convective envelope. Hence we have computed 4 different mass bins (0.5, 0.7, 0.9 and 1.1 Msol) and several rotation rates (from 1/8 up to 5 times the solar rate). Moreover we have considered the dynamical coupling to an inner radiative stable interior, hence often modeling more than 50% of the whole star. This has never been done before our study. Over the duration of the Spacelnn project more than 15 million nodes hours have been used to perform such parameter space study, this represents the equivalent of 2 millennia of computation on a single processor. These results have been published in several peer-review journals (see references below) and presented in international conferences (for instance 2nd Solar net meeting, IAU general assembly or IAU Symposium 328).

The main focus of the study was in one hand to characterize the convection and large scale mean flows (differential rotation and meridional circulation) of these stars and then to compute the dynamo MHD equivalent, to assess their level of magnetism. We have successfully done so, by having the help of the hired Spacelnn postdoc Dr. Jacobo Varela. Thanks to our ab-initio study of solar-like star convection we were able to define a criteria helping observers to assess the state of rotation of observed stars. This criterion is based on the Rossby number as defined in fluid dynamics $Ro=\frac{V}{2\Omega_0 R}$, where $V$ is a characteristic convective velocity, $\Omega_0$ is the star’s rotation rate and $R$ its radius.

Thanks to this criterion, we have started a study looking at Kepler satellite data with R.A. Garcia on the existence of anti-solar stars, e.g. stars rotating with a differential rotation profile having slow equator and fast poles. We present in the following figures the main results of our study.

In Figure 1 we show the parameter space study as a function of mass and rotation rate and the Rossby number criterion that we have derived using both Mixing length theory and 3-D HD and MHD numerical simulations. For large Rossby number (larger than one), one expects to have stars rotating with an anti-solar differential rotation.

In Figure 2, we show the differential rotation profile realized in the 3-D hydrodynamical simulations. This is a temporal and azimuthal average of the angular velocity in the 15 3-D simulations performed with the ASH code and published in Brun et al. (2015,2016). We note the 3 states of rotation that may exist in stars: solar-like, anti-solar like and Jupiter-like.

In Figure 3, we show how dynamo generated magnetic field in stars modify the differential rotation contrast (making it weaker) and how the presence of magnetic field yield more realistic trends of angular velocity contrast with rotation rate and mass. We expect the differential rotation to be more sensitive to a change of mass and aspect ratio than to a change of rotation rate, as observed and found in our numerical nonlinear 3-D simulations.
Overall the study of solar-like stars by means of 3-D high performance numerical simulation within the Space-Inn project has been very successful and as provided key input for upcoming missions such as ESA/PLATO. These project results provide the community an easy and straightforward way of categorizing observed stars by applying the Rossby number criterion. The numerical simulations can be obtained by directly contacting Dr. A.S. Brun at sacha.brun@cea.fr or by going to the web page: http://www.spaceinn.eu/data-access/wp4/simul/. Such simulations can further be used to perform direct modeling of wave propagation and to probe physical processes such as convective motion, mean flows or magnetic field structures. They also demonstrate how diverse are solar-like stars.

Figure 1: Contour plot of the fluid Rossby number as a function of stellar mass and rotation rate. Blue tones indicate rapidly rotating stars and red tones slowly rotating ones with respect to their convective motions. The circle show the 15 3-D numerical simulation that were used to calibrate the plot and the solar vs anti-solar state of rotation separation. For more details see Brun et al. (2016).
Figure 2: The differential rotation realized in our simulations for four masses 0.5, 0.7, 0.9 and 1.1 Msol, and for four rotation rates: 'S' models (with respectively 1/8, 1/4 and 1/2) and one, three, and five times the solar rate. Red tones indicate prograde flows and blue tones retrograde flows with respect to the rotating frame. We note 3 states of differential rotation: solar-like (fast equator - slow poles), anti-solar like (slow equator - fast poles) and Jupiter-like (alternance of prograde and retrograde jets) for very rapidly rotating stars (Ro < 0.2). See Brun et al. (2015, 2016) for more details.
Figure 3: Differential rotation between the equator and 75° latitude (A) and differential rotation kinetic energy versus Rossby number Ro (B), logarithmic scale in the axis. Differential rotation versus rotation (C). Differential rotation versus mass (D). The MHD data are the circles and the hydro data are the cross-circles. The dotted (dashed) line shows the linear fit of the MHD (Hydro) data. We note that MHD trends have different slopes that are in better qualitative agreement with observations. For more details see Varela et al. (2016).

References:
- Varela, J., Strugarek, A., Brun, A.-S. 2016, Advances in Space Research 58, 1507-1521,
- Brun et al. 2015, Space Sci. Rev., 16, 303 (solar-stellar connection);