Proteus Stars: Evidence of New Magnetic Transitions in Late-Type Dwarfs from the Second Gaia Data Release

Alessandro C. Lanzafame\textsuperscript{1,2} and Elisa Distefano\textsuperscript{2} \\
Sydney A. Barnes\textsuperscript{3} \\
Federico Spada\textsuperscript{4}

\textsuperscript{1}Università di Catania, Dipartimento di Fisica e Astronomia, Italy \\
\textsuperscript{2}INAF-Osservatorio Astrofisico di Catania, Italy \\
\textsuperscript{3}Leibniz Institute for Astrophysics (AIP), Potsdam, Germany \\
\textsuperscript{4}Max Planck Institute for Solar System Research, Göttingen, Germany

(Received May 29, 2018; Revised; Accepted) 
Submitted to ApJL

Abstract

The second Gaia data release contains the identification of 147,535 rotation modulation variables candidates of the BY Dra class, together with their rotation period and modulation amplitude. The richness, the period and amplitude range, and the photometric precision of this sample make it possible to unveil, for the first time, structures in the amplitude-period density diagram that are signatures of different magnetic regimes. The modulation amplitude distribution shows a clear bimodality, with an evident gap at periods $P \lesssim 2$ d. The low amplitude branch, in turn, shows a period bimodality with a major group of relatively slow rotating stars with periods $P \approx 5 - 10$ d and a group of ultra-fast rotators at $P > 0.5$ d. The amplitude-period multimodality is correlated with the position in the period-absolute magnitude (or period-color) diagram, with the low- and high-amplitude stars occupying different preferential locations. Here we argue that such a multimodality represents a further evidence of the existence of different surface magnetic field configurations in young and middle-age low-mass stars and we lay out possible scenarios for their magnetic evolution which manifestly include rapid transitions from one configuration to another. The multimodality can be exploited to identify stars in the field belonging to the slow-rotator low-amplitude sequence, for which the age can be estimated from the rotation period via gyrochronology relationships.

Keywords: stars: rotation — stars: magnetic field — stars: evolution — stars: late-type

1. INTRODUCTION

In the second half of last century, the seminal work of Parker (1958); Weber & Davis (1967); Skumanich (1972); Kawaler (1988, 1989) opened a new frontier in deriving stellar age from rotation, which represents an appealing alternative to isochrone fitting during the stellar evolution on the main sequence where stellar color and luminosity change very slowly. Observations of young open clusters, however, revealed a wide dispersion of rotation rates, mainly attributed to initial conditions and different disk interaction lifetime during the stellar contraction towards the main sequence, that seemed to prevent the possibility of obtaining sufficient accuracy from dating methods based on rotation (e.g. Edwards et al. 1993). The power-law dependence of the angular momentum loss on the rotational velocity, i.e. the Kawaler (1988) $J \propto \Omega^3$ wind-braking law, where $J$ is the stellar angular momentum and $\Omega$ the angular velocity, ensures a decrease of the rotation dispersion in time, but this appears insufficient to explain...
the rotational evolution seen in open clusters younger than the Hyades (600 Myr). Barnes (2003) identified a sequence of slowly rotating stars in the color-period diagram of young open clusters that becomes increasingly prominent with increasing cluster’s age, starting from the Pleiades age. Stars in this sequence follow approximately the Skumanich (1972) \( P \propto \sqrt{t} \) law, strictly related to the Kawaler (1988) \( J \propto \Omega^3 \) wind-breaking law\(^1\), which produces a progressive decrease of the rotation scatter on this sequence. The dominating scatter in young open clusters, however, is due to the presence of a fast rotating population, that is progressively depleted as the age increase.

Barnes (2003) postulated that different types of dynamo operate in fast- and slow-rotators in open clusters younger than the Hyades, with a convective dynamo characterising the fast rotators (C-sequence) and an interface (tachocline) dynamo characterising the slow rotators (I-sequence). In such a scenario, stars in the C-sequence would switch to the I-sequence at \( \approx 100-300 \) Myr, depending on mass, converging quite rapidly to the slow-rotator sequence (gap phase). A closer reproduction of the fast- and slow-rotator distribution in open cluster has been obtained by Brown (2014) by assuming a metastable dynamo that produces stochastic transitions from fast- to slow-regimes.

Direct evidences of different magnetic topologies that may lead to different level of coupling with the stellar wind are based on Zeeman-Doppler-Imaging (ZDI) analyses (e.g. Folsom et al. 2016, 2018, and references therein). The scenario that is being delineating is that T Tauri stars have complex and strong large-scale magnetic fields dominated by a poloidal component, while older pre-main sequence (PMS) and main sequence stars have less axisymmetric and more toroidal magnetic fields (see also Gregory et al. 2008). The magnetic properties of older PMS and main sequence stars are similar, with a similar dependence on age and Rossby number. The mean large-scale magnetic field strength decreases from 20 Myr onwards, with a maximum dispersion at ages \( \approx 120 \) Myr and a clearer decreasing trend with age, rotation and Rossby number between 250 and 650 Myr.

Ultra-fast rotators (UFR) show evidence of high polar activities (e.g. LO Peg, see Piluso et al. 2008, and references therein) or structure in the polar regions showing greatest concentration in a particular longitude range (e.g. Speedy Mic, Barnes 2005), as well as saturation of large-scale magnetic fields (Strassmeier 2009; Folsom et al. 2016, 2018).

In this letter we argue that the period and amplitude of the BY Dra\(^2\) rotational modulation variable candidates contained in the second Gaia data release (Lanzafame et al. 2018) unveil a global picture of the modifications of the stellar surface inhomogeneities that provides further evidence of rapid transitions amongst different magnetic regimes in the first 600 Myr of the stellar evolution.

2. CLUSTERING IN THE AMPLITUDE-PERIOD DIAGRAM

Lanzafame et al. (2018) presented the methods devised for the analysis of rotational modulation variables in the framework of the Gaia Data Processing and Analysis Consortium (DPAC) and described the general characteristics of the BY Dra candidates data included in Gaia DR2. In particular, they showed that the Gaia amplitude-period density diagram displays a major rotation amplitude bimodality with a manifest gap between the low- and high-amplitude groups at \( P \leq 2 \) d (see their Fig. 8 and Figs. 1 and 2). Furthermore, the high-amplitude population is more prominent at lower mass and is gradually depleted as we consider higher mass, until it almost disappear in the 1.15 - 1.25 \( M_\odot \) range. Conversely, the low-amplitude population in the \( P \leq 2 \) d region is very poorly populated

\(^1\) with modifications due to the transfer of angular momentum from the core to the envelope in the first \( \approx 1 \) Gyr (see, e.g. Soderblom et al. 1993; Spada et al. 2011; Lanzafame & Spada 2015)

\(^2\) In this paper we shall refer to dwarf, sub-giant, and T Tauri stars showing flux modulation induced by surface inhomogeneities and rotation as BY Dra variables, after the archetype BY Draconis.
for $M \leq 0.85 M_\odot$, but it is increasingly populated at increasing mass.

Fig. 1 shows the amplitude-period density diagram for the whole Gaia DR2 BY Dra sample. In this diagram we identify three major populations: high-amplitude rotators (HAR; $A \geq 0.05$), low-amplitude slow-rotators (LASR; $A \leq 0.05$ and $P \geq 2$ days), and low-amplitude fast-rotators (LAFR: $A \leq 0.05$ and $P \leq 2$ days). Ultra-Fast Rotators (UFR) are considered a sub-group of the LAFR with $P < 0.5$ d. Their segregation, i.e., the presence of clear gaps among these groups, is a strong evidence of the very rapid timescales with which stars evolve from from one group to the other.

Fig. 2 shows the amplitude-period density diagram of the K-type stars ($M_G \approx 5.8 – 7$) in the Gaia DR2 BY Dra sample. Focusing on the K stars alone allows a simpler, but still general, description of the features of the diagram. All three groups can be easily identified in panel (c) of Fig. 2, and can be further illustrated with the help of the other panels. By projecting the density diagram along the modulation dimension (panel b), the bimodality in $A$ is immediately apparent. Dividing the entire sample into its low- and high-amplitude components makes the further segregation with respect to $P$ more easily identifiable. With reference to panel (a) of Fig. 2, while the high-amplitude population has a broad unimodal distribution over $P$, the low-amplitude population is manifestly bimodal, with a minimum density at $P \approx 1$ d.

The faster rotation end of the amplitude-period diagram reveals another interesting behaviour. Stars close to break-up rotational velocity ($P < 0.5$ d) tend to cluster on the low-amplitude sequence, with a rather abrupt inversion of the relative density of the high- and low-amplitude branches at decreasing periods below $P \approx 2$ d (Fig. 2, panel (c) and Fig. 3). Such a clustering gives an intuitive criterion for the definition of UFR as stars with low modulation amplitude and $P < 0.5$ d.

As these stars undergo their well-known rotational evolution, which in broad terms goes from fast to slow rotation, except for the radius contraction phase prior to the zero-age main sequence, they switch among the three groups identified in the amplitude-period density diagram. This implies that rapid changes in $A$, which reflect changes in the distribution of starspots and faculae, and therefore of the appearance of the stellar surface, occur in parallel with the period evolution.

3 These rapid changes of appearance are reminiscent of the attributes of the mythological Greek sea god Proteus (Πρωτεύς), which inspired the title of this letter.

3. RELATIONSHIPS WITH THE PERIOD-ABSOLUTE MAGNITUDE OR PERIOD-COLOUR DIAGRAM

As already noted in Lanzafame et al. (2018), the more numerous group in the amplitude-period density diagram, the LASR group, corresponds to a collection of Barnes (2003) I-sequence. For this group of stars, therefore, the gyrochronology relations can be applied to derive their age from the rotation period. The $P$ vs absolute magnitude $M_G$ diagram of the subsample of this group for which the extinction $A_G$ has been derived by Andrae et al. (2018) is shown in Fig. 4. The Lanzafame & Spada (2015) non-parametric fit to open clusters slow-rotator (or I-) sequence in the $P$ vs ($B - V$) plane are translated to the $P$ vs $M_G$ plane using the photometric relationships of Evans et al. (2018). The comparison shows that most of the stars in this group have ages between 100 and 600 Myr, as expected given the low Gaia sensitivity for $P > 10$ d in the first 22-months observation baseline of Gaia DR2 (Distefano et al. 2012; Lanzafame et al. 2018). The expected evolution of stars in this group is towards longer period (rightward in the $A$–$P$ and upward in the $P$–$M_G$ diagrams) with approximately $P \propto \sqrt{t}$.

Stars in the HAR branch are expected to be a mixture of main sequence stars that have not yet settled on the LASR sequence (the C-sequence and the gap in Barnes 2003 terminology, see also Barnes 1997) and PMS stars (see, e.g., Moraux et al. 2013). The former are expected to converge towards the LASR sequence, with the apparent segregation between these two groups in the amplitude-period diagram suggesting a rather rapid transition. The latter have the possibility to spin-up, i.e., of moving leftwards in the amplitude-period density diagram while contracting to the zero-age main sequence (ZAMS), except, perhaps, for the first $\lesssim 5$ Myr of disk interaction phase during the early pre-main sequence. After settling on the ZAMS, stars move towards increasing period, and eventually undergo a transition onto the LASR sequence as above.

Cool stars are known to arrive on the ZAMS with a range of rotation rates ranging roughly from breakup ($\sim$ a tenth of a day) to several days, with a mild dependence on stellar mass. While some stars arrive at the ZAMS already as slow rotators, others of identical age (as sampled in open clusters) arrive as fast rotators. Both kinds of stars spin down over time, but the fast rotators additionally undergo a rapid spindown from fast- to slow type, on a mass-dependent timescale of zero for F-type stars to several hundred Myr for M-type stars (Barnes 2003).
4. ULTRA-FAST ROTATORS

While one can work-out an evolutionary path in the *Gaia* amplitude-period density diagram for stars in the HAR and LASR branches based on previous knowledge as above, the real difficulty posed by the *Gaia* data is to lay out a possible evolutionary path in the amplitude-period density diagram that leads to the UFR region first and then, from this region, to the LASR sequence. A star passing through the UFR stage must originate from the HAR branch as a PMS star. Then it moves leftwards in the contraction phase towards the ZAMS and eventually it spins up to almost break-up velocity.

The *Gaia* amplitude-period density diagram shows that in this phase the star undergoes a very rapid transition toward a magnetic configuration that produces a low modulation amplitude, and therefore from the HAR branch to the UFR region. The UFR condition may well be characterised by a polar spot or cap, or a rather uniform distribution of active region at high latitude. Irrespective of the details, the distribution of the surface features producing the amplitude modulation must be very different from that in the HAR branch.

What happens next? If the magnetic configuration had a one-to-one correspondence with the rotation ve-
velocity, the star would return very rapidly to the HAR branch as it spins down below the $P \approx 0.5\,\text{d}$ limit. Then, from there, the star would make its path towards the LASR as the other HAR stars. However, the 2D density distribution suggests an alternative scenario. The UFR region is connected with the LASR sequence by a rather low density bridge, while it seems almost completely disconnected from the HAR branch. This suggests that, while there is no alternative for a PMS star that becomes UFR but to jump abruptly from the HAR branch to the UFR over-density region, there is a non-negligible probability that the UFR makes then its way directly to the LASR sequence on the low-amplitude branch without returning to the HAR branch first.

The existence of this alternative evolutionary path strengthen the idea that there is no simple one-to-one relationship between magnetic configuration and rotation on the early main-sequence, which has an analogy with the high-amplitude – low-amplitude bimodality at $P > 2\,\text{d}$. Furthermore, this would imply also a dependence on the stellar rotation history of the surface magnetic field configuration.

5. CONCLUSIONS

The data of BY Dra rotational modulation variables contained in Gaia DR2 reveal, for the first time, signatures of different regimes of their surface magnetic structure in the first 600 Myr of their evolution. These signatures are evident in the amplitude-period density diagram, where we identify three major clusterings: high-amplitude; low-amplitude slow-rotators; low-amplitude fast-rotators. The Gaia very detailed amplitude-period density diagram permits also an intuitive and rigorous definition of ultra-fast rotators (UFR) as a sub-group with $P < 0.5\,\text{d}$ of the low-amplitude fast-rotator group.

The manifest segregation of these three groups in the amplitude-period density diagram, together with the prior knowledge that all stars end up in the low-amplitude slow-rotator group as they age, hints at rather rapid transitions from one regime to another. In other words, stars change their appearance quite rapidly at some stage of their early evolution and some of them even more than once\footnote{Like Menelaus (Μενέλαος), we should trap Proteus (Προτέας) [the star] before he changes aspect again and again, and force him to reveal his secrets.}.

The transition from the high-amplitude group to the low-amplitude slow-rotator group has a correspondence to the Barnes (2003)\footnote{Barnes (2003) I-sequence to which gyrochronology relationships can be applied.} transition from the C-sequence to the I-sequence through a gap phase or the equivalent transition in the metastable dynamo models of Brown (2014). What is entirely new is the possible evolutionary path leading to the UFR conditions and then, from such conditions, to the low-amplitude slow-rotator regime. The Gaia amplitude-period diagram suggests that stars passing through the UFR regime undergo first a very rapid transition from the high-amplitude branch to the low-amplitude branch when they contract and spin-up to almost break-up rotational velocity ($P < 0.5\,\text{d}$). Then, as the star spins down, it remains along the low-amplitude branch and, when $P > 0.5\,\text{d}$, it passes quite rapidly from the low-amplitude fast-rotator group to the final low-amplitude slow-rotator group.

Finally, the amplitude multimodality can be exploited to remove the $P$ degeneracy in field stars, for which a period-colour diagram cannot be used to identify the Barnes (2003) I-sequence to which gyrochronology relationships can be applied. In fact, stars with low-amplitude modulation ($A < 0.05\,\text{mag}$) and $P \geq 2\,\text{d}$ are expected to belong to the LASR population and therefore their age can be estimated from their rotational period, provided a useful proxy of the star mass and an estimate of the metallicity is available.

This work makes use of results from the European Space Agency (ESA) space mission Gaia. Gaia data are being processed by the Gaia Data Processing and Analysis Consortium (DPAC). Funding for the DPAC is provided by national institutions, in particular the institutions participating in the Gaia MultiLateral Agreement (MLA). This work was supported by the Italian funding agencies Agenzia Spaziale Italiana (ASI) through grants I/037/08/0, I/058/10/0, 2014-025-R.0, and 2014-025-R.1.2015 to INAF (PI M.G. Lattanzi). The Gaia mission...
Figure 4. Gaia period-magnitude diagram for the low-amplitude slow-rotator group compared with the open clusters slow-rotator sequence non parametric fit of Lanzafame & Spada (2015).

website is https://www.cosmos.esa.int/gaia. The Gaia Archive website is http://gea.esac.esa.int/archive/.

REFERENCES

Andrae, R., Fouesneau, M., Creevey, O., et al. 2018, ArXiv e-prints. https://arxiv.org/abs/1804.09374
Barnes, J. R. 2005, MNRAS, 364, 137, doi: 10.1111/j.1365-2966.2005.09544.x
Barnes, S. A. 1997, PhD thesis, Yale University
—. 2003, "Astrophys. J.", 586, 464, doi: 10.1086/367639
Brown, T. M. 2014, ApJ, 789, 101, doi: 10.1088/0004-637X/789/2/101
Distefano, E., Lanzafame, A. C., Lanza, A. F., et al. 2012, MNRAS, 421, 2774, doi: 10.1111/j.1365-2966.2012.20441.x
Edwards, S., Strom, S. E., Hartigan, P., et al. 1993, AJ, 106, 372, doi: 10.1086/116646
Evans, D. W., Riello, M., De Angeli, F., et al. 2018, ArXiv e-prints. https://arxiv.org/abs/1804.09368
Folsom, C. P., Petit, P., Bouvier, J., et al. 2016, MNRAS, 457, 580, doi: 10.1093/mnras/stv2924
Folsom, C. P., Bouvier, J., Petit, P., et al. 2018, MNRAS, 474, 4956, doi: 10.1093/mnras/stx3021
Gregory, S. G., Matt, S. P., Donati, J.-F., & Jardine, M. 2008, MNRAS, 389, 1839, doi: 10.1111/j.1365-2966.2008.13687.x
Kawaler, S. D. 1988, "Astrophys. J.", 333, 236, doi: 10.1086/166740
—. 1989, "Astrophys. J.", 343, L65, doi: 10.1086/185512
Lanzafame, A. C., & Spada, F. 2015, A&A, 584, A30, doi: 10.1051/0004-6361/201526770
Lanzafame, A. C., Distefano, E., Messina, S., et al. 2018, ArXiv e-prints. https://arxiv.org/abs/1805.00421
Moraux, E., Artemenko, S., Bouvier, J., et al. 2013, A&A, 560, A13, doi: 10.1051/0004-6361/201321508
Parker, E. N. 1958, ApJ, 128, 664, doi: 10.1086/146579
Piluso, N., Lanza, A. F., Pagano, I., Lanzafame, A. C., & Donati, J.-F. 2008, MNRAS, 387, 237, doi: 10.1111/j.1365-2966.2008.13153.x
Skumanich, A. 1972, ApJ, 171, 565, doi: 10.1086/151310
Soderblom, D. R., Stauffer, J. R., MacGregor, K. B., & Jones, B. F. 1993, ApJ, 409, 624, doi: 10.1086/172694
Spada, F., Lanzafame, A. C., Lanza, A. F., Messina, S., & Collier Cameron, A. 2011, MNRAS, 416, 447, doi: 10.1111/j.1365-2966.2011.19052.x
Strassmeier, K. G. 2009, A&A Rv, 17, 251, doi: 10.1007/s00159-009-0020-6
Taylor, M. B. 2005, in Astronomical Society of the Pacific Conference Series, Vol. 347, Astronomical Data Analysis Software and Systems XIV, ed. P. Shopbell, M. Britton, & R. Ebert, 29
Weber, E. J., & Davis, L. J. 1967, "Astrophys. J.", 148, 217