Magnetic activity in stars on the giant branches: Twenty years of observations

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Abstract. We present our results of twenty years of study of the magnetic activity in single G, K and M giants by means of spectroscopy, spectropolarimetry and photometry, carried out at Rozhen NAO, Pic du Midi Observatory, CFHT, OHP, Terskol Observatory, Crimean AO, AO - Belogradchik and Stephanion Observatory, Greece.

Key words: stars: late-type giants: stars - magnetic activity

Introduction

Late–type G and K single giants were suspected in magnetic activity for first time by Deutsch (1967). Later, in the late 80s and in the 90s, snapshot studies of activity indicators in such giants have began (Fekel et al. 1986; Strassmeier & Hall 1988, Simon & Drake 1989; Fekel & Balachandran 1993; Schröder et al. 1998, Gondoin 1999, among others). However, the results then were not convincing, and in the 90s very few people believed that single late-type giants could be magnetically active, because of their big radii and slow rotation.

We started our study of single G,K giants in 1993. 14 stars with fast rotation and/or with some activity signatures were selected. The aims of the study were:

1. Verification of the existing hypotheses for magnetic activity in single late-type giants: angular momentum dredge-up from the stellar interior that accelerates the stellar rotation and causes an $\alpha-\omega$ dynamo operation (Simon&

Drake, 1989), and triggering of magnetic dynamo and activity by planet engulfment (Siess & Livio, 1999).

2. Detailed study of the activity properties in the stars confirmed as active.

Later, in 2002 we extended our sample with four M giants, possessing fast rotation and enhanced X–ray emission. The last stage of the study, after 2007 includes magnetic field study in 59 G, K and M giants by means of spectropolarimetry obtained with the new generation spectropolarimeters Nar-val at TBL, Pic du Midi Observatory, France and ESPaDOnS at CFHT, Hawaii (Auriére 2003). These instruments enable direct detection of the surface magnetic fields and study of their structures.

Nowadays, 20 years later, experts in magnetic field and dynamo find this topic as a "gold mine" for the study of the interplay between the convection, rotation and magnetic field in advanced evolutionary stages after the main sequence (MS).

Magnetic activity in late-type giants - early studies (1994 – 2005)

Our early studies started at a time when people doubted the existence of magnetic activity in single late-type giants. Almost nothing was known about the properties of the activity in these objects, too.

To explore this area and to give a conclusion, a complex study of a sample of stars was necessary:

1. Spectral and photometric observations for activity indicators CaII K&H, H_α, rotational modulation due to spots, flare activity, X-ray data.

2. Radial velocity and Vsini high-precision measurements to study if the stars are binary ones, and to get knowledge about their rotation.

3. Mass and evolutionary stage determination on the basis of situation on the H-R diagram, chemical abundances, mainly C,N,O and Li.

A sample of 14 stars was constructed on the basis of some activity signatures and/or fast rotation rate (Konstantinova-Antova 2001a). We also included Li–rich giants taking into account some hints on relation between high Li and magnetic activity at this evolutionary stage (Brown et al. 1989; Fekel & Balachandran 1993). In addition, in 2002 we started observations of 4 M giants with X-ray emission (Hünsch et al. 1998).

All these studies were carried out by a number of specialists in different fields of the astronomy, as follows:

1. The optical spectral and photometric observations were performed mainly by the Bulgarian team at Rozhen and Belogradchik observatories. The Ukrainian team at Terskol and the Greek collaborators at Stephanion Observatory contri-buted to the study of the flares in active giants. XMM data for the M type giants came by M. Hunsch and K.-P. Schroder, Germany.

2. CORAVEL and ELODIE data for all giants were obtained at Haute-Provence Observatory, France by J.R. de Medeiros and A. Lebre.

3. Evolutionary status is determined on the basis of the tracks by Schaller et al. (1992). Together with Hipparcos data and other data on chemical abundances (Drake et al. 2002, and references therein), we had the possibility for a more precise determination of the evolutionary status for the studied giants.

As a result of this study we found that:

1. Only 4 of all these 14 giants were found to be active ones (OP And, V390 Aur, 37 Com and κ Her A). Another one, HD 121107, was suspected to be active.

2. There is a difference in the activity properties and the origin for fast rotation between the low-mass and the more massive intermediate-mass giants. An interesting fact is also that low-mass active fast rotating giants occupy a narrow mass range in the interval 1.5 - 2 $M_\odot$.

3. The study of the selected Li-rich giants found no evidences for activity in them (except for one fast rotator, OP And), nevertheless their masses and situation on the H-R diagram are similar to the most known single active giants, and according to the recent theoretical studies, the conditions in the convective envelopes of these two groups stars should be similar.

4. The first results of the activity study in four M giants (EK Boo, 15 Tri, 42 Her and HD 187372) revealed CaII K&H, Halpha and CaI 6572.8A variability in one of them, EK Boo. Considering this fact together with its enhanced and variable X-ray emission and fast rotation rate, Vsini=11 km/s, we concluded that these properties are probably due to magnetic activity (Hunsch et al. 2004). All these stars are low mass ones and are situated at the tip of the RGB and on the AGB.

The detailed study of the active giants revealed that:

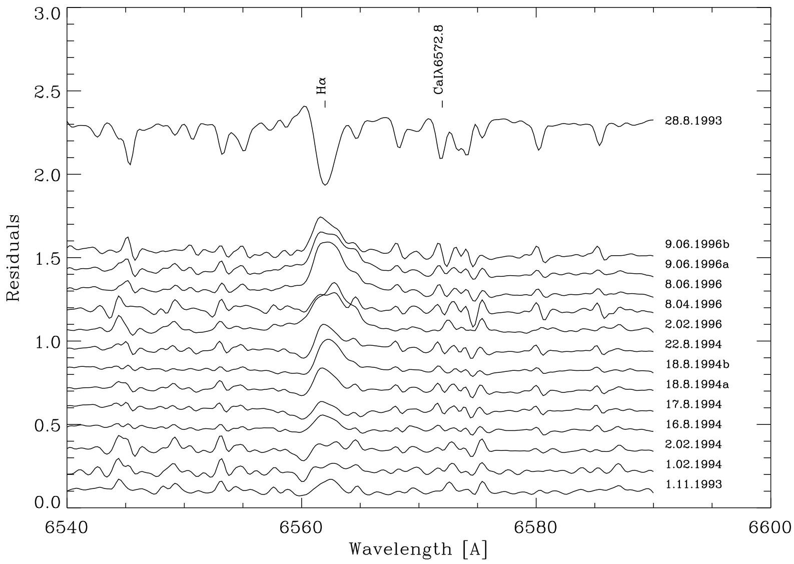

Fig. 1. H_α variability in OP And. All the spectra are subtracted from the first spectrum obtained on 28.8.1993 and the residuals are shown.

1.OP And, a K1 giant of 1.6 $M_\odot$ at the end of the first dredge-up phase has strong variability in the activity indicators H_α and CaI 6572.8 A as shown in Fig.1 (Konstantinova-Antova et al. 1995). Its rotational period is determined to be 76d (Strassmeier& Hall 1988; Konstantinova-Antova 2001a). Flares (Fig.2) were also detected (Konstantinova-Antova & Antov 2000). The star appears at the right from the Mg dividing line (Fig.3) and shows evidences for mass loss. It is suspected as a hybrid star (Konstantinova-Antova et al. 2005a).

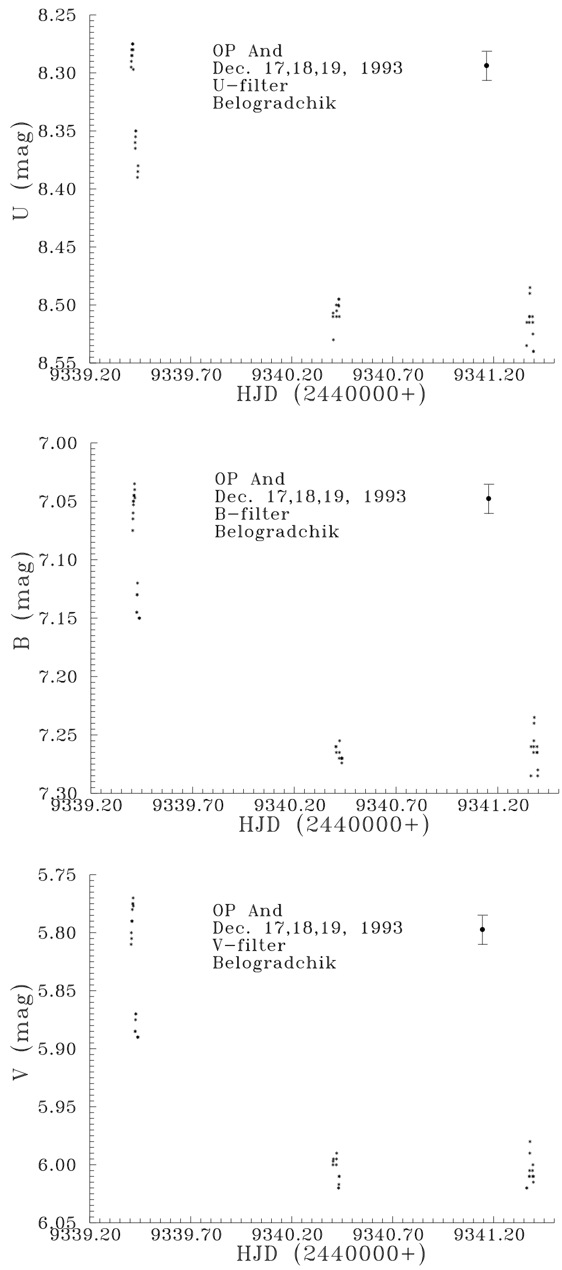

Fig. 2. Flare detected in OP And.

2.V390 Aur, a G8 giant of about $2M_{\odot}$ at the first dredge-up region on the H–R diagram shows rotational modulation due to spots with a period

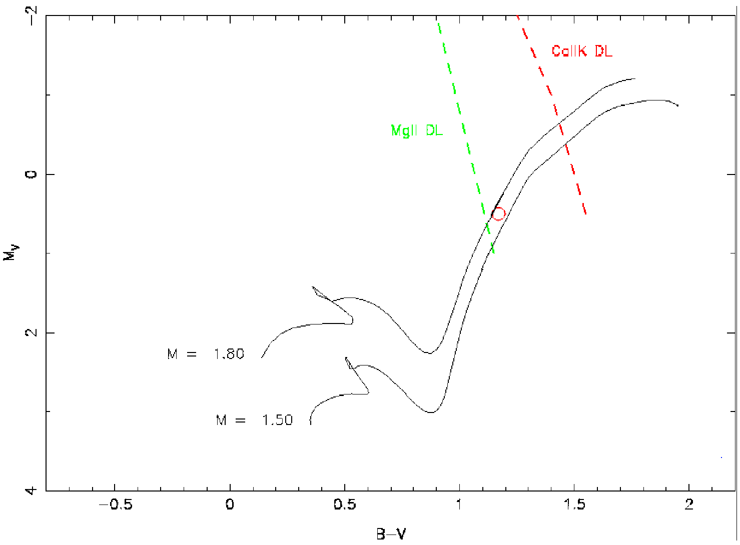

Fig. 3. The situation of OP And on the H-R diagram regarding the MgII and CaII dividing lines.

of 9.8d (Strassmeier & Hall 1988), optical (Fig.4) and X-ray flare activity (Konstantinova-Antova et al. 2000; Konstantinova-Antova et al. 2005b; Gondoin 2003).

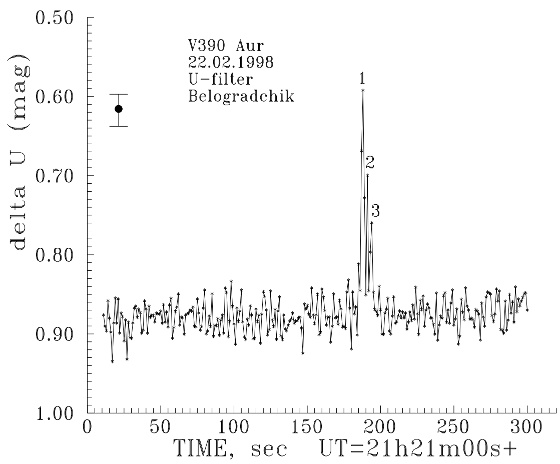

Fig. 4. A complex flare observed in V390 Aur.

3.HD112989 = 37 Com, a G9 III-II class star of about $5M_\odot$ supposed to be evolved to the He-burning region of the H-R diagram has a weaker activity level according to spectral activity indicators and photometric variability (de Medeiros et al. 1999).

4.HD145001 = κ Her A, a G8 III intermediate mass star situated in the first dredge-up region posses a weaker activity level, found on the basis of spectral activity indicators and photometry (Konstantinova-Antova 2001a).

5.EK Boo, a M5 III single star situated at the tip of the red giant branch (RGB) or at the assymptotic giant branch (AGB) exhibits spectral and X-ray variability and is a relatively fast rotator for its evolutionary stage (Hünsch et al. 2004).

6.HD121107, a G5 III star in the Hertzsprung gap remained suspected in activity. The object has enhanced X-ray emission and photometric variability from time to time (Gondoin 1999; Lockwood et al. 1997). No CaII K & H emission cores were detected (Konstantinova-Antova 2001a).

7.HD185358 an intermediate mass, evolved slight after the base of the RGB, well-mixed star has an enigmatic behavior. Its Vsini = 10 km/s. But, no evidences for activity were found during several years of observations (Konstatinova-Antova 2001a).

The situation of the known active giants on the tracks for the evolution of the rotation after the MS presented in Pasquini et al. (2000)explains partly the origin for their fast rotation (Fig. 5). For the more massive active stars (M greater than 2 $M_{\odot}$) it appears a remnant from their fast rotation at the MS. For stars with smaller masses, however, this could not be the case, because they deviate up the rotational tracks and some additional angular momentum is required to explain their fast rotation and activity (Konstantinova-Antova 2001b).

In conclusion of this study, it appeared that magnetic activity do exist in single late-type giants, but may be not so common among them. The reasons for fast rotation, magnetic activity and abundance anomalies in some single stars at advanced evolutionary stages remained still unexplained and required further observational and theoretical efforts for a better understanding of the conditions in the stellar interiors along the RGB and beyond. On the other hand, the proper time-dependent activity behavior in single late-type giants required further observations, nevertheless our first results obtained in this direction (Konstantinova-Antova, 2001b).

The "New age": magnetic field study in G,K,M single giants with Narval and ESPaDOnS

After 2005, new sensitive spectropolarimetric equipments were mounted at the 3.6m CFHT (Hawaii) and 2m TBL (Pic du Midi, France). They allow not only studies on spectral lines activity indicators, but also on magnetic fields. The new generation spectropolarimeters make available a precise detection of magnetic fields of few Gauss and even less. Using the spectro-polarimeters Narval and ESPaDOnS (Auriére 2003) we began an extensive program for magnetic field study in single G-K-M giants (Konstantinova-Antova et al. 2008a). Our new sample contained 59 stars, selected on the basis of some evidences for magnetic activity and/or fast rotation. In this way, 10 G and K fast rotators, mostly studied for activity before at NAO - Rozhen (Konstantinova-Antova 2001a) and by Fekel & Balachandran (1993), 17 slow rotators taken from Gondoin(1999) and Tarasova (2002), 7 thermohaline deviants (Charbonnel, priv.

comm.), 9 M giants (Hünsch et al. 1998; Zamanov et al. 2008), for 4 of them, activity indicators studies were carried out before at NAO (Hünsch et al. 2004), and 16 bright giants (CFHT snapshot program) were observed.

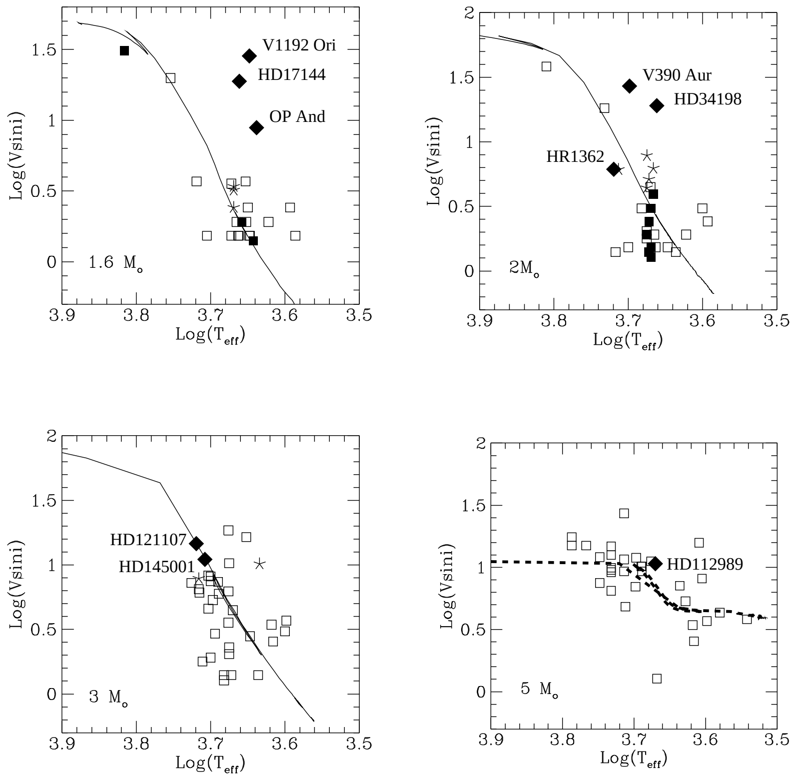

Fig. 5. Situation of some active late-type single giants on the tracks for the evolution of the rotation after the main sequence, adopted by Pasquini et al. (2000).

We aimed to answer the question about the origin of the magnetic field and activity in giant stars - for the faster rotators: planet engulfment in faster rotators, or angular momentum dredge-up from the interior as a result of the stellar evolution, or remnant fast rotation from the MS for the more massive of the active giants. For the slower rotators: remnant magnetic fields from Ap stars (Stepien 1993) or a turbulent dynamo (Brandenburg 2001). Also, we aimed to study the dynamo regimes in RGB and AGB stars, the range and properties of the activity and how long it lasts.

Our observations covered the period 2007 - 2012 and were carried out at TBL, Pic du Midi Observatory and CFHT at Hawaii. Each star was observed at least 2-3 times, and for many stars with detected magnetic field we organized a monitoring to study their magnetic field and spectral activity indicators behavior.

For detection and measurement of the magnetic field we applied the Least Squares Deconvolution (LSD, Donati et al. 1997). This cross-correlation method uses thousand of absorption lines from the spectrum and improves the S/N ratio. It obtains the mean profiles of Stokes I and V and detects weak magnetic signatures which would not be visible in individual lines.

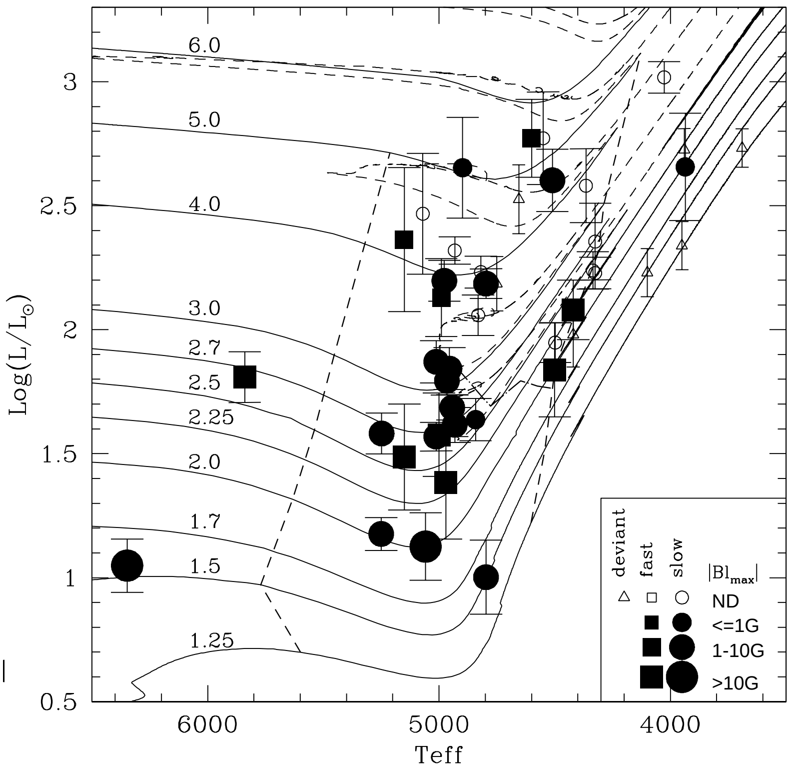

Fig. 6. Situation of the studied G and K single giants on the H-R diagram The giants with faster rotation (Vsini greater than 8 km/s) are designated by squares. Open symbols stand for non-detected stars, triangles stand for the deviants. The two vertical dashed lines indicate the region of the first dredge-up. The evolutionary tracks are from the standard models of Charbonnel & Lagarde 2010.

For the cool giants, the method enables to average about 12 000 lines to get Stokes I and Stokes V profiles with greatly improved S/N. The longitudinal magnetic field B_l is computed in Gauss using the first moment method (Donati et al. 1997; Rees& Semel, 1979). The method and the equipment enable a precise B_l determination with an accuracy of the order one G and even less for our sample stars.

G and K giants

The Zeeman observations of V390 Aur, our first detected giant (Konstantinova-Antova et al. 2008b), were very encouraging and we continued with a larger sample of G and K giants. Later, 26 of the observed sample G and K giant stars were Zeeman detected. The longitudinal magnetic field B_l is in the interval 0.25 - 100 G. They are mainly late-type giants with some evidences for activity observed at TBL and 3 giants from the CFHT snapshot program. None of the deviants were detected. Their evolutionary status has been determined on the basis of their T_{eff}, M_{bol}, calculated using Hipparcos parallaxes and the evolutionary models by Charbonnel & Lagarde (2010).

The situation of our sample G and K stars on the H–R diagram is presented in Fig.6. Also, for 17 stars with known rotational periods P_{rot}, we plotted the absolute values of the maximal longitudinal magnetic field B_l detected versus P_{rot} and the same we did for the S – index of the CaII H & K emission cores (Fig.7). We found, that most of the detected stars are situated in the first dredge-up phase on the HRD (Fig.6). Few isolated cases appear in the Hertzsprung gap, He-burning region and tip of the RGB. No stars with mass less 1.5 $M_{\odot}$ are detected indicating that for our Zeeman detected giants the MS progenitors are of spectral class F0-2 and earlier. The clumping of the stars near the base of the RGB, rules out the planet engulfment hypothesis for the fast rotators, because in a case of planet engulfment, we should observe fast rotating active giants along the whole RGB. A clear dependence on rotation for periods up to 200 days is found in 14 of our sample giants with known rotational period, and the S-index has similar behavior as $|B_l|$ max. That means, that one and the same type dynamo operates in both so-called in the past "fast"and "slow" rotators on the RGB (Vsini=8 km/s as a criterium, i.e.about 3 times the average value of Vsini for G and K giants (de Medeiros et al. 1996)). All these facts lead us to the conclusion that the dynamo operation in intermediate–mass RGB stars is likely a result of changes in the interior structure due to the evolution of the star after the MS. It is also possible, the interiors of the slower rotators with detected magnetic field to rotate faster than surface, enabling α - ω dynamo to operate also there (Schröder et al. 1998).

For some deviants for this relationship, stars that rotate slowly, but have a stronger magnetic field, like EK Eri and β Cet the most likely explanation is that they originate from Ap stars on the MS (Aurière et al. 2008, 2011; Tsvetkova et al. 2013).

Zeeman Doppler Imaging for selected G,K giants

For 7 giants with detected magnetic field, we began a program for studying the surface distribution of their magnetic fields. The Zeeman Doppler Imaging technique (ZDI, Donati et al. 2006a and b) was applied for reconstruction of the radial, azimuthal and meridional surface field in V390 Aur, HD232862, OP And, 37 Com, EK Eri, beta Cet, Pollux. We have already maps for 5 of them: V390 Aur (Konstantinova-Antova et al. 2012), HD232862, OP And (Konstantinova-Antova et al. 2013) - fast rotators, EK Eri (Aurière et al. 2011) and for β Cet (Tsvetkova et al. 2013) - slow rotators and Ap star descendants.

Magnetic field in M giants

Until recently, M giants were not known to host surface magnetic fields. Nevertheless the theoretical predictions for dynamo operation on the Asymptotic Giant Branch (AGB), (Soker & Zoabi, 2002; Nordhaus et al. 2008, Brandenburg 2002) data on magnetic activity in such stars are rare and indirect (Hünsch et al. 1998; Karovska et al. 2005; Herpin et al. 2006). Here we present our results on the magnetic field study of 9 single M giants.

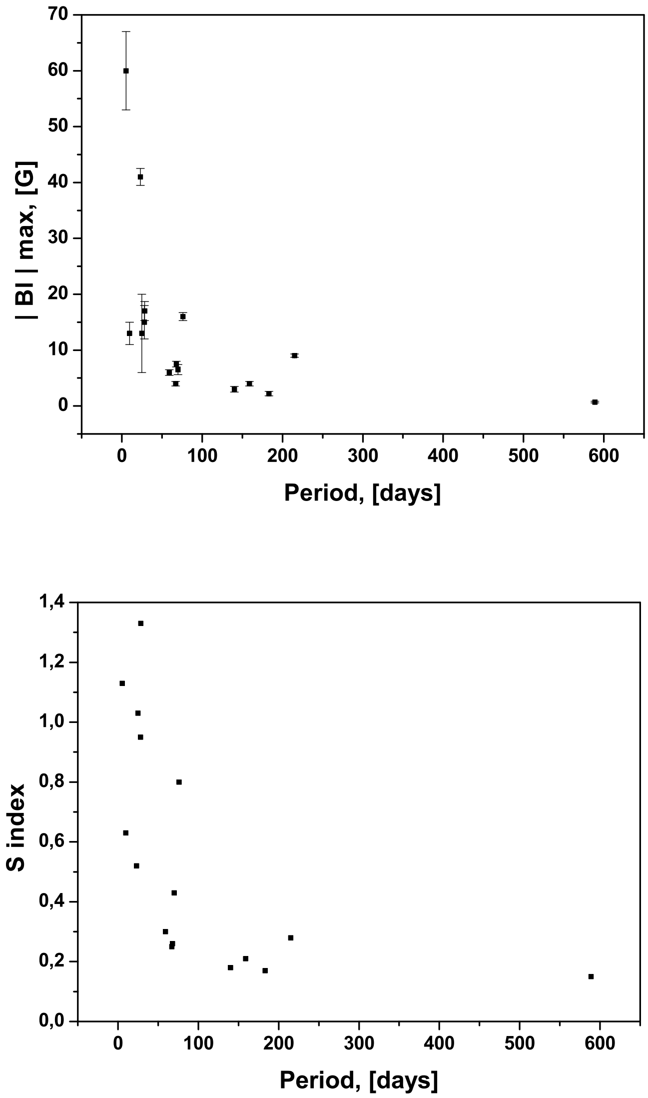

Fig. 7. Dependence of the maximal absolute value $|B_l|_{max}$ of the longitudinal magnetic field and S-index on P_{rot} for G and K giants with known P_{rot}. EK Eri (P=306 d), an Ap star descendant with a strong magnetic field, is excluded from the figure for a better visibility of the relationship. Another candidate for Ap star descendant, β Cet (P=215d) presents in the figure, but deviates the relationship.

These are stars of spectral class M0–M6 and were selected on the basis of their faster rotation (Zamanov et al. 2008) and/or X-ray emission (Hünsch et al. 1998). They were observed with Narval at TBL on snapshot basis since 2008 till the end of 2011. For one of them, EK Boo we have also studied the magnetic field variability (Konstantinova-Antova et al. 2010).

For seven of our nine M giants a magnetic field was detected. Relevant data for them are presented in Table 1. For these stars the behavior of the magnetic field is characterized by periods of detection followed by periods of non-detection. This fact is indicative that magnetic fields are not distributed uniformly at the stellar surface. There are hints for a dependence of $|B_l|$ max on Vsini (Fig. 8). The sample stars have masses between 1 and 4 $M_\odot$ and are located on the AGB and close to the tip RGB (Konstantinova-Antova et al. 2010).

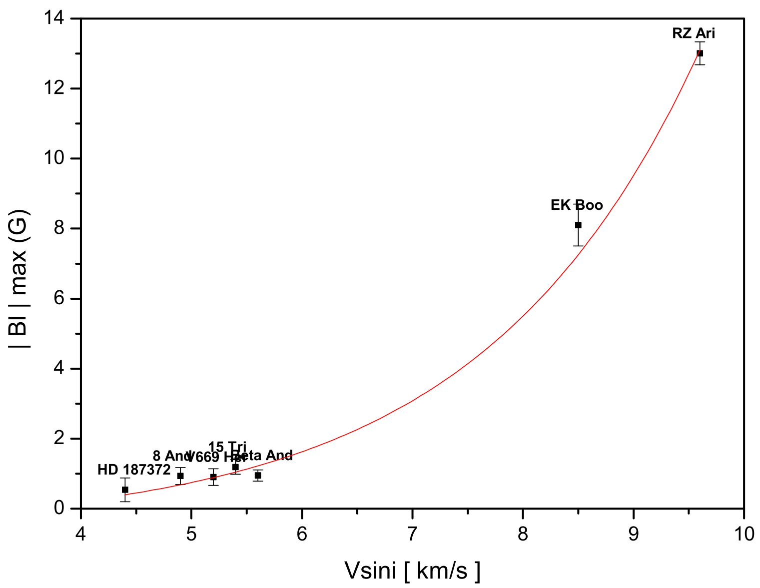

Fig. 8. Dependence of $|B_l|_{max}$ on Vsini for the detected M giants.

Dynamo operation in M giants and activity properties

On the AGB (i.e. after the He-core burning) intermediate-mass stars have a complex internal structure: inert C-O core, He- and H-burning shells, and a very extended convective envelope. On the early-AGB phase the second dredge-up takes place and begins when the nuclear fuel is exhausted and the core begins to contract, while the convective envelope expands and cools (e.g. Herwig, 2005). During this phase, we may expect some dredge-up of angular momentum together with that of chemicals from the faster rotating core. The existence of turbulent motions and fast rotation could result in dynamo action of $\alpha - \omega$ type, as described in Nordhaus et al. (2008). The other possibility for the faster rotation obesrved recently in some M giants (Zamanov et al. 2008; Massarotti et al. 2008) is a planet engulfment at the tip of the RGB to accelerate the stellar rotation.

The dependence of B_l max on Vsini is in support of an $\alpha - \omega$ dynamo being in operation during this evolutionary stage as predicted by Nordhaus et al. (2008). More studies of the MF behavior in these stars are required. Maps of the surface MF in M giants could give more information about the dynamo type, too. The work is under progress for 2 M giants.

Table 1. Data for the sample of M giants. DD stands for definite detection, MD-mediate detection, nd - no detection.

Star	Other Name	Sp class	vsini km/s	log Lx	Detection	Bl max G	σ G
HD130144	EK Boo	M5III	8.5	30.30-31.50	DD	-8.10	0.60
HD6860	beta And	M0III	5.6		DD	-0.95	0.16
HD16058	15 Tri	M3III	5.4	30.80	DD	1.19	0.21
HD18191	RZ Ari	M6III	9.6		DD	13.01	0.33
HD150450	42 Her	M2.5III	2.5	29.41	nd		
HD167006	V669 Her	M3III	5.2		DD	-0.90	0.24
HD184786	V1743 Cyg	M5III	7.8		nd		
HD187372		M2III	4.4	30.64	MD	0.54	0.34
HD219734	8 And	M2III	4.9		MD	-0.93	0.24

The other possibility for dynamo operation on the AGB is the turbulent dynamo, where the turbulent motions may lead to field amplification and restoration of the poloidal component (Brandenburg, 2002). However, such a dynamo is expected to be less efficient than the $\alpha - \omega$ one on the AGB. Indeed Soker & Zoabi (2002) estimated that in these stars magnetic field can reach value less than 1G only. This is not consistent with what we observe in EK Boo and RZ Ari.

In conclusion, our first study for magnetic fields and their variability in nine single M giants found that magnetic field is detected in seven of them, and its variability is studied in three of them. Our sample unveils a new class of magnetically active stars. The magnetic field variability (periods of detection followed by periods of non-detection) favors the assumption for a non-uniform surface distribution of the magnetic areas in these stars. There are hints on dependence of the max $|B_l|$ on Vsini indicating that the dynamo depends on rotation in these M giants. Further study of the surface magnetic field distribution in selected stars using ZDI could give more knowledge about the dynamo regime in the advanced evolutionary stages.

Conclusion

Starting our study two decades ago, we believed that magnetic activity in single late-type giants exists only in a small number of stars, mostly fast rotating ones.

Our first results confirmed, that magnetic activity exists in single late giants and that these active stars are situated near the base of the RGB, during their first dredge-up phase. Because of the small number of such stars, we supposed that some special conditions play role for their fast rotation and activity.

Our further study on the magnetic activity and its properties in a sample of 59 single G,K and M giant stars with different rotation, situated at RGB, He-burning phase, tip of the RGB and AGB, revealed that magnetic field and activity is more common than expected before and present in about 50 percents of these stars.

Two reasons for magnetic activity in the single G and K giants exist:

1. Some of them, stars with long rotation periods, but with strong magnetic field and activity, are descendants of Ap stars on the main sequence like EK Eri, 14 Cet, β Cet (Auriére et al. 2008, 2011, 2012; Tsvetkova et al. 2013);

2. For the rest G and K giants we find a dependence of the magnetic field strength (and also of the S-index) on the rotation period for periods up to 200 days and conclude that $\alpha - \omega$ type dynamo is responsible for the magnetic field generation and activity in them. These are intermediate mass stars and most of them are situated near the base of the RGB, experiencing the first dredge-up phase (Auriére et al. 2013, in prep.). For giants with longer periods, we haven't sufficient data to verify if this relationship still exists, nevertheless, it might be still valid (e.g. Pollux, Auriére et al. 2009, 2013).

3.All so-called fast rotating giants (periods less than 70 days) are situated in the first dredge-up phase. This result could not be explained by the hypothesis of planet engulfment and favours the angular momentum dredge-up as an explanation for the fast rotation and dynamo operation in the stars with masses below 4 $M_{\odot}$. For the more massive ones, fast rotation may be a remnant of the rotation they had on the MS.

4.Significant part of the studied M giants are Zeeman detected. They are situated either at the tip of RGB or in the early AGB phase. A dependence of the magnetic field strength on Vsini is found that is indicative that $\alpha - \omega$ dynamo may be a possible reason for their magnetic field and activity.

Nevertheless all these results, because our sample of stars is biased by its selection on the basis of some activity signatures and/or fast rotation, it cannot answer the question about the percentage of the active single late-type giants among all of them. Further study of a volume limited sample single late-type giants in the Solar vicinity, available for observations with Narval at TBL is in progress. This study aims to answer the question how common is the magnetic activity among the stars on the red giant branches and to give a more global view on the evolution of the stellar magnetism in small and intermediate mass stars after the main sequence - from the Hertzsprung gap up to the AGB phase.

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