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The exceptional Herbig Ae star HD 101412: The first detection of resolved magnetically split lines and the presence of chemical spots in a Herbig star*

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In our previous search for magnetic fields in Herbig Ae stars, we pointed out that HD 101412 possesses the strongest magnetic field among the Herbig Ae stars and hence is of special interest for follow-up studies of magnetism among young pre-main-sequence stars. We obtained high-resolution, high signal-to-noise UVES and a few lower quality HARPS spectra revealing the presence of resolved magnetically split lines. HD 101412 is the first Herbig Ae star for which the rotational Doppler effect was found to be small in comparison to the magnetic splitting and several spectral lines observed in unpolarized light at high dispersion are resolved into magnetically split components. The measured mean magnetic field modulus varies from 2.5 to 3.5 kG, while the mean quadratic field was found to vary in the range of 3.5 to 4.8 kG. To determine the period of variations, we used radial velocity, equivalent width, line width, and line asymmetry measurements of variable spectral lines of several elements, as well as magnetic field measurements. The period determination was done using the Lomb-Scargle method. The most pronounced variability was detected for spectral lines of He I and the iron peak elements, whereas the spectral lines of CNO elements are only slightly variable. From spectral variations and magnetic field measurements we derived a potential rotation period $P_{\rm rot}$=13.86 d, which has to be proven in future studies with a larger number of observations. It is the first time that the presence of element spots is detected on the surface of a Herbig Ae/Be star. Our previous study of Herbig Ae stars revealed a trend towards stronger magnetic fields for younger Herbig Ae stars, confirmed by statistical tests. This is in contrast to a few other (non-statistical) studies claiming that magnetic Herbig Ae stars are progenitors of the magnetic Ap stars. New developments in MHD theory show that the measured magnetic field strengths are compatible with a current-driven instability of toroidal fields generated by differential rotation in the stellar interior. This explanation for magnetic intermediate-mass stars could be an alternative to a frozen-in fossil field.

1 Introduction

It is generally accepted that accretion from a disk is an integral phase of star formation. A number of Herbig Ae stars and classical T Tauri stars are surrounded by active accretion disks and, probably, most of the excess emission seen at various wavelength regions can be attributed to the interaction of the disk with a magnetically active star (e.g. Muzerolle et al. 2004). This interaction is generally referred to as magnetospheric accretion. Recent magnetospheric accretion models for these stars assume a dipolar magnetic field geometry and accreting gas from a circumstellar disk falling ballistically along the field lines onto the stellar surface.

In our recent study, we reported new detections of a magnetic field at a level higher than 3σ in six Herbig Ae stars (Hubrig et al. 2009). In that work, the largest longitudinal magnetic field, $\langle B_{\rm z}\rangle = -454\pm42$ G, was detected in the Herbig Ae star HD 101412 using hydrogen lines. The presence of a magnetic field in this star was already reported by Wade et al. (2005), who suggested an age of $\sim$2 Myr. HD 101412 was observed by us on two consecutive nights in May 2008, revealing a change of the mean longitudinal magnetic field strength by $\sim$100 G, from $\langle B_{\rm z}\rangle = -454\pm42$ G to $\langle B_{\rm z}\rangle = -317\pm35$ G. As we already reported in this previous study, UVES spectra retrieved from the ESO archive exhibited a conspicuous variability of metal lines reminiscent of peculiar main-sequence magnetic Ap stars. Since the age of HD 101412 is only $\sim$2 Myr this star is observed at an evolutionary stage where the magnetic field plays a critical role in controlling accretion and stellar wind. Hence, the magnetic nature of this object makes it a prime candidate for studies of the relation between magnetic field and physical processes occurring during stellar forma-

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tion. In this work we present a more detailed study of the magnetic field and spectral variability of this unique Herbig Ae star based on high-resolution high signal-to-noise UVES spectra and a few lower quality HARPS spectra acquired during 2009.

2 Observations and measurements

2.1 Spectroscopic material

Since this star exhibits the strongest magnetic field and hence is of special interest, we applied for observing time with UVES at Kueyen/UT2 at the VLT to obtain multi-epoch high-resolution spectra in service mode to study the magnetic field, to characterise the behaviour of the chemical elements on the surface of HD 101412, and to determine the rotation period. Due to the replacement of the UVES red mosaics MIT CCD by another chip with an improved quantum efficiency in the far red optical spectral region in May-July 2009, instead of the requested 12 UVES spectra it was only possible to obtain five UVES spectra. In these observations we used the UVES DIC2 390+760 standard setting covering the spectral range from 3290 Å to 4500 Å in the blue arm and the spectral range from 5680 Å to 9460 Å in the red arm. The slit width was set to $0\farcs3$ for the red arm and $0\farcs4$ for the blue arm, corresponding to a resolving power of $\lambda/\Delta\lambda \approx 110,000$ and $\approx 90,000$, respectively. The spectra have been reduced with the software packages in the MIDAS environment provided by ESO to extract one-dimensional spectra. Four additional spectra were taken during technical tests with the HARPS spectrograph installed at the 3.6 m telescope on La Silla on June 3 2009 and July 4 2009. The spectra cover the spectral range from 3780 Å to 6860 Å. To enlarge our material we also use in this study high-resolution UVES spectra with the standard setting RED580 in the spectral range 4780 Å to 6808 Å available from the ESO archive. These spectra were taken at a resolution of $\sim$80,000.

The logbook of the available spectroscopic observations is presented in Table 1. In the first column we indicate the spectrograph and the setting used. The MJD values for the middle of each exposure are listed in Column 2 and in Column 3 we present achieved signal-to-noise ratios (S/N) in the spectral region around 6150 Å. The radial velocities listed in Column 4 were measured using numerous Fe lines. The measurement accuracy is of the order of 0.1 km s^{-1} for UVES spectra and 0.3 km s^{-1} for HARPS spectra.

In Fig. 1 we present the most prominent emission features appearing in the Hα and Hβ lines. Double-peaked Hα emission lines indicate the presence of a temporal variability of the circumstellar disk. Temporal variability is also clearly detectable in the Hβ and other Balmer lines. van der Plas et al. (2008) suggest that the disk of HD 101412 is in transition between flaring and being self-shadowed.

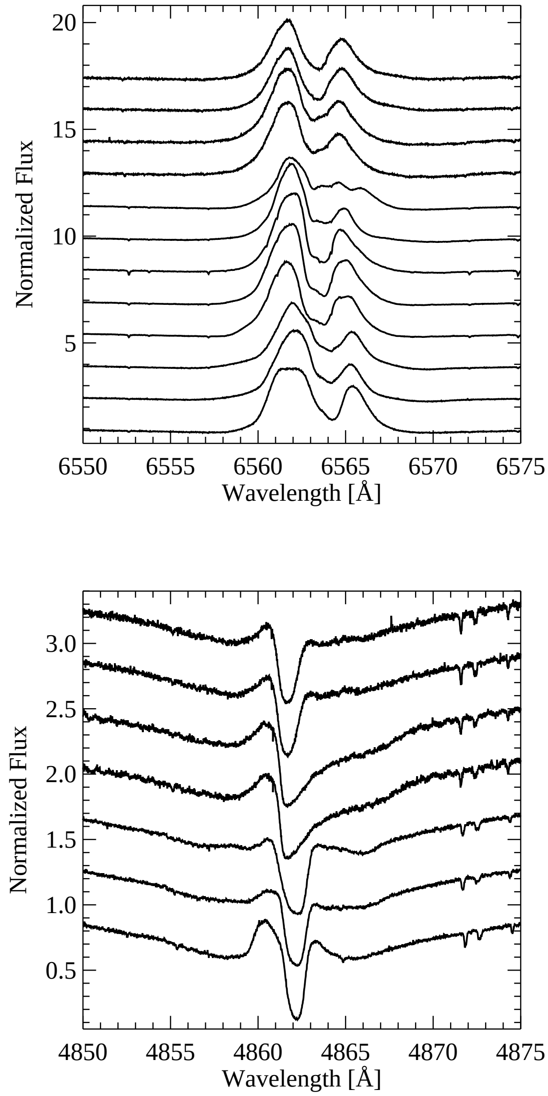

Fig. 1 UVES and HARPS spectra of HD 101412 obtained at different epochs in spectral regions around the Hα line (top) and the Hβ line (bottom). The spectra are presented with MJD dates increasing from bottom to top and offset in vertical direction for clarity. Please note that Hβ falls into the gap of the UVES DIC2 390+760 setting.

2.2 The mean magnetic field modulus

Our previous inspection of three UVES spectra retrieved from the ESO archive, which were recorded on three different dates, indicated distinct variations of line intensities and spectral profiles. Specifically, the Zeeman doublet Fe II at λ 6149.258, which is the best diagnostic line to detect surface magnetic fields in slowly rotating classical Ap stars with strong magnetic fields, appeared slightly resolved, indicating the presence of a rather strong surface magnetic field. The study of this Zeeman doublet in magnetic stars presents an excellent opportunity to determine

Table 1 Logbook of the spectroscopic observations of HD 101412, and of the magnetic field measurements.

Instrument	MJD	S/N	RV [km s^{-1}]	$\langle B \rangle$ [kG]	$\langle B_q \rangle$ [kG]
UVES RED 580	53870.986	180	17.28	3.52	4.85
UVES RED 580	53872.041	220	16.72	2.97	4.25
UVES RED 580	53919.996	150	15.79	2.60	3.81
UVES DIC2 390+760	54928.120	340	16.40	2.65	3.76
UVES DIC2 390+760	54930.076	320	16.36	2.53	3.55
UVES DIC2 390+760	54936.153	310	17.37	2.51	2.90
UVES DIC2 390+760	54943.151	305	16.11	2.73	3.53
UVES DIC2 390+760	54951.065	315	17.06	2.87	3.52
HARPS	54985.116	75	16.56	2.54	–
HARPS	54985.131	80	16.46	2.58	–
HARPS	55017.000	90	16.96	2.79	–
HARPS	55017.018	85	16.78	2.75	–

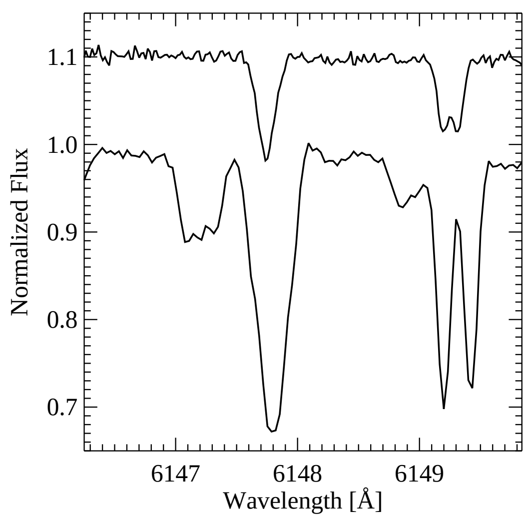

Fig. 2 Portion of the spectra of HD 101412 (vertically shifted in intensity by 0.1 for clarity) and of the typical Ap star HD 116458 containing the lines of Fe II λ 6147.741 and λ 6149.258.

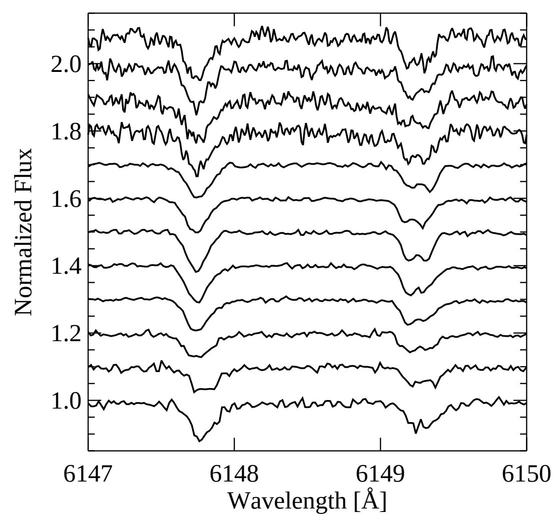

Fig. 3 Line profile variations of the Zeeman doublet Fe II λ 6149.258 in UVES and HARPS spectra obtained at different epochs. The spectra are presented with MJD dates increasing from bottom to top.

in a straightforward, mostly approximation-free, model-independent way, and with particularly high precision the mean magnetic field modulus $\langle B \rangle$, that is, the average over the visible stellar hemisphere of the modulus of the magnetic vector, weighted by the local line intensity. The newly acquired UVES spectra confirm our previous suspicion of the presence of magnetically split Zeeman patterns. In Fig. 2 we present the Fe II λ 6149.258 line exhibiting a resolved Zeeman doublet structure at MJD 54936.153. For comparison, we present in the lower panel of this figure a typical example for splitting in the spectrum of the bright A0p star HD 116458, with a magnetic field modulus of the order of 4.7 kG.

In the approximation of the linear Zeeman effect, the mean magnetic field modulus is related to the wavelength separation of the Zeeman components through the relation

$$\langle B \rangle = \Delta\lambda / (9.34 \cdot 10^{-13}\ \lambda_c^2\ g_{\rm eff}),$$

where $\langle B \rangle$ is the mean magnetic field modulus in Gauss, $\lambda_{\rm c}$ is the central wavelength of the line in Å, $\Delta\lambda$ is the wavelength separation between the centroids of the σ-components and $g_{\rm eff}$ is the effective Landé factor. The wavelengths $\Delta\lambda$ of the centres of gravity of the split doublet components are usually determined either by direct integration of the whole component profiles or by fitting a Gaussian simultaneously to each of them (see Mathys et al. 1997 for more details). The multi-Gaussian fitting is preferred in our measurements since the λ 6149.258 line is only marginally

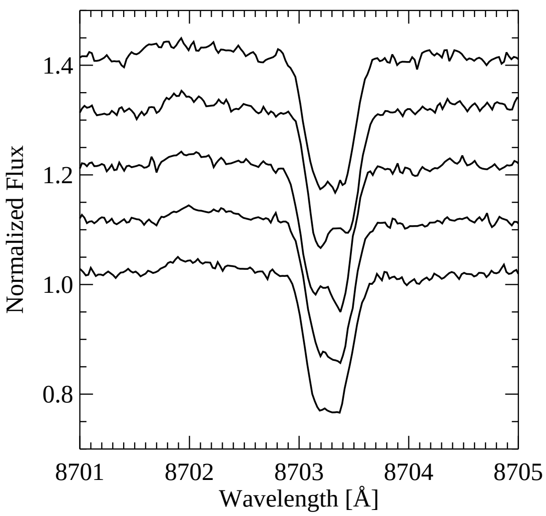

Fig. 4 Variations of the observed profile of the Zeeman doublet N I λ 8703.24 in the five UVES spectra obtained in the near-IR spectral region. The spectra are presented with MJD dates increasing from bottom to top.

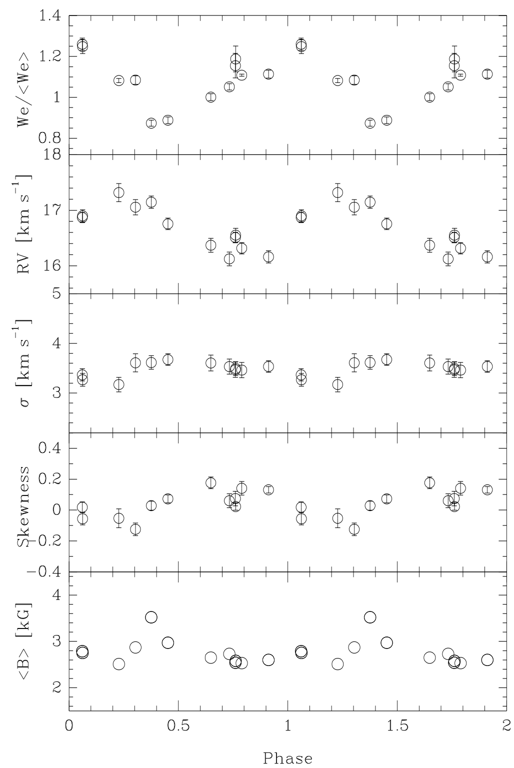

Fig. 5 Variations of equivalent width, radial velocity, line width, line asymmetry, and mean magnetic field modulus as a function of the rotational phase.

resolved. The typical standard deviation of our measurements is of the order of ≈30–50 G obtained for the spectra in which the Zeeman components are well resolved and mostly symmetric. In the worst cases, using the spectra with low S/N, the accuracy of the measurement is of the order of 100–200 G. The results of our measurements are presented in Column 5 of Table 1. The observed variable asymmetry of the split components is usually explained by the variable combination of Zeeman and Doppler effects across the stellar surface. The behaviour of the red and blue split components of the Fe II λ 6149.258 line in all available spectra of HD 101412 is presented in Fig. 3. In the same Figure the neighbouring line Fe II λ 6147.741, which is a Zeeman pseudo-quadruplet, appears variable too. At the epoch MJD54936.153 the shape of Fe II λ 6147.741 is clearly triangular indicating that the σ-components of the line are very weak at this rotation phase due to the predominance of a transversal field.

An additional example of a Zeeman split doublet is presented in Fig. 4. The line N I λ 8703.24 arises from a transition between two levels having a total angular momentum quantum number J=1/2, of which one has a Landé factor equal to zero (that is, this level is unsplit in a magnetic field). Partial splitting was also detected in Fe I lines at λ 4259.997 and λ 6336.82, and in the Fe II line λ 6238.392. The field modulus measured in the spectral lines with the most evident splitting is in good agreement with our measurements using the Fe II λ 6149.258 line.

2.3 The mean quadratic magnetic field

Another approach to study the presence of magnetic fields is to determine the value of the mean quadratic magnetic field,

$$\langle B_q \rangle = (\langle B^2 \rangle + \langle B_z^2 \rangle)^{1/2},$$

which is derived through the application of the moment technique, described in detail by Mathys (1995) and Mathys & Hubrig (2006). Here, $\langle B^2 \rangle$ is the mean square magnetic field modulus (the average over the stellar disk of the square of the modulus of the field vector, weighted by the local emergent line intensity), while $\langle B_z^2 \rangle$ is the mean square longitudinal field (the average over the stellar disk of the square of the line-of-sight component of the magnetic vector, weighted by the local emergent line intensity). The mean quadratic magnetic field is determined from the study of the second-order moments of the line profiles recorded in unpolarised light (that is, in the Stokes parameter I). The analysis is usually based on a consideration of samples of reasonably unblended lines of Fe I and Fe II in spectra with a rather high S/N. Our measurements using exclusively UVES spectra, which have higher S/N compared to HARPS spectra, are presented in the last column of Table 1. The accuracy of measurements of $\langle B_q \rangle$ is usually less than for the measurements of the mean magnetic field modulus, accounting for 0.3–0.6 kG in our study. Interestingly, the lowest quadratic field $\langle B_q \rangle$=2.9 kG was measured at the epoch

MJD54936.153, where the shape of Fe II λ 6147.741 appears triangular (Fig. 3, sixth spectrum from the bottom). This low value is probably due to a smaller contribution of the mean longitudinal magnetic field. Clearly, to properly constrain the magnetic field geometry, additional spectropolarimetric measurements including the measurement of the longitudinal magnetic field to better sample the rotation phases of HD 101412, are necessary.

2.4 Spectrum variability

The inspection of our spectroscopic material indicates the presence of the elements He, C, N, O, Na, Mg, Al, Si, S, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Zn, Sr, Y, Zr, and Ba. Almost all spectral lines show variations in line intensity and line profile, with the most pronounced variability detected for lines of the elements He, Si, Mg, Ca, Ti, Cr, Fe Sr, Y, Zr, and Ba. Since also the magnetically insensitive lines show clear profile variations, we assume that the detected spectral variability is a combination of both Zeeman splitting and abundance spots. The potential period of variations, which we assume to correspond to the rotation period, analogous to magnetic Ap stars, was determined from line profile variations and the magnetic field modulus measurements.

The line profiles of the Fe lines have been characterized calculating the first statistical moments of the flux distribution within the line profiles. Twenty Fe lines have been measured, from which the mean value and its standard error were calculated. A probable rotation period of P_{rot}=13.86 d was derived from the measurements of radial velocity, equivalent width, and magnetic field modulus, using the Lomb-Scargle method (Press & Rybicki 1989). In Fig. 5 we present the variations of equivalent width, radial velocity, line width, line asymmetry, and mean magnetic field modulus as a function of the rotational phase. To combine the equivalent widths for different spectral lines, the measurements of the individual lines were normalised with the mean value for each spectral line. Thus, the upper panel shows the typical fractional variation in the equivalent width of the Fe lines.

The variations of the measured parameters are significant and are correlated with each other, as it is expected for the presence of abundance patches on the surface: for example, there is a 1/4 cycle shift between the equivalent width curve and the radial velocity curve. At phase zero, when the equivalent width of the Fe lines is at maximum and the radial velocity in increasing, the region with the largest Fe abundance would be facing the observer. The maximum of the surface magnetic field corresponds to the minimum of the Fe abundance. We note that the number of spectra is rather small and further observations are needed to confirm this periodicity.

An example of the line profile variations for a few elements with this period is presented in Fig. 6. Our study reveals that the character of variability is different for different elements, as it is usually expected for a horizontal inhomogeneous element distribution over the stellar surface of Ap stars. Further, the profiles of Mg II λ 4481 and of the Ca II K lines exhibit strong broad wings and sharp cores, which cannot be fitted with the same abundance, hinting at a vertical stratified abundance of these elements. Such appearance and variations of metal line profiles are reminiscent of chemically peculiar main-sequence magnetic Ap stars, where the variability of chemical elements, especially of rare earth elements, is one of the defining characteristics. On the other hand, no spectral lines belonging to exotic elements, such as the lanthanide rare earths, or heavier elements were identified in our spectra. We note that this is the first time the presence of element spots is detected on the surface of a Herbig Ae star.

Preliminary indications from the Fe I/Fe II equilibrium, as well as Balmer profile fits suggest that the temperature is lower than the values one might infer from the spectral type B9/A0V. We estimate $T_{\rm eff}$ between 8000 and 9000 K. The low Balmer lines (apart from Hα) are well fitted by a model with $T_{\rm eff}$=8300 K, log g=3.8, but reasonable fits are also obtained with $T_{\rm eff}$=8800 K, log g=3.8. If the temperature is as low as 8300 K, iron could be as much as a factor of 4 underabundant.

3 Discussion

Longitudinal magnetic fields of the order of a few hundred Gauss have been detected in about a dozen Herbig Ae stars (e.g., Hubrig et al. 2004, 2006, 2007a, 2009; Wade et al. 2005, 2007; Catala et al. 2007). For the majority of these stars rather small fields were measured, of the order of only 100 G or less. Our observations revealed that HD 101412 possesses the strongest magnetic field ever measured in any Herbig Ae star, with a surface magnetic field $\langle B \rangle$ up to 3.5 kG. HD 101412 is the first Herbig Ae star for which the rotational Doppler effect was found to be small in comparison to the magnetic splitting and several spectral lines observed in unpolarized light at high dispersion are resolved into magnetically split components. It is also the first time that the presence of element spots is detected on the surface of a Herbig Ae star. The most pronounced variability was detected for spectral lines of He I and the iron peak elements, whereas the spectral lines of CNO elements are only slightly variable. Due to its very young age serves HD 101412 as a unique object, setting the timescale for the development of photospheric chemical peculiarities. Wade et al. (2005) claimed that another Herbig Ae star, HD 72106A, shows abundance patches on it surface. However, Folsom et al. (2008) showed that this star is a bona fide young Bp star whereas the companion HD 72106B is actually the Herbig Ae star displaying neither the presence of a magnetic field nor of element spots.

Our previous study of Herbig Ae stars revealed a trend towards stronger magnetic fields for younger Herbig Ae stars, confirmed by statistical tests. This is in contrast to a few other (non-statistical) studies claiming that mag-

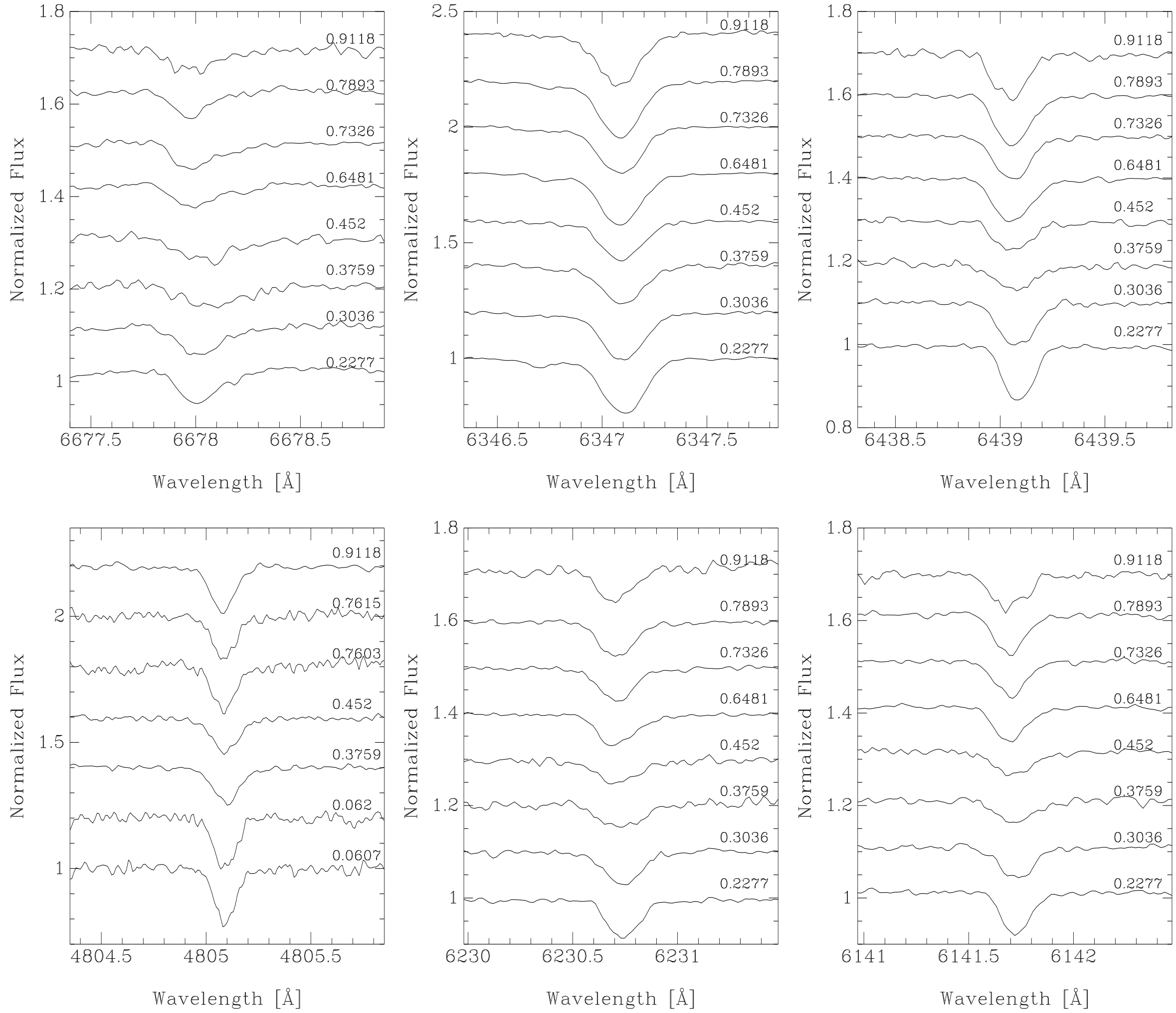

Fig. 6 Variations of line profiles for different rotation phases in UVES spectra. Upper panel, from left to right: He I λ 6678.149, Si II λ 6347.091, and Ca I λ 6439.073. Lower panel, from left to right: Ti II λ 4805.105, Fe II λ 6230.856, and Ba II λ 6141.718. The rotation phase increases from bottom to top. Individual spectra are shifted in vertical direction for clarity.

netic Herbig Ae stars are progenitors of the magnetic Ap stars (e.g. Wade et al. 2005). The disappearance of magnetic Herbig Ae stars (Hubrig et al. 2009) and the emergence of Ap stars during the main-sequence life (e.g., Hubrig et al. 2000, 2007b) are an indication that magnetic fields are not necessarily passive fossil fields leading to the observed features. Instead, the present observations of HD 101412 are compatible with the theoretical scenario that the strong fields of Ap stars and magnetic fields in Herbig Ae stars are the result of a magnetic instability of internal toroidal fields. The current-driven Tayler instability (e.g., Vandakurov 1972, Tayler 1973) is suppressed for very fast rotation. HD 101412 is most likely a slower rotator, for which the Tayler instability could set in more easily, even during its pre-main-sequence phase. The instability delivers surface poloidal magnetic fields, which can be observed in contrast to the internal toroidal fields. At an estimated age of 2 Myr, the star has passed its surface acceleration by accretion (Stępień 2000). That exerts surface torques, while the interior is likely to be rotating differentially, thereby winding up strong enough toroidal magnetic fields to be supercritical for the Tayler instability.

A simplified estimate of the toroidal magnetic field strength necessary for the Tayler instability gives about 1 MG, according to the relation by Pitts & Tayler (1985) saying that the Alfvén velocity should be smaller than the rotational velocity for stability. These fields are in principle possible to be created by differential rotation, but also smaller field strengths – even below 100 kG in our example – are unstable in a more sophisticated treatment, at the expense of considerably longer growth times (Rüdiger & Kitchatinov 2010). The growth time for a Pitts-and-Tayler field strength is only a few rotations. When a 100-kG field becomes unstable, the considerably longer growth time will still be of the order of years, which is much shorter than the evolutionary timescale. The observed fields are nonaxisymmetric remainders emerging from the instability and are expected to be one order of magnitude weaker than the original, unstable toroidal field.

The rather strong magnetic field of the star HD 101412 could thus be an example of an early emergence of magnetic fields due to slower rotation or unknown environmental differences compared to other Herbig Ae stars (Arlt & Rüdiger, in preparation). Other A stars can suppress the onset of the Tayler instability because of their faster rotation and may turn into Ap stars only after their pre-main-sequence life, when winds have taken away a considerable amount of angular momentum. While the mechanism of producing the surface poloidal fields would be the same, the observed magnetic Herbig Ae stars are not progenitors of Ap stars.

Generally, stellar magnetic fields in A-type stars on the main sequence are not symmetric relative to the rotation axis, so that the polarization signal is changing with the same period as the stellar rotation. The most simple modeling includes a magnetic field approximated by a dipole with the magnetic axis inclined to the rotation axis. The vast majority of the studied Ap stars with magnetically resolved lines have average magnetic field moduli in the range 3–9 kG. It was previously discussed by Mathys et al. (1997) that the low field end shows a rather sharp cutoff. Indeed, the magnetic field moduli extends below 3kG only for two stars, reaching 2.9 kG (HD 29578) and 2.7 kG (HD 75445), although we would expect to be able to detect resolved magnetically split lines for weaker fields, down to 1.7 kG. For HD 101412, the average of the mean field modulus is 2.6 kG, determined from UVES spectra with highest S/N ratios. This value is less than the threshold of 2.7 kG, but still much larger than 1.7 kG. Thus, we confirm the previous conclusion of Mathys et al. (1997) that the absence of any star with a phase-averaged field modulus lower than 2.5–2.7 kG among the known stars with resolved magnetically split lines is not due to observational limitations, but rather reflects an intrinsic stellar property. This result is puzzling as, similar to Ap stars, the distribution of the mean longitudinal field in Herbig Ae stars is strongly skewed towards small field values, down to the limit of detectability (e.g. Hubrig et al. 2009). Since the age of HD 101412 is only $\sim$2 Myr, this star is observed at an evolutionary stage where the magnetic field plays a critical role in controlling accretion and stellar wind. Due to the insufficient number of magnetic field measurements, in particular of mean longitudinal magnetic field measurements, which are sensitive to field geometry, the real structure of the magnetic field remains presently unknown. Clearly, the strong magnetic nature of this object makes it a prime candidate for future studies of the relation between magnetic field and physical processes occurring during stellar formation.

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