The A-star puzzle
Proceedings IAU Symposium No. 224, 2004
J. Zverko, J. Žižňovský, S.J. Adelman, & W.W. Weiss, eds.

DOI: 10.1017/S1743921304004429

First signatures of strong differential rotation in A-type stars

A. Reiners[1,2] and F. Royer[3,4]

[1]Astronomy Department, University of California, Berkeley, CA 94720, USA
email: areiners@astron.berkeley.edu

[2] Hamburger Sternwarte, Universität Hamburg, Gojenbergsweg 112, 21029 Hamburg, Germany

[3]Observatoire de Genève, 51 chemin des maillettes, 1290 Sauverny, Switzerland
email: frederic.royer@obs.unige.ch

[4]GEPI/CNRS UMR 8111, Observatoire de Paris–Meudon, 92195 Meudon cedex, France

Abstract. We reanalyzed high quality spectra of 158 stars of spectral types A0–F1 and $v \sin i$ values between 60 and 150 km s^{-1}. Using a least squares deconvolution technique we extracted high S/N broadening profiles and determined the loci of the Fourier transform zeros q_1 and q_2 where the S/N-ratio was high enough. For 78 stars q_2 could be determined and the ratio q_2/q_1 was used as a shape parameter sensitive to solar-like differential rotation (the equatorial velocity is faster than the near polar velocities). Seventy-four of the 78 stars have values of q_2/q_1 consistent with solid body rotation; in four of the 78 cases, values of q_2/q_1 are not consistent with rigid rotation. Although these stars may be binaries, none of their profiles shows any signatures of a companion. The Fourier transforms do not indicate any distortions and the broadening profiles can be considered due to single objects. One of these candidates may be an extremely rapid rotator seen pole-on, but for the other three stars of spectral types as early as A6, differential rotation seems to be the most plausible explanation for the peculiar profiles.

Keywords. Stars: rotation, stars: early-type, stars: activity, stars: individual (HD 6869, HD 44892, HD 60555, HD 109238)

---

1. Introduction

A substantial difference between the photospheres of solar-type stars and A-type stars is the existence of a convective envelope. Due to the ionization of hydrogen the cooler late-type stars harbour convective envelopes where turbulent motions of the photospheric plasma can occur. Stars of spectral types earlier than about F2 lack or have only very thin convective envelopes and the properties of granular flows change fundamentally.

The generally accepted activity paradigm places the stellar dynamo, believed to cause stellar activity, at the boundary between the convective envelope and the radiative core. Differential rotation drives the dynamo action by winding up and amplifying magnetic flux tubes. The interaction of magnetic fields, differential rotation and the convective envelopes is believed to be ultimately responsible for stellar activity.

Many investigators have searched for the onset of convection. It is generally accepted that the onset of stellar activity occurs between spectral types A7 and F5 depending on the observational strategy. Wolff *et al.* (1986) studied C II and He I emission and placed the onset of activity near $B-V = 0.28$, i.e., around spectral type F0. Schmitt (1997) concluded from X-ray data that coronal emission is universal in the spectral range A7 to G9 implying an onset of activity around spectral type A7. Hotter stars are expected to harbour shallow convective envelopes. These stars have higher convective velocities which peak at about spectral type A3 until convection disappears altogether at about spectral type A1 (Renzini *et al.* 1977). Gray & Nagel (1989) directly searched for the onset of convection by analyzing line bisectors of slowly rotating stars. In their targets the Doppler-shift distribution of the granulation dominates the broadening of spectral lines and a bisector reversal was found around spectral type F0. Stronger asymmetries were found in the stars at the hot side of the boundary indicating higher convective velocities.

Although stellar activity is not observed in early A-type stars, it is not clear whether differential rotation may take place in early-type stars. The absence of activity may simply reflect inefficient coupling of surface magnetic fields and the lack of an interface between the radiative core and the convective envelope. There is no reason to believe that rapidly rotating A-stars should rotate rigidly. For the later-type Sun the surface rotation law can be approximated by

$$\Omega(l) = \Omega_{\mathrm{Equator}}(1 - \alpha \sin^2 l), \tag{1.1}$$

with l the latitude and $\alpha_\odot \sim 0.2$ as derived from sunspots. Gray (1977) searched for differential rotation in line profiles of six A-stars and found none within his error bars.

Also using line profiles, Reiners & Schmitt (2003) found signatures of differential rotation in a sample of F-type stars. The earliest object in their sample indicating differential rotation is of spectral type F0IV/V. Applying the method used by Reiners & Schmitt (2003), we search for signatures of differential rotation in a large sample of A-star spectra. The results are presented in the following sections and have already been published by Reiners & Royer (2004a).

2. Observations and data analysis

The spectra were observed with the ECHELEC spectrograph (ESO/La Silla) and are part of a larger sample collected in the framework of an ESO Key Programme. The sample is described by Grenier *et al.* (1999) who measured the radial velocities and Royer *et al.* (2002, hereafter RGFG) who derived the rotational velocities from these spectra.

To search for the spectral signatures of stellar rotation laws, broadening profiles were derived by applying a Least Squares Deconvolution process (LSD). After constructing a δ-template comprising the strongest 150 lines taken from the Vienna Atomic Line Database (Kupka *et al.* 1999) and according to stellar temperature, a first-guess broadening profile was deconvolved using each pixel as a free parameter in the fit. Since the theoretical line depths match the observed ones poorly, the equivalent widths of the incorporated lines were optimized in a second step while leaving the broadening profile fixed. During a few iterations the broadening profile and the equivalent widths were optimized. Using this technique the spectral lines are effectively deblended, the information contained in every spectral line is used and the signal-to-noise ratio is significantly enhanced. Consistency of the fit is checked by comparing theoretical line depths to the derived ones.

Following Reiners & Schmitt (2002) we Fourier transformed the broadening functions and measured the position of the first and second zeros (q_1, q_2). The ratio q_2/q_1 is a robust observable for the shape of a rotational broadening function and a direct indicator for solar-like differential rotation with the equator rotating faster than the polar regions (Reiners & Schmitt 2002). We measured the ratio q_2/q_1 for all stars the LSD procedure yielded a stable and symmetric broadening function.

The spectral quality used in this analysis in principle was sufficient to follow the Fourier transformed broadening functions to the second zero q_2 in stars with projected rotational velocities in the range $60\,\mathrm{km\,s^{-1}} < v\,\sin i < 150\,\mathrm{km\,s^{-1}}$.

https://doi.org/10.1017/S1743921304004429 Published online by Cambridge University Press

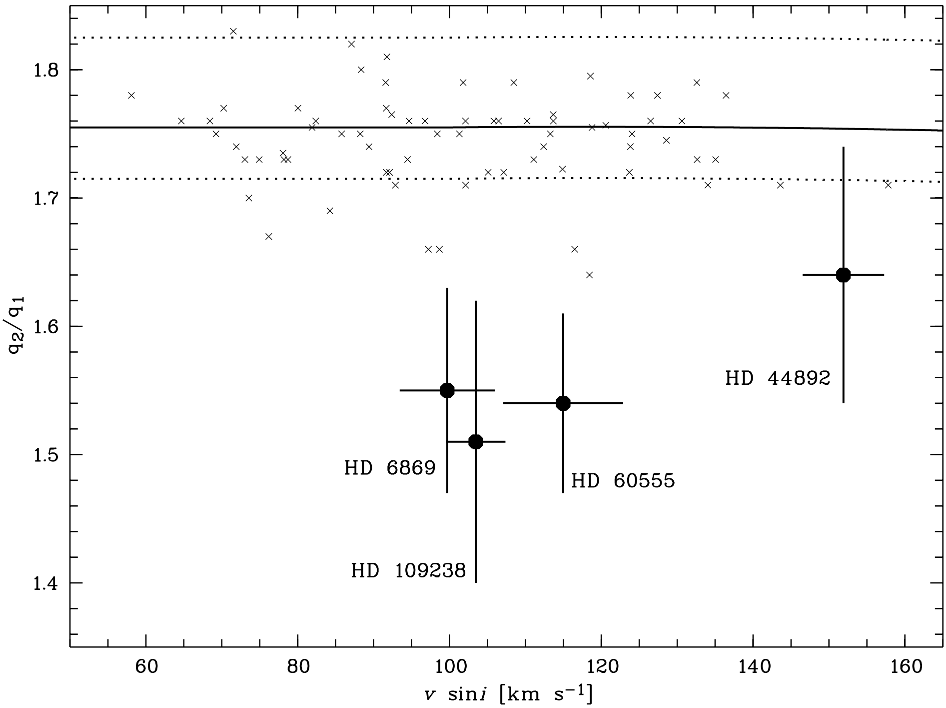

Figure 1. Derived values of q_2/q_1 plotted against $v \sin i$ as derived from the first zero of the Fourier transform (with 1-σ uncertainties). The region between dashed lines is consistent with solid body rotation for arbitrary limb darkening. For linear limb darkening with $\epsilon = 0.6$, $q_2/q_1 = 1.76$ is expected (solid line). Crosses indicate results consistent with solid body rotation, typical errors are of the order of $\Delta q_2/q_1 = 0.1$ (not plotted). Four stars not consistent with $q_2/q_1 = 1.76$ are indicated by solid circles, error bars are plotted for them.

3. Results

This method was applied to the spectra of 158 stars of spectral types A0–F1. The rotational velocity $v \sin i$ was derived from the first zero q_1 and is in good agreement with the results from RGFG. For 78 of our sample stars the ratio q_2/q_1 could be determined. For the discarded 80 stars, either the data quality was insufficient or the derived broadening function showed obvious peculiarities probably due to binarity.

We measured the second zeros of the Fourier transformed broadening profiles to calculate the ratios q_2/q_1. The results are plotted in Fig. 1. Typical errors are of the order of $\Delta q_2/q_1 \approx 0.1$. A rigid rotator is expected to yield a value of q_2/q_1 between 1.72 and 1.83 assuming a linear limb darkening law (indicated by the dashed lines in Fig. 1). For the stars of our sample linear limb darkening coefficients between 0.5 and 0.75 are expected during their time on the main sequence (Claret 1998). Assuming a limb darkening parameter of $\epsilon = 0.6$ rigid rotation would yield $q_2/q_1 = 1.76$ (solid line in Fig. 1). The results that are consistent with a value of $q_2/q_1 = 1.76$ within the error bars are indicated by small crosses in Fig. 1. For the sake of readability no errors are plotted for them. The second zero q_2 can only be determined in spectra where the signal exceeds the noise level beyond q_2, i.e., when a second sidelobe is detectable. Unfortunately the amplitude of the second sidelobe is in the noise level for many of our stars. These measurements of q_2 must be interpreted as lower limits; thus some of the measurements of q_2/q_1 plotted as

https://doi.org/10.1017/S1743921304004429 Published online by Cambridge University Press

crosses in Fig. 1 are essentially lower limits. For 74 of the 78 stars analyzed the broadening profiles are consistent with solid body rotation.

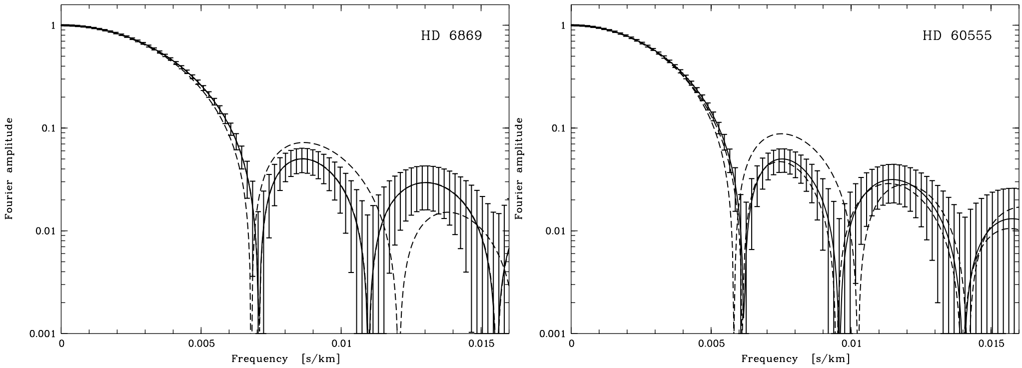

Figure 2. Fourier transforms of HD 6869 and HD 60555 plotted with error bars. These stars show extremely small values of q_2/q_1. The spectra of HD 154876 and HD 29920 have values of q_2/q_1 expected for rigid rotators and are plotted with dashed lines for comparison in the left and right panels, respectively.

Table 1. Derived values of $v \sin i$ and q_2/q_2 for the four stars with values of q_2/q_1 significantly smaller than 1.76. Also given are the strength of the differential rotation in terms of α (cp. Eq. 1.1) and the required values of the equatorial velocities $v_{\rm e,rigid}$ and inclination angles i if the value of q_2/q_1 is explained by rapid rotation seen pole-on (Sect. 3.2). Distances in pc and ROSAT X-ray luminosities are given in columns 8–9, respectively.

HD	Type	$v \sin i$ (km s^{-1})	q_2/q_1	α	$v_{\rm e,rigid}$ (km s^{-1})	i	d (pc)	$L_{\rm X}$ (W m^{-2})
6869	A9V	100 ± 6	1.55 ± 0.08	0.28 ± 0.10	(460)	(13°)	87	570
60555	A6V	115 ± 7	1.54 ± 0.07	0.29 ± 0.08	(470)	(14°)	134	
109238	F0IV/V	103 ± 4	1.51 ± 0.11	0.32 ± 0.13	(500)	(13°)	133	
44892	A9/F0IV	152 ± 5	1.64 ± 0.10	0.16 ± 0.16	400	22°	160	

Four of our measurements are inconsistent with $q_2/q_1 = 1.76$. They are indicated by solid circles in Fig. 1 and errors bars are plotted for them. For three of those — HD 6869 (A9V), HD 60555 (A6V) and HD 109238 (F0IV/V) — the values of q_2/q_1 are significantly smaller than 1.7. The fourth star (HD 44892, A9/F0IV) has a value of q_2/q_1 marginally consistent with $q_2/q_1 > 1.7$ within its error bars. We will discuss this star in Sect. 3.2.

The Fourier transforms of our candidate stars are illustrated by the plots of HD 6869 and HD 60555 with error bars in Fig. 2. Overplotted are the Fourier transformed line profiles of stars with similar values of $v \sin i$ that are consistent with rigid rotation ($q_2/q_1 = 1.76$). While different velocity fields, e.g., turbulence, may influence the amplitudes of the sidelobes, the zeros of the Fourier transform arise from rotational broadening (Gray 1976). One mechanism known to change the ratio q_2/q_1 in the manner found in HD 6869, HD 60555 and HD 109238 is solar-like differential rotation. The strength of differential rotation in terms of the parameter α in Eq. 1.1 can be calculated from q_2/q_1 (Reiners & Schmitt 2003), and the respective values of α are given in Table 1 together with the spectral types and $v \sin i$ of the four suspected differential rotators.

https://doi.org/10.1017/S1743921304004429 Published online by Cambridge University Press

3.1. *Binarity*

Using our deconvolution method, we find indications for double peaks in the broadening functions of 23 of our targets, but not in the spectra of these four stars. This does not mean that the 135 others are single stars since luminous A-type stars dominate spectra of, e.g., binaries consisting of an A-type and a G-type star. The G-type spectrum will easily be hidden in the light of the A-type star. To be complete we checked the shape of the correlation function by cross-correlating our template with the spectra and found no indications for binarity either.

For HD 44892 and HD 109238, the literature gives hints about a single star status. There is no evidence of binarity for HD 44892 neither in the HIPPARCOS data nor in Speckle observations (Mason *et al.* 2001). It can be considered as single with a high level of confidence, and its spectrum is surely not affected by any significant contamination. HD 109238 is part of the sample observed by Abt & Morrell (1995). Their MK classification is F0V with no suspicion of spectroscopic binarity.

We have two spectra each of both HD 6869 and HD 60555 in our data set. Individual observations of HD 6869 and HD 60555 are separated by 383 d and 767 d, respectively. Inspection of the broadening functions derived from the individual spectra yields no indication of variability due to the relative motions of binary components. Coadded spectra were used to derive the values of q_2/q_1 for both stars.

3.2. *Extremely fast rotation*

As an alternative to differential rotation, the shape of the broadening function and the value of q_2/q_1 can also be affected by very rapid rotation and gravity darkening possibly observed in pole-on stars (Reiners 2003). Flux is redistributed from the line's wings to the center when the equator becomes cooler due to gravity darkening. As far as the lines considered are not dominated by temperature and gravity variations over the stellar surface — which is the case, e.g, in the weak lines of early A-type stars as shown by Gulliver *et al.* (1994) — the value of q_2/q_1 is diminished by this effect. According to Reiners (2003), the ratio q_2/q_1 then only depends on the equatorial velocity v_e and on the gravity darkening law. We assume a linear gravity darkening law according to Claret (1998) and calculate the equatorial velocities $v_\mathrm{e,rigid}$ required to produce the measured values of q_2/q_1 assuming solid body rotation for the four suspected differential rotators. The results and the respective inclination angles i are given in columns six and seven of Table 1.

For HD 6869, HD 60555 and HD 109238 the values of $v_\mathrm{e,rigid}$ are larger than breakup velocity; for these stars rapid solid body rotation can be ruled out as the mechanism solely responsible for the diminished ratio q_2/q_1. In case of HD 44892 the rotational velocity required for the measured ratio $q_2/q_1 = 1.64$ is of the order of breakup velocity. Thus differential rotation as well as rapid solid body rotation are the two possible explanations for the measured profile shape of HD 44892.

4. Conclusions

We reanalyzed high quality data previously discussed by Grenier *et al.* (1999) and Royer *et al.* (2002) to search for differential rotation in early-type stars. With an iterative Least Squares Deconvolution method we obtained high quality broadening profiles of 158 stars with projected rotational velocities in the range $60\,\mathrm{km\,s^{-1}} < v\sin i < 150\,\mathrm{km\,s^{-1}}$. We discarded the profiles of 80 of them due to obvious asymmetries or multiplicity. For 78 stars the broadening profiles apparently reflect the rotational broadening law. Profile distortions were analyzed in terms of the ratio of the first two zeros of the Fourier transform q_2/q_1. Within the errors, 74 of the 78 measured profiles are consistent with the assumption of rigid rotation. Due to data quality many measurements must be considered lower limits and from this sample no conclusion can be drawn concerning values of q_2/q_1 possibly larger than 1.8.

For none of our sample stars interferometric measurements are avaliable, but Altair has been recently analyzed by Reiners & Royer (2004b) with this method. They find no signature of differential rotation and that Altair is seen with an inclination angle greater than $i = 68°$, improving the determination based on interferometric data.

Four stars are analyzed in detail. The profile of the A9/F0IV star HD 44892 is only marginally consistent with rigid rotation. It is likely that its profile is distorted either by differential rotation or by very rapid rotation seen pole-on; in the latter case HD 44892 would be the first star that directly shows signatures of gravity darkening in mean profile broadening as proposed by Reiners (2003). Comparison with interferometric results would be especially interesting for this star.

The broadening functions of the three stars HD 6869 (A9V), HD 60555 (A6V) and HD 109238 (F0IV/V) are not consistent with rigid — even very rapid — rotation since their equatorial velocities would be larger than breakup velocity. Although some authors suspect these stars are binaries, in our high quality spectra we find no indications of multiplicity neither in their data nor in Fourier space. Since contamination due to secondaries are easily visible in Fourier space — where no sharp zeros should occur in case of the profile being a sum of two — we consider their spectra single star spectra. Differential rotation seems to be the most plausible explanation for the observed profile distortions. For these three stars the equator is rotating about 30% faster than the polar regions. Thus we conclude that significant differential rotation seems to take place even in early-type stars not harbouring deep convection zones. The earliest object is the A6 dwarf HD 60555.

If differential rotation is the driving mechanism for stellar activity, these stars should be active, too. X-ray emission from HD 6869 was detected with the ROSAT mission and the other stars may also be X-ray sources, but were simply too far away for a detection. Whether differential rotation is a common phenomenon in these stars cannot be answered by this study since only very strong differential rotation is detectable with our method. The finding of strong differential rotation among A-type stars indicates that there is no abrupt change in the rotational laws of stars around the boundary where surface convection sets in.

References

Abt, H. A., & Morrell, N. I., 1995, *ApJS*, **99**, 135
Claret, A., 1998, A&AS, 131, 395
Gray D. F., 1976, The observation and analysis of stellar photospheres, Wiley, New York
Gray, D. F., 1977, *ApJ*, **211**, 198
Gray, D. F., & Nagel, T., 1989, ApJ, 341, 421
Grenier, S., Burnage, R., Faraggiana, R., *et al.* , 1999, A&AS, 135, 503
Gulliver, A. F., Hill, G., & Adelman, S. J., 1994, ApJ, 429, L81
Kupka, F., Piskunov, N.E., Ryabchikova, T.A., Stempels, H.C., & Weiss, W.W., 1999, A&AS, 138, 119
Mason, B. D., Hartkopf, W. I., Holdenried, E. R., & Rafferty, T. J., 2001, AJ, 121, 3224
Reiners, A. & Royer, F., 2004a, A&A, 415, 325
Reiners, A. & Royer, F., 2004b, A&A, in press [astro-ph/0408194]
Reiners, A., & Schmitt, J.H.M.M., 2002, A&A, 384, 155
Reiners, A., & Schmitt, J.H.M.M., 2003, A&A, 398, 647

https://doi.org/10.1017/S1743921304004429 Published online by Cambridge University Press

Reiners, A., 2003, A&A, 408, 707
Renzini, A., Cacciari, C., Ulmschneider, P., & Schmitz, F., 1977, A&A, 61, 39
Royer, F., Gerbaldi, M., Faraggiana, R., & Gómez, A. E., 2002, A&A, 381, 105 (RGFG)
Schmitt, J.H.M.M., 1997, A&A, 318, 215
Wolff, S.C., Boesgaard, A.M., & Simon, T. 1986, *ApJ*, **310**, 360

Discussion

Khalack: Could the anomalous low ratio q_2/q_1 be due to the nonspherical (ellipsoidal) shape of the aforementioned four stars?

Royer: In the case of Altair (Reiners & Royer 2004b), whose oblateness has been measured by interferometry, the q_2/q_1 ratio is 1.77, higher than ratios obtained for our four differential rotator candidates. The effect of nonsphericity on $v \sin i$ is discussed in Reiners (2003).

Mkrtichian: The primaries of Algol-type semidetached close binary systems might show a strong differential rotation of the surface equatorial latitudes due to a gas stream impact on the surface of the accretor. Did you consider the possibility that a few stars from your sample exhibiting strong pole/equator differential rotation might be A-type mass-accreting primary components of noneclipsing ($i \approx 80°$) Algols? In such systems the contribution of low luminosity secondaries may be small and their spectral lines are not visible. For checking this hypothesis - have you any information about the radial velocity variabilty of your stars on time scales of several days?

Royer: We used our broadening functions obtained by least square deconvolution as well as cross-correlation functions to find indications of binarity in our sample stars. We did discard 23 of our targets with this criterion. As detailed in Reiners & Royer (2004a) some of our candidate stars are indicated as binaries in the literature, HD 6869 for instance. The Fourier transforms of the derived broadening functions are probably not affected by secondary spectra, but the hypothesis of differential rotation caused by mass transfer is to be investigated. Our candidate stars should be monitored in terms of radial velocities, and the method we used to detect differential rotation could be applied to a known semi-detached system.