A&A 429, L55–L58 (2005)
DOI: 10.1051/0004-6361:200400112

Astronomy & Astrophysics

Rotational periods of four roAp stars[*]

T. Ryabchikova[1,2], G. A. Wade[3], M. Aurière[4], S. Bagnulo[5], J.-F. Donati[6], S. V. Jeffers[7], N. Johnson[3], J. D. Landstreet[8], F. Lignières[4], T. Lueftinger[1], S. Marsden[9], D. Mouillet[4], F. Paletou[6], P. Petit[10], P. Reegen[1], J. Silvester[3,11], S. Strasser[12], and N. Toque[4]

[1] Institute for Astronomy, University of Vienna, Türkenschanzstrasse 17, 1180 Wien, Austria
e-mail: ryabchik@jan.astro.univie.ac.at
[2] Institute of Astronomy, Russian Academy of Sciences, Pyatnitskaya 48, 109017 Moscow, Russia
[3] Physics Department, Royal Military College of Canada, Kingston, Ontario, K7K 7B4, Canada
[4] Observatoire Midi Pyrénées, 57 avenue d'Azereix, BP 826, 65008 Tarbes Cedex, France
[5] European Southern Observatory, Casilla 19001, Santiago 19, Chile
[6] Observatoire Midi-Pyrénées, 14 avenue Édouard Belin, Toulouse, France
[7] School of Physics and Astronomy, University of St Andrews, St Andrews, Fife, KY16 9SS, UK
[8] Department of Physics & Astronomy, The University of Western Ontario, London, Ontario, N6A 3K7, Canada
[9] Institute of Astronomy, ETH-Zentrum, 8092 Zurich, Switzerland
[10] Max-Planck Institut fuer Sonnensystemforschung Max-Planck-Str. 2, 37191 Katlenburg-Lindau, Germany
[11] Department of Physics, Queen's University, Kingston, Ontario, Canada
[12] Deptartment of Astronomy, University of Minnesota, 116 Church St. S.E., Minneapolis, MN 55455, USA

Received 8 November 2004 / Accepted 26 November 2004

Abstract. Forty-five new measurements of the mean longitudinal magnetic fields and mean equivalent widths of 4 roAp stars have obtained using the MuSiCoS spectropolarimeter at Pic du Midi observatory. These new high-precision data have been combined with archival measurements in order to constrain the rotational periods of HD 12098, HD 24712 = HR 1217, HD 122970 and HD 176232 = 10 Aql. We report a revised rotational period for HD 24712 ($P_{\rm rot}$ = 12.45877 ± 0.00016 d, crucial for interpretation of upcoming MOST observations of this star), new rotational periods for HD 12098 and HD 122970 ($P_{\rm rot}$ = 5.460 ± 0.001 d and $P_{\rm rot}$ = 3.877 ± 0.001 d, respectively) and evidence for an extremely long period for HD 176232.

Key words. stars: individual: HD 12098, HD 24712, HD 122970, HD 176232 – stars: peculiar – magnetic fields

1. Introduction

The rapidly oscillating Ap stars (roAp stars) form a group of cool magnetic Ap stars showing single- or multi-period pulsations of low degree with typical periods of 4–16 min. They are very important objects for asteroseismology; therefore several roAp stars have been selected as targets for the *Microvariability and Oscillations of Stars (MOST)* space mission (Walker et al. 2003). To fit the observed pulsation data both qualitatively and quantitativly, Kurtz (1982) proposed the *oblique pulsator model*, in which the stellar pulsations are symmetric about its magnetic field axis, itself inclined to the rotation axis. In this model the amplitude of pulsation is maximal along the magnetic field lines at the magnetic poles and minimal at the magnetic equator, and hence should vary in phase with the magnetic field as the star rotates. To study the role of the magnetic field in mode excitation and selection, we need to connect the magnetic field and pulsation amplitude variations. In other words, we need to know rotational periods of roAp stars with the highest possible accuracy.

In this paper we employ new and archival measurements of the mean longitudinal magnetic field and equivalent width to constrain the rotational periods of 4 roAp stars.

2. Observations and data reduction

Forty-five new circular polarisation spectra of the 4 roAp stars HD 24712, HD 12098, HD 122970 and HD 176232 have been obtained using the MuSiCoS spectropolarimeter (Baudrand & Böhm 1992; Donati et al. 1999) on the 2 m Bernard Lyot telescope at Pic du Midi Observatory, within the context of a large-scale survey of the magnetic properties of the coolest Ap stars (e.g. Johnson et al. 2004). These observations will be described in detail in a forthcoming paper.

The spectra were processed in the manner described by e.g. Shorlin et al. (2002): reduced using the ESpRIT optimal reduction tool (Donati et al. 1997), and Least-Squares Deconvolved (LSD, Donati et al. 1997) to produce mean Stokes I and V profiles from each spectrum, using a line mask

---

[*] Table 1 is only available in electonic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/429/L55

computed for an effective temperature of 7500 K, containing all lines deeper than 10% of the continuum. Mask abundances were modified according the the Ap SrCrEu scheme described by Shorlin et al. (2002). The equivalent width was determined from each Stokes I mean profile, and the mean longitudinal magnetic field was determined from each Stokes I/V mean profile couplet, by numerical integration (Donati et al. 1997; Wade et al. 2000). The details of these measurements are presented in Table 1 (available only in electronic form at the CDS), where heliocentric Julian date of the middle of exposure, $\langle B_z \rangle$ value, error and equivalent width of LSD Stokes I in km s^{-1} are given in consecutive columns.

Period searches were performed using the program SIGSPEC (Reegen 2004a). The SIGSPEC periods correspond to maximum significance (i.e. minimum false-alarm probability) of the Fourier amplitude in the frequency range between 0 and 1 d^{-1}, using theoretically-evaluated significance spectra. Identified periods were confirmed using conventional least-squares harmonic fitting (Press & Rybicki 1989). The (1σ) errors of the adopted periods, amplitudes, and phases are the results of numerical simulations using the EPSIM code (Reegen 2004b). The synthetic data for these simulations were generated by forming a sinusoidal signal with given frequency, amplitude, and phase, and adding Gaussian noise. The standard deviation of this noise was set equal to the rms error of the observational residuals. These uncertainties were also confirmed, using conventional χ^2 analysis (e.g. Bevington 1969).

3. HD 24712 = HR 1217

HD 24712 is well-known roAp star (e.g. Kurtz 1982) which pulsates in a several modes with periods close to 6.15 min. By combining the b-band photometry of Wolff & Morrison (1972), Preston's (1972) and Bonsack's (1979) Eu II data and his own photometric measurements averaged over the pulsational cycle, Kurtz derived a rotation period $P_{\rm rot}$ = 12.4580 ± 0.0015 d. This period compares well with previously-determined periods of 12.448 d (Preston 1972) and 12.460 d (Bonsack 1979) derived from magnetic field and equivalent width variations. Later, Kurtz & Marang (1987 – KM) redetermined the rotation period and the resulting value, $P_{\rm rot}$ = 12.4572 ± 0.0003 d, has been used in most subsequent studies of HD 24712. Mathys (1991) proposed a slightly longer period, $P_{\rm rot}$ = 12.4610 d, based solely on magnetic measurements. The latest revision of the rotation period of HD 24712 was performed by Leone & Catanzaro (2004), who derived $P_{\rm rot}$ = 12.4582 ± 0.0006 day based on analysis of equivalent width data available from 1968 to 2002. A small discrepency exists between the period determined by Mathys (based solely on magnetic field data) and the periods determined using equivalent width and photometric data.

Apart from the very first measurements of the mean longitudinal magnetic field $\langle B_z \rangle$ made by Preston (1972) (with no error estimates given), no high-precision magnetic observations covering the entire rotation period have ever been obtained. This produces some difficulties in searching for a period using the magnetic data. In order to solve this problem and to determine the current phase of HD 24712, 16 new measurements of HD 24712 have been obtained, and are presented here. These data were secured during the period 1998–2004, sample the entire rotation cycle, and allow us to perform a period search with high precison using all magnetic data from 1970 to 2004. Besides Preston's TiCrFe longitudinal field measurements and our new multielement (primarily Cr–Fe) LSD results, measurements by Mathys (1991), Mathys & Hubrig (1997), and Leone & Catanzaro (2004 – values averaged from Ti, Cr, Fe lines) have been employed in the search. Effective field measurements from hydrogen line polarimetric photometry (Ryabchikova et al. 1997) were included as well, although we found them to be larger by ≈400 G than the measurements from metal lines[1]. The period search of the magnetic data set (53 measurement) results in $P_{\rm rot}$ = 12.45902 ± 0.00044 d with a significance of 7.05, where significance is the logarithm of inverse false-alarm probability (fap). The new MuSiCoS $\langle B_z \rangle$ data, when considered alone, indicate a period of $P_{\rm rot}$ = 12.464 ± 0.0014 d, with a significance of 3.05 (i.e. a fap 10^{-4} times lower than the entire data set).

We have also performed an independent period search based on the relative equivalent widths $W_\lambda/\langle W \rangle$ of rare-earth element lines (where $\langle W \rangle$ is the value averaged over the rotation cycle), mainly belonging to Eu II, Pr III, Nd II and Nd III[2]. We combined published $W_\lambda/\langle W \rangle$ data by Bonsack (1979) and Ryabchikova et al. (1997), together with our present mean values from 6 strong Pr III + Nd III lines, and add to them $W_\lambda/\langle W \rangle$ data measured from spectra obtained in radial velocity pulsational campaigns (see Ryabchikova et al. 2000b; Sachkov et al. 2003, 2004). The period search of the $W_\lambda/\langle W \rangle$ data set (51 measurements) results in a period of $P_{\rm rot}$ = 12.45853 ± 0.00018 d with a significance of ∼10. The new MuSiCoS $W_\lambda/\langle W \rangle$ data, when considered alone, indicate a somewhat longer period of $P_{\rm rot}$ = 12.4561 ± 0.0023 d.

A final period search constrained by both the complete $\langle B_z \rangle$ and $W_\lambda/\langle W \rangle$ data sets gave the final adopted ephemeris for HD 24712:

$$\mathrm{HJD}(\langle B_z \rangle\ \mathrm{max}) = 2\,453\,235.18(40) + 12.45877(16) \cdot E.$$

Due to the firm determination of the phase of HD 24712 at the epoch of the MuSiCoS measurements, the uncertainty in the current (JD 2 453 300) phase of HD 24712 results almost entirely from the uncertainty in the zero-point, and is equal to ±0.03 cycles.

Using this ephemeris, derived only from spectroscopic and polarimetric data, we obtain mutually consistent variations of the different global parameters described in the framework of the oblique rotator/oblique pulsator models for roAp stars: the

---

[1] There are sometimes differences between Balmer line field measurements and metal line measurements at the level of a few hundred G, and sometimes not. No-one yet understands where these differences come from, although they may be related to the approximate interpretation of Balmer-line polarimetric measurements, or due to the presence of abundance non-uniformities which weight metallic-line measurements more heavily to particular regions of the magnetic field.

[2] Preston's (1972) equivalent widths were excluded from this analysis because they are in fact "relative strengths" rather than equivalent widths.

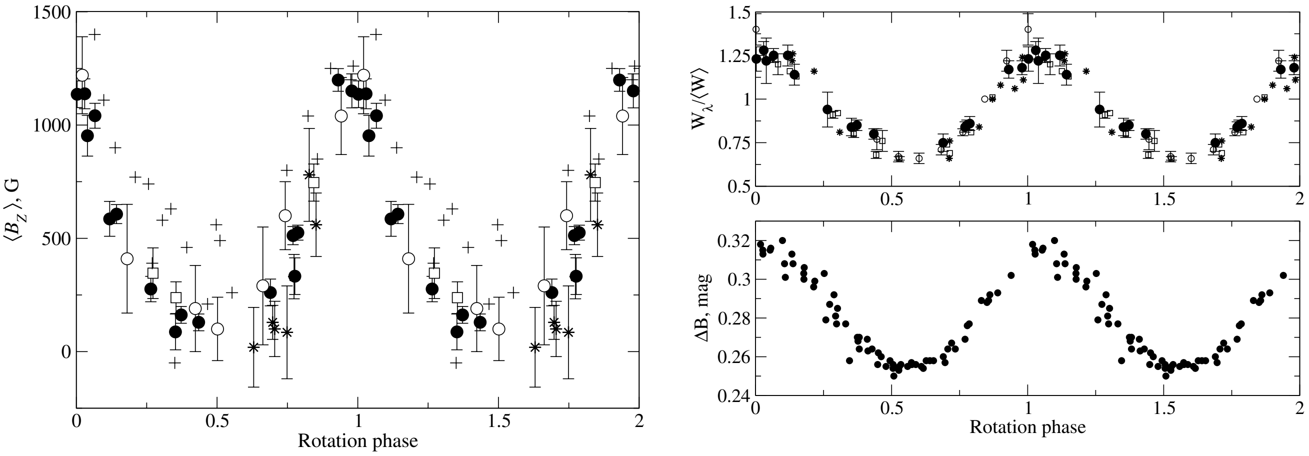

Fig. 1. Variations of $\langle B_z \rangle$ (*left panel*), $W_\lambda/\langle W \rangle$ (*right top panel*), and mean light in the Johnson B filter (taken from KM and references therein, right lower panel) of HD 24712, phased according to the adopted rotation period. The new MuSiCos data are represented by filled circles in both the $\langle B_z \rangle$ and $W_\lambda/\langle W \rangle$ frames. Open circles – Balmer-line magnetometer and $W_\lambda/\langle W \rangle$ data from Ryabchikova et al. (1997) (with $\langle B_z \rangle$ decreased by 400 G). Asterisks – $\langle B_z \rangle$ data from Mathys (1991) and Mathys & Hubrig (1997) and $W_\lambda/\langle W \rangle$ data from Bonsack (1979). Open squares – $\langle B_z \rangle$ data from Leone & Catanzaro (2004) and $W_\lambda/\langle W \rangle$ data from pulsational observations. Pluses (+) represent Preston's (1972) $\langle B_z \rangle$ measurements from TiCrFe lines.

broadband light, $W_\lambda/\langle W \rangle$, and pulsational amplitude all vary in phase with the magnetic field variations (Fig. 1).

The accurate new rotational ephemeris for HD 24712 derived here will be of great value in the interpretation of the upcoming MOST observations.

4. HD 12098

HD 12098 was discovered to be a pulsating Ap star by Girish et al. (2001). The authors proposed a 1.22 d rotation period based on a frequency analysis of the photometric pulsations. This period also explained the strong modulation of the pulsation amplitude, although not in a completely convincing way. The 17 new magnetic measurements of HD 12098 reported here allow us to derive an unambiguous rotation period:

$$\mathrm{HJD}(\langle B_z \rangle \max) = 2\,451\,889.42(12) + 5.460(1) \cdot E$$

$\langle B_z \rangle$ measurements derived using the multielement (primarily Cr+Fe) mask show remarkable variations when phased according to the adopted rotation period of 5.460 d (Fig. 2, top panel). The relative LSD Stokes I equivalent widths also vary with this same period, and in spite of the small range of variation there is an obvious tendancy for REE lines to vary in antiphase with lines of the Fe peak elements.

Using the derived ephemeris, we have phased the photometric pulsation amplitudes of Girish et al. (2001) according to the rotation period (Fig. 2, bottom panel). A clear correlation of the pulsation amplitudes with the magnetic field extrema favours the oblique pulsator model (Kurtz 1982) and the adopted period. Scatter in the photometric lightcurve may be explained by a beating effect in this multi-mode pulsator.

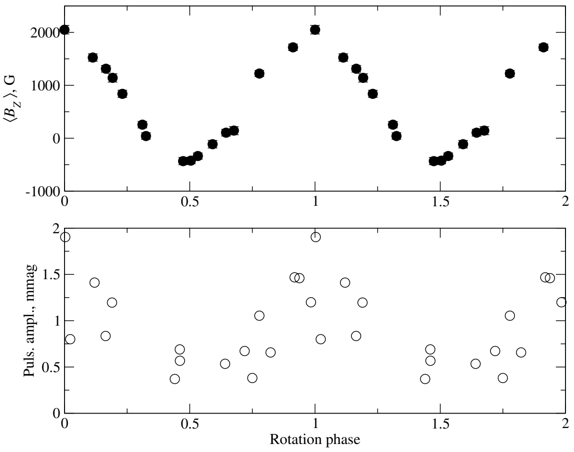

Fig. 2. HD 12098: mean longitudinal magnetic field (*top panel*) and pulsation amplitudes (Girish et al. 2001) phased according to the 5.46 day rotation period. Uncertainties associated with the $\langle B_z \rangle$ measurements are about the same size as than the symbols.

5. HD 122970

HD 122970 was discovered to be pulsating by Handler & Paunzen (1998), who determined a pulsation period of about 11 min. Nothing is known about its rotation period. Ryabchikova et al. (2000a) derived a projected rotational velocity $v \sin i = 5.5 \pm 0.5$ km s^{-1} and also estimated a mean magnetic field modulus of $B_\mathrm{s} = 2.0$–2.3 kG based on Zeeman line broadening. The only published $\langle B_z \rangle$ measurement was reported by Hubrig et al. (2004). A frequency analysis of the 9 new magnetic measurements gives a minimum reduced χ^2 at $P_\mathrm{rot} = 3.877 \pm 0.001$ day (Fig. 3). The measurement of Hubrig et al. (2004) seems to support the derived period, although the small amplitude of variability and the small number of data points permit a large range of other solutions. If the 3.877 d period is real, then taking into account $v \sin i = 5.5$ km s^{-1} and the radius $R = 1.85 \pm 0.25\ R_\odot$ (Ryabchikova et al. 2000a) we obtain $i = 13 \pm 5°$ assuming rigid rotation. This implies that HD 122970 is viewed nearly pole-on, which is supported by the small amplitude of the field variations, the absence of

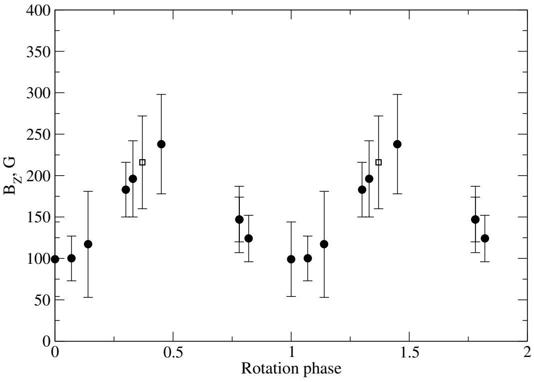

Fig. 3. HD 122970: longitudinal magnetic field variations with the rotational period 3.877 day (filled circles). One measurement from Hubrig et al. (2004) is shown by open square.

significant equivalent width variations and the lack of detection of rotational light modulations in the HIPPARCOS photometry (see Handler et al. 2002).

6. HD 176232 = 10 Aql

HD 176232 is an roAp star of very low pulsation amplitude both in photometry (Heller & Kramer 1988) and in spectroscopy (Kochukhov et al. 2002). Babcock's (1958) 5 measurements of the longitudinal magnetic field gave a hint of possible long-period variations. Nine measurements made by Preston (1970) in 1967 resulted in a constant value $\langle B_z \rangle = +500 \pm 100$ G, which also favoured a long rotation period. Our 5 measurements, obtained over a timespan of almost 1 year in 2003–2004, give a constant mean value of $\langle B_z \rangle = +456$ G, are in a perfect agreement with Preston's result, and indicate a constant longitudinal field within the remarkable median 12 G error bars. This result underscores the excellence of MuSiCoS circular polarisation spectra analysed using LSD, and suggests that the rotational period of HD 176232 may be extremely long, possibly (given the lack of *any* detectable variability during the past 37 years) hundreds of years. The low $v \sin i = 2.0 \pm 0.5\ \mathrm{km\,s^{-1}}$ (Kochukhov et al. 2002), when realistically considered as an upper limit on combined rotational, pulsational, and unaccounted-for magnetic broadening, also supports this conclusion. Although we are neither able to determine the rotation period of this star, nor are we able to fully rule out a pole-on (low inclination) orientation, MuSiCoS Stokes V observations, analysed using LSD, are clearly extremely well-suited to seaching for weak modulation of $\langle B_z \rangle$. Furthermore, linear polarisation Stokes Q and U observations could potentially be used to constrain the stellar geometry.

7. Conclusion

Rotation periods and rotation period constraints are obtained for 4 roAp stars based on new (45 measurements) and archival longitudinal magnetic field and equivalent width data. Amongst these 4 stars, we observe a diversity of rotational characteristics: two stars with relatively short periods (HD 122970 at 3.877 d and HD 12098 at 5.460 d), one star with a somewhat longer period (HD 24712 at 12.45843 d), and one star with an apparently very long period (HD 176232, for which the field appears not to have varied significantly since 1967).

Acknowledgements. We acknowledge support from the Austrian FWF project P14984 (T.R., T.L. and P.R.), from the Natural Sciences and Research Council of Canada (G.A.W. and J.D.L.), from the Department of National Defence (Canada) (N.M.J. and G.A.W.), from a Personal Marie Curie Fellowship funded by the European Union and the University of St Andrews (S.V.J.), and from RFBR grant 04-02-16788 (TR).

References

Babcock, H. W. 1958, ApJS, 3, 141
Baudrand, J., & Böhm, T. 1992, A&A, 259, 711
Bevington, P. R. 1969, Data reduction and error analysis for the physical sciences (McGraw-Hill)
Bonsack, W. K. 1979, PASP, 91, 648
Donati, J.-F., Semel, M., Carter, B. D., Rees, D. E., & Cameron, A. C. 1997, MNRAS, 291, 658
Donati, J.-F., Catala, C., Wade, G. A., et al. 1999, A&AS, 134, 149
Girish, V., Seetha, S., Martinez, P., et al. 2001, A&A, 380, 142
Handler, G., & Paunzen, E. 1998, A&AS, 135, 57
Handler, G., Weiss, W. W., Paunzen, E., et al. 2002, MNRAS, 330, 153
Heller, C. H., & Kramer, K. S. 1988, PASP, 100, 583
Hubrig, S., Szeifert, T., Schöller, M., Mathys, G., & Kurtz, D. 2004, A&A, 415, 685
Johnson, N. M., Wade, G. A., Aurière, M., et al. 2004, in The A-star Puzzle, IAUS 224, in press
Kochukhov, O., Landstreet, J. D., Ryabchikova, T., Weiss, W. W, & Kupka, F. 2002, MNRAS, 337, L1
Kurtz, D. W. 1982, MNRAS, 2000, 807
Kurtz, D. W., & Marang, F. 1987, MNRAS, 229, 285
Leone, F., & Catanzaro, G. 2004, A&A, 425, 271
Mathys, G. 1991, A&AS, 89, 121
Mathys, G., & Hubrig, S. 1997, A&AS, 124, 475
Press, W. H., & Rybicki, G. B. 1989, ApJ, 338, 277
Preston, G. W. 1972, ApJ, 175, 456
Reegen, P. 2004a, in The A-Star Puzzle, IAUS, 224, in press
Reegen, P. 2004b, in Stellar Structure and Habitable Planet Finding, ed. F. Favata, & S. Aigrain, ESA SP-538, 389
Ryabchikova, T. A., Landstreet, J. D., Gelbmann, M. J., et al. 1997, A&A, 327, 1137
Ryabchikova, T. A., Savanov, I. S., Hatzes, A. P., Weiss, W. W., & Handler, G. 2000a, A&A, 357, 981
Ryabchikova, T. A., Tsymbal, V. V., Malanushenko, V. P., & Savanov, I. S. 2000b, in Magnetic Fields of Chemically Peculiar and Related Stars, ed. Yu. V. Glagolevskij, & I. I. Romanyuk, Proc. Int. Meeting at SAO of Russian AS, Moscow, 180
Sachkov, M., Ryabchikova, T., Kochukhov, O., et al. 2003, in Variable Stars in the Local Group, IAU Coll. 193, ed. D. W. Kurtz, & K. R. Pollard, ASP Conf. Ser., 310, 208
Sachkov, M., Ryabchikova, T., Ilyin, I., Kochukhov, O., & Lüftinger, T. 2004, in The A-Star Puzzle, IAUS 224, poster GP2, in press
Shorlin, S. L. S., Wade, G. A., Donati, J.-F., et al. 2002, A&A, 392, 637
Wade, G. A., Donati, J.-F., Landstreet, J. D., & Shorlin, S. L. S. 2000, MNRAS, 313, 851
Walker, G., Matthews, J., Kuschnig, R., et al. 2003, PASP, 115, 1023
Wolff, S. C., & Morrison, N. D. 1973, PASP, 85, 141