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δ Sct pulsation in magnetic Ap stars: the discovery of δ Sct pulsations in HD 218994AB and measurement of the magnetic fields of HD 218994A and HD 21190[⋆]

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ABSTRACT

We have discovered that at least one component of the visual binary star HD 218994AB is a δ Sct star. The primary star of this system is a known rapidly oscillating Ap (roAp) star; therefore, it is possible that it is both an roAp star and a δ Sct star – a hybrid. There are no confirmed such hybrid roAp–δ Sct stars, and they are predicted theoretically not to exist. More probably, HD 218994B is the δ Sct star, as it is 0.54 mag fainter than the primary and also lies in the δ Sct instability strip. It then offers the potential to determine $T_{\rm eff}$ and L for the primary which appears to be one of the more evolved roAp stars and an important test the theoretically calculated roAp star instability strip. In this case, the system also is important since the stars are a co-eval pair of very similar mass, yet one is a magnetic roAp star and the other is probably a non-magnetic δ Sct star with a normal spectrum. We detect a significant longitudinal magnetic field strength of 440 ± 23 G in the roAp star HD 218994A. We also present the first measurement of the longitudinal magnetic field strength for the δ Sct star HD 21190, the most-evolved Ap star known. We obtain a formally significant value of 47 ± 13 G. If confirmed, this will make HD 21190 the first magnetic δ Sct star known.

Key words: binaries: visual – stars: chemically peculiar – stars: individual: HD 218994 – stars: magnetic fields – stars: variables: other.

1 INTRODUCTION

The rapidly oscillating Ap (roAp) stars are mid-A to early-F hydrogen core-burning stars with strong, global magnetic fields with strengths as high as 24 kG (Hubrig et al. 2005). They pulsate in high radial overtone p modes with periods in the range 5.65–21.2 min. Saio (2005) showed for an appropriate 1.9-$M_\odot$ model that magnetic field strengths in excess of about 1 kG suppress low radial overtone pulsations driven by the κ-mechanism in the He II ionization – pulsations typical of δ Sct stars – while high radial overtone, low-degree pulsations driven by the κ-mechanism in the H I ionization zone are excited.

It is thus expected that strongly magnetic Ap stars will not be observed to pulsate simultaneously in low radial overtone p modes characteristic of the δ Sct stars and high overtone p modes characteristic of the roAp stars. We refer to a star that does both as a 'hybrid' roAp–δ Sct star. Observations support the prediction that they do not exist, although the pulsation periods of the two classes do overlap. The shortest period known for a δ Sct star is 18.12 min in the pre-main-sequence Herbig Ae star HD 34282 (Amado et al. 2004), while the longest known pulsation period for an roAp star is 21.2 min for HD 116114 (Elkin et al. 2005). Although these periods overlap, the radial overtones of the stars do not. HD 34282 lies near the blue edge of the δ Sct instability strip and is estimated to be pulsating in radial overtone $n \sim 7$. For the cooler roAp stars, overtones of $n \sim 20$ are expected for the longer period stars such as HD 116114, and much higher overtones for the shorter period roAp stars. Thus, the exclusion between the two classes appears to be complete in terms of the radial overtones of the modes excited.

We say 'appears to be' because there are several stars that are very peculiar spectroscopically that are known to be δ Sct stars. Joshi et al. (2006) discuss this is detail and give the few known examples. The situation remains unresolved because of possible confusion between the non-magnetic Am stars and the magnetic Ap stars. There is no known case of an Ap star with a confirmed strong magnetic field that shows δ Sct pulsations. In this paper, we present the first measurement of a longitudinal magnetic field of

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$\langle B_z \rangle = +47 \pm 13$ G in the δ Sct star HD 21190, the most-evolved Ap star known (Koen et al. 2001; González et al. 2008). If this apparent detection is confirmed, it will show that δ Sct pulsation can exist in a star with a magnetic field. This is not in conflict with Saio's models for stars with field strengths of 1 kG, or greater. The longitudinal field strength depends on viewing aspect and typically is variable with rotation in Ap stars. Further observations are needed to confirm the detection and to determine the polar field strength for HD 21190.

Should a hybrid roAp–δ Sct star be found, then it will show that low radial overtone p modes can exist simultaneously with high overtone p modes in the presence of a strong magnetic field. The particular characteristics of such a hypothetical star would illuminate the pulsation–magnetic field interaction that is the subject of many theoretical studies; see e.g. (Dolez & Gough 1982; Dziembowski & Goode 1985; Shibahashi & Takata 1993; Takata & Shibahashi 1995; Dziembowski & Goode 1996; Gautschy, Saio & Harzenmoser 1998; Bigot et al. 2000; Cunha & Gough 2000; Balmforth et al. 2001; Bigot & Dziembowski 2002; Saio & Gautschy 2004; Cunha 2005, 2006, 2007; Gough 2005; Saio 2005).

HD 218994 is thus intriguing, since González et al. (2008) have recently discovered it to be a new roAp star with a pulsation period of either 14.2 or 5.1 min, and we show in this paper that one of the stars in the HD 218994AB system is also a δ Sct star with pulsation periods just under 1 h. If HD 218994A is an roAp–δ Sct hybrid, then it is of considerable importance, although it may still not be in conflict with theory because of the strength of its magnetic field. We announce in this paper a measurement of the longitudinal magnetic field of HD 218994A to be $\langle B_z \rangle = +440 \pm 23$ G. Given the unknown aspect for this measurement, for a simple dipole field we expect the polar field of the order of 1 kG, or more. Thus, if HD218994A is an roAp–δ Sct hybrid, it could test the limit of Saio's (2005) model; or the polar field strength could be substantially greater, thus giving a conflict between observation and theory. More importantly, the simultaneous presence of low-overtone and high-overtone pulsations samples the stellar interior differently, thus constrain asteroseismic models much better than a narrow range of pulsation frequencies do. That is what would make a hybrid of most use asteroseismically.

However, HD 218994 may not be the hypothetical hybrid at all; that is still to be determined. There is another possibility that is also interesting and useful: HD 218994AB is a visual binary with a separation of $\rho = 1.094$ arcsec, position angle $\theta = 75\overset{\circ}{.}4$ and $\Delta H_{\rm p} = 0.54$ (ESA 1997). In the discovery of roAp pulsations in radial velocity variations of HD 218994A González et al. (2008) observed HD 218994AB with little contamination from the light of the secondary with the Ultraviolet and Visual Echelle Spectrograph (UVES) on the VLT, but for the photometric observations presented in this paper both components were necessarily in the observing aperture of the photoelectric photometer used. Thus, HD 218994A could be an roAp star and HD 218994B a δ Sct star since, as we show in this paper, HD 218994B is within the δ Sct instability strip. This is, however, by no means a certain conclusion.

If HD 218994A is an roAp star and HD 218994B a δ Sct star, then it will be possible to determine $T_{\rm eff}$ and L for the roAp primary from independent spectra of the two stars. $T_{\rm eff}$ and L are notoriously difficult to determine with precision for Ap stars. Their exceedingly peculiar spectra can lead to temperature uncertainties (or at least disagreements) up to 1000 K in the case of Przybylski's star, but more typically of many hundreds of kelvin. Except for a few stars with good *Hipparcos* parallaxes, the luminosities are very uncertain: Both photometric and spectroscopic luminosity criteria fail, and fine analyses of the spectra give different results for different spectral lines because of element stratification.

If HD 218994B is a δ Sct star, then it will probably have a normal spectrum on which we can perform a fine analysis and determine $T_{\rm eff}$, $\log g$ and L to high precision, using standard star calibrations. We can see some spectral lines of the secondary in our UVES spectra, as we show in Section 3 below, from which we estimate $v \sin i = 80\,{\rm km\,s^{-1}}$ for HD 218994B, a typical value for a δ Sct star. The components of the visual binary are probably a physically bound pair (both have *Hipparcos* parallaxes of $\pi = 3.64 \pm 2.11$ mas and identical proper motions of 36.9 $\rm mas\,yr^{-1}$ in right ascension and -21.7 $\rm mas\,yr^{-1}$ in declination), so we will be able to constrain $T_{\rm eff}$, $\log g$ and L for the primary much better than is possible for a single Ap star.

Importantly, HD 218994A appears to be more evolved than all but a few of the 14 roAp stars studied by Hubrig et al. (2000) for which luminosities were determined from *Hipparcos* parallaxes. Cunha (2002) calculated a theoretical instability strip for roAp stars and predicted longer periods for stars near the terminal age main-sequence than had previously been found in roAp stars. Subsequently, Elkin et al. (2005) found a more luminous roAp star, HD 116114, with the longest period known in the class of 21.2 min, tending to support Cunha's prediction. Freyhammer et al. (2008), however, surveyed nine luminous Ap stars with *Hipparcos* parallaxes that placed them near the terminal age main-sequence with high-precision radial velocities using UVES on the VLT. They found no pulsation in any of the nine stars, with upper limits on radial velocity amplitude of $60\,{\rm m\,s^{-1}}$, and less.

Determining the $T_{\rm eff}$ and L of HD 218994A with better precision by reference to HD 218994B will be very useful, if it turns out that the component A is an roAp star and component B is a normal δ Sct star. It is not known why or how, for two similar stars in a binary system, one becomes a magnetic peculiar star, and the other does not. Thus, this system could also inform our understanding of this problem.

In this paper, we demonstrate confidently our discovery that the binary system of HD 218994AB contains a low-amplitude ($\sim$3 mmag) δ Sct star. We show this with time-series photometry taken on several nights over a span of 24 yr.

2 HERTZSPRUNG–RUSSELL DIAGRAM

To locate the two stars in the Hertzsprung–Russell (HR) diagram, it is necessary to know their individual temperatures and luminosities, which are not available separately. On the one hand, although the spectral lines of the primary are clearly visible in the spectrum, even for this star the effective temperature can not be easily derived due to its peculiar character. On the other hand, multicolour photometry is not available for the two stars separately. In fact only the *Hipparcos* catalogue gives the magnitude difference in the $H_{\rm p}$ band. We cannot estimate the relative luminosities of the two components from the relative strengths of their spectral lines – even though some lines of the secondary are present – since from the UVES service mode acquisition image the exact position of the secondary on the spectrograph slit cannot be determined.

Consequently, we evaluate the possible location of HD 218994A and B in the HR diagram using the *Hipparcos* magnitude difference, and the published photometry combined for the whole system to constrain the stellar temperatures. We used the Strömgren β index as a temperature indicator, which is appropriate for mid-A type stars and is reddening free. In addition, we assumed the global stellar parameters to correspond to two normal main sequence stars of the

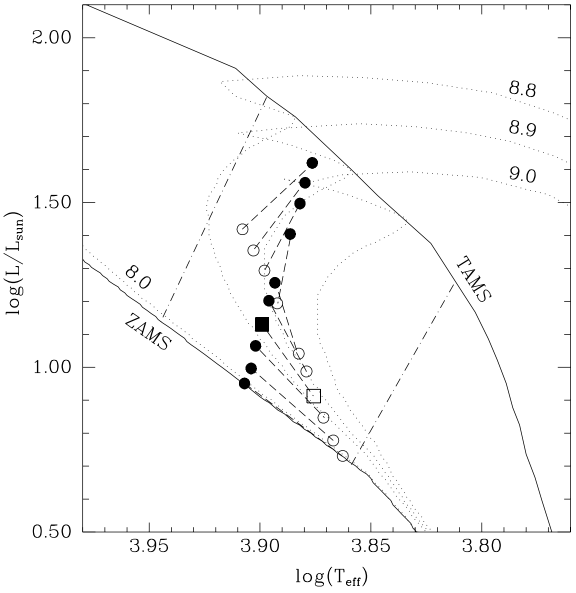

Figure 1. The positions of the primary and secondary stars in the HR diagram for different ages. The filled and open circles denote the primary and secondary stars, respectively. For the same age, both stars are connected by a dashed line. Isochrones are plotted with the dotted lines and labelled with log (age). All positions for the secondary star are within the observed δ Sct instability strip. The solution corresponding to the *Hipparcos* parallax and the observed apparent magnitude is marked with the squares.

same age, so we used the Geneva theoretical stellar models for solar composition to describe the stars.

To find a possible configuration for the system, we proceeded as follows: for each stellar model of a given isochrone that is assumed to correspond to the primary star, we interpolated the parameters corresponding to the secondary star to give the point on the same isochrone that is 0.54 mag fainter. For both stars, we then derived the β index from the stellar temperature using the Moon & Dworetsky (1985) calibration. Finally, we calculated the composite β for the pair and compared this value with the observed one. In this way, for the given isochrone the points corresponding to the two stars are uniquely determined. Fig. 1 shows the positions of the primary and secondary stars in the HR diagram for different ages. To further limit the possible parameters, it would be necessary to constrain the luminosities and/or the radii of the stars. In this sense, we note that the *Hipparcos* parallax is not accurate enough to provide a useful constraint. All of the configurations showed in Fig. 1 are consistent with the observed apparent magnitude and the *Hipparcos* parallax within one sigma error.

3 THE SECONDARY SPECTRUM

We have identified in the spectrum some broad lines that we believe belong to the secondary star. One of the clearest cases is the Ca I triplet shown in Fig. 2. The predicted spectral positions of these lines are marked with vertical lines. These broad features are consistent with a radial velocity of $+10 \pm 5$ km s^{-1} with respect to the primary star and a rotational velocity of the order of $v \sin i \approx 80$ km s^{-1}. The similarity of the radial velocity to that of the primary supports the contention that the two components are a bound and co-eval pair. The rotational velocity is typical of a δ Sct star.

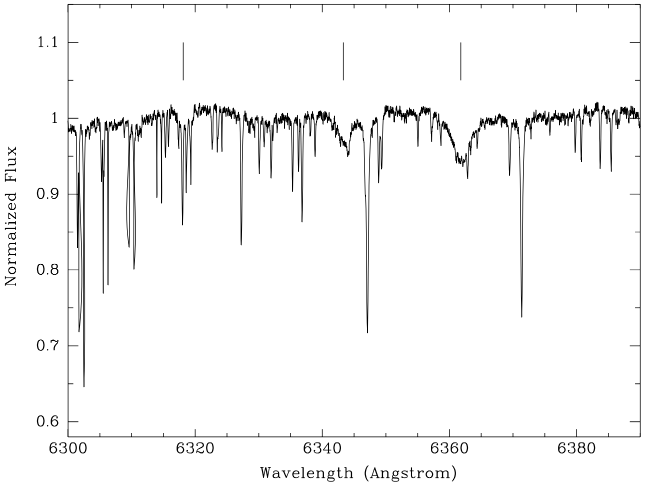

Figure 2. A portion of the UVES spectrum of HD 218994 showing the presence of broad Ca I lines (marked with vertical lines) from the secondary component for the Ca I triplet at λλ6318.11 Å, 6343.29 Å and 6361.79 Å.

4 MAGNETIC MEASUREMENTS

To measure the magnetic fields in HD 21190 and HD 218994A, we used the multi-mode instrument FORS 1 mounted at the 8-m Kueyen telescope of the VLT with the GRISM 600B. At the beginning of 2007 April, a new mosaic detector with blue optimized E2V chips was implemented in FORS 1. It has a pixel size of 15 μm (compared to 24 μm for the previous Tektronix chip) and higher efficiency in the wavelength range below 6000 Å. To achieve the highest possible signal-to-noise ratio (S/N) – as is required for accurate measurements of stellar magnetic fields – while avoiding saturation in most seeing conditions, we used the (200 kHz, low, 1 × 1) readout mode, which makes it possible to achieve an S/N of more than 1000 with only a single exposure. With the new mosaic detector and the grism 600B we are now also able to cover a much larger spectral range, from 3250 to 6215 Å. The FORS 1 resolution of $R \sim 2000$ was obtained with a slit-width of 0.4 arcsec. A detailed description of the assessment of the longitudinal magnetic field measurements using this instrument is given by (and references therein Hubrig et al. 2004).

We measure the longitudinal magnetic field of HD 218994 to be $\langle B_z \rangle = +440 \pm 23$ G, and of HD 21190 to be $\langle B_z \rangle = +47 \pm 13$ G. The high S/N obtained in our spectra with the new mosaic detector (up to 1100 for each individual spectrum of the six spectra of HD 21190, and up to 800 for each individual spectrum of the six spectra of HD 218994) partially explains the excellent precision for our magnetic field determinations of only 13 G for HD 21190. Furthermore, the standard error of the measurements depends on the spectral type, the complexity of the spectra of the studied targets and on their rotational velocity. Our targets are moderately rotating and because of their late A spectral types present in their spectra numerous absorption lines. On the other hand, previous measurements with the old Tektronix chip on FORS1 have shown virtually no spurious detections at about a level of 30 G (see e.g. Bagnulo et al. 2006, who also report probable magnetic field detections with errors of only 18–20 G). Due to the limited experience yet obtained with the new mosaic detector, it is possible that as-yet-unknown instrumental effects could introduce additional noise when working very close to the detection threshold. Hence, the measurement in HD 21190 is insecure. Conservatively, we consider the systematic error to be no larger than that for the old chip, 30 G, so that the

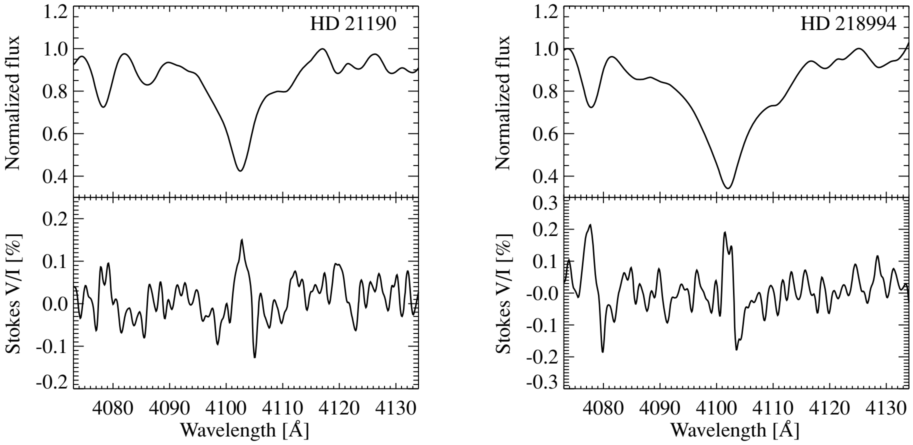

Figure 3. The left-hand panels show the Stokes *I* and *V*/*I* spectra of the δ Sct Ap star HD 21190 in the vicinity of the Hδ line. The right-hand panels show the same for the roAp star HD 218994A.

magnetic field detection is only at the 1.6σ confidence level. More measurements over the rotation cycle of this star, as well as some additional tests to establish the highest accuracy obtainable with FORS 1 are needed. In Fig. 3, we present both the Stokes *I* and *V*/*I* spectra of these stars in the vicinity of the Hδ line. We see such Zeeman features in all the H lines in our wavelength range.

5 HD 218994 PHOTOMETRIC OBSERVATIONS AND ANALYSIS

Following the discovery of roAp star pulsations in radial velocity variations of HD 218994 (González et al. 2008), we observed this star for 6 and 5 h on two consecutive nights – 2007 September 16–17 (JD 245 4360) and September 17–18 (JD 245 4361) – with the South African Astronomical Observatory (SAAO) 0.5-m telescope through a Johnson *B* filter using the Modular Photometer. This is a photoelectric photometer, so both components of the binary system were included in the 30-arcsec aperture. Continuous 10-s integrations were used with occasional sky background measurements. The data were corrected for coincidence losses, nightly extinction and some very low frequency sky transparency variation. The data were then averaged to 40-s integrations to reduce some high frequency scatter for ease of viewing the light curves, yet with sufficient time-resolution for a search for the roAp pulsations discovered in the radial velocity variations (González et al. 2008).

Variations on a time-scale of just under 1 h are evident in the light curves, as can be seen in the left-hand column of the top two rows of Fig. 4. The amplitude spectra in the right-hand column confirm this. Martinez & Kurtz (1994) observed this star for a little over 1 h on two nights in 1991 and found no evidence of the roAp-type short-period pulsations for which they were searching. Their light curves both do show variation on a time-scale of 1 h, but since the observations were only of duration 1 h, this could not be distinguished with confidence from possible sky transparency variations, so they did not note the δ Sct pulsation. Some years earlier in 1983 DWK observed HD 218994 photometrically on two nights with the same SAAO 0.5-m telescope for 3 h each night and found the δ Sct pulsation, but never published this. We have recovered those data from his archives and show a light curve and amplitude spectrum from 1983 August 8–9 (JD 244 5555) in the bottom row of Fig. 4, leaving no doubt that at least one of the components of the binary system HD 218994 is a δ Sct star. Peter Martinez (unpublished) also observed the star photometrically once more in 1994 and the δ Sct variation can be seen there, too. Table 1 lists the nights for which we have photometric time series observations of HD 218994, and gives a least-squares fit of the highest peak in the amplitude spectrum for each night to those data. There is an indication of multiperiodicity; this is expected for a δ Sct star, but the case for it is not yet strong with the available data. For all light curves the amplitude is of the order of 2–3 mmag.

For a magnitude difference between the components of 0.54, the flux from the secondary is 0.61 that of the primary. For such small-amplitude variations, linear scaling is a good approximation, so if this δ Sct variation is in the primary component, the amplitude needs to be scaled by 1.64; if it is in the secondary component, it needs to be scaled by 2.64. In either case, this remains in the realm of small-amplitude pulsation for a δ Sct star, for example, increasing the pulsation amplitude for the secondary star only to about 6 mmag.

Our initial purpose in obtaining observations on 2007 September 16–17 and 17–18 was to search for photometric variations on the time-scale of the roAp star pulsations. We can rule those out for those two nights of data at the 0.3 mmag level – the level of the highest noise peaks; this is equivalent to about 4σ in amplitude S/N. Fig. 5 shows this. Of course, this also needs to be scaled up by the factor of 1.64 for variations in the primary star. We thus may rule out photometric variations at the roAp frequency of 1.2 mHz, as observed in the radial velocity variations (González et al. 2008), at the level of the highest peaks scaled to 0.5 mmag.

There is no clear correlation between photometric pulsation amplitude in Johnson *B* and radial velocity pulsation amplitude in roAp stars. Some stars with radial velocity amplitudes similar to that of HD 218994 (up to 1 km s^{-1} for spectral lines of some rare earth elements) do show detectable photometric variations. The roAp stars also show rotational amplitude modulation and multiperiodicity. We have no information yet for these for HD 218994A, and the photometric observations are not simultaneous with the spectroscopic observations; thus, the non-detection of photometric variability at the frequency of the roAp variations is a weak constraint. It is included here for completeness.

6 CONCLUSION

We conclude that HD 218994AB shows δ Sct pulsation in its light curves. Additional magnetic field measurements are needed for

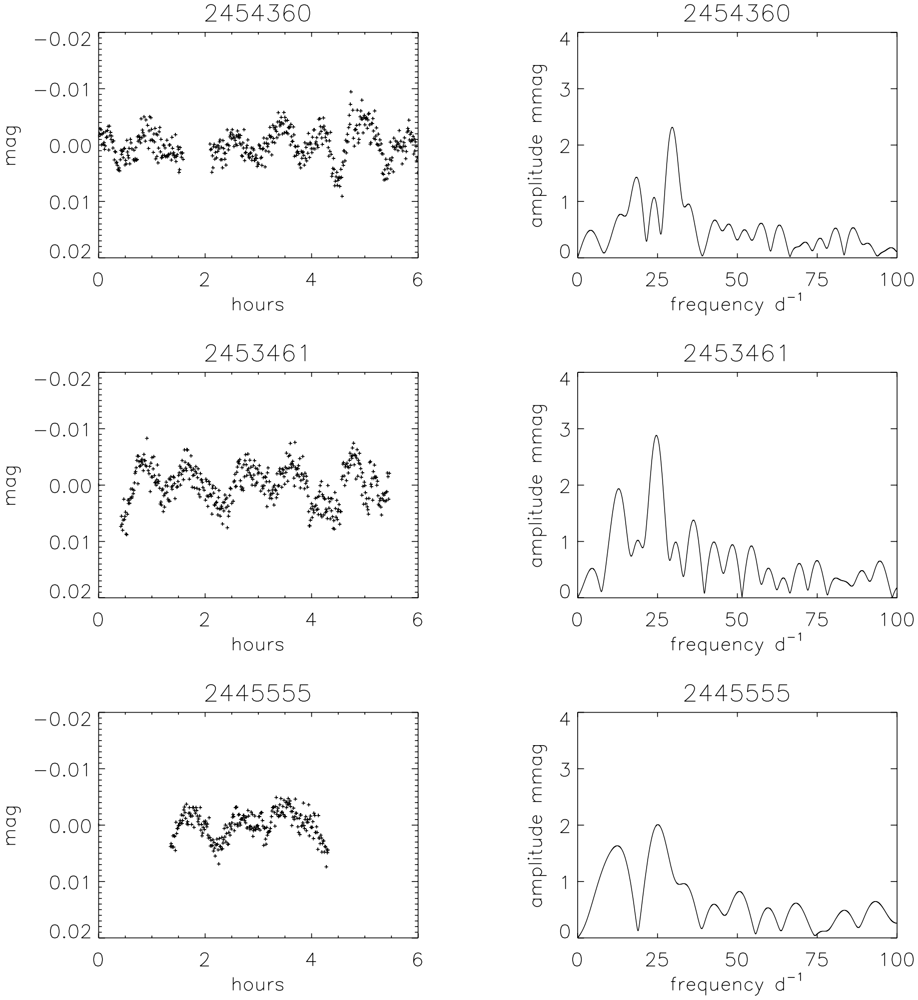

Figure 4. The left-hand panels show three light curves and the right-hand panels show their corresponding amplitude spectra. The top row shows the 6.04-h light curve for HD 218994AB obtained by FvW on 2007 September 16–17 (JD 245 4360) with the SAAO 0.5-m telescope through a Johnson *B* filter. The middle row shows the 5.04-h B light curve obtained with the same telescope on the following night (JD 245 4361). The bottom row shows a 2.96-h B light curve obtained with the same 0.5-m telescope 24 yr earlier by DWK on 1983 August 8–9 (JD 244 5555). A period of the order of 1 h is evident in all three light curves and amplitude spectra indicating that at least one component of the HD 218994AB system is a δ Sct star. The highest amplitude peak in each case is near 25 d^{-1} with an amplitude of 2–3 mmag.

Table 1. A least-squares fit of the highest-amplitude peak in the amplitude spectrum for each light curve of HD 218994. The observations span 24 yr. All were obtained with the SAAO 0.5-m telescope. The function fitted by least squares was $\Delta B = \cos\,[2\pi f(t - t_0) + \phi]$, where t_0 is given in the last column. The column labelled Δt gives the duration of the observations in hours.

Date	Observer	JD 240 0000+)	Δt (h)	Frequency (d^{-1})	Amplitude (mmag)	Phase (radians)	σ (mmag)	t_0 (HJD)
1983 August 9–10	DWK	455 55	2.96	25.1	2.58 ± 0.23	2.55 ± 0.09	2.67	244 5555.0
1983 August 13–14	DWK	455 60	3.06	28.3	1.85 ± 0.66	-0.54 ± 0.35	3.14	244 5560.0
1991 July 13–14	PM	484 51	1.04	29.4	2.95 ± 0.38	-1.71 ± 0.13	2.55	244 8451.0
1991 August 5–6	PM	484 74	1.10	33.4	1.10 ± 0.18	1.64 ± 0.17	1.26	244 8474.0
1994 July 19–20	PM	495 53	1.20	21.4	3.95 ± 0.37	-2.08 ± 0.10	2.75	244 9553.0
2007 September 16–17	FvW	543 60	6.04	29.6	2.30 ± 0.14	-1.26 ± 0.06	2.20	245 4360.0
2007 September 17–18	FvW	543 61	5.04	24.7	2.88 ± 0.18	0.98 ± 0.06	2.66	245 4361.0

HD 21190 – the most-evolved Ap star – for which our measurements suggest the first magnetic field detection for a star of this type. HD 218994A is known to be an roAp star (González et al. 2008), thus it could be an roAp–δ Sct hybrid of considerable importance. A working hypothesis is that HD 218994A is an roAp star, and the 0.54 mag fainter HD 218994B is a δ Sct star. In that case, high-resolution spectra of the components separately will allow determination of $T_{\rm eff}$ and L for the roAp star with greater confidence than is possible for single roAp stars. Given the star's relatively evolved state compared to most roAp stars, this will be useful.

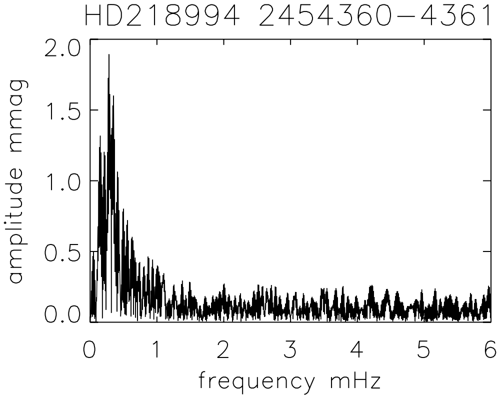

Figure 5. An amplitude spectrum for the two nights JD 245 4360–245 4361 showing the low-frequency δ Sct pulsation clearly. This places an upper limit for any photometric pulsation at the roAp star frequency of 1.2 mHz of 0.3 mmag at the level of the highest noise peaks, or 0.5 mmag when accounting for the light of the other star. This is a 4σ upper limit.

With a separation of 1.1-arcsec, high-precision photometry of the individual components of HD 218994AB is not a good prospect with ground-based observations. On the other hand, time-resolved radial velocity studies of the two components separately are possible with this separation. These should be carried out to determine unequivocally which component is the δ Sct star. The high-S/N average spectra that will result from such a study will provide the material for detailed abundance analyses that will provide T_{eff} and L for HD 218994A, presuming that HD 218994B has a normal spectrum. If not, then the system is more complex and more important. We leave further speculation to a time when more information is available.

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