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Discovery of pulsational line profile variations in the δ Scuti star HD 21190 and in the Ap Sr star HD 218994*

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ABSTRACT

Asteroseismology has the potential to provide new insights into the physics of stellar interiors. We have obtained Ultraviolet and Visual Echelle Spectrograph high time-resolution observations of the δ Scuti star HD 21190 and of the Ap Sr star HD 218994 to search for pulsational line profile variations. We report the discovery of a new roAp star, HD 218994, with a pulsation period of 14.2 min. This is one of the most evolved roAp stars. No rapid pulsations have been found in the spectra of the cool Ap star – δ Scuti star HD 21190. However, we detect with unprecedented clarity for a δ Scuti star moving peaks in the cores of spectral lines that indicate the presence of high-degree non-radial pulsations in this star.

Key words: stars: chemically peculiar – stars: individual: HD 21190 – stars individual: HD 218994 – stars: oscillations.

1 INTRODUCTION

Asteroseismology has the potential to provide new insights into the physics of stellar interiors. Among the most promising objects that can be studied through this technique are the rapidly oscillating Ap (roAp) stars. They pulsate in high overtone, low degree, non-radial *p*-modes, with periods in the range 5.65–21.2 min. In a previous study, Hubrig et al. (2000) discussed the relationship between the roAp stars and the non-oscillating Ap (noAp) stars, and concluded that the noAp stars are, in general, slightly more evolved than the roAp stars. Cunha (2002) predicted the theoretical edges of the instability strip appropriate to roAp stars and compared them with the observations. According to her predictions, stars that are more luminous and/or more evolved should pulsate with longer periods in the 20–25-min range, and, as a result, their oscillations might have escaped detection in photometric surveys that have had low sensitivity to periods of this order. Freyhammer et al. (2008) have studied nine evolved Ap stars near the terminal age main sequence with high spectral resolution, high time-resolution spectra obtained with the Ultraviolet and Visual Echelle Spectrograph (UVES) on the Very Large telescope (VLT). At precisions less than 60 m s^{-1}, they found no pulsation in any of the nine stars, lending support to Hubrig et al.'s (2000) conclusion that that noAp stars are somewhat more evolved than roAp stars. Nevertheless, there is one known evolved roAp star with a 21.2-min period, HD 116114 (Elkin et al. 2005), so we do know that more evolved Ap stars can pulsate.

It is important to our understanding of the driving mechanism for roAp star pulsations to find what physical parameters govern which stars pulsate, and which do not. A current working hypothesis is that the pulsations are driven mostly by H ionization (see e.g. Balmforth et al. 2001; Saio 2005). The models of Saio (2005) lead to a clear prediction that lower radial overtone pulsation modes typical of δ Scuti stars (δSct stars) are suppressed by the magnetic field in Ap stars, hence should not be found amongst the roAp stars. This is in general agreement with observations: at present, there is no known magnetic δ Sct star. There are δ Sct stars that are classified as Ap stars, but at classification dispersions magnetic Ap stars and non-magnetic Am stars can be confused, so that measurements of the magnetic fields are independently needed for δ Sct stars classified as Ap stars.

The most evolved star known that is classified as an Ap star is HD 21190 (Koen et al. 2001) which is also a known δ Sct star. In this paper, we discuss our search for pulsational line profile variations in high time-resolution UVES spectra of HD 21190 to test if it is an roAp star, as well as a δ Sct star. We also give a more detailed analysis of the discovery of roAp pulsations in the Ap Sr star HD 218994, which was included in the sample of non-pulsating binary Ap stars in the study Hubrig et al. (2000). Both of these stars are unusual, hence important: HD 218994 is one of the most luminous roAp stars; hence, the discovery of pulsation makes it a potential test of Cunha's (2002) theoretical instability strip. HD 21190 is the only cool Ap star that is also a δ Sct star.

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Whether it is magnetic is still to be determined. Our observations show it to be the best known example of a δ Sct star with moving bumps in its line profiles characteristic of high-degree pulsation – making it a prime target for further study.

2 OBSERVATIONS

The spectroscopic time-series for HD 21190 and HD 218994 have been obtained on 2006 November 8 and November 3, respectively, at ESO with the VLT UV-Visual Echelle Spectrograph UVES at UT2. We used the UVES DIC2 standard setting covering the spectral range from 3300 to 4500 Å in the blue arm and from 5700 to 7600 Å in the red arm. The slit width was set to 0.″3 for the red arm, corresponding to a resolving power of $\lambda/\Delta\lambda \approx 1.1 \times 10^5$. For the blue arm, we used the slit width of 0.″4 to achieve a resolving power of $\approx 0.8 \times 10^5$. Further, we used the fast readout mode (625 kHz, 1 × 1, low) to keep readout and overhead time to about 30 s. For both stars, we used exposure times of 3 min, obtaining time-series with a resolution of about 3.7 min. The spectra were reduced by the UVES pipeline Data Reduction Software (version 2.5; Ballester et al. 2000) and using standard IRAF routines. The signal-to-noise ratio (S/N) of the obtained UVES spectra range from 40 in the near ultraviolet (UV) (3500 Å) to 150–200 in the visual region (4000–7000 Å).

3 THE δ SCT STAR HD 21190

HD 21190 is a known δ Sct star with a variability period of 3.6 h, discovered by the *Hipparcos* mission. Koen et al. (2001) determined the spectral type to be F2 III SrEuSi, making it the most evolved Ap star known. According to Cunha (2002), longer period oscillations (20–25 min) in magnetic roAp stars should exist in the more evolved stars. To search for pulsational line profile variations on time-scales shorter than typical δ Sct star pulsations (of the order of hours), we obtained for this star 14 UVES spectra covering about 50 min, corresponding to $\sim \frac{1}{4}$ of the known δ Sct pulsation period. Using *Hipparcos* and ASAS (Pojmanski 2002) photometric data bases, we re-calculated the ephemeris and found that our observations correspond to the phase interval of decreasing brightness.

The obtained spectra show broad spectral lines ($v\sin i \sim 72\,\mathrm{km\,s^{-1}}$) with small variable peaks in the line profiles (Fig. 1). In the bottom of Fig. 1, we present all the observed spectra stacked in two-dimensional images for two spectral regions. It can clearly be seen that three peaks are moving smoothly towards the red with a speed of $21\,\mathrm{km\,s^{-1}}$/h. However, no spectral features moving at higher frequencies were found in our spectra. To measure the radial velocities of these peaks, we filtered lower spectral frequencies and used the cross-correlation method.

Similar splitting in the line profiles has been recently detected by Yushchenko et al. (2005) in two other δ Sct stars, δ Sct itself and HD 57749. Also, high-S/N spectroscopic time-series observations by Poretti for the δ Sct star FG Vir, as reported by Mittermayer & Weiss (2003), clearly show line profile variations similar to those found in our spectra. These are the typical blue-to-red moving bumps that are seen for non-radial pulsations of non-axisymmetric *m*-modes in rapidly rotating stars where radial velocity Doppler shifts the travelling waves of the individual pulsating surface segments, the seminal example being the late O star ζ Oph (Vogt & Penrod 1983).

4 THE NEW RAPIDLY OSCILLATING AP STAR HD 218994

HD 218994 is a close visual binary system with a separation of 1.2 arcsec (Renson, Gerbaldi & Catalano 1991). It is classified as A3 Sr in the Michigan Spectral catalogue (Houk & Cowley 1975). Strömgren and Hβ photometry were measured by Martinez (1993) who found $V = 8.565, b-y = 0.154, m_1 = 0.196, c_1 = 0.826$ and $\beta = 2.807$. Hubrig et al. (2000) estimated $T_{\mathrm{eff}} = 7600$ K from the β index. Martinez found $\delta m_1 = 0.008$ and $\delta c_1 = 0.032$ which

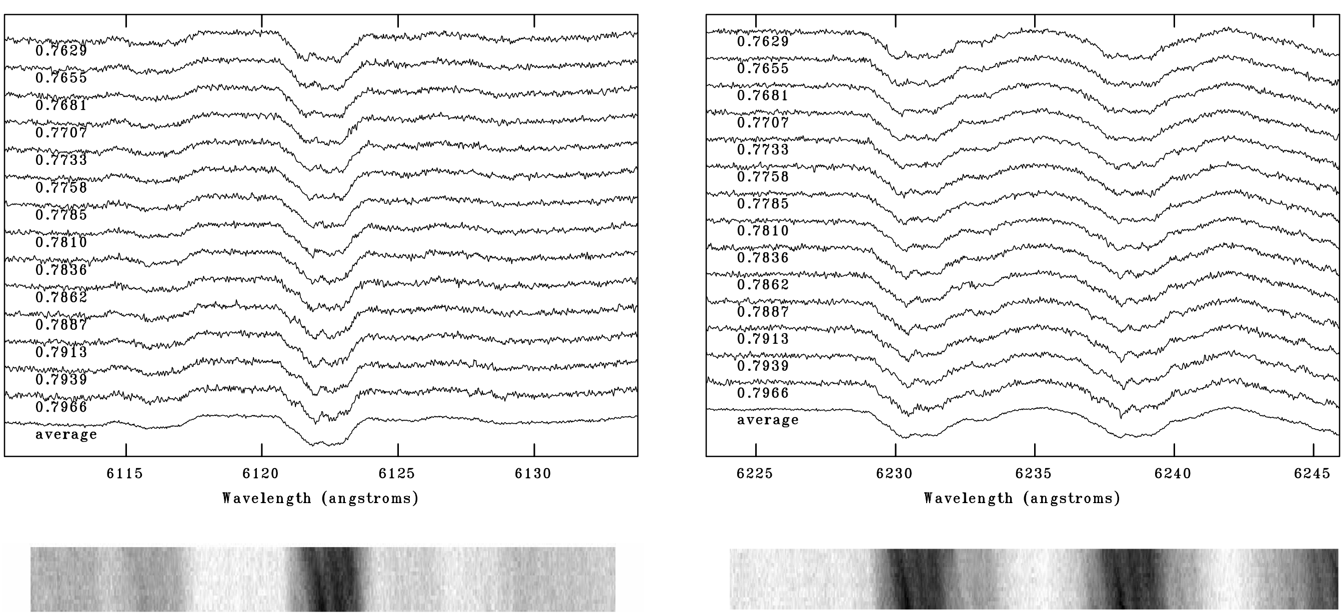

Figure 1. Spectral profile variability of Mn II 6122 Å, Fe I 6231 Å and Fe II 6238 Å lines in the UVES spectra of HD 21190. Spectra are labelled with Julian dates (HJD 2454047). The average spectra are plotted in the bottom of each panel. The two-dimensional images present, for the same spectral regions, the 14 observed spectra stacked. In these images, the *y*-dimension corresponds to the observing time, increasing downwards. Three moving peaks are clearly visible in the cores of all presented spectral lines.

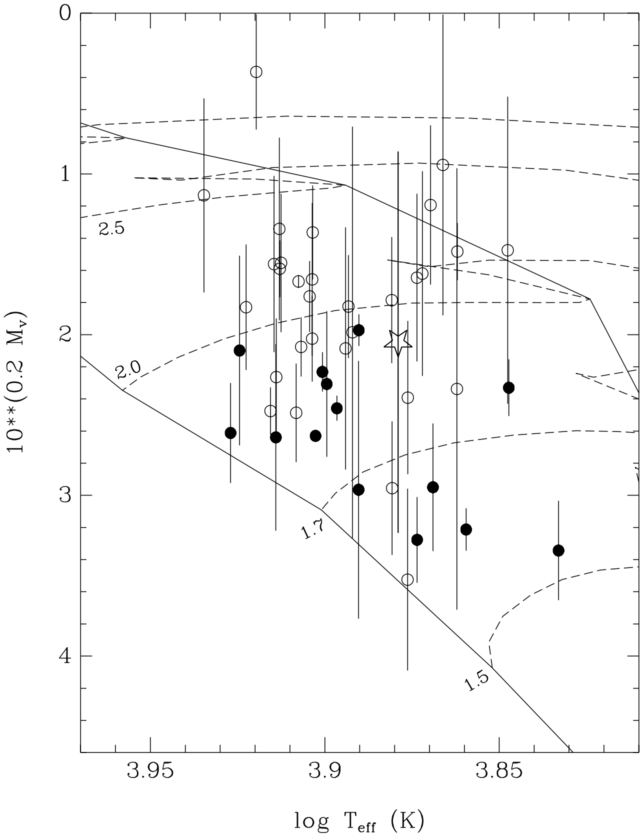

Figure 2. Hertzsprung-Russell (HR)-diagram of the sample of roAp (full dots) and of the noAp stars (open dots) studied by Hubrig et al. (2000). HD 218994 is indicated by a star.

are typical for a normal, main-sequence A star. He showed that correction for reddening increases the m_1 index by about 0.02 and decreases the c_1 index by about 0.03. This star is unusual among the roAp stars for its nearly normal m_1 and c_1 indexes. Since most of the 36 known roAp stars (see Kurtz et al. 2006 for a list) were found by photometric searches, this is an indication that radial velocity studies will discover many more roAp stars that are difficult to detect in photometric studies. HD 218994 is located in the same region of the parameter space in which rapid pulsations have been detected (Fig. 2), but an earlier search for pulsations in the Cape Survey yielded no detection (Martinez & Kurtz 1994). We have several additional unpublished photometric runs on this star that do not show roAp-type pulsations.

We obtained for this star 15 UVES spectra with a time resolution of ∼3 min. From our spectra, we estimate $v \sin i = 5.2 \pm 0.6\,\mathrm{km\,s^{-1}}$ using the first zero of the Fourier transform of the spectral line profile of the magnetically insensitive lines. Numerous lines of rare earth elements (such as those of Nd II, Nd III, Pr III, Eu II and Tb III) have been easily identified. To search for pulsational line variability, we calculated the average spectrum of the observed 15 spectra and subtracted it from the original spectra. We found for several rare earth lines a clear indication of variability. This star is thus the 36th known roAp star.

The lines of Fe I, Fe II and the Fe-peak elements show no radial velocity variations with a 1σ standard deviation per line in the range 40–70 $\mathrm{m\,s^{-1}}$. However, clear radial velocity variations are detected in the doubly ionized rare earth elements lines of Nd III and Pr III, as is typical for the roAp stars (see e.g. Savanov, Malanushenko & Ryabchikova 1999; Kurtz, Elkin & Mathys 2005). We note that the mean radial velocity for different elements is different with a range of a few $\mathrm{km\,s^{-1}}$, indicating the presence of chemical inhomogeneities on the stellar surface.

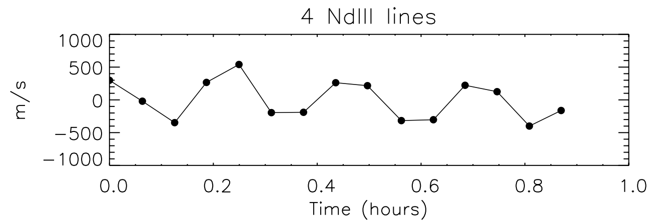

Figure 3. A radial velocity curve for the average of four Nd III lines where the 14.2-min pulsation can be clearly seen. The radial velocity error per observation is 220 $\mathrm{m\,s^{-1}}$.

We analysed five Nd III lines, eight Pr III lines and a few lines of other ions for radial velocity variations using a discrete Fourier transform (Kurtz 1985). Individual lines of Nd III and Pr III show the same peak with a frequency of 1.17 mHz ($P = 14.2$ min), confirming that the variation is in the star and is not instrumental. Fig. 3 shows a radial velocity curve for four of the Nd III lines averaged where the 14.2-min pulsation is easily seen. Fig. 4 shows the amplitude spectra for five Nd III lines and for eight Pr III lines out to beyond the sampling frequency of 4.5 mHz. Two peaks are seen, symmetrically placed on either side of the Nyquist frequency. With the known range of pulsation periods of roAp stars, 5.65–21.2 min, and our data sampling time of 3.7 min, there is thus a potential ambiguity

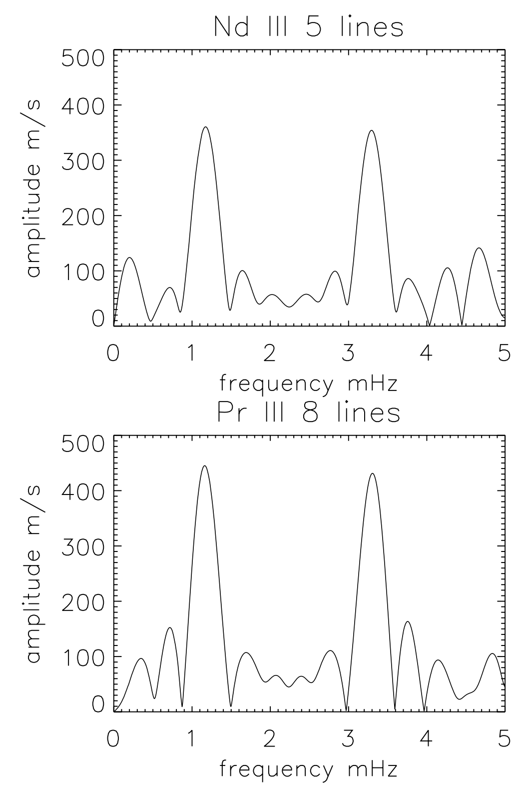

Figure 4. Top panel: an amplitude spectrum for 5 Nd III lines out to just beyond the sampling frequency of 4.5 mHz. Two peaks are seen, as is expected, at 1.2 and 3.3 mHz, which is the sampling frequency minus 1.2 mHz. Bottom panel: the same amplitude spectrum for eight Pr III lines showing the same alias ambiguity.

Table 1. A least-squares fit of the frequency $\nu = 1.17$ mHz to the radial velocity variations of a selection of spectral lines of HD 218994. The third column gives the average radial velocity for each line; the range is indicative of horizontal abundance variations. The zero point for phases is MJD 54042.0. The last columns give the standard deviation per observation of the 15 radial velocity measurements to the fit, and the ratio between the amplitude and standard deviation of the amplitude, i.e. the S/N in the detection of pulsation.

λ (Å)	Ion	RV (km s^{-1})	Amplitude (m s^{-1})	Phase (rad)	σ (m s^{-1})	amp/Δamp
5845.020	Nd III	24.98 ± 0.09	259 ± 106	−2.75 ± 0.42	292	2.4
5956.035	Pr III	26.49 ± 0.08	222 ± 95	2.94 ± 0.44	265	2.3
5987.683	Nd III	24.88 ± 0.10	457 ± 66	−2.67 ± 0.15	182	6.9
6052.981	Pr III	27.32 ± 0.10	268 ± 110	−2.97 ± 0.42	305	2.4
6089.985	Pr III	26.64 ± 0.12	360 ± 127	−2.87 ± 0.36	353	2.8
6141.713	Ba II	25.22 ± 0.04	71 ± 51	−1.17 ± 0.71	139	1.4
6145.068	Nd III	24.34 ± 0.04	171 ± 35	−2.59 ± 0.21	95	4.9
6147.741	Fe II	25.45 ± 0.03	91 ± 39	−1.13 ± 0.42	107	2.3
6160.215	Pr III	26.51 ± 0.22	931 ± 178	−2.48 ± 0.19	490	5.2
6195.611	Pr III	25.52 ± 0.14	510 ± 116	−2.07 ± 0.23	304	4.4
6327.265	Nd III	25.15 ± 0.13	600 ± 93	−2.75 ± 0.16	258	6.5
6550.231	Nd III	24.84 ± 0.07	299 ± 58	−2.93 ± 0.20	162	5.2
6562.797	Hα	25.11 ± 0.12	121 ± 57	−1.30 ± 0.46	155	2.1
6645.064	Eu II	24.96 ± 0.09	205 ± 107	0.99 ± 0.52	293	1.9
6910.146	Pr III	24.92 ± 0.14	352 ± 172	2.90 ± 0.50	477	2.0
7030.388	Pr III	25.22 ± 0.13	586 ± 94	−2.76 ± 0.17	262	6.2
7076.618	Pr III	25.12 ± 0.14	511 ± 138	−2.78 ± 0.28	383	3.7
5 lines	Nd III	–	355 ± 38	−2.74 ± 0.11	238	9.3
8 lines	Pr III	–	437 ± 53	−2.73 ± 0.12	412	8.2

for the pulsation period of HD 218994. The Nyquist frequency for our data is $\nu_{\rm Ny} = 2.25$ mHz. As is expected for a purely sinusoidal variation and Gaussian noise, there is a peak in Fig. 4 at 3.3 mHz ($\nu_S - \nu = 4.5$–$1.2 = 3.3$ mHz; $P = 5.1$ min). See Kurtz (1983) for a graphical demonstration of this effect.

We consider it more likely that the 14.2-min period is the correct alias peak seen in Fig. 4. But given that the shortest known period for an roAp star (HD 134214) is only 5.65 min, we do not rule out the possibility that the 3.3 mHz peak is the correct one. Higher time-resolution data will resolve this issue, as is usual with questions of Nyquist aliases. Without another physical constraint on the choice of peak in Fig. 4, either choice is equally valid. We consider higher frequency Nyquist aliases to be physically implausible – the usual assumption for roAp stars. Since each observational point represents the radial velocity averaged over the exposure time, the observed amplitude is reduced by a factor that depends on the ratio between the exposure time and the period. This effect reduces the observed amplitudes by a factor of 0.52 for the 5.1-min period and by a factor of 0.93 for the 14.1-min period. We thus expect higher amplitudes to be measured with higher time-resolution data.

Table 1 shows the least-squares fit of the frequency 1.17 mHz to the radial velocity variations of some selected lines and for sets of Nd III and Pr III lines. These results show that only Pr III and Nd III lines have significant radial velocity variations, with amplitudes at least four times the standard deviation of the measurements. The data suggest, but do not prove, a higher amplitude for the Pr III lines than for the Nd III lines. There is no significant phase shift between them. In many roAp stars, there appears to be an outwardly running wave with Pr III lines forming higher in the atmosphere than Nd III lines, hence a phase shift between them. It is often the case that the Pr III lines show higher amplitude, as is expected with the dropping atmospheric density. As our purpose here is to demonstrate unequivocally that pulsation is present, and as the data are sparse, we defer further interpretation to the acquisition of a more extensive data set.

5 CONCLUSIONS

We report the discovery of a new roAp star, HD 218994, with a pulsation period of 14.2 min, or 5.1 min. This is one of the most evolved of all roAp stars, hence is an important test of theoretical models of pulsation driving and pulsation periods in roAp stars. No rapid pulsations have been found in the spectra of the cool Ap – δSct star HD 21190, hence it is not an roAp star. However, we detect moving peaks in the cores of spectral lines – with a clarity never seen before in a δ Sct star – which indicate the presence of non-axisymmetric non-radial pulsations in this star. Its combination of cool Ap spectral type and high-degree δ Sct pulsation makes it an important target for more in depth study.

REFERENCES

Ballester P., Grosbol P., Banse K., Disaro A., Dorigo D., Modigliani A., Pizarro de la Zglesia J. A., Boitquin O., 2000, in Quinn P. J., ed., Proc. SPIE Vol. 4010, Observatory Operations to Optimize Scientific Return II. SPIE, Bellingham, p. 246

Balmforth N. J., Cunha M. S., Dolez N., Gough D. O., Vauclair S., 2001, MNRAS, 323, 362

Cunha M. S., 2002, MNRAS, 333, 47

Elkin V. G., Riley J. D., Cunha M. S., Kurtz D. W., Mathys G., 2005, MNRAS, 358, 665

Freyhammer L. M., Kurtz D. W., Cunha M. S., Mathys G., Elkin V. G., Riley J. D., 2008, MNRAS, in press

Houk N., Cowley A. P., 1975, Michigan Catalogue of Two-Dimensional Spectral Types for the HD star. University of Michigan, Ann Arbor

Hubrig S., Kharchenko N., Mathys G., North P., 2000, A&A, 355, 1031

Koen C., Kurtz D. W., Gray R. O., Kilkenny D., Handler G., Van Wyk F., 2001, MNRAS, 326, 387

Kurtz D. W., 1983, Inf. Bull Var. Stars, 2285, 1

Kurtz D. W., 1985, MNRAS, 213, 773

Kurtz D. W., Elkin V. G., Cunha M. S., Mathys G., Hubrig S., Wolff B., Savanov I., 2006, MNRAS, 372, 286

Kurtz D. W., Elkin V. G., Mathys G., 2005, EAS, 17, 91

Martinez P., 1993, PhD thesis, Univ. Cape Town
Martinez P., Kurtz D. W., 1994, MNRAS, 271, 129
Mittermayer P., Weiss W., 2003, A&A, 407, 1097
Pojmanski G., 2002, Acta Astron., 52, 397
Renson P., Gerbaldi M., Catalano F. A., 1991, A&AS, 89, 429
Saio H., 2005, MNRAS, 360, 1022
Savanov I. S., Malanushenko V. P., Ryabchikova T. A., 1999, Astron. Lett., 25, 802
Vogt S. S., Penrod G. D., 1983, ApJ, 275, 661
Yushchenko A., Gopka V., Kim Chulhee, Musaev F., Kang Y. W., Kovtyukh V., Soubiran C., 2005, MNRAS, 359, 865

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