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

DOI: 10.1017/S1743921305009580

A spectroscopic atlas of the magnetic CP star HR 8216 (A6pCr) $\lambda\lambda$3830-4770

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Abstract. We present samples from a spectroscopic atlas of the sharp-lined, magnetic Chemically Peculiar star HR 8216 (A6pCr) based on spectrograms obtained with the long camera of the 1.22-m telescope of the Dominion Astrophysical Observatory using a Reticon detector. For the spectral region $\lambda\lambda$3830-4770 the inverse dispersion is 2.4 Å mm^{-1} with a 2 pixel resolution of 0.072 Å. At the continuum the mean signal-to-noise ratio is 200. The wavelengths in the laboratory frame, the equivalent widths, and the identifications of the various spectral features are given. This atlas should provide useful guidance for studies of similar stars and for atomic physicists interested in improving atomic line parameters.

Keywords. Line: identification, techniques: spectroscopic, atlases, stars: chemically peculiar, stars: individual: (HR 8216)

1. Introduction

HR 8216 (HD 204411, BD+48^o 3390, NSV 13718, SAO 50867, HIP 105898) is a sharp-lined star. Recently Adelman (2002) used its Hipparcos parallax to determine that its position on the HR diagram is slightly above the Zero Age Main Sequence. It has a mass of 1.9 $M_\odot$. The spectral type of HR 8216 is A6pCr. Caliskan (2004), analyzed the spectroscopic material used for this atlas and summarized information on previous studies of this star. The atlas is assembled from a set of high quality spectra obtained with a Reticon on a spectrograph with a known amount of scattered light which has been removed.

2. Observations and reductions

This spectral atlas of HR 8216's spectrum $\lambda\lambda$3830-4770 is composed of 2nd order exposures obtained with a Reticon detector and the IS96B image slicer with wavelength coverage of 67Å at the long camera of the 1.22-m telescope of the Dominion Astrophysical Observatory (DAO) and with a resolution of 0.072 Å (two pixels) or a resolving power of 60000. Its mean signal-to-noise (S/N) ratio is 200. The central wavelengths of the 17 spectral sections between λ3830 and λ4770 were separated by 55 Å providing several Å overlap between adjacent sections. A central stop placed in the beam removed light in the same manner as the secondary mirror of the telescope. The exposures were flat fielded with those of an incandescent lamp placed in the coudé mirror train as viewed through a filter.

Table 1. HR 8216 spectrograms

Central λ(Å)	Heliocentric Julian Date	Radial velocity (km s^{-1})	Number of lines used for each spectrum
3860	49201.7753	-14.30±0.47	10
3915	47702.8690	-15.00±0.60	16
3970	47701.8728	-17.38±0.57	09
4025	47700.9057	-15.29±0.65	13
4080	47704.9254	-15.02±0.34	10
4135	47336.9329	-15.12±0.36	11
4190	47751.8540	-14.47±0.25	16
4245	49134.9235	-14.84±0.62	17
4300	47337.9236	-14.60±0.24	11
4355	48222.7036	-14.69±0.35	11
4410	47835.6988	-14.76±0.41	16
4465	47831.6970	-15.31±0.34	16
4520	47832.6731	-14.73±0.35	14
4575	48093.8952	-14.38±0.60	15
4630	48479.8884	-14.94±0.47	11
4685	48480.8624	-14.93±0.49	14
4740	48844.8508	-14.31±0.20	10
Average		-15.00±0.70	

We reduced Reticon exposures to one-dimensional FITS files with the Program RET72 (Hill & Fisher 1986) utilizing the lamp exposures. Flat images were summed to create mean flat exposures. The arc and stellar exposures were then divided by the mean flat image.

We measured interactively the arc files using the relevant routine in the spectrophotometric reduction and analysis program REDUCE (Hill & Fisher 1986). Heliocentric radial velocity corrections were calculated with the program VSUN (Hill & Fisher 1986). Using the arc files wavelength-calibrated spectra were produced with REDUCE. The wavelength scale accuracy is better than 0.005 Å.

The spectrograms with their central wavelengths, Heliocentric Julian Dates at the mid-points of their exposures, the derived radial velocities and their associated errors, and the number of lines used to determine the radial velocities are listed in Table 1. Each section's S/N ratio was estimated from the root-mean-square deviation for the continuum point intervals, usually smooth regions without lines close to the continuum, as part of the rectification process. The mean of these S/N ratios is about 200:1. The radial velocity of each spectrum was measured by identifying clean lines and using their laboratory and observed wavelengths.

The stellar intensity files were rectified with REDUCE so that the continuum was calculated from locally averaged points. We completed the rectification by interpolating between the averaged data with Hermite spline functions, which always pass through the averaged continua at the selected wavelengths. The scattered light along the spectrum was assumed to be 3.5% of the continuum (Gulliver, Hill & Adelman 1996). The resultant rectified spectrum served as the basis for the analysis of the spectrum reported in Caliskan (2004).

The final stellar parameters of HR 8216 were determined, as described in Caliskan (2004), by fitting the energy distribution including the λ5200 feature and the Hγ profile to the predictions of ATLAS9 (Kurucz 1993) metal-rich model atmospheres. The microturbulence of 0.1 km s^{-1} was found by both minimizing the scatter about the mean and

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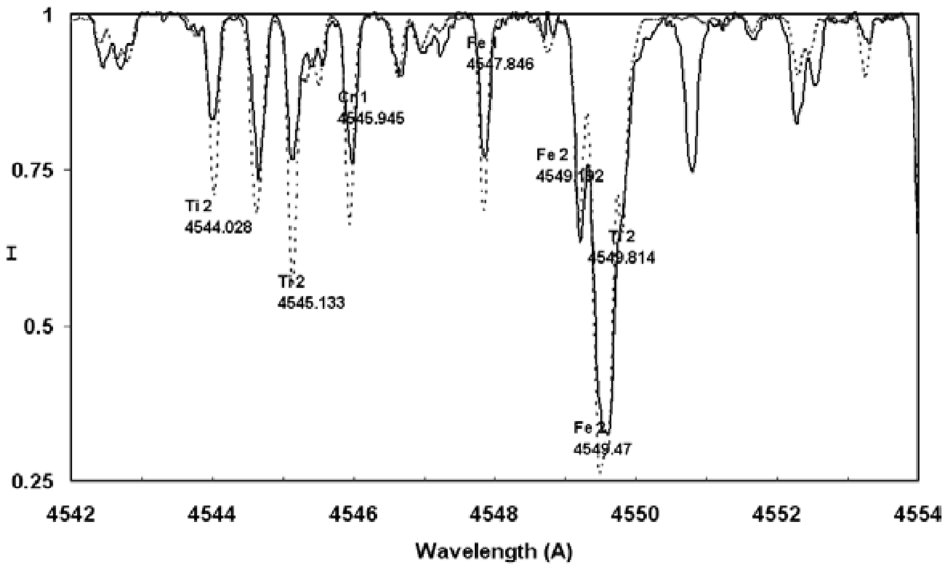

Figure 1. $\lambda\lambda$4542-4550 section of the HR 8216 (solid line) and the synthetic spectrum (dashed line)

by insuring that the abundances for the atomic species were independent of equivalent width. These stellar parameters were used in turn in the program, SYNTHE (Kurucz & Avrett 1981), to generate the synthetic spectrum that was convolved with a digitally sampled instrumental profile with a FWHM of 0.072 Å.

3. Atlas

To illustrate the atlas, Figures 1 and 2 show two adjacent 10 Å pieces, $\lambda\lambda$4540-4550 and $\lambda\lambda$4550-4560 of the section centered at 4575 Å. Although the majority of the line identifications for this section are reproduced in the figures, multiple possible identifications of a given feature are not included to avoid overcrowding.

Figures 1 and 2 also include the final synthetic spectrum. The differences between the observed and synthetic spectra clearly illustrate the deficiencies in the atomic line parameters. This atlas and others like it can be used to improve these values.

4. Line identifications

We used the program VLINE (Hill & Fisher 1986) to measure for each line the equivalent width, the central wavelength, the line depth, and the full width at half maximum of the fitted profile, which was taken to be a Gaussian for metal lines. Our rotational velocity estimate based on non-blended lines near Mg II λ4481 was 5.5 km s^{-1}.

To begin the line identification process, we identified the cleanest lines in the spectrum which are minimally affected by noise and by blending components. These can often be confirmed by examining stellar line identification lists of stars of similar temperature, previous studies of HR 8216, or working with standard references. As not all atomic

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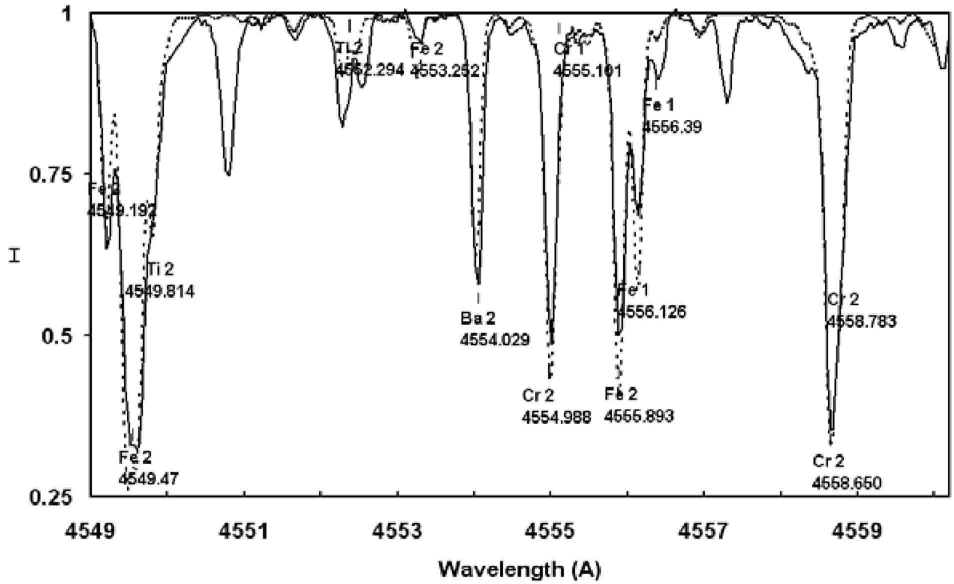

Figure 2. $\lambda\lambda$4550-4560 section of the HR 8216 Atlas (solid line) and the synthetic spectrum (dashed line)

wavelength studies have equally well-determined wavelengths, we preferred to use those whose values are consistent with modern interferometric determinations for Fe I and Fe II. Stellar lines were first identified with the general references A Multiplet Table of Astrophysical Interest by Moore (1945), Wavelengths and Transition Probabilities for Atoms and Atomic Ions, Part 1 by Reader & Corliss (1980), and selected references from the bibliography of Adelman & Snijders (1974) whose most recent update is Adelman (2001). We used line identifications by Adelman and his associates for other stars which they have analyzed using DAO spectrograms.

A sample of the line identifications is presented in Table 2 for the $\lambda\lambda$4542-4560 section. To identify as well as possible the lines in the spectrum of HR 8216 after the elemental abundances were initially determined, a synthetic spectrum was calculated using Program SYNTHE with the adopted model atmosphere, solar abundances, the atomic data of Kurucz & Bell (1995) as updated to include NIST values, the instrumental profile of the long camera of the DAO coudé spectrograph, and the other parameters initially found for HR 8216. It was a good, but not perfect match. A list of lines which contributed significantly to the spectrum was made and used to help identify particularly the unidentified features. The major changes were the identification of Co II lines and some additional Fe II and Ni II lines. The synthesized spectrum of this atlas was calculated after these additional clean lines which were found to be present were used to improve the derived abundances while those lines which were initially used and found to be blended were removed.

In Table 2 the far left column contains the letters B and R, standing for blue and red, which are guides to the range of lines whose wings are at least somewhat blended together. For example in Figure 2, the features corresponding to Fe II λ4555.893 and Fe I λ4556.390 are labelled B and R, respectively, because they are blended with the shortward

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Table 2. Line measurements of HR 8216 ($\lambda\lambda$4542-4560 region)

	Laboratory λ(Å)	W_λ (mÅ)	Depth	Width (Å)	Identification(s)
	4541.516	74.1	0.418	0.17	Fe II(38)4541.523(4);Cr I(149)4541.513(25)
B	4542.442	15.1	0.083	0.17	Fe I(891)4542.422((2))
R	4542.691	18.7	0.087	0.20	Cr I(149,275)4542.621(35);Fe I(827)4542.720((2))
B	4543.709	6.0	0.026	0.22	Cr I(100)4543.740(20)
R	4544.001	31.9	0.177	0.17	Ti II(60)4544.009(tr)
	4544.651	52.5	0.254	0.19	Cr I(33)4544.619(50);Ti I(42)4544.607(30)
	4545.126	40.4	0.225	0.17	Ti II(30)4545.144(tr)
	4545.960	44.8	0.239	0.18	Cr I(10)4545.956(50)
	4546.640	18.5	0.094	0.18	Fe I(989)4546.680(p)
B	4546.980	12.7	0.062	0.19	Ni I(261)4546.930(5)
R	4547.241	11.4	0.056	0.19	Ni I(146)4547.237(3)
	4547.851	38.9	0.236	0.16	Fe I(755)4547.851(4)
B	4549.196	51.7	0.325	0.15	Fe II(186)4549.214(4)
R	4549.485	153.4	0.617	0.23	Fe II(38)4549.467(10)
	4550.776	51.2	0.247	0.20	
	4551.656	6.1	0.035	0.16	Fe I(972)4551.667((1))
	4552.284	35.9	0.172	0.20	(Ti II(30)4552.250(p))
	4552.536	18.1	0.112	0.15	Fe I(-)4552.544((3))
	4553.266	5.4	0.039	0.13	Ni I(135)4553.175((3))
	4554.028	73.4	0.423	0.16	Ba II(1)4554.033(1000R)
	4554.489	3.9	0.026	0.14	Fe I(319)4554.467((1))
B	4554.788	7.5	0.032	0.22	Cr I(173)4554.830(25)
R	4554.992	88.9	0.482	0.17	Cr II(44)4555.01(30)
B	4555.888	92.3	0.497	0.17	Fe II(37)4555.890(30)
	4556.130	55.2	0.306	0.17	Fe I(410,820,974)4556.129(4n)
R	4556.394	18.7	0.105	0.17	
	4556.942	5.4	0.029	0.17	Fe I(638)4556.939((1))
	4557.282	23.3	0.132	0.17	(Sc I(-)4557.237(5)
B	4558.354	34.3	0.075	0.43	V II(212)4558.46(20)
	4558.647	120.5	0.614	0.18	Cr II(44)4558.659(100)
R	4558.804	45.3	0.270	0.16	Cr II (44)4558.830(p)
	4559.539	9.4	0.046	0.19	
	4560.093	13.7	0.083	0.15	Fe I (823) 4560.096((2))

For those lines not in Moore (1945), letters are used in place of multiplet numbers to indicate the other sources: C = Catalan, Meggers & Garcia-Riquelme (1964), D = Dworetsky (1971), G = Guthrie (1985), H = Hudlt, Johansson & Litzen (1982), I = Iglesias, Cabeza & de Luis (1988) for V II and Iglesias & Velasco (1964) for Mn II, J = Johansson (1978), K = Kiess (1953), Kiess (1958), KX = Kurucz & Bell (1995), L = Litzen (2002), MCS = Meggers, Corliss & Scribner (1975), N = Nilsson, Johansson & Kurucz (1991), and P = Pettersson (1983). Some multiplet numbers are from Moore (1965) for Si II and from Moore (1993) for C I and O I.

and longward wings of the Fe I λ4556.126 . The remaining columns are the laboratory wavelength in Å (the stellar wavelength as corrected for the stellar radial velocity of each spectrum), the equivalent width (W_λ) in mÅ, the line depth as a fraction of the continuum height, the line width (FWHM) in Å, and the identified atomic lines which cause the observed feature. The stellar and the laboratory wavelengths should be close, but blending and errors can produce discrepancies. Possible identifications are given in parentheses and brackets indicate that an identified line may be contributing to two measured stellar features. We found lines of the following species to be present: H I, C I, Mg I, Mg II, Al I, Si I, Si II, Ca I, Ca II, Sc II, Ti I, Ti II, V II, Cr I, Cr II, Mn I, Mn II, Fe I,

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Fe II, Fe III, Co I, Ni I, Ni II, Zn I, Y II, Mo II, Ba II, La II, Ce II, Pr II, Nd II, Sm II, Eu II, and Hg II.

Acknowledgments

HC's studies were partly supported by the Research Fund of the University of Istanbul, project number UDP-314/25052004. Those of SJA and AGF were supported in part by grants from The Citadel Foundation and the National Sciences and Engineering Research Council of Canada, respectively. SJA and AFG thank Dr. James E. Hesser, Director of the Dominion Astrophysical Observatory for the observing time.

References

Adelman, S. J. 2001, *PASP* 113, 344
Adelman, S. J. 2002, *Baltic Astronomy* 11, 475
Adelman, S. J., Gulliver, A. F., & Heaton, R. J. 2004, accepted by *A&A*
Adelman, S. J., & Snijders, M. A. J. 1974, *PASP* 86, 1018
Adelman, S. J., Pyper, D. M., Shore, S. N., White, R. E., & Warren, W. H., 1989, *A&AS* 81, 221
Caliskan, H. 2004, in preparation
Catalan, M. A., Meggers, W. F., & Garcia-Riquelme, O. 1964, *JRNBS* 68A, 9
Dworetsky, M. M. 1971, Ph. D. thesis, University of California at Los Angeles
Gulliver, A. F., Hill, G., & Adelman, S. J. 1996 in Model Atmospheres and Spectrum Synthesis, eds. S. J. Adelman, F. Kupka, & W. W. Weiss, *ASP Conf. Ser.* 108, p. 232
Guthrie, B. N. G. 1985, *MNRAS* 216, 1
Hill, G., & Fisher, W. A. 1986, *Publ. Dom. Astrophys. Obs. Victoria* 16, No. 13
Hill, G., Gulliver, A. F., & Adelman, S. J. 1996 in Model Atmospheres and Spectrum Synthesis, eds. S. J. Adelman, F. Kupka, & W. W. Weiss, *ASP Conf. Ser.* 108, p. 184
Hill, G., Gulliver, A.F., Adelman, S.J. 2004, in preparation
Huldt, S., Johansson, S., Litzen, U., & Wyart J.-F. 1982, *Phys. Scripta* 25, 401
Iglesias, L., Cabeza, M. I., & de Luis, B., 1988, *Publ. del Instituto de Optica de Madrid* No. 47
Iglesias, L., & Velasco R. 1964, *Publ. del Instituto de Optica de Madrid* No. 23
Johansson, S. 1978, *Phys. Scripta* 18, 217
Kiess, C. C. 1953, *JRNBS* 51, 247
Kiess, C. C. 1958, *JRNBS* 60, 375
Kurucz R. L., 1993, Atlas9 Stellar Atmosphere Programs and 2 km/s grid, Kurucz CD-Rom No. 13, Smithsonian Astrophysical Observatory, Cambridge, MA
Kurucz, R. L., & Avrett, E. H. 1981, Smithsonian Astrophys. Obs. Spec. Rep., 391
Kurucz, R. L., & Bell, B. 1995, Kurucz CD-Rom No. 23, Smithsonian Astrophysical Observatory, Cambridge, MA.
Litzen, U. 2002, private communication
Meggers, W. F., Corliss, C. H., & Scribner, B. F., 1975, Tables of Spectral-Line Intensities Part I - Arranged by Elements, 2nd edition, (Washington, DC: Government Printing Office)
Moore, C. E. 1945, A Multiplet Table of Astrophysical Interest, Princeton University Observatory
Moore, C. E. 1965, NSRDS-NBS 3, Section 1 (Washington, DC: US Government Printing Office)
Moore, C. E. 1967, NSRDS-NBS 3, Section 2 (Washington, DC: US Government Printing Office)
Moore, C.E. 1993, Tables of Spectra of Hydrogen, Carbon, Nitrogen, and Oxygen Atoms and Ions, CRC Series in Evaluated Data in Atomic Physics, ed. J. W. Gallagher (Boca Raton, FL: CRC Press Inc.)
Nilsson, A. E., Johansson, S., & Kurucz, R. L., 1991, *Phys. Scripta* 44, 226
Pettersson, J. E. 1983, *Phys. Scripta* 28, 421
Reader, J., & Corliss C. H. 1980, NSRDS-NBS 68, Part 1, US Government Printing Office, Washington, DC