A high resolution spectral atlas of α Per Persei $\lambda\lambda$ 3810-8100 Å[1]

Byeong-Cheol Lee[2], G.Galazutdinov[3], Inwoo Han
and Kangmin Kim

Korea Astronomy and Space Science Institute, 61-1, Whaam-Dong, Youseong-Gu, Daejeon 305-348, Korea

bclee@boao.re.kr, gala@boao.re.kr, iwhan@kasi.re.kr, kmkim@boao.re.kr

and

A.V. Yushchenko[4] and Jongho Kim

Astrophysical Research Center for the Structure and Evolution of the Cosmos (ARCSEC) Sejong University, Seoul, 143-747, Korea

yua@arcsec.sejong.ac.kr

and

V. Tsymbal[5]

Taurian National University, Simferopol, Crimea, Ukraine

vad@starsp.org

and

M.- G. Park

Department of Astronomy and Atmospheric Sciences, Kyungpook National University, Daegu 702-701, Korea

mgp@knu.ac.kr

ABSTRACT

---

[2]Department of Astronomy and Atmospheric Sciences, Kyungpook National University, Daegu 702-701, Korea

[3]Special Astrophysical Observatory, Russian Academy of Sciences, Nizhnii Arkhyz, Karachai Cherkess Republic, 369167, Russia

[4]Odessa Astronomical observatory, Odessa National University, Park Shevchenko, Odessa, 65014, Ukraine

[5]Institute for Astronomy, University of Vienna, Tüurkenschanzstraße 17, A-1180 Vienna

We present a high resolution ($\lambda/\delta\lambda$=90,000) spectral atlas of the F5Ib star α Per covering the 3810 – 8100 Å region. The atlas based on data carried out with the aid of the echelle spectrograph BOES fed by 1.8-m telescope at Bohyunsan observatory (Korea), is a result of co-addition of few well-exposed spectra with final signal-to-noise ratio ∼800 at ∼6000 Å is compared with synthetic spectrum computed with the code based on Kurucz (1995) software and databases. The spectral lines have been identified by matching a synthetic spectrum with the observed one. The atlas is presented in figures and available in digital form at http://www.boao.re.kr/ bclee/atlas/hd20902.html as well as synthetic spectrum and spectral lines identification tables.

Subject headings: stars:atlases – stars:individual (α Per) – stars: supergiants

1. Introduction

Since the publication of the optical spectral atlas by Morgan et al. ((1943)), many stellar spectral atlases covering a broad range in spectral and luminosity classes were published. Spectral atlases provide the basic data needed for studies of peculiar stars, composite systems (multiple systems, stellar clusters and galaxies), automated spectral classification, testing of stellar atmospheric models, etc. However, most of existing atlases are of low or medium spectral resolution.

Recently, several high resolution (R $\geq$ 90,000) and extremely high signal-to-noise ratio spectral atlases were published: atlas of HD 175640 in the region $\lambda\lambda$ 3040-10 000 Å (Castelli & Hubrig (2004)); atlas of o Peg in the region $\lambda\lambda$ 3826–4882 Å (Gulliver et al. (2004)); atlas of Deneb in the region $\lambda\lambda$ 3826–5212 Å (Albayrak et al. (2003)) and atlas of Arcturus in the region $\lambda\lambda$ 3727–9300 Å (Hinkle et al. (2000)). One of most popular and widely used spectral atlases is a solar atlas in the region $\lambda\lambda$ 2960–13,000 Å by Kurucz et al.((1984)).

In this paper we present a high resolution and high signal-to-noise ratio atlas of α Per - the brightest star in the well-studied cluster of the same name. α Persei (33 Persei, HD 20902, HR 1017, SAO 38787, HIP 15863) is a well studied F-type supergiant with sharp-lined features. The star is slightly reddened (E(B-V)=0.04, Gray (1991)) object with weak longitudinal magnetic fields of B_l=1±2 G (Shorlin et al. ((2002)). The latter circumstance allows to neglect Zeeman splitting effect in calculation of synthetic spectra. More detailed information about the star one can get in the article by Evans et al.(1996).

The aim of this article is to present high quality atlas of α Persei and give identification of spectral features. The detailed abundance analysis will be presented in a separate publication.

[1]Based on data collected at the 1.8-m telescope operated on BOAO Observatory, Korea

2. Observations and data reduction

High resolution spectra of α Per have been acquired using fiber echelle spectrograph BOES [2] fed by 1.8-m telescope of Bohyunsan Optical Astronomy Observatory (BOAO) in Korea. The spectra were recorded during several observing runs in the period October 2004 – October 2005 (see Table 1).

The spectrograph has 3 observational modes with different resolving power: 30,000; 45,000 and 90,000. Our spectra are in the highest resolution. The spectrograph allows us to cover in a single exposure the wavelength range ∼3700 Å – ∼10000 Å, divided into ∼80 spectral orders with CCD camera equipped with a 4096×2048 pixels matrix (pixel size 15μm$\times 15\mu$m). The achieved resolution allows precise measurements of wavelengths and intensities of interstellar features.

All the observed spectra are listed in Tables 1, where the heliocentric Julian date of the middle of exposure, number of object frames, name of object, spectrum of which was used for telluric lines removal, estimated S/N ratios are given.

Our reduction of the echelle spectra have been performed using both the IRAF (Tody 1986) and the DECH codes (Galazutdinov 1992). The programs allow us to perform all standard procedures of CCD spectra processing and analyzing. The wavelength scale was constructed on the basis of a global polynomial of the form described in detail in Galazutdinov et al. (2000).

IRAF was used for image processing and extraction of spectra from 2-D images. Further data processing and analysis have been performed using the DECH code (Galazutdinov 1992).

Data processing were performed in several step. The first one was telluric lines removal. Each original α Per spectrum is blended with telluric lines from wavelength longer than ∼5800 Å. To eliminate them we especially recorded spectra of so called divisors - hot and rapidly rotating stars without reddening which allows to remove telluric lines. Observed divisors are HD 87901 (α Leo), HD 120315 (η UMa) and HD 218045 (α Peg). Before using, all stellar lines seen in spectra of divisor were eliminated using normalization by pseudo-continuum. Figure 1 demonstrates the effect of telluric lines removal procedure. However, in a case of very strong telluric lines, it is hard to remove them completely as is seen in two wavelength ranges: $\lambda\lambda$ 6868–6940 Å and $\lambda\lambda$ 7594–7652 Å.

To improve the signal-to-noise ratio of the final spectrum we combined all spectra of α Per, listed in Table 1. The S/N ratio of the final spectrum is ∼800-1000 in 5500 Å region. Before co-adding, wavelength scale of each individual spectrum was shifted to the rest wavelength velocity frame (in our spectra a global dispersion curve is applied). This allows the procedure of adding up the reduced spectra which increases S/N ratio of resulting spectrum up to ∼800 at ∼6000 Å.

The co-added spectrum was finally smoothed to remove high frequency noise pattern. For

[2] A detailed description of the spectrograph is given at http://www.boao.re.kr/BOES/BOESppt3.files/frame.htm.

Table 1: The list of α Persei spectra.

Date	Number of spectra	HJD[a]	Divisor	S/N[b]
20 Oct. 2004	5	2453299.14037	HD 218045	400
21 Nov. 2004	20	2453331.16379	HD 218045	330
22 Nov. 2004	22	2453332.11928	HD 218045	340
23 Nov. 2004	23	2453333.26396	HD 120315	300
13 Dec. 2004	20	2453353.13167	HD 218045	450
13 Mar. 2005	4	2453442.98274	HD 87901	320
14 Mar. 2005	4	2453443.98124	HD 87901	300
20 Mar. 2005	4	2453449.95428	HD 120315	300

[a] Heliocentric Julian data of middle of exposure

[b] S/N ratio at ∼6000 Å.

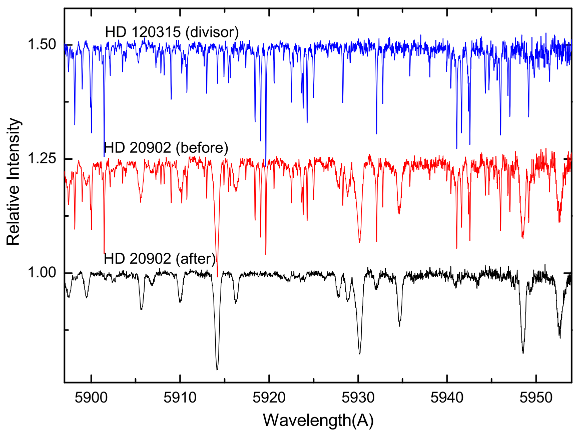

Fig. 1.— Demonstration of telluric lines removal. From top to bottom: divisor (HD 120315), original spectrum of α Per and, resulting spectrum where telluric lines are divided out.

smoothing we applied convolution with gauss profile. To avoid degradation of spectral resolution we adopted individually the full width at half maximum (FWHM) of the gaussian profile for each spectral order. A final value of FWHM is 2.3 pixels that correspond to 0.044 – 0.09 Å according to the linear dispersion of the corresponding spectral orders ranging from 0.019 Å pix^{-1} (at 3950 Å) to 0.039 Å pix^{-1} (at 8000 Å). In Figure 2 we demonstrate an influence of the smoothing effect. As one can see, the chosen FWHM of gauss profile allowed to increase resulting S/N ratio up to 40 % without loss of spectral resolution.

The last procedure we have been performed with the atlas spectrum is refining of continuum position using synthetic spectrum described below. An example of final spectrum is shown (Fig.3). For clarity, each piece of spectrum is shown two times in a single panel. One spectrum is shown in the whole intensity scale, but second (actually, the same one) is shown in scale of 5 % of intensity. The idea of such figures is to provide a possibility of detailed examining of weak lines profiles.

The complete atlas of α Per is downloadable in the Internet[3] as well as synthetic spectrum, and line identification tables.

3. Atmosphere parameters and metallicity

The detailed review of determination of atmosphere parameters, angular diameter and interstellar reddening for α Per was published by Evans et al. (1996). Using IUE spectra, $BVRIJK$ photometry, and model atmospheres Evans et al. (1996) found effective temperature T_{eff}=6270 K (surface gravity and microturbulent velocity were fixed as log g=1.5 and v_{micro}=4 km s^{-1}respectively).

Later, Andrievsky et al. (2002) estimated physical parameters of the star as follows: T_{eff}= 6200 K, log g= 0.7, [Fe/H]=-0.2, v_{micro}=2.9 km s^{-1}. They using several broadband photometrical calibrations and high resolution spectra. Takeda & Takeda-Hidai (1995, 1998, 2002) reported abundances of light elements in the atmosphere of α Per and used a bit different physical parameters: T_{eff}= 6250 K, log g= 0.9, [Fe/H]=+0.03, v_{micro}=4 km s^{-1}. Using Geneva's system photometrical data taken from SIMBAD database and Kunzli et al. (1997)'s calibration we found that T_{eff}= 5967 K, log g= 0.71, [Fe/H]=-0.29.

Then, we tried to fit the spectral energy distribution of α Per using the grid of fluxes calculated by Kurucz (1993). In order of this task we calculated the mean spectral energy distribution in ultraviolet using IUE exposures LWP02909RS, LWP03009RS, LWR03027RS, LWR03102RS, LWR03293RS, LWR03294RS, LWR04227RS, LWR04228RS, LWR05780RS, LWR09992RL, LWR11329RS, LWR11330RS, LWR12715RS taken from INES database.

In the visual spectrum region the mean energy distribution were constructed using catalogues III/201 (Alekseeva et al., 1997), III/202 (Kharitonov 1988), III/208 (Glushneva, 1984) from SIM-

[3] http://www.boao.re.kr/ bclee/atlas/hd20902.html

BAD database. A $JKLMN$ photometry data from SIMBAD and IRAS fluxes were used also. Using these observations we interpolated Kurucz fluxes and found the best fit with the following parameters: $T_{\rm eff}$= 6005±50 K, log g= 0.00, [Fe/H]=-0.08±0.05 in the range of E($B-V$) from 0.00 to 0.06.

It should be noted that the direct and precise (1% uncertainty) measurements of the angular diameter of α Per allowed Mozurkewich et al. (2003) to estimate the significantly different temperature $T_{\rm eff}$= 6750±85 K. Even larger difference can be found for other high luminocity stars. Apparently, the problem of creation of reliable atmosphere models for supergiants is still waiting for solution.

Described above difference of α Per physical parameters calculated on base of photometrical measurements led us to conclusion to use stellar parameters found directly from the spectrum. As a first step we adopted the atmospheric parameters of α Per derived by Andrievsky et al. (2002). These parameters were used to find the continuum level and to identify the unblended iron lines in the spectrum. Equivalent widths of these lines were used to find more precise values of the above mentioned parameters and microturbulent velocity.

We used the method used by Yushchenko et al. (1999) to find the parameters of the atmospheres for the components of the spectral binary system 66 Eri and by Gopka et al. (2004) for single halo giant HD221170. This method was also used for the spectral binary system HD153720 by Yushchenko et al.(2004a) and for barium star HD202109 (Yushchenko et al. 2004b). Briefly, the method is based on calculation of iron abundances for a set of models with different values of temperatures, surface gravities and microturbulent velocities. For all models we calculate a correlation level between the abundances of iron, derived from the individual iron lines, equivavent widths and energies of the lower level of these lines. The rms errors of the mean iron abundance were also calculated for all models.

It is commonly accepted that the zero values of correlations between the abundances, equivalent widths and energies of low levels correspond to the model with true parameters. In the above mentioned papers (the most detailed description was made by Gopka et al. (2004)) it was shown, that it is insufficient, and some additional tests should be done. Yushchenko et al. (1999) proposed to use the rms error of mean iron abundance. So, this method was applied to find the atmosphere parameters of α Per .

We interpolated Kurucz (1993) grid of atmosphere models with metallicity [Fe/H]=0.0. A set of atmosphere models with $T_{\rm eff}$ from 5875 K to 7250 K and surface gravities from log g=0.5 to log g=2.0 was created for the first iteration. The steps in effective temperature and surface gravity were 125 K and 0.1, respectively. The microturbulent velocities were chosen in the interval from 0.1 km s^{-1} to 9.9 km s^{-1}. The iron abundances were calculated using Kurucz (1993)'s WIDTH9 code for all these models and microturbulent velocities on basis of equivalent widths of 71 lines of neutral and 34 lines of ionized iron.

Oscillator strengths were taken mainly from Kurucz (1993) and Hirata & Horaguchi (1995).

For part of the lines, we calculated solar equivalent widths using the Liege Solar Atlas (Delbouille et al. 1973) and Grevesse & Sauval (1999) solar model. Kurucz (1993) SYNTHE and Yushchenko (1998) URAN codes were used to fit the calculated solar spectrum to the observed one. A more detailed description of the calculation procedure can be found in Gopka et al. (2004) for the case of HD221170.

The last iteration was calculated using the set of models with $T_{\rm eff}$ from 6000 K to 6400 K (10 K step) and surface gravities from log g=0.3 to log g=0.9 (0.02 dex step). The grid with metallicity [Fe/H]=–0.3 was used. Finally, fe found a matched abundance values of neutral and ionized iron ([Fe/H]=–0.28±0.06) for the following parameters $T_{\rm eff}$=6240±20 K, log g=0.58±0.04, $v_{\rm micro}$= 3.20- ±0.05 km s^{-1}. These parameter were used for calculation of the synthetic spectrum.

The uncertainties of the parameters are in the range of internal errors of the method applied. However, we should emphasize that at least gravity of the star is uncertain and as a result, real values of effective temperature and abundances may be different from our ones that is a result of shortcomings of the Kurucz's models of atmosphere in application for supergiants.

4. Synthetic spectrum and line identification

The final synthetic spectrum was calculated using Kurucz (1993) SYNTHE program and line data. Additional line data were taken from DREAM database as well as data form Morton (2000), Biemont et al. (2002), Piskunov et al. (1995).

We estimated the projected rotational velocity of the star by iteratively matching our atlas of α Per with the synthetic spectrum, convolved with gauss profile of different width and found, that $v\sin i$ =20 km s^{-1}. Because of the problem with determination of a reliable effective temperature for the atmosphere model, no efforts were made to remove lines with uncertain oscillator strengths. We decided that synthetic spectra should serve for lines identification only. A precise analysis of chemical composition of the star is a separate task beyond of the current article.

5. Summary

In summary, we present a high resolution and high signal-to-noise ratio atlas of α Per together with synthetic spectrum and line identification tables. All data are downloadable in digital form at the site of the Bohyunsan observatory (*http://www.boao.re.kr/bclee/hd20902.html*). We hope that the atlas will provides useful information for future studies as an example of high-quality spectrum of F5Ib supergiant.

The synthetic spectrum is calculated in limitations of static, plane parallel, blanketed model atmospheres that does not allow to make agree some fundamental parameters like gravity. However, the final synthetic spectrum adequately represent most of spectral features of α Per and confidently may be used for identification purposes.

We used the data from NASA ADS, SIMBAD, NIST, DREAM, INES databases, and we thank the teams and administrations of these projects.

GAG is grateful to the Korea MOST (Ministry of Science and Technology) (grant M1-0222-00-0005) and KOFST for providing an opportunity to work at KASI through Brain Pool program.

AY acknowledges the Astrophysical Research Center for the Structure and Evolution of the Cosmos (ARCSEC, Sejong University) of the Korea Science and Engineering Foundation (KOSEF) through the Science Research Center (SRC) program.

VT acknowledges the Austrian science fund FwF (project P17580) and the fund BM:BWK (project COROT).

REFERENCES

Albayrak, B., Gulliver, A. F., Adelman, S. J., Aydin, C., & Kocer, D. 2003, A&A, 400, 1043

Alekseeva, G.A., Arkharov, A.A. , Galkin, V.D. , Hagen-Thorn, E.I., Nikanorova, I.N., Novikov, V.V., Novopashenny, V.B., Pakhomov, V.P., Ruban, E.V., Shchegolev, D.E. 1997, 1997 Baltic Astron. 6, 481 (1997)

Andrievsky, S.M., Egorova I.A., Korotin S.A., & Burnage R. 2002, A&A, 389, 519

Biemont, J., Palmeri, P., & Quinet, P. 2002, Database of rare earths at Mons University // http://www.umh.ac.be/ãstro/dream.html

Castelli, F., & Hubrig, S. 2004, A&A, 425, 263

Dellbouille, L., Rolland, G., & Neven, L. 1973, Photometric Atlas of the Solar Spectrum from λ 3000 to λ 10000, (Institute de Astrophisique de Universitete de Liège).

Evans, N.R., Teays, T.J., Taylor, L.L., Lester J.B., Hindsley R.B., 1996, AJ, 11, 2099

Galazutdinov, G.A. 1992, Preprint 92, SAO RAN (Spets. Astrofiz. Obs. Ross. Akad. Nauk, Nizhnij Arkhyz), 1

Galazutdinov, G.A., Musaev F.A., Krełowski, J., Walker, G.A.H., 2000, PASP, 112, 648

Glushneva, I.N., Doroshenko, V.T., Fetisova, T.S., Khruzina, T.S., Kolotilov, E.A., Mossakovskaya, L.V., Ovchinnikov, S.L., Voloshina, I.B., 1984, Trudy Gosud. Astron. Inst. Shternberga, 54, 3

Glushneva I. N., Kharitonov A. V., Kniazeva L. N., Shenavrin V. I., 1992, A&AS, 92, 1

Gopka, V.F., Yushchenko, A.V., Mishenina, T.V., Kim, C., Musaev, F.A., & Bondar, A.V. 2004, Astronomy Reports, 48, 577

Grevesse, N., & Sauval, A.J. 1999, A&A, 347, 348

Gray R.O. 1991, A&A, 252, 237

Gulliver, A. F., Adelman, S. J., & Friesen, T. P. 2004, A&A, 413, 285

Hatzes, A. P., & Cochran, W. D. 1995, ApJ, 452, 401

Hinkle, K., Wallace, L., Valenti, J., & Harmer, D. 2000, Visible and Near Infrared Atlas of the Arcturus Spectrum 3727-9300 Å ed. Kenneth Hinkle, Lloyd Wallace, Jeff Valenti, and Dianne Harmer. (San Francisco: ASP) ISBN: 1-58381-037-4, 2000

Hirata, R., Horaguchi, T. 1995, SIMBAD Catalog VI/69

Kharitonov, A.V., Tereshchenko, V.M., Knyazeva, L.N., 1988, Spectrophotometric Catalogue of Stars, Alma-Ata, Nauka, 484 p.

Kunzli, M., North, P., Kurucz, R.L., Nicolet, B., 1997, A&AS, 122, 51

Kupka, F., Piskunov, N., Ryabchikova, T. A., Stempels, H. C., & Weiss, W. W. 1999, A&AS, 138, 119

Kurucz, R. L., Furenlid, I., Brault, J., & Testerman, L. 1984, National Solar Observatory Atlas, Sunspot, New Mexico: National Solar Observatory, 1984

Kurucz, R.L. 1993, CDROMs No. 1-23 (Cambridge, MA, Smithsonian Astrophys. Obs.)

Moore, C. E., Minnaert, M. G. J., & Houtgast, J. 1966, The solar spectrum 2935 Å to 8770 Å, National Bureau of Standards Monograph, Washington: US Government Printing Office (USGPO), 1966

Morgan, W. W., Kellman, Edith 1943, Science, 97, 536

Morton, D.C. 2000, ApJS, 130, 403

Piskunov, N.E., Kupka, F., Ryabchikova, T.A., Weiss, W.W., Jeffery, C.S., 1995, A&AS, 112, 525

Shorlin, S. L. S., Wade, G. A., Donati, J.-F., et al. 2002, A&A, 392, 637

Takeda, Y., Takata-Hidai, M., 1995, PASJ, 47, 169

Takeda, Y., Takata-Hidai, M., 1198, PASJ, 50, 629

Takeda, Y., Takata-Hidai, M., 2002, PASJ, 52, 113

Tody, D., 1986, "The IRAF Data Reduction and Analysis System" in Proc. SPIE Instrumentation in Astronomy VI, ed. D.L. Crawford, 627, 733

Yushchenko, A.V. 1998, in Proceedings of the 20th Stellar Conference of the Czech and Slovak Astronomical Institutes, Ed. by J. Dusek (ISBN 80-85882-08-6, Brno), p. 201.

Yushchenko, A.V., Gopka, V.F., Khokhlova, V.L., Musaev, F.A., Bikmaev, I.F. 1999, Astron. Lett., 25, 453

Yushchenko, A.V., Gopka, V.F., Khokhlova, V.L., Lambert, D.L., Kim, C., Kang, Y.W. 2004a, A&A, 425, 171

Yushchenko, A.V. Gopka, V.F., Kim, C., Liang, Y.C., Musaev, F.A., Galazutdinov, G.A. 2004b, A&A, 413, 1105

This preprint was prepared with the AAS LaTeX macros v5.2.

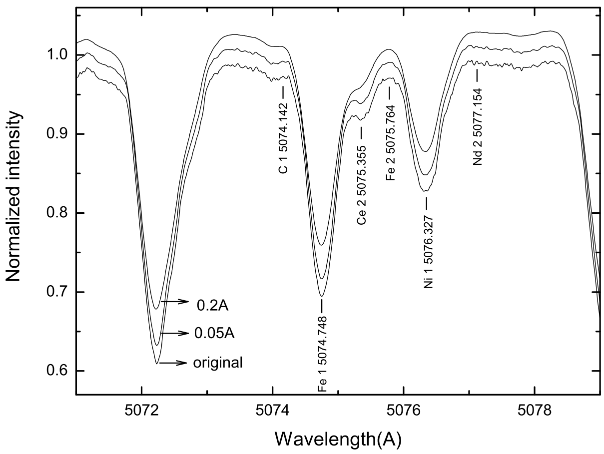

Fig. 2.— A demonstration of smoothing procedure. The original spectrum (bottom) is shown together with convolved ones. Top spectrum is result of convolution with gaussian of 0.2 Å FWHM and middle one - 0.05 Å. Note Ce II (5075.355 Å) profile behaviour. Excessive convolution (middle case) leads to the profile degradation.

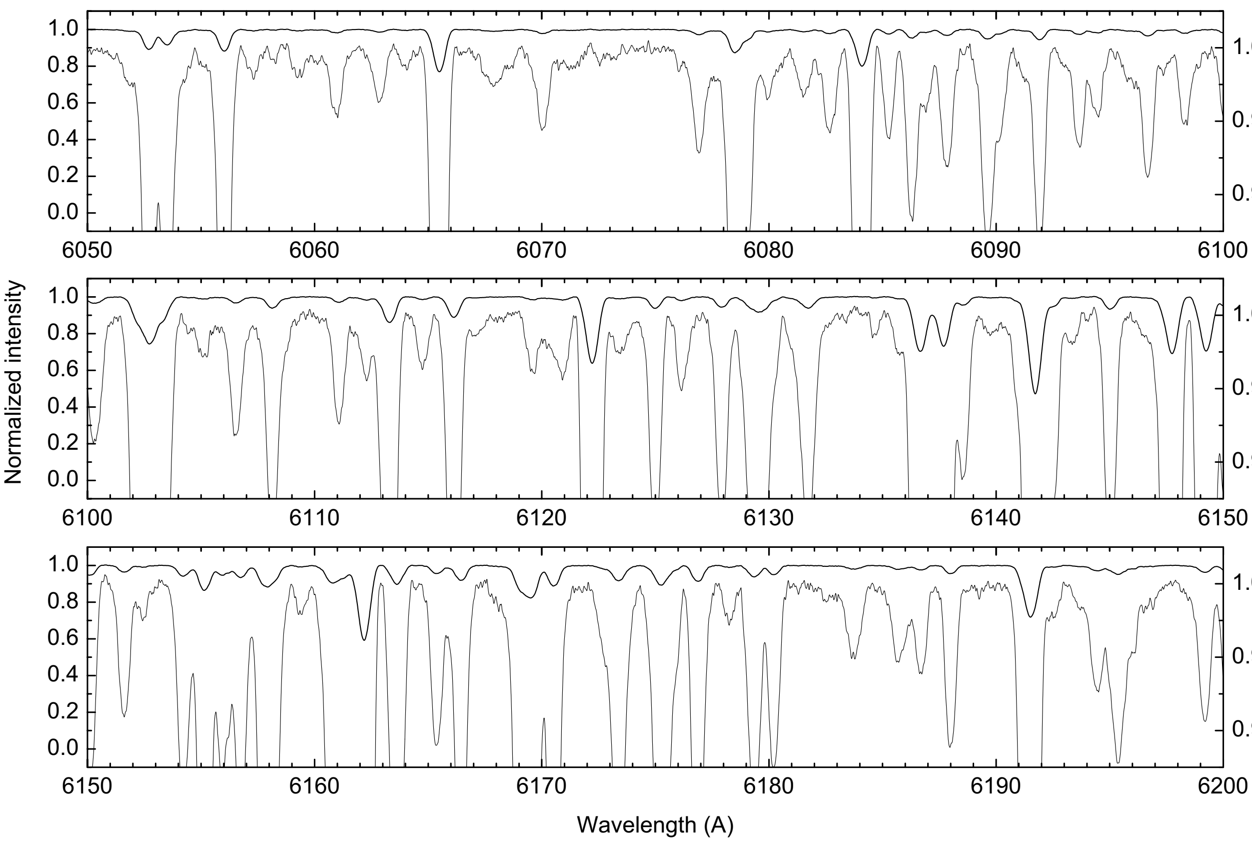

Fig. 3.— An example of spectral atlas of the α Persei.