MODEL ATMOSPHERE OF HD101065 WITH INDIVIDUALIZED ABUNDANCES

S.A. Khan, D.V. Shulyak

Department of Astronomy, Tavrian National University after V.I. Vernadskiy

ABSTRACT. We have calculated the model atmosphere of extremely peculiar roAp star HD101065. The line opacity with individualized abundances has been executed by «line-by-line» method. Due to lack of data for the REE lines we scaled D.R.E.A.M. data base by ten. The synthetic spectrum and indices in photometric system *uvby* have been calculated as: $b\text{-}y = 0.713$, $m_1 = 0.336$, $c_1 = -0.121$. We had obtained good agreement between an observation and modelling.

Key words: peculiar star, model atmosphere, infividualized abundances, HD101065.

1. Introduction

At present time observed spectra of stars are main sources of the information for stellar astrophysics. Because of most of the radiation originates in outer layers of a star, named stellar atmosphere, we have to build sufficient atmosphere model for proper analysis of stellar spectra.

The evolution of atmospheric models was closely related to the evolution of our conception of the energy transfer in outer layers of stars and the historical progress of the computer power. From 70"s great necessity appeared to create the opacity tables and the spectral lines lists. The most important projects became the works of Kurucz, OPACITY and OPAL projects (1988-96), VALD (1995-99) [1,2]. For the cool stars it is very important to consider molecular sources of opacity, that is why a number of authors created lines lists of molecules: H_2O, TiO_2, TiO, OH, CH, H_2 and other. Lately, more attention was paid to the lists of REE lines among which we want especially note the D.R.E.A.M. database of REE lines [3].

Currently there are several methods of opacity calculation. The main methods are: OPDF and OS. The most actively used OPDF (Opacity Distribution Function) method. The OPDF method is realised in ATLAS9 [4] code of Kurucz. It should be noted that using of OPDF method is complicated because it requires calculation of opacity distribution function each time for given abundances, sets of temperatures, pressures and microturbulence velocities. It is possible to make calculations more easier by using the set of pre-calculated OPDF tables for different abundances, for example the abundances scaled to solar composition (Kurucz, 1992-93) [5]. Thus, set of tables makes possible quick calculation atmosphere models with tabulated values of T_{eff}, lg *g* and metallicity [*A*] for normal stars. Though, in case of chemically peculiar (CP) stars it is impossible to take into account wide range of potential abundances. Therefore, stars of this kind require calculations of individual OPDF tables (Piskunov, Kupka, 1998-2001) [6] or use of other opacity calculation method, such as Opacity Sampling method.

The main idea of Opacity Sampling (OS) method lies in fitting the number of points along frequency in given range so as mean statistical dependency of the absorption coefficient in spectral lines is reproduced satisfactory. Points upon the frequency are chosen either with fixed step or randomly (Monte-Carlo method). By increasing the number of points we can achieve convergence in atmosphere structure to approach, which is got if opacity is calculated by direct method for great number of points. Using of OS technique leads to less calculation time in comparison to OPDF method only an average resolution of 4000 or less, that is fully insufficiently for CP stars modelling. OS technique realised in ATLAS12, Phoenix, SAM12 and other codes.

The methods described above have generic deficiency. These methods do not allow efficient calculations of models with stratified abundances. The fact is that stratification of the abundances with depths leads to changing of absorption coefficient with depths for given wavelength range. Consideration of stratification by OPDF technique is very difficult and time-consuming, by the OS technique is not trustworthy enough because of its statistical character.

Till present time the guess about chemical homogeneity of atmosphere along depth did not call in question. Though indications had appeared of possible stratification due to help of high quality spectra. Especially, taking into account that nature of such phenomenon has been determined – diffusion of atoms under the influence of radiative field or magnetic field.

The method which allows to avoid limitations described above is the direct method of opacity calculation. It allows to calculate the model atmosphere with individualized and stratified abundances. Though this method is simple by its ideology it was very difficult to employ it till recently because of insufficient computer power.

2. Calculations

In present work we made the model atmosphere calculations by LLModels code (V. Tsymbal, D. Shulyak) [7], which computes opacity by direct method. The LLModels code was created on base of the ATLAS9 code of Kurucz and code of calculation of synthetic spectrum from set of programs STARSP of Tsymbal [8]. Modelling is performed with guesses of plane-parallel structure of atmosphere and LTE for early and intermediate type of stars.

The absorption coefficient in lines is calculated for each wavelengths point including opacities produced by neighbouring lines. The step of calculations must be small enough to provide accurate lines profiles calculations (approximately 300-400 thousands of points in field of radiation maximum of a star). This leads to the full account of frequency and depths dependencies of the line absorption coefficient. This method is named line-by-line method, further in article we will use this term.

The calculation of opacity in continuum is performed with 1A step. We found that using of 1A step does not change atmosphere structure in comparison with calculations with the same step as in lines opacity computing. The hydrogen lines are also calculated with 1A step excluding the range ±50A from the center of hydrogen lines where calculations are performed with the same step as in lines opacity calculations.

The computing of correction to integral of density in column unit is performed by same method as in TCORR subroutine of ATLAS9 code. Whereas using of rosseland mean tables is unwarranted for stars with stratified abundances we have applied different approach. The equation of hydrostatic equilibrium is resolved at t_{5000}, k_{5000} set instead of t_{ross}, k_{ross}. Owing to the fact that obtained values are interpolated backward to standard set of rosseland depths and opacities it is necessary to provide agreement between values of physical arguments, which used in following iterations. Therefore, absorption coefficients for current set of temperatures and pressures are calculated for wavelength 5000A excluding lines opacities.

We performed elimination of spectral lines which don't make significant contribution to lines opacity for speed-up of calculation. The criteria of selection is:

$$\frac{a_L}{a_C} \le x,$$

where a_l, a_c are coefficients of absorption in line and continuum respectively, x is a criteria of selection. The testing calculation shows that using criteria 10^{-2} is well enough for accurate model calculation.

We used LOWLINES.DAT lines list of Kurucz [9] which includes more than 31 millions lines for elements up to fifth ionization stage. It should be noted that for hot stars it is necessary to add HILINES.DAT list which includes about 10 millions lines up to ninth ionization stage.

The elimination of spectral lines allows considerably decrease computing time of a atmosphere model. Thus, for example, using criteria 10^{-4} and 10^{-2} reduces the number of lines needed for opacity calculation by a factor 20 and 100 respectively.

In process of lines selections it is appropriate to use prepared Kurucz solar scaled model or to calculate the model using ATLAS9. Here, values of T_{eff}, lg g should be chosen at the nearest parameters values of the sought model. Scale parameter $[A]$ – metallicity should be chosen so as abundances correspond or slightly increase expected or known mean abundances in investigated star.

The method was approved on Vega. We have calculated atmosphere model for Vega with ATLAS9 (OPDF), ATLAS12 (OS) and «line-by-line» codes. The T-t_{ross} relation, synthetic fluxes and colours didn't show any significant differences among various opacity techniques and observed values. The accounting of faint spectral lines (criteria of selection 10^{-4}) in opacity calculation doesn't show any distinctions (more than error of calculation) in comparison with criteria 10^{-2}.

3. Model atmosphere of HD101065

The HD101065 star (Przybylski's star) is often called the most unusual roAp star. At the 32 IAU colloquium in 1975 Przybylski attracts attention to spectral features of this star. He notes deficiency or strong weakening of iron peak lines and points to serious restriction in selection of model atmosphere. First lines identifications works were made by Przybylski [10, 11], Warner [12], Wegner and Petford [13]. They confirmed excess of rare-earth elements (+4 dex). Cowley used method of wavelength coincidence statistics to show the presence of weak Fe lines [14].

The main problem in model atmosphere calculation lies in the difficulty of the effective temperature determination. The presence of strong opacity caused by great number of REE lines made impossible correct finding of the effective temperature by use of observed photometry values. The considering of REE opacities was heavy due to the lack of atomic data for REE lines. The analysis of hydrogen lines [15] gives value of T_{eff}=7500K. Observed photometric indices in 6-colours system leads to conclusion that effective temperature is about 6000K. This disagreement could be well explained by influence of strong opacity in REE lines which leads to changes in atmosphere structure.

The most detailed abundance analysis of HD101065 is performed by Cowley and Mathys [16] in wavelengths range 3900–6500A. They point the presence of doubly ionized rare-earth elements (Pr III, Nd III, Ce III) that indicate unusual structure of model atmosphere. The last work devoted to analysis of abundances of HD101065 was made by Cowley and others [17]. As this work presents the most detailed analysis at present time we are describing its major results below.

Cowley derived abundances for 54 elements (including a lot of rare-earth elements). The fundamental parameters of model atmosphere were derived as: T_{eff} = 6600K, lg g = 4,2. He showed, that convection plays no significant role in the temperature structure through strong blanketing and magnetic field. The magnetic broadening of spectral lines might be roughly approximated with a microturbulence velocity u_{micro} = 1 km·s^{-1} for iron peak lines and u_{micro} = 2 km·s^{-1} for rare-earth elements. Cowley used model atmosphere with individualized abundances calculated by the method of Piskunov and Kupka [6] which based on the OPDF method.

The considering of absorption in REE lines was complicated because trustworthy atomic data are known only for 13000 lines of neutral and once ionized rare-earth elements. That is why to compensate for missing line opacities caused by the incompleteness of rare-earth line lists Piskunov [6] and Cowley [17] increased the abundances of iron peak elements by 1.5 dex. It should be noted that described procedure is just empirical operation. The increasing value of iron peak elements was determined with best agreement between observations and theoretical study.

In present work we attempted to calculate model atmosphere of HD101065 with consideration of opacity caused by REE lines. The parameters of atmosphere: effective temperature, acceleration of gravity and abundances were taken from Cowley's work: T_{eff} = 6600K, lg g = 4,2, microturbulence u_{micro} = 2 km·s^{-1}; the range of optical depths: from −8 to +2 with step 0.1.

We used LOWLINES.DAT lines list of Kurucz, which includes more than 31 millions lines for elements up to fifth ionization stage. In selection of lines which have significant influence on opacity

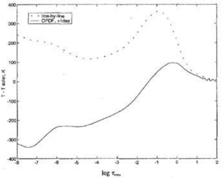

Figure 1: Temperature difference between a model atmosphere for HD101065 with individualized abundances and model with solar abundances. The difference between a model with scaled metallicity (+1 dex) and solar abundance model is displayed as well.

we used model calculated by ATLAS9 code of Kurucz. Cowley work shows that abundances of non rare-earth elements in atmosphere of HD101065 are near or less than solar ones, that is why we used OPDF tables for $[A] = 0$. The abundances were taken from Cowley's work. The criteria of selection of spectral lines was picked up as 10^{-2}. Thus, about 280 thousands of spectral lines were selected in range 500–30000A of the maximum radiation of the star.

The addition of Kurucz preselected list by data about REE lines was made by using D.R.E.A.M. database, which includes more than 56 thousands lines of CeII, DyIII, ErIII, HoIII, LaIII, LuII, LuIII, NdIII, PrIII, TbIII, ThIII, TmII, TmIII, YbII,

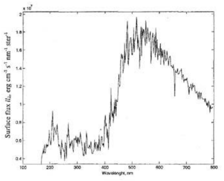

Figure 2: Synthetic fluxes for model atmosphere HD101065 with individualized abundances. Strong absorption features in the 400 nm region smoothes the Balmer jump.

YbIII, YbIV, calculated with known Cowan's code [18]. Unfortunately, at present time D.R.E.A.M. includes data of a quarter of all rare-earth elements. Granting this fact and possible stages of elements ionization we scaled database by ten. Resulting list has been united with preselected Kurucz's list LOWLINES.DAT and used in further calculations of opacity. The total number of lines is about 850 thousands.

Then we calculated model atmosphere of HD101065 with individualized abundances. Fig. 1 shows temperature difference between a model atmosphere for HD101065 with individual composition and a corresponding model with solar abundance. For comparison, the difference between a model with scaled solar abundance (+1 dex) is also shown in Fig. 1. It should be noted that all models have been calculated with the same fundamental parameters.

The HD101065 model with specific chemical composition is quite different from the scaled abundance model. Its enhanced opacity leads to higher temperatures than the solar abundance model. Unlike, the heating found for the model with scaled solar abundances is less than 100K in layers deeper than $t_{ross} = -1,4$.

Fig. 2 shows synthetic fluxes for calculated model with individual chemical composition. It also shows that the Balmer jump is smooth out because of a strong absorption features in the 400 nm. It is a common knowledge that index c_1 of photometric system *uvby* mensurates the height of the Balmer jump. Conducted calculations show that $c_1 = -0.121$, the observed data [19] is $c_1 = -0{,}012$.

Table 1 gives a summary of the *uvby* photometric indices. The observed data are adduced accordingly to the reference [19]. The data from Cowley paper [17] are also represented in Table 1. The table shows that calculated indices are well agreed with observed ones with consideration that HD101065 is extremely peculiar star that significantly differs from usual CP stars.

Table 1: Comparison between the observed Stromgren indices and calculated ones

	Observations	Cowley's values	«line-by-line» model
b-y	0.452	0.387	0.713
m_1	0.430	0.582	0.336
c_1	-0.012	0.298	-0.121

4. Conclusions

Conducted computations of HD101065 model atmosphere showed that accounting of opacity caused by lines is extremely important in model atmosphere calculations of peculiar stars. This fact becomes especially important for stars with unusual abundances (extremely peculiar stars), for which it is impossible to make correct model atmosphere by scaling abundances to solar ones. In general case the task of analysis of CP stars is essentially nonlinear. We must consider not only individual abundances for opacities calculations but also possible stratification with depth. The used line-by-line code of opacity calculation allows to make such computing.

The executed work shows that model atmosphere of HD101065 calculated only with individualized abundances presents a large step towards precision analysis of this star, although it should be noted that calculated colours are still not in excellent agreement with observations.

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