THE CHEMICAL COMPOSITION OF VEGA

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ABSTRACT. A non-LTE abundance determination of magnesium, iron, and barium was carried out for the atmosphere of Vega. The results indicate marked underabundances of these elements relative to the solar values. First preliminary results of numerical simulations of convective and oscillatory phenomena in the atmosphere of Vega are briefly described.

1. INTRODUCTION

In spite of the importance of Vega (αLyr, AOV) as a primary standard for flux measurements and as a reference for abundance studies, comparatively little is known about the chemical composition of this star. Contrary to earlier studies, more recent LTE abundance determinations suggest marked deficiencies of many elements relative to the Sun.

Our investigation, based on high-dispersion, high S/N photographic spectrograms recorded by R. and R. Griffin at Mount Wilson and covering a wavelength range from 3050 Å to 6850 Å, aims at a reliable assessment of element abundances for three elements: magnesium (representing the light elements), iron ('iron peak' elements), and barium (heavy elements). Departures from LTE are taken into account explicitly for these elements.

In what follows we briefly describe some of the results. Details are given elsewhere (Gigas, 1986 and 1987).

2. MODEL ATMOSPHERE AND COMPUTATIONAL PROCEDURE

The abundance determination is carried out with a line-blanketed ATLAS6 LTE model atmosphere with T_{eff} = 9500 K, log g = 3.90 (Lane and Lester, 1984), and an overall metallicity of [M/H] = -0.5 dex. A depth-dependent microturbulence with an average value of $\xi \sim 2.0$ km/s was employed for the line analysis.

The non-LTE calculations are carried out with the code developed by W. Steenbock, which is based on the complete linearization scheme of Auer and Heasley (1976; see also Steenbock and Holweger, 1984).

G. Cayrel de Strobel and M. Spite (eds.), The Impact of Very High S/N Spectroscopy on Stellar Physics, 395–399.

3. MODEL ATOMS AND ATOMIC DATA

The model atoms were constructed with the intention of including all relevant energy levels and strong radiative transitions. In the case of sparsely populated ionization stages, special attention was paid to the inclusion of a relatively large number of high-lying energy levels, which may be important for the collisional coupling to the next ionization stage.

Our model atoms comprise 71+28+1 (Mg I/Mg II/Mg III), 79+20+1 (Fe I/Fe II/Fe III), and 42+1 (Ba II/Ba III) energy levels with 41+30 (Mg I/Mg II), 52+23 (Fe I/Fe II), and 36 (Ba II) line transitions treated explicitly. All atomic data were selected after a critical survey of recent experimental and theoretical results.

4. DEPARTURES FROM LTE AND NON-LTE ABUNDANCE CORRECTIONS

4.1. Magnesium

Except for the two lowest Mg I levels, which are slightly underpopulated for $\log \tau_{5000} < -0.5$, all Mg I level occupation numbers are close to their LTE values for optical depths larger than $\log \tau_{5000} \sim -1.5$. While the Mg II ground state and the Mg II 3p level are hardly affected by departures from LTE, higher levels show an underpopulation relative to LTE. For some levels (e.g. the 4f level) non-LTE effects become noticeable already at optical depths of $\log \tau_{5000} \sim -1.0$, while others (e.g. the 3d level) start deviating from LTE at $\log \tau_{5000} \sim -2.5$. The Mg III continuum is overpopulated relative to its LTE occupation number in the outer atmospheric layers.

Non-LTE abundance corrections are small for weak lines of Mg I and Mg II; corrections of -0.10 dex are present for stronger transitions.

4.2. Iron

Fe I levels are in LTE for $\log \tau_{5000} > 0.0$; towards smaller optical depths there is an increasing underpopulation due to the effects of photoionization. We note that in the range $-1.5 < \log \tau_{5000} < 0.0$ (a region important for the formation of many spectral lines) all Fe I levels are subject to similar departures from LTE due to their mutual coupling by electron collisions. Fe II levels are generally in LTE up to $\log \tau_{5000} \sim -2.5$. Some high-lying levels of Fe II and the Fe III continuum exhibit moderate departures from LTE in the outermost layers.

Non-LTE abundance corrections of the order of +0.32 dex are derived for Fe I lines. Except for some strong transitions in the near UV, they are in general negligibly small for lines of Fe II.

4.3. Barium

All Ba II levels are more or less underpopulated at optical depths smaller than $\log \tau_{5000} \sim -0.2$. High-lying levels exhibit only small departures while the underpopulation is most pronounced for the ground state. The Ba III continuum population number differs only slightly from its LTE value.

Our investigation yields non-LTE abundance corrections for the Ba II resonance lines comparable to those derived for lines of Fe I.

5. ELEMENT ABUNDANCES RELATIVE TO THE SUN

Comparing our results with the solar abundance values compiled by Grevesse (1984), we arrive at the following element abundances relative to the Sun:

Magnesium	[Mg/H]	= (-0.58 ± 0.15) dex
Iron	[Fe/H]	= (-0.55 ± 0.22) dex
Barium	[Ba/H]	= (-0.21 ± 0.23) dex

Abundance values derived from both ionization stages of magnesium and iron agree within their mutual error limits. Our results thus indicate a definitely non-solar composition of the atmosphere of Vega.

6. HYDRODYNAMIC STABILITY OF THE ATMOSPHERE

Atmospheres of A0-type stars are generally assumed to be static. For Vega, mixing-length theory (ATLAS6 model) predicts maximum convective velocities of only ∿ (0.25 - 0.50) km/s. Nevertheless, a microturbulence (convective velocities? pulsational phenomena?) of ∿ 2.0 km/s is derived from line analyses, even if non-LTE effects are accounted for.

To seek a possible explanation for this discrepancy, we are currently performing numerical simulations of convective phenomena in A-type stellar atmospheres. Our code is based on the method of bicharacteristics as described by Stefanik et al. (1984), which solves the time-dependent nonlinear equations of motion in two dimensions on the assumption of cylindrical symmetry.

First preliminary results indicate the presence of atmospheric oscillations with flow velocities considerably larger than those predicted by mixing-length theory and comparable to the observed microturbulence. Further work on this subject is in progress.

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DISCUSSION

RUTTEN Let me first comment that it is ridiculous to have to cram so much outstanding work into a ten-minute presentation ! I have many questions, but the one I want to ask now is how sensitive your NLTE underpopulations and abundance deficiencies are to the gradient of the model atmosphere. It might be much flatter in reality than you have assumed due to mechanical heating by the motions you observe, and also by yet stronger line blanketing in the ultraviolet.

GIGAS It is possible that alterations of the thermal structure may influence the derived departures. Since the amount of mechanical heating is still unknown, the influence of shock wave dissipation could not be checked. The impact of mechanical heating on the derived departures will also depend on the atmospheric layers in which mechanical energy is dissipated. To get an assessment of the importance of alterations of the atmosphere's thermal structure, I computed departure coefficients for atmospheric models with slightly different values of effective temperature and overall metallicity. The changes of the non-LTE abundances derived depend on the element investigated ; they are larger for Fe I, Mg I, and Ba II than for Mg II and Fe II.

GRAY Do you find any correlation between temperature and velocity in your oscillation calculations ? As you may recall from D. Dravins' talk, Sirius shows inverse line asymmetries. Admittedly Vega is not Sirius, but they are close enough so one would expect similar asymmetries in Vega. (A correlation of temperature with velocity is needed to produce asymmetries).

GIGAS The models calculated so far are characterized by an almost horizontally homogeneous temperature distribution while vertical temperature differences may occur. Whether there is a correlation between temperature and velocity fields has not been investigated by now. In any case, observations of line shape asymmetries should provide an important test for the accuracy of gas flows simulations in stellar atmospheres.

R. CAYREL I am surprised by your conclusion that elements are underabundant as a result of your NLTE analysis, if you have the departure coefficients b's smaller than one. You would then expect that the LTE abundances must be corrected upwards and not downwards.

GIGAS We are computing abundance values from observed equivalent widths. To account for an observed equivalent width in the presence of level underpopulations due to non-LTE effects, a higher element abundance will be derived if non-LTE effects are taken into account. In an LTE analysis, an even larger underabundance would result for Fe I and Ba II than in the case of a non-LTE abundance determination.

ANDERSEN Your oscillation computations seem to predict a radial velocity variation with a period of perhaps 10-20 min and an amplitude of 1-2 kms^{-1}. This should be readily detectable with present techniques (if the oscillations are in phase over the stellar surface).

GIGAS Since I could only present preliminary results of first computations at this Symposium, periods and amplitudes of these oscillations will have to be investigated in more detail.

GUSTAFSSON The fact that the Fe II lines also give this low iron abundance seems to indicate that the thermal-structure uncertainties and the uncertainties in the non-LTE calculations should not be too important for the main abundance results. So we have to face that this young star probably only has 1/3 of the solar Fe and Mg abundances. You must have some speculations concerning the reason for this.

GIGAS According to a recent paper by Michaud and Charland (Astrophys. J. 311, 326 (1986)), metal underabundances present in the atmospheres of λ Boo stars (a group of metal deficient A-type stars) may be explained by diffusion processes in the presence of (small) mass losses. Perhaps similar processes have been going on in Vega as well.

CHALABAEV Recently, J. Borsenberger computed a non-LTE model atmosphere for T_{eff} = 9500°K and log g = 4 (see Chalabaev et al. in this volume). He found that the thermal structure of the atmosphere is quite different from an LTE case. The different temperature profile in the atmosphere can change the derivate abundances.

GIGAS At present, fully line-blanketed non-LTE model atmospheres are not available for A-type stars. Thus, one has to choose between model atmospheres computed including departures from LTE for H and certain light elements (Hubeny, Astron. Astrophys. 98, 96 (1981)), but neglect of line-blanketing effects, and LTE model atmospheres computed with a detailed treatment of line blanketing (Kurucz, Astrophys. J. Supp. 40, 1 (1979)). The impact on the derived abundances will also depend on the optical depths in which LTE and non-LTE temperature profiles differ.

FURENLID Can you give some numbers for the NLTE departures in the ionization equilibra of the studied elements ?

GIGAS In principle, departure coefficients for ionization equilibria (e.g. Fe I/Fe II) can easily be derived from the departures of all levels involved in the computation. In the case of Fe I, almost all levels show uniform departures for log $\tau \geqslant -1.5$. The ionization equilibrium in this region should thus be shifted by about the same amount.

JUGAKU

1) Which gf-values of Fe II lines did you use ?

2) Sadakane et al. (1985) found $v_{(\text{micro-turbulence})}$ = 2.0±0.5 km/sec from Fe II lines in the region 2100–3000 Å. Combined with your analysis I am inclined to think that v is not dependent of optical depth. Would you comment on this point ?

GIGAS

1) Fe II transition probabilities were compiled after a critical survey of recent experimental and theoretical results. In particular, I consulted the recent critical NBS compilation of atomic gf-values (Martin et al., in preparation).

2) It is encouraging to see that a depth-independent microturbulence of v = 2.0 km/sec gives a reasonable fit to the line data as well. However, I feel that this fit can be improved by using a depth-dependent v like the one employed in my investigation, which, moreover, was derived taking into acount departures from LTE for Fe levels.