TOWARDS ACCURATE STELLAR PHOTOMETRY: THE ROLE OF C, N, O AND ALPHA-PROCESS ELEMENTS

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ABSTRACT

Stars provide most of the light we detect in the universe and enrich our knowledge of chemical evolution of galaxies. In order to have the real view we should know to which extent stars reflect the material from which they were formed and to which they expose effects of their internal evolution. Crucial chemical elements in this sense are carbon and nitrogen, an alteration of which in evolved stars is already a recognized fact. Abundances of oxygen and α-process elements also differ in galactic populations of stars to about a factor of three. In this contribution, on the basis of new stellar model atmospheres, we discuss the sensitivity of stellar spectra to C, N, O and α-process element abundances in order to take this effect into account in photometric observations at the Gaia orbiting observatory. The synthetic spectra of these evolved stars show an enhancement of the NH band at 3300–3500 Å by about 10% and several weakened CH and C_2 features. Such spectral changes can be observed photometrically and should be taken into account in the photometric classification of giants. Carbon features in stellar atmospheres show a particularly complex behaviour being very dependent on mixing processes in stars, and on the abundance of oxygen which can also be altered by different reasons. NH bands are more independent indicators of mixing processes in stars. Abundances of α-process elements can be evaluated photometrically by using the direct indicators – Ca II H and K lines and Mg I b triplet.

Key words: Stars: fundamental parameters; Techniques: photometry; Surveys; Galaxy: general; Gaia.

1. INTRODUCTION

Stellar photometry has a long history. The main task of early observations (Templeton 1845, Johnson 1853, Pickering et al. 1879, Parkhurst 1900) was to obtain photographic magnitudes of stars. The early photometric studies in two colours (Shapley & Davis 1920, Guthnik & Hügeler 1920, Stebbins 1931 and others) also were measuring magnitudes of stars. A possibility of determining photometrically stellar temperatures, surface gravities, metallicities, interstellar reddening and other parameters came with the introduction of multi-colour photometric systems. The first such system (*UVBGRI*) was proposed by Stebbins & Whitford (1943). The *UBV* system, which is in active use till present time, was introduced by Johnson & Morgan (1951) and Johnson (1955). Other popular photometric systems like *Strömgren* (Strömgren 1962, 1963a,b), *Geneva* (Golay 1963, Rufener et al. 1964) and *Vilnius* (Straižys 1963, 1964; Zdanavičius & Straižys 1964) were proposed also more than 40 years ago. We refer the reader to the monograph by Straižys (1992) for a comprehensive description of photometric systems.

In the present paper, we would like to pay attention to the fact that most of widely used photometric systems were created when little was known about internal stellar processes. For example, the famous paper by Burbidge, Burbidge, Fowler & Hoyle which has described in detail the thermonuclear reactions taking place in stars and determining their evolution came only in 1957 (Burbidge et al. 1957). The first dredge-up of material processed in stellar interiors was revealed by Iben (1965), evidences of extra-mixing of processed material in low mass stars came with works by Day et al. (1973), Pagel (1974) and many other studies later on. And finally, in 1983 a new component of the Galactic disc – thick disc – was discovered (Gilmore & Reid 1983), which seems to contain stars with systematically enhanced abundances of oxygen and α-elements compared to 'thin-disc' stars of similar metallicities (cf. Fuhrmann 1998, Prochaska et al. 2000, Mashonkina & Gehren 2001, Tautvaišienė et al. 2001, Bensby et al. 2003). All these abundance changes have their reflection into the stellar energy fluxes and consequently in appropriately defined photometric colours.

Growing knowledge as well as a number of new questions on the Galactic and stellar evolution naturally raise a question of whether photometric observations can give us new and more accurate scientific information. In this paper, which follows our previous studies published in Tautvaišienė & Edvardsson (2002) and Tautvaišienė et al. (2003), we continue the investigations of the sensitivity of stellar spectra to C, N, O and α-element abundance changes and the corresponding consequences to photometric observations.

2. MODEL ATMOSPHERES WITH CHANGED C, N, O AND α-ELEMENT ABUNDANCES

A long and difficult way has now been passed since the first attempts to model stellar atmospheres using physical laws (McCrea 1931, Williamson 1943, Münch 1947, Aller & Pierce 1952 and others). Remarkable progress in understanding of the physics of stellar atmospheres and in their modelling, which has been done during this period, was widely discussed at the IAU Symposium 210 on 'Modelling of stellar atmospheres' (Piskunov et al. 2003).

A number of recent developments was introduced in the construction of *MARCS* model atmospheres (Gustafsson et al. 2003). For our purposes it is important that the *MARCS* model atmospheres of stars can be calculated with changed carbon, nitrogen and α-element abundances. By α-elements we here mean O, Ne, Mg, Si, S, Ar, Ca and Ti. This makes it possible to study the effects of abundance changes of various elements to stellar spectra, and to see if these effects can be studied photometrically, and if these changed abundances can affect the determinations of [Fe/H][1] and other stellar atmospheric parameters.

Calculation, documentation and checking of a full grid of models will take much time, and since we need to work out a photometric system for Gaia already this year, we are providing for the Gaia community some results of investigations in this contribution.

3. SENSITIVITY OF STELLAR SPECTRA TO CARBON AND NITROGEN ABUNDANCES

The standard stellar evolution theory predicts the first dredge-up in stellar atmospheres when hydrogen burning takes place in a shell and stars start to climb the red giant branch. Then the convective envelope deepens enough to dredge up some CN-cycled material. At this point, atmospheric abundances of carbon become lowered by about 30%, nytrogen becomes overabundant by about 80% and the carbon isotopic ratio drops from the solar value of about 90 to 30 or 20 (Lambert 1981, Charbonnel et al. 1998 and references therein).

In order to see what spectral regions are most sensitive to carbon and nitrogen abundance alterations in stellar spectra, we computed stellar model atmospheres and corresponding surface fluxes with a wavelength sampling of $R \approx 20\,000$ for a typical giant after the first dredge-up with unaltered and altered carbon and nitrogen abundances. Figure 1a shows the smoothed ratio of the flux distributions with $\Delta[\mathrm{C/Fe}] = -0.2$ and $\Delta[\mathrm{N/Fe}] = +0.4$ for a star of $T_{\mathrm{eff}} = 4500\,\mathrm{K}$, $\log g = 3.0$, [Fe/H]$= -0.4$. From the flux ratio we can see that the spectral changes are noticeable. The stronger absorption by NH and CN features is followed by weakened CH and C_2 bands.

[1] In this paper we use the customary spectroscopic notation [X/Y]$\equiv \log_{10}(N_{\mathrm{X}}/N_{\mathrm{Y}})_{\mathrm{star}} - \log_{10}(N_{\mathrm{X}}/N_{\mathrm{Y}})_{\odot}$

For a comparison, in Figure 1b, the effect of decreasing the surface gravity by 1.0 dex is shown. The sensitivity of the spectrum to changes in overall metallicity and effective temperature are shown in Figures 1c and 1d, respectively.

In Figure 2, along with the ratio of modelled surface energy fluxes from Figure 1a, we display the five medium-band photometric systems proposed for Gaia: *K2* by Knude & Høg & (2004), *3F* by Jordi et al. (2004), *V2* by Straižys et al. (2004), *2X* by Vansevičius (2004) and *HFD-1M* by Bailer-Jones (2004). The ratio of surface energy fluxes is for the model with $T_{\mathrm{eff}} = 4500$ K, $\log g = 3.0$, [Fe/H]$= -0.4$, $\Delta[\mathrm{C/Fe}] = -0.2$ and $\Delta[\mathrm{N/Fe}] = +0.4$. It is seen that quite many filters bluewards from 5500 Å lie on carbon and nitrogen features, changes of which are quite noticeable. The nitrogen molecular NH band at 3300–3500 Å is enhanced by about 8%. The C_2 and CH molecular bands are lowered. The CN bands differ as well. According to theoretical predictions by Sweigart et al. (1989), Charbonnel (1994), El Eid (1994), Bressan et al. (1993), Dearborn (1992) and others, the extent of abundance changes of carbon and nitrogen depends on stellar mass and metallicity. It is found that the extent of abundance alterations during the first dredge-up is larger for stars with higher masses and lower metallicities.

Moreover, for some time now it has been clear that evolved low-mass stars exhibit chemical anomalies which are not predicted by standard stellar evolution theory. The first discrepancies from the standard theory came in 1973-74 when Arcturus was found to have a much lower carbon isotope ratio (Day et al. 1973) and clump stars in the open cluster M 67 appeared to have enhanced CN bands (Pagel 1974). So, the low-mass giants at some point of their evolution have also a deep extra-mixing (cf. Lambert & Ries 1981, Carbon et al. 1982, Sneden et al. 1986, Gilroy & Brown 1991, Briley et al. 1997, Kraft et al. 1997, Tautvaišienė et al. 2000, Gratton et al. 2000b). It seems that extra-mixing affects more than 95% of the low mass stars (Charbonnel & do Nascimento 1998). The extend of this evolutionary event was theoretically modelled by Dearborn et al. 1978, Sweigart & Mengel 1979, Smith & Tout 1992, Charbonnel 1994, Denissenkov & Weiss 1996, Boothroyd & Sackmann 1999). These elemental abundance alterations can be clearly seen in evolved helium-core-burning stars since they reflect all the events which have happened to the star during its evolution on the giant branch. In Figure 3, the ratio of surface energy fluxes is presented for a typical red horizontal-branch star. The model is of $T_{\mathrm{eff}} = 5000\,\mathrm{K}$, $\log g = 2.5$, [Fe/H]$= -1.5$ with $\Delta[\mathrm{C/Fe}] = -0.5$ and $\Delta[\mathrm{N/Fe}] = +0.6$. The differences of carbon features are smaller, however the nitrogen molecular NH band at 3300–3500 Å is enhanced by about 12%, and this is even more than in the case presented in Figure 2.

Thus, the evolutionary alterations of carbon and nitrogen abundances can cause noticeable spectral changes and, if not taken into account, may yield misleading photometric [Fe/H] determinations. In order to approximately evaluate how large is the influence of evolutionary abundance changes in stellar atmospheres to photometric determinations of [Fe/H], one can to compare the results of [Fe/H]

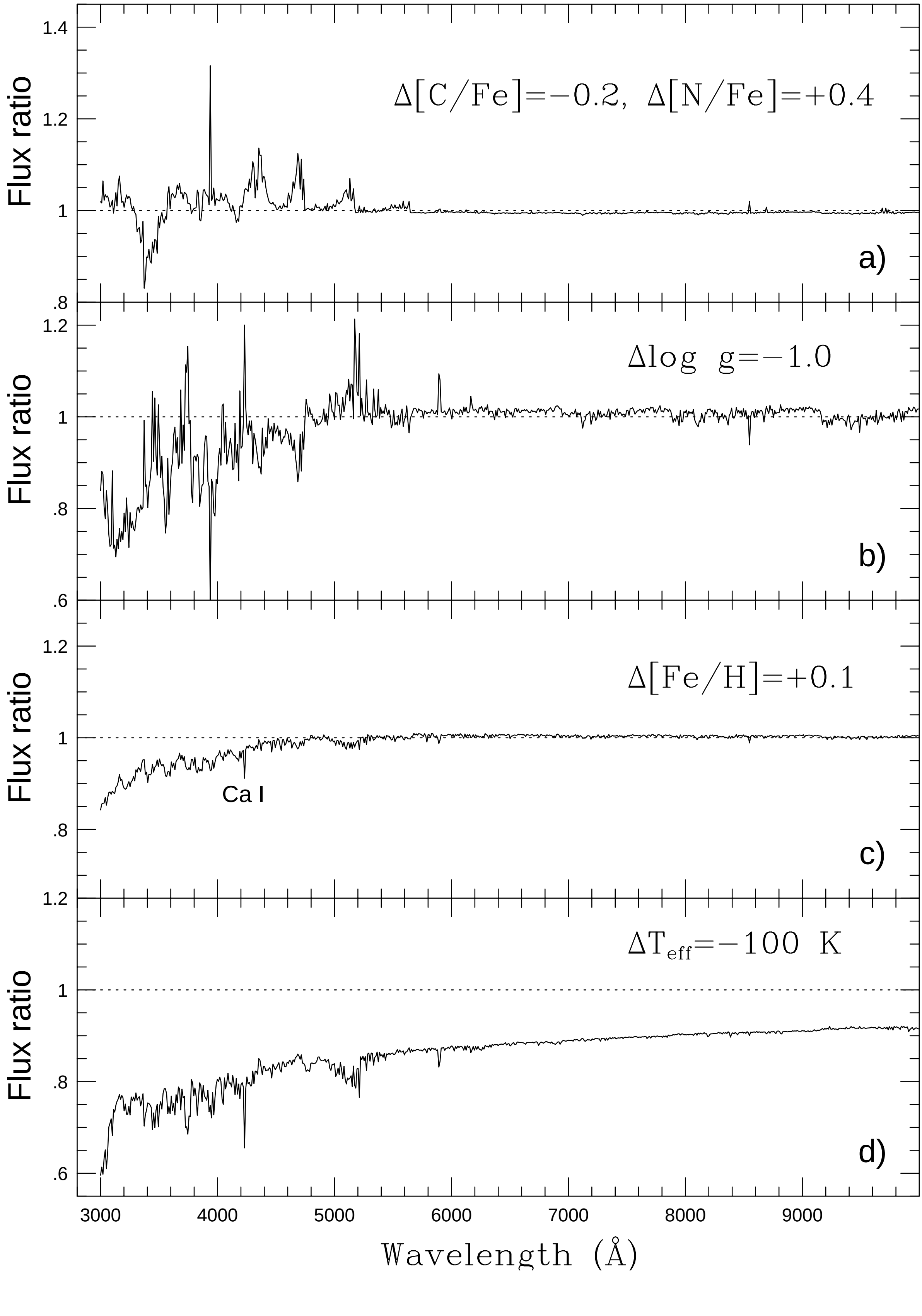

Figure 1. Sensitivities of the modelled surface energy flux ratios to variations in fundamental parameters and chemical abundances. The standard model is of $T_{\rm eff}$ = 4500 K, $\log g$ = 3.0 and [Fe/H] = −0.4.

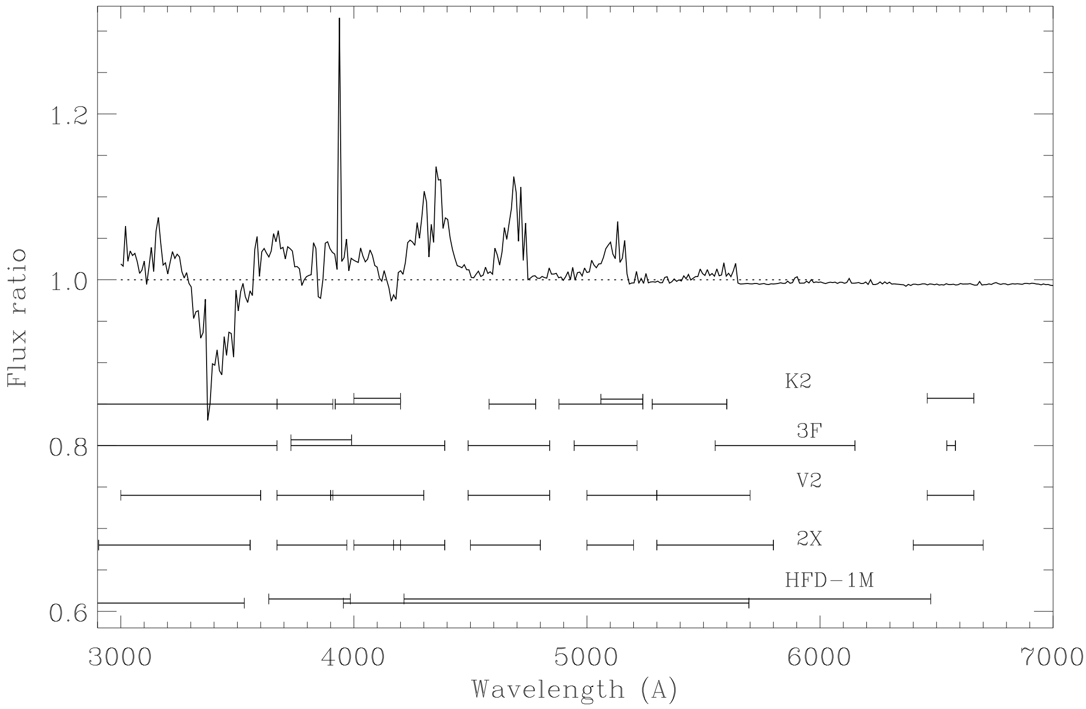

Figure 2. Sensitivity of the modelled surface energy flux ratio to the variation in carbon and nitrogen abundances. The models have the same $T_{\rm eff}$ = 4500 K, $\log g$ = 3.0 and [Fe/H] = −0.4, and different carbon and nitrogen abundances – Δ[C/Fe] = −0.2 and Δ[N/Fe] = +0.2. The positions of some medium band photometric systems proposed for Gaia are indicated as well (see Section 3 for references).

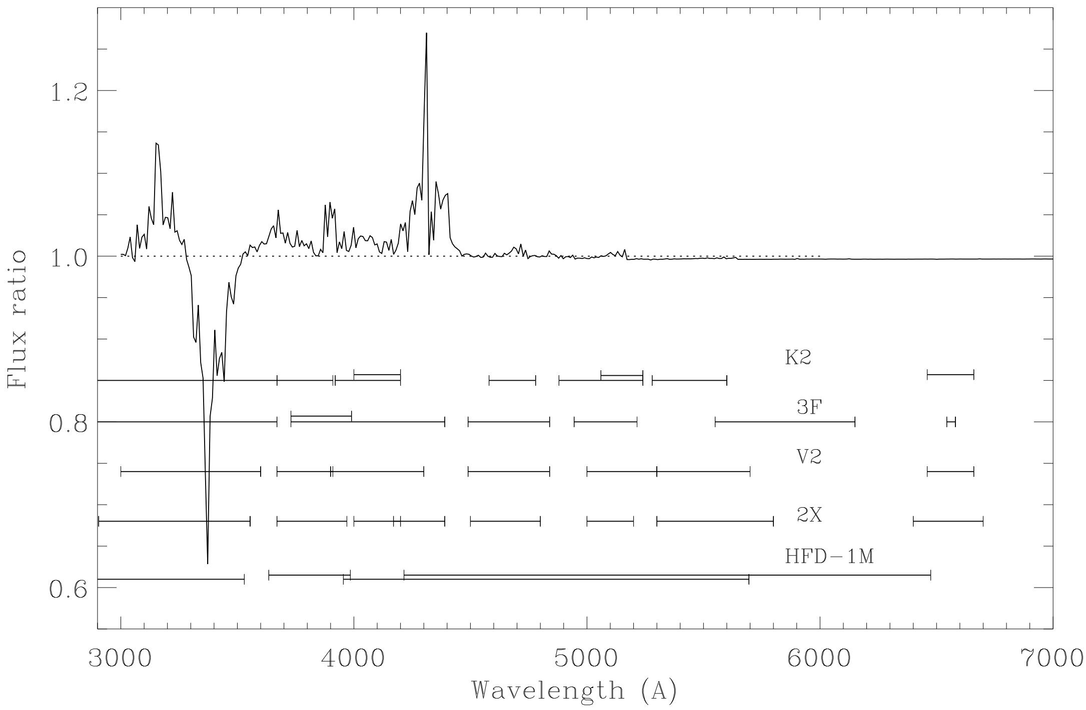

Figure 3. Sensitivity of the modelled surface energy flux ratio to the variation in carbon and nitrogen abundances. The models have the same $T_{\rm eff}$ = 5000 K, $\log g$ = 2.5 and [Fe/H] = −1.5, and different carbon and nitrogen abundances – Δ[C/Fe] = −0.5 and Δ[N/Fe] = +0.6. The positions of some medium band photometric systems proposed for Gaia are indicated as well (see Section 3 for references).

obtained for stars of different evolutionary stages in open or globular clusters. Metallicities of stars in such objects are supposedly identical. The open cluster NGC 7789 was recently observed in the Vilnius photometric system by Bartašiūtė & Tautvaišienė (2004). Photometric metallicity and other atmospheric parameters were determined for 11 helium-core-burning 'clump' stars and 11 first-ascent-giants, located in the colour-magnitude diagram above the clump. It was found that for the giants the mean [Fe/H]= -0.21 ± 0.03 and for the clump stars [Fe/H]= -0.15 ± 0.03. In the work by Tautvaišienė et al. (2004), the open cluster NGC 7789 was analysed by means of high resolution spectroscopy and it was found that the C/N ratios are lowered in the giants to the value of 1.9 and in the clump stars to 1.3. The influence of such alterations on stellar spectra was illustrated by theoretically modelled flux ratios by Tautvaišienė et al. (2003). Since the giants and clump stars in the NGC 7789 are both evolved the difference in [Fe/H] determined is not very large. It would be interesting to compare [Fe/H] determined from the unevolved main sequence stars and evolved clump stars. A possibility for the general user to obtain model atmospheres with altered C and N abundances has been opened very recently, so the complex spectrometric, photometric and theoretical study of spectra of evolved stars is in the initial stage and should be continued.

Changes of spectral carbon features can be caused not only by mixing processes in evolving stars but also by changes of oxygen abundances since these chemical elements are tied together by the molecular equilibrium in stellar atmospheres. In order to monitor the evolutionary effects in giants the best indicators are nitrogen features. The nitrogen molecular NH band at 3300–3500 Å is enhanced by about 10% even in metal-deficient horizontal-branch stars, thus can serve for the evaluation of mixing in stars pretty well.

4. SENSITIVITY OF STELLAR SPECTRA TO OXYGEN AND ALPHA-PROCESS ELEMENT ABUNDANCES

The study of the origin and evolution of the Galaxy is to an important part performed through the investigation of the fossilised record of the history of the abundances of chemical elements. Details of this history are revealed by the overall metallicities and the relative abundances of individual elements and groups of elements in combination with the stellar locations and kinematics. The α-elements are the most abundant group of metals, often represented by O, Mg, Si and Ca, which are predicted to be produced predominantly by massive, short-lived stars. Therefore the relative abundances of α-elements are expected to be high in stars formed very early in the Galaxy or in regions with rapid star formation where the α-element abundances have the time to build up before 'slower elements' catch up. Observationally this seems to be confirmed by the high α-element abundances seen in most halo stars; [α/Fe] = +0.3 to +0.5 (Pagel & Tautvaišienė 1995, Samland 1998, François et al. 2004 and references therein). There also seems to exist a halo population of stars with systematically lower α-element abundances (cf. Carney et al. 1996, Nissen & Shuster 1997, Gratton et al. 2003).

Also more metal-rich stellar populations show distinctive differences in [α/Fe] at similar [Fe/H]: the so called 'thick-disc' stars show up to 0.2–0.3 dex higher α-element abundances relative to younger and kinematically cooler 'thin-disc' stars of similar metallicity, see e.g. Fuhrmann (1998), Gratton et al. 2000a, Prochaska et al. (2000), Tautvaišienė et al. (2001), Mashonkina et al. (2003), Bensby et al. (2003).

In Figure 4 we present an example of sensitivity of the modeled surface energy flux ratio to the abundance of α-process elements. The ratio of modelled surface energy fluxes with $\Delta[\alpha/\mathrm{Fe}] = +0.3$ for $T_{\mathrm{eff}} = 5500$ K, $\log g = 4.0$ and [Fe/H] = -0.4 is plotted together with the indication of filter positions of the medium band photometric systems proposed for Gaia. The Ca II H and K lines, Mg I b triplet and OH bands are sensitive direct indicators of α/Fe abundance changes. A passband of about 100 Å width centered on the Ca II H and K lines, and of about 80 Å centered on the Mg I b triplet are optimal for measuring of α-element abundances. According to Tautvaišienė & Edvardsson (2002), in the interval of the spectrum 3905–4005 Å with the Ca II lines, the intensity of the spectrum drops down by 8% in dwarfs and by 11% in giants. In the interval 5160–5240 Å with the Mg I b triplet, the intensity of the spectrum drops by 2% and 5%, respectively.

The strong gravity effect on the Ca II lines make their use for α-element determinations quite dependent on a precise $\log g$ determination. It is interesting to notice the opposite gravity effects on the Ca II and the Mg I features. The former are radiation damped (thus not pressure-sensitive) and strengthened by the decreasing H^- continuous opacity and increasing degree of ionization, while the latter are pressure-broadened and thus weakened both by the weaker gas pressure and by the higher degree of ionization.

In the spectrum with larger abundances of oxygen and α-process elements, along with enhanced OH, Ca II and Mg I features there is a number of lowered CH, C_2 and CN bands. The complex behavior of spectral carbon features has to be taken into account very carefully. They can be changed both by stellar internal mixing, and also due to changes in oxygen abundance which binds more free carbon into CO. NH bands should serve for the evaluation of mixing processes in stars and for the interpretation of carbon spectral lines.

In Figure 5 we show sensitivities of the modelled surface flux ratios to variations in chemical abundances of C, N, O for a giant star with the standard model of $T_{\mathrm{eff}} = 5000$ K, $\log g = 2.5$, [Fe/H]= -0.5. One ratio of modelled surface fluxes is for the case of $\Delta[\mathrm{C/Fe}] = -0.12$ and $\Delta[\mathrm{N/Fe}] = +0.31$, and another is for the case of the same Δ[C/Fe] and Δ[N/Fe] and extra $\Delta[\alpha/\mathrm{Fe}] = +0.2$. It is seen how complicated is the behaviour of carbon spectral features. The passbands *3F386* in the *3F* system and *2X38* in the *2X* system, which measure both CN and Ca II in the spectral interval from 3800–4000 Å,

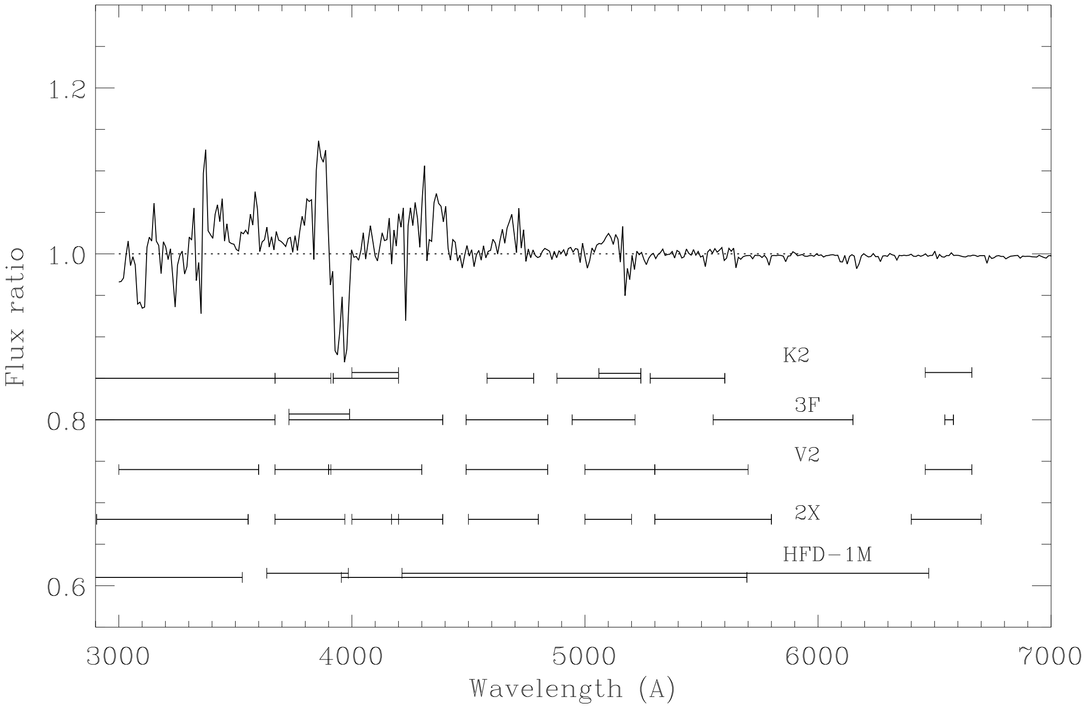

Figure 4. The ratio of modelled surface energy fluxes with $\Delta[\alpha/\mathrm{Fe}] = +0.3$ for $T_{\mathrm{eff}} = 5500\,K$, $\log g = 4.0$ and [Fe/H] = -0.4, plotted together with the indication of filter positions of the medium band photometric systems proposed for Gaia (see Section 3 for references).

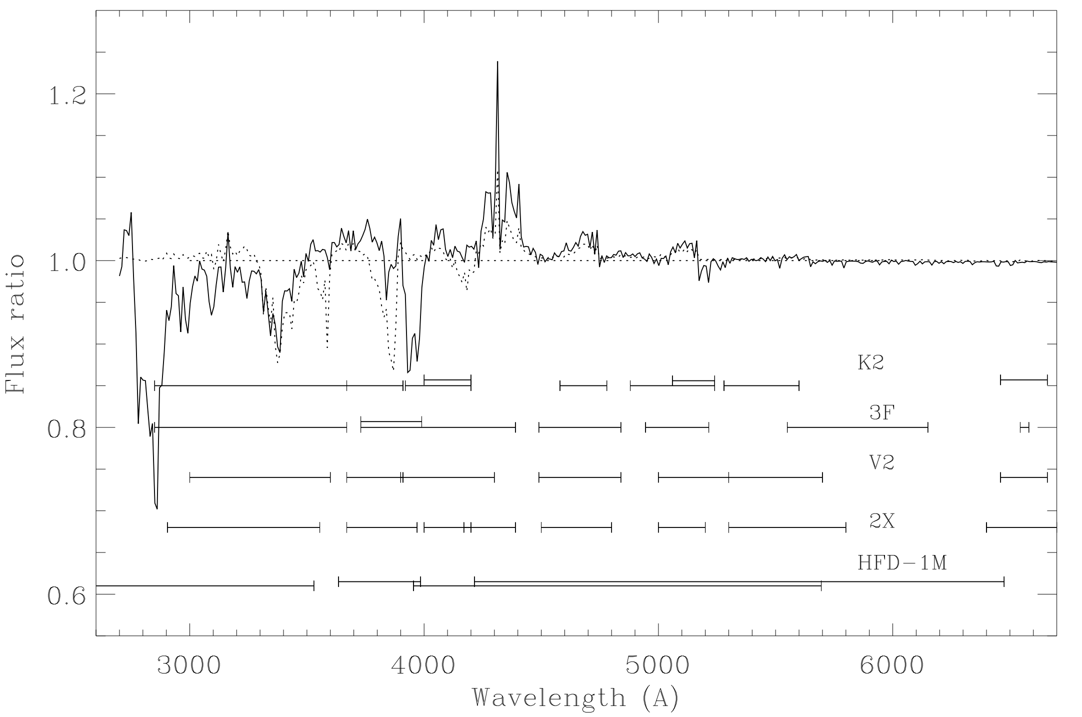

Figure 5. The ratios of modelled surface fluxes with the same $T_{\mathrm{eff}} = 5000\,K$, $\log g = 2.5$ and [Fe/H] = -0.5, and in the case of the dashed line with $\Delta[\mathrm{C/Fe}] = -0.12$ and $\Delta[\mathrm{N/Fe}] = +0.31$, and in the case of the plain line with the same Δ[C/Fe] and Δ[N/Fe] and extra $\Delta[\alpha/\mathrm{Fe}] = +0.2$. A strong Mg I resonance line located below 3000Å is a strong indicator of α-process element abundances. The carbon features are changed in both cases. The positions of some medium band photometric systems proposed for Gaia are indicated as well (see Section 3 for references).

if selected for the Gaia, would cause a very difficult interpretation.

In Figure 5 we can see a strong Mg I resonance line located at 2852Å. This line is a strong indicator of α-process element abundances. The Mg I resonance line in the region of 2750–2950 Å is enhancing the flux by about 14%. It is a pity that both the stellar radiation and sensitivity of detectors are low in the ultraviolet. When looking into positions of the photometric systems, it is worthwhile to mention that the blue edges of *3F326* and *K2M326* passbands are located almost in the middle of this relatively strong spectral feature, and this is not a good solution. The blue passbands of *V2* and *2X* systems are in much more favourable positions.

A few words should be said concerning the filters at about 5150 Å, which includes both C_2, MgH and Mg I b lines. The presence of carbon and magnesium spectral features in one band might cause a confusion of interpretation in giants.

Very recently, after the Gaia Symposium in Paris, several new systems were proposed, which have much better locations of bands with respect to measuring the α-element variations. The filter *K5M395* of the *K5* system (Høg & Knude 2004) and *V3M395* of the *V3* system (Straižys 2004) are of optimal width and are centered exactly on the Ca II doublet. The filters of the *3F* (and of all its other modifications, Jordi & Carrasco 2004), of *2X* and *HFD-1* systems are quite broad and may cause difficulties in accounting for α-element variations. All the photometric systems proposed for Gaia have to be carefully tested for their possibilities in α-element abundance investigations.

5. CONCLUSIONS

Photometric classification of stars should provide as many physical parameters as possible. Depending on the accuracy with which the fundamental parameters are known, we should seek to determine abundances not only of α-elements but of carbon and nitrogen as well.

Carbon and nitrogen abundance changes have quite a large influence on stellar spectra. The synthetic spectra of evolved stars show enhancement of the NH band at 3300–3500 Å by about 10% and quite many weakened CH and C_2 features. Such spectral changes can be observed photometrically and should be taken into account in the photometric classification of giants. The NH band at 3300–3500 Å can be used for monitoring of the C, N and O abundance mixing in stars.

The qualitative investigation of sensitivity of stellar spectra to α/Fe abundance variations indicates that the spectral sensitivity to α/Fe abundance changes is noticeable. It has both direct and indirect influence to stellar spectra. A possibility to employ the Ca II H and K lines and Mg I b triplet can be considered for the photometric determination of α/Fe abundance ratios with Gaia photometry.

The new information on C, N, O, and α-element abundance alterations and consequent spectral changes in stars encourages us to build a new modern astrophotometric system which could answer an increasing number of questions on stellar and Galactic evolution. Such a possibility can be realised by the Gaia satellite, which is currently in preparation.

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