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STELLAR CLASSIFICATION FROM SIMULATED DIVA SPECTRA. I. SOLAR METALLICITY STARS

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Abstract. The orbiting telescope with the Double Interferometer for Visual Astrometry (DIVA) will obtain, apart from astrometry, low-resolution spectra ($\lambda/\Delta\lambda \simeq 20$) covering the optical range (350 to 1000 nm) for over 10 million stars. The classification of such spectra according to T_e and $\log g$ for solar metallicity is investigated by synthetic photometry. Simulated DIVA raw data have been produced in the spectral range from 313 nm to 999 nm, with different degrees of binning of CCD pixels (four or eight) into photometric samples, leading to 66 and 32 spectral bands, respectively. The band width (resulting mainly from the PSF of the DIVA optics) varies between 16 and 38 nm for 66 bands and between 22 and 40 nm for 32 bands. Kurucz stellar model fluxes were scaled to $V = 10, 11, 12, 13, 14$ mag and appropriate photon and detector noise was added. The resulting DIVA spectra were subjected to stellar classification software. The results show that stellar classification with good astrophysical precision can be achieved for millions of stars, not affected by interstellar reddening.

Key words: techniques: photometric – stars: fundamental parameters, classification – orbiting observatories: DIVA

1. INTRODUCTION

Multicolour photometry of stars is one of the principal tools for astronomers to obtain information about the physical properties of stars (effective temperature T_e, gravity $\log g$, metallicity and reddening). For the photometric classification of stars many different photometric systems, have been proposed during the last 40 years, see Straižys (1992). Most of these systems use spectral bands measuring the absorption features sensitive to the main physical parameters of stars. The starlight is thereby measured subsequently through the different filters.

The small satellite DIVA (**D**ouble **I**nterferometer for **V**isual **A**strometry) – planned for launch in 2003 – will apply a new kind of multicolour stellar photometry using dispersed fringes preserving the whole spectrum instead of using different selected filters (Bastian & Röser 1996). A design of such an instrument using disperse fringes and direct fringe detection has been also proposed for the FAME project by Seidelmann et al. (1995) and Johnston et al. (1996).

The optical layout to create dispersed fringes needs either an objective prism or a grating. The optical layout for DIVA is described in detail by Holota et al. (1997) and Seifert et al. (1998). The investigation of the present paper takes the changes of the optical layout described by Röser (1999) into account.

2. THE SIMULATION OF THE DIVA SPECTRA

The following input parameters were used for the simulations of the DIVA spectra:

- stellar model spectra $F_\lambda(V,\lambda)$ of Kurucz (1995) (313 to 999 nm), properly scaled to apparent magnitude V,
- transmission of the optical system $T_{\rm opt}(\lambda)$ ($\approx 44\%$),
- quantum efficiency of the CCD $QE(\lambda)$ (max. 85%),
- two interferometer apertures $A_{\rm ap} = 112.2\,{\rm cm}^2$,
- exposure time per field-of-view transit $t_{\rm exp} = 1$ s,
- number of transits per star over the mission $n_{\rm t} = 120$.

The expected total photo-electron number for a given V magnitude and from a wavelength interval $\Delta\lambda$ was calculated by:

$$n_{\rm e}(V,\lambda) = F_\lambda(V,\lambda)\,A_{\rm ap}\,t_{\rm exp}\,n_{\rm t}\,\Delta\lambda\,\frac{\lambda}{hc}\,QE(\lambda)\,T_{\rm opt}(\lambda). \qquad (1)$$

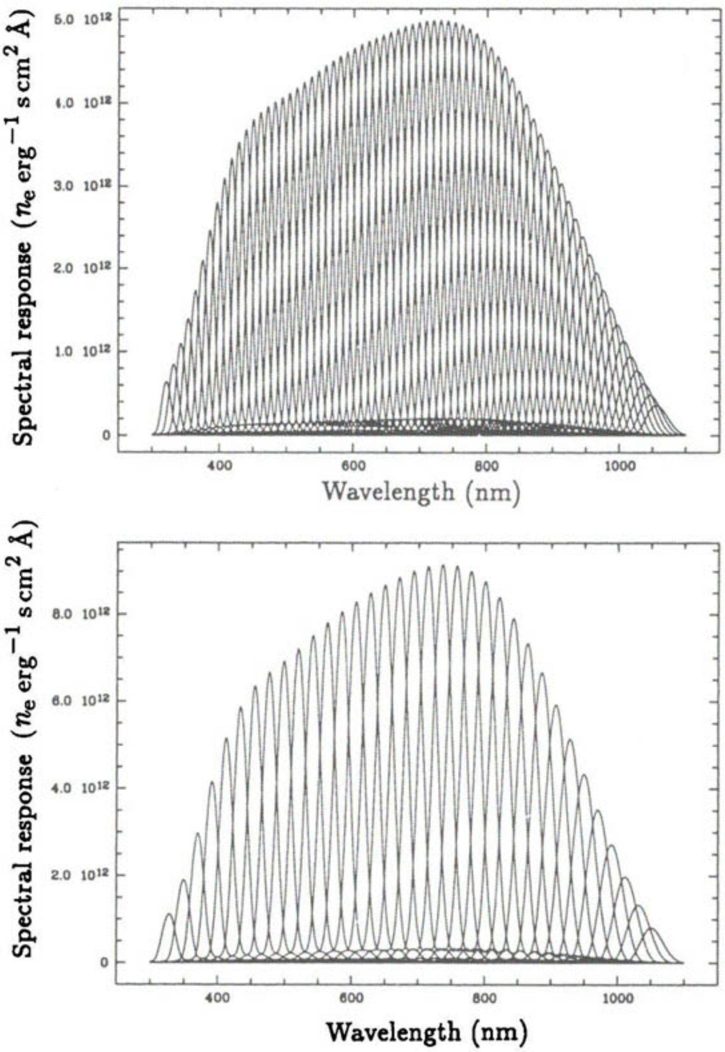

Fig. 1. The set of 66 and 32 spectral response curves used for the present investigation, as derived from the optical properties of the planned DIVA instrument.

From this, noise-free DIVA spectra were simulated, taking into account:

- the wavelength-dependent monochromatic diffraction pattern of the interferometer;
- the linear dispersion of the grating (200 nm/mm);

- the pixel structure of the detector surface and the binning of pixels to yield 32 or 66 spectral passbands;
- the random location of the star images, which differs for each field-of-view transit (this dictated the precise definition of the wavelength bands).

To reduce the data rate of the satellite, four CCD pixels will be combined by on-chip binning, resulting in an effective pixel. The random location of star images which differs for each field-of-view transit was taken into account by introduction of a triangular weighting function. One spectral band contains one effective pixel but has a total width of two effective pixels as shown in Fig. 2.

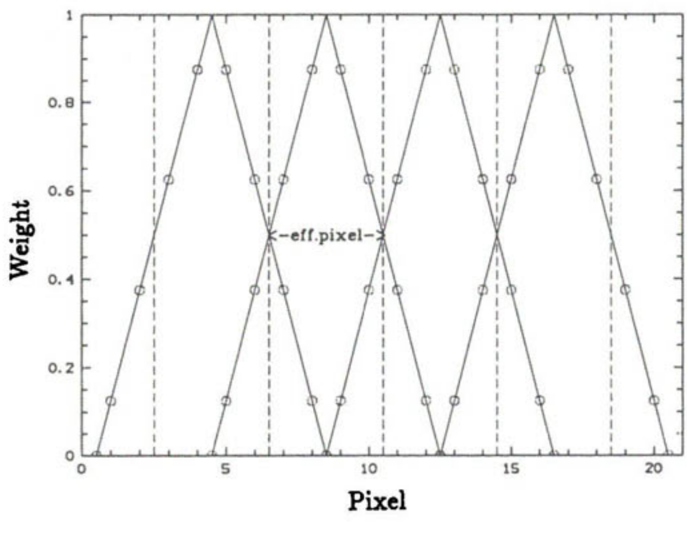

Fig. 2. The weights of the pixels for the calculation of the spectral bands taking into account the random location of star images, which differs for each field-of-view transit. An effective pixel contains four physical CCD pixels which are combined by on-chip binning. A spectral band contains one effective pixel but has a total width of two effective pixels.

This gave the expected electron numbers $n_e(i)$ for each passband i. Examples for simulated spectra are given in Fig. 3 (A-type star) and Fig. 4 (G-type star). The upper graph shows the theoretical high-resolution spectra, the graph in the middle a sample DIVA spectrophotometry using 66 spectral bands and the lower for 32 spectral bands.

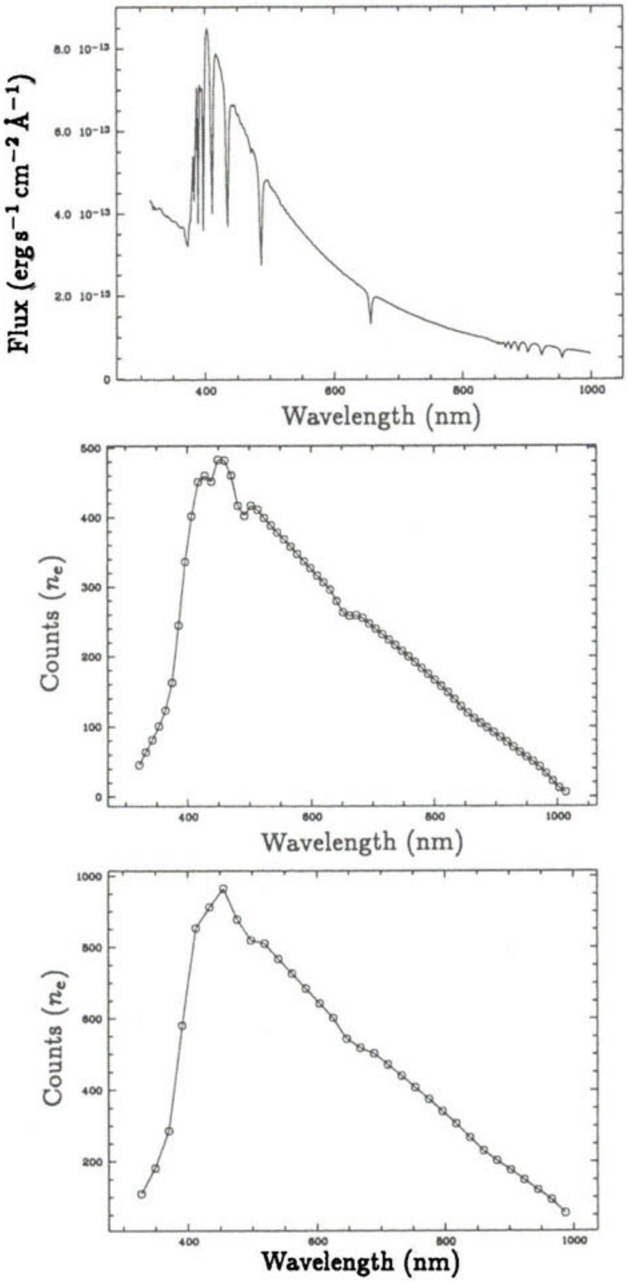

Fig. 3. A0 V star of V=10 mag, the upper panel shows the theoretical high-resolution spectrum (the flux as a function of wavelength), the middle panel is a sample of DIVA spectrophotometry using 66 spectral bands and the lower panel is for 32 spectral bands (the electron counts as a function of wavelength), see Fig. 1.

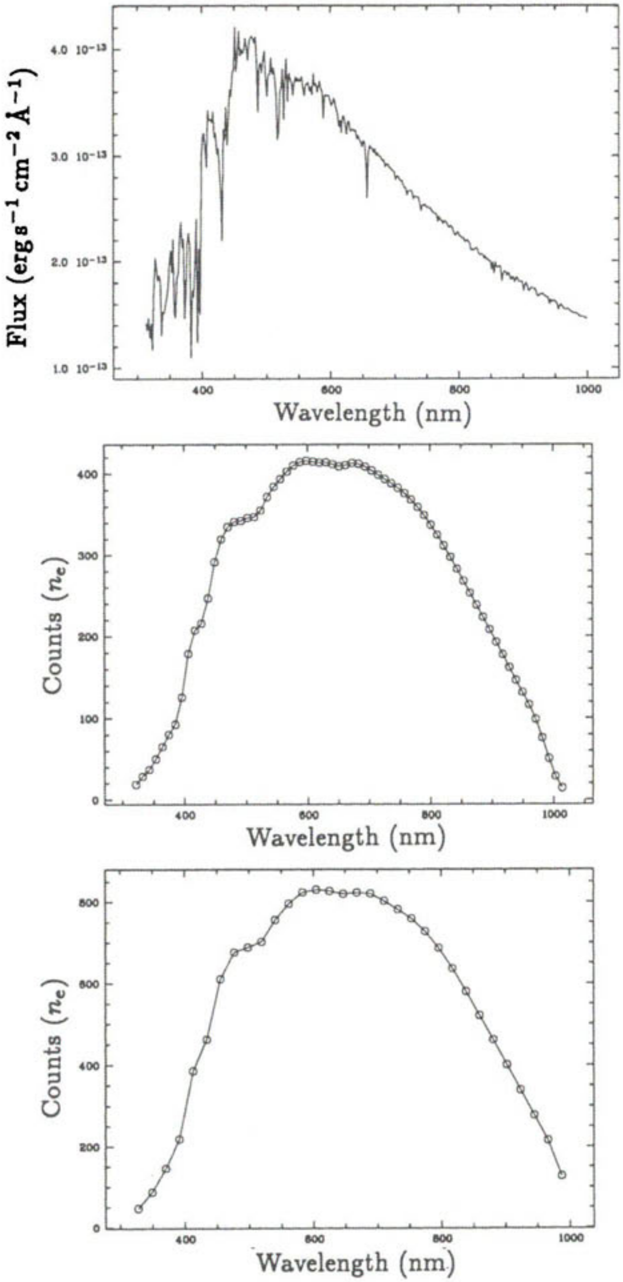

Fig. 4. G2 V star of V=10 mag, the upper panel shows the theoretical high-resolution spectrum (the flux as a function of wavelength), the middle panel is a sample of DIVA spectrophotometry using 66 spectral bands and the lower panel is for 32 spectral bands (the electron counts as a function of wavelength), see Fig. 1.

The standard deviation $n_e(i)$ for the whole DIVA mission of n_t = 120 transits was calculated by the formula of aperture photometry:

$$\sigma_i = \sqrt{0.9\, n_e(i) + n_p(D + \sigma_r^2)}, \qquad (2)$$

with dark current $D = 20\,(8)\, e^-$/effective pixel/s, readout noise $\sigma_r = 4.8\,(2.4)\, e^-$/effective pixel/s and the number of effective pixels binned into each photometric band $n_p = n_t \cdot 4.0\, \frac{\lambda}{500\,\mathrm{nm}}$ for 66 bands and $n_p = 2 \cdot n_t \cdot 4.0\, \frac{\lambda}{500\,\mathrm{nm}}$ for 32 bands. The factor 0.9 occurs because only the inner three fringes in the scan direction, which contain ≈ 90 % of the infalling light, will be used for the spectrophotometry. The numbers in brackets above denote optimistic values σ_{min}, the others σ_{max} are considered conservative.

3. SIMULATION OF STELLAR CLASSIFICATION

For the stellar classification, the simulated DIVA spectra were compared with the same set of Kurucz synthetic spectra of stellar atmospheres from which they were generated. The original Kurucz set contains 409 models with T_e ranging from 50 000 K to 3500 K and $\log g$ from 5.0 to 0.0 for solar metallicity. These flux distributions can be considered to represent real stars with sufficient accuracy for all stars earlier than M-type stars (see Straižys et al. 1997).

This set of 409 model atmospheres was enlarged by linear interpolation. The resulting set of 5677 models is hereafter called the interpolated set.

The classification method is based on Straižys et al. (1998): for each set of the 409 original Kurucz models, 100 noise-laden ("observed") DIVA spectra $n_{e,obs}(i)$ are simulated, using Equations (1) and (2) for the expectation values and noise levels, respectively. Noise was generated using:

$$n_{e,obs}(i) = n_e(i) + \sigma_i\, r_m, \qquad (3)$$

with r_m being a random variable drawn from a normal distribution by the Box-Müller method (Bevington & Robinson 1994).

Each of the "observed" spectra is compared with noise-free DIVA spectra for the entire interpolated set, using the rms deviation:

$$\Delta_M = \sqrt{\sum_i (n_{e,obs}(i) - n_{e,M}(i))^2 / n_{\mathrm{bands}}} \qquad (4)$$

as criterion. Here, the index M counts the 5677 interpolated models, $n_{\rm bands}$ is the number of spectral bands used, and the sum is over the band index i. The minimum in Δ_M defines the assignment of the "observed" spectrum to one of the spectra in the interpolated set. The resulting 100 "observed" classifications form a cluster of 100 points in the $T_{\rm e}, \log g$ plane which can be circumscribed by a 95% (2σ) confidence ellipse. This confidence ellipse is used to characterize the precision of the stellar classification achieved with DIVA observations.

The results will be shown in the form of four $T_{\rm e}$, $\log g$ diagrams, corresponding to the following temperature intervals: 30 000–10 000 K (B-type stars), 10 000–7500 K (A-type stars), 7500–5000 K (F–G-type stars) and 5000–3500 K (K–M-type stars). Trying to avoid overcrowding of the diagrams, ellipses for only 128 models are plotted, i.e. only for about 1/3 of all combinations of $T_{\rm e}$ and $\log g$.

4. RESULTS

The precision of classification depends on apparent magnitude and on the position in the $T_{\rm e}, \log g$ plane. Figures 5 to 20 display the results for different V magnitudes, number of spectral bands and optimistic $\sigma_{\rm min}$ and conservative $\sigma_{\rm max}$ values. The classification accuracy using only 32 spectral bands is lower than the accuracy using 66 bands by a factor which depends on the position in the diagram.

Thus, DIVA will use the denser sampling for the treatment of the operational data. The results using optimistic CCD parameters are much better than those using conservative values. With the same precision the optimistic CCD parameters reach fainter stars by nearly one magnitude. Fig. 14 e.g. shows the result for $V = 12$ mag, 66 spectral bands and the conservative CCD parameters.

For hot stars the precision of these parameters is $\simeq 0.5$ in $\log g$ and $\simeq 10\,\%$ in $T_{\rm e}$. For stars of intermediate temperature it is 0.15 in $\log g$ and 5 % in $T_{\rm e}$. For the coolest stars it is even better. Between 6000 and 4800 K the gravity determination turns out to be problematic.

For $V = 14$ mag stellar classification is not possible with the described method. The confidence ellipses thereby overlap significantly in the whole $T_{\rm e}, \log g$ plane.

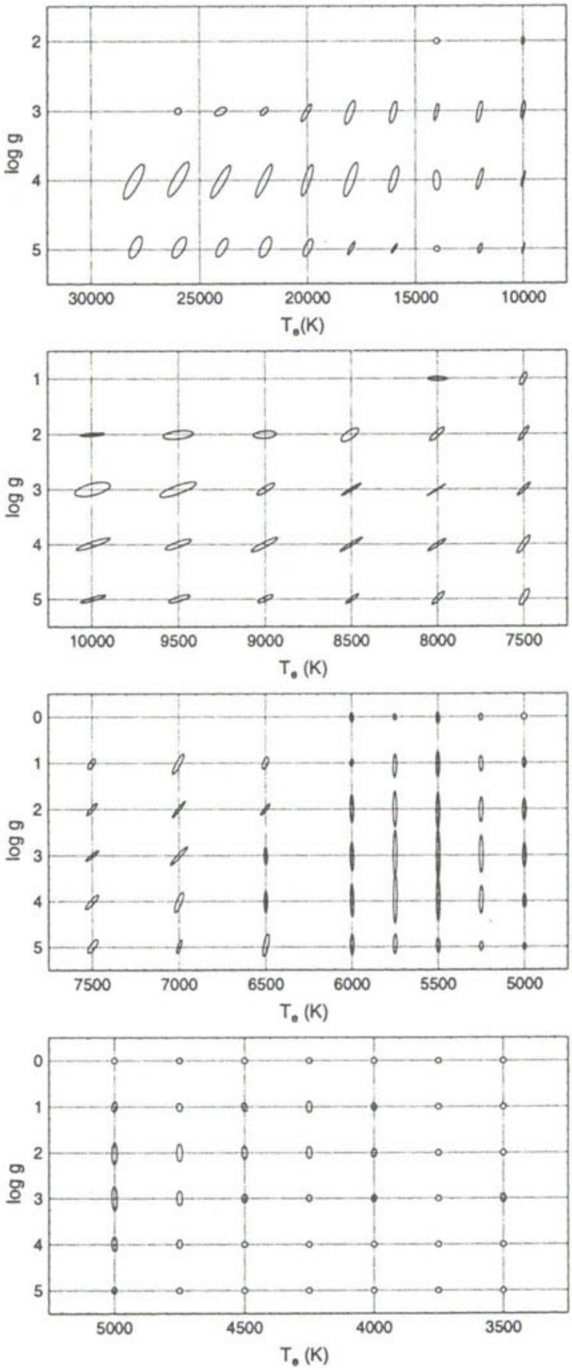

Fig. 5. The $\log g$, T_e diagram for the simulated DIVA observations of unreddened stars for $V = 10$ mag, with 32 spectral bands and σ_{max}.

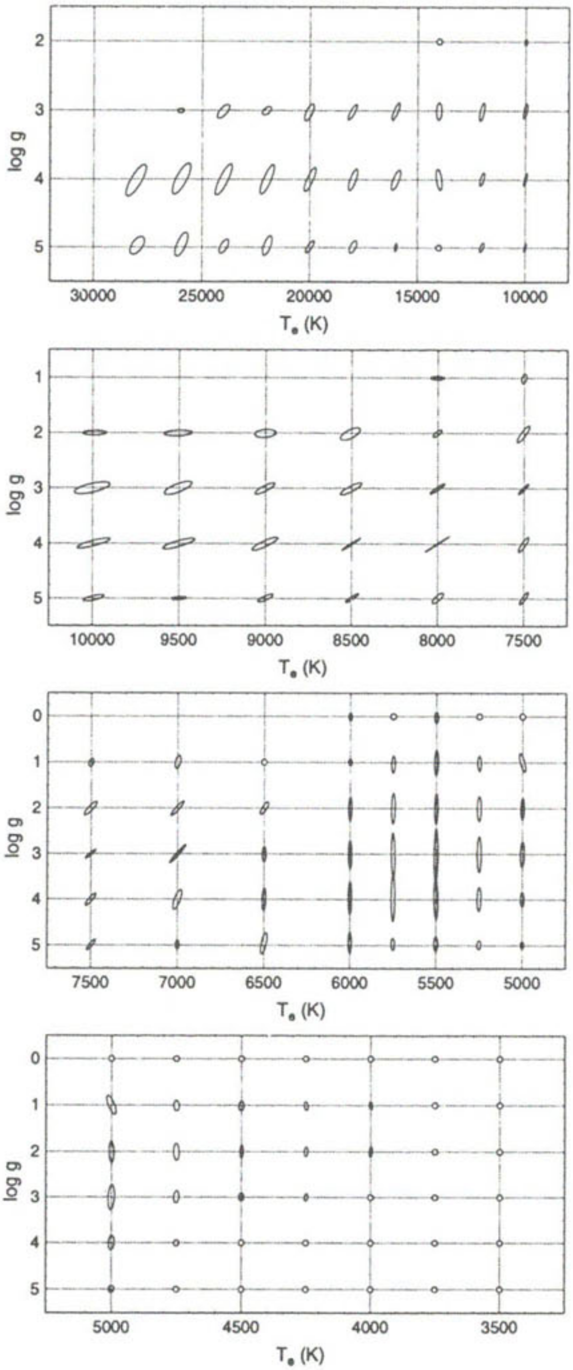

Fig. 6. The $\log g$, T_e diagram for the simulated DIVA observations of unreddened stars for $V = 10$ mag, with 66 spectral bands and σ_{max}.

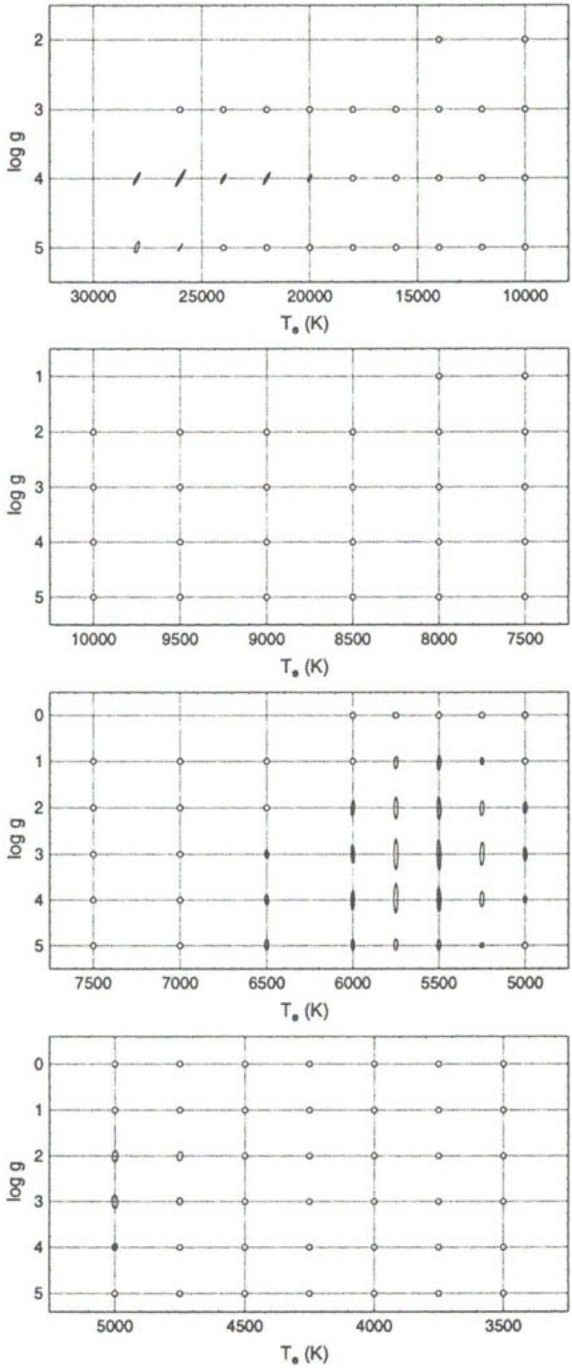

Fig. 7. The $\log g$, T_e diagram for the simulated DIVA observations of unreddened stars for $V = 10$ mag, with 32 spectral bands and $\sigma_{\min}$.

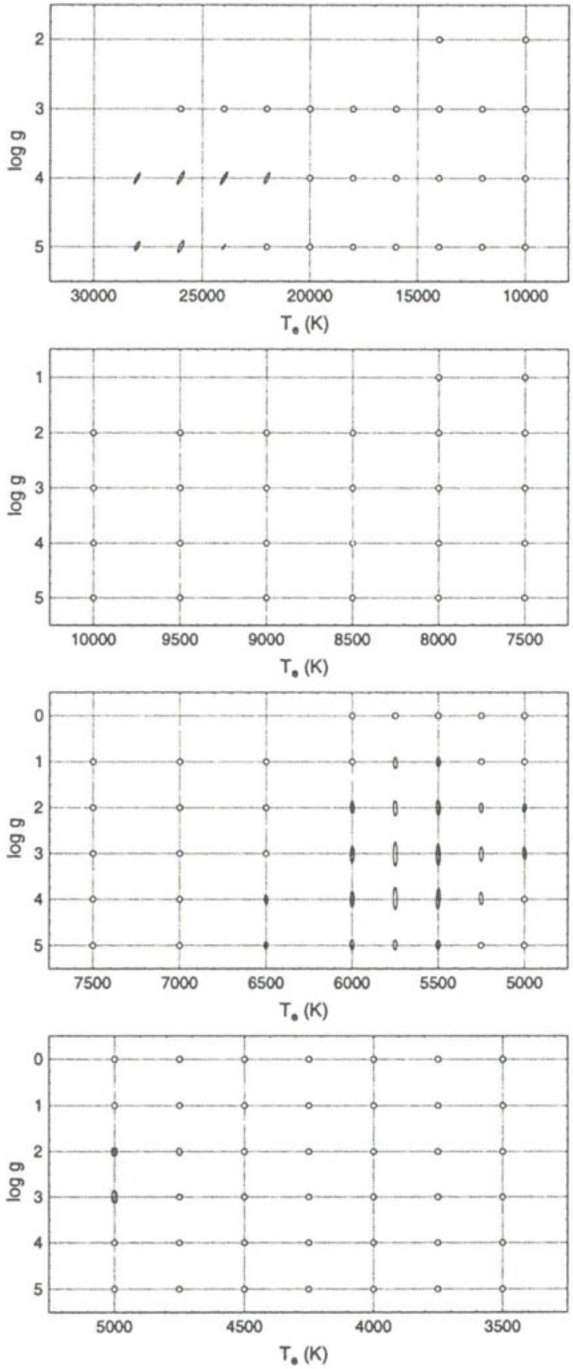

Fig. 8. The $\log g$, T_e diagram for the simulated DIVA observations of unreddened stars for $V = 10$ mag, with 66 spectral bands and $\sigma_{\min}$.

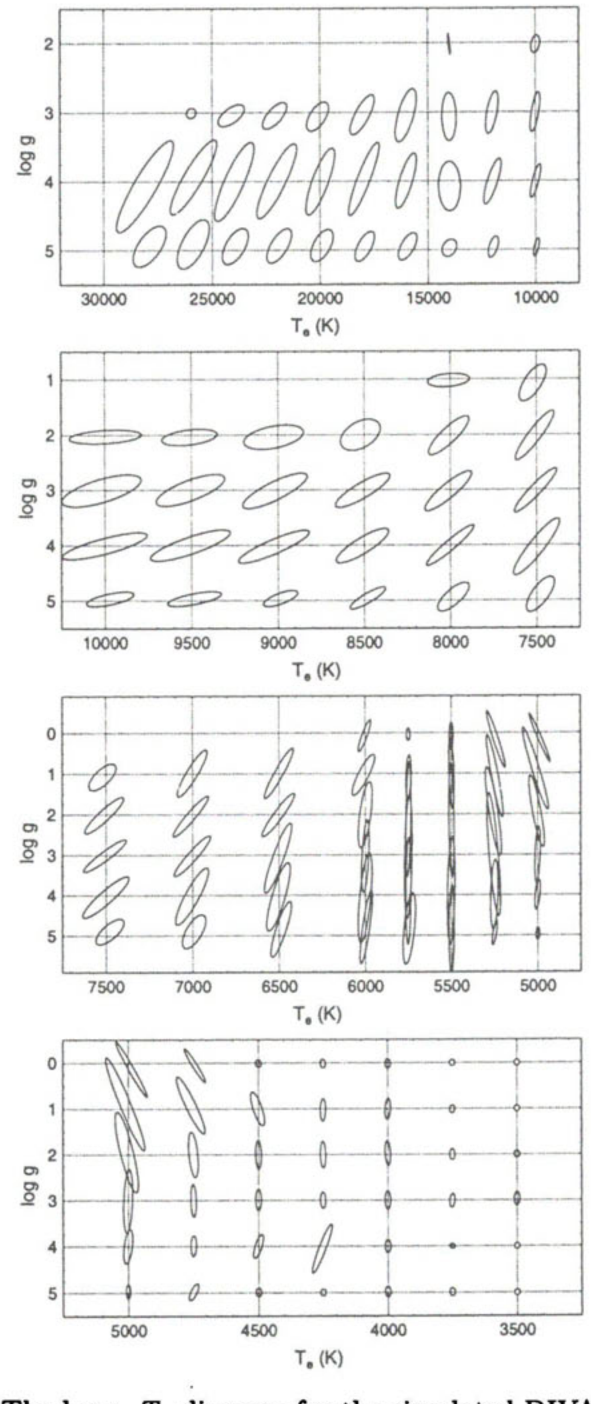

Fig. 9. The $\log g$, T_e diagram for the simulated DIVA observations of unreddened stars for $V = 11$ mag, with 32 spectral bands and σ_{max}.

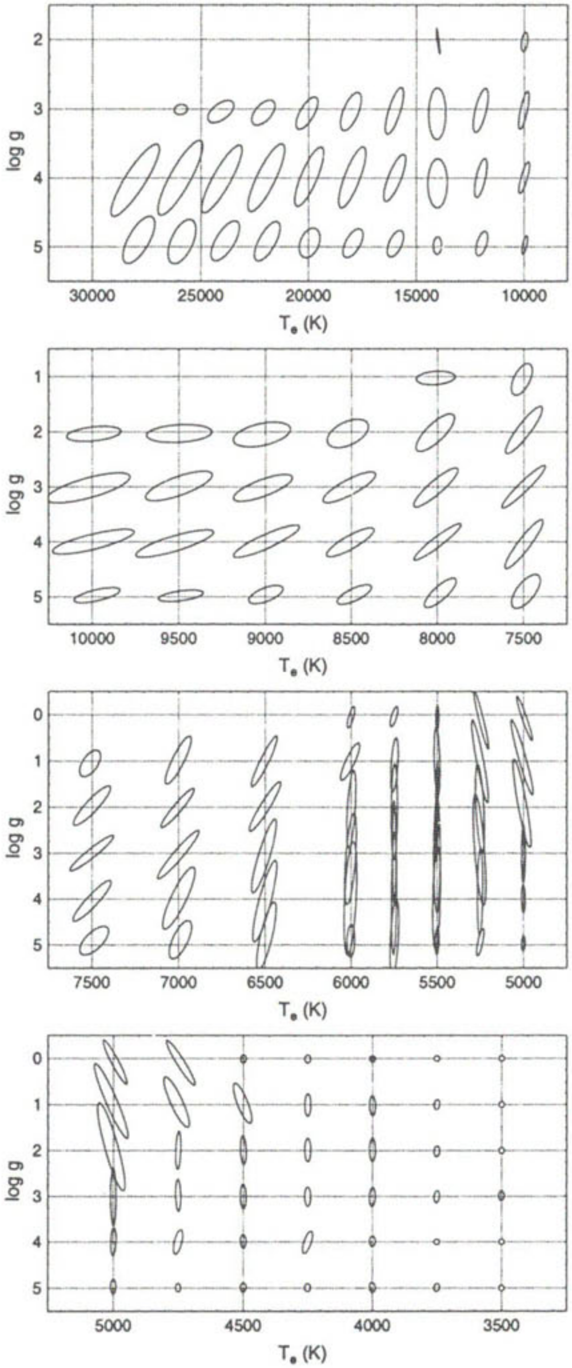

Fig. 10. The log g, T_e diagram for the simulated DIVA observations of unreddened stars for $V = 11$ mag, with 66 spectral bands and $\sigma_{\mathbf{max}}$.

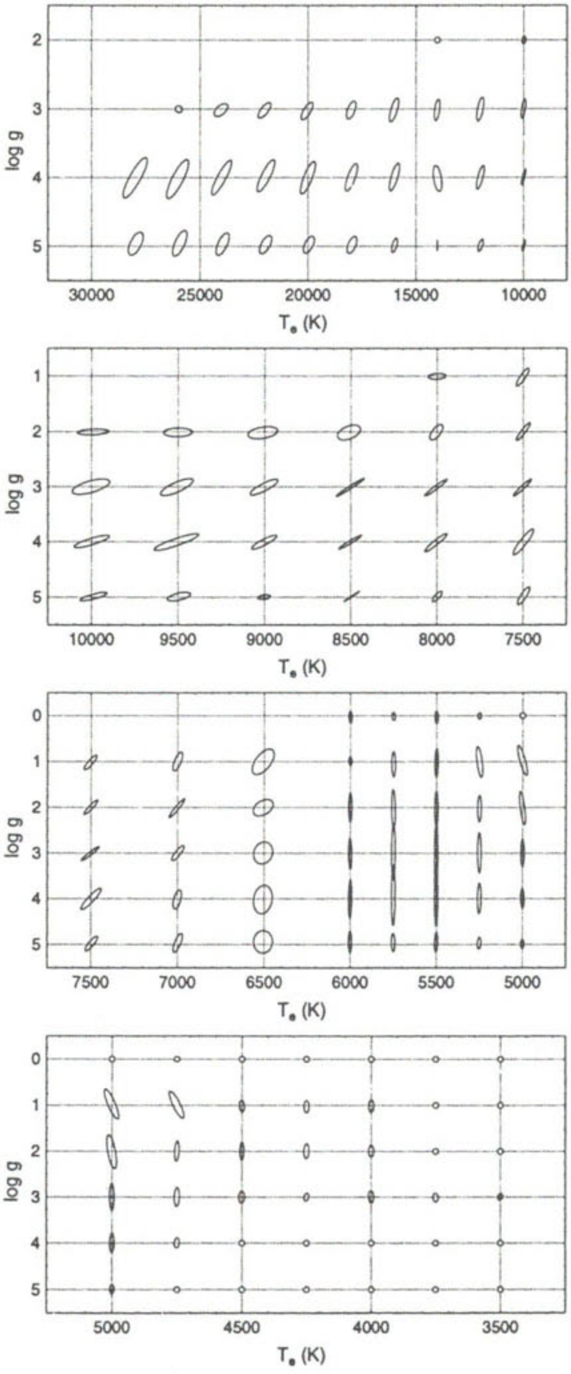

Fig. 11. The $\log g$, $T_{\rm e}$ diagram for the simulated DIVA observations of unreddened stars for $V = 11$ mag, with 32 spectral bands and $\sigma_{\rm min}$.

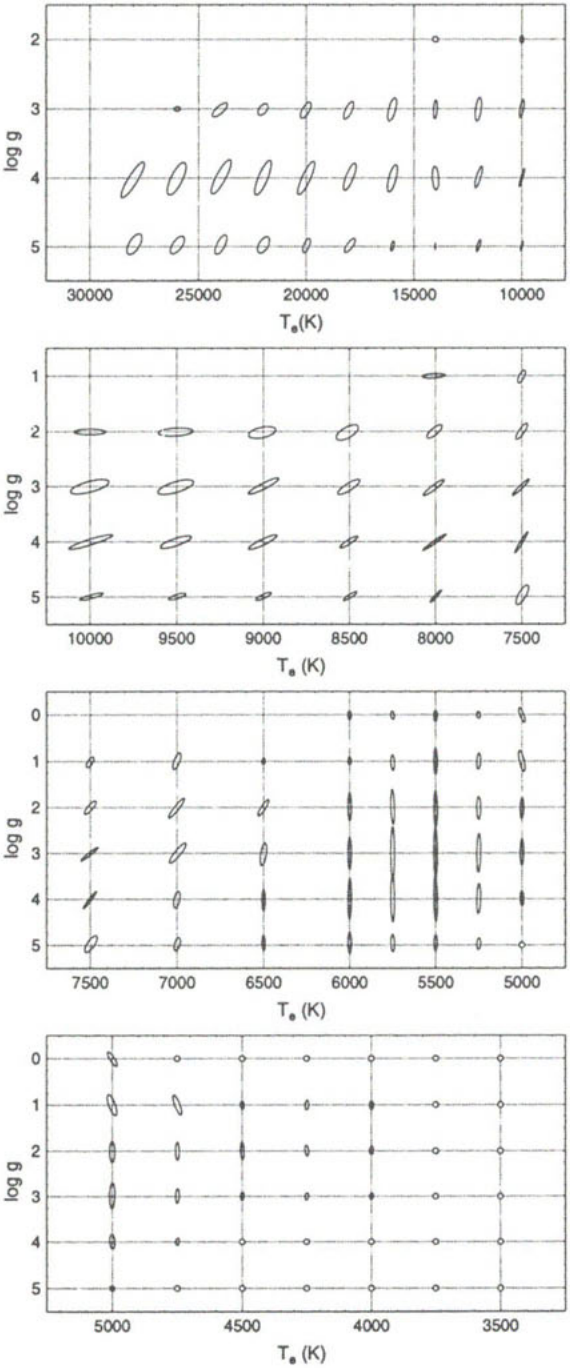

Fig. 12. The log g, T_e diagram for the simulated DIVA observations of unreddened stars for $V = 11$ mag, with 66 spectral bands and $\sigma_{\min}$.

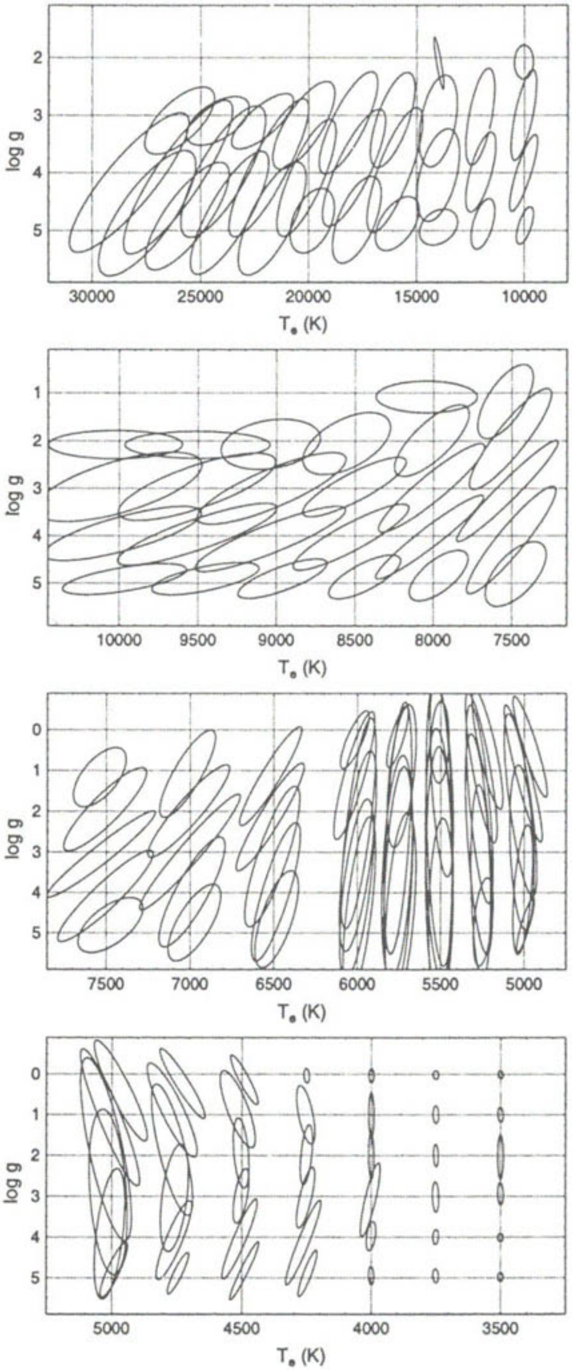

Fig. 13. The $\log g$, T_{e} diagram for the simulated DIVA observations of unreddened stars for $V = 12$ mag, with 32 spectral bands and $\sigma_{\max}$.

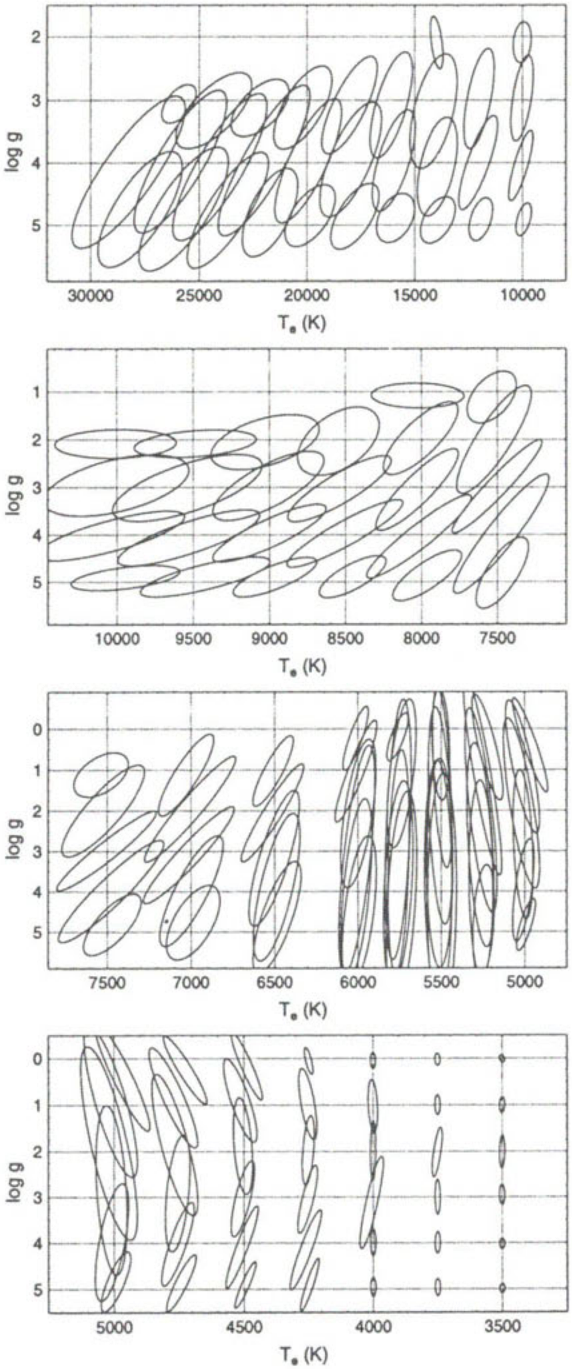

Fig. 14. The $\log g$, T_e diagram for the simulated DIVA observations of unreddened stars for $V = 12$ mag, with 66 spectral bands and $\sigma_{\max}$.

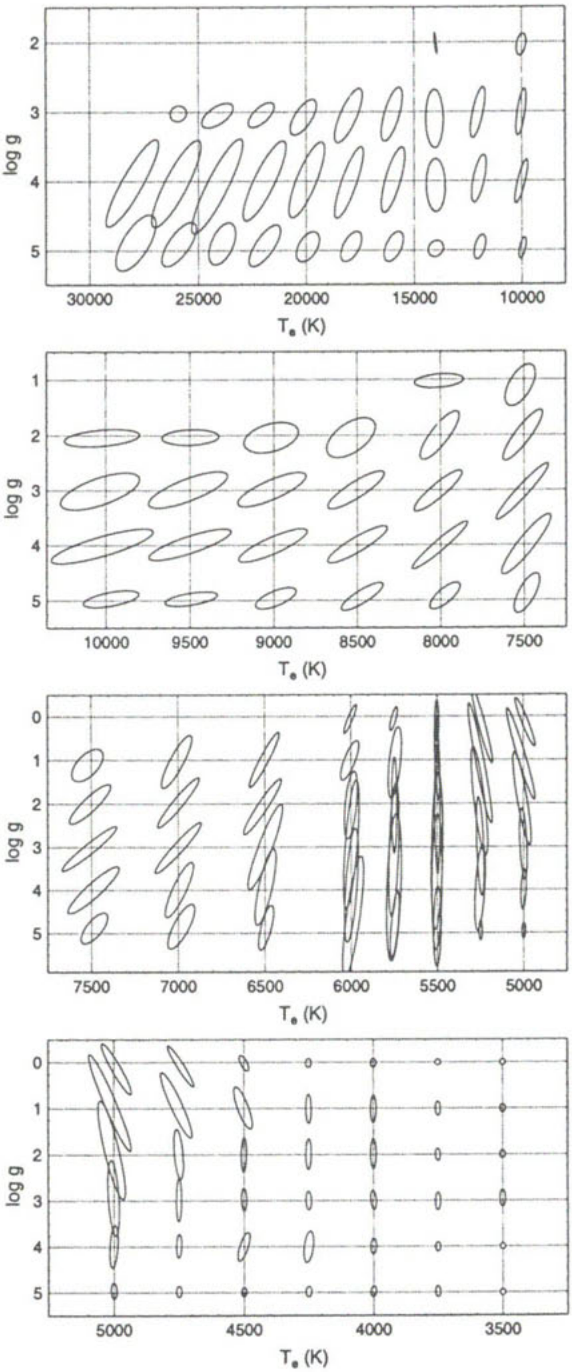

Fig. 15. The $\log g$, $T_{\rm e}$ diagram for the simulated DIVA observations of unreddened stars for $V = 12$ mag, with 32 spectral bands and $\sigma_{\rm min}$.

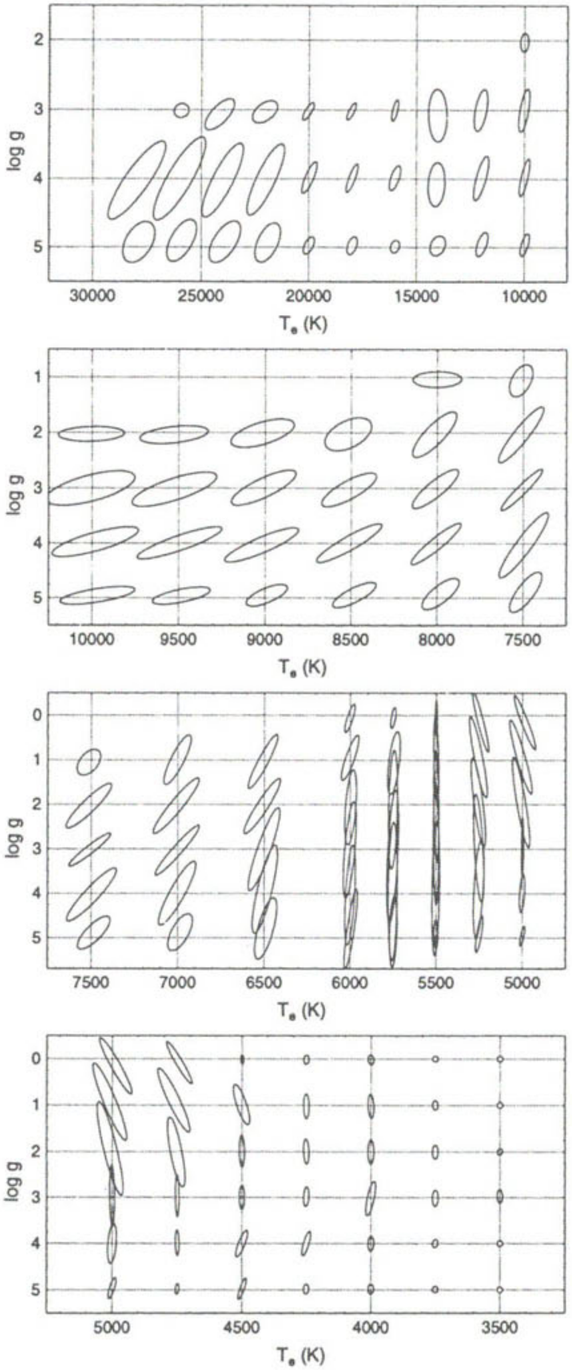

Fig. 16. The $\log g$, T_e diagram for the simulated DIVA observations of unreddened stars for $V = 12$ mag, with 66 spectral bands and $\sigma_{\min}$.

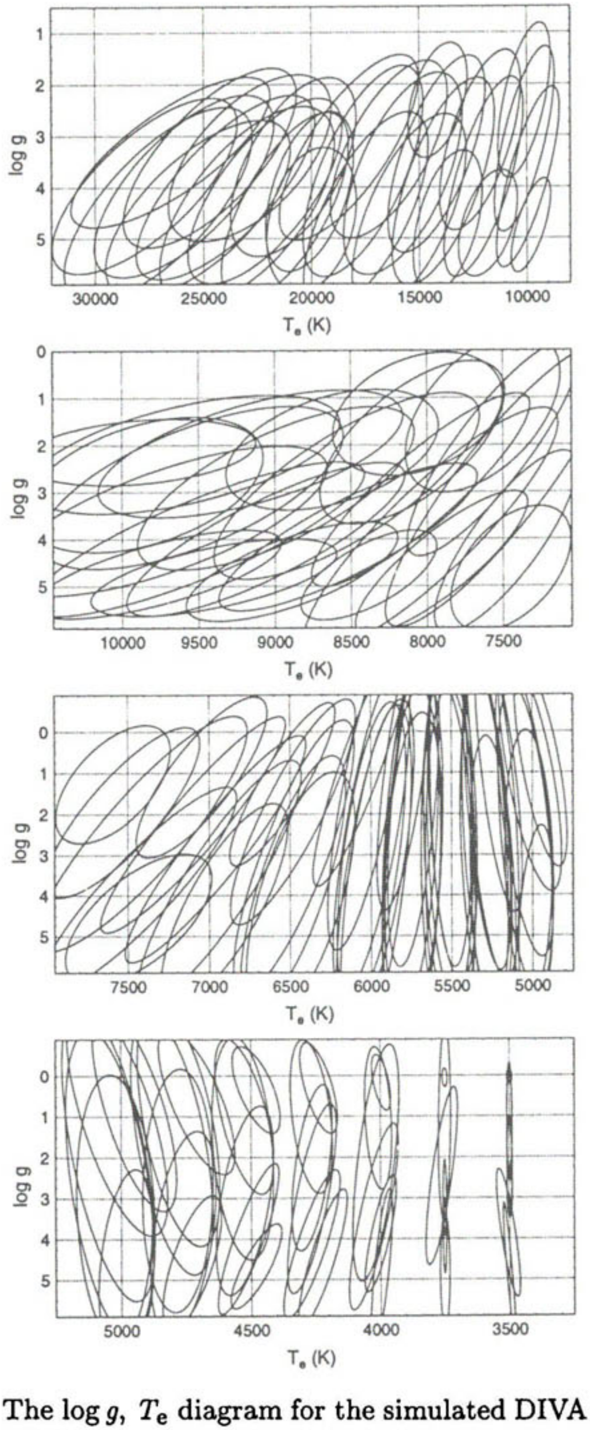

Fig. 17. The $\log g$, T_e diagram for the simulated DIVA observations of unreddened stars for $V = 13$ mag, with 32 spectral bands and σ_{max}.

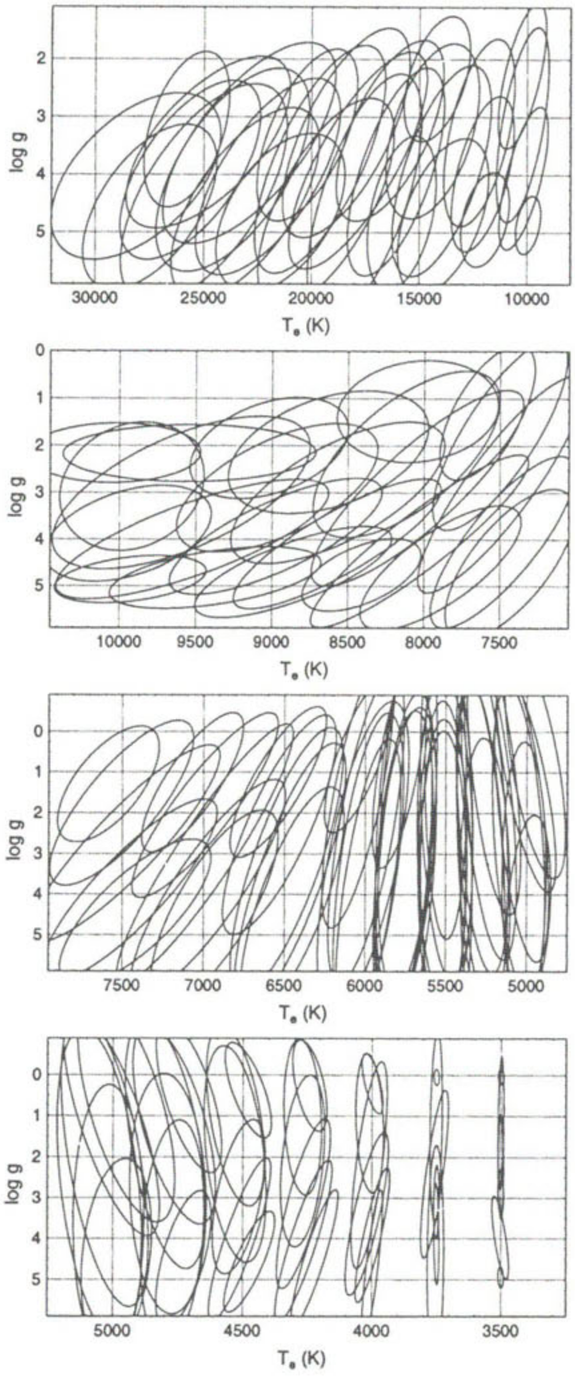

Fig. 18. The $\log g$, $T_{\rm e}$ diagram for the simulated DIVA observations of unreddened stars for $V = 13$ mag, with 66 spectral bands and $\sigma_{\rm max}$.

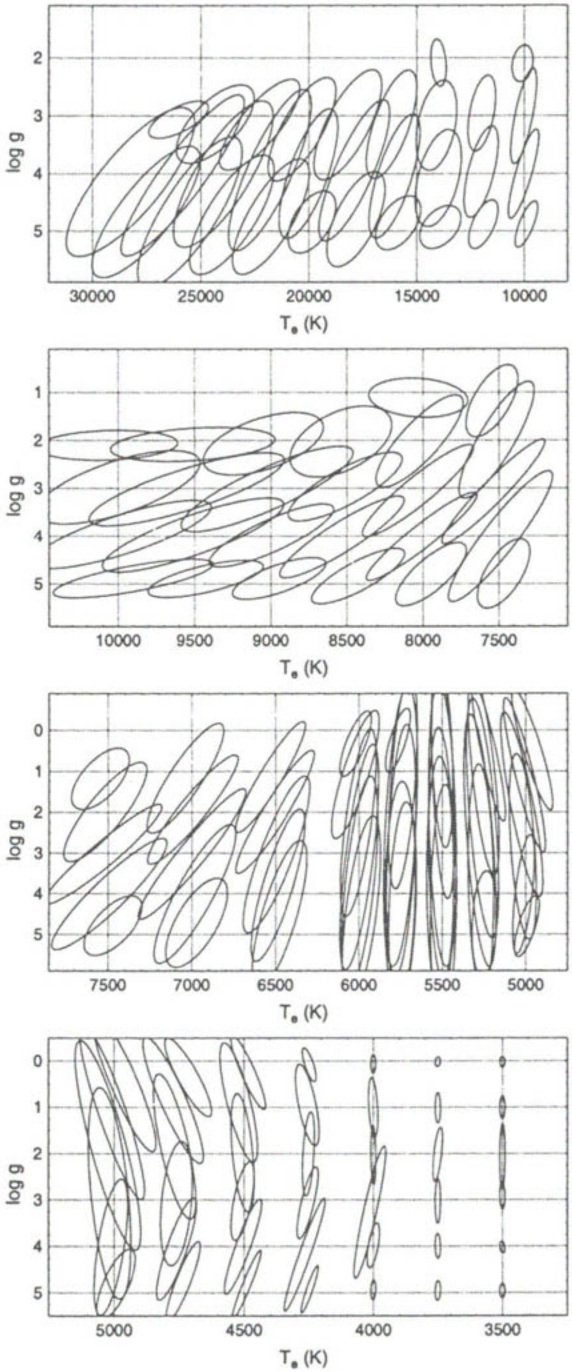

Fig. 19. The log g, $T_{\rm e}$ diagram for the simulated DIVA observations of unreddened stars for $V = 13$ mag, with 32 spectral bands and $\sigma_{\rm min}$.

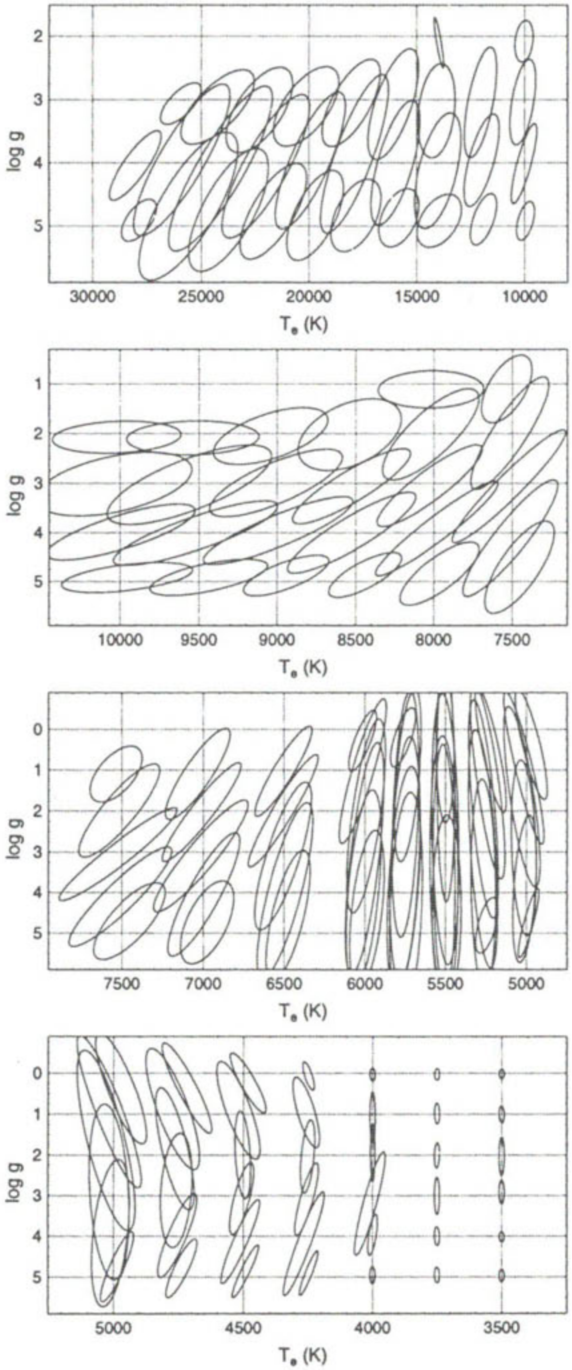

Fig. 20. The $\log g$, T_e diagram for the simulated DIVA observations of unreddened stars for $V = 13$ mag, with 66 spectral bands and $\sigma_{\min}$.

5. CONCLUSIONS

Stellar classification of at least the quality shown in Fig. 14 will be achieved for about 2.5 million stars, and with somewhat lower precision for another 7 million stars.

The accuracy of the classification of B–A–F stars might be much better if the ultraviolet radiation between 300–400 nm were measurable. We are ready to investigate this possibility.

This study also has to be extended to include the interstellar reddening effects and different metallicities. Reddening will be important for distant stars at low galactic latitudes.

A somewhat higher precision of astrophysical parameters might be reached if not all spectral bands were used or different spectral bands would get different weights depending on their sensitivity on the investigated parameter.

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