Proceedings of 12th Cambridge Workshop on Cool Stars, Stellar Systems, & The Sun, 2003 University of Colorado.

Far-UV Continuum as a Diagnostic for Temperature Structure in the Atmospheres of G-type Stars [1]

C. Morossi[2], M. Franchini[2], M.L. Malagnini[3], M. A. Chavez[4]

Abstract.
Investigations of IUE ultraviolet spectra of field G and K-type stars (Morossi et al. 1993, Morossi et al. 1998, Franchini et al. 1998a) showed that the spectral energy distributions (SED's) of cool stars present a significant excess in the UV with respect to the fluxes predicted by the atmosphere models characterized by a monotonic decrease of temperature. We combine HST, IUE and visual observations to construct accurate SED's to be used for deriving empirical estimate of the temperature distribution in the atmosphere of G-type stars. Template objects are used to compare pure LTE model predictions with those from semi-empirical structures designed for the solar case (Vernazza et al. 1981). Particular attention is devoted to the determination of the position of the temperature minimum layer by computing "semi-empirical $T_{\rm min}$ models" (Morossi et al. 1993 and Franchini et al. 1998b).

1. Introduction

G type stars play an important role in the study of the structure and evolution of the Galaxy; in fact they are long-lived enough to still be on the Main Sequence (MS) even if they belong to ancient stellar populations. Their chemical composition provides information on the history of Galactic nucleosynthesis, while their positions and kinematics provide information on the dynamical evolution of the Galaxy.

The analysis of the atmosphere of G-type stars takes advantage of the information available through the study of the Sun. As a consequence, it is possible to model not only the photosphere of these stars but also those regions, like temperature minimum region, chromosphere and corona, which are characterized by non-thermal phenomena.

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[1]Based on data dearchived from INES at the Italian National Centre and on observations made with the NASA/ESA *Hubble Space Telescope*, obtained from the data archive at the Space Telescope Science Institute. STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

[2]INAF - Osservatorio Astronomico di Trieste

[3]Università degli Studi di Trieste, Dipartimento di Astronomia

[4]Instituto National de Astrofísica Óptica y Electrónica (INAOE)

In the atmospheres of stars of spectral type later than F0, the presence of non radiative heating is already well established (see for instance Ayres et al. 1995). We consider of the utmost importance to ascertain, before all, the relative weight of radiative and non radiative mechanisms in the global energy balance that determines the temperature structure of the stellar atmospheres.

The analysis of the spectral energy distributions (SED's) of cool stars received a strong incentive in recent years from the availability of improved models and extended observational facilities from ground and space. In particular, great attention was paid to the (far) ultraviolet region, accessible through IUE, where chromospheric activity of late type stars shows up with prominent features. More recently, both joint observations in X-ray and UV and new data from HST greatly improved the understanding of atmosphere properties of G-type stars.

While most papers on this subject are based on the analysis of emission lines (see, for instance, the review On Advances in Solar-Stellar Astrophysics by Haisch and Schmitt, 1996, and references therein), our work focuses on the study of the UV flux itself as a signature of the presence of non-radiative heating in the outer atmosphere and, in particular, of the temperature minimum region. This second approach has several advantages since it is less model dependent and can be applied to the study of a large number of objects (even faint) because does not require Hi-Res spectroscopy.

In the framework of a systematic comparison between observed and computed spectra of cool stars, we already analyzed a sample of K-type stars in the IUE ultraviolet region (Morossi et al. 1993). The main result of the analysis of the K-type stars was the failure of theoretical classical models in predicting the near UV (2200-3000 Å) of stars showing, even at low resolution, chromospheric features such as the Mg II resonance doublet in emission. Similar results were obtained from the analysis of a limited sample of G8 giants of Population II (Malagnini et al. 1994). The discrepancies are due to the fact that the temperature structure in classical atmosphere models is characterized by a monotonic decrease towards the stellar surface, and there is no modeling of the temperature minimum followed by a temperature rise expected in real stars, and specifically in the active ones.

Morossi et al. (1993) presented semi-empirical models (hereafter $T_{\rm min}$ models) based on a modified temperature structure with respect to classical models. The $T(m)$ model structure was modified according to the following formula:

$$T(m) = max(T(m), R \times T_{\rm eff})$$

where m is the mass column density in g cm^{-2} and R is the ratio $T_{\rm min}$ over $\mathrm{T_{eff}}$. It results that the $T_{\rm min}$ models predict a "UV flux excess" as a consequence of lower blanketing. The higher the R ratio, the larger the effect. In Franchini et al. (1998b), the authors compared the observed spectral energy distributions of 53 field G-type stars with predictions from atmosphere models. While the fluxes computed from classical models describe very well the near UV region, they fail to do so in the IUE SW region. On the other hand, the theoretical fluxes computed from $T_{\rm min}$ models provide good agreement with observations down to 1600 Å, thus confirming that the $T_{\rm min}$ atmospheric region determines the level of the emerging flux in the 1600-2000 Årange. The failure of the classical models in predicting the observed far UV fluxes indicates the inadequacy of the current atmosphere models in computing the radiative transfer in the external layers.

A first attempt to construct a more realistic atmosphere model describing photosphere, chromosphere, and transition region layers can take as a starting point the so-called *solar-stellar* connection. Several papers have been published on this topic (e.g. Vernazza et al. 1973, 1976, 1981; Kelch et al. 1979; Haisch & Basri 1985; Maltby et al. 1986; Andretta & Giampapa 1995; Carpenter et al. 1999).

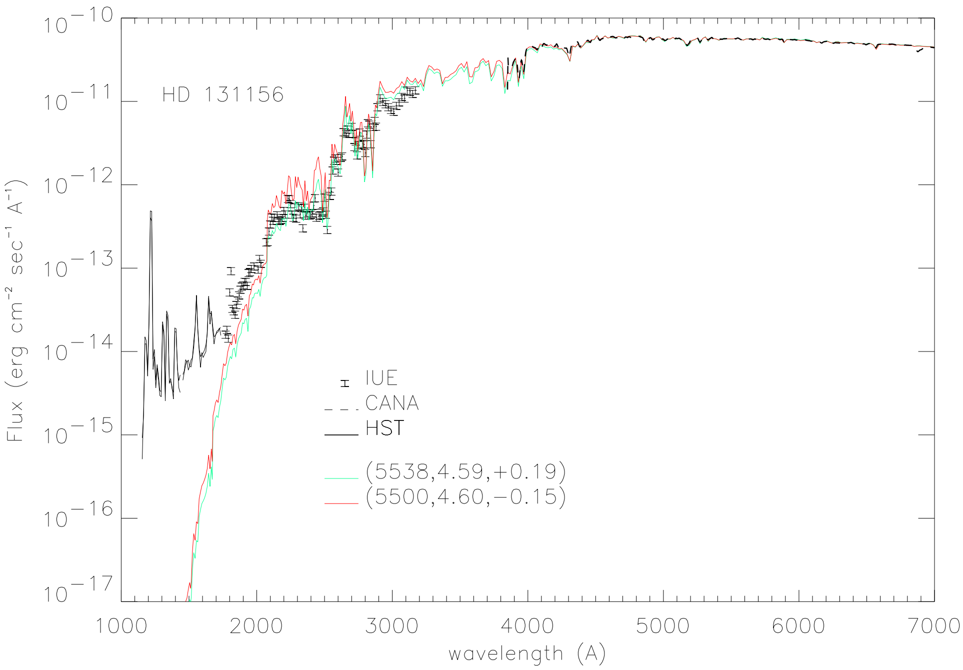

Figure 1. Comparison of observations (black) with theoretical fluxes (green and red) computed from two Kurucz models

On the basis of spectrophotometric observations, that we are collecting at the Guillermo Haro Observatory (Cananea, Mexico), and data from IUE, HST and FUSE databases, we have started a research project with the following aims: a) to uniformly analyze a large sample of spectra of F to K type stars to fully understand the characteristics of the minimum temperature region; b) to compute hybrid stellar atmosphere models for F to K stars by using as a template the semi-empirical model of the solar atmosphere; c) to evaluate the effects of different temperature structures in the atmosphere on the chemical abundance determinations in cool stars. In the following section we will present, as an example, preliminary results on the comparison of observed and computed SED's of HD 131156.

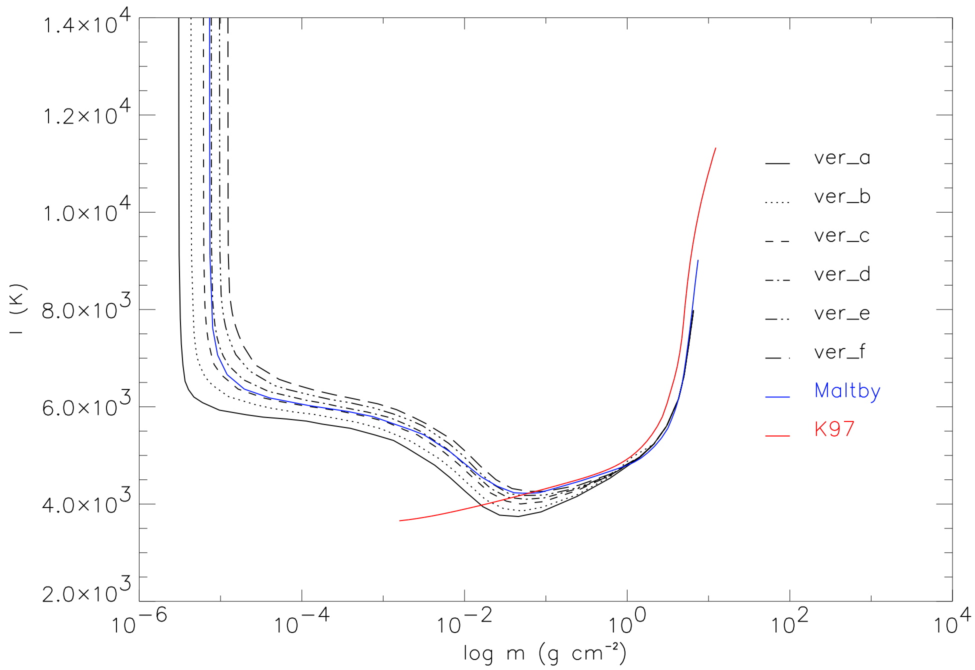

Figure 2. Comparison among $T(m)$ structures of scaled semi-empirical solar models (black, blue) and K97 (red) model

2. HD 131156

Fig 1. shows the Spectral Energy distribution of HD 131156 (G8 V) as derived from our spectrophotometric data, IUE spectra from INES, and HST-GHRS data retrieved from the STScI archive. The observed SED is compared with the prediction of two Kurucz (1997) models computed with atmosphere parameter values from Cayrel et al. (1997). The visual and near-UV ranges allowed us to discriminate between the two different models and indicate that the model characterized by the highest metallicity should be preferred. The UV excess already described in Sec 1. is clearly evident shortwards of 2200 Å.

Fig 2. compares the $T(m)$ structure of the (5538,4.59,+0.19) Kurucz model with those of scaled semi-empirical solar models derived from those proposed by Vernazza et al. (1981) and Maltby et al. (1986). The scaling of the published solar $T(m)$'s was accomplished by adopting 5538 K as the value of the effective temperature of HD 131156 by using the following formula:

$$T(m) = \frac{T_{\rm eff}}{T_{\odot}} \times T_{\odot}(m)$$

Fig 3. shows the corresponding SED's computed by means of ATLAS9 (Kurucz 1993). As can be seen, a part from few artifacts due to some ATLAS9 inadequacy in computing emergent fluxes at very low m (particularly evident at $\sim$ 2300 Å for the "hottest" Vernazza models), the semi-empirical SED's

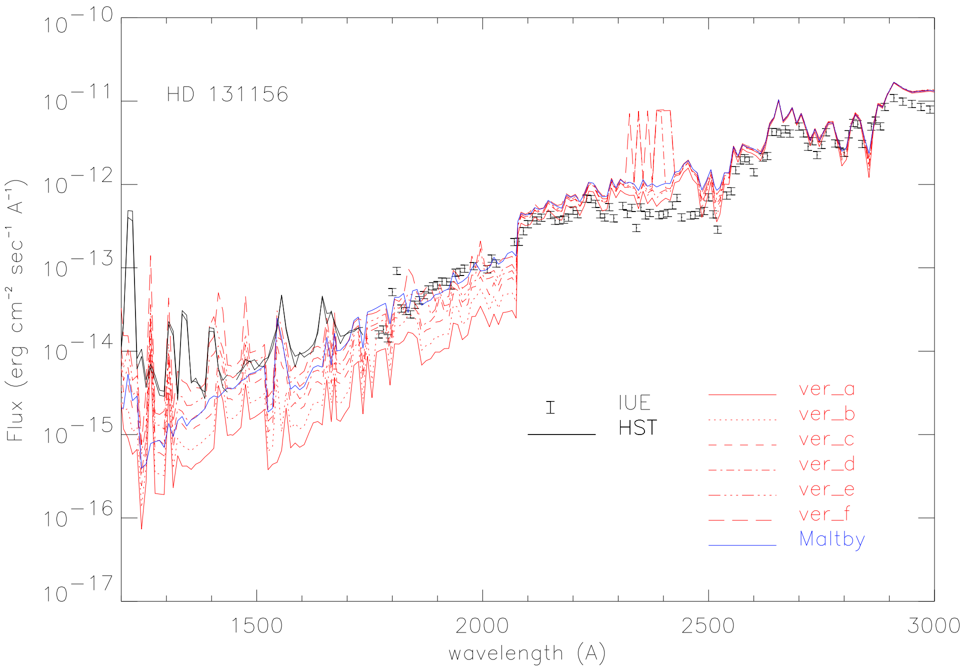

Figure 3. Comparison of observations (black) with theoretical fluxes (red and blue) computed from scaled semi-empirical solar models

are in better agreement with the far-UV observations than the Kurucz fluxes (see Fig 1.). Nevertheless there is an intermediate region, around 1900-2500 Å, where the predicted fluxes do not reproduce well the observations thus suggesting that the minimum temperature region is not well described by the scaled semi-empirical solar models.

Fig 4. compares the $T(m)$ structure of the (5538,4.59,+0.19) Kurucz model with those of the T_{min} model computed with $R = 0.80$ and of an "Hybrid" model which assumes a linear increase in $T(m)$ above the T_{min} region. Fig 5. shows the corresponding SED's. As can be seen, the T_{min} SED reproduces well the UV observation longward of 1750 Å, while the "Hybrid" model predicts quite satisfactorily the underlying continuum in the region 1400-1750 Å. These preliminary results seem to suggest that the $T(m)$ structure of the atmosphere of HD 131156 is characterized by an extended plateau or a very shallow gradient at a T_{min} value slightly higher than the scaled solar one (see Fig 6.). The analysis of a large sample of G-type stars to understand if such a result can be generalized is in progress.

Acknowledgments. Partial support from MURST 60% (Università degli Studi di Trieste) and COFIN2000 grants is acknowledged.

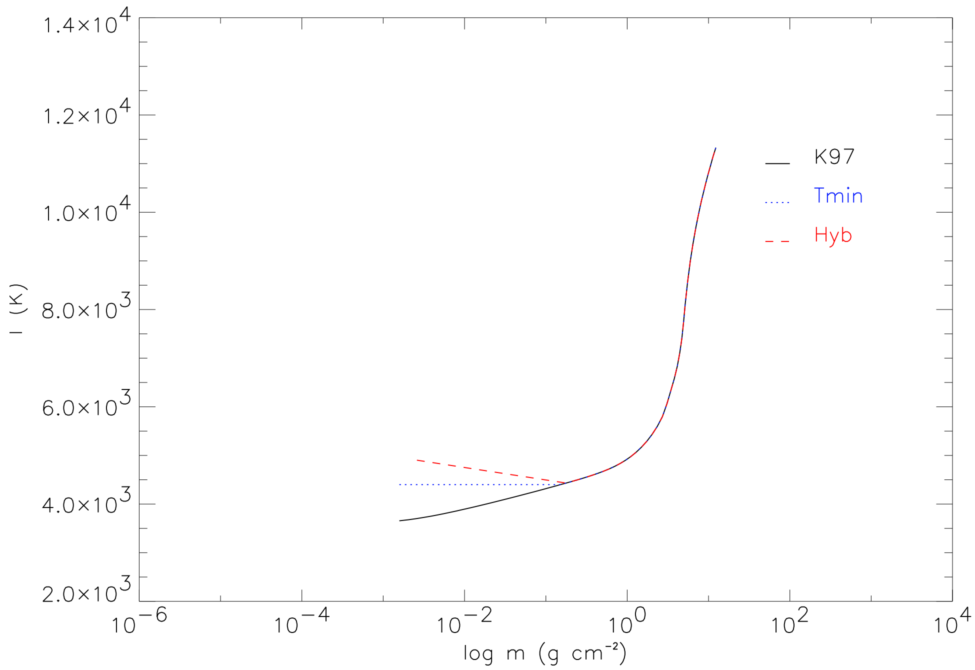

Figure 4. Comparison among $T(m)$ structure of the (5538,4.59,+0.19) Kurucz model with those of the $\mathrm{T_{min}}$ model computed with $R = 0.80$ and of an "Hybrid' model

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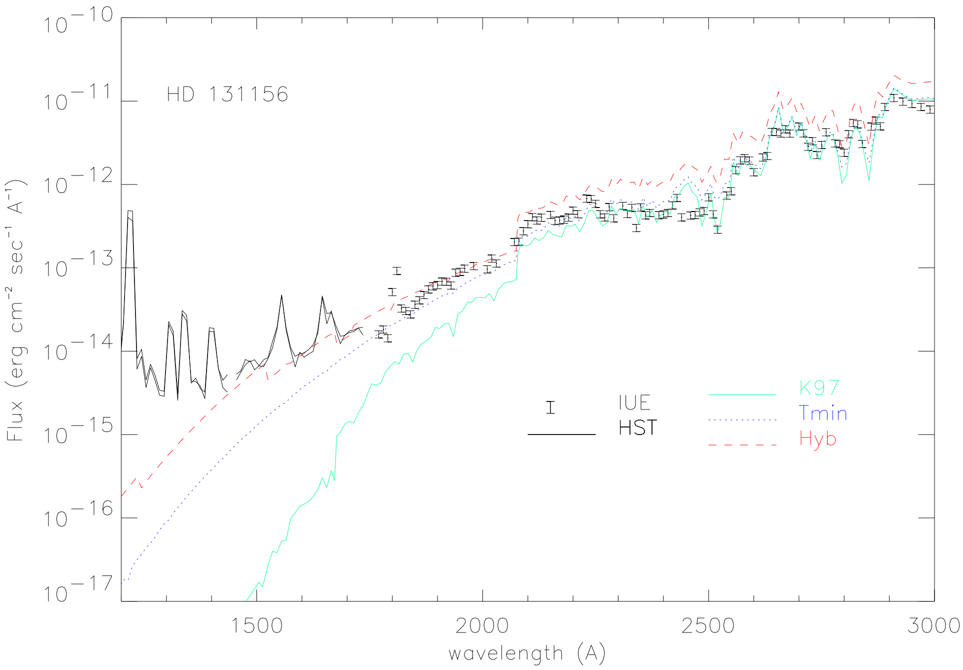

Figure 5. Comparison of observations (black) with theoretical fluxes computed from (5538,4.59,+0.19) Kurucz , T_{min} and "Hybrid" model (green, blue and red respectively)

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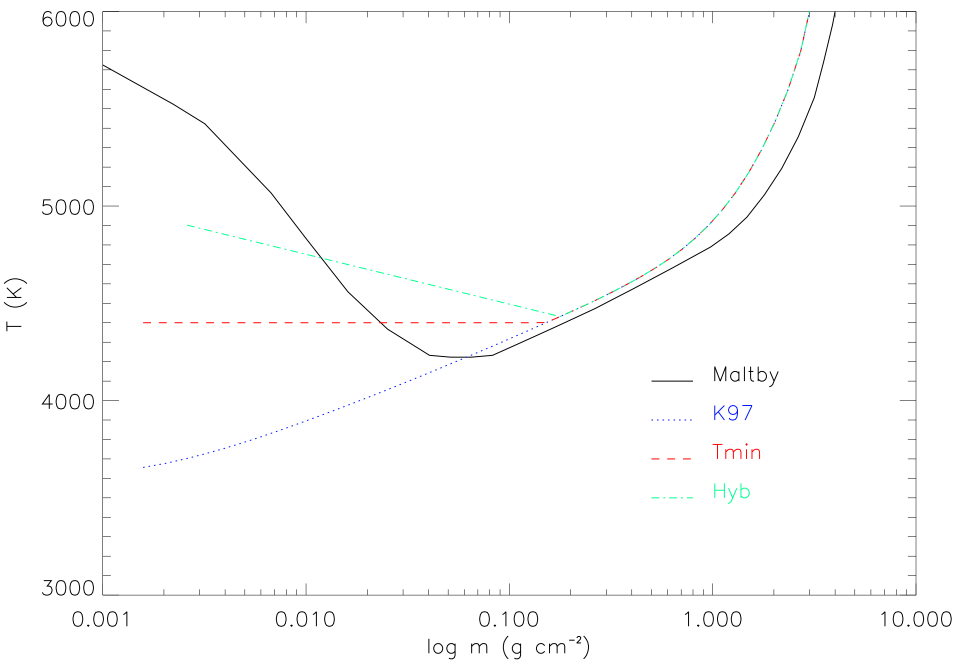

Figure 6. Comparison among $T(m)$ structures of the scaled semi-empirical solar Maltby, K97, T_{min} and "Hybrid" models