The A-Star Puzzle
Proceedings IAU Symposium No. 224, 2004
J. Zverko, J. Žižňovský, S.J. Adelman, & W.W. Weiss, eds.

DOI: 10.1017/S174392130500935X

Observational signatures of atmospheric velocity fields in Main Sequence stars

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Abstract. In stars with sufficiently small projected rotational velocities (less than a few km s^{-1}), it is often possible to detect signatures of the atmospheric velocity field in line profiles. These signatures may be as subtle as small asymmetries in the profile ("line bisector curvature") or as obvious as profile shapes that strongly depart from those predicted by simple microturbulence models. We have recently carried out a high resolution survey of sharp-line stars to search for these symptoms of local velocity fields. We report the first results of a comparison of models with the observed profiles.

Keywords. Convection, techniques: spectroscopic, line: profiles, stars: atmospheres, stars: individual (HD 103578, HD 147084, HD 160762, HD 175640, HD 185395), stars: rotation

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1. Introduction

One of the major areas in which better physics is required to advance modelling of stellar atmospheres and interiors is the description of convection, especially where it is relatively inefficient. The model normally used, the mixing-length theory (MLT), is essentially an order-of-magnitude estimate with a free parameter. It allows one to make reasonable estimates of the effects of convection, but because it embodies only a very incomplete description of convection, it is not at all accurate.

One method of improving the situation is through direct numerical computation of motions and heat transport in a layer that is unstable to convection. However, even this method has considerable limitations (limited number of grid points, need to model sub-grid scale dissipation, long thermal relaxation time for dense gas, etc.), and the computations are sufficiently costly in cpu cycles and memory that direct computation does not offer a realistic general alternative to MLT for modelling stellar convection.

In recent years, a variety of new models of convection have been introduced. In each of these, the intention is to incorporate more of the relevant physics so that the model is more like real convection, while still having a model that is computationally useful for a wide variety of applications. An example of this kind of development is the convection model of Canuto & Mazzitelli (1992).

One of us (FK) has been actively developing such models. The overall approach has been to start from moment equations describing average quantities such as velocity,

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temperature, density, pressure, etc, and their higher order moments. Such equations always have higher-order terms which require closure (Canuto 1992, 1993, 1997), and various methods of doing this have been tried (e.g., Kupka 1999).

These models are reaching a stage where comparison of various models with each other, with numerical hydrodynamical computations, and with various kinds of observations, are valuable. Comparisons with mixing length results and numerical computations have recently been carried out by Kupka & Montgomery (2002) for A star envelopes and by Kupka & Montgomery (2004) for white dwarfs.

Another obvious way in which these new convection models may be tested is by using the models to predict the effects of atmospheric convection on spectral line profiles, which may then be compared to observed spectral line profiles. This paper reports the first stages of such a project, in which we acquire a suitable database of high-resolution spectra, and identify stars whose spectra are useful for such a comparison.

2. Observations

The observed spectral lines of a star may be shaped by numerous mechanisms, including thermal broadening, stellar rotation, pulsation, magnetic fields, mass loss, and the velocity field produced by the top of an outer convection zone. In various parts of the HR diagram, the profiles are typically dominated by different broadening mechanisms. On the lower Main Sequence where rotation is usually very slow ($v \sin i$ less than a few km s^{-1}) and mass loss is weak, the effects of the convective velocity field in shaping the line profiles are often easily detected. Similarly, many giants and supergiants have low $v \sin i$ values and their line profiles often show the influence of surface velocity fields. In contrast, most upper Main Sequence stars rotate with $v \sin i$ values of hundreds of km s^{-1}, making it very difficult to detect the effects of other broadening mechanisms.

A first stage in this project has then been to observe a number of stars for which available data suggest that they have small enough values of $v \sin i$ to allow other broadening mechanisms to be detected. For the present project, the stars observed range in spectral type from early B to late F Main Sequence stars, and include a small sample of giants and supergiants. Since a large fraction of really sharp-line early-type Main Sequence stars are chemically peculiar, the sample includes a number of such stars. Observations have been obtained of about 50 stars using the Gecko single-order high-resolution spectrograph at the Canada-France-Hawaii Telescope. The spectra have resolving power $R \approx 120000$ and typically are about 70 Å long. (Although most of these stars observed have previously been observed spectroscopically, our observations are usually at considerably higher resolving power than previous studies.) Most observations have been obtained in a window at $\lambda\lambda$4530-4600. The typical signal-to-noise ratio in the continuum is about 200. The spectra have been reduced and continuum normalized using IRAF.

3. Spectrum modelling

For a first exploration of these spectra, we have modelled them using the spectral synthesis code ZEEMAN.F (Landstreet 1988, Landstreet et al. 1989, Wade *et al.* 2001). Temperatures and gravities for individual stars have either been obtained using *uvby* colours with the programme UVBYBETANEW.F of Napiwotzki *et al.* (1993), or taken from previous analyses in the literature. Model atmospheres are interpolated in an experimental grid computed by Piskunov (private communication) with ATLAS9. The line lists used were obtained from the VALD database (Kupka *et al.* 1999). Using ZEEMAN, we search for a best fit to the observed spectrum, assuming that all elements are

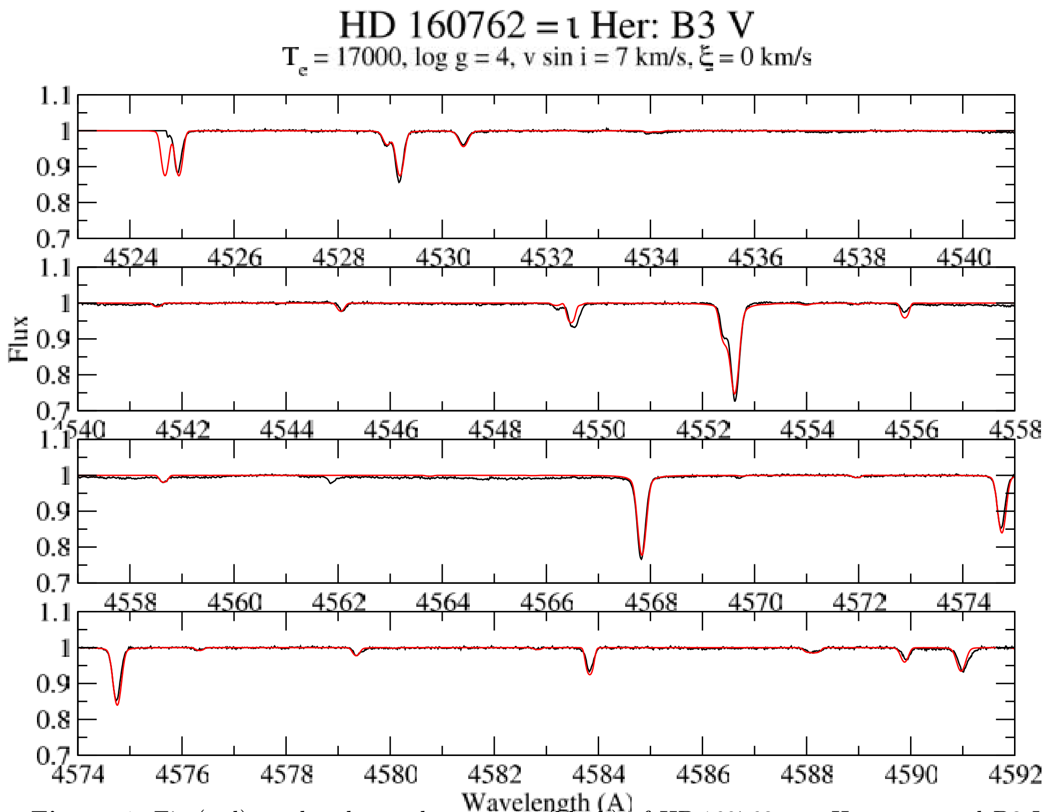

Figure 1. Fit (red) to the observed spectrum (black) of HD 160762 = ι Her, a normal B3 V star. Our model atmosphere has $T_{\rm eff}$ = 17000 K and $\log g$ = 4.0. The best fit $v \sin i$ = 7 km s^{-1}, and the microturbulence parameter is not determined by the lines in the observed window (none are sufficiently saturated). Abundances are generally fairly close to solar values except for Si which appears overabundant, but this may be a non-LTE effect.

homogeneously distributed horizontally and vertically, and that a height-independent microturbulence is present. The fitting procedure allows us to determine the rotational velocity $v \sin i$, the radial velocity $v_{\rm r}$, the abundances of several common elements (Fe, Cr, Ti, and sometimes Si, Ca and/or Ba for cooler stars, N, Ar, Al, Si, S, and Fe in early B stars), and in most cases to derive a value for the microturbulence parameter ξ.

The value of ξ, which probably reflects typical convective velocities in the atmosphere, provides us with a first indication of the state of motion of the atmosphere, and the value of $v \sin i$ provides a useful guide to the stars to examine closely for agreement between computed and observed line profiles. For Main Sequence stars only when $v \sin i$ is less than about 7 or 8 km s^{-1} have clear indications been found in the line profiles of the local surface velocity fields (see Landstreet 1998, Gray 1992).

At this point the synthesis of stars in the sample is not yet complete, but we discuss some examples of the kind of results that are found. The quality of our fits are displayed in Figures 1 – 5.

3.1. *HD 160762 = ι Her*

ι Her is a single-line spectroscopic binary, and a β Cep pulsating variable. However, no systematic discrepancies between computed and observed line profiles are found, It appears that even the very small $v \sin i$ (ι Her is one of the sharpest-line normal B stars known) is enough to mask the signature of any atmospheric convective velocity field

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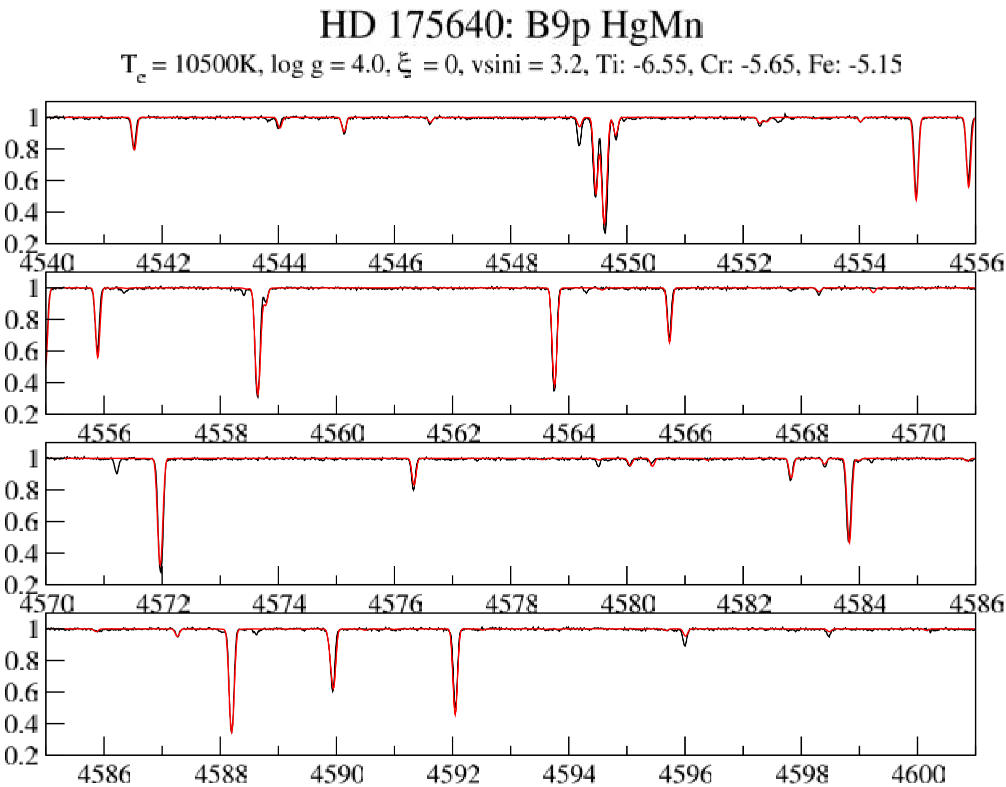

Figure 2. Fit to spectrum of the B9 III HgMn star HD 175640. The model used has $T_{\rm eff}$ = 10500 K and $\log g = 4.0$. The $v \sin i$ value is 2.9 km s^{-1}. The microturbulence is not significantly different from 0 (0.3 ± 0.3). Abundances are found for Ti, Cr, Fe and Ba; Cr is about one dex more abundant than the solar value, while Fe is underabundant by almost the same factor.

which might be present, and the same small $v \sin i$ prevents the β Cep oscillations from appearing in the profiles. The observed window does not contain any really strong lines, so we are unable to use the curve of growth to determine the value of the microturbulent parameter ξ. Thus in spite of the small value of $v \sin i$, our observations provide no information about atmospheric velocity fields.

3.2. *HD 175640*

HD 175640 is a single-line spectroscopic binary and a cool HgMn star. It has one of the smallest values of $v \sin i$ known among A and B stars. The best fit to the observed spectrum is obtained with $\xi = 0$, so this indicator suggests that the star has no significant atmospheric convection. The computed and observed profiles match very closely, assuming no microturbulent broadening and $v \sin i = 3.2$ km s^{-1}. thus the line profiles of this star provide no information about velocity fields despite the extremely small value rotational broadening.

3.3. *HD 103578 = 95 Leo*

This star shows clearly the departure of the line profiles from the simple model used. All the strong lines have a depressed blue line wing compared to the model lines. Furthermore, the $v \sin i$ value that reproduces the strong lines seems too large for the weak lines belonging to the primary star. Both of these characteristics are observed in a few other A stars (cf Landstreet 1998). (Numerous weak lines not modelled are from the secondary

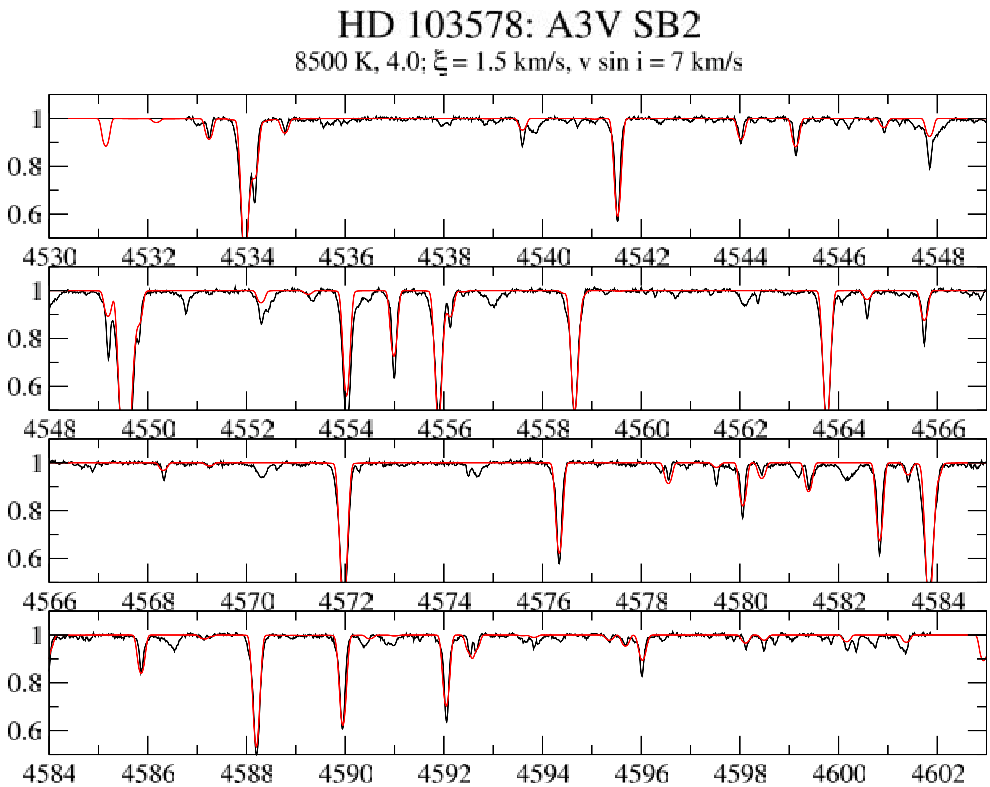

Figure 3. A fit to the spectrum of the A3 V star HD 103578. The star is an SB2 system. The spectrum has been corrected by subtracting 9% of the light to remove the secondary contribution to the line depth of the primary, but the secondary lines are still present in the spectrum. The model atmosphere has $T_{\rm eff} = 8500$ K and $\log g = 4.0$, which gives about the right ionization balance. The best microturbulence parameter is $\xi = 1.5 \pm 0.3$ km s^{-1}, and a value of $v \sin i =$ 7 km s^{-1} fits the stronger lines well. Abundances of the iron peak elements Ti, Cr and Fe, and that of Ba, are close to solar values.

star.) After (approximate) removal of the secondary lines from the observed spectrum, this star should provide a considerable amount of information about its surface velocity field.

3.4. *HD 185395* = θ *Cyg*

This star is a typical sharp-line F star. The red wings of the observed profiles of the strong lines generally are a little lower than the computed profiles; this corresponds to the "C"-shaped bisector curvature found in solar-type stars.

3.5. *HD 147084* = *o Sco*

This star has been suspected as a member of the Sco-Cen OB association, but the Hipparcos parallax shows that it is too far away. It is intermediate between a giant and a supergiant. The line profiles clearly show the effects of what is usually modelled as macroturbulence. The observed lines have depressed wings compared to the models, and clear bisector curvature. The $v \sin i$ that fits the strong lines seems too large for the weak lines. Such stars provide a lot of information about surface velocity fields in their line profiles.

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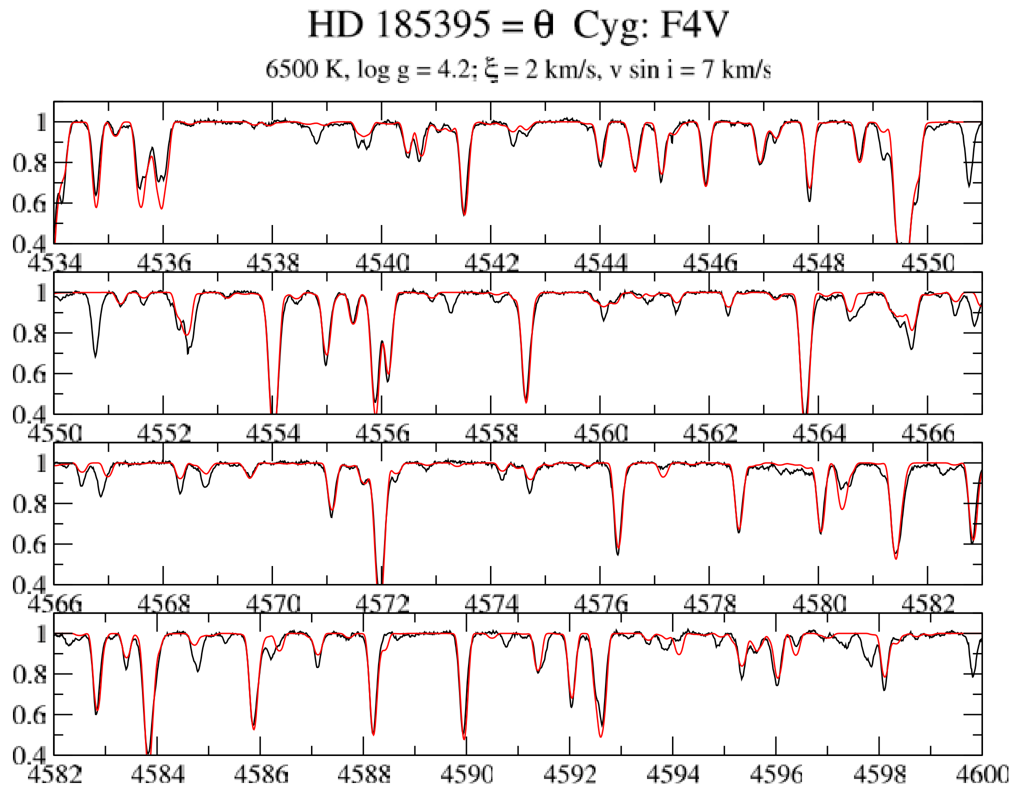

Figure 4. A fit to the spectrum of the sharp-line (and high-velocity) F4V star θ Cyg = HD 185395. The model atmosphere used by us has $T_{\rm eff}$ = 6500 and $\log g$ = 4.2. The best microturbulence is $\xi = 2 \pm 0.3$ km s^{-1}, and $v \sin i$ = 7 km s^{-1}. Abundances were fitted for Ca, Ti, Cr and Fe. With the effective temperature we have assumed, we find that the iron peak elements are of order 0.5 to 1 dex below solar values, unlike Adelman *et al.* (1997) who assume $T_{\rm eff}$ = 6810 K and find abundances close to solar.

4. Conclusions

From the data we have obtained and analyzed so far, three conclusions stand out.

• The stars whose profiles reveal the atmospheric velocity field are very rare among early-type stars on or near the Main Sequence.

• The classical spectral line model fits the line profiles of some early-type stars (even ones with very small v sin i) extremely well. However, in these stars we do not detect a non-zero microturbulence.

• In a very few stars with detectably non-zero microturbulence and $v \sin i$ less than about 5 or 6 km s^{-1}, the line profiles depart significantly from those of the classical line model. These are stars whose spectra contain further information about the atmospheric velocity fields.

The next step will be to use the new convection models to try to reproduce the profiles of stars for which the classical model gives unsatisfactory results.

Acknowledgements

We gratefully acknowledge financial support by the Natural Sciences and Engineering Research Council of Canada. FK acknowledges support from the IAU to attend Symposium 224.

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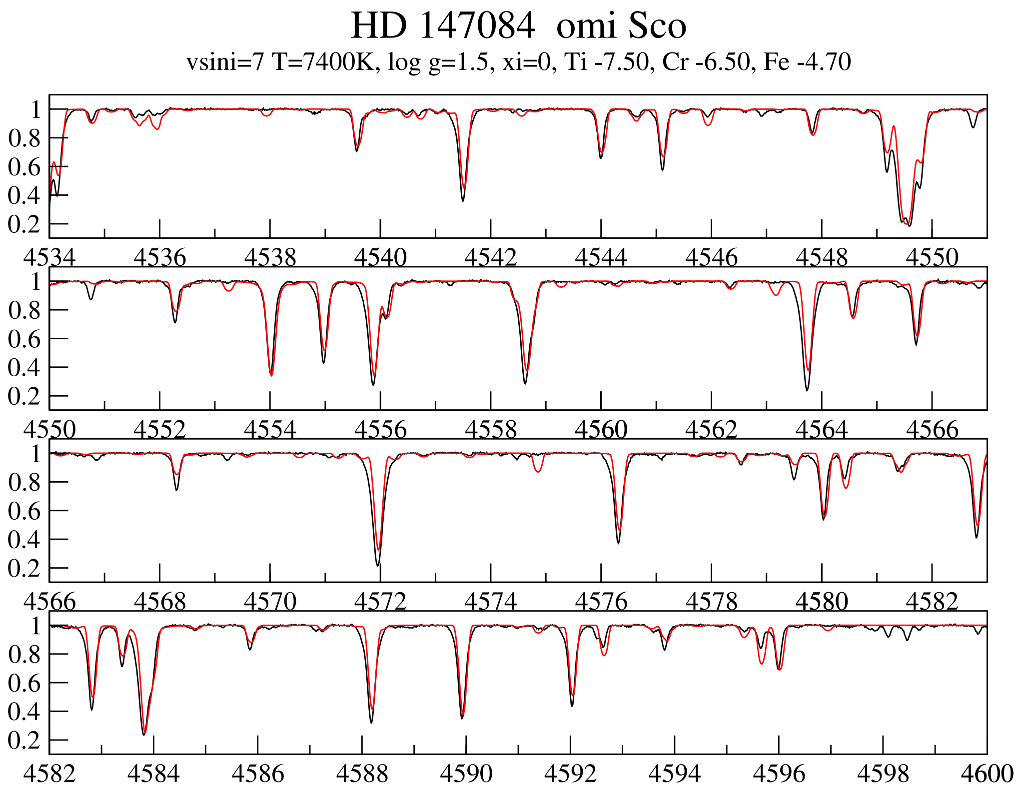

Figure 5. Fit to spectrum of the A4 II star o Sco = HD 147084. The model has $T_{\rm eff} = 7400$ and $\log g = 1.5$. The microturbulence parameter is found to be 1.3 ± 0.3 km s^{-1}. Abundances are found for Ti, Cr and Fe.

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